THE WESTERN UTAH THRUST BELT IN THE LARGER CONTEXT OF THE SEVIER OROGENY

Donna M. Herring[1] *and David C. Greene*[2]

ABSTRACT

The Confusion Range in west-central Utah was previously described as a synclinorium with little overall shortening, and recently shown to be an east-vergent, fold-thrust belt recording significant (~10–15 km) horizontal shortening during the late Jurassic to Eocene Sevier orogeny. This thrust belt, named the Western Utah thrust belt (WUTB) is exposed for more than 130 km along strike, and potential correlations suggest a total 400 km. The WUTB is thus similar in age, length, and displacement to the Central Nevada thrust belt (CNTB), and they together record significant shortening in what has been considered the hinterland of the Sevier orogenic belt. The WUTB, as a reinterpreted structural element of the Cordilleran orogenic belt at the latitude of about 39N, may fill part of a gap between predicted and observed propagation distances in the Sevier orogenic system, and easily fits into recent palinspastic reconstructions. We believe that the recently delineated Eastern Nevada fold belt (ENFB), between the CNTB and WUTB, will also be found to consist of at least one similar thrust system. When considered together, available age constraints suggest the CNTB, the ENFB, and the WUTB are intimately related to the Canyon Range thrust in time. The similar timing suggests that these structural elements are together connected to the Luning-Fencemaker fold-thrust belt (LFTB) via a shared decollement. If this correlation is correct, the initiation of the LFTB began the first eastward propagation of the Sevier orogeny, at ~165 Ma. Then, at about ~150 Ma, eastward propagation was transferred on the decollement and rapidly progressed to create several moderate-displacement fold and thrust systems (CNTB, ENFB, WUTB) that moved with the large-displacement Canyon Range thrust (~146 Ma initiation) of the western system of the Sevier frontal thrust belt. Propagation was transferred to the Pavant thrust of the western system at about 110 Ma, and from the Pavant to the eastern system frontal thrusts at about 88–90 Ma. Regional thrusting was terminated by ~50 Ma, when movement on the eastern system ceased.

INTRODUCTION

The Problem

A flurry of recent structural studies in eastern Nevada and western Utah (figure 1) have shed light on a few poorly understood mountain ranges in this very complex area. In particular, the work of Long (2012, 2015), Greene (2014), Long and others (2014), Greene and Herring (2013), Taylor and others (2000), and Taylor (2002) have addressed previously unrecognized or seemingly isolated or obscure structures, and confirmed that what had been considered the Sevier orogenic hinterland was in fact tectonically active during most of the time Sevier frontal thrusts were being emplaced. As Taylor and others (2000) indicated when they correlated various shorter-strike thrust systems into the 400 km-long Central Nevada thrust belt (CNTB) (figure 1), this evidence of an active hinterland suggests that the Sevier orogeny was more broadly active than supposed. Delineation of the Western Utah thrust belt (WUTB) in the Confusion Range of Millard, Beaver, and Juab counties confirms additional significant deformation in the hinterland (Greene, 2014). Here, we review the recent recognition of hinterland structures in the Sevier orogenic system, in particular the Western Utah thrust belt. We correlate the WUTB in time and space with similar structures to the east and west near the latitude of 39N, including the Sevier frontal thrust belt, the CNTB, and the Eastern Nevada fold belt (ENFB). (References herein to compass directions are present-day.) We integrate this new interpretation into the evolving understanding of the Sevier thrust system, and suggest further work for discernment of additional hinterland structures we believe remain obscured by Miocene and younger extension.

Regional Geologic History

An understanding of the overarching geologic history of the region is critical to the question of relative timing and recognition of individual thrust systems and their components. Below is a summary of current consensus, parts of which will be expanded in later sections.

A sub-linear rifted edge in the Precambrian and older crystalline rocks of the craton crosses what is now Utah

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[1] *Petroglyph Consulting*
PO Box 586
Granville, OH 43023
dmherring@voyager.net

[2] *Department of Geosciences*
Denison University
Granville, OH 43023

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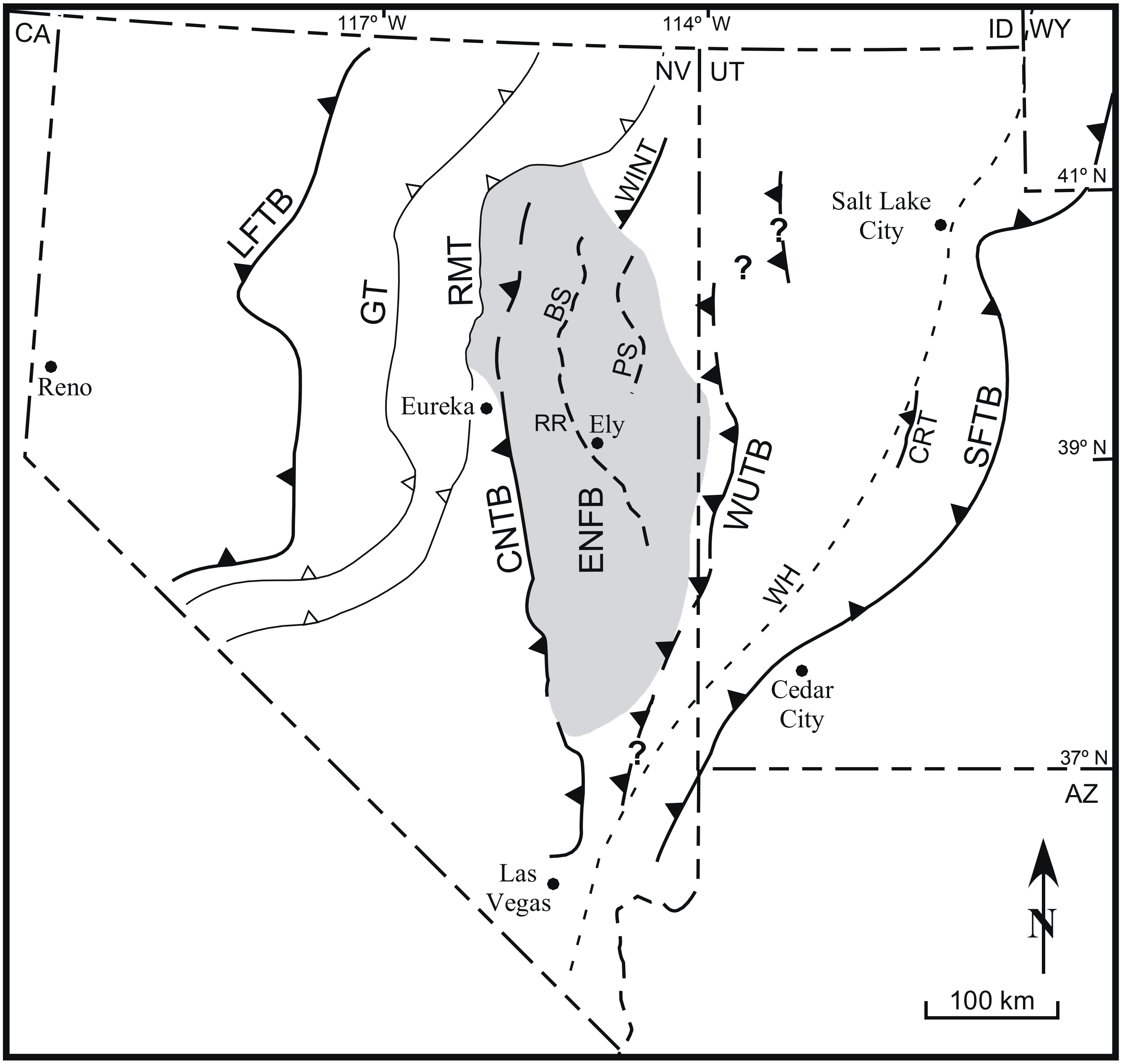

Figure 1. *Index map of the Sevier orogenic frontal and hinterland areas in Nevada and Utah, USA, in their present configuration. The light dashed line traces the Wasatch Hingeline (WH), also called the Cordilleran or Utah Hingeline, which marks both the edge of Neoproterozoic rifted continental crust, and, the transition between a thick miogeoclinal sediment wedge to the west and a thin blanket of sediments with many disconformities to the east. Gray lines with open triangles indicate frontal thrusts of pre-Sevier thrust systems comprising the Roberts Mountains thrust (RMT) and Golconda thrust (GT). Sevier orogenic features include: LFTB=Luning-Fencemaker fold-thrust belt; CNTB=Central Nevada thrust belt; within the Eastern Nevada fold belt (ENFB, in gray shading), the BS=Butte synclinorium, PS=Pequop synclinorium, and RR=Radar Ridge; WINT=Windermere thrust; WUTB=Western Utah thrust belt; CRT=Canyon Range thrust; SFTB=Sevier frontal thrust belt eastern system leading edge.*

in a SSW-NNE orientation and is known as the Wasatch (or Cordilleran, or Utah) Hingeline (figure 1, see especially Allmendinger and others, 1986). For hundreds of kilometers east of the Hingeline, sedimentation from Precambrian through most of the Devonian was thin to nonexistent over a flat plain surface near sea level. For 300–500 km west of the Hingeline, Precambrian through late Devonian miogeoclinal sediments accumulated in marine environments on a slowly subsiding, relatively shallow continental shelf. Beyond the wedge of miogeoclinal sediments on the continental shelf, sediments accumulated very slowly at abyssal depths in what is now western Nevada.

The miogeocline comprises approximately 13 km of strata that thin dramatically or pinch out toward the Hingeline.

These strata include 4 km or more of Neoproterozoic and lower Cambrian predominantly clastic strata, overlain by 9 km of middle Cambrian to Devonian strata, mostly carbonates, deposited in a stable passive margin setting (Link and others, 1993; Hintze and Davis, 2003; Cook and Corboy, 2004; Hintze and Kowallis, 2009).

The miogeocline was first disrupted beginning in late Devonian time, when the passive margin edge ruptured, oceanic crust began to be subducted, and a Devonian intraoceanic arc approached the continent (see especially the review paper of Dickinson [2006] and references therein). Abyssal sediments were obducted eastward over the western edge of the miogeoclinal passive margin assemblages during this, the Antler orogeny, and buried the outer miogeoclinal sedimentary rocks to depths of 5–15 km (Dickinson, 2006). The Antler obduction persisted through early Mississippian; east of the Antler frontal thrust (the Roberts Mountains thrust) the foreland basin contains sediments as young as early Mississippian and is overlapped by a sequence from latest Mississippian through earliest Triassic. In Pennsylvanian time, some obscure structures and relatively shallow basins developed within and to the east of the Antler thrust front, apparently in response to stresses originating far afield to the east and potentially related to the Ancestral Rockies (Trexler and others, 2004; Dickinson, 2006).

Disturbance related to the Permian-Triassic Sonoma orogeny overprinted the Antler orogenic and Pennsylvanian structures (Trexler and others, 2004; Dickinson, 2006). During the Sonoma orogeny, the Golconda allochthon was emplaced via the Golconda and associated thrusts, overlapping the western Antler allochthon. This emplacement was a consequence of compression as Permian arc assemblages were accreted outboard of the Devonian arcs that were previously accreted to the west edge of the continent (Dickinson, 2006, 2013).

Early in the Jurassic, a Cordilleran continental magmatic arc developed as an oceanic plate was being consumed beneath the North American continent, ahead of the arrival of the Farallon plate (Dickinson, 2013). By mid- to late-Jurassic, the edge of the Farallon plate had begun to subduct beneath the North American continent and its various accreted terranes. Compression intensified as an island arc on the leading edge of the Farallon plate collided with the Cordilleran arc, and resulted in initiation of the backarc mid-Jurassic Luning-Fencemaker fold-thrust system, which overthrust the western Golconda allochthon.

The backarc region, in what is now eastern Nevada and western Utah, experienced mantle upwelling beginning in the Jurassic, which warmed the crust cratonward of the Cordilleran arc. Separate backarc thermal events during the Cretaceous and Tertiary also emplaced widely distributed plutons of various chemistry and associated metamorphism (Hose and Blake, 1976; Wright and Wooden, 1991; Hintze and Davis, 2007).

In the Late Jurassic and continuing into the Paleocene, retroarc fold-thrust deformation continued generally parallel to the Cordilleran arc, with a predominately west-to-east progression (Royse, 1993; DeCelles, 2004; DeCelles and Coogan, 2006; Yonkee and Weil, 2011, 2015; DeCelles and Graham, 2015). The frontal edge of the retroarc thrust system did not progress far past the Wasatch Hingeline; the segment of this thrust system now exposed in a sweeping crescent through southern Nevada and central Utah (figure 1) has been termed the Sevier belt (Armstrong, 1968; DeCelles and Coogan, 2006), which is our primary interest here.

During the early to middle phases of Sevier thrusting (late Jurassic to mid-Cretaceous), a broadly uplifted backarc region termed the Nevadaplano is interpreted to be related to thickened crust (Coney and Harms, 1984; DeCelles, 2004; Best and others, 2009; Long and others 2015). The region likely consisted of a high-elevation, low-relief plateau (Nevadaplano), with a steep topographic front and foreland basin to the east (Coney and Harms, 1984; DeCelles, 2004; Best and others, 2009; Henry, and others, 2012). Within the Nevadaplano plateau, local basins and paleochannels—provisionally attributed to early extensional collapse by some workers (Hodges and Walker, 1992), and to piggyback or wedge top basin formation by others (DeCelles and Currie, 1996; Bonde and others, 2014; Yonkee and Weil, 2015)—accumulated Late Cretaceous to Paleogene conglomerates, lacustrine limestones and interbedded volcanics (Vandervoort and Schmitt, 1990; Constenius, 1996; Greene and Herring, 1998; Hintze and Davis, 2003; Druschke and others, 2011; Lechler and others, 2013). Sevier thrusting ceased about 50 Ma, in response to Cordilleran arc shutdown.

Widespread pyroclastic volcanism (e.g. Coney, 1978; Best and others, 2009, 2013) began in the mid-Eocene and continued through early Miocene, along a front that migrated from northeast to south (Dickinson, 2006). In the wake of this “ignimbrite flareup”, from northern Idaho to near the latitude of Las Vegas, and similarly progressing from north to south, localized rapid exhumation of metamorphic core complexes occurred (Dickinson, 2006).

Beginning in the early Miocene, predominantly high-angle extensional faulting formed the typical Basin and Range topography observed today (e.g. Dickinson, 2006). Synchronous but uncommon low-angle extensional faulting formed several significant structures, most notably the Sevier Desert Detachment (a controversial structure, see especially DeCelles and Coogan [2006] and Christie-Blick and Anders [2007]).

In the Basin and Range of Nevada, north- to northeast-striking, fault-bounded valleys averaging 20–30 km wide formed adjacent to uplifted ranges of similar widths. The valleys contain up to 3000 m of fluvial, alluvial, and lacustrine sediments with interbedded volcanics, and the ranges rise up to 1800 m above the valley surface. In Utah, the valleys are on average wider and shallower than in Nevada.

DOCUMENTING SEVIER HINTERLAND DEFORMATION

Geologic scrutiny related to minerals and petroleum exploration and US Geological Survey mapping projects in central Nevada generated new data for the complexly deformed and often altered rocks in the hinterland of the Sevier fold-and-thrust system, particularly in the 1950s through 1970s. This mid-century research detailed mainly Paleozoic thrust systems active in the Devonian-Mississippian (Antler orogeny) and Permian-Triassic (Sonoma orogeny) in west central Nevada. The Antler orogeny (Roberts and others, 1958; Speed and Sleep, 1982), and Sonoma orogeny (see Silberling and Roberts, 1962) were marked by juxtaposition of very different rock systems. These Paleozoic orogenies were separate events and not related to the Mesozoic Sevier orogenic system in terms of stress fields or deformation, but the condition of the crust post-Sonoma orogeny influenced the processes of at least the early stages of the Mesozoic deformation (DeCelles, 2004).

In this section, we first briefly review the Antler and Sonoma orogenies and their resultant allochthons. Next, we summarize the history and structure of the Sevier thrust belt frontal zone. Then we review the history of the hinterland of the frontal Sevier thrust system, including the Luning-Fencemaker fold-thrust belt, the CNTB, the WUTB, and the ENFB—all of which are older than the frontal system. Finally, we make some predictions about other hinterland structures yet to be documented.

In the following section, we present a timeline of the sequence of events for the Sevier thrust system from the Cordilleran arc to the frontal thrusts, and from Jurassic through Eocene, at about 39N latitude and in light of the reinterpreted hinterland.

Antler and Sonoma orogenies

The Antler and Sonoma allochthons were the result of incoming island arcs accreted from the west in Devonian and Permian time, respectively (Dickinson, 2006). The Antler allochthon, originally consisting of nearly 5 km (16,000 ft) of abyssal facies of continent-derived sediment, was obducted >200 km over continental shelf sediments (DeCelles, 2004; Dickinson, 2006). The frontal thrust of the Antler orogeny, the Roberts Mountains thrust, was active in latest Devonian to earliest Mississippian, emplaced subparallel to and about 300 km west of the Hingeline (Dickinson, 2013). An extensive foreland basin developed cratonward of the Antler frontal thrust and was well preserved (see especially Giles and Dickinson, 1995). The Sonoma allochthon consisted of much younger abyssal facies originally deposited in the Havallah Basin, derived both from the Cordilleran arc to the west and from the Antler allochthon to the east. The frontal thrust of the Sonoma orogeny, the Golconda thrust, was emplaced subparallel to the Roberts Mountains thrust and overlapping the western portion of the Antler allochthon by about 60–80 km (Dickinson, 2006).

The highlands of the Sonoma allochthon produced a sedimentologic record less easily interpreted than the Antler foreland, because of later significant erosion. A possible early Sonoma foreland basin is evidenced by a Late Permian narrow band of siliciclastics trending N–S through Eureka, Nevada, and by a sub-parallel possible backbulge basin band of similar age sediments in western Utah (Anna, 2007). In the Early Triassic, the axis of the possible Sonoma foreland basin had moved eastward as the allochthon advanced, depositing marine sediments in a narrow NNE-trending seaway centered at Ely NV (Anna, 2007). Widespread lower to middle Triassic Moenkopi sediments have an eastern source in eastern exposures (Dickinson and Gehrels, 2008), but central and western accumulations may have been derived primarily from the Sonoma highland (Stewart and others, 1972; Anna and others, 2007; DeCelles and Graham, 2015) as were siliciclastic facies of the Triassic Thaynes Formation (DeCelles and Currie, 1996; DeCelles, 2004; Dickinson, 2013). By early to middle Triassic the retroarc foreland basins had been filled, and sediments overlapped both the Antler and Golconda allochthons.

Sevier thrust belt frontal zone

The frontal zone of the east-vergent Sevier thrust belt was active from Early Cretaceous to Eocene, and has been divided into eastern and western systems (Peyton and others, 2011; Yonkee and Weil, 2015; DeCelles and Graham, 2015). The Sevier frontal thrust belt near the latitude of 39N accounts for at least 220 km of shortening distributed among four main thrusts: the Canyon Range and Pavant thrusts of the western system, and the Paxton and Gunnison thrusts of the eastern system (DeCelles and Coogan, 2006). The eastern system represents the later stages of thrust emplacement. The western system was active earlier, and most closely relates to deformation previously considered to be in the hinterland, such as the WUTB and ENFB.

The eastern system in Wyoming and northern Utah is a well-studied classic "thin-skinned" overthrust belt, reasonably well understood because significant petroleum accumulations have been found there and subsurface data is widely available. Along strike to the south in Utah, the eastern system was at first less well understood because most of it lies within the zone of Basin and Range extension, which has obscured previously continuous structures. However, using models generated in the Wyoming portion of the thrust belt, and increasingly available subsurface drilling data, the Utah salient has been confirmed as a classic thin-skinned thrust system as well, though dismembered. The "thin-skinned" nature of the frontal thrusting is related to the fact that these thrusts are developed in the thin end of the Paleozoic miogeoclinal sediment wedge; individual sedimentary units are much thinner here than on the outer edge of the miogeocline 300 km west (Lawton and others, 1994; DeCelles, 2004) (figure 1).

The eastern system of the Sevier frontal thrust belt was active ~90 Ma to 50 Ma, mid-Cretaceous (Albian) through mid-Eocene (DeCelles and Coogan, 2006; Peyton and others, 2011). The eastern system has long been accepted as a generally eastward-younging progression, however it is now recognized as having notable out-of-sequence deformation (Yonkee and Weil, 2011, 2015; Long, and others, 2014) that may in part be cyclical (DeCelles and Graham, 2015).

The western system of the Sevier frontal thrust belt is defined as those recognized older, higher thrusts immediately west of the thin-skinned eastern thrust system, that involve thicker, older, miogeoclinal units in the thrust structures. The western system transported thick sections of the basal miogeocline clastic units long distances, and western system thrusts cut down below the miogeocline into the crystalline basement in part (DeCelles and Coogan, 2006; Greene, 2014).

The (western system) Canyon Range and Pavant thrust sheets include a thick, strong Precambrian to lower Cambrian quartzite sequence that supported long-distance eastward transport. Allmendinger and others (1983) and DeCelles and Coogan (2006) among others suggest that these western system thrust sheets root at midcrustal levels beneath the Confusion Range and are continuous eastward under the Sevier Desert basin. The westernmost surface expressions of these thrust sheets are long hanging wall-on-footwall flats that ramp to the surface in the Canyon Range.

The Pavant thrust was active ~110–88 Ma, and exhibits 74 km of shortening accommodated by movement on the main thrust (48 km) plus duplexing and imbricates (26 km) (DeCelles and Coogan, 2006). Estimates of initiation of movement on the Canyon Range thrust have been from ~146 Ma (Ketcham and others, 1996) to 130 Ma (Lawton and others, 2010). Given that the ~146 Ma age is based on synorogenic conglomerate at the toe of the thrust, and the 130 Ma age is based on deposits 100-200 kilometers away in the foredeep, we believe the older date is most representative of the initiation of movement on the thrust. The Canyon Range thrust might reflect as much as 117 km of shortening (DeCelles and Coogan, 2006).

Hinterland thrust and fold systems

Luning-Fencemaker fold-thrust belt The Luning-Fencemaker fold-thrust belt (LFTB), primarily active in the mid- to Late Jurassic (~165–150 Ma) with >100 km displacement (Wyld and others, 2003), lies west of the Golconda thrust. Prior to initiation of the Luning-Fencemaker deformation and onset of the Sevier orogeny, development of the Antler (Devonian-Mississippian) and Sonoma (Permian-Triassic) allochthons had thickened the crust substantially. Though the crust was thickened, the older allochthons were also eroded and overlapped by marine sediments and probably had low regional elevations through Middle Jurassic (DeCelles, 2004). The Cordilleran continental magmatic arc had developed coherency by mid-Triassic (Dickinson, 2013), and by mid-Jurassic, the Cordilleran arc and Farallon plate had between them consumed the Mezcalera plate, and the arc and Farallon plate had been (briefly) sutured (Dickinson, 2006, 2013). During continued compression before incipient subduction of the Farallon plate, the Cordilleran arc had gained regional elevation and was providing substantial volcaniclastic sediment and airborne ash to the retroarc region (DeCelles, 2004; Dickinson, 2006, 2013), and the Luning-Fencemaker fold-thrust belt was initiated (figure 2A).

The LFTB placed metamorphosed and intensely folded deep marine Triassic and Jurassic facies above shallow marine rocks of the same age (Wyld, 2002; DeCelles, 2004) that are correlative with the overlap assemblages covering the Golconda allochthon. Though some workers (Wyld, 2002; Wyld and others, 2003) suggested the early initiation of the LFTB precluded relationship to the Sevier system, other workers have suggested the LFTB shared a decollement with the Sevier system (e.g. Oldow, 1983; Speed and others, 1988). Paleocurrent and provenance data from Jurassic rocks in and east of eastern Utah have been cited by others to support the association of the LFTB with the Sevier system (Royse, 1993; Currie, 1997, 1998; DeCelles, 2004; DeCelles and Coogan, 2006). Wyld (2002) also documented a minor mid-to-Late Cretaceous (pre-100 Ma) contractional event on the LFTB and suggested (Wyld and others, 2003) that this minor late contraction might be related to the Sevier frontal system. Wyld and others (2003) indicate 7–14 km of overburden on the LFTB, further thickening the crust.

Central Nevada thrust belt In the area near and south of Eureka, Nevada (figure 1), thrust faulting correlative among several mountain ranges was initially bracketed as Early Triassic to mid-Cretaceous, and Ketner (1984) collectively called this system the Eureka thrust belt, which was the term used for some years following (e.g. Fryxell, 1988; Speed and others, 1988). The rocks involved in both hanging wall and footwall are typically early- to late-Paleozoic miogeoclinal and Antler or Sonoma foreland basin and overlap units, and the thrusts are generally east-vergent. Work by Taylor and others (1993, 2000) and

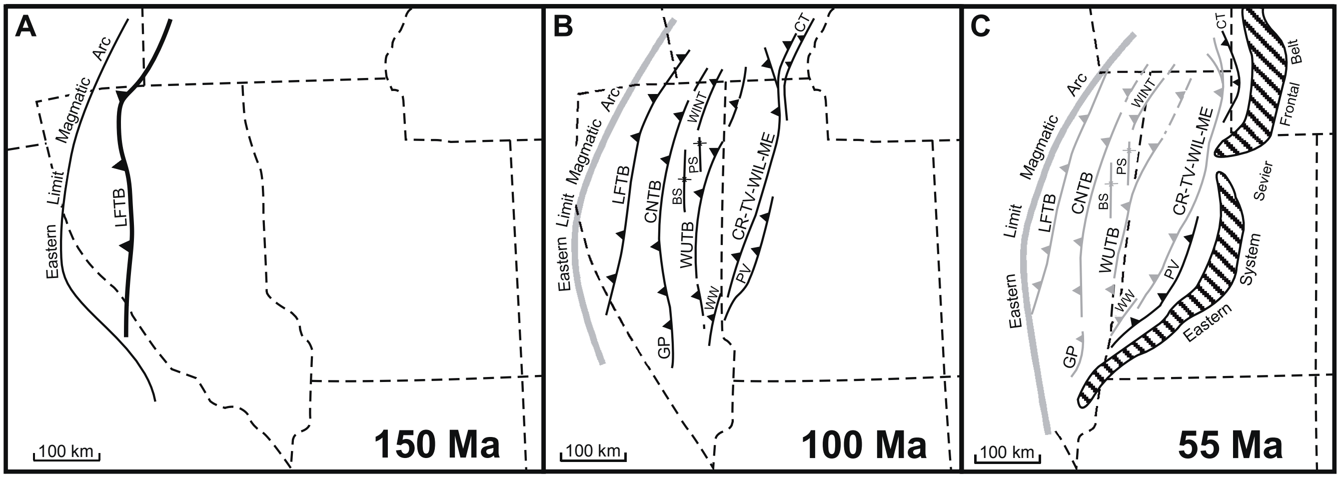

Figure 2. *Palinspastic sketch maps for major Sevier orogenic tectonic elements; features in black have been active within 10 Ma prior to the date given. (A) ~150 Ma, Luning-Fencemaker fold-thrust belt (LFTB) emplacement east of the Cordilleran magmatic arc, representing >100 km of shortening. (B) ~100 Ma, Canyon Range decollement emplacement, with associated movement along: the Central Nevada thrust belt (CNTB) and Gass Peak thrust (GP); Eastern Nevada fold belt including the Butte synclinorium (BS) and Pequop synclinorium (PS); Western Utah thrust belt (WUTB); Wah Wah thrust (WW); Canyon Range thrust system including the Canyon Range thrust, Tintic Valley thrust, Willard thrust, and Meade-Paris thrusts (CR-TV-WIL-ME); Pavant thrust (PV); Crawford thrust (CT); note that there is Cretaceous pre-100 Ma movement in the LFTB, and that the Windermere thrust (WINT) moved in this window, as well; shortening for this period may total ~230-250 km. (C) ~55 Ma, final stages of the Sevier orogeny near the latitude of 39N, with features in gray that completed shortening more than 10 Ma previous to 55 Ma; in black are western system thrusts PV and CT; the striped patterned area includes the eastern system frontal thrusts; total shortening for this period may be ~80 km. Palinspastic base maps modified from Yonkee and Weil (2015) and McQuarrie and Wernicke (2005).*

Gilbert and Taylor (2001) correlated additional thrusts to the south including the Garden Valley thrust system of Bartley and Gleason (1990), expanded the interpreted width and length of the thrust system, named it the Central Nevada thrust belt (CNTB), and further correlated one of the thrusts to the Gass Peak thrust of the southern Nevada section of the Sevier frontal thrust system.

The CNTB is exposed for 250 km along strike in south central Nevada. Correlation with structures as far north as the Adobe Range extends the strike length of the CTNB to greater than 400 km (Taylor and others, 2000); shortening of 10–15 km is likely (Taylor and others, 1993, 2000; DeCelles, 2004).

Taylor and others (2000) reported that pluton U/Pb date intercepts indicated an age no younger than 85–100 Ma for cessation of movement in the CNTB, consistent with overlap and syndeformation of the Cretaceous Newark Canyon Conglomerate. Timing constraints are minimal, but deformation was probably active between Late Jurassic (~150 Ma) and middle Cretaceous (~100 Ma) (Taylor and others, 1993, 2000; DeCelles, 2004). Long and others (2014) cited a date of 116 Ma for outcrops of overlapping and folded Newark Canyon Formation conglomerates near the CNTB Eureka culmination at the south end of the Diamond Mountains, and suggested that this pinned the age of final contraction in the CNTB to Aptian, older than the ~100 Ma interpreted by Taylor and others (2000). In any case, the CNTB was active during most of the period the Canyon Range thrust was active, and the latest deformation in the CNTB post-dates most movement on the Canyon Range thrust.

As noted by Taylor and others (2000), the recognition of the CNTB as a significant tectonic element linked in time and space with the Sevier frontal belt refuted earlier interpretations of a quiescent Sevier hinterland “characterized by non-ductile deformation and insignificant metamorphism” (Allmendinger and Jordan, 1981). Further, Taylor and others (2000) suggested the CNTB might have been an early thrust system in the Sevier orogeny, with deformation passing eastward into the foreland such that the CNTB eventually lay in the hinterland.

Western Utah thrust belt In western Millard County, Utah, the miogeoclinal assemblage is well-exposed in the Confusion Range, which lies between the Snake Range and the House Range and is separated from them by Snake Valley and Tule Valley, respectively (figure 3). The Confusion Range had long been interpreted as a synclinorium involving the miogeoclinal units in a set of folds (e.g. Hose, 1977; Anderson, 1983; Gans and Miller, 1983; Smith and others, 1991; Allmendinger, 1992; DeCelles, 2004; Rowley and others, 2009; Long, 2012). The few thrust faults exposed at the surface in the range have relatively short traces and omit little section, and had been considered incidental to the folding.

The work of our group (Dubé and Greene, 1999; Yezerski and Greene, 2009; Matteri and Greene, 2010; Greene and others, 2011; Greene and Herring, 2013; Greene,

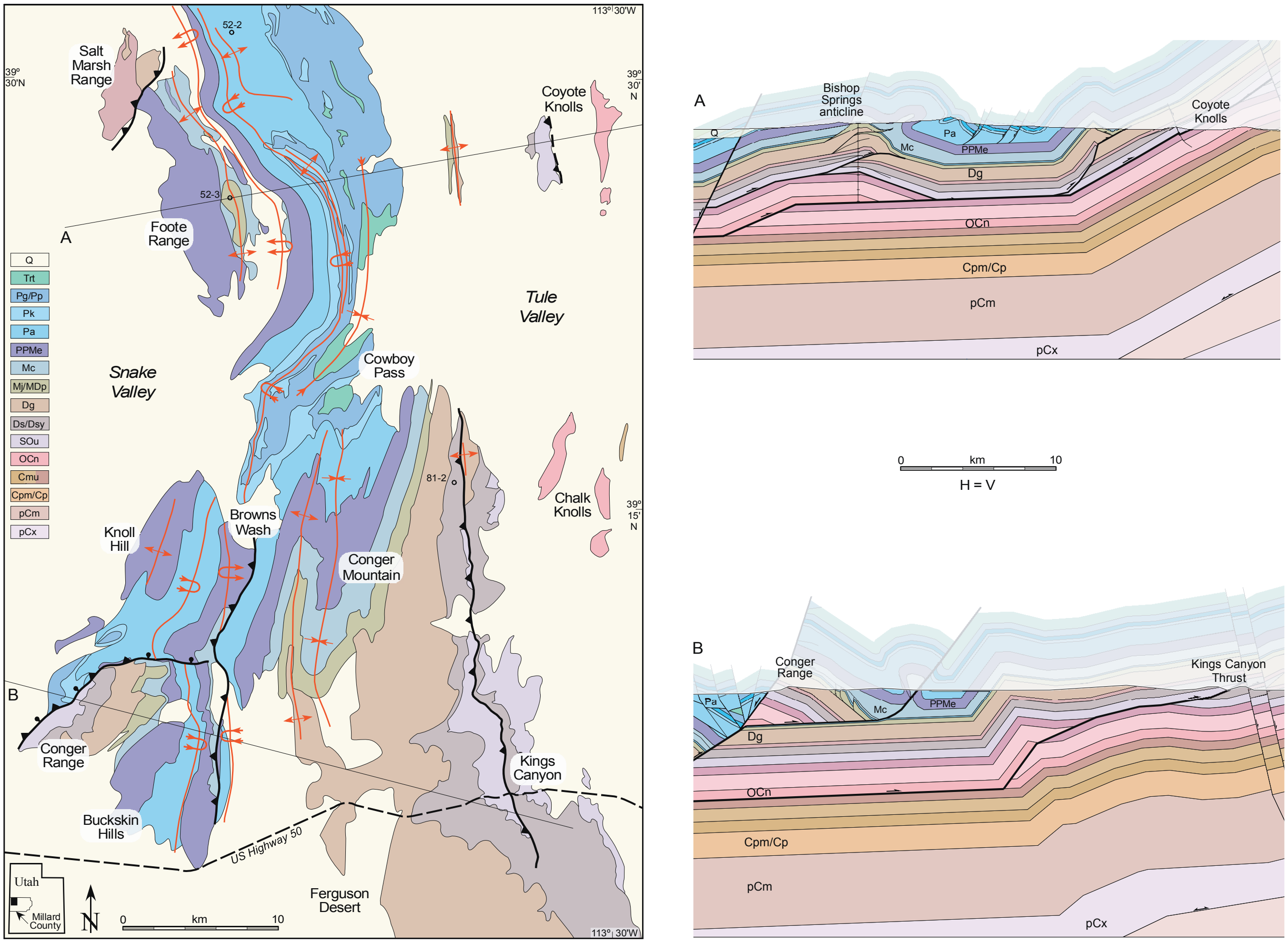

Figure 3. *Simplified geologic map of the type area of the Western Utah thrust belt in the Confusion Range of western Millard County, Utah, USA. Excerpts from two cross sections from Greene (2014) are shown to illustrate the structural architecture. Q=Quaternary undifferentiated; Trt=Triassic Thaynes Formation; Pg/Pp=Permian Gerster and Plympton formations; Pk=Permian Kaibab Formation; Pa=Permian Arcturus Formation; PPMe=Permian-Pennsylvanian-Mississippian Ely Limestone; Mc= Mississippian Chainman Formation; Mj/MDp=Mississippian Joanna Limestone and Mississippian-Devonian Pilot Shale; Dg=Devonian Guilmette Formation; DsDsy=Devonian Simonson and Sevy formations; SOu=Silurian and Ordovician, undifferentiated; OCn=Ordovician-Cambrian Notch Peak Formation; Cmu=Middle Cambrian undifferentiated; Cpm/Cp=Cambrian Prospect Mountain Quartzite and Pioche Formation; pCm=Precambrian McCoy Creek Group; pCx=Precambrian crystalline basement.*

2014), and that of Nichols and others (2002), indicates that the Confusion Range is more accurately characterized as an east-vergent, fold-thrust belt, with significant (~10–15 km) horizontal shortening during the Sevier orogeny. Greene (2014) formally proposed and defined this as the Western Utah thrust belt (WUTB), presenting four balanced cross sections passing east-west from Snake Valley, through the Confusion Range, across Tule Valley, and into the House Range; a fifth, north-south section ties the balanced sections (figure 3). Detailed descriptions of these cross sections and the structural architecture of the Confusion Range can be found in Greene and Herring (2013) and Greene (2014).

Fold and thrust structures and structural style are continuous from the Confusion Range southward into the Burbank Hills and Mountain Home Range (Hintze, 1986, 1987; Hintze and Best, 1987; Hintze, 1997; Hintze and Davis, 2002b), indicating the WUTB has a strike length of at least 130 km (figure 1). South of the Mountain Home Range, Paleozoic rocks and structures are buried by Tertiary volcanic rocks of the Indian Peak caldera, but structural trends (e.g. Steven and others, 1990) and subcrop stratigraphic patterns (Long, 2012) suggest that the thrust belt can be correlated southward into Sevier thrust systems exposed in southern Nevada or southwestern Utah.

North of the Confusion Range, the continuation of the WUTB is less certain. North-northwest trending structures at the northern tip of the range are obscured by Cenozoic cover in northern Snake Valley, and appear to terminate against Tertiary normal faults bounding Neoproterozoic strata on the west edge of the Deep Creek Range. Mesozoic contractional structures have been reported in the Deep Creek Range (Rodgers, 1989; Nutt and Thorman, 1994), and the Gold Hill area (Nolan, 1935, Robinson, 1993) to the north, and in the Cedar Mountains (Moore and Sorensen, 1979; Clark and others, 2012) to the northeast. If the presumed 47 km of top-to-the-west normal displacement on the Sevier Desert Detachment (DeCelles and Coogan, 2006) is restored, upper Paleozoic rocks and structures in the Confusion Range align with similar upper Paleozoic strata and fold and thrust structures in the Cedar Mountains.

These structural correlations to the north and south suggest that the WUTB is a separate fold-thrust belt that diverges from the Sevier frontal thrust belt in southern Nevada or southwestern Utah and can be traced northward into west central Utah, for a total possible length of over 400 km. The WUTB is comparable in length, width, and general structural style to the CNTB, which is presently located 175 km to the west. When extension associated with the Snake Range core complex and with the younger Basin and Range event is restored, the WUTB lies about 50 km east of the CNTB and 75 km west of the Canyon Range thrust (Greene, 2014). The restored position of the Canyon Range thrust is about 75 km west of the frontal Paxton-Gunnison thrust system (DeCelles, 2004).

A notable difference between the Central Nevada and Western Utah thrust belts, however, is that the WUTB coincides with a regional structural low, the Confusion Range structural trough of Hose (1977), where rocks as young as early Triassic (590 m of Thaynes Formation) are preserved, with the oldest overlapping rocks being volcanics of Late Eocene age. The CNTB, in contrast, according to Taylor and others (2000) folds rocks only as young as Pennsylvanian and is overlapped by Oligocene units in the south. However, Vandervoort and Schmitt (1990) report Early Cretaceous wedge-top basin sediments in unconformable contact with folded Jurassic rocks within the northern area of the CNTB.

Additionally, in the WUTB, erosional exhumation was apparently generally low, in the range of 1–3 km according to Long (2012), and the dominant thrust geometry is ramp-flat with smaller stratigraphic throws, lacking any (recognized) organized, thick, thrust-front conglomeratic accumulations. In contrast, the CNTB appears to be a zone of high structural relief with erosional exhumation in the range of 4–6 km (Long, 2012); this fits with the observations of Taylor and others (1993, 2000) that thrust faults in the CNTB are characteristically steeply dipping (prior to Cenozoic rotation) with large stratigraphic throws, and with the data of Vandervoort and Schmitt (1990) showing landslide deposits and rapid development of topographic relief in Late Cretaceous in the CNTB.

Timing indicators are presently insufficient to closely constrain deformation in the WUTB. Lower Triassic (~240 Ma) rocks are involved in the folding, and Late Eocene (~35 Ma) deposits overlap. Geophysical data indicates that the mid-Jurassic Notch Peak pluton (170 Ma) outcropping in the House Range is rootless (Ren and others, 1989), likely the result of a low-angle fault truncation and transport (Ren and others, 1989; Hintze and Davis, 2003), and our balanced cross sections confirm this truncation is plausible as part of the WUTB deformation. The western system thrusts of the Sevier orogenic system at this latitude were active only until about 90 Ma (DeCelles, 2004), so, the maximum likely range for deformation in the WUTB might be closer to ~165 to 90 Ma.

Documentation of the WUTB adds to the mounting evidence that the Sevier hinterland was not an undeformed interior zone. The WUTB also fits neatly into recent models of the Sevier orogenic tectonic regime. For instance, DeCelles and Currie (1996) indicated the likely existence of an orogenic, Middle-Late Jurassic, source terrane in Nevada and western Utah, which timing would coincide with the duration of the LFTB propagation, and with earliest thrusting in the CNTB and WUTB. DeCelles (2004) located the Sevier culmination at a high structural level directly to the west of the Canyon Range (i.e. in the House and/or Confusion ranges) at the cessation of regional shortening in the Paleogene. DeCelles and Coogan (2006) suggest that restoration of Cenozoic slip on the Sevier Desert Detachment places the Sevier culmination to the west of the Canyon Range thrust—which implies that the potential structural correlation we make of the Confusion Range to the Cedar Range is reasonable, and supports the existence of the WUTB as a pre-Cenozoic structural and topographic high.

DeCelles and Coogan (2006) note that the sum of distances of shortening and forward propagation in a thrust belt should approximately equal the total migration distance of the forebulge. For the Sevier system, there is a significant negative gap between these numbers if the commonly accepted forebulge migration distance of 250 km (shown, for instance, in Currie, 1997) is used for the calculation. There is a much smaller, and positive, gap if the more controversial proposal of White and others (2002) of 450–500 km is accepted, and the WUTB and the similar structures we postulate below as yet-to-be-discovered would neatly fill this gap. Both the 250 km and 450–500 km migration distance figures have stratigraphic evidence more and less in support, and perhaps the documentation of the WUTB shortening will spur a fresh look at the question of forebulge migration.

Eastern Nevada fold belt Long (2015) recently proposed a Cordilleran “valley and ridge” fold belt, the Eastern Nevada fold belt (ENFB), in a location midway between the CNTB and the WUTB. The ENFB deforms Paleozoic through Lower Jurassic rocks, and in one locality folds

Aptian (~122–116 Ma) Newark Canyon Formation. This fold system is postulated to have formed during or after the initial migration of the master Sevier decollement into Utah (Long, 2015), which is deduced from apatite fission track data to be ~146 Ma for the Canyon Range thrust (Ketcham and others, 1996; Stockli and others, 2001).

The ENFB has no surface-breaking regional thrust faults. The first-order folds have pre-Paleogene amplitudes of 2–4 km and wavelengths of 20–40 km, with axial strike lengths of 100–200 km. Second order folds have amplitudes of <1 km, wavelengths of ~1–10 km, and can be traced for up to 10 km; shortening related to these folds was not estimated by Long (2015).

Undiscovered hinterland structures The insufficiency in reported shortening relative to migration of the foreland bulge noted above suggests that one or more throughgoing thrust belts of 10–15 km shortening similar to the CNTB and WUTB might be hidden in the extended terrain of eastern Nevada and western Utah. Prospective locations for these hidden thrust belts would most likely be within the region assigned by Long (2015) to the ENFB, one in particular associated with the Butte synclinorium: Radar Ridge (figure 1), which has an east limb with restored dip from 30° to overturned. As another possibility, the Windermere thrust sheet, likely active ~153–84 Ma per Camilleri and Chamberlain (1997) or ~142–112 Ma per DeCelles (2004), might be related to the northern extensions of either the Butte or Pequop synclinoria. We note that the Confusion Range was for decades considered a synclinorium, and acknowledge that teasing out the thrust structure took many years and many different workers attempting to draw cross sections through the range.

TIMELINE OF SEVIER DEFORMATION SEQUENCE

Here, we present a timeline (figure 4) of the sequence of events for the Sevier thrust system from the Cordilleran arc (west) to the frontal thrusts (east), and from Jurassic through Eocene, at about 39N latitude. This timeline is based on the discussion above, and presents several hypotheses not yet tested.

DeCelles (2004) describes six major tectonic elements of the Cordilleran retroarc region at this latitude, from west to east: 1) the Luning-Fencemaker fold-thrust belt; (2) the Central Nevada thrust belt; (3) the hinterland metamorphic belt; (4) the Sevier thrust belt; (5) the foreland basin system; and, (6) the Laramide intraforeland uplifts and basins. To these six should now be added at least two more tectonic elements: the Western Utah thrust belt (Greene, 2014) and the Eastern Nevada fold belt (Long, 2015). The CNTB, ENFB, and WUTB spatially overlap the "hinterland metamorphic belt", and are probably kinematically related to it in the same way various workers (as summarized by DeCelles, 2004) have suggested for the western system of the Sevier thrust belt, that is, that crustal warming (related to widespread intrusions) facilitated deformation. The foreland basin and Laramide intraforeland deformation and sedimentation are not a focus of this paper and are not discussed below.

Luning-Fencemaker fold-thrust belt

The LFTB was active in the early to Late Jurassic (~165–150 Ma), with >100 km displacement (Wyld, and others 2003). Metamorphosed and intensely folded deep marine Triassic and Jurassic facies were emplaced above shallow marine rocks of the same age (Wyld, 2002; DeCelles, 2004), correlative with the overlap assemblages covering the Golconda allochthon. The LFTB allochthon probably contributed abundant sediment to basins to the east, per DeCelles (2004), DeCelles and Coogan (2006), and references therein. Eastward propagation may have been transferred to the CNTB at ~150 Ma.

Central Nevada thrust belt

Timing of movement on the CNTB has been poorly constrained, though Gilbert and Taylor (2001) suggested initiation of movement as early as Late Jurassic, and a range of about 150 Ma to 100 Ma. Total shortening across the CNTB is in the range of 10–15 km (Gilbert and Taylor, 2001; DeCelles, 2004). DeCelles and Graham (2015) preferred to assign a range of 130–110 Ma, which better fits their concept of cyclicity in the Cordilleran orogenic system. Late Precambrian to Pennsylvanian rocks of the miogeocline are involved in the CNTB deformation (Taylor and others, 2000), as well as Jurassic rocks (Vandervoort and Schmitt, 1990), and individual thrusts reflect 0.6 to 5 km of contraction (Taylor and others, 2000).

Eastern Nevada fold belt

The ENFB deforms miogeoclinal Paleozoic rocks through mid-Cretaceous (~122–116 Ma) Newark Canyon Formation. Long (2015) suggests the fold belt did not form until the Sevier decollement had passed through to Utah, correlative to ~146 Ma for the Canyon Range thrust in west central Utah; this gives a total range of ~146 Ma to perhaps 110 Ma, nearly the same as Gilbert and Taylor (2001) propose for the CNTB. We believe at least some of the ENFB folds are probably related to thrusting that would have occurred as movement on the CNTB was transferred forward, perhaps sometime earlier than the arrival of the decollement to the Canyon Range thrust. Years of work will be required to test this hypothesis, and even if the ENFB can be reasonably proven to be a thrust belt (or two) it might still show activation at a time that is out-of-sequence to the Sevier frontal system.

Western Utah thrust belt

The least well-constrained for age of the Cordilleran orogenic elements at this latitude, the WUTB was active within the range of ~165 to 55 Ma, though probably only

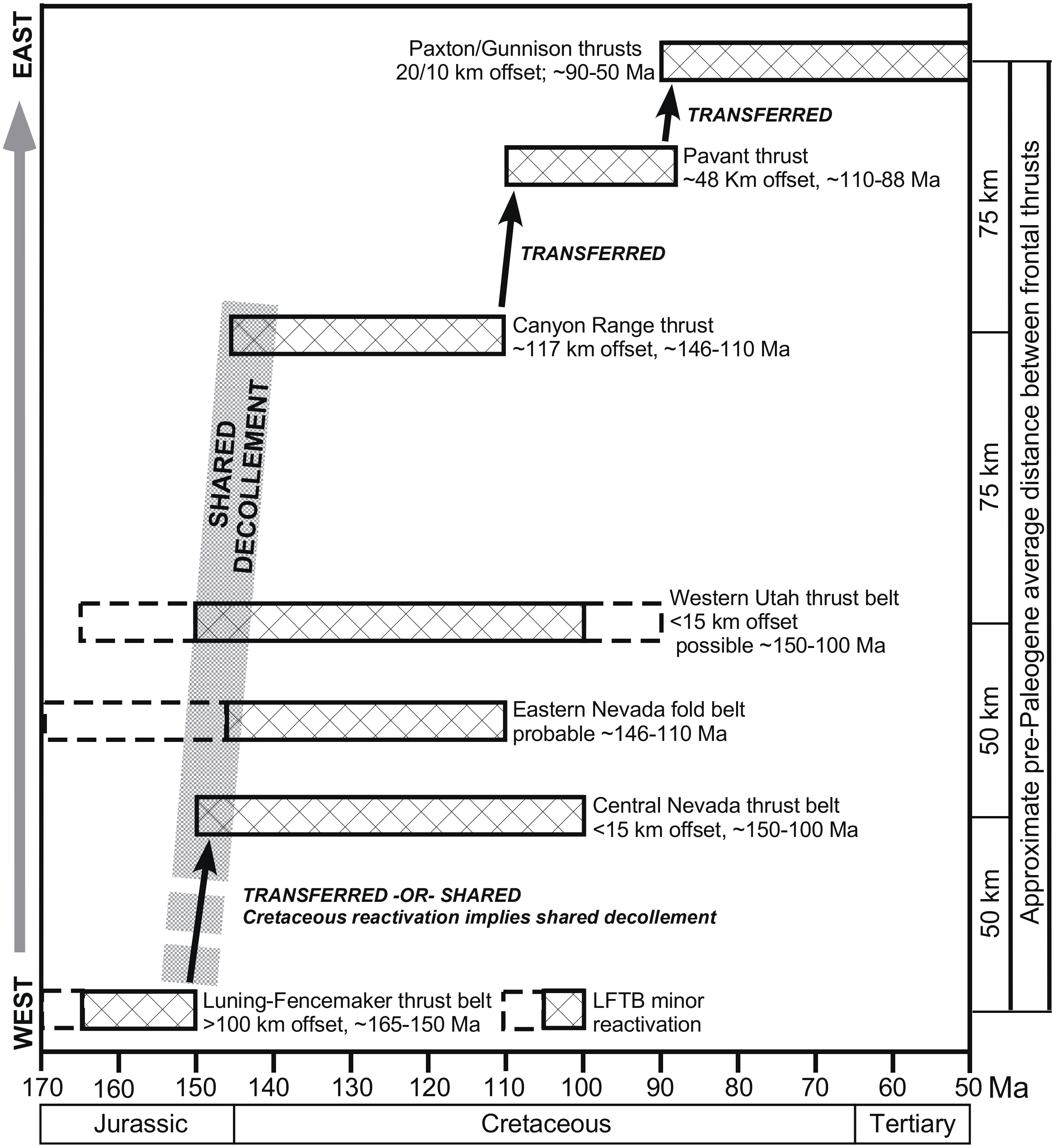

Figure 4. *Chart relating in time and space the likely initiation of movement on major thrusts and folds related to the Sevier orogeny near the latitude of 39N. References in the text discussion section: Timeline of Sevier deformation sequence.*

in a 50 My window similar to that of the CNTB. Miogeoclinal and overlap rocks through Lower Triassic are involved, and total shortening is 10–15 km across the belt. Much work is yet to be done to confirm timing and correlations of this belt, particularly to the north.

Western system Sevier thrusts

The (western system) Canyon Range and Pavant thrust sheets involve the central part of the miogeoclinal prism, probably root at midcrustal levels beneath the WUTB, and probably share a decollement with the WUTB. The Canyon Range thrust was active ~146–110 Ma, and exhibits 117 km of shortening; the Pavant thrust was active ~110–88 Ma, and contributed 74 km of shortening in the system (DeCelles and Coogan, 2006).

Note that it appears from these dates that the Canyon Range thrust moved essentially concurrently with deformation in the CNTB and WUTB, and for most of the timing of the ENFB. If this is true, then the transfer of eastward propagation from the LFTB to the Canyon Range thrust was rapid, perhaps as little as 4 to 5 My, with deformation of linked thrust and fold systems along the decollement continuing for about 40 My before propagation was transferred to the Pavant thrust. This is in contrast to the suggestion of DeCelles and Graham (2015) of a "kinematic jump" from the LFTB directly to the Canyon Range thrust, and development of the lesser intervening thrust systems only later. Cretaceous reactivation of the LFTB near the end of the time of Canyon Range decollement movement and transfer to the Pavant thrust supports the interpretation that the LFTB shares the decollement (figure 4).

Yonkee and Weil (2015) report convergence rates at the continental margin were rapid during 170–145 Ma (that is, through the period of emplacement of the LFTB, and initiation of the CNTB, ENFB, WUTB, and Canyon Range thrust), and decreased ~145–125 Ma. DeCelles and Coogan (2006) indicate the most-rapid shortening in the Sevier belt was while the Canyon Range and Pavant thrusts were active, ~146–88 Ma.

Eastern system Sevier thrusts

Shortening was transferred from the western to the eastern system of the Sevier frontal thrust belt ~88–90 Ma. The eastern system, at this latitude consisting of the Paxton and Gunnison thrust systems, was active ~90 Ma to 50 Ma, (DeCelles and Coogan, 2006; Peyton and others, 2011). This classic "thin-skinned" thrusting is developed in the thin end of the Paleozoic miogeoclinal sediment wedge (DeCelles, 2004) and the thin, late Jurassic back-bulge basin sediments into which the miogeoclinal facies transition. The transference of displacement from the western to the eastern decollement does clearly involve a "kinematic jump": the western decollement involves crystalline basement, but the eastern decollement is decoupled at and above the boundary between the basement and the miogeoclinal/back-bulge basinal sediments (DeCelles and Graham, 2015). Regional thrusting was terminated by 50 Ma (DeCelles and Coogan, 2006; DeCelles and Graham, 2015; Yonkee and Weil, 2015).

SUMMARY AND CONCLUSIONS

The Western Utah thrust belt (WUTB), as a reinterpreted structural element of the Cordilleran orogenic belt at the latitude of about 39N, is one of several regional structural systems relatively recently delineated that challenge—even put to rest—the idea of a quiescent Sevier hinterland. The WUTB may fill part of a gap between predicted and observed propagation distances in the Sevier orogenic system, and easily fits into recent palinspastic reconstructions. We believe that the Eastern Nevada fold belt (ENFB), not far west of the WUTB, will also be found to consist of at least one similar thrust system.

When considered together, the Central Nevada thrust belt (CNTB), ENFB, and WUTB structural elements of the Sevier orogenic system appear to be intimately related to the Canyon Range thrust in time. Most likely, these structural elements share a decollement, and they may together be connected to the Luning-Fencemaker fold-thrust belt via a shared decollement as well. If this correlation is correct, the initiation of the Luning-Fencemaker fold-thrust belt began the first eastward propagation of the Sevier orogeny, at ~165 Ma. Then, at about ~150 Ma, eastward propagation was transferred on the decollement and rapidly progressed to create several moderate-displacement fold and thrust systems (CNTB, ENFB, WUTB) that moved with the large-displacement Canyon Range thrust (initiated ~146 Ma) of the western system of the Sevier frontal thrust belt. Propagation was transferred to the Pavant thrust of the western system at about 110 Ma, and from the Pavant to the eastern system frontal thrusts at about 88-90 Ma. Regional thrusting was terminated ~50 Ma, with cessation of movement on the eastern system thrusts.

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