Regional structure and kinematic history of the Sevier fold-and-thrust belt, central Utah

Peter G. DeCelles[†]
Department of Geosciences, University of Arizona, Tucson, Arizona 85721, USA

James C. Coogan[‡]
Department of Geology, Western State College of Colorado, Gunnison, Colorado 81231, USA

ABSTRACT

The Canyon Range, Pavant, Paxton, and Gunnison thrust systems in central Utah form the Sevier fold-and-thrust belt in its type area. The Canyon Range thrust carries an ~12-km-thick succession of Neoproterozoic through Triassic sedimentary rocks and is breached at the surface by the Neogene extensional Sevier Desert detachment fault. The Pavant, Paxton, and Gunnison thrusts carry Lower Cambrian through Cretaceous strata and have major footwall detachments in weak Jurassic rocks. The Canyon Range thrust was active during latest Jurassic–Early Cretaceous time. The Pavant thrust sheet was emplaced in Albian time, formed an internal duplex beneath the Canyon Range during the Cenomanian, and then developed a frontal duplex during the Turonian. The Paxton thrust sheet was initially emplaced during the Santonian, and subsequently formed the Paxton duplex during the early to mid-Campanian. Some slip on the Paxton system was fed into a frontal triangle zone along the Sanpete Valley antiform. The Gunnison thrust system became active in late Campanian time and continued to feed slip into the frontal triangle zone through the early Paleocene. The Canyon Range and main Pavant thrust sheets experienced long-distance eastward transport (totaling >140 km) mainly because they are composed of relatively strong rocks, whereas the eastern thrust sheets accommodated less shortening and formed multiple antiformal duplexes in order to maintain sufficient taper for continued forward propagation of the fold-and-thrust belt. Total shortening was at least 220 km. Upper crustal thickening of ~16 km produced crust that was >50 km thick and a likely surface elevation >3 km in western Utah. Shortening across the entire Cordilleran retroarc thrust belt at the latitude of central Utah may have exceeded 335 km. The Late Cretaceous paleogeography of the fold-and-thrust belt and foreland basin was similar to the modern central Andean fold-and-thrust belt, with a high-elevation, low-relief hinterland plateau and a rugged topographic front. The frontal part of the Sevier belt was buried by several kilometers of nonmarine and shallow-marine sediments in the wedge-top depozone of the foreland basin system. The Canyon Range thrust sheet dominated sediment supply throughout the history of shortening in the Sevier belt. Westward underthrusting of a several hundred-kilometer-long panel of North American lower crust beneath the Cordilleran magmatic arc is required to balance upper-crustal shortening in the thrust belt, and may be petrogenetically linked to a Late Cretaceous flare-up of the magmatic arc as preserved in the Sierra Nevada Batholith.

Keywords: Cordilleran tectonics, fold-and-thrust belts, foreland basins, Utah.

INTRODUCTION

The Sevier fold-and-thrust belt in central Utah (western interior USA) is the type area of one of the world's classic fold-and-thrust belts and was among the first to be systematically characterized in terms of modern concepts of thrust-belt geology and geophysics (Armstrong and Oriel, 1965; Armstrong, 1968; Dahlstrom, 1970; Royse et al., 1975; Burchfiel and Davis, 1975; Lamerson, 1982; Allmendinger et al., 1983, 1986, 1987; Smith and Bruhn, 1984). Armstrong (1968) defined the Sevier belt as the linear group of closely spaced thrust faults and related folds that extends from the Las Vegas, Nevada, area to the Idaho state line (Fig. 1). Subsequent work by many authors has shown that contemporaneous thrust systems (in the sense of Boyer and Elliott, 1982) continue for ~3000 km to the north into northwestern Canada. Thus, the Sevier belt may be regarded as a segment of the larger Cordilleran retroarc fold-and-thrust belt (Fig. 1), which formed during late Mesozoic through Eocene time along the inboard side of the Cordilleran magmatic arc and various allochthonous terranes (see reviews by Burchfiel et al., 1992; Allmendinger, 1992; Miller et al., 1992; Dickinson, 2004; DeCelles, 2004).

Although many of the geometric details of the Sevier belt in central Utah are well documented, the regional kinematic history and the relationships between shortening in the Sevier belt and tectonic processes in the Cordilleran magmatic arc and hinterland region remain obscure. The most recent synthesis of regional structure and kinematic history in the Sevier belt of central Utah is now nearly two decades old (Villien and Kligfield, 1986). Numerous more recent studies have provided abundant new information on the structural geology, kinematic history, and erosional unroofing history of the region (e.g., Royse, 1993; DeCelles et al., 1995; Lawton et al., 1997; Mitra, 1997; Stockli et al., 2001; Currie, 2002; Hintze and Davis, 2002, 2003; Ismat and Mitra, 2001, 2005), such that a revised synthesis is overdue. The purpose of this paper is to provide such a synthesis. We draw upon subsurface data, new mapping, new chronostratigraphic constraints on the ages of proximal synorogenic sediments derived from the Sevier belt, and recent thermochronological studies to develop a sequential kinematic restoration of the fold-and-thrust belt. The regional balanced cross section that forms the basis for this restoration was constructed using a combination of GeoSec and LithoTect software. Thrust-related deformation was modeled using a flexural slip algorithm for fault-bend folds.

[†]E-mail: decelles@geo.arizona.edu.
[‡]E-mail: jcoogan@western.edu.

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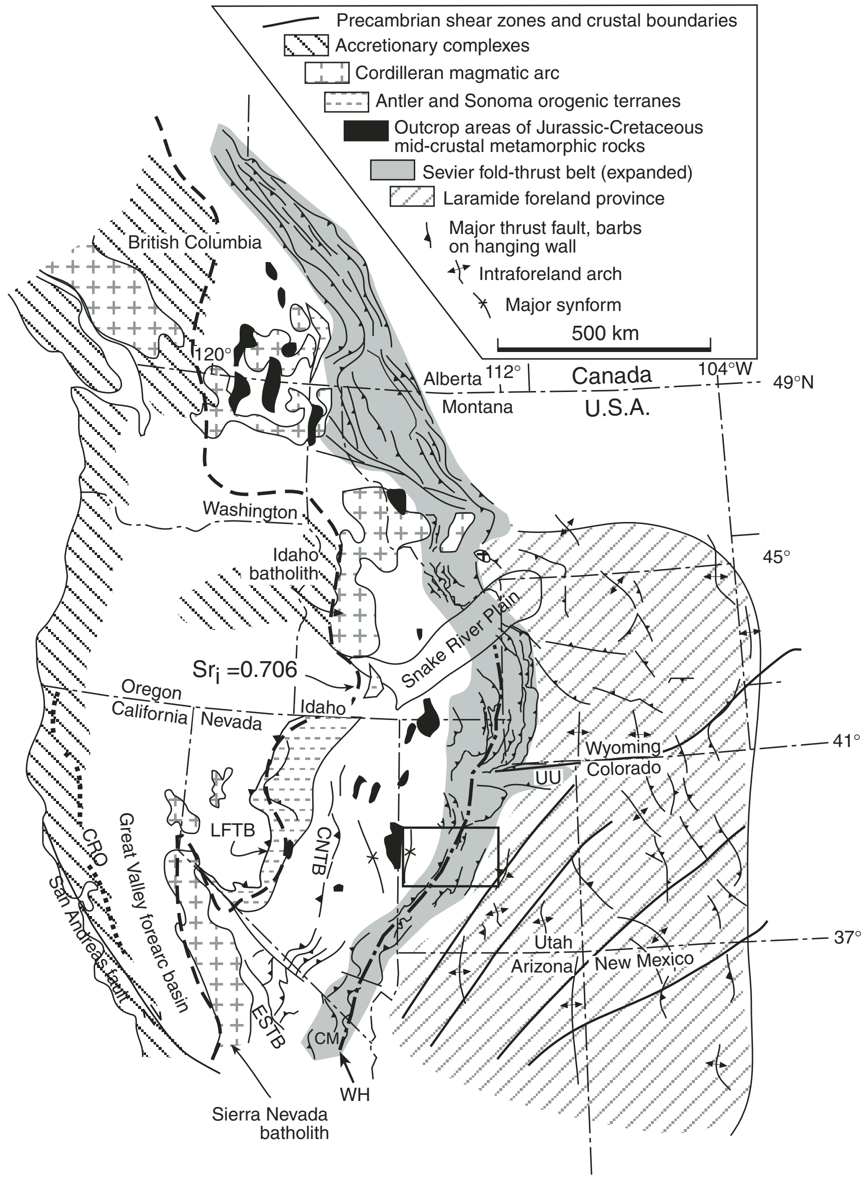


Figure 1. Generalized tectonic map of the western United States showing the major elements of the Cordilleran orogenic belt (modified after DeCelles, 2004). The initial Sr ratio line (Sr_i) is from Armstrong et al. (1977) and Kistler and Peterman (1978). Abbreviations are as follows: LFTB—Luning-Fencemaker thrust belt; CNTB—Central Nevada thrust belt; ESTB—East Sierran thrust belt; UU—Uinta Mountains uplift; WH—Wasatch hinge line; CM—Clark Mountains; CRO—Coast Range Ophiolite. Study area is outlined by rectangle in central Utah. Precambrian shear zones are after Karlstrom and Williams (1998).

The sequential restoration combined line-length and area balancing techniques that ensure <5% error between deformed- and restored-state cross-sectional areas for all stratigraphic levels. The results of this study have implications for the history of the adjacent Cordilleran foreland basin, the Cordilleran magmatic arc to the west, and crustal thickening and elevation gain in the central part of the orogenic belt.

TECTONIC SETTING

The Sevier fold-and-thrust belt is a segment of the frontal part of the greater Cordilleran retroarc thrust belt. The Cordilleran thrust belt is a complex system of major thrust faults that spans the palinspastically restored 100–450 km gap between the Cordilleran magmatic arc and foreland basin system (Figs. 1 and 2; Allmendinger, 1992; DeCelles, 2004). Central Utah is in the widest part of the Cordilleran orogenic belt, where major thrust faults form an enormous eastward-convex salient with a north-south chord length of 1500 km. The Cordilleran magmatic arc formed along the western margin of the North American plate in response to eastward subduction of oceanic plates from Late Triassic to Late Cretaceous time (e.g., Hamilton, 1969; Dickinson, 1976; Saleeby and Busby-Spera, 1992). The roots of the arc are exemplified by the Sierra Nevada Batholith, a 40×10^3 km^2 body of granodiorite and tonalite that forms the bulk of the Sierra Nevada. The batholith developed over an ~140 m.y. time span beginning at 220 Ma (Bateman, 1983; Barton et al., 1988; Barton, 1996; Coleman and Glazner, 1998; Ducea, 2001).

Directly east of the Sierra Nevada Batholith lies the Luning-Fencemaker thrust belt (Fig. 1), which is mainly composed of Triassic fine-grained, deep-marine facies (Elison and Speed, 1988; Oldow et al., 1990) that were tectonically transported eastward and southeastward by imbricate thrust faults and emplaced upon autochthonous shallow-marine shelf facies during Middle Jurassic to Early Cretaceous time (Speed, 1978; Oldow, 1983, 1984; Wyld, 2002). Total shortening of 50%–75% (amounting to perhaps ~75–180 km) was accompanied by low-grade metamorphism (Wyld, 2002). Based on partial overlap in the timing of shortening in the Luning-Fencemaker and Sevier belts, Oldow (1983, 1984) and Speed et al. (1988) suggested that the two thrust belts shared a common, mid-crustal décollement and bracketed a broad region in Nevada and western Utah that was relatively little deformed. This structural and paleogeographic scenario is remarkably similar to the modern central Andean retroarc thrust belt in Bolivia, where the strongly deformed high-elevation Western and Eastern Cordilleras bracket the low-relief, high-elevation, relatively little deformed Altiplano (e.g., Lamb and Hoke, 1997; Horton et al., 2002; McQuarrie, 2002; Elger et al., 2005). On the other hand, Wyld (2002) noted that the temporal overlap in thrusting in the Luning-Fencemaker thrust belt and the Sevier belt is minor (Cretaceous thrust displacements in the Luning-Fencemaker thrust belt are minimal) and concluded that the Sevier belt operated independently of the Luning-Fencemaker thrust belt. In this paper, we sidestep the issue of connectivity and simply treat all of the thrust systems east of the magmatic arc that were active during Late Jurassic to Eocene time as manifestations of the Cordilleran orogenic wedge (DeCelles, 2004). If the central Andean analogy is appropriate, the Luning-Fencemaker thrust belt may be considered as a hinterland zone of shortening that ultimately propagated several hundred kilometers

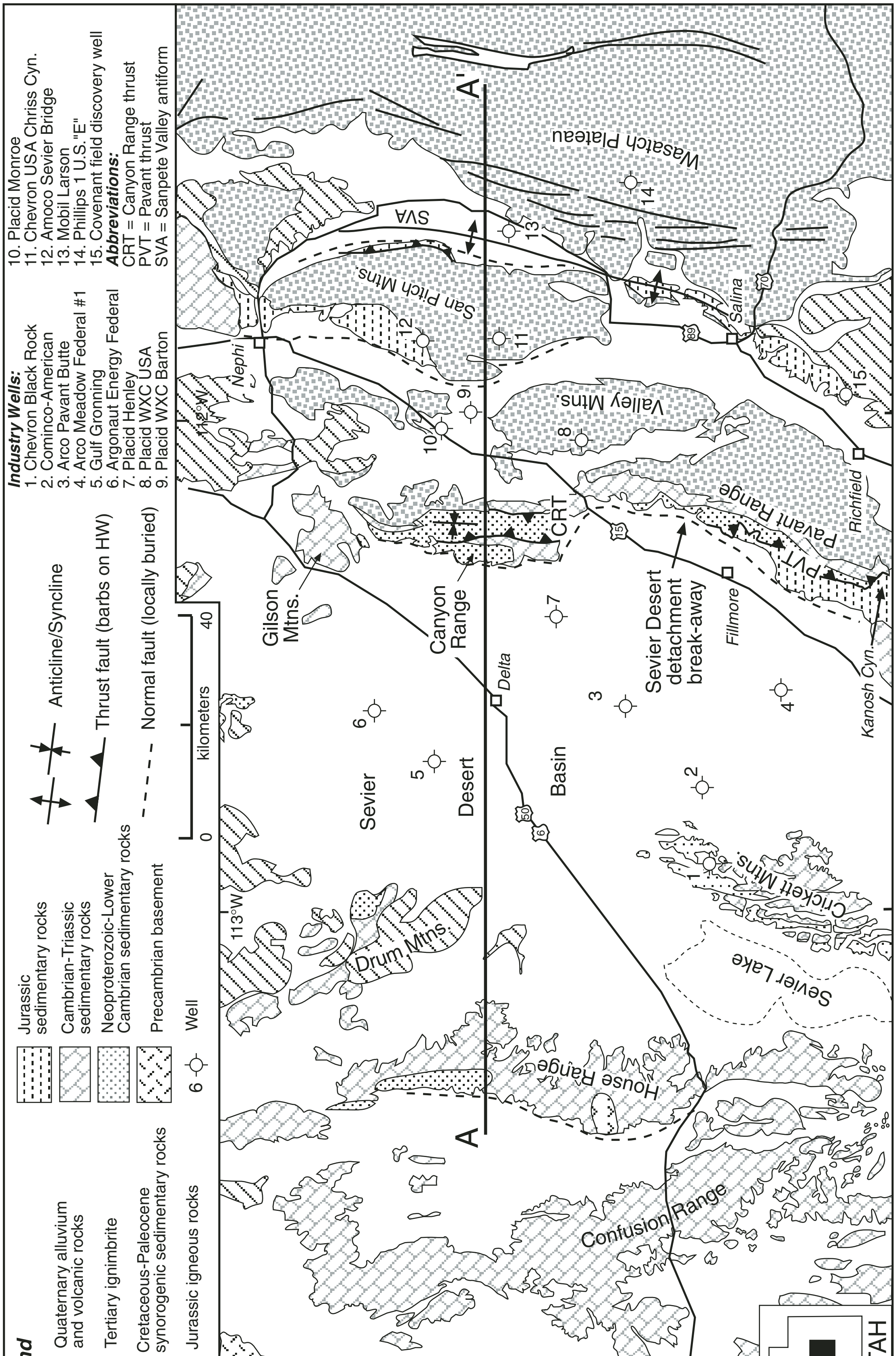


Figure 2. Geological map of central Utah after Hintze (1980), showing relevant hydrocarbon industry wells. A–A′ marks the line of cross section shown in Figure 3. HW—hanging wall.

eastward into central Utah. This approach is justified by the fact that the western margin of the North American plate was tectonically consolidated by ca. 155 Ma with the closure of marginal oceanic basins and fringing arcs (Harper and Wright, 1984; Ingersoll and Schweickert, 1986; Dickinson et al., 1996). From that time forward until mid-Cenozoic time, the Farallon plate subducted continuously eastward beneath North America, and the rate of convergence between the Farallon and North American plates generally increased through time (Engebretson et al., 1984; Cole, 1990).

To the east of the Luning-Fencemaker belt lie two older orogenic terranes, the Golconda and Roberts Mountains allochthons (Fig. 1). The Roberts Mountains allochthon, consisting of Cambrian-Devonian deep-marine turbidites, chert, and mafic igneous rocks, was juxtaposed against shallow-marine shelf rocks during the late Devonian–early Mississippian Antler orogenic event (e.g., Speed, 1977; Speed and Sleep, 1982; Dickinson, 2000). The Golconda allochthon consists of late Devonian–Permian turbidites, chert, argillites, and metabasalts that were structurally disrupted and emplaced eastward on top of the Roberts Mountains allochthon during the Early Triassic Sonoma orogenic event (Oldow, 1984; Miller et al., 1992; Dickinson, 2000). By Late Jurassic time, these older orogenic terranes lay in the foreland of the Luning-Fencemaker thrust belt, but the crust in this region was probably not anomalously thick, because marine rocks of Triassic age overlap the Roberts Mountains allochthon.

An additional belt of thrust faults of middle to Late Cretaceous age is present in east-central Nevada (the central Nevada thrust belt, Eureka belt, and Elko orogenic belt; Speed et al., 1988; Carpenter et al., 1993; Taylor et al., 2000). The broad region between the Sevier belt and the central Nevada thrust belt is largely undeformed by pre-Cenozoic, surface-breaking faults and related shortening, and is commonly referred to as the Sevier hinterland region (e.g., Armstrong, 1968; Hodges and Walker, 1992; Allmendinger, 1992; Smith et al., 1993; Camilleri et al., 1997; Wells, 1997). However, thermochronological and kinematic data from mid-crustal metamorphic rocks exposed in the belt of Eocene-Oligocene metamorphic core complexes of eastern Nevada and northwestern Utah indicate that shortening, cooling, and decompression, the latter presumably associated with extensional unroofing by mid-crustal detachment faults, were taking place in this region during Late Jurassic and Cretaceous time (Miller et al., 1983, 1988; Miller and Gans, 1989; Hodges and Walker, 1992; Smith et al., 1993; Camilleri et al., 1997; Camilleri and Chamberlain, 1997; Wells, 1997; Hoisch et al., 2002; Lee et al., 2003).

The Sevier belt in central Utah comprises the Canyon Range, Pavant, Paxton, and Gunnison thrust systems (Figs. 2 and 3; Christiansen, 1952; Standlee, 1982; Villien and Kligfield, 1986; Royse, 1993). The Canyon Range thrust is well exposed in the Canyon Range (also referred to as the Canyon Mountains on U.S. Geological Survey [USGS] topographic maps; Holladay, 1983), and the Pavant thrust sheet is well exposed in both the Canyon Range (Holladay, 1983) and the Pavant Range (Burchfiel and Hickcox, 1972). The Paxton and Gunnison thrust systems are buried beneath synorogenic sediments of the Cordilleran foreland basin and Cenozoic graben fills (Standlee, 1982; Royse, 1993). The synorogenic sediments that overlap the frontal ~40 km of the Sevier belt consist of Albian-Paleocene alluvial fan, fluvial, lacustrine, and marginal-marine facies (Lawton et al., 1993, 1997) that thicken irregularly eastward in a classic wedge-top geometry (DeCelles and Giles, 1996). The effective structural front of the Sevier belt lies along the Sanpete Valley antiform, which has been partly inverted by Miocene normal faults (Lawton et al., 1993). East of the Sanpete Valley lies the foredeep of the Cordilleran foreland basin system, in which ~3 km of fluvial and marine strata accumulated from middle through Late Cretaceous time. Laramide basement-cored intraforeland uplifts and intervening basins began to partition the region by Campanian time (ca. 80–85 Ma; Lawton, 1983, 1986; Roberts and Kirschbaum, 1995; Guiseppe and Heller, 1998). Upper Jurassic and Lower Cretaceous foreland basin deposits are also present in central Utah, where they are involved in the frontal three thrust systems.

Additional insight into the regional structure of the Sevier belt in central Utah is provided by seismic-reflection data collected by industry and academic groups. The Consortium for Continental Reflection Profiling (COCORP) deep-crustal seismic-reflection profile is particularly illuminating for the regional tectonic issues addressed in this paper. The major features of the COCORP and other seismic-reflection lines are incorporated into cross-section A–A′ (Fig. 3). Westward-dipping reflectors beneath the western end of the cross section were inferred by Allmendinger et al. (1983, 1986) to be mid-crustal thrust faults, possibly related to a crustal-scale duplex or ramp anticline, which was referred to as the Sevier culmination by DeCelles et al. (1995).

East of the Sevier culmination lies the 40–60-km-wide, Oligocene-Pleistocene Sevier Desert basin. The basin is underlain by the Sevier Desert reflection, a high-amplitude, 5–10°W-dipping seismic reflection that can be traced ~70 km from its eastern limit near the western flank of the Canyon Range into the region beneath the Cricket and Drum Mountains blocks. Some workers interpret the Sevier Desert reflection as a low-angle extensional detachment fault (McDonald, 1976; Wernicke, 1981; Allmendinger et al., 1983, 1986, 1987; Smith and Bruhn, 1984; Von Tish et al., 1985; Mitchell and McDonald, 1987; Planke and Smith, 1991; Allmendinger and Royse, 1995; Coogan and DeCelles, 1996; Stockli et al., 2001; Carney and Janecke, 2005), whereas others consider the reflection to represent an unconformity between Cenozoic and Paleozoic rocks (Anders and Christie-Blick, 1994; Hamilton, 1994; Anders et al., 1995; Wills and Anders, 1999; Anders et al., 2001). Although our analysis is focused on the pre-extensional history of central Utah, our thrust belt reconstruction begins with restoration of 47 km of slip along the Sevier Desert detachment fault (Fig. 3). As a result, our balanced cross-section methodology implicitly demonstrates the geometric and kinematic validity of the detachment interpretation for the Sevier Desert reflection. More importantly, we provide a synthesis of the local and regional geometric, geochronologic, sedimentologic, paleotopographic, flexural, and isostatic constraints that require large-magnitude extensional restoration of the western Canyon Range and Pavant thrust sheets to the present area of the Sevier Desert basin. Our principal objections to the unconformity interpretation are its focus on local and equivocal data sets, such as microfracture density in millimeter-scale cuttings from boreholes that penetrate the reflection (Anders and Christie-Blick, 1994; Anders et al., 2001), as well as what we consider to be an underconstrained interpretation of the geometry of pre-Cenozoic uplift and late Cenozoic subsidence of the Sevier Desert region (Wills and Anders, 1999). The balanced cross section and sequential restoration presented in this paper provide a well-constrained geometric framework for future evaluation of the seismic structure of the Sevier Desert region.

STRATIGRAPHY OF THE SEVIER BELT

The stratigraphy of the Sevier fold-and-thrust belt is documented in numerous reports that date back to the 1940s. Here, we provide only a brief summary that is directed toward clarifying some of the regional structural aspects of central Utah. For more thorough reviews, the reader should consult Hintze (1988), Link et al. (1993), and Hintze and Davis (2003).

As in other parts of the Cordilleran miogeocline (Stewart, 1972; Burchfiel et al., 1992), the Neoproterozoic, Paleozoic, and Triassic stratigraphy of central Utah can be divided into a western, extremely thick and relatively offshore district, and an eastern, relatively thin platformal district. The palinspastically restored transition between these two districts lies between the Canyon Range and the Wasatch Plateau (Fig. 2; Hintze, 1988). Within the study region, Precambrian (1.6–1.75 Ga) crystalline basement rocks do not crop out; however, basement was penetrated by the Arco #1 Meadow Federal Unit borehole west of the Pavant Range (Well #4 in Fig. 2; Standlee, 1982) at a depth of ~4.1 km (Allmendinger and Royse, 1995). Presumably similar basement underlies the entire region (Hintze and Davis, 2003).

The strata of the offshore region are >13 km thick near the Utah-Nevada border, consisting of >4 km of Neoproterozoic and Lower Cambrian predominantly clastic strata (Christie-Blick, 1982, 1997; Link et al., 1993) and 8–9 km of mid-Cambrian through Triassic strata. Eastward, these strata become thinner; for example, in the Pavant Range, the Paleozoic–lower Mesozoic section is 3–4 km thick (Hintze, 1988; Baer et al., 1982). The Neoproterozoic strata are mainly thickly bedded quartzites, with subordinate argillites and shales. The mid-Cambrian through Triassic succession is predominantly composed of limestone and dolostone, with minor shale and quartzitic sandstone. The Neoproterozoic and Paleozoic strata of the western district were transported eastward by the Canyon Range and Pavant thrust systems and are absent from the two eastern thrust sheets (Fig. 3; Armstrong, 1968).

The Paleozoic strata of the platformal district in the Wasatch Plateau are only ~1.1 km thick (Standlee, 1982) and consist of quartzose sandstone, limestone, dolostone, and shale. Neoproterozoic strata are absent in the footwall of the Pavant thrust, based on penetration of only Lower Cambrian quartzite above basement rocks in the Arco #1 Meadow Federal Unit borehole (Well #4 in Fig. 2; Standlee, 1982). The Paleozoic section east of the Canyon Range is overlain by a Triassic-Jurassic succession of shale, sandstone, carbonate, and evaporite that is ~2.6 km thick, with local structural thickening (Standlee, 1982).

Resting on top of the Jurassic section in the eastern platformal district, but generally absent west of the Canyon Range (with one exception in the Cricket Mountains), is a succession of Cretaceous–early Tertiary strata that varies drastically in thickness and lithology. In the San Pitch Mountains (Gunnison Plateau), the Cretaceous-Paleocene rocks are up to ~4.3 km thick (Villien and Kligfield, 1986; Lawton et al., 1993), but they decrease in thickness toward structural highs that were active during deposition (Fig. 3). These sediments are the proximal

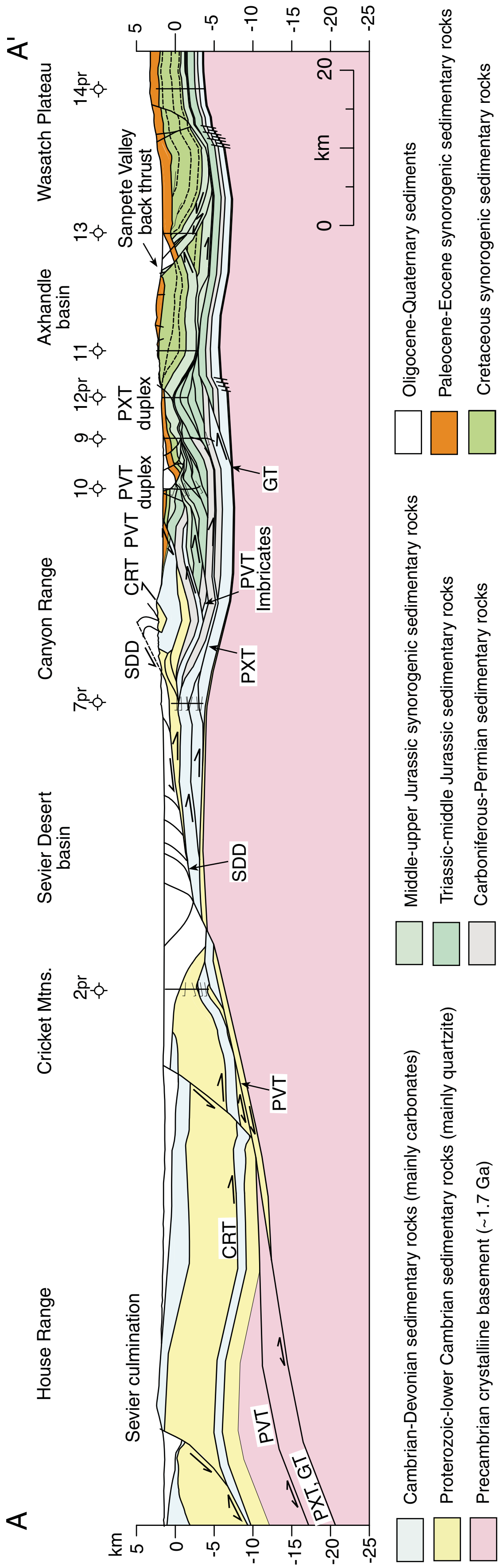


Figure 3. Regional balanced cross-section A–A′ of the Sevier fold-and-thrust belt in central Utah, based in part on Coogan et al. (1995), Royse (1993), Standlee (1984), and Consortium for Continental Reflection Profiling (COCORP) deep seismic-reflection profile (Allmendinger et al., 1983, 1986). Numerals indicate industry wells that were used to constrain the section. Letters (pr) after well numbers indicate where data were projected more than a few kilometers into the plane of the cross section. See Figure 2 for location of cross section and legend of industry wells. CRT—Canyon Range thrust; PVT—Pavant thrust; PXT—Paxton thrust; GT—Gunnison thrust; SDD—Sevier Desert detachment.

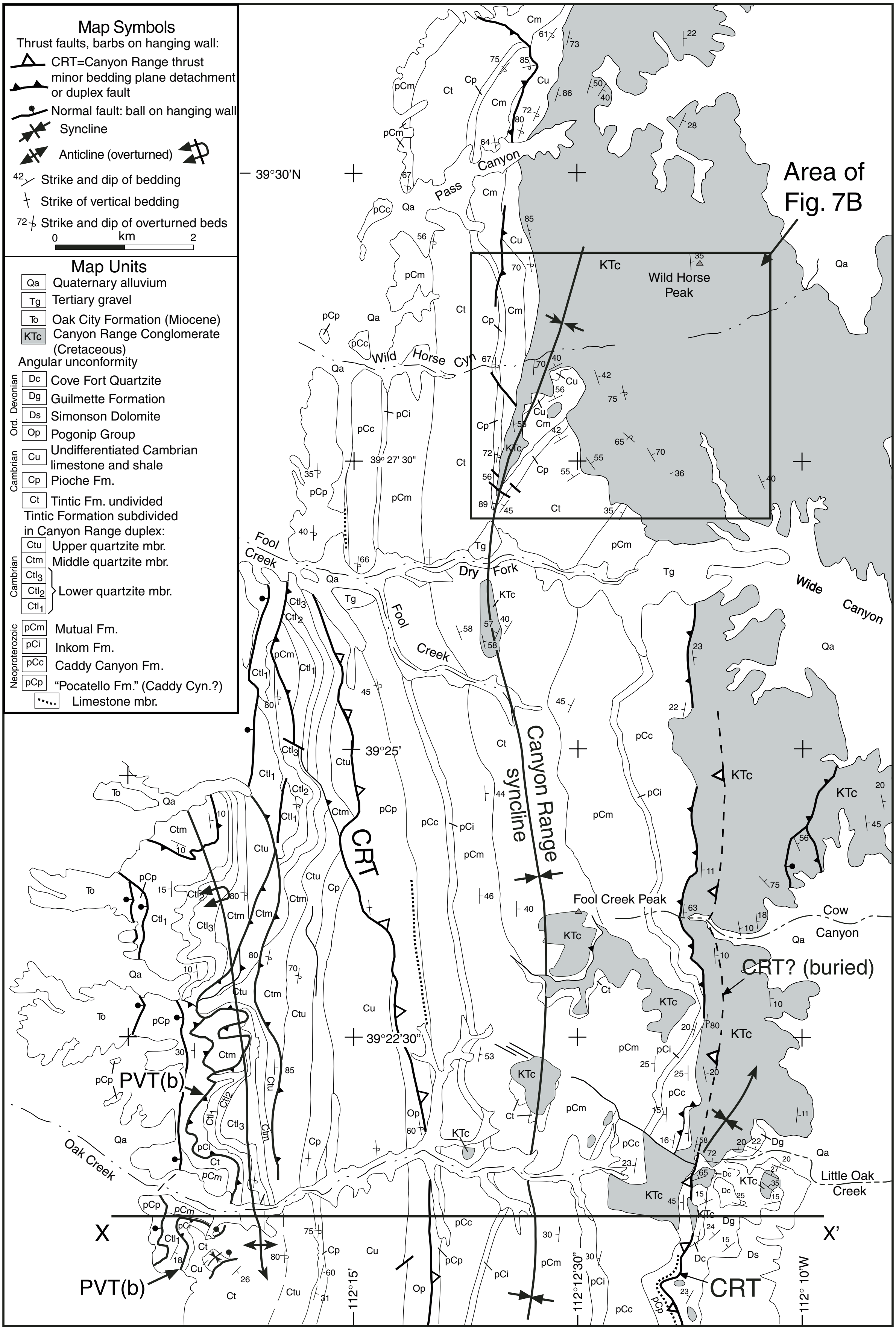

Map Symbols
Thrust faults, barbs on hanging wall:
CRT=Canyon Range thrust
minor bedding plane detachment or duplex fault
Normal fault: ball on hanging wall
Syncline
Anticline (overturned)
42 Strike and dip of bedding
Strike of vertical bedding
72 Strike and dip of overturned beds
0 km 2
Map Units
Qa Quaternary alluvium
Tg Tertiary gravel
To Oak City Formation (Miocene)
KTc Canyon Range Conglomerate (Cretaceous)
Angular unconformity
Ord. Devonian
Dc Cove Fort Quartzite
Dg Guilmette Formation
Ds Simonson Dolomite
Op Pogonip Group
Cambrian
Cu Undifferentiated Cambrian limestone and shale
Cp Pioche Fm.
Ct Tintic Fm. undivided
Tintic Formation subdivided in Canyon Range duplex:
Ctu Upper quartzite mbr.
Ctm Middle quartzite mbr.
Ctl3 Ctl2 Ctl1 Lower quartzite mbr.
Neoproterozoic
pCm Mutual Fm.
pCi Inkom Fm.
pCc Caddy Canyon Fm.
pCp "Pocatello Fm." (Caddy Cyn.?)
Limestone mbr.
39°30'N
Pass Canyon
Area of Fig. 7B
Wild Horse Peak
Wild Horse Cyn
39° 27' 30"
Fool Creek
Dry Fork
Wide Canyon
39°25'
CRT
Canyon Range syncline
Fool Creek Peak
Cow Canyon
CRT? (buried)
39°22'30"
PVT(b)
Oak Creek
Little Oak Creek
X
X'
112°15'
112°12'30"
112° 10'W

Figure 4. Geological map of the central part of the Canyon Range, after Lawton et al. (1997) with minor modifications by the authors and Ismat and Mitra (2005). X–X′ marks the line of cross section shown in Figure 5. PVT(b)—hanging wall imbricate of the Pavant thrust sheet.

wedge-top and foredeep fill of the Cordilleran foreland basin system, and were derived entirely from the growing Cordilleran orogenic belt (including the Sevier fold-and-thrust belt; Spieker, 1946; Villien and Kligfield, 1986; Schwans, 1988; DeCelles et al., 1995; Mitra and Sussman, 1997; Lawton et al., 1997).

The major exposed detachment levels of the Sevier belt in central Utah lie in the shaly upper part of the Neoproterozoic Pocatello Formation (which may be part of the lower Caddy Canyon Formation; Christie-Blick, 1982), Cambrian shale (Ophir Formation), Triassic shale (Woodside, Thaynes, and Ankareh Formations), and Middle Jurassic evaporite and shale (Arapien Formation) (Fig. 3). The Neoproterozoic–Lower Cambrian quartzites, Cambrian carbonates, and the Triassic-Jurassic Navajo Sandstone are the principal mechanically competent units. The mechanically incompetent Arapien Formation is particularly influential in controlling structural style in the frontal Sevier belt (Standlee, 1982; Villien and Kligfield, 1986).

STRUCTURE OF THE SEVIER BELT

Canyon Range Thrust

The Canyon Range thrust sheet is exposed as an isolated klippe in the Canyon Range (Christiansen, 1952; Holladay, 1983; Figs. 3 and 4). However, Neoproterozoic and Lower Cambrian strata inferred to lie in the hanging wall of the Canyon Range thrust are also exposed in the Cricket and Drum Mountains to the southwest and west of the Sevier Desert basin (Figs. 2 and 3; Allmendinger et al., 1983). In the Canyon Range, the Canyon Range thrust carries a 3.9-km-thick succession of Neoproterozoic and Cambrian strata. The rocks in the footwall of the Canyon Range thrust are Neoproterozoic to Devonian and are at least 3.5 km thick (Fig. 5). In the Canyon Range, the Canyon Range thrust is folded into a north-trending synform such that two traces of the fault are exposed (Figs. 4 and 5). The eastern trace dips moderately westward (~40°W) and juxtaposes 40°W-dipping quartzite of the Neoproterozoic Pocatello Formation against 25°W-dipping Devonian carbonate strata in the footwall. The western trace of the fault in the southern part of the range dips moderately eastward (40°), but becomes increasingly steep toward the north until it is overturned, dipping 40–50°W in the northern part of the range (Mitra and Sussman, 1997; Ismat and Mitra, 2001; Mitra and Ismat,

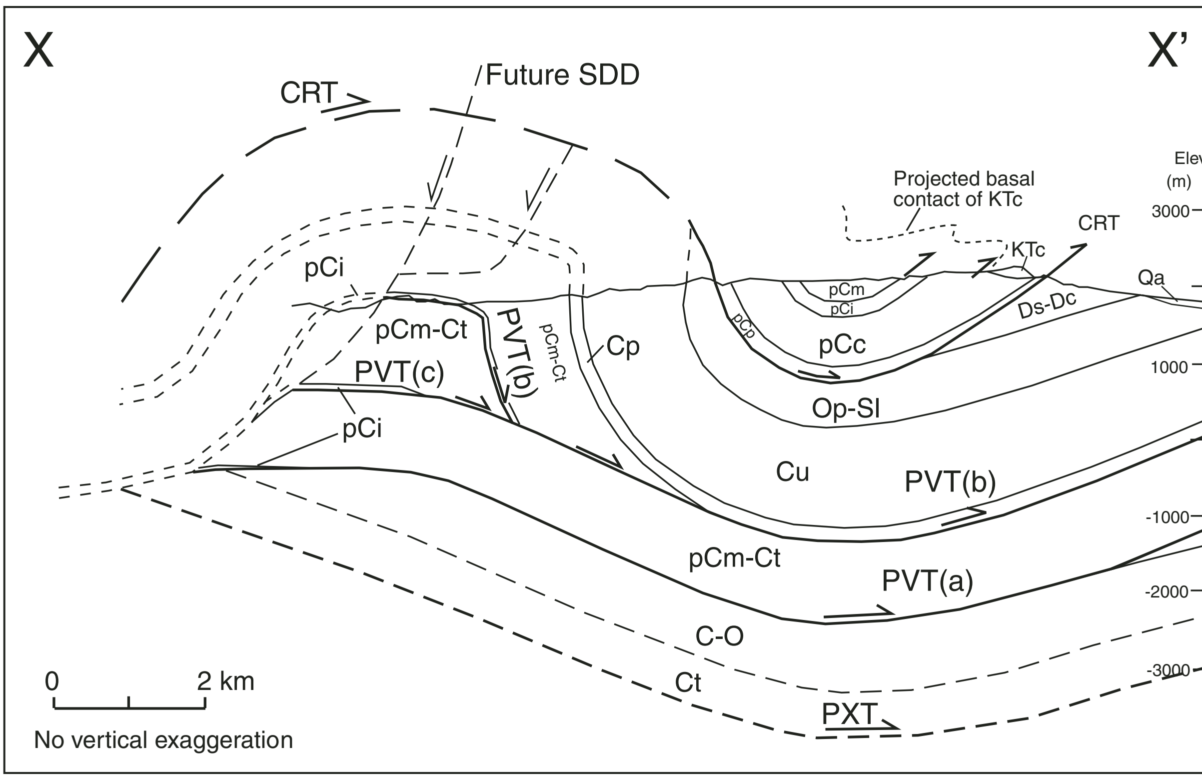


Figure 5. Cross section X–X′ through the central part of the Canyon Range. See Figure 4 for location of section line. Symbols are abbreviated as follows: CRT—Canyon Range thrust; PVT(a)—main Pavant thrust; PVT(b) and PVT(c)—hanging wall imbricates of the Pavant thrust sheet that are involved in the Canyon Range duplex; C-O—undivided Cambrian-Ordovician in footwall of Pavant thrust; Ds-Dc—Devonian Simonson and Sevy, Guilmette, and Cove Fort Formations; Op-Sl—Ordovician Pogonip Group, Eureka Quartzite, Fish Haven Dolomite, and Silurian Laketown Dolomite. Other symbols are listed in legend of Figure 4.

2001). Along the western trace, east-dipping (in the southern part of the range) to overturned, west-dipping (in the northern part of the range) Pocatello strata in the hanging wall are juxtaposed against steeply east-dipping to overturned Cambrian and Ordovician strata (Fig. 4). A stratigraphic separation diagram (Fig. 6) shows that, in the tectonic transport direction, the Canyon Range thrust juxtaposes Neoproterozoic rocks that are cut at a low angle to the fault in the hanging wall with rocks that are cut at a moderate angle in the footwall—i.e., a configuration that indicates juxtaposition of a low-angle hanging-wall ramp on a frontal footwall ramp (Fig. 5). Along its northern exposed portion, the western trace of the Canyon Range thrust cuts down-section laterally toward the north, indicating that a lateral ramp exists in the footwall as well (Figs. 4 and 6).

To the west of the western trace of the Canyon Range thrust, the fault is inferred to lie in the shallow subsurface along the western flank of the Canyon Range (Mitra and Sussman, 1997; Mitra and Ismat, 2001). The evidence for this interpretation is the presence of outcrops of the Pocatello Formation, which have been displaced downward to the west by a normal fault along the western flank of the range. The Canyon Range thrust was folded into an antiform-synform pair in the Canyon Range prior to disruption by erosion and normal faulting (Fig. 5; Ismat and Mitra, 2005).

An important feature of the Canyon Range thrust sheet is its close association with the Canyon Range Conglomerate (Figs. 5 and 7; Stolle, 1978). The conglomerate consists of coarse alluvial fan, fluvial, and possibly shallow-marine lithofacies (DeCelles et al., 1995; Lawton et al., 1997). The only published constraint on the age of the conglomerate is that it contains quartzite clasts that yielded a mid-Cretaceous (96.8 ± 10.6 Ma) apatite fission-track age (Stockli et al., 2001). This age is consistent with unpublished Cenomanian-Turonian palynological ages from outcrops higher in the section (T. White, 2002, personal commun.). The Canyon Range Conglomerate buries the Canyon Range thrust, but contains growth structures that indicate that it was deformed as it accumulated by slip on minor bedding-plane detachments in the hanging wall of the thrust (Fig. 7C). Contrary to previous interpretations (e.g., Stolle, 1978; Royse, 1993; DeCelles et al., 1995; Mitra and Sussman, 1997; Schwans and Campion, 1997), the conglomerate is not cut by the Canyon Range thrust in outcrops along the eastern flank of the range; rather, it overlaps the frontal

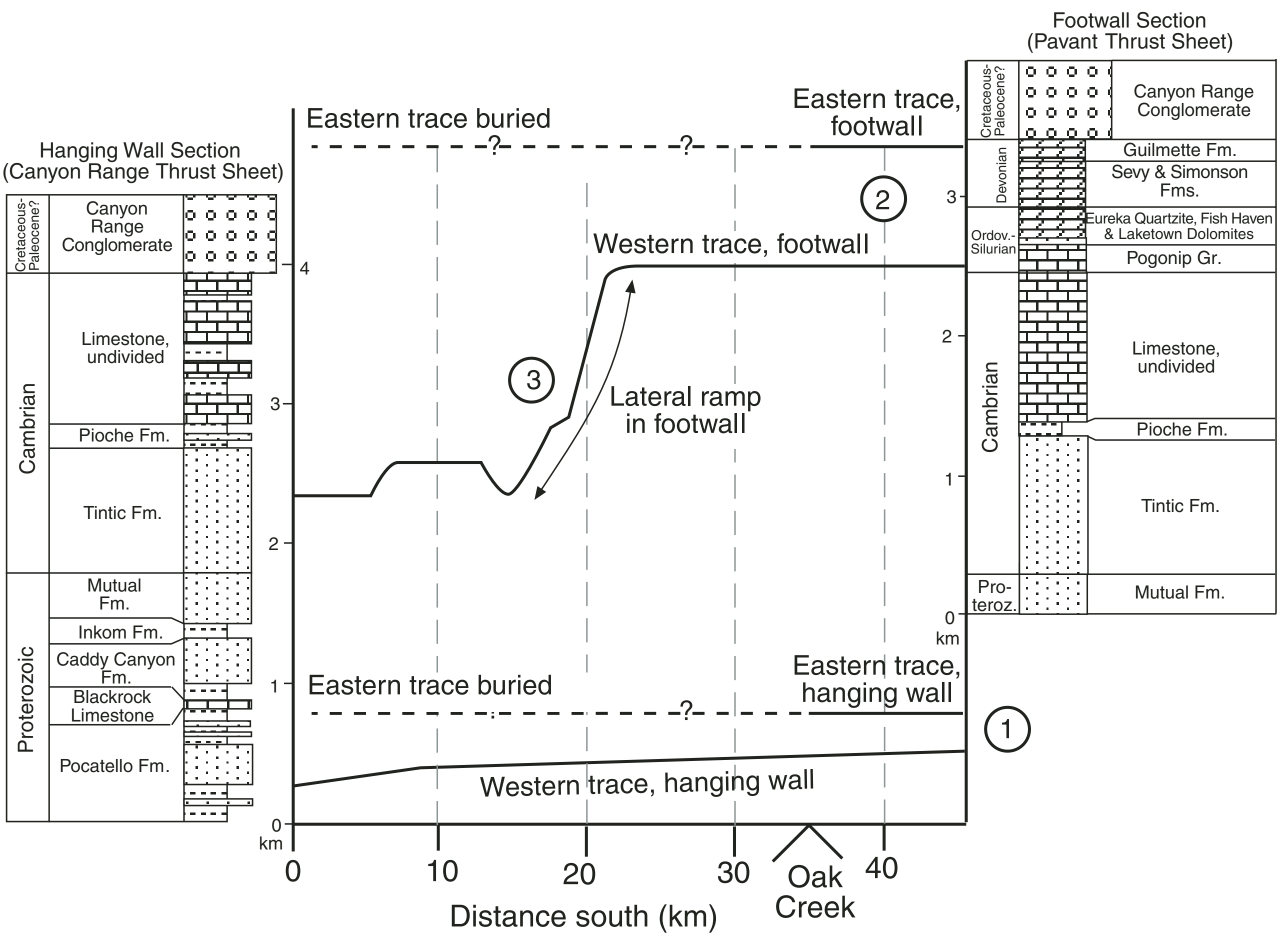


Figure 6. North-south–oriented stratigraphic separation diagram for the Canyon Range thrust in the map area of Figure 4. Circled numbers highlight the following important aspects of the diagram: (1) Canyon Range thrust climbs ~250 m in the hanging-wall stratigraphy from west to east across the range, indicating the presence of a low-angle hanging-wall ramp and corresponding hanging-wall cutoffs; (2) in the southern part of the Canyon Range, the thrust climbs ~1 km in the footwall from west to east, indicating a relatively high-angle footwall ramp, whereas farther north the thrust climbs ~2.5 km from west to east in the footwall; (3) from north to south, the thrust climbs ~1.5 km in the footwall stratigraphy, indicating the presence of a major northward-dipping footwall lateral (or oblique) ramp.

part of the thrust sheet in buttress unconformity (Figs. 4 and 7C). The significance of the growth structures in the Canyon Range Conglomerate for the regional kinematic history of the Sevier belt is discussed in a subsequent section.

On a regional scale, the geometry and displacement for the Canyon Range thrust depend on matching the hanging-wall geometry exposed in the Canyon Range with footwall cutoff locations interpreted beneath the Cricket Mountains and the House Range along the COCORP seismic line. Low-angle, Neoproterozoic-level hanging-wall cutoffs are documented across the Canyon Range thrust in the Canyon Range (Fig. 6). Total thrust displacement therefore depends on the location of equivalent footwall cutoffs interpreted from the COCORP data. The interpretation hinges on a series of continuous high-amplitude reflections beneath the Cricket Mountains and House Range that was recognized by Allmendinger et al. (1983, 1986), Sharp (1984), Planke and Smith (1991), and Royse (1993) as correlating, in part, to the Middle Cambrian carbonates and Lower Cambrian quartzite sequence penetrated beneath the Canyon Range thrust by the Cominco American well through the Cricket Mountains block (Well #2 in Figs. 2 and 3). Published displacement estimates vary from 40 to 70 km (Sharp, 1984; Royse, 1993), to 116 km (Currie, 2002), to the >150 km of displacement implied in the pre-extension reconstruction of the House Range, Utah, and Snake Range, Nevada, by Bartley and Wernicke (1984). The variation in displacement estimates for the Canyon Range thrust reflects the different interpretations of where the Canyon Range thrust cuts down-section westward to Neoproterozoic footwall levels from the Cambrian footwall level of the Cominco well. The balanced and restored cross section through the Cricket Mountains and House Range in Figures 3 and 8 places Neoproterozoic-level footwall cutoffs west of the House Range, indicating a pre-extension Canyon Range thrust displacement of ~107 km at the Lower Cambrian level. This estimate is based in part on the constant thickness of the high-amplitude reflection package ("events C" of Allmendinger et al., 1983) beneath the Canyon Range thrust sheet upon depth conversion. The constant reflection interval is consistent with a constant thickness of Cambrian through Neoproterozoic footwall strata that were penetrated by the Cominco well beneath the Canyon Range thrust. When combined with the surface outcrop data and internal reflections for the Canyon Range hanging wall, the resulting geometry for the Canyon Range thrust is that of a hanging-wall Neoproterozoic-level flat superimposed on a Cambrian-level footwall flat beneath the entire House Range (Fig. 3). This interpretation constrains the easternmost location of Neoproterozoic footwall cutoffs for the Canyon Range thrust as somewhere west of the House Range, with a resulting Canyon Range thrust displacement of more than 100 km (see also Currie, 2002). We estimate ~117 km of total fold-and-thrust shortening during main-phase emplacement of the Canyon Range sheet (Fig. 8B).

Pavant Thrust and Canyon Range Culmination

The Pavant thrust is known from outcrops in the Pavant Range that expose a major thrust fault that places Lower Cambrian Tintic Formation quartzite on top of Jurassic sandstone, shale, and carbonate (Fig. 2; Burchfiel and Hickcox, 1972; Villien and Kligfield, 1986). In the Pavant Range, the thrust is tilted into a gentle (<15°) eastward dip. The Tintic Formation is intensely deformed at the micro- and mesoscale, with numerous tight folds that indicate top-to-the-east sense of shear (Sprinkel and Baer, 1982). However, the outcrop pattern and the mapped shape of the fault indicate that it is nearly parallel to the rocks above and below. The frontal tip of the Pavant thrust is buried in the subsurface to the east of the Pavant Range.

A second area of exposure of the Pavant thrust sheet is in the Canyon Range, where Pavant thrust hanging-wall strata crop out along the southeastern and western flanks of the range. In the western Canyon Range, an antiformal duplex composed of repeated horses of Tintic and Mutual Formation quartzite and Inkom Formation shale forms a structural culmination referred to as the Canyon Range culmination (Fig. 5; DeCelles et al., 1995; Mitra and Sussman, 1997; Ismat and Mitra, 2001, 2005). The growth of this duplex folded the overlying Canyon Range thrust sheet into an antiform (Fig. 5). The upper thrust sheet in the duplex along the line of the cross section consists of a complete stratigraphic succession from the Inkom Formation to the Ordovician carbonate rocks (Fig. 5), which we interpret to be a western exposure of the Pavant thrust sheet. The duplex itself also consists of horses of the Pavant sheet (Ismat and Mitra, 2001; Mitra and Ismat, 2001). Farther north of our cross-section line, Mitra and Sussman (1997) mapped a structurally higher horse of Tintic Formation directly west of (structurally beneath) the western trace of the Canyon Range thrust (Fig. 4).

The regional geometry and displacement for the Pavant thrust are constrained by minimum limits on the separation between Paleozoic-level hanging-wall and footwall cutoffs. Cambrian and Ordovician hanging-wall cutoffs are exposed on the north wall of Kanosh Canyon in the southern Pavant Range (Fig. 2; Hintze et al., 2003) and must lie directly east of the Devonian rocks of the Pavant hanging wall in the eastern Canyon Range (Figs. 3 and 4; Hintze and Davis, 2003). The easternmost possible location of the equivalent footwall cutoffs is beneath the western edge of the Sevier Desert basin. Five wells and extensive seismic profiles across the basin demonstrate that the Cenozoic fill is underlain by a continuous sequence of Lower Paleozoic strata (Planke and Smith, 1991). The structural position of these strata is defined by their continuous correlation to Cambrian and Ordovician rocks drilled in the Placid Henley well (Well #7 in Figs. 2 and 3), which lie beneath Neoproterozoic and Cambrian quartzites exposed in the Pavant hanging wall of the western Canyon Range. Thus, the Lower Paleozoic rocks beneath the Sevier Desert basin fill form the continuous footwall of the Pavant thrust where the hanging wall has been extensionally stripped from the area of the Sevier Desert basin. These hanging-wall and footwall cutoff constraints yield published estimates for Pavant thrust displacement that vary from 29 km from a cross section across the Pavant Range and southern Sevier Desert by Royse (1993), to up to 45 km from a series of alternative balanced cross sections through the Canyon Range and northern Sevier Desert by Sharp (1984). Our balanced cross section (Fig. 3) and reconstruction (Fig. 8) result in ~42 km of Lower Cambrian–level displacement on the Pavant thrust and its hanging wall duplex thrusts in the Canyon Range, with total fold-and-thrust shortening of ~48 km.

Pavant Thrust Footwall Imbricates

The Pavant thrust system also contains extensive footwall imbricates for which displacement has not been emphasized or quantified in previous studies. The Pavant footwall imbricates include two splays of the Red Ridge thrust in the southernmost Pavant Range (Hintze et al., 2003). The main Red Ridge thrust trace places Permian through Triassic strata over Jurassic strata. Surface hanging-wall and footwall cutoffs limit east-west displacement across the Red Ridge thrust to ~16 km. An unnamed hanging-wall imbricate of the Red Ridge thrust places Mississippian and Pennsylvanian strata over Permian strata. East-west displacement across this thrust is a minimum of 18 km between the preserved Mississippian footwall cutoff and the eroded Mississippian hanging-wall rocks along the frontal trace of the fault.

Correlation of the Pavant footwall imbrication 70 km northward to the Canyon Range (Fig. 3) is based on the similar structural position, stratigraphic level, and displacement for

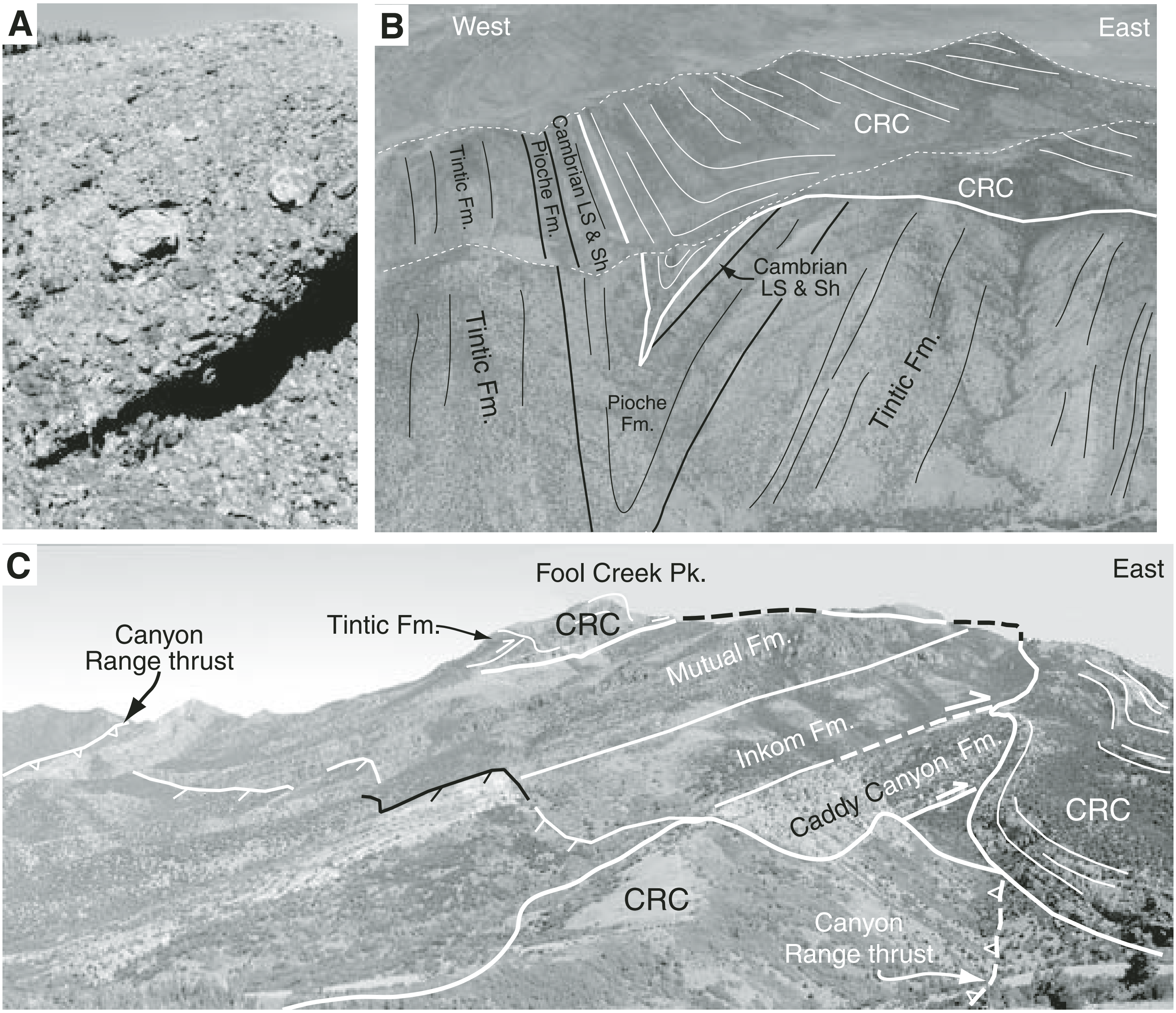


Figure 7. (A) Boulder-conglomerate lithofacies, dipping westward, in Canyon Range Conglomerate just below Fool Creek Peak. (B) Oblique aerial photograph of the core of the Canyon Range synform between Dry Fork and Wildhorse Peak (see Fig. 4 for location). Note the tight synclinal fold in the Paleozoic section, the overlapping angular unconformity at the base of the Canyon Range Conglomerate (CRC), and the growth syncline in the CRC. LS—limestone; Sh—shale. Width of image is ~3 km. (C) Panoramic photograph of the north side of Oak Creek Canyon, showing the western trace of the Canyon Range thrust (far left), the approximate location of the eastern, buried trace of the thrust (lower right), the eastern limb of the Canyon Range synform, and overlapping, growth-folded Canyon Range Conglomerate (CRC). Width of image is ~5 km.

imbricate thrusts, which have been interpreted from proprietary seismic profiles across the Canyon Range and tied to a well east of the Canyon Range. The Placid Monroe well (Well #10 in Figs. 2 and 3) penetrated four thrust sheets of Triassic through Middle Jurassic strata east of and structurally beneath Devonian-level exposures of the Pavant thrust sheet. These thrust faults are interpreted as footwall imbricates of the Pavant thrust that may be correlative to the Red Ridge thrust system to the south. This Triassic- through Jurassic-level displacement in the well is balanced westward by equivalent Upper Paleozoic–level shortening interpreted from seismic-reflection data beneath the Pavant thrust sheet of the Canyon Range. Cambrian-level thrust displacement, and total shortening for the Pavant footwall imbricate system, is ~26 km in Figure 8, in which post-Eocene extension is removed from the present-day balanced cross section in Figure 3.

Paxton Thrust System

The Paxton thrust is the least described of the four thrust systems in central Utah because it does not crop out at the surface. However, the fault is identified beneath the Pavant thrust on the basis of published seismic and well data across the southern Pavant Range (Royse, 1993). The Paleozoic- through Jurassic-level footwall ramp of the Paxton thrust is clearly imaged in published seismic data on the western side of the southern Pavant Range near Fillmore, Utah ("sub-Pavant thrust(?)" of Mitchell and McDonald, 1987). The equivalent hanging-wall cutoffs are located near the Placid #1 Paxton well on the east side of the southern Pavant Range (Royse, 1993; south of the area shown in Fig. 2). The Paxton well penetrated Cambrian rocks of the Paxton hanging wall, faulted over footwall Jurassic rocks at 4.3 km depth. From these constraints alone, Paxton displacement is at least 28 km beneath the southern Pavant Range. A proprietary seismic line confirms the continuity of these fault observations beneath the range.

Similar constraints bracket the basic geometry of the Paxton thrust and its displacement along the central Canyon Range transect, 70 km north of the Pavant Range data. The footwall ramp zone of the Paxton system is interpreted in the Placid Henley well west of the Canyon Range (Well #7 in Figs. 2 and 3). The well penetrated a thrust fault that places the base of the ~1.2-km-thick Cambrian carbonate sequence over Ordovician strata, with a smaller thrust in the Cambrian carbonate section near the bottom of the well. Dipmeter data indicate that the lowest thrust in the well forms a gently west-dipping ramp relative to the gently east-dipping footwall. The changes in dip in hanging-wall rocks above the lowest thrust indicate that the two thrusts encountered in the well may form a small antiformal duplex, an interpretation that is supported by the apparent domal and internal lateral ramp geometries of this thrusted section imaged on a published seismic line that ties to the well (Mitchell and McDonald, 1987). The position of these thrusts beneath the Pavant hanging-wall rocks exposed in the Canyon Range and their similar structural position to the Paxton footwall ramp zone near Fillmore, Utah, indicate that the Henley well drilled the Lower Paleozoic footwall ramp of the Paxton thrust. The interpreted duplex thrust zone encountered in the well is consistent with minor collapse of the footwall ramp, which is a common structural motif in fold-and-thrust belts (Boyer and Elliott, 1982).

The limit of the Paxton thrust system east of the Canyon Range is interpreted from two wells. The Placid WXC Barton well (Well #9 in Figs. 2 and 3) penetrated a steeply dipping and overturned Lower Triassic and Upper Paleozoic section above a thrust fault 4.8 km below the surface. Upper Triassic through Devonian footwall strata dip ~15° to the west in what is interpreted as the hanging wall of the Gunnison thrust. The Barton well therefore defines the Upper Paleozoic hanging-wall cut-off of a thrust sheet that is east of and structurally below the Pavant footwall imbricate zone drilled by the Placid Monroe well (Well #10 in Fig. 3). This thrust occupies an equivalent structural position to the eastern edge of the Paxton thrust defined by the Paxton well to the south. The large Paleozoic-level displacement of the thrust in the Barton well is consistent with the amount of Triassic- through Middle Jurassic–level shortening near the Amoco Sevier Bridge well (Well #12 in Figs. 2 and 3) directly to the east. The Sevier Bridge well penetrated the east limb of an antiform that is cored by multiple thrust sheets of Triassic through Middle Jurassic strata. The well is interpreted to have penetrated the upper two horses of a Triassic-Jurassic–level duplex. The two underlying horses are interpreted from the seismic geometry of the eastern limb of the antiform and from the structural relief penetrated in the Sevier Bridge well above equivalent Jurassic strata in the Chevron USA Chriss Canyon well to the east (Well #11 in Figs. 2 and 3). The balanced cross section indicates that the duplex penetrated by the Sevier Bridge well (the Paxton duplex) accommodated ~20 km of thrust displacement at the Triassic–Lower Jurassic stratigraphic level, which is equivalent to the Paleozoic-level thrust displacement required for the Paxton thrust system between the footwall ramp in the Henley well (Well #7) and the hanging-wall cutoffs in the Barton well (Well #9).

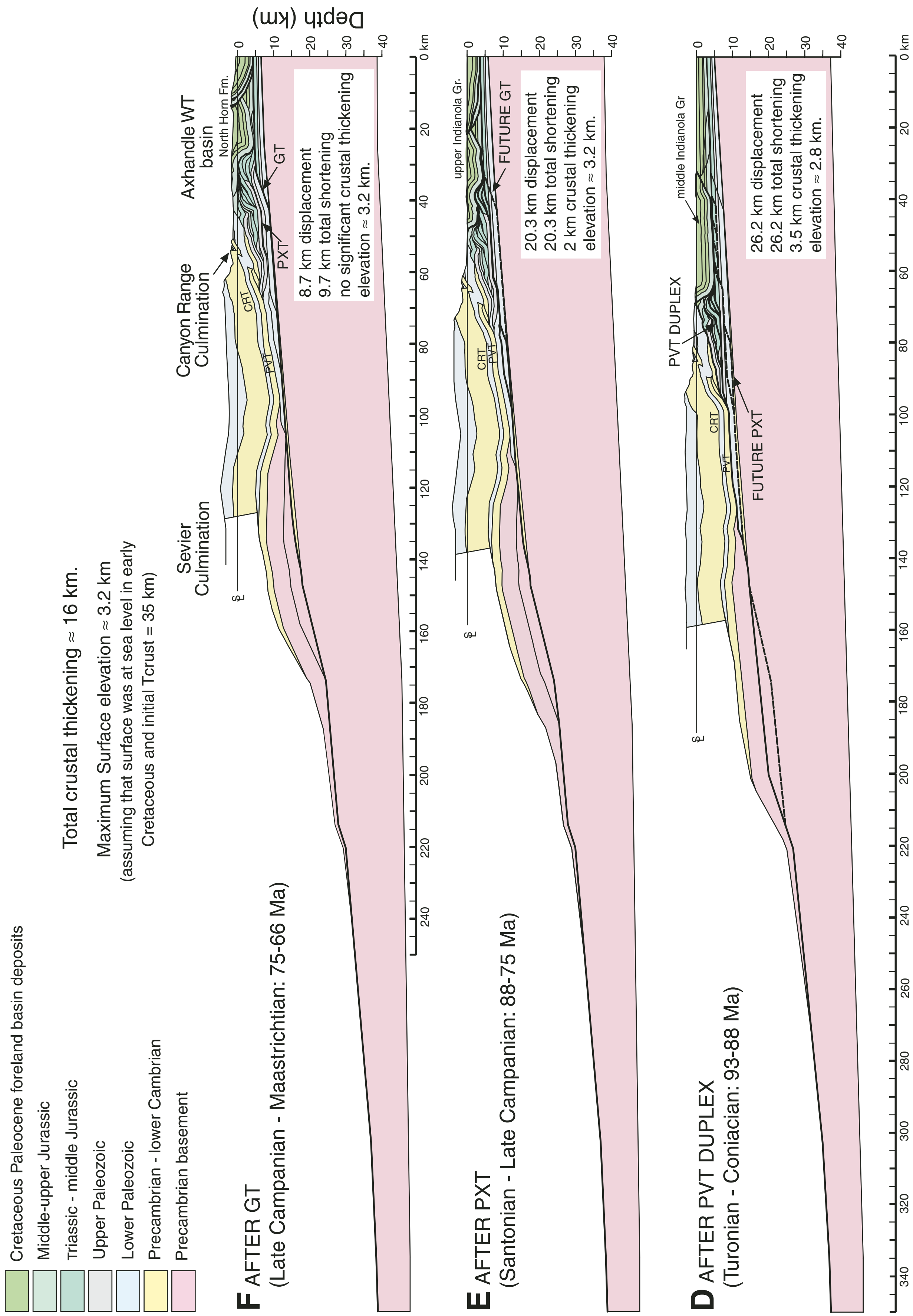
Structural balancing of the Triassic through Upper Cretaceous strata indicates that the Paxton thrust contributed an early phase of slip to a frontal imbricate and passive back-thrust system, which developed as a triangle zone above Middle Jurassic evaporites at the front of the thrust wedge. The restoration (Fig. 8) indicates that this frontal back-thrust system remained intermittently active throughout the remainder of Sevier belt shortening.

Gunnison Thrust System

The Gunnison thrust system has been documented in industry boreholes and seismic profiles (Standlee, 1982; Lawton, 1985; Villien and Kligfield, 1986; Royse, 1993). The thrust sheet is currently the focus of renewed drilling and seismic acquisition near the site of the 2004 Covenant oil field discovery on the Gunnison thrust sheet near Richfield, Utah (Stefanic, 2005). Along our transect, the Gunnison thrust sheet consists of a single fault-bend anticline in Cambrian through Middle Jurassic strata, with displacement at Middle Jurassic through Cretaceous levels accommodated by further growth of the frontal passive back-thrust system, which was established during Paxton thrusting (Fig. 8). The frontal back thrust was partially reactivated by a normal fault that forms the western margin of the Sanpete Valley, and the antiformal structure associated with the back thrust is referred to as the Sanpete Valley antiform (Lawton et al., 1993). The Paleozoic through Lower Jurassic footwall cutoffs for the Gunnison thrust are assumed to underlie the ~15° west-dipping panel of Paleozoic strata at the base of the Placid WXC Barton well (Well #9 in Figs. 2 and 3). The corresponding hanging-wall cutoffs are placed directly west of the Chevron USA Chriss Canyon well (Well #11 in Figs. 2 and 3), which bottomed in flat-lying Lower Jurassic rocks of the seismically defined Gunnison footwall. Displacement on the Gunnison thrust is estimated at 8.7 km after removal of the Neogene normal slip on the interconnected Sanpete Valley back thrust (Fig. 8). Total shortening, as measured by displacement of the rear of the thrust wedge, is ~9.7 km for the Gunnison thrust system. For comparison, Royse (1993) delineated ~6.8 km of displacement for the Gunnison thrust near Salina, Utah, which would increase if Neogene extension were removed.

Sevier Culmination

The Sevier culmination, or Sevier arch (Harris, 1959), is a broad antiformal structure (Fig. 3) defined by the erosional pattern of Paleozoic subcrop beneath the basal Tertiary unconformity in western Utah (Harris, 1959; Hintze and Davis, 2003), and by broadly arched seismic reflectors documented on the COCORP profile at depths of 5–10 km (Allmendinger et al., 1983, 1986; Allmendinger, 1992). Allmendinger et al. (1983) interpreted at least one additional, gently westward-dipping reflection in the middle crust as a major thrust fault in the basement within the core of the culmination, possibly associated with a broad antiformal duplex. Restoration of ~47 km of Cenozoic slip on the Sevier Desert detachment fault (Coogan and DeCelles, 1996) places the Sevier culmination at a high structural level directly to the west of the Canyon Range at the cessation of regional shortening (Fig. 8). The Pavant, Paxton, and Gunnison thrusts are inferred to root beneath the Sevier culmination, whereas the Canyon Range thrust is passively folded above the arch (Fig. 3; Allmendinger et al., 1986).


Cretaceous Paleocene foreland basin deposits
Middle-upper Jurassic
Triassic - middle Jurassic
Upper Paleozoic
Lower Paleozoic
Precambrian - lower Cambrian
Precambrian basement
Total crustal thickening ≈ 16 km.
Maximum Surface elevation ≈ 3.2 km
(assuming that surface was at sea level in early
Cretaceous and initial Tcrust = 35 km)
F AFTER GT
(Late Campanian - Maastrichtian: 75-66 Ma)
Sevier
Culmination
Canyon Range
Culmination
Axhandle WT
basin
North Horn Fm.
GT
PXT
CRT
PVT
8.7 km displacement
9.7 km total shortening
no significant crustal thickening
elevation ≈ 3.2 km.
Depth (km)
E AFTER PXT
(Santonian - Late Campanian: 88-75 Ma)
upper Indianola Gr.
FUTURE GT
20.3 km displacement
20.3 km total shortening
2 km crustal thickening
elevation ≈ 3.2 km.
D AFTER PVT DUPLEX
(Turonian - Coniacian: 93-88 Ma)
middle Indianola Gr
PVT DUPLEX
FUTURE PXT
26.2 km displacement
26.2 km total shortening
3.5 km crustal thickening
elevation ≈ 2.8 km.
0 km

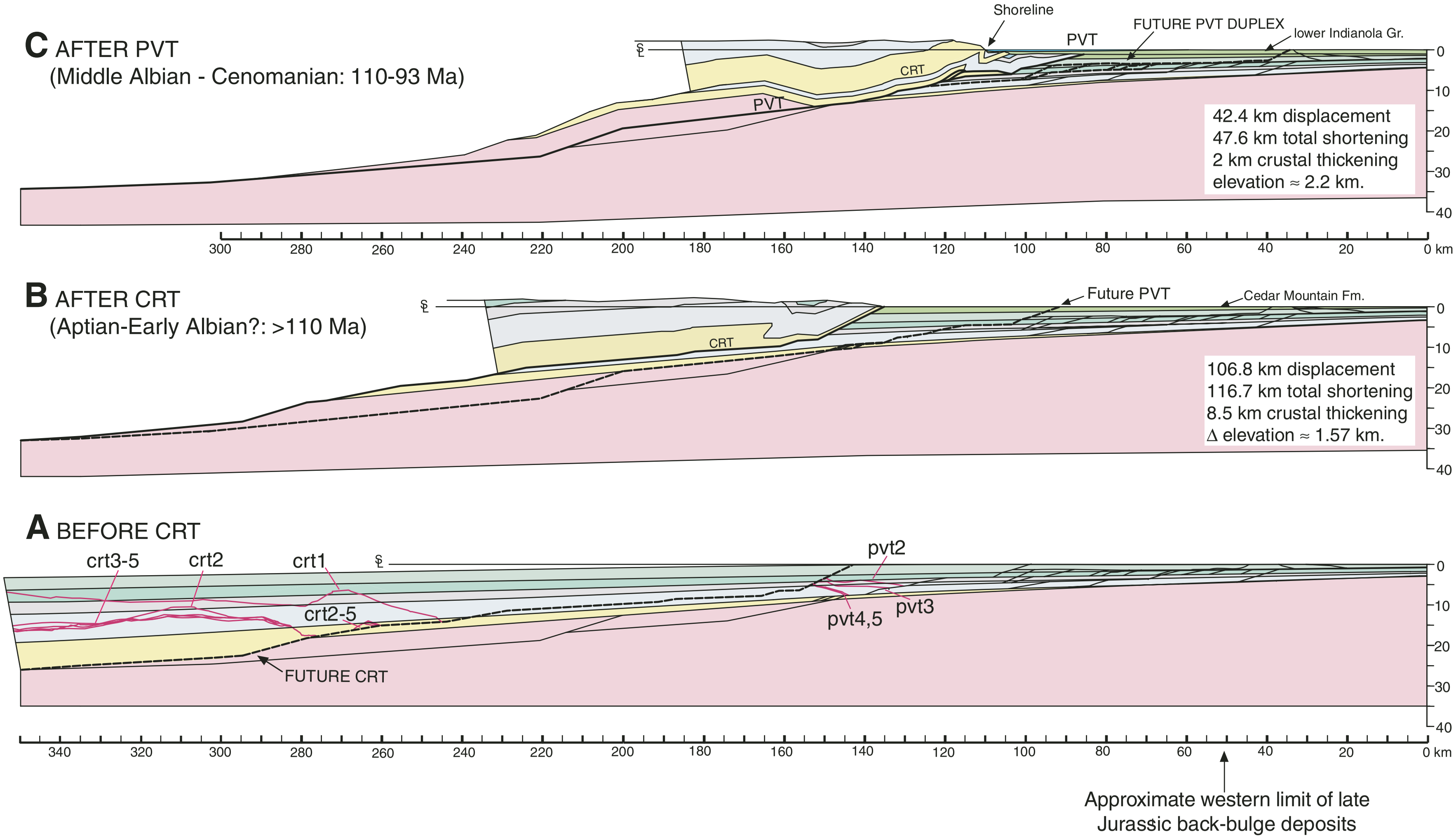


Figure 8 (*on this and previous page*). **Balanced, incremental retrodeformation of the central Utah segment of the Sevier thrust belt, based on initial deformed state (with Cenozoic extension restored) of cross section shown in Figure 3. In panel A, the dotted lines represent erosion surfaces in the Canyon Range (CRT) and Pavant (PVT) thrust sheets through time. PXT—Paxton thrust; GT—Gunnison thrust; SDD—Sevier Desert detachment.**

KINEMATIC HISTORY

Sources of Information

A variety of information may be used to reconstruct the kinematic history of the Sevier belt in central Utah, including crosscutting and overlapping relationships between rock units of known ages, ages and provenance of synorogenic conglomerate units in the wedge-top part of the foreland basin system, and apatite fission-track (AFT) ages from sediments (detrital ages) and in situ bedrock exposures (Stockli et al., 2001). The AFT ages may be reasonably interpreted as the times at which the rocks passed through the apatite partial annealing zone (~3–5 km below the surface) as the rocks were being exhumed (Stockli et al., 2001). The synorogenic conglomerates are locally dated by palynology and magnetostratigraphy (Fouch et al., 1983; Talling et al., 1994), and their source terranes can be identified on the basis of clast types. In some cases, dated growth structures in the synorogenic sediments may be directly tied to specific structures, providing some relative temporal precision (e.g., DeCelles et al., 1995; Talling et al., 1995; Lawton et al., 1997). Because the main sources of information on kinematic timing are the ages of conglomerates, which are inherently difficult to date (e.g., Jordan et al., 1988), our overall reconstruction must be regarded as a first approximation that should improve with the acquisition of better age data. Our discussion proceeds in a time slice fashion (Fig. 8) and refers to the kinematic restorations shown in Figures 8 and 9.

Canyon Range Thrusting (ca. 145–110 Ma)

The kinematic history of the Sevier fold-and-thrust belt during Late Jurassic through Early Cretaceous time has been a source of considerable debate over the past fifteen years. The principal reason for the uncertainty is that major surface-breaking thrust faults of clear-cut Jurassic age are either absent or sparse in western Utah (e.g., Allmendinger et al., 1987). Early workers interpreted the sedimentary lithic-rich compositions of Upper Jurassic sandstones and conglomerates in Wyoming and Utah as the products of erosion in the hinterland of the Sevier belt and inferred that the thrust belt must have been concurrently active (Spieker, 1946; Armstrong and Oriel, 1965; Armstrong, 1968; Royse et al., 1975; Wiltschko and Dorr, 1983). This interpretation was supported by more detailed provenance and paleocurrent studies of Jurassic–Lower Cretaceous sandstones and conglomerates in Montana, Wyoming, and Utah (Suttner, 1969; Furer, 1970; DeCelles, 1986; DeCelles and Burden, 1992). However, Heller et al. (1986) and Heller and Paola (1989) noted that the Upper Jurassic Morrison Formation does not have the expected geometry of a foredeep deposit, which typically thickens markedly toward the fold-and-thrust belt. These workers suggested that Late Jurassic sedimentation occurred in a broad, symmetrical depocenter that was possibly controlled by tectonothermal subsidence. In contrast, Bjerrum and Dorsey (1995) and Allen et al. (2000) proposed that flexural foreland basin subsidence in the western interior United States commenced long before deposition of the Morrison Formation, perhaps as early as Early Jurassic time, in response to thrust loads in western Nevada. Royse (1993) pointed out that restored regional cross sections in central Utah and eastern Nevada leave ample space (up to several kilometers) for an Upper Jurassic foredeep deposit that could have been eroded during subsequent Cretaceous thrusting and regional uplift. The maximum thickness of such a foredeep is limited to ~2–5 km, based on thermal information provided by conodont alteration indices from Mississippian rocks of eastern Nevada (Sandberg and Gutschick, 1984). DeCelles and Currie (1996) proposed that the Morrison Formation in Utah and Wyoming accumulated in a back-bulge depozone, to the east of a flexural forebulge, the passage through central Utah and western Wyoming of which would later be marked by the major disconformity (and ~10 m.y. hiatus) that separates Jurassic and Cretaceous strata in the western Cordilleran foreland basin. In agreement with Royse's (1993) suggestion, this model would require an active Late Jurassic fold-and-thrust belt in western Nevada, and a foredeep in eastern Nevada and western Utah (DeCelles, 2004).

Although a resolution of this debate is beyond the scope of this paper, we note that thrust displacements in the Luning-Fencemaker thrust belt of western Nevada are documented to have taken place during Middle and Late Jurassic time (Elison and Speed, 1988; Elison, 1991; Wyld, 2002), overlapping with the age of the Morrison Formation (DeCelles and Burden, 1992; Kowallis et al., 1991; Peterson, 1994; Currie, 1997, 1998). Moreover, Late Jurassic thrusting has been bracketed by U-Pb zircon ages in the East Sierran thrust belt (Walker et al., 1990; Dunne and Walker, 1993, 2004; Wrucke et al., 1995) and the Clark Mountains of southeastern California (Walker et al., 1995). Apatite fission-track modeling suggests that exhumation of the Canyon Range thrust sheet may have commenced by ca. 146 Ma (Fig. 10; Ketcham et al., 1996; Stockli et al., 2001). Synkinematic white mica $^{40}Ar/^{39}Ar$ ages (Yonkee et al., 1989, 1997) and fission-track ages (Burtner and Nigrini, 1994) from the Willard thrust sheet in northern Utah and southeastern Idaho indicate thrusting and exhumation by ca. 140–143 Ma. Moreover, evidence for mid-crustal ductile shortening, Barrovian metamorphism, and magmatism during the Late Jurassic is preserved in several locations in Nevada, western Utah, and southern California (Smith et al., 1993). Thus, regardless of the large-scale geometry of Upper Jurassic strata in Utah, the notion that the Late Jurassic–Early Cretaceous was a period of tectonic quiescence in the retroarc region is no longer tenable (DeCelles, 2004). Restoration of ~250 km of regional Cenozoic extension in central Nevada (Gans and Miller, 1983; Wernicke, 1992; Saleeby and Busby-Spera, 1992) leaves a 300 km gap between the front of the Luning-Fencemaker thrust belt and the longitude of the inferred Late Jurassic forebulge (Currie, 1997). Assuming typical continental rigidities, this is a reasonable width for a foredeep depozone (Currie, 1998), and gives credence to Royse's (1993) Late Jurassic "phantom foredeep." However, it is also plausible that Late Jurassic subsidence in the western interior United States was strongly affected by regional dynamic subsidence (Lawton, 1994; Currie, 1998; DeCelles, 2004).

The oldest unequivocal evidence in the foreland basin system for active thrusting in the Idaho-Wyoming-Utah portion of the Sevier fold-and-thrust belt is provided by the conglomeratic fluvial deposits of the Lower Cretaceous Kelvin, Cedar Mountain, and San Pitch Formations in Utah and the Gannett Group in Wyoming and Idaho, which have characteristics of typical foredeep deposits (DeCelles and Currie, 1996; Currie, 1997, 1998, 2002). Most importantly, the Cedar Mountain and Kelvin Formations thicken from ~100 m in eastern Utah and western Wyoming to >1000 m in central and northern Utah. In southeastern Idaho, Lower Cretaceous conglomerate is involved in a growth structure along the Meade thrust (DeCelles et al., 1993). Compositions of Lower Cretaceous conglomerates and sandstones in Utah, Wyoming, and Idaho indicate erosion of Neoproterozoic through Upper Paleozoic and Lower Mesozoic rocks, and paleocurrent data indicate that the source terranes were to the west-southwest (Furer, 1970; Lawton, 1982, 1985; DeCelles, 1986; DeCelles and Burden, 1992; DeCelles et al., 1993; Lawton et al., 1997; Mitra, 1997; Currie, 1997, 2002). The Cedar Mountain Formation in central Utah has been dated by palynology, charophytes, ostracodes, plant macrofossils, dinosaurs, and $^{40}Ar/^{39}Ar$ (sanidine) as Barremian-Albian in age (Katich, 1951; Stokes, 1952; Simmons, 1957; Thayn, 1973; Kirkland, 1992; Tschudy et al., 1984; Witkind et al., 1986; Weiss et al., 2003; DeCelles and Burden, 1992;

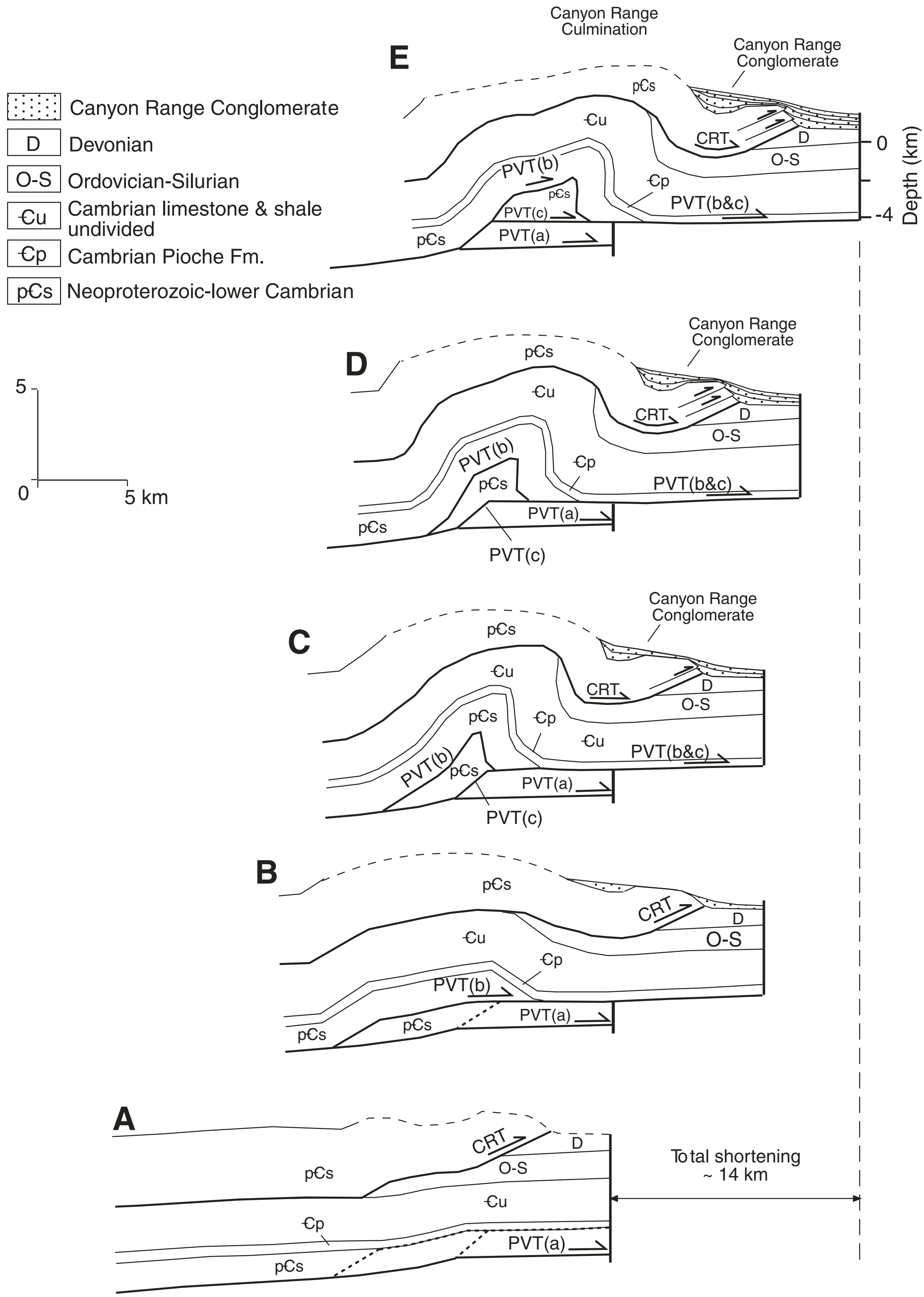


Figure 9. Balanced, incremental retrodeformation of cross-section X–X′ through the Canyon Range (shown in Figure 5). The initial state of the cross section (lower panel) represents the structure immediately after displacement on the main Pavant thrust (PVT[a]). Faults labeled PVT(b) and PVT(c) are hanging-wall imbricate splays that facilitated construction of the Canyon Range duplex in stages B–E. CRT—Canyon Range thrust. Canyon Range Conglomerate is projected into plane of cross section for purpose of illustrating general geometric relationships. Dashed upper surface of the antiformal culmination is an approximate erosional surface through time.

Lawton et al., 1997; Cifelli et al., 1997; Sprinkel et al., 1999). Taken together, the provenance, paleocurrent, and geochronologic data from the Cedar Mountain Formation (and its equivalents) and the thermochronologic data from the Canyon Range thrust sheet (Ketcham et al., 1996) suggest that Upper Jurassic–Lower Cretaceous (ca. 145–110 Ma) foreland basin deposits date the initial displacement on the Canyon Range thrust (Lawton, 1985; Schwans, 1988; DeCelles et al., 1995; Currie, 2002).

In central Utah, no proximal alluvial fan facies are preserved in Lower Cretaceous strata (e.g., Yingling and Heller, 1992; Lawton et al., 1997; Currie, 1997, 2002). The westernmost outcrops of Lower Cretaceous strata are in the antiformal Paxton duplex along the western flank of the San Pitch Mountains, the palinspastic (pre-Neogene extension) location of which lay 60–70 km east of the likely topographic front associated with the Canyon Range thrust (Fig. 8B). Currie's (2002) reconstruction of the Early Cretaceous foreland basin system in central Utah indicates that the crest of the forebulge was located ~120–140 km farther east. Thus, the Early Cretaceous foredeep was on the order of 200 km wide in this region.

Pavant Thrusting and Duplexing (Late Albian–Coniacian, ca. 110–86 Ma)

The next major phase of thrusting took place along the Pavant thrust and involved a complex

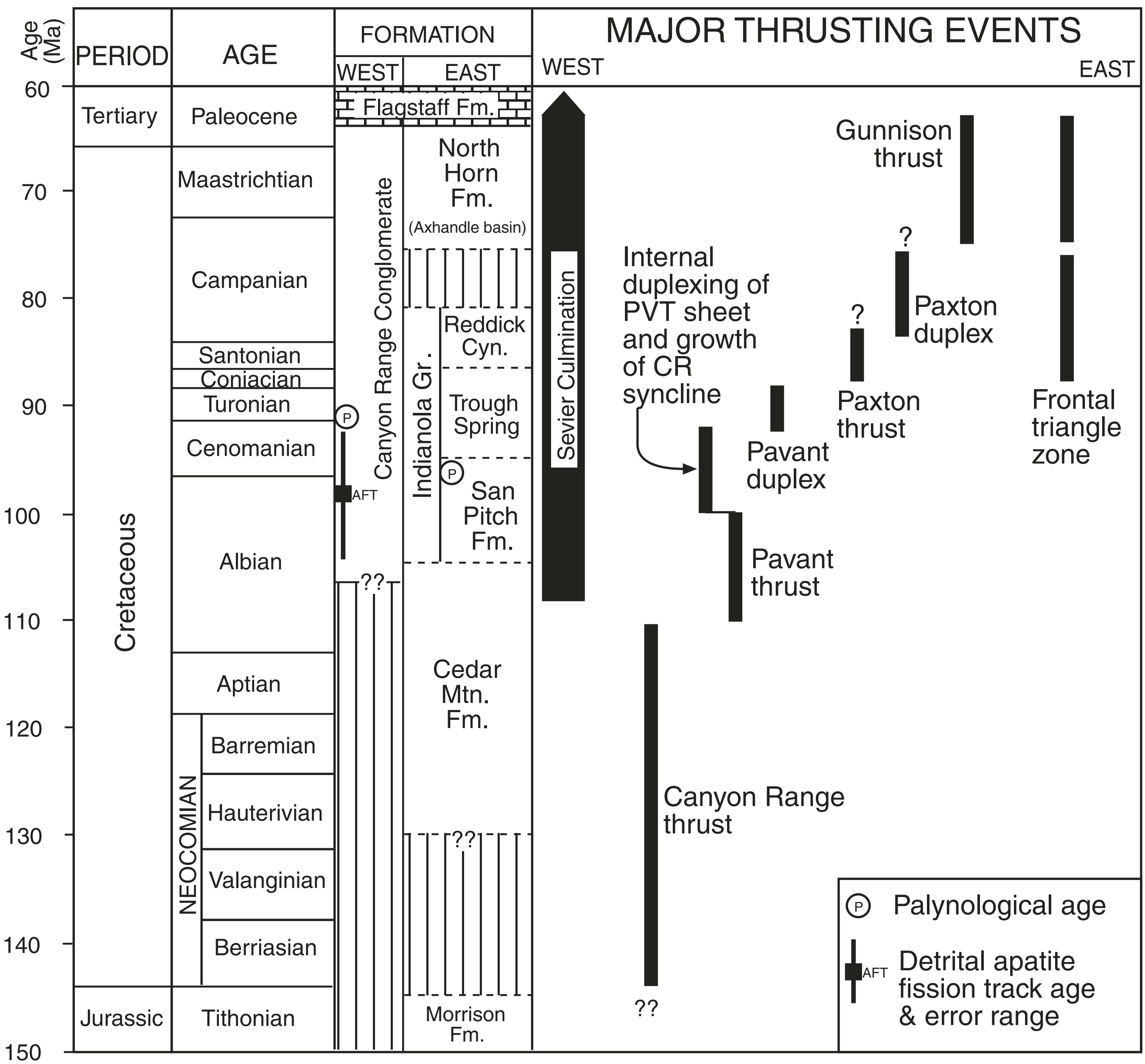


Figure 10. Chart showing the timing of major thrusting events and growth of the Sevier culmination in the central Utah segment of the Sevier fold-and-thrust belt. CR—Canyon Range; PVT—Pavant thrust.

series of in-sequence and out-of-sequence events (Figs. 8, 9, and 10). The total minimum slip on the Pavant system is ~68.6 km, which includes 42.4 km of initial slip on the main thrust and subsequent internal shortening during growth of the Canyon Range duplex, followed by 26.2 km of slip accommodated on Pavant imbricates and within the Pavant duplex (Figs. 8 and 9). The late Albian–Cenomanian age of initial Pavant sheet emplacement is based on the compositions of conglomerates in the palynologically dated late Albian–Cenomanian San Pitch Formation (lower Indianola Group) in the western San Pitch Mountains (DeCelles et al., 1995; Lawton et al., 1997; Sprinkel et al., 1999). In addition, growth structures in the Canyon Range Conglomerate provide constraints on the timing of thrusting in the Canyon Range duplex (DeCelles et al., 1995; Mitra and Sussman, 1997).

As mentioned already, the Canyon Range thrust sheet was folded into an anticline-syncline pair in the Canyon Range. Approximately 10° of the westward dip of the eastern limb of the syncline probably developed during emplacement of the Canyon Range thrust along its frontal footwall ramp (Fig. 9A). The anticline developed when the Canyon Range duplex grew beneath the Canyon Range thrust sheet (Mitra and Sussman, 1997; Mitra, 1997; Ismat and Mitra, 2005). Progressive eastward tilting of the shared fold limb (Fig. 9C–E) caused a space problem in the core of the syncline that was relieved by bedding-parallel slip along shale zones in the Pocatello and Inkom Formations. Growth structures in the Canyon Range Conglomerate developed in association with these minor detachments (Fig. 7B–C; DeCelles et al., 1995; Mitra and Sussman, 1997). Minor (several hundred meters) slip along the base of the Caddy Canyon Formation quartzite (Fig. 7C) actually cut the lower part of the Canyon Range Conglomerate; this thrust relationship previously has been mistaken for reactivation of the Canyon Range thrust, but recent mapping shows that the real Canyon Range thrust is buried by the conglomerate north of Little Oak Creek Canyon (Fig. 4) and was not reactivated. The Canyon Range Conglomerate consists of coarse-grained, proximal alluvial fan facies (Fig. 7A) that alternate in vertical succession with more distal, finer-grained, better-organized fluvial facies. The alluvial fan conglomerates were derived mainly from the western limb of the Canyon Range syncline, whereas the fluvial conglomerates were derived from more distal sources to the west of the Canyon Range on the crest of the Sevier culmination, as well as from the rocks of the Canyon Range syncline (DeCelles et al., 1995; Lawton et al., 1997).

In the structural model (Fig. 9), the Canyon Range duplex is composed of Neoproterozoic-Ordovician quartzite and carbonate rocks of the Pavant thrust sheet (Mitra and Sussman, 1997). The duplex formed as thrusts broke up the internal part of the Pavant thrust sheet after it had been emplaced at a high structural level by slip on the main Pavant thrust (PVT[a] in Fig. 9). Slip on thrusts within the duplex could have been fed updip (eastward) into a detachment in the lower part of the Paleozoic succession (e.g., in the Pioche [or Ophir] Formation, which is composed mainly of shale), now buried along the eastern flank of the Canyon Range. Alternatively, thrust faults in the duplex could have ramped upsection and connected with the Canyon Range thrust, forming a connecting splay duplex (Mitra and Sussman, 1997; Mitra and Ismat, 2001). For the connecting splay model to work as explained by Mitra and Sussman (1997), some slip on duplex faults must have been transferred into the hanging wall of the Canyon Range thrust. In part, this interpretation is based on a branch point between the Canyon Range thrust and a structurally lower splay mapped by Mitra and Sussman (1997) ~4.5 km north of cross-section X–X′ (Fig. 4; near 39°30′N, 112°15′W). However, the fact that the eastern trace of the Canyon Range thrust does not cut the Canyon Range Conglomerate requires that slip transferred from the duplex must have been accommodated by internal folding and minor bedding-parallel detachment faults, which are common in the eastern limb of the Canyon Range syncline. Mitra and Sussman (1997) and Ismat and Mitra (2005) showed that fault-propagation folding and cataclastic flow in a connecting splay duplex may have accommodated most of the duplex shortening, limiting the need to transfer large amounts of slip into the overlying thrust sheet. In our structural model, the Canyon Range duplex is depicted as a simple antiformal duplex with a single horse of Neoproterozoic rocks in its core, because along the line of cross-section X–X′ no connecting splays can be demonstrated in the surface geology. It is conceivable, however, that the faults within the duplex are connected to the Canyon Range thrust sheet by a buried connecting splay (Mitra and Ismat, 2001). It is also possible that the Canyon Range duplex is a hybrid, consisting of a connecting splay duplex in the northern part of the Canyon Range and a conventional antiformal stack in the central part of the range.

Although the Canyon Range duplex could have developed before the frontal portion of the Pavant sheet was emplaced (i.e., as a forelandward propagating series of thrusts), our preferred model satisfies the requirement that the duplex must have developed at a shallow level (<5 km below the surface; Fig. 9B–E), whereas the alternative model does not. The alternative model would have the duplex form at a depth of ~10 km and then be transported to a higher structural level during development of the frontal part of the Pavant thrust system. Three lines of information indicate that the duplex developed near the surface. First, the intimate association of duplex growth, folding of the west limb of the Canyon Range syncline, and deposition and deformation of the Canyon Range Conglomerate demands that the duplex formed close to the surface (e.g., Mitra and Sussman, 1997). Second, microstructural data presented by Sussman and Mitra (1995), Sussman (1995), Ismat and Mitra (2001, 2005), and Mitra and Ismat (2001) show that deformation in the quartzites of the duplex and in the Canyon Range thrust sheet occurred in the elastico-frictional regime at depths not greater than ~5 km. Third, as noted previously, the Canyon Range Conglomerate, which was partly derived from the western limb of the Canyon Range syncline as it was uplifted during duplex growth, rests upon Cambrian strata in the hanging wall of the Canyon Range thrust and upon Devonian strata in the footwall of the thrust. Thus, a substantial amount of erosion (several kilometers) must have occurred before deposition of the conglomerate, which in turn suggests that duplexing occurred after the rocks in the footwall of the Canyon Range thrust had been structurally elevated and exposed at the surface.

Palynological data and detrital apatite fission-track ages from the Canyon Range Conglomerate constrain the age of the conglomerate and the growth of the Canyon Range duplex. Growth strata in the Canyon Range Conglomerate are mainly in the lower to middle part of the unit. A fission-track age of ca. 97 Ma (Stockli et al., 2001) from a quartzite clast in the lower-middle part of the conglomerate indicates that this part of the conglomerate cannot be older than that age. Palynological data collected by T. White (2002, personal commun.) suggest a Cenomanian-Turonian age for beds in the middle part of the conglomerate. These data are consistent with age data from the San Pitch Formation, which indicate an Albian-Cenomanian age, and support the partial correlation of these two units as proposed by Lawton et al. (1997; Fig. 10). The minimum age of the Canyon Range Conglomerate remains uncertain; it could extend into the early Paleocene (Lawton et al., 1997). However, the younger part of the conglomerate apparently was not affected by growth of the Canyon Range syncline and other structures related to Pavant thrusting (Lawton et al., 1997).

The preceding reconstruction of tectonic events in the Canyon Range helps to explain the compositions of conglomerates in the San Pitch Formation (Sprinkel et al., 1992; DeCelles et al., 1995). These conglomerates contain clasts of Neoproterozoic quartzite, Paleozoic chert, carbonate, and quartzite, and small amounts of quartzose sandstone with frosted, eolian grains. The Neoproterozoic quartzites could have been derived only from the Canyon Range thrust sheet, whereas the Paleozoic clasts could have been derived from both the Canyon Range and Pavant sheets. The eolian sand grains may reflect erosion of Jurassic strata from a structure associated with the frontal tip of the Pavant thrust (Fig. 8C). The Albian-Cenomanian age of the San Pitch Formation and the likely Cenomanian-Turonian age of the Canyon Range Conglomerate in the Canyon Range syncline (DeCelles et al., 1995; Stockli et al., 2001) suggest that the main phase of Pavant thrusting was Albian, whereas the internal breakup and duplexing of the Pavant sheet took place during Cenomanian-Turonian time (Fig. 10).

Paxton Thrusting (Santonian–Early Campanian? ca. 86–75 Ma)

The Paxton thrust sheet is defined entirely from subsurface data with only nonresistant Jurassic and Cretaceous rocks exposed in broad hanging-wall folds above the Paxton duplex and along the frontal triangle zone. The age of the Paxton thrust is therefore primarily constrained by a profound angular unconformity at the base of the North Horn Formation, which defines the uplifted western and eastern margins of the Campanian-Paleocene Axhandle wedge-top basin in the San Pitch Mountains (Fig. 2; Lawton et al., 1993; Talling et al., 1995). The unconformity overlies the eastern limb of the Paxton duplex on the western side of the San Pitch Mountains, where it separates ~25–45° east-dipping beds of the late Albian–early Campanian Indianola Group from ~5° east-dipping Maastrichtian strata of the North Horn Formation (Mattox, 1987; Weiss et al., 2003). Thus, the principal growth of the Paxton duplex is inferred to have been complete before Maastrichtian time in this area, although a last increment of uplift is attributed to slip on the underlying Gunnison thrust after cessation of Paxton slip (Fig. 8E–F). On the eastern side of the San Pitch Mountains, a phase of early slip on the frontal triangle zone is recorded by the ~90° angular unconformity that separates overturned, east-dipping Albian-Turonian beds of the Indianola Group from steeply to moderately west-dipping late Campanian strata of the North Horn Formation (Lawton and Weiss, 1999). Thus, an early phase of triangle zone deformation is pre–late Campanian in age (Fig. 8D). Triangle zone thrust displacement that is rooted to the Paxton thrust is necessary to balance Middle Jurassic– through Cretaceous-level shortening with deeper-level shortening of the main Paxton thrust sheet and duplex (Fig. 8E). The broad synchronicity between uplift above the Paxton duplex and the frontal triangle zone corroborates the structural correlation of early triangle zone displacement to the Paxton thrust system.

Because of the shallow erosion levels of the Paxton thrust sheet and the continued exposure of resistant lithologies from the previously emplaced Canyon Range and Pavant thrust sheets, the Paxton sheet provided no diagnostic unroofing signal in the foreland basin. The main effect of Paxton thrusting on the unroofing history of the proximal foreland basin system was erosion of Jurassic fine-grained rocks during Paxton duplexing (Figs. 8E and 10). The nonresistant character of the Jurassic rocks may account for the influx of fine-grained facies documented in the San Pitch Mountains during Santonian time (Lawton, 1985; Lawton et al., 1993). This was also a time of marine transgression in the foreland basin, and deltaic and marginal-marine environments developed in the wedge-top depozone of the foreland basin system.

Gunnison Thrusting (Late Campanian–Maastrichtian, ca. 75–65 Ma)

Displacement on the Gunnison thrust system transported the previously formed Paxton duplex up and over the Gunnison ramp from Cambrian to Middle Jurassic levels, and displacement at higher levels was accommodated by the frontal back-thrust system and Sanpete Valley antiform along the eastern side of the Axhandle wedge-top basin (Figs. 8F and 10). The timing of thrusting in the Gunnison thrust system is relatively well dated at middle-to-late Campanian through Paleocene time because of the coeval development of the Axhandle wedge-top basin (Lawton and Trexler, 1991; Lawton et al., 1993; Talling et al., 1994, 1995). This basin accumulated up to 1.1 km of conglomerate, sandstone, mudstone, and limestone between the Paxton duplex and the frontal Sanpete Valley antiform. Growth structures along the eastern flank of the basin track the kinematic history of the back-thrust system associated with the Sanpete Valley antiform (Lawton et al., 1993), and an eastward-fanning progressive unconformity in late Campanian–Maastrichtian sandstones in the westernmost Wasatch Plateau formed along the east limb of the antiform (Lawton et al., 1997). The eastern limb of the Paxton duplex also experienced minor eastward tilting (<10°) during or after Maastrichtian time (Mattox, 1987; Lawton et al., 1993; Weiss et al., 2003).

By the time that the Axhandle basin began to develop, the frontal part of the Sevier fold-and-thrust belt lay buried beneath a several-kilometer-thick pile of conglomerate and sandstone. Thus, the only source of durable, coarse-grained detritus lay in the hanging wall of the Canyon Range thrust, ~40 km west of the frontal back-thrust system. The Paxton duplex was erosionally breached down to the level of the Middle Jurassic Arapien Formation, but it could provide only fine-grained detritus. From mid-Campanian time onward, therefore, conglomerates in the proximal foreland basin system were dominated by Neoproterozoic quartzite clasts derived from the Canyon Range. The Canyon Range thrust sheet, however, probably was not tectonically active after its initial emplacement during Early Cretaceous time (Fig. 10).

DISCUSSION

Regional Paleogeography

The kinematic reconstruction can be used to assess regional paleogeography in the central Utah Sevier fold-and-thrust belt and its hinterland during Late Jurassic–Late Cretaceous time. The maximum crustal thickening in the Sevier belt was ~16 km (accounting for the effects of erosional removal of material; Fig. 8). If the crust was 35 km thick prior to Sevier belt thrusting, and if no significant lateral crustal flow occurred, then the crust in western Utah could have been up to 51 km thick by the end of the Cretaceous. Assuming a mantle density of 3300 kg/m^3, crustal density of 2650 kg/m^3, and Airy isostatic compensation at long wavelengths (Turcotte and Schubert, 2002, p. 122–123), the predicted regional paleoelevation in western Utah at the end of the Cretaceous is ~3.2 km (Fig. 8). This estimate is consistent with paleoelevation reconstructions based on paleofloral data (Chase et al., 1998) and restorations of regional extension (Gans and Miller, 1983; Coney and Harms, 1984) for early Tertiary time. This suggests that the Sevier belt in western Utah formed a 250-km-wide, essentially flat to broadly dome-shaped hinterland region—perhaps a high-elevation "Nevadaplano" analogous to the Altiplano in the central Andes (Allmendinger, 1992)—sandwiched between the Luning-Fencemaker and Sevier fold-and-thrust belts and broken in the middle by relatively minor faulting along the Central Nevada thrust belt (Figs. 11 and 12; DeCelles, 2004). The high plateau was flanked on the east by the Canyon Range culmination, where paleoelevation dropped steeply to near sea level in the foreland basin directly to the east. The frontal 40 km of the thrust belt was buried by wedge-top synorogenic sediment and episodically inundated by the Western Interior Seaway during late Albian through Santonian time. Marine water may have actually reached as far west as the western limb of the Canyon Range syncline during deposition of fan delta facies in the Canyon Range Conglomerate (DeCelles et al., 1995).

Rates of Shortening, Propagation, and Flexural Wave Migration

The rates (or distances) of shortening and propagation in the Sevier fold-and-thrust belt and the rate of eastward migration of the flexural wave through the foreland basin are of interest for assessing potential linkages between processes in the fold-and-thrust belt and the Cordilleran magmatic arc. The shortening estimates from our reconstructions are based on explicit constraints for hanging-wall and footwall cutoff positions for each major thrust system along our transect. Our estimate of displacement on the Canyon Range thrust is very close to Currie's (2002) estimate, which was based on an earlier-generation cross section similar to Figure 3 (Coogan et al., 1995). Our displacement estimates for the other three thrust systems are within 18%–25% of those from previous studies. Our estimates are lower than published estimates for the Paxton (Royse, 1993) and Pavant imbricate thrust systems (derived from Hintze et al., 2003), in the middle of the range of published estimates for the Pavant thrust (Sharp, 1984; Royse, 1993), slightly higher for the Gunnison thrust (Royse, 1993), and at the higher end of estimates for the Canyon Range thrust (Sharp, 1984; Bartley and Wernicke, 1984; Royse, 1993; Currie, 2002). Much of this variation is attributable to changes in individual thrust displacements between widely separated study areas along strike, as well as acceptable kilometer-scale variation in absolute hanging-wall and footwall cutoff positions deduced by other workers from the same outcrop, well, and seismic constraints near our transect. The total shortening estimated from our kinematic reconstruction of the Sevier belt is 220 km, which is comparable to Currie's (2002) estimate. The general agreement of displacement estimates for individual thrust systems from workers using different data sets provides a reasonable basis for comparing incremental shortening across the Sevier belt with the flexural response of the foreland basin.

The Canyon Range and main phase of Pavant thrust slip events involved more than 140 km of displacement and involved thick thrust sheets dominated by strong Neoproterozoic–Lower Cambrian quartzites (Fig. 8). In contrast, subsequent thrusting events farther east involved mainly weak Mesozoic strata and formed multiple antiformal duplexes. Once the basal décollement had climbed into Jurassic evaporitic shales, the style of thrusting became dominated by duplexing (Fig. 8D–F).

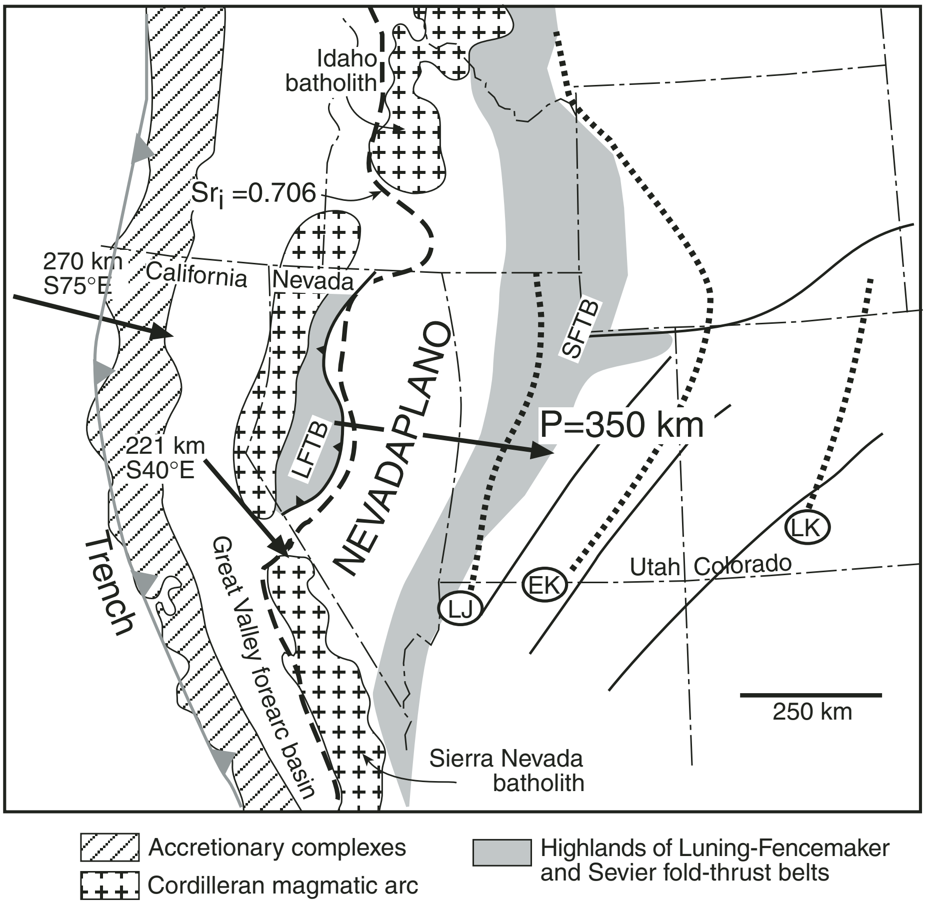


Figure 11. Palinspastically reconstructed tectonic-paleogeographic map of the North American Cordilleran orogenic belt in the western United States. Arrows indicate distances and directions of restored Neogene extension, from Wernicke et al. (1988), Snow and Wernicke (1994), and Dickinson and Wernicke (1997). Bold arrow labeled P indicates approximate distance of forward propagation of the thrust belt from Late Jurassic through Cretaceous time. Solid lines in eastern Utah and southern Wyoming represent Precambrian shear zones after Karlstrom and Williams (1998). Dashed lines indicate approximate restored positions of the crest of the forebulge in the foreland basin system at times corresponding to the labels as follows: LJ—Late Jurassic (Currie, 1997); EK—Early Cretaceous (Currie, 2002; DeCelles and Burden, 1992); LK—Late Cretaceous (White et al., 2002). LFTB—Luning-Fencemaker thrust belt; SFTB—Sevier fold-and-thrust belt.

The sum of the distances of shortening and forward propagation (defined as the amount of lengthening of the thrust belt in the transport direction as it grows) of the fold-and-thrust belt should approximately equal the total migration distance of the flexural wave in the foreland lithosphere (DeCelles and DeCelles, 2001). Approximately 164 km of the total 220 km of shortening occurred before 90 Ma, at an average rate of ~3 mm/yr. During the same time interval, the front of the orogenic wedge propagated eastward at an average rate of ~5.5 mm/yr from the Luning-Fencemaker thrust belt to the Pavant thrust, a palinspastic east-west distance of ~300 km (Fig. 11). The sum of shortening and propagation values (164 km + 300 km) suggests roughly 464 km of flexural wave migration by 90 Ma. Foreland basin isopach patterns can be used to track the location of the forebulge through time, which approximates the rate of flexural wave migration. Palinspastic locations of the crest of the forebulge suggest that it migrated roughly 250 km during Late Jurassic to Early Cretaceous time (Fig. 11; Currie, 1997), well short of the

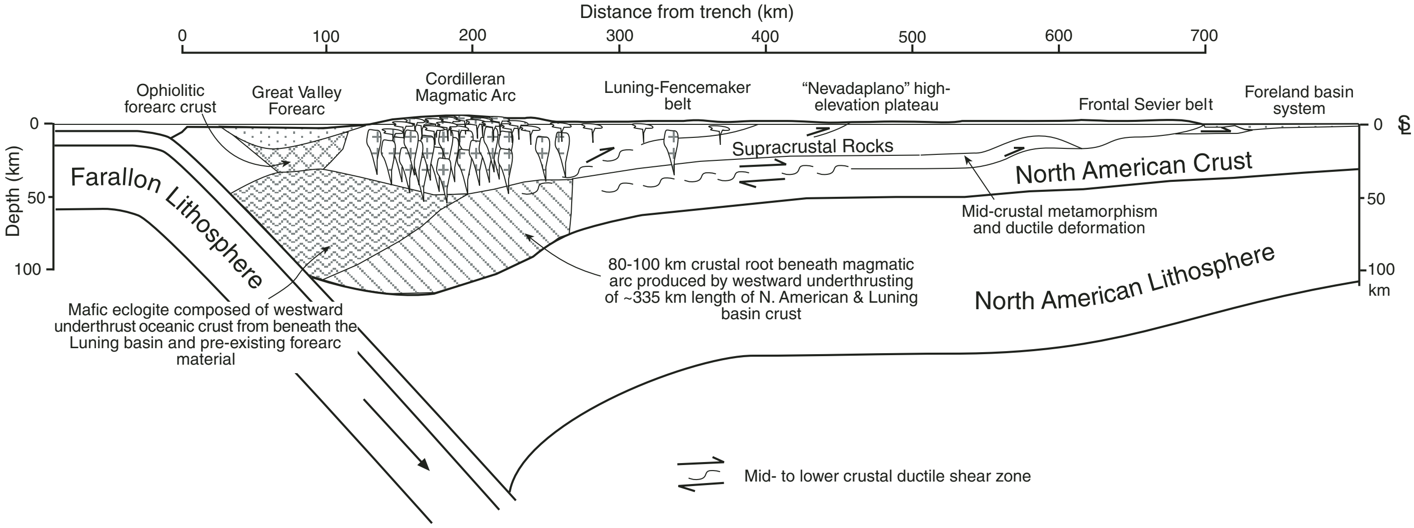


Figure 12. Schematic, reconstructed cross section of the Cordilleran orogenic belt at the latitude of central Utah during Late Cretaceous time. Geology beneath the magmatic arc is after Ducea (2001).

predicted 464 km. White et al. (2002) attributed stratigraphic complexities in late Cenomanian strata in western Colorado to the presence of a forebulge; if correct, this would raise the flexural wave migration distance to ~450–500 km, which is in good agreement with the predicted distance. However, the White et al. (2002) forebulge is >200 km east of the easternmost position of forebulge crests reported by most workers during Late Cretaceous time (Jordan, 1981; Pang and Nummedal, 1995; Currie, 1997, 2002; Liu and Nummedal, 2004). In fact, most workers agree that a forebulge is difficult to locate in Upper Cretaceous isopach patterns, perhaps because of the onset of Laramide-style deformation and regional dynamic subsidence in the foreland region (Cross, 1986; Dickinson et al., 1988; Pang and Nummedal, 1995; Currie, 2002; Liu and Nummedal, 2004). Jordan (1981) first recognized that the flexural signal of the Cordilleran foredeep depozone had stalled in eastern Utah and western Wyoming at ca. 90–85 Ma. Modeling results of Waschbusch and Royden (1992) showed that the forebulge might have become "hung up" and amplified on reactivated basement faults in the foreland crust. Two Precambrian shear zones that strike approximately parallel to the Cretaceous forebulge in eastern Utah (Karlstrom and Williams, 1998) may have arrested the progress of the flexural wave (Fig. 11; Currie, 2002).

Inclusion of the ~50-km-wide Luning-Fencemaker thrust belt (active ca. 165–148 Ma; Oldow, 1983; Wyld, 2002) raises the total propagation distance of the front of the Cordilleran thrust belt to ~350 km (DeCelles, 2004). If the Luning-Fencemaker thrust belt has >50% shortening (Wyld, 2002), then an additional ~100 km of shortening may be added to the Sevier belt total. Shortening estimates in the central Nevada thrust belt are on the order of 15 km (Taylor et al., 2000; W.J. Taylor, 2003, personal commun.), bringing the total shortening in the retroarc region to ~335 km (see also Elison, 1991). The long-term average rate of shortening from 165 Ma to 65 Ma was ~3.3 mm/yr.

Implications for the Magmatic History of the Cordilleran Arc

Because all of the ~335 km of shortening in the Cordilleran thrust belt involved middle to upper crustal rocks, an equal length of lower crust and lithosphere must have been underthrust beneath the Cordilleran magmatic arc, with potentially significant implications for the history of arc magmatism. Barton (1996), Coleman and Glazner (1998), and Ducea (2001) showed that the history of magmatism in the Sierra Nevada Batholith was volumetrically dominated by two arc flare-ups during Late Jurassic (160–150 Ma) and Late Cretaceous (100–85 Ma) time. The Cretaceous event, which actually began around 120 Ma, accounts for roughly three-quarters of the total exposed batholith. Noting that these pulses of intrusive activity cannot be equated simply with changes in the rate or obliquity of convergence along the western margin of North America, Ducea (2001, 2002) proposed that the history of thrusting in the retroarc region controlled magma production in the arc. This model predicts that melt-fertile North American lower crust was underthrust westward beneath the arc, where it melted and produced voluminous granitic magmas with isotopically evolved compositions (Fig. 12). Melting should have postdated underthrusting and ductile deformation of granulites in the lower crust of the arc by 10–20 m.y., depending on thermal equilibration times. It is interesting to observe that the period of most-rapid shortening in the Sevier belt was during the Early Cretaceous while the Canyon Range and Pavant thrusts were active, and commenced roughly 20 m.y. before the Late Cretaceous arc flare-up. If the portion of the slab of underthrust lower crust between Idaho and southeastern California was 15–20 km thick, its volume would have been 3–4 × 10^6 km^3, easily enough to generate the 80–100-km-thick crustal root beneath the arc during the Late Cretaceous (Fig. 12; Ducea, 2001).

CONCLUSIONS

A regional kinematic reconstruction of the type area of the Sevier fold-and-thrust belt in central Utah yields a total shortening of 220 km. Shortening took place from Early Cretaceous through Maastrichtian time on four major thrust systems, with the main detachments in shale and evaporite horizons. The western thrust faults, including the Canyon Range and Pavant thrusts, carried thick Neoproterozoic quartzites along lengthy regional thrust flats and accounted for 190 km of the total shortening. In contrast, the two eastern thrust systems, the Paxton and Gunnison, climbed abruptly upsection from a Cambrian décollement into weak Jurassic salt and shale and developed tightly spaced, complex antiformal duplexes.

Growth structures, provenance of synorogenic sediment, and thermochronologic data indicate that the Sevier belt propagated eastward through time in central Utah, with one significant out-of-sequence thrusting event. This event involved internal breakup of the Pavant thrust sheet and the growth of a duplex beneath the present Canyon Range.

Provenance data from proximal synorogenic sediments indicate that much of the sediment in this part of the Cordilleran foreland basin system was derived from the Neoproterozoic quartzite and Paleozoic carbonate rocks of the Canyon Range thrust sheet. Rapid sediment flux into the foreland basin swamped the frontal part of the thrust belt with sediment, creating an ~40-km-wide wedge-top depozone. Frontal structures of the Paxton and Gunnison thrust systems were developed in relatively nonresistant Jurassic rocks, and therefore provided relatively little of the coarse-grained fill in the proximal part of the foreland basin system.

Crustal thickening due to thrusting amounted to ~16 km in western Utah. This amount of thickening would have been sufficient to support >3 km of regional elevation in the Sevier hinterland and suggests that a broad "Nevadaplano" may have existed in the hinterland, much like the modern central Andes. Approximately half of the total thickening took place during Canyon Range and Pavant thrusting, from Early Cretaceous through Cenomanian time (ca. 145–90 Ma). This may explain the major subsidence events that occurred in the distal foredeep of central-eastern Utah during this time frame.

Total upper-crustal shortening in the Cordilleran retroarc region at the latitude of central Utah was ~335 km. Westward underthrusting of a corresponding length of North American lower crust beneath the Cordilleran magmatic arc roughly accounts for the volume of arc crust based on previously published petrological arguments (Ducea, 2001).

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