Late Paleogene extensional collapse of the Cordilleran foreland fold and thrust belt

Kurt N. Constenius


Copyright not claimed on content prepared wholly by U.S. government employees within scope of their employment. Individual scientists are hereby granted permission, without fees or further requests to GSA, to use a single figure, a single table, and/or a brief paragraph of text in subsequent works and to make unlimited copies of items in GSA's journals for noncommercial use in classrooms to further education and science. This file may not be posted to any Web site, but authors may post the abstracts only of their articles on their own or their organization's Web site providing the posting includes a reference to the article's full citation. GSA provides this and other forums for the presentation of diverse opinions and positions by scientists worldwide, regardless of their race, citizenship, gender, religion, or political viewpoint. Opinions presented in this publication do not reflect official positions of the Society.
Late Paleogene extensional collapse of the Cordilleran foreland fold and thrust belt

Kurt N. Constenius  Department of Geosciences, University of Arizona, Tucson, Arizona 85721

ABSTRACT

The Cordilleran foreland fold and thrust belt collapsed and spread to the west during a middle Eocene to early Miocene (ca. 49–20 Ma) episode of crustal extension. The sedimentary and structural record of this event is preserved in a network of half grabens that extends from southern Canada to central Utah. Extensional structures superposed on this allochthonous terrain are rooted to the physical stratigraphy, structural relief, and sole faults of preexisting thrust-fold structures. The sole faults dip 3°–6° west above an undeformed Precambrian crystalline basement and accommodate tectonic transport of a thick (up to 20+ km) eastward-tapering hanging wall during regimes of crustal shortening and extension. The chronology of tectonism for the foreland fold and thrust belt is established here by dating latest thrusting and initial normal faulting and is best defined where thrusts and normal faults are linked by common detachment surfaces. Dated movement on two extensionally reactivated thrusts, the Lewis thrust of northwest Montana and southeast British Columbia and the Medicine Butte thrust of southwest Wyoming and northeast Utah, suggests that the hiatus between the end of crustal shortening in the early or early middle Eocene and the start of extension in the early middle Eocene was brief.

Lateral spreading and extensional basin formation in the Cordilleran foreland fold and thrust belt were partly concurrent with formation of metamorphic core complexes and regional magmatism. Conceptually linking extensional processes that were simultaneously deforming both the hinterland and foreland of the late Paleogene Cordilleran orogenic wedge is accomplished by applying the extensional-wedge Coulomb critical-taper model. The rapid drop in North America–Pacific plate convergence rate and/or steepening of the subducted oceanic slab at ca. 50 Ma resulted in a large reduction in east-west horizontal compressive stress in the Cordillera. As a result, the Cordilleran orogenic wedge was left unsupported, and it gravitationally collapsed and horizontally spread west until a new equilibrium was established at ca. 20 Ma. Subsequently, crustal extension and magmatism during the Basin and Range event (ca. 17–0 Ma) overprinted much of this earlier phase of extension.

INTRODUCTION

This paper examines a widespread belt of late Paleogene crustal extension that is expressed as a network of half grabens superposed on the Cordilleran foreland fold and thrust belt from southern British Columbia to central Utah (Fig. 1). Regional studies of the foreland fold and thrust belt identified the structural style and general ages of extension but considered the half grabens to be of local importance (Armstrong and Oriel, 1965; Bally et al., 1966; Dahlstrom, 1970; Royse et al., 1975; Fermor and Moffat, 1993; Royse, 1993). Detailed studies of individual half grabens in the thrust belt also focused on structure and ages of basin-fill assemblages but failed to consider the development of these structures in the context of an integrated system of extension that affects large parts of the Cordillera (e.g., Kuenzi and Fields, 1971; Royse et al., 1975; Sprinkel, 1979; Constenius, 1982). Previous studies generally considered the half grabens to be late Paleogene and Neogene “Basin and Range” phenomenon that developed 10 to 20 m.y. or more after thrust-fold deformation (e.g., Pardee, 1950; McMannis, 1965; Bally et al., 1966; Constenius, 1982; Lamerson, 1982; Fields et al., 1985). Recently it has been proposed that some of the half grabens encompass a rift zone in Idaho and Montana (Janecke, 1994).

The primary goal of this paper is to document the structural setting and ages of contractional and extensional deformation that bear on the origin of the late Paleogene half grabens. Additionally, data presented here provide evidence for temporal and structural linkage of extensional structures in the foreland fold and thrust belt with formation of metamorphic core complexes and low-angle detachment faults. The following hypotheses are proposed regarding the transition from contractile to extensional deformation, the ages of extensional deformation, and the genesis of crustal extension in the foreland fold and thrust belt. First, the hiatus between the cessation of crustal shortening and the inception of crustal extension was brief, ~1–5 m.y. Second, two temporally and tectonically distinct episodes of normal faulting and basin-fill sedimentation are recognized: (1) a late Paleogene episode that was partly coeval with formation of metamorphic core complexes in the hinterland of the Cordillera and (2) a Neogene episode related to Basin and Range tectonism. Third, changes in the rate and style of North America–Pacific plate convergence in late Paleogene time resulted in the gravitational collapse of the Cordilleran orogenic wedge.

Evidence to support these hypotheses comes from tabulation of chronostratigraphic and geochronologic data that describe the timing of latest contractile and the onset and duration of extensional deformation in the foreland fold and thrust belt. The timing of extensional basin formation in the Cordilleran foreland is examined here in both dip and strike directions and with respect to the time-space pattern of regional magmatism. Detailed discussion of two systems of linked thrust and normal fault structures found at the northern and southern ends of the half graben network, the Lewis thrust–Kishenehn basin system of northwest Montana and southeast British Columbia and the Medicine Butte thrust–Fowkes half graben system of southwest Wyoming and northeast Utah (Fig. 1), is used to illustrate the timing and structural styles of contractile and extensional deformation. These two basins contain thick sequences of nonmarine, late
Paleogene sedimentary rocks that are bounded by listric normal faults that sole into preexisting thrust faults, the Lewis and Medicine Butte thrusts, respectively (Bally et al., 1966; McMechan, 1981; Constienius, 1982; Lamerson, 1982).

The Lewis and Medicine Butte detachments and related structures were the focus of this investigation because it was possible to construct an excellent record of the ages of thrust and normal displacements on these faults, and the structural geometry of these fault systems has been well documented. Three fundamental relationships establish a tectonic chronology for these areas (Fig. 2). First, the end of crustal shortening was determined from dating the youngest thrust(s) by crosscutting relationships, provenance data, dating of fault gouge, and thermochronologic studies. Second, extensional reactivation of the "youngest" thrust faults was identified where listric normal faults sole downward to former thrust surfaces. Finally, the age of initial crustal extension was determined from dating basin-fill sedimentary units that were deposited synchronously with displacements on the bounding listric normal fault.

### MONTANA DISTURBED BELT AND SOUTHERN CANADIAN ROCKIES

#### Structure of the Lewis Thrust and Its Footwall

The Lewis thrust is a classic folded thrust with a strike dimension of 457 km (Mudge and Earhart, 1980) that places a 6- to 7-km-thick slab of Proterozoic and lower Paleozoic rocks (Ross, 1959; Childers, 1964) onto a complexly deformed footwall of Paleozoic and Mesozoic strata (Figs. 3 and 4). Displacement on parts of the fault have been estimated in the range of 100–115 km (Van der Velden and Cook, 1994; Price, 1988) and may exceed ~135 km. A striking feature of this thrust is its prominent, centrally located salient, which protrudes 40 km northeastward toward the foreland. The Lewis thrust terminates near Mount Kidd, British Columbia, in the north, and Steamboat Mountain, in the south, along shear zones in tightly folded Mississippian rocks (Dahlstrom et al., 1962; Mudge and Earhart, 1980). Laterally from these tips, the Lewis thrust cut symmetrically down-section in the hanging wall, eventually truncating Proterozoic rocks. The systematic geometry of the lateral ramps reflects changes in the slip and stratigraphic throw on the fault. The symmetric nature of this "scooped-shaped" thrust controlled the extensional geometry of the Kishenehn basin, which resulted from inversion along the Lewis thrust (Constienius, 1988).

The Lewis thrust has been folded upward ~3.0–3.5 km by formation of the Flathead and Waterton duplex zones in the footwall of the thrust (Fig. 4) (Bally et al., 1966; Fermor and Moffat, 1993). The geometry of the hanging wall of the Lewis hanging wall is that of a flat in the lower Belt Supergroup strata, whereas the footwall has flat-ramp-flat relations in which the thrust cut upsection from the middle Cambrian to the Upper Cretaceous from southwest-northeast. Pre-erosional thickness of the Lewis thrust sheet is fixed at ~7–8 km, because Lower Cretaceous strata in the hanging wall were downdropped and preserved beneath basin-fill deposits of the Kishenehn Formation (Fig. 4). Additionally, McGimsey (1982), Fermor and Price (1987), and Yin (1993) have documented extensive intraplate thrust-fold structures in lower Belt rocks that locally thicken the Lewis sheet. Collectively, the Flathead ramp and Flathead duplex raised and folded the ~7- to 8-km-thick Lewis thrust sheet, which created an immense structural culmination and locally overthickened the crust.

#### Age of Final Slip on the Lewis Thrust

The end of crustal shortening in the southern Canadian Rockies and the Montana disturbed belt is generally considered to be latest Paleocene to early Eocene in age (Bally et al., 1966; Mudge, 1982; Hoffman et al., 1976; Harlan et al., 1988). Cessation of shortening on the Lewis thrust has not been precisely determined because the thrust sheet has been deeply eroded, removing any Late Cretaceous–early Eocene strata that may have overlain or been truncated by the fault. Consequently, establishing a date of youngest movement on the thrust requires relative age determination from crosscutting relationships, indirect geochronologic dating methods, age determination of associated thrusts and footwall-duplex zones formed concurrently with deformation of the Lewis thrust, and provenance studies. The Lewis thrust truncates many subsidiary thrusts in the eastern part of the Disturbed Belt (Mudge and Earhart, 1980; Childers, 1965), and, hence, latest movement on the Lewis is relatively young. Interpretation of the Lewis thrust using a synchronous thrusting model (Boyer, 1992) suggests that the entire region was undergoing shortening even though only a minor part may have been actively deforming. Furthermore, Boyer (1992) suggested that the youngest imbricate thrusts are part of the Flathead duplex, the site of later superposed
Radiometric age determinations of thrust fault displacements in the Front Ranges belt of the southern Canadian Rockies give ages of 65–55 Ma for the Lewis thrust and indicate that the age of thrusting for this area spanned from about 100 to 53 Ma (Covey et al., 1994). These thrust-displacement ages were based on K/Ar dating of illite and illite-smectite clays from fault gouge and are subject to uncertainties as high as 10 m.y. Absolute age determinations from four Montana disturbed belt studies restrict the terminal thrust-fold event to between ca. 58 Ma and ca. 48 Ma. First, K/Ar dating (illite-smectite) of low-grade “burial” metamorphism in Cretaceous bentonite beds that resulted from stacking of thrust sheets limits the time of thrusting to between 72 and 56 Ma (Hoffman et al., 1976). Recalculation of some of the youngest dates reported by Hoffman et al. (1976) using revised decay constants gives ages of 57.6, 58.3, and 58.4 Ma (Marvin et al., 1980). These are “disturbed” ages rather than “reset” ages, however, which means that the time of burial metamorphism can be no older than the cited apparent ages. Second, in the Wolf Creek area, a sill of quartz monzonite porphyry folded and cut by thrust faults yielded a K/Ar date (biotite) of 59.6 ± 1.6 Ma (Schmidt, 1978; Whipple et al., 1987). Third, K/Ar dating of intrusive igneous rock bodies that cut or intrude along thrusts in the southern Montana disturbed belt led Mudge (1982) to conclude that most, if not all, deformation in this area occurred during Paleocene time. His conclusion is based in part on dating of an undeformed hornblende-monzonite dike that yielded a K/Ar date (hornblende) of 47.5 ± 1.3 Ma (Schmidt, 1978; Whipple et al., 1987). Geochronologic and paleomagnetic data published by Harlan et al. (1988) regarding the age and timing of undeformed alkaline igneous rocks in the northwest part of the Crazy Mountains basin that intruded thrust-deformed rocks of the Fort Union Group (Puercan–middle Tiffanian; ca. 66–60 Ma) (Hartman, 1989; Hartman et al., 1989) indicate that thrusting occurred prior to the late early or early middle Eocene (ca. 52–48 Ma).

The youngest unit truncated by the Lewis thrust is the Campanian Belly River–Two Medicine Formation (ca. 79–74 Ma; Eberth and Ryan, 1992). The youngest sedimentary unit truncated by thrusts in the footwall of the Lewis thrust (Price, 1986; Mudge and Earhart, 1983) is the Willow Creek Forma-
Albertasyncline has been tilted (Douglas, 1950; Fox, 1990). The Porcupine rocks of the Porcupine Hills Formation can to early Tiffanian (ca. 65–61 Ma) is found in early to late Paleocene (Puere) deposition of the Willow Creek Formation. Evidence that shortening continued after deposition of the Willow Creek Formation. Factors on the Lewisthrust was subsequent to conclu -
ding in the northern Cordillera.

Structure of the Flathead Normal Fault

The Kishenehn basin is situated south-west of the Lewis thrust salient (Fig. 3) as a narrow, asymmetric graben 150 km long and 2 to 13 km wide. The Flathead listric normal fault system, the master structure that controlled basin origin, borders the Kishenehn basin to the northeast. Estimates of maximum slip on the Flathead fault are on the order of 15 km (Constenius, 1988). The southwest basin margin is either bounded by faults antithetic to the Flathead system, or it is onlapped by Kishenehn basin strata. Subsidence along these faults created an asymmetric graben containing up to 3400 m of nonmarine, late Paleogene sedimentary rocks of the Kishenehn Formation.

The structural position of the Kishenehn basin with respect to the Lewis thrust salient reflects the common fault surface that accommodated both shortening and extension (Constenius, 1988; McMechan, 1981). The termini of the basin and the longitudinal extent of the Flathead fault system roughly coincide with the reentrants of the Lewis thrust salient (Fig. 3). In addition, slip on the west, such as the Lewis and Eldorado thrusts, and consist of 50%–80% argillite and quartzite of Belt Supergroup, 1%–5% Paleozoic rocks, 20%–40% Late Cretaceous igneous rocks (Elkhorn and Adel Mountain volcanic rocks?), and <1% chert and conglomerate (Hearn et al., 1964). The average grain size of the conglomerate clasts and the percentage of limestone clasts decrease from west to east across the Bearpaw Mountains—an indication of eastward transport from a western source area (Hearn et al., 1964; Bryant et al., 1960). The Wasatch Formation has been assigned an early Eocene age (Wasatchian; ca. 57–54 Ma) based on flora and vertebrate fossils (Marvin et al., 1980; Brown and Pecora, 1949) and is overlain with angular unconformity by intrusive rocks of the Bearpaw Mountains volcanic field (Hearn, 1976), which have been isotopically and paleobotanically dated as late early–early middle Eocene (ca. 54–50 Ma) (Marvin et al., 1980; Wing and Greenwood, 1993). The Missouri Breaks diatremes are early middle Eocene in age (ca. 52–47 Ma) (Marvin et al., 1980).

Similar stratigraphic relationships are found in the Highwood Mountains, ~100 km southwest of the Bearpaw Mountains, where early-middle Eocene volcanic rocks (ca. 53–50 Ma) overlie and intrude coarse alluvial-fan conglomerate of the Wasatch Formation (Marvin et al., 1980; O’Brien, 1991). Wasatch conglomerate in the Highwood Mountains consists of clasts of Archean granite gneiss, Cambrian quartzite, and Paleozoic limestone and dolomite, indicating a different source area than related conglomerate in the Bearpaw Mountains. However, both units represent syntectonic sedimentation associated with the unroofing of Laramide foreland and thrust-fold structures, respectively. The Wasatch Formation is the last unit related to thrust-fold shortening in the northern Great Plains, and the early to middle Eocene igneous rocks that overlie and intrude this unit signal the onset of mid-Cenozoic crustal extension and magmatism in the northern Cordillera.
Flathead and Lewis faults is bilaterally symmetrical, and their centerlines of symmetry and inferred loci of maximum displacement coincide (Constenius, 1982; McMechan, 1981). Ultimately, these relationships are related to the symmetry and dimensions of the Lewis footwall ramp (Flathead ramp; Boberg, 1993), which cuts upsection across ~2.5 km of middle Cambrian to Lower Cretaceous strata (Figs. 4, 5, and 6; Bally et al., 1966; Fermor and Moffat, 1993). Critical relationships identified in Figures 4 and 6 are as follows.

1) The Flathead fault is superposed on the west flank of a major structural culmination composed of two overlapping tectonic elements, the Flathead duplex, and the Flathead ramp (Fritts and Klipping, 1987).

2) The Flathead fault is a listric normal fault that merges with the reactivated segment of the Lewis thrust. The fault dips ~40°–50° southwest near the surface and flattens at depth, and it is layer-parallel in the basal Cambrian detachment horizon that dips conformably with autochthonous basement about 2°–3° (35–52 m/km) southwest (Yoos et al., 1991; Bally et al., 1966). Displacement on the Flathead fault is about 13–15 km to the southwest (Constenius, 1988; McMechan, 1981).

3) The Kishenehn basin is a half or asymmetric graben in the central and northern parts of the basin. The dip of the Kishenehn Formation is ~40°–50° in the lowest beds and decreases systematically upsection and toward the Flathead fault to ~20°–25° (Constenius, 1981; McMechan, 1981). Hence, preserved in these middle Eocene to early Miocene synextensional strata is a record of ~40°–50° of total rotation of the hanging wall, ~20°–30° of growth-fault-related rotation, and ~20°–25° postdepositional rotation. To the south in the Middle Fork region (Fig. 5), strata of the Kishenehn Formation are middle Eocene in age and have been rotated as much as 50°, 20° of which is growth-fault-related rotation and about 30° of which represents post depositional rotation.

**Figure 5.** Geologic cross section B–B’ of southern Kishenehn basin showing listric normal faults of Flathead fault system (Roosevelt and Blacktail faults) soling into reactivated part of Lewis thrust and associated rotation of hanging-wall strata. Kishenehn strata display a gradual flattening of dip up-section and thicken toward Roosevelt fault, a manifestation of concurrent sedimentation and slip on a curved fault surface. Stratigraphic position of middle Eocene (Uintan) fossil localities and dated tephra deposit are indicated. Rock unit abbreviations: Yap/Yal, Ygl, Ye, Ys, Ysh, Yms, Ybo, and Ymc, formations of Proterozoic Belt Supergroup; TcL, Tccm, Tccu, and Tp, Coal Creek (lower, middle, and upper sequences) and Pinchot members of Kishenehn Formation; Yap/Yal, Appekunny and Allyn Formations; Ygl, Grinnell Formation; Ye, Empire Formation; Yh, Helena Formation; Ysn, Snowslip Formation; Ysh, Shepard Formation; Yms, Mount Shields Formation; Ybo, Bonner Quartzite; Ymc, McNamara Formation.

Age of Slip on the Flathead Normal Fault

The synextensional nature of the Kishenehn Formation has been established using study of sedimentary structures, facies relationships, provenance, paleocurrent directions, and stratigraphic successions (Constenius, 1981, 1982, 1989; McMechan and Price, 1980; McMechan, 1981). Synextensional sedimentary sequences display stratal growth relationships, a systematic thickening of strata toward the basin-bounding listric normal fault, and a gradual flattening of dip in successively younger units (Dahlstrom, 1970; McMechan and Price, 1980). The strong rotational control on sedimentation associated with listric normal faulting results in a half graben or asymmetric graben with a wedge-shaped sedimentary prism. Strata of the Coal Creek member of the Kishenehn Formation dip 50°NE at the base and progressively decrease to 32°NE near the top of the unit (Fig. 5). This indicates that displacement and rotation along the Roosevelt and Blacktail fault seg-
Figure 6. Simplified regional geologic cross section R1–R1′ of northwest Montana based on results of seismic reflection and refraction profiles, Bouguer gravity data, well control, and balanced cross sections (Bally et al., 1966; Harris, 1985; Fritts and Klipping, 1987; Constenius, 1981, 1988; Boberg et al., 1989; Yoos et al., 1991; Harrison et al., 1992; Sears and Buckley, 1993; Van der Velden and Cook, 1994). Hanging wall rocks above ~3° west-dipping regional detachment constitute a westward thickening extensional wedge with a tip delineated by Flathead fault and ~20 km maximum thickness west of Purcell anticlinorium. The Archean crystalline basement (fine-line stipple) has remained undeformed in spite of considerable supracrustal shortening and extension. Rocks of lower Proterozoic Belt Supergroup are shaded (Prichard Formation and equivalents); middle and upper Belt rocks (Ravalli-Missoula Groups) and Phanerozoic rocks are unshaded; Cretaceous intrusives have linestipple; late Paleogene basin fill is heavy stipple. Sense of motion on thrusts and extensionally reactivated thrusts indicated are by arrows; other normal faults are unmarked.

ments of the Flathead fault system were synchronous with sedimentation.

Many investigators have used the age of the Kishenehn Formation as the time of initial crustal extension in the region and, consequently, as an upper time limit of contractual deformation (e.g., McMannis, 1965; Bally et al., 1966; McMechan, 1981; Constenius, 1982). Previous age determinations of the Kishenehn Formation, which relied on dating fossil mammals, mollusks, leaves, and pollen from exposures in Canada (Russel, 1954, 1964; Hopkins and Sweet, 1976; McMechan, 1981), concluded that the unit was late Eocene to early Oligocene in age. Recent discoveries of mammal fossils from the Coal Creek member of the Kishenehn Formation suggest a middle Eocene age (Uintan, ca. 48–42 Ma) (M. R. Dawson and A. R. Tabrum, personal commun., 1993). Isochronous analysis of a tephra from the Coal Creek member also established a middle Eocene age for this unit. Single-crystal laser fusion 40Ar/39Ar dating of 12 biotite grains from this tephra resulted in an age of 46.2 ± 0.4 Ma (R. C. Walter, written commun., 1990). Fission-track analysis of 7 zircon grains from this tephra yielded a date of 43.5 ± 4.9 Ma (C. W. Naeser, written commun., 1990; revised from 33.2 ± 1.5 Ma reported by Constenius et al., 1989). Approximately 1150 m and 1450 m of exposed section underlie the dated tephra and mammal beds, respectively. Using assumed sedimentation rates on the order of 500 m/m.y. (McMechan, 1981), age estimates of the lower exposures of the Coal Creek would be 2.0 to 2.5 m.y. older than the dated units, or roughly 48–49 Ma, early Uintan to Bridge-

Regional Style of Normal Faulting

The Flathead fault defines the eastern boundary of an ~180-km-wide belt of extension in the Cordilleran foreland fold and thrust belt (Fig. 6). Listric normal faults bounding the Kishenehn basin, South Fork basin, southern Rocky Mountain Trench (Flathead Valley), and numerous other normal faults sole into the extensionally reactivated regional detachment fault. Hanging wall rocks above this regional detachment constitute a westward-thickening extensional wedge with a tip delineated by the Flathead fault and a maximum thickness of ~20 km found west of the Purcell anticlinorium.

Total extension across this belt has been estimated at ~25 km (McMechan and Price, 1984; Harrison, 1988) but may exceed ~30 km because displacements on listric normal faults bounding the Kishenehn basin, South Fork basin, and southern Rocky Mountain Trench are ~15 km, ~7 km, and ~10 km, respectively (Constenius, 1981, 1988; Van der Velden and Cook, 1994). Numerous small normal faults that have displacements in the range of 0–100 m that are not resolvable seismically or depicted on regional maps or cross sections collectively contribute significantly to total extension.

Interpretations of seismic reflection profiles, Bouguer gravity data, well control and balanced cross sections in northwest Montana and southern British Columbia indicate that the regional detachment fault dips west at ~3° and that the underlying Archean crystalline basement is undeformed (Bally et al., 1966; Harris, 1985; Fritts and Klipping, 1987; Boberg et al., 1989; Yoos et al., 1991;
forward in this area because syntectonics and deformation are preserved in juxtaposition with thrust-fold and extensional structures. These relationships have been defined by detailed surface mapping, biostratigraphic analysis, and extensive borehole and seismic data. In addition to the Fowkes half graben, there are several other late Paleogene half grabens in this region, the bounding faults of which are interpreted to sole into preexisting thrusts. However, west of the Wasatch fault, these half grabens have been overprinted by later Basin and Range extension. Two distinct phases of extension are exemplified by interpretation of seismic and borehole data from the Great Salt Lake that reveal a late Paleogene half graben buried under several kilometers of Neogene basin fill.

**Structure of the Medicine Butte Thrust**

The Medicine Butte thrust is a frontal footwall imbricate of the Crawford thrust that is situated above the major footwall ramp and associated fault-bend fold of the Absaroka thrust (Coogan, 1992; DeCelles, 1994). In the footwall ramp, the Absaroka thrust cuts from Cambrian through to Lower Cretaceous strata. The resultant fault-bend fold in the hanging wall has about 5.0 to 5.5 km of structural relief and is cored by lower Paleozoic rocks (Lamerson, 1982; Platt and Royse, 1989). Slip on the Medicine Butte thrust is difficult to determine but is at least 3 to 4 km. Surface and subsurface data indicate that at its leading edge the thrust consists of a zone of imbricate thrust slices of Jurassic Preuss Formation and Upper Jurassic-Lower Cretaceous Gannet Group. The oldest rock unit in the Medicine Butte thrust sheet is the evaporite unit of the Preuss Formation. The Preuss evaporite unit is one of the main detachment surfaces, not only for the Medicine Butte thrust, but also the Bridger Hill thrust, the Absaroka thrust and its many imbricates, and the Acocks and Almy listric normal faults (Royse, 1983; Lamerson, 1982).

**Age of Final Slip on the Medicine Butte Thrust**

The Medicine Butte thrust fault truncated and displaced units as young as the late Paleocene part of the Evanston Formation. Exposures of even younger units such as the basal conglomerate, lower member, and Main Body of the early Eocene Wasatch Formation in the Medicine Butte footwall have sustained thrust-related folding and internal deformation. Exposures of near-vertical or overturned Evanston Formation and/or basal conglomerate member of the Wasatch Formation can be found along the trace of the thrust (Veatch, 1907; Lamerson, 1982; Bryant, 1990). Footwall rocks consisting of the Main Body of the Wasatch and Green River Formations dip from 62° to 71° away from the toe of the Medicine Butte thrust. Data relevant to the age of the Evanston and Wasatch Formations are included in studies by Gazin (1952, 1956, 1962, 1969), Oriel and Tracey (1970), Jacobson and Nichols (1982), Lamerson (1982), and Nichols and Bryant (1990); a synthesis of their work follows.

The upper Evanston has been assigned a late Paleogene (Torrejonian-Tiffanian, ca. 63–59 Ma) age based on vertebrate fauna, leaves, and palynomorphs. The age of the basal conglomerate member of the Wasatch is indeterminate. Oriel and Tracey (1970) assigned the unit an early Eocene age based on a single gastropod fossil, whereas Nichols and Bryant (1990) considered its age to be late Paleocene. Rocks of the lower member unconformably overlie the basal conglomerate member, and the fossil fauna and flora suggest an early Eocene age. The main body of the Wasatch contains an extensive vertebrate fauna with early to middle Early Eocene affinities (i.e., Gray Bull and Lysite ages of the Wasatchian, ca. 57–53 Ma). The remaining three members of the Wasatch—the sandstone tongue, the mudstone tongue, and the Tunp member—are not preserved in direct contact with the Medicine Butte thrust but do provide a record of early to middle Eocene (i.e., passive uplift and rotation over the Hogsback footwall ramp) and last displacements on the Tunp and Crawford thrusts. Although fossils have not been found in the Tunp member, stratigraphic relationships indicate that its age is equivalent to the whole of the Wasatch Formation, and, therefore, it is mainly early Eocene (ca. 57–51 Ma) in age. The upper part of the Tunp may be latest early to middle Eocene based on stratigraphic correlation and dating of gastropods in stratigraphically equivalent beds in the Green River Formation. Thus, the timing of the Medicine Butte thrust is very young and coeval with movement on the Hogsback and Tunp thrusts. Consequently, this area provides evidence...
that the region was subjected to regional shortening through early Eocene and possibly early middle Eocene (ca. 57–51 Ma) time.

**Structure of the Acocks-Almy Fault System**

The Acocks-Almy listric normal fault system has reactivated the segment of the Medicine Butte thrust that is superposed on the west limb of the Absaroka fault-bend fold. Lamerson (1982, p. 336) noted that “nearly all the extension in the southern Fossil Basin by normal faults such as the Acocks-Almy system, is concentrated on the hanging wall of the Medicine Butte thrust.” About 3 km of retrograde displacement has taken place on the Medicine Butte thrust plane. Down-dropping and rotation of the Medicine Butte hanging wall along the Acocks-Almy listric fault system created a network of half grabens in which up to 1500 m of middle Eocene Fowkes Formation and at least 600 m of the Norwood Tuff were deposited and preserved (Figs. 8 and 9). Interpretation of borehole data, field evidence, and seismic data supports the contention that

![Figure 7. Geologic index map of southwestern Wyoming and northeastern and central Utah highlighting late Paleogene grabens and major structural elements of the Cordilleran foreland fold and thrust belt. Structures and basin outlines adapted from Hintze (1980), Love and Christiansen (1985), Witkind and Weiss (1991), and Bryant (1992).](image-url)
Fowkes sedimentation was coeval with Acocks-Almy normal faulting (Lamerson, 1982, p. 332–334). Principal indications of synextensional sedimentation in the Fowkes half graben are as follows: (1) the occurrence of Fowkes Formation only in the hanging wall of these faults, (2) thickening of units into the fault and in certain areas flattening of dip in successively younger beds (Figs. 8 and 9), and (3) development of unconformities within the Fowkes Formation limited to the western margin of the half graben. Parts of the Fowkes half graben where the synextensional units lack stratal growth geometries but are tilted may indicate considerable displacement and rotation after deposition of the Fowkes Formation, dissolution and collapse of the Preuss evaporite unit in the footwall of the Acocks-Almy fault system attains thicknesses as much as 1.2 km (Lamerson, 1982).

**Age of Slip, Acocks-Almy Normal Faults**

The Fowkes Formation contains the first sedimentary record of extension in this area. The Fowkes unconformably overlies the Wasatch Formation and consists of up to 1500 m of dominantly tuffaceous mudstone, sandstone, and conglomerate and siliceous limestone (Nelson, 1973). A middle to late Eocene age for the Fowkes Formation was assigned by Oriel and Tracey (1970) based on fossil gastropods, leaves, and a hornblende K/Ar date of 48.2 ± 1.5 Ma (recalculated). More-recent vertebrate paleontologic and radiometric work by Nelson (1973, 1974, 1979) has established that the lower Fowkes Formation is early middle Eocene in age (Bridgerian, ca. 49–48 Ma). The biotite K/Ar age from a tephra in the Fowkes Formation in Nelson’s study was 49.1 ± 1.9 Ma (recalculated using critical table; Dalrymple, 1992).

In the southern part of the Fowkes half graben, on Porcupine Ridge, the Fowkes Formation is overlain by late Eocene to late Oligocene synextensional deposits of the Norwood Tuff (Bryant, 1990) (Fig. 8). Rocks of the Norwood Tuff have not been dated at Porcupine Ridge, but the Norwood Tuff and its stratigraphic equivalent, the Moroni Formation, are found in association with several other half grabens in northeast and central Utah (e.g., East Canyon, Morgan Valley–Huntsville, Great Salt Lake, Tibble, Little Diamond Creek; Figs. 1 and 7). The Norwood Tuff–Moroni Formation, which ranges in thickness from about 1.0 to 4.5 km, consists of tuff, volcaniclastic sandstone and...
conglomerate, lahars, a few thin flow brec-
cias, interbedded with conglomerate con-
taining sedimentary clasts (Bryant et al.,
1989; Witkind and Marvin, 1989; Bryant,
1990). Synextensional stratal growth geom-
etries of Norwood Tuff–Moroni Formation
deposits in these half grabens indicate that
sedimentation was concurrent with normal
faulting in late Eocene to late Oligocene
time (Royse, 1983; Hopkins and Bruhn,
1983; Riess, 1985; Houghton, 1986; Bryant
et al., 1989; Constenius, 1995). Collectively,
isotopic age determinations from these ba-
sin-fill deposits suggest that the Norwood
Tuff–Moroni Formation is late Eocene to
late Oligocene (ca. 39–27 Ma) in age (Crit-
tenden and Sorensen, 1985; Van Horn and
Crittenden, 1987; Bryant et al., 1989; Wit-
kind and Marvin, 1989). Mammal fossils
from the Norwood Tuff are rare but indicate
a late Eocene (Duchesnean and Chadron-
ian, ca. 41–34 Ma age range) age for these
rocks (Nelson, 1971). Recent discovery of
the camel fossil, Blicokomylus near B. ga-
lushai, from the upper part of the Moroni
Formation may extend the time-range of
this formation to the late early Miocene
(Hemingfordian, ca. 21–16 Ma) (M. R.
Dawson, personal commun., 1995). Analysis of
dipmeter data indicates Neogene strata dip 5°–12°
east to northeast, whereas, late Paleogene beds dip 15°–35° south to southwest. Zircon fission-track ages bracket unconformity and establish an age for rocks in buried half graben: 10.3 ± 1.0 and 29.9 ± 1.3 Ma at depths of 2721 and 3674 m, respectively (Bryant et al., 1989). Thickness of late Paleogene rocks (Norwood Tuff equivalent) is ~2.0 km. Seismic data courtesy of Amoco Production Company (FWK-1 and GSL-3) and CGG (WDF-1).

Neighboring volcanic fields, such as the Tin-
tic Mountains, Park City, and Traverse
Range volcanic fields, which are also
thought to be sources of sediment for the
Norwood Tuff and Moroni Formation, range in age from ca. 40–28 Ma (Laughlin et al., 1969; Nelson, 1971; Morris and Lover-
ning, 1979; Crittenden et al., 1973; Bromfield
et al., 1977; Bryant et al., 1989).

Physiographically, some exposures of ba-
sin fill in the Fowkes half graben, such as
those found on Porcupine Ridge, are in-
verted with respect to the modern drainage
basin by as much as 200–300 m, implying
that this basin is no longer actively subsid-
ing. In low-lying areas along the Bear River
drainage, the Fowkes Formation is overlain
by only a thin mantle of Quaternary sedi-

conglomerate, lahars, a few thin flow brec-
cias, interbedded with conglomerate con-
taining sedimentary clasts (Bryant et al.,
1989; Witkind and Marvin, 1989; Bryant,
1990). Synextensional stratal growth geom-
etries of Norwood Tuff–Moroni Formation
deposits in these half grabens indicate that
sedimentation was concurrent with normal
faulting in late Eocene to late Oligocene
time (Royse, 1983; Hopkins and Bruhn,
1983; Riess, 1985; Houghton, 1986; Bryant
et al., 1989; Constenius, 1995). Collectively,
isotopic age determinations from these ba-
sin-fill deposits suggest that the Norwood
Tuff–Moroni Formation is late Eocene to
late Oligocene (ca. 39–27 Ma) in age (Crit-
tenden and Sorensen, 1985; Van Horn and
Crittenden, 1987; Bryant et al., 1989; Wit-
kind and Marvin, 1989). Mammal fossils
from the Norwood Tuff are rare but indicate
a late Eocene (Duchesnean and Chadron-
ian, ca. 41–34 Ma age range) age for these
rocks (Nelson, 1971). Recent discovery of
the camel fossil, Blicokomylus near B. ga-
lushai, from the upper part of the Moroni
Formation may extend the time-range of
this formation to the late early Miocene
(Hemingfordian, ca. 21–16 Ma) (M. R.
Dawson, personal commun., 1995). Analysis of
dipmeter data indicates Neogene strata dip 5°–12°
east to northeast, whereas, late Paleogene beds dip 15°–35° south to southwest. Zircon fission-track ages bracket unconformity and establish an age for rocks in buried half graben: 10.3 ± 1.0 and 29.9 ± 1.3 Ma at depths of 2721 and 3674 m, respectively (Bryant et al., 1989). Thickness of late Paleogene rocks (Norwood Tuff equivalent) is ~2.0 km. Seismic data courtesy of Amoco Production Company (FWK-1 and GSL-3) and CGG (WDF-1).

Neighboring volcanic fields, such as the Tin-
tic Mountains, Park City, and Traverse
Range volcanic fields, which are also
thought to be sources of sediment for the
Norwood Tuff and Moroni Formation, range in age from ca. 40–28 Ma (Laughlin et al., 1969; Nelson, 1971; Morris and Lover-
ning, 1979; Crittenden et al., 1973; Bromfield
et al., 1977; Bryant et al., 1989).

Physiographically, some exposures of ba-
sin fill in the Fowkes half graben, such as
those found on Porcupine Ridge, are in-
verted with respect to the modern drainage
basin by as much as 200–300 m, implying
that this basin is no longer actively subsid-
ing. In low-lying areas along the Bear River
drainage, the Fowkes Formation is overlain
by only a thin mantle of Quaternary sedi-
ments. Hence, the Fowkes half graben was structurally active from early middle Eocene to late Oligocene time (ca. 49–27 Ma). However, fault scarp associated with Quaternary to recent extensional reactivation of the Hogsback and Absaroka thrusts have been mapped 15 to 25 km east of the Fowkes half graben (West, 1993).

**Regional Style of Normal Faulting**

Extensional reactivation of the Medicine Butte thrust and formation of the Fowkes half graben were, in part, synchronous with the late Eocene to late Oligocene development of the East Canyon, Woodruff, Morgan Valley–Huntsville, and Great Salt Lake half graben. These structures are superposed on the Wasatch culmination, a thrust structure that had ~10 km of structural relief (Coogan, 1992; Young, 1992; Royse, 1993; DeCelles, 1994; Figs. 7 and 9). The faults that bound the Morgan Valley–Huntsville, Farmington–Wasatch Front, and Great Salt Lake half graben and the Salt Lake salient are interpreted as west-dipping listric normal faults that sole into the basal Cambrian footwall detachment that had been the master fault for earlier thrusting (Royse et al., 1975; Coogan, 1992). The East Canyon normal fault is an east-dipping fault related to extensional rejuvenation of the East Canyon–Crawford–Medicine Butte thrust complex (DeCelles, 1994). The basal Cambrian detachment dips ~3°–6° west and the underlying crystalline basement is undeformed (Royse et al., 1975; Lamerson, 1982). Above this regional detachment, hanging wall rocks form an extensional wedge with a maximum thickness of ~10–11 km at the Wasatch culmination.

Therefore, beginning in middle Eocene and continuing through late Oligocene time, the ~10- to 11-km-thick hanging wall above the basal Cambrian detachment in this region was displaced horizontally to the west. Total net horizontal extension in the hanging wall of the sole fault is on the order of 8–10 km for the area east of the Wasatch fault (Royse, 1993) and may be as much as 20 km for the region shown in Figure 9. Similarly, the half grabens superposed on the Charleston-Nebo allochthon record a phase of late Eocene to early Miocene tectonism, in which the sole thrust was extensionally reactivated and the ~10-km-thick allochthon was displaced about 5–7 km to the west (Royse, 1983; Reiss, 1985; Houghton, 1986; Constenius, 1995).

**TIME-SPACE PATTERNS OF HALF GRABENS, SOUTHERN CANADA–CENTRAL UTAH**

The Kishenehn basin and Fowkes half graben are elements of a network of late Paleogene half grabens that extends from southern British Columbia to central Utah and is superposed on the Cordilleran foreland fold and thrust belt. In the northern part of this extensional belt, the ages of slip on the Lewis thrust and Flathead fault indicate that crustal shortening ended in early Eocene time (ca. 55 Ma), whereas extensional faulting initiated in middle Eocene time (ca. 48 Ma). Tectonism and sedimentation in the Kishenehn basin continued until late Oligocene or early Miocene time (ca. 25–21 Ma). Data related to the timing of the Medicine Butte thrust and Arocks-Allyn normal fault system indicate that the latest phase of thrust-fold shortening was late early Eocene (late Wasatchian, ca. 55–51 Ma) in age, and that onset of extension was in early middle Eocene time (Bridgeurian, ca. 49–48 Ma).

Synextensional middle Eocene–early Miocene deposits in the Kishenehn basin and Fowkes half graben are not unique in the Cordilleran fold and thrust belt. Similar basin-fill deposits are found in several basins in southwest Montana and Idaho (Fields et al., 1985; Fritz and Harrison, 1985; Hanneman and Wideman, 1991; M’Gonigle and Dalyrpyle, 1993; Janeiro, 1992, 1994), southwest Wyoming and northeast-central Utah (Oriel and Tracey, 1970; Lamerson, 1982; Royse, 1983), and central Utah (Standlee, 1982; Royse, 1983; Riess, 1985; Constenius, 1995). However, it has recently been proposed that rocks of the Renova Formation found in many of the half grabens in southwest Montana are unrelated to extensional basin formation, whereas other half grabens in Idaho and western Montana are part of an ~100-km-wide, north- to north-northwest-trending rift superposed on the thrust-belt belt (Fritz and Searls, 1993; Janeiro, 1994).

The Renova Formation has been characterized by Janeiro (1994) as fine-grained, thin, and laterally continuous, flood-basin and lacustrine deposits that formed in a broad, quiescent basin. However, these criteria alone cannot be used to discriminate between tectonic and non-tectonic deposits for the following reasons. (1) Modern and ancient synextensional deposits are commonly fine-grained, especially in lacustrine–flood-basin settings (e.g., Lake Tanganyika, Africa; Neogene Great Salt Lake basin, Utah; late Paleogene Kishenehn Formation, Montana; Triassic and Jurassic Newbark Supergroup, eastern North America) (Cohen, 1990; Bortz et al., 1985; Constenius, 1981, 1989; Olsen, 1990). Ironically, the Sixmile Creek Formation, a synextensional unit overlying the Renova Formation, is lithologically so much like the Renova Formation that differentiating these units can be difficult (Hanneman and Wideman, 1991). Additionally, the fine-grained stratigraphic criterion has been inappropriately applied because the Renova Formation and its equivalent the Kishenehn Formation are found in three half grabens in the hypothesized rift, Kishenehn, South Fork, and Big Hole basins (Fields et al., 1985; Constenius, 1988, 1989). The thickness of the Renova Formation measured at the surface and in wells indicates that it can be quite thick (e.g., ~1180 m, Deer Lodge basin; ~1600+ m, Jefferson Valley; ~1800–3000 m, Townsend Valley; and ~500–2450 m, Big Hole basin) (Mertie et al., 1951; Kuenzi and Fields, 1971; Fields et al., 1985; Constenius, 1988).

(3) Modern and ancient lake and flood-basin deposits are known to bridge across accommodation zones and horsts in extensional settings (e.g., East African Rift lakes, Quaternary-Neogene Lake Bonneville, and Great Salt Lake areas) (Rosendahl et al., 1986; Lambise, 1990; R. A. Johnson, personal commun., 1995). Synextensional origin of the Renova Formation is supported by stratigraphic thickening toward basin-bounding faults, inordinate thickness, and intercalated course-elastic deposits (Rasmussen and Fields, 1983; Fields et al., 1985). The structural setting and style of many of these basins are akin to the Kishenehn basin in that basin-bounding listric normal faults have reactivated folded and thrust rocks (Rasmussen and Fields, 1983; E. H. John- son, written commun., 1995).

Plotting the latitudinal distribution of ages of late Paleogene basin-fill deposits with respect to youngest foreland-basin deposits and overlap assemblages, Paleogene volcanic deposits, age ranges of metamorphic core complex extension, and ages of Neogene basin-fill deposits reveals the following time-space trends (Fig. 10).

(1) Dating of youngest foreland-basin deposits in the fold and thrust belt between latitudes 40°30’N and 49°N indicates that the end of contractile deformation occurred between 54 and 51 Ma. Foreland-basin sedimentation south of 40°30’N ended in late Campanian to early Maastrichtian time (Lawton, 1985), but deposition of overlap
assemblages consisting of the North Horn, Colton, Green River, and Uinta Formations was continuous from latest Cretaceous to late middle Eocene (ca. 42–40 Ma) time. Stratigraphic data from basins in the foreland indicate crustal shortening ended in early and middle Eocene (ca. 55–50 Ma) time north of 42°N and late Eocene (ca. 40–35 Ma) time south of 42°N (Dickinson et al., 1988).

(2) Middle Eocene volcanic deposits postdated the end of foreland basin sedimentation and preceded synextensional basin-fill sedimentation. Magmatism and basin-fill sedimentation were temporally discrete north of 43°N (minor coeval magmatism and extension) but were coeval in late Eocene to late Oligocene time south of 43°N.

(3) The hiatus between contractile and extensional sedimentation where narrowly bracketed was brief: 5 m.y. in the north and 2 m.y. in the south. However, throughout much of the Cordilleran foreland, the hiatus is long (~16–25 m.y.).

(4) Extension in the metamorphic core complexes in the hinterland of the Cordilleran partly overlapped with synextensional basin-fill sedimentation in the foreland north of 43°N. Extension in the foreland and hinterland was concurrent south of 43°N.

(5) Late Paleogene synextensional sedimentation records an episode of tectonism discrete from older foreland basin sedimentation and later Basin and Range deformation. Basin-fill sedimentation spanned from middle and late Eocene to early Miocene (ca. 49–21 Ma) north of latitude 40°30′N. South of 40°30′N, basin-fill sedimentation starts in late Eocene time (ca. 39 Ma), about 10 m.y. later than the start of synextensional sedimentation to the north, and ends in the early Miocene.

(6) A regional Hemingfordian-age unconformity (Rasmussen, 1973; Fields et al., 1985) separates late Paleogene synextensional deposits from younger, middle Miocene to recent (17 to 0 Ma) deposits that were the product of Basin and Range extension and magmatism. The hiatus associated with this unconformity is about 5 m.y.

LATE CRETACEOUS–PALEOGENE MAGMATISM: A RECORD OF CHANGING PLATE REGIMES

Studies of the Cordillera in the southwestern United States and northern Mexico have used the concept of a “magmatic sweep,” which is the migration of arc-magmatism spatially through time, to draw insights into the timing and mode of Cenozoic tectonism. This concept was originally applied by Coney and Reynolds (1977) who documented systematic Late Cretaceous and Tertiary shifts in magmatism in the southern Rocky Mountains and proposed that the ~1000-km-eastward migration of the magmatic arc was related to Late Cretaceous and early Tertiary crustal shortening concomitant with flattening of the subducted oceanic slab beneath North America. Late Cretaceous–Eocene crustal shortening in the Cordillera has also been linked to (1) high relative plate convergence rates (>70–150 km/m.y.), (2) subduction of abnormally buoyant lithosphere, (3) subduction of very young oceanic lithosphere, and/or (4) increased rates of absolute motion of the overlying plate toward the trench (Cross and Pilger, 1982; Miller et al., 1992, and references therein; Ward,
The validity of the dipping-slab hypothesis (Coney and Reynolds, 1977) has been challenged by Ward (1991, 1995), who also demonstrated the hazards of generalizing from “magmatic sweep” diagrams. Middle Tertiary silicic volcanism and metamorphic-core-complex–related extensional deformation in western North America has been correlated with westward migration of arc-magmatism (e.g., Dickinson, 1991). This pivotal change from contractile to extensional deformation may have resulted from one, or a combination, of the following factors: (1) slowing of relative Pacific–North America plate convergence rates, (2) age of the subducted plate, (3) a change to subduction at steeper angles beginning in middle Eocene time, and (4) subduction of a linear aseismic ridge (Wernicke, 1992, and references cited therein; Dickinson et al., 1988; Engebretson et al., 1985; Ward, 1995).

Patterns of migrating arc-magmatism are viewed here as a tectonic signal of rates of plate convergence and state of the subducted slab and are used to delineate the timing of contractile versus extensional regimes in the northern U.S. Cordillera. Published isotopic ages of late Cretaceous through Eocene igneous rocks, age-of-deformation data, and stratigraphic-age data were compiled for the northern U.S. Cordilleran foreland on a line of projection orthogonal to the orogenic belt (N65°E) (Figs. 11 and 12). Deformational-age and stratigraphic-age data were included to compare tectonic regimes predicted from the magmatic-sweep diagram and to place bounds on interpretations. The following relationships are interpreted from Figure 11: (1) Accelerated plate convergence rates and/or flattening of the subducted slab were concomitant with ~600 km eastward progression of magmatism and crustal shortening during Late Cretaceous to early Eocene (ca. 72–54 Ma) time; (2) in early-middle Eocene time (ca. 53–51 Ma) markedly reduced plate convergence rates and/or slab-steepening resulted in westward migration of the subducted slab (rollback) and inception of widespread magmatism; and (3) middle Eocene (ca. 49–48 Ma) initiation of normal faulting and basin-fill sedimentation in the Cordilleran thrust belt was related to westward passage of the subducted slab from beneath the Great Plains to a position closer to the Pacific coast (Fig. 12). Inspection of Figure 11 reveals that the initiation of magmatism is about 5–6 m.y. younger in central Idaho than in central Montana, 600 km to the east. The rate of slab rollback based on this age-distance comparison is about 100 km/m.y. This interpretation is bracketed by dating phases of contractile and extensional deformation in the thrust belt and cessation of foreland basin sedimentation (Wasatch Formation). Independent dating of deformational phases agrees with tectonic regimes predicted from the magmatic-sweep diagram; that is, eastward migration of arc-magmatism is equated with crustal shortening, and westward migration of arc-magmatism correlates with late Paleogene magmatism and subsequent extension. Models of North America–Pacific plate convergence reported by Engebretson et al.
(1985) and Cole (1990) show a dramatic change from rates as high as \(120–150\) km/m.y. and near orthogonal convergence in Late Cretaceous to early Eocene time, to rates as low as \(50–86\) km/m.y. and convergence with an oblique component in late Eocene to early Miocene time.

Extensional basin formation in both the foreland and hinterland of the Cordillera is the structural response of a crust preconditioned by contractile deformation that has been left unsupported by lower rates and changes in orientation of plate convergence concomitant with slab rollback. Passage of the subducted slab from beneath the Great Plains to the Cordillera at ca. 49–48 Ma signals widespread breakup of the Cordilleran orogen, which collapsed under its own weight and spread to the west. Magmatism preceded extensional basin formation by \(1–3\) m.y. in the Horse Prairie–Medicine Lodge and East Central Idaho half grabens (M’Gonigle and Dalrymple, 1993; Janecke, 1992, 1994), whereas there are no middle Eocene volcanic fields within a \(100\) km radius of the Kishenehn basin and Fowkes half graben. These observations preclude a genetic link between local magmatism and extension (10–100 km radius; Axen et al., 1993) but are consistent with thermal weakening of the crust and lithosphere and/or changes in stress transmitted from the subducted slab.

### EXTENSIONAL MECHANISMS

Extension of supracrustal rocks in the Cordilleran foreland and thrust belt occurred in areas that had been thickened during crustal shortening and subsequently failed along weaknesses imparted by thrust-fold deformation due to their high gravitational potential. Extensional collapse preferentially reactivated preexisting thrust surfaces and was superposed on large-relief thrust-fold structural features such as structural culminations, duplex zones, thrust ramps, and associated fault-bend folds. The principal factors that increased the gravitational potential and facilitated late Paleogene normal faulting are (1) inherited structural weaknesses in the rock column, such as preexisting faults and physically incompetent rock units, (2) large structural relief created by stacking of thrust-fold structures, (3) the structural framework of the hanging wall (long, west-dipping panels of strata), and (4) the 3–6° west dip of the sole fault.

Inspection of Figures 4, 6, 8, and 9 reveals that late Paleogene normal faulting is su-
performed on major thrust-fold structures with large vertical dimensions. The ramp-geology of the Lewis and Medicine Butte thrust surfaces combined with the formation of footwall duplex zones created structural relief of about 4 and 7 km, respectively. The critical aspect of these structures with respect to crustal instability, however, is that they formed ~25-km-long, ~15° west-dipping panels of anisotropic strata weakened by detachments. The enhanced structural relief and resultant increase in the potential energy of Lewis and Medicine Butte hanging wall masses drove backsliding on the detachment surfaces. Additionally, certain stratigraphic units are ideal slip surfaces for accommodating both thrusting and low-angle normal faulting. The Medicine Butte fault is mainly an evaporite detachment, whereas the Lewis detachment juxtaposes argillite, siltite, quartzite, and dolomite on shale, sandstone, and limestone. In the case of the Medicine Butte thrust, the Preuss evaporite unit not only is the preferred horizon for the sole fault, but it also may be the mechanically weakest part of the entire stratigraphic column.

Recent literature regarding extension and low-angle normal faulting in active orogens such as the Himalayas-Tibet and Andes provide Neogene analogs of the role of gravitationally driven extension in high relief areas (Burchfiel et al., 1992a; Mercier et al., 1992; Sebrier et al., 1985). The ancient Cordilleran differs from these modern high mountain chains in that there is presently no evidence of extension coeval with Late Cretaceous to early Eocene crustal shortening in the foreland fold and thrust belt. Studies of the age of normal faults in the Idaho-Wyoming-Utah thrust belt have concluded, with one possible exception, that all normal faults formed subsequent to thrust-fold deformation (Armstrong and Oriel, 1965; Wiltschko and Dorr, 1983). Furthermore, the detachments that accommodated the collapse of the orogen were deep in the subsurface rather than exposed at the surface in topographically high areas. The Late Cretaceous to early Eocene paleotopographic relief of the Lewis thrust sheet west of the Flathead fault is difficult to assess, but the inferred presence of highly erodible Cretaceous rocks in the hanging wall of the Lewis thrust implies low local relief. Correlation of Paleocene and early Eocene stratigraphic units across the Medicine Butte thrust indicates that it had comparatively little paleotopographic relief. On a regional scale, however, the Lewis thrust sheet and Wasatch culmination were major contributors of coarse-elastic sediments to the foreland basin, which implies that they had significant paleotopographic relief (Hearn et al., 1964; DeCelles, 1994).

**STRUCTURAL GENESIS**

Comparison of the northwest Montana and southwest Wyoming–northeast Utah extensional systems reveals similarities in the style and timing of tectonism and yields insights into local and regional processes that shaped the Cordilleran. These two areas, though widely spaced, record an episode of regional gravitational collapse of the Cordilleran foreland fold and thrust belt that initiated in the early middle Eocene (ca. 49–48 Ma) and ended in early Miocene time (ca. 20 Ma). Concurrently, in the Cordilleran hinterland, deep-seated crustal extension and magmatism reshaped an even thicker part of the gravitationally unstable orogenic wedge (Coney and Harms, 1984; Coney, 1987; Harms and Price, 1992).

Large-scale crustal extension in hinterland areas has been attributed to gravitational spreading of thickened, structurally preconditioned, and thermally weakened crust triggered by changes in the regional stress regime (e.g., Harms and Coney, 1984; Axen et al., 1993). The correspondence of extension and westward sweep of late Paleogene magmatism presented here suggests that collapse of the Cordilleran orogen was related to slowing of plate convergence rates and steepening of the subducting slab (Figs. 11 and 12) (Lipman, 1992; Severinghaus and Atwater, 1990).

Linkage of late Paleogene extensional processes that simultaneously deformed both the hinterland and foreland of the Cordilleran may be conceptualized using the Coulomb critical taper hypothesis (Davis et al., 1983). Contemporary thinking regarding contractile deformation, propagation, and structural thickening of thrust belts and accretionary wedges has effectively relied on the Coulomb critical taper model, and conversely, the extensional wedge concept has been used to explain regional continental extension (Xiao et al., 1991). Extensional wedges are defined by (1) a gently dipping basal detachment down which the tapered hanging wall slides, (2) overlying the basal detachment, a related system of normal faults cuts the wedge, and (3) the footwall beneath the basal detachment is relatively undeformed (Wernicke, 1981; Xiao et al., 1991). Normal fault systems superposed on the Cordilleran foreland fold and thrust belt satisfy these criteria as shown in Figures 6 and 9.

Extensional wedges are the inverse of compressional wedges, but both share the relationship that they are critically tapered when on the verge of failure throughout the wedge. An extensional wedge whose taper exceeds a certain critical taper deforms by internal normal faulting and reduces its taper until it is critical. If the extensional wedge is narrower than the critical taper it can slide without internal deformation down the inclined basal detachment (Xiao et al., 1991). In late Paleogene time, the dramatic reduction in east-west horizontal compressive stress at ca. 50 Ma left the Cordilleran orogenic wedge largely unsupported to the west. Consequently, the orogen switched from a state of failure under shortening to one dominated by extension, and it gravitationally collapsed and horizontally spread to the west until an equilibrium was established at ca. 20 Ma. The Lewis thrust salient and the Wasatch culmination were predisposed to large-scale normal faulting and development of late Paleogene half grabens because these were areas of heightened structural and paleotopographic relief that required considerable extension to achieve critical taper.

**CONCLUSIONS**

(1) Development of late Paleogene extensional basins in the Cordilleran foreland fold and thrust belt overlapped or was coeval with formation of the metamorphic core-complexes, low-angle detachment faulting, and regional-scale magmatism. Extensional structures in the foreland like the Kishenehn basin were not formed as discrete and isolated entities, but are a manifestation of late Paleogene gravitational collapse and breakup of the entire Cordillera. The Cordilleran foreland fold and thrust belt failed as an extensional wedge governed by Coulomb critical taper criteria.

(2) The beginning of extension in the Cordilleran foreland fold and thrust belt closely followed the termination of contractile deformation after a brief hiatus. Even though rollback of the subducted Pacific plate and concomitant middle Eocene magmatism initiated in the northern Great Plains at ca. 53–51 Ma, the period of extensional basin formation and collapse of the Cordillera commenced at ca. 49–48 Ma.

(3) In the Cordilleran foreland fold and thrust belt, the late Paleogene episode of
extensional collapse and the Basin and Range extensional event are two distinct episodes of crustal extension whose sedimentary successions are separated by a major angular unconformity (3–15 m. y.). Many of the present topographic basins, which were constructed largely during Basin and Range–Holocene extension, have variously buried, broken up, and/or reactivated the earlier late Paleogene half grabens and grabens.

ACKNOWLEDGMENTS

I am grateful to Mary Dawson, Alan Tabrum, Chris Beard, Harold Pierce, John N., and Leona Constenius, Mark Wilson, and Robert C. Walter, members of the Kienehn Basin Study Project, for volunteering their time and expertise. I thank Pat Jackson, John Miers, Paul Ettinger, Ted Fons, and Marty Williams for logistical support. Discussions and suggestions by Roy Johnson, Jim Coogan, Peter Coney, Robert Mueller, Eric Johnson, and Peter DeCelles improved this paper. Critical reviews were provided by Susanne Janeciek, Michael Wells, Peter Ward, and Arthur Sylvester. This research was supported by Amoco Production Company, Geophysical Micro Computer Applications Ltd., and National Science Foundation grants EAR-9205605 and EAR-9219505. Amoco and CGG American Services, Inc., generously allowed me to publish proprietary seismic data.

REFERENCES


