Magnitudes and spatial patterns of erosional exhumation in the Sevier hinterland, eastern Nevada and western Utah, USA: Insights from a Paleogene paleogeologic map

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ABSTRACT

The hinterland of the Sevier orogenic belt in Nevada and western Utah (United States) has been interpreted as an ancient high-elevation orogenic plateau, or Nevadaplano, that collapsed extensionally during Tertiary time. To illustrate the preextensional structural relief of this region, a new paleogeologic (or subcrop) map showing the distribution of Neoproterozoic to Triassic rocks exposed beneath a regional Paleogene unconformity is presented here. The map area extends between the traces of the westernmost major Sevier thrust system and the Roberts Mountains thrust. Three across-strike subcrop domains can be defined: (1) Cambrian to Mississippian subcrop levels in the leading part of the Delamar–Wah Wah–Canyon Range (DWC) thrust sheet, indicating high (as much as 7 km) structural relief; (2) a broad region of eastern Nevada and westernmost Utah devoid of surface-breaching thrust faults, with Mississippian–Triassic subcrop levels, indicating low (2 km) structural relief; and (3) subcrop levels varying between Neoproterozoic and Permian in the central Nevada thrust belt (CNTB), indicating high (as much as 8 km) structural relief.

Using published isopach maps of depositional thickness of Neoproterozoic to Triassic sedimentary rocks, the paleogeologic map has been converted into a map that contours the thickness of rock eroded between the top of the Triassic section and the Paleogene subcrop level, and thus illustrates magnitudes and spatial patterns of synorogenic erosional exhumation. Characteristic exhumation magnitudes for the three subcrop domains are: (1) 4–8 km in the leading part of the DWC thrust sheet; (2) 4–10 km, 2 km, and 4–6 km in the southern, central, and northern parts of the CNTB, respectively; and (3) 1–3 km in the intervening low-relief region.

Isolated exposures of southern CNTB structures can be correlated by their subcrop and exhumation patterns into two through-going thrust systems that connect with structures of the Sevier thrust belt in southern Nevada. This supports previously suggested correlations, and implies a direct structural link between these two thrust systems. Subcrop and exhumation patterns do not reveal a surface-breaching thrust trace that would represent a southern continuation of the Windermere thrust south of the Pequop or Ruby Mountains. Thus, if the Windermere thrust model is correct, this implies either termination at a lateral structure such as a tear fault, or a transition to a blind geometry.

The ~2 km structural relief that characterizes much of the Sevier hinterland indicates that the majority of high-magnitude (>1–2 km throw), regionally distributed, surface-breaking normal faulting that dismembered the orogenic highland and produced the high structural relief observed today had to be post-Oligocene. Although the traces of 70 normal faults that are overlapped by the Paleogene unconformity are identified, the throw on nearly all of these structures is limited to a maximum of 1–2 km. This further highlights the paradox of extensive Late Cretaceous and Paleogene exhumation of mid-crustal rocks now exposed in metamorphic core complexes without corresponding high-magnitude upper crustal extension.

The close spatial association of high exhumation magnitudes with the hanging walls of major thrust faults suggests that erosional exhumation is a response to relief generation accompanying contractional deformation in orogenic plateaus. The lack of significant along-strike exhumation variability within much of the Sevier hinterland implies that relief generation was relatively uniform along strike. The steep across-strike exhumation gradient between the leading part of the DWC sheet and the low-exhumation region to the west is interpreted as the result of shielding of the western area from headward erosion by long-lived uplift, erosion, and relief development through passive eastward translation of the DWC thrust sheet and growth of antiformal culminations at depth.

A significant difference between the Sevier and central Andean orogenic plateaus is emphasized here. Much of the interior part of the Sevier plateau was an eroding highland, composed of preorogenic rocks, with low structural relief, while the interior part of the Andean plateau consists of a variably deformed and exhumed, synorogenic hinterland basin as much as 12 km thick, with very high structural relief. Thus, comparison of the structural level of the stratigraphic contact between preorogenic and synorogenic rocks indicates a difference in rock uplift between the interior parts of these two plateaus of as much as 14–15 km.

INTRODUCTION

The Mesozoic–Paleogene North American Cordillera is the birthplace and testing ground for models of the genesis and development of magmatic arcs, fold-thrust belts, and foreland basins, which have been used to explain orogenic systems worldwide. In the western interior United States, major components of the Cordillera include the Sierra Nevada magmatic arc in California, a broad hinterland region in Nevada, and the Sevier fold-thrust belt in Utah, which is the type locality of the Cordilleran foreland fold-thrust belt system (e.g., Armstrong, 1968). The hinterland region has been interpreted as an ancient high-elevation (~3–4 km) orogenic

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Geosphere; August 2012; v. 8; no. 4; p. 881–901; doi:10.1130/GES00783.1; 4 figures; 3 plates; 1 supplemental figure.
Received 9 January 2012 ♦ Revision received 3 May 2012 ♦ Accepted 5 May 2012 ♦ Published online 16 July 2012

plateau, or Nevadaplano, after comparison to the modern Andean Altiplano-Puna plateau (e.g., Coney and Harms, 1984; Dilek and Moores, 1999; DeCelles, 2004; Best et al., 2009). Thus, the Sevier hinterland is an ideal locality for studying tectonic processes that govern the genesis of continental orogenic plateaus. However, the hinterland region has undergone a complex history of Tertiary extensional and topographic collapse (e.g., Coney and Harms, 1984; Wernicke, 1992; Dickinson, 2006). The cumulative effects of this extensional deformation have obscured evidence for a relict low-relief plateau, and have hindered our understanding of the preextensional structural geometry and structural relief of the hinterland region.

In regions with complex, multipart deformation histories, construction of a paleogeologic map is a technique that has proven successful for discriminating between the cumulative effects of superposed deformation events (e.g., Armstrong, 1968). To generate a detailed paleogeologic map, multiple exposures of a regionally extensive unconformity are required to allow compilation of data on the spatial distribution and ages of rocks exposed beneath it. In the Sevier hinterland region in eastern Nevada and western Utah, a regional unconformity exists beneath Eocene to Oligocene volcanic rocks (e.g., Coney, 1978, 1980; Stewart and Carlson, 1978; Armstrong and Ward, 1991; Best and Christiansen, 1991), and locally beneath latest Cretaceous to Eocene sedimentary rocks (e.g., Fouch et al., 1979, 1991; Vandervoort and Schmitt, 1990; Druschke et al., 2009b). In this study, these unconformities are utilized to generate a Paleogene paleogeologic (or subcrop) map of the Sevier hinterland, in order to illustrate the preextensional structural relief of this region.

In addition, using published isopach maps of depositional thickness of Neoproterozoic–Triassic sedimentary rocks (Stewart, 1980), the paleogeologic map is converted to a map of exhumation, with contours of the thickness of sedimentary rock eroded off of the Sevier hinterland after the Triassic but prior to the end of the Paleogene. Thus, this map illustrates magnitudes and spatial patterns of synorogenic erosional exhumation in the Sevier hinterland.

Several important regional implications of these subcrop and exhumation data sets are examined, including evidence in favor of structural correlations between the central Nevada and Sevier thrust belts originally suggested by Taylor et al. (2000), constraints on the map pattern of the Windermere thrust of Camilleri and Chamberlain (1997), and a valuable contribution to the vigorously debated controversy over the timing, magnitude, and spatial distribution of pre–Middle Miocene extensional deformation in the Sevier hinterland (e.g., Gans and Miller, 1983; Vandervoort and Schmitt, 1990; Best and Christiansen, 1991; Hodges and Walker, 1992; Camilleri and Chamberlain, 1997; Snoke et al., 1997; McGrew et al., 2000; Henry, 2008; Wallace et al., 2008; Colgan and Henry, 2009; Colgan et al., 2010; Druschke et al., 2009a, 2009b, 2011; Henry et al., 2011, 2012). In addition, a comparison of exhumation patterns between the Sevier and central Andean orogenic plateaus is included, as well as a discussion of the first-order controls on exhumation patterns in orogenic plateaus.

GEOLOGIC SETTING

The Jurassic–Eocene Cordilleran orogenic belt extends for >6000 km from Mexico to Alaska, and is the archetypal example of an ancient orogen that formed between converging continental and oceanic plates (e.g., DeCelles, 2004). In the western interior United States (Fig. 1), major components of the Cordillera include, from west to east: (1) a magmatic arc exemplified by the Sierra Nevada Batholith in California (e.g., Ducea, 2001); (2) the Jurassic Luning-Fencemaker thrust belt in western Nevada (e.g., Oldow, 1984; Wyld, 2002); (3) the central Nevada thrust belt (CNTB) (e.g., Taylor et al., 2000); (4) the Sevier hinterland, a broad region of eastern Nevada and western Utah that exhibits broad, low-amplitude folding, but lacks regional-scale surface-breaking thrust faults (e.g., Armstrong, 1972; Gans and Miller, 1983); (5) the Late Jurassic to Paleocene Sevier retroarc fold-thrust belt in Nevada, Utah, Idaho, and Wyoming (e.g., Armstrong, 1968; Burchfiel and Davis, 1975; DeCelles, 2004); and (6) the Late Jurassic–Paleocene, flexural foreland Western Interior Basin (e.g., DeCelles, 2004).

A recent synthesis of the Sevier fold-thrust belt in its type locality in west-central Utah (DeCelles and Coogan, 2006) provides a detailed view of the geometry, kinematics, timing, and magnitude of deformation. Here the thrust belt consists of four major east-vergent thrust sheets that accommodated a total of 220 km of crustal shortening between the latest Jurassic and Late Cretaceous (ca. 145–66 Ma). To the west of the thrust belt, the hinterland region has been interpreted by many as a Nevadaplano, an ancient orogenic plateau

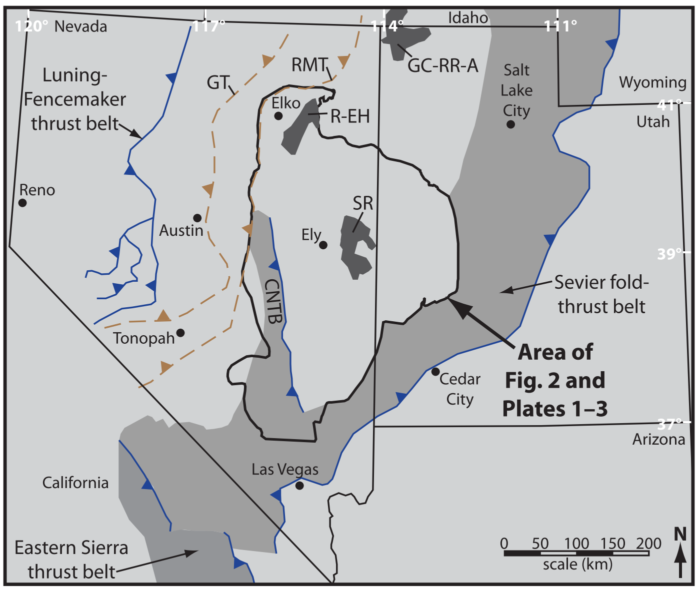

Figure 1. Map showing major Paleozoic–Mesozoic thrust systems of Nevada, Utah, and southeast California (modified from Best et al., 2009; Gans and Miller, 1983; DeCelles, 2004). Brown dashed lines are Paleozoic thrust systems, including the Golconda thrust (GT) and the Roberts Mountain thrust (RMT). Approximate deformation fronts of Mesozoic thrust systems are shown in blue, and extents of these thrust systems are shaded. Abbreviations: CNTB—central Nevada thrust belt; GC-RR-A—Grouse Creek–Raft River–Albion core complex; R-EH—Ruby–East Humboldt core complex; SR—Snake Range core complex.

similar to the modern Andean Altiplano-Puna (e.g., Coney and Harms, 1984; Molnar and Lyon-Caen, 1988; Allmendinger, 1992; Jones et al., 1998; Dilek and Moores, 1999; House et al., 2001; DeCelles, 2004; Best et al., 2009), that has since undergone extensional (and likely topographic) collapse. The hinterland is often characterized as a broad region of high elevation (~3–4 km) and low relief (e.g., Armstrong, 1968, 1972; Gans and Miller, 1983; Miller and Gans, 1989; DeCelles, 2004). The Sevier hinterland underwent relatively little upper crustal deformation during contraction in the foreland fold-thrust belt, but underwent intense ductile deformation and metamorphism at middle and lower crustal depths, as recorded by Late Cretaceous peak Barrovian metamorphism in rocks now exposed in metamorphic core complexes (Fig. 1) (e.g., Miller et al., 1988; Miller and Gans, 1989; Wells et al., 1997; Lewis et al., 1999; McGrew et al., 2000; Sullivan and Snoke, 2007; Wells and Hoisch, 2008). This is interpreted to represent the timing of maximum crustal thickening and tectonic burial.

Although the Sevier hinterland is largely devoid of surface-breaching thrust faults, it is broken in the middle by the CNTB (Fig. 1) (e.g., Taylor et al., 2000). The CNTB is a zone of east-verging thrust faults and associated folds that accommodated ~10–15 km of shortening (Bartley and Gleason, 1990; Taylor et al., 2000). The timing of deformation within the CNTB is broadly constrained between Pennsylvanian and Late Cretaceous time (Taylor et al., 2000).

PALEOGENE PALEOGEOLOGIC MAP

In an attempt to discriminate between the cumulative effects of superposed Tertiary extensional deformation and pre-Tertiary contractional deformation in eastern Nevada and western Utah, a new map showing the distribution of Neoproterozoic–Triassic sedimentary rocks that are exposed under a regional unconformity beneath Late Eocene to Oligocene volcanic rocks, and locally beneath latest Cretaceous–Eocene sedimentary rocks, is presented here. This form of paleogeologic (or subcrop) map is a valuable tool that removes the effects of differential uplift and erosion associated with Oligocene and younger extensional tectonism, and reveals the preextensional structural relief of the Sevier hinterland. This technique was pioneered by Armstrong (1968), who focused on the Sevier fold-thrust belt in Utah and southeast Nevada. Classic studies of Sevier hinterland structure in east-central Nevada have also included subcrop maps (Armstrong, 1972; Gans and Miller, 1983); however, the map presented here encompasses a much larger area of the hinterland, and is the first to show subcrop patterns of the CNTB. In addition, this map also shows the broader structural context of the Sevier hinterland, using a detailed thrust correlation scheme for the Sevier thrust belt in Utah, southern Nevada, and southeast California.

Methods

The paleogeologic map was constructed by compiling the locations of exposures of a regional unconformity beneath the oldest post-Triassic rocks, and documenting the ages of Neoproterozoic to Triassic sedimentary rocks immediately beneath it, divided by period. A map showing relevant geographic names is shown in Figure 2, the subcrop data used for construction of the map are shown in Plate 1, and the paleogeologic map is shown in Plate 2. Across the majority of the study area, the oldest preserved post-Triassic rocks are Late Eocene and Oligocene intermediate to silicic lavas and tuffs of the ignimbrite flareup (e.g., Hose and Blake, 1976; Coney, 1978, 1980; Armstrong and Ward, 1991; Best and Christiansen, 1991; Henry, 2008; Best et al., 2009). However, in several places in western Utah and eastern Nevada, scattered exposures of alluvial and lacustrine rocks between latest Cretaceous (Maastrichtian) and Middle Eocene age, including the Sheep Pass Formation and correlative strata (e.g., Vandervoort and Schmitt, 1990; Fouch et al., 1991; Potter et al., 1995; Camilleri, 1996; Dubiel et al., 1996; Druschke et al., 2009a, 2009b, 2011), are the oldest preserved post-Triassic rocks. The subcrop data compiled in Plate 1 do not distinguish between localities where Eocene–Oligocene or latest Cretaceous–Eocene rock units overlie the unconformity. Thus, the total age range of unconformities compiled spans the Paleogene, and locally is as old as latest Cretaceous (Maastrichtian).

In addition, in the region surrounding the town of Eureka in east-central Nevada, sedimentary rocks of the Early Cretaceous Newark Canyon Formation (Nolan et al., 1956; Smith and Ketner, 1976; Fouch et al., 1979; Hose, 1983; Vandervoort and Schmitt, 1990) are preserved in several isolated exposures, unconformably overlying Paleozoic rocks. The present-day spatial extents of exposures of the Newark Canyon Formation are shown in Plates 1 and 2, along with data available on their subcrop level.

The primary map data sources were the 1:500,000-scale state geologic maps of Nevada (Stewart and Carlson, 1978) and Utah (Hintze et al., 2000), with additions from multiple smaller scale map data sources cited in Plates 1 and 2. In many places where the Paleogene unconformity was not exposed, the age of the youngest subcrop unit was compiled (data marked with Y in Plate 1); this constrains the lowest possible stratigraphic position of the unconformity. Location and formation top logs from 180 drill holes (Hess et al., 2004; Utah Department of Natural Resources, 2011a, 2011b) were also used to locate the exact or lowest possible stratigraphic position of the Paleogene unconformity. The paleogeologic map (Plate 2) was constructed by interpolating stratigraphic and structural contacts between the subcrop and drill hole data compiled in Plate 1; thus, except in the very few places where they are directly exposed beneath the Paleogene unconformity, these contacts should be interpreted as approximately located (for a visual guide to the decisions used in interpolation of structural and stratigraphic contacts, please refer to Supplemental Fig. 1[1]). Plates 1 and 2 are presented here at a scale of 1:1,125,000.

The boundaries of the map area were dictated by the traces of major structures and the spatial limits of dense exposures of the Paleogene unconformity. The western and northwestern part of the boundary is the approximate trace of the Roberts Mountains thrust in central and northeast Nevada, as estimated by the easternmost locations of outcrops of rocks in its hanging wall (Plate 1). The southwestern and southern part of the boundary represents the approximate limit of exposure of the Paleogene unconformity, and a general transition to Miocene volcanics as the oldest Tertiary rocks toward the southwest. The southeastern and eastern part of the boundary is the approximate trace of the westernmost major thrust system of the Sevier fold-thrust belt in southeast Nevada and western Utah. The northern boundary represents the approximate limit of dense exposures of the Paleogene unconformity in northeast Nevada and northwest Utah.

[1]Supplemental Figure 1. Map showing all Paleogene subcrop data, the Paleogene subcrop map, and the exhumation contour map of eastern Nevada and western Utah (Plates 1–3). This map is designed as an interactive PDF that allows examination of layers of specific spatial datasets individually. To see the list of available layers, click on the "layers" tab in the left-hand table of contents in the PDF viewer. Layers of interest can be turned on and off by clicking on the eye symbol to the left of the name of the appropriate layer. This allows for specific combinations of any of the layers to be shown, which facilitates evaluation of decisions used in interpolation between isolated subcrop data points. The map also has a layer showing the locations and magnitudes of the 921 individual exhumation data points used in the construction of Plate 3 ("exhumation data" layer). If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00783.S1 or the full-text article on www.gsapubs.org to view Supplemental Figure 1.

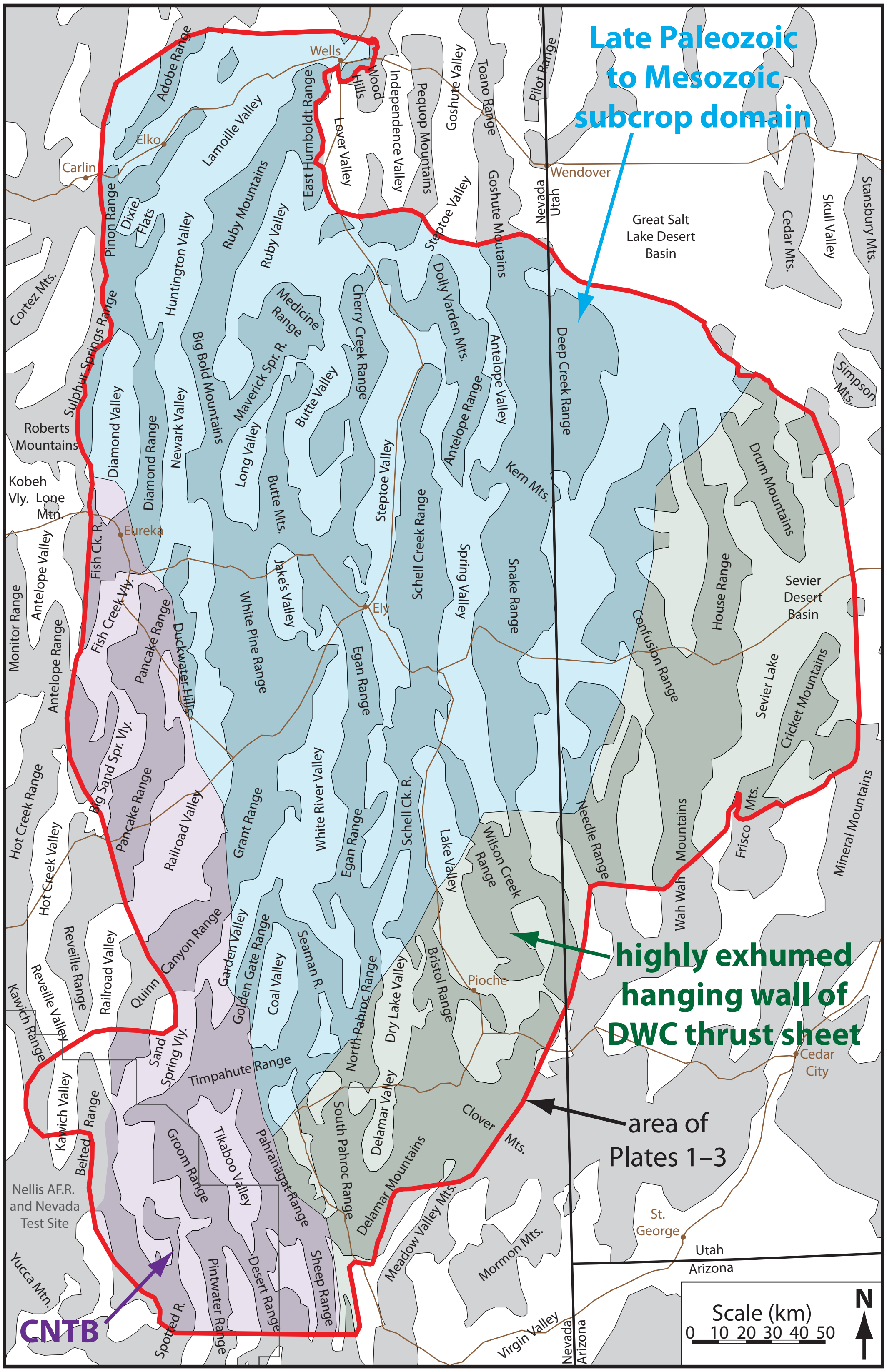

Figure 2. Map showing geographic place names relevant to discussion in the text, including ranges, valleys, and towns (see Fig. 1 for map border outline). Also shown are boundaries of the three subcrop domains. CNTB—central Nevada thrust belt; DWC—Delamar–Wah Wah–Canyon Range.

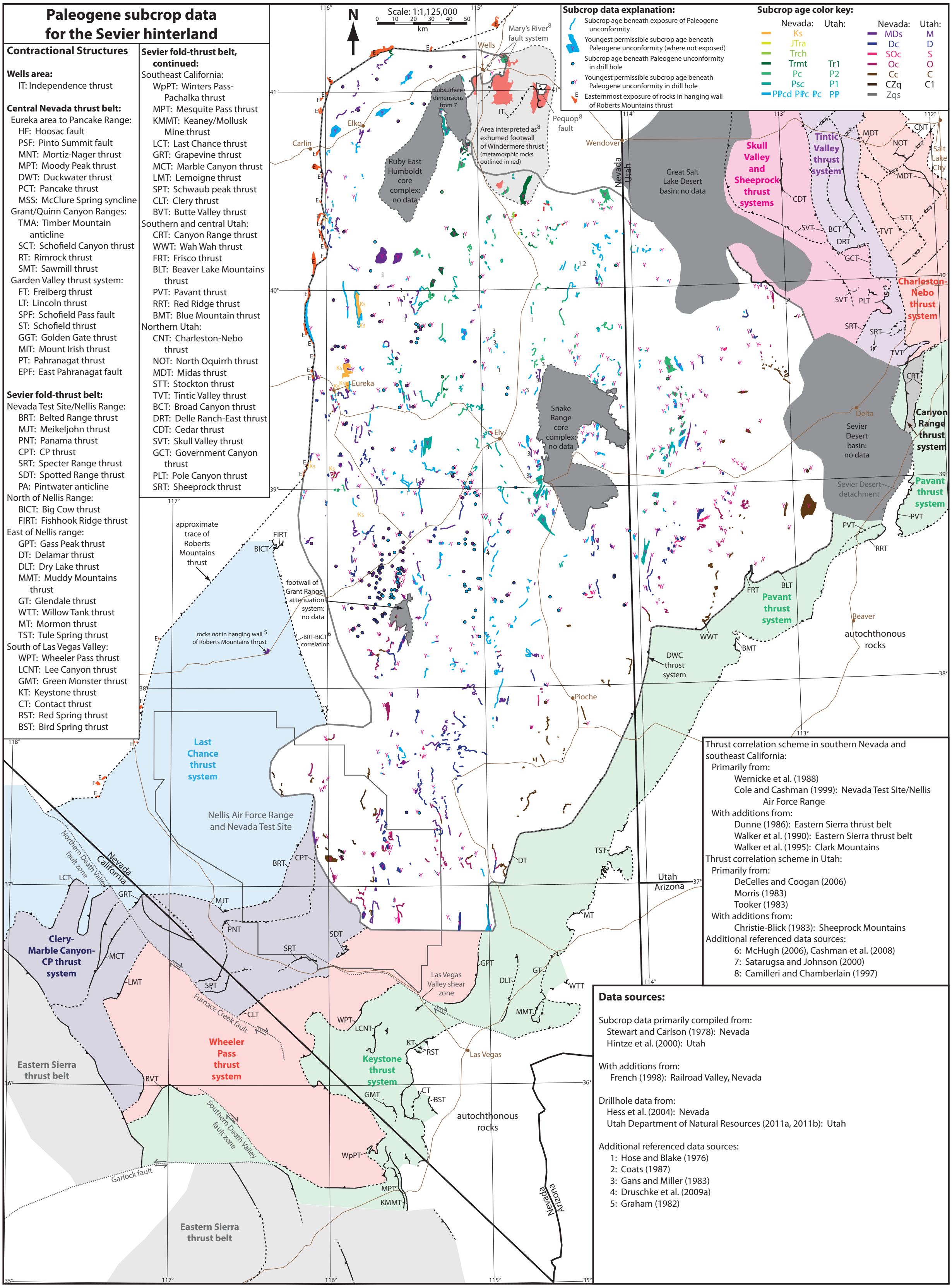

Plate 1. Map showing Paleogene subcrop source data for the Sevier hinterland used in the construction of Plate 2. This map is intended to be viewed at a size of 17.0 x 22.8 in. For the full-sized PDF file of Plate 1, please visit http://dx.doi.org/10.1130/GES00783.S2 or the full-text article on www.gsapubs.org.

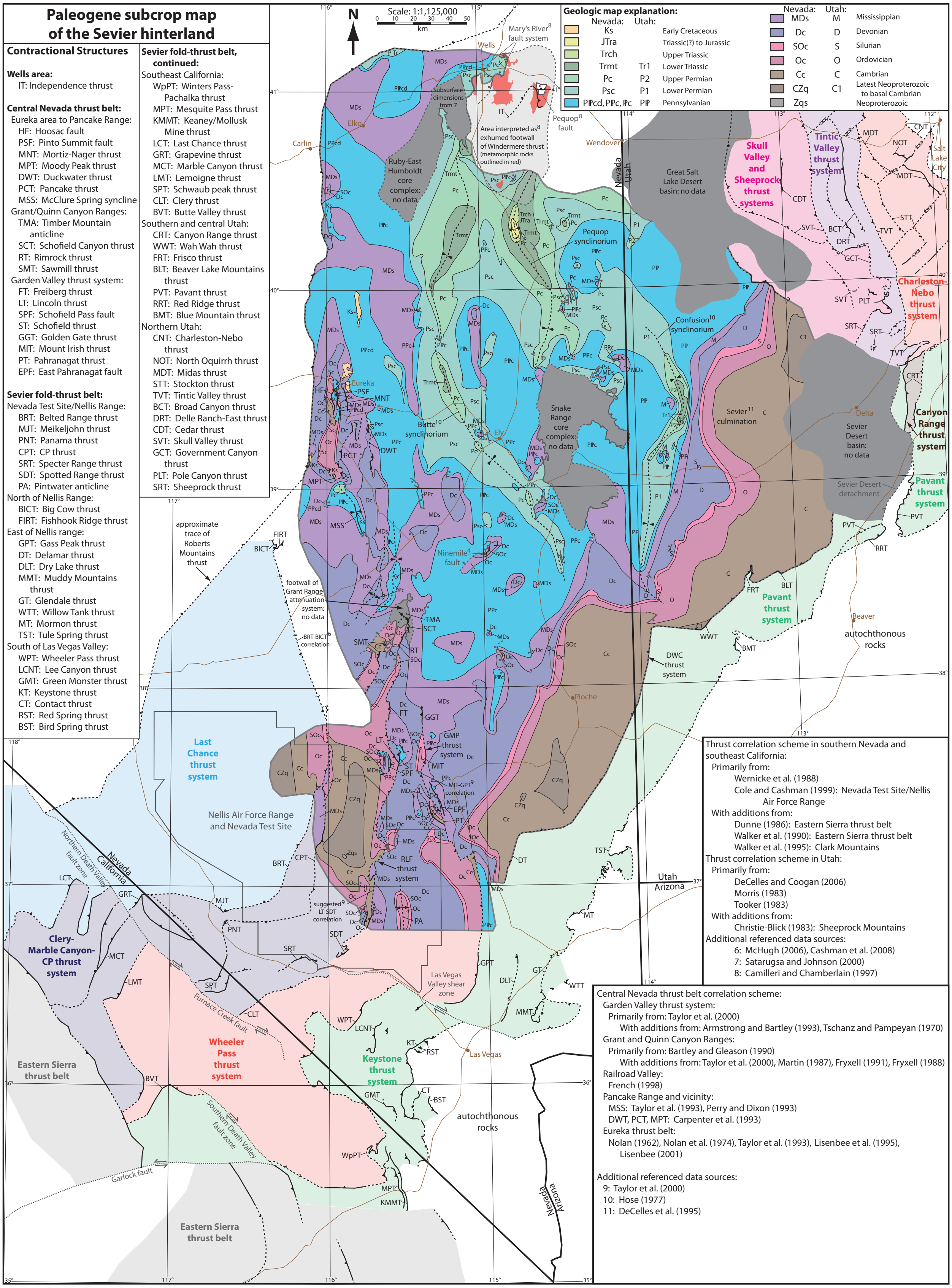

Plate 2. Paleogene subcrop map of the Sevier hinterland. This map is intended to be viewed at a size of 17.0 x 22.8 in. For the full-sized PDF file of Plate 2, please visit http://dx.doi.org/10.1130/GES00783.S3 or the full-text article on www.gsapubs.org.

Several extensive areas where data are not available are shown on the map, including the Great Salt Lake Desert and Sevier Desert basins, and the highly exhumed footwalls of the Snake Range and Ruby–East Humboldt metamorphic core complexes.

Assumptions and Caveats

Assumptions and caveats in interpretation of Plates 1 and 2 are as follows.

1. It is assumed that the rocks above and below the Paleogene unconformity are correctly identified and assigned to the correct geologic period, and that interpretations of the nature of the unconformable contact (i.e., stratigraphic and not structural) on source maps are correct. It is acknowledged that much of the study area has been mapped at a scale no finer than 1:250,000, and more detailed mapping would undoubtedly improve the density and accuracy of subcrop data.

2. Interpreting elongated north-south subcrop patterns as the axes of folds requires assuming that topographic relief was small relative to structural relief during the Paleogene. In support of this assumption, many have argued that much of the Sevier hinterland was a tectonically quiescent, low-relief, externally drained landscape that persisted until initiation of regional extension in the Middle Miocene (e.g., Henry et al., 2004, 2011, 2012; Faulds et al., 2005; Henry, 2008; Best et al., 2009; Colgan and Henry, 2009; Colgan et al., 2010). However, in contrast, several authors have argued for locally rugged topography in the Sevier hinterland as a result of localized extensional faulting possibly as old as latest Cretaceous, which continued through the middle Cenozoic (e.g., Vandervoort and Schmitt, 1990; Fouch et al., 1991; Potter et al., 1995; Camilleri, 1996; Dubiel et al., 1996; Druschke et al., 2009a, 2009b, 2011). This indicates that additional work is needed to justify the assumption of low relief, and for this reason only regional-scale subcrop patterns suggesting folding are labeled with fold axes in Plate 2.

3. The resolution of the construction technique does not allow mapping of pre-unconformity folds that have insufficient structural relief to expose rocks of different Neoproterozoic–Triassic periods between their hinges and limbs, and pre-unconformity faults that do not juxtapose rocks of different Neoproterozoic–Triassic periods. Thus, it is likely that many smaller scale folds and faults in the map area are not shown.

4. The subcrop map removes the effects of Neogene differential uplift and subsidence; however, no attempt has been made to remove or account for Neogene extension, translation, or rotation. Note that the entire map area is within the Basin and Range extensional province, which has undergone variable amounts of Neogene, east-west–directed extension. Quantification of Tertiary extension magnitude, geometry, and timing in Nevada and Utah is a subject of ongoing research (e.g., McQuarrie and Wernicke, 2005; Colgan and Henry, 2009). Thus, Plate 2 should not be interpreted as a tectonic reconstruction, but as a regional view of the distribution of different stratigraphic levels exposed at the surface during the Paleogene.

Results

The subcrop map can be divided into the following three structural domains (Fig. 2 and Plate 2).

Highly Eroded Leading Part of Delamar–Wah Wah–Canyon Range Thrust Sheet

In southeast Nevada and western Utah, a north-northeast–trending pattern of Cambrian subcrop levels that young to the west-northwest to levels between Mississippian and Triassic is consistently observed for an along-strike distance of more than 350 km (Plate 2). This subcrop pattern was first described by Armstrong (1968), and was interpreted as the map pattern of a highly eroded, gently west-northwest–dipping, regionally persistent thrust sheet with a Cambrian decollemont level. This is the westernmost regional thrust sheet of the Sevier fold-thrust belt (e.g., Armstrong, 1968; DeCelles and Coogan, 2006).

Although only exposed east of the Sevier Desert basin, the Canyon Range thrust is interpreted as the basal bounding fault at depth under this thick thrust sheet in west-central Utah, west of Delta (DeCelles and Coogan, 2006). Farther to the south, this thrust sheet is bound at its base by the Wah Wah and Frisco thrusts in southwest Utah (Morris and Lovering, 1979; Morris, 1983). Although its trace is obscured under Tertiary volcanic rocks, the Wah Wah thrust can be traced by its subcrop pattern to southeast Nevada, where Armstrong (1968) interpreted that it correlates to the Gass Peak thrust. However, Taylor et al. (2000) suggested that the intervening Delamar thrust (Tschanz and Pampeyan, 1970; Page, 1992) correlates with the Wah Wah thrust, and that the Gass Peak thrust correlates with CNTB structures further to the north (see following discussion, Garden Valley Thrust System). In this paper, the correlation scheme of Taylor et al. (2000) is used, and this regional thrust sheet is referred to here as the Delamar–Wah Wah–Canyon Range (DWC) thrust sheet.

In the hanging wall of the DWC sheet in west-central Utah, the Sevier culmination, a regional-scale structural high in Cambrian through Devonian subcrop originally recognized by Harris (1959), is visible in Plate 2. This structural high is interpreted to overlie an antiformal duplex cored by crystalline basement rocks at depth (Allmendinger et al., 1983, 1986; DeCelles et al., 1995; DeCelles and Coogan, 2006). The Canyon Range thrust sheet is inferred to have been passively translated and folded above this structural arch, and subsequently eroded (Allmendinger et al., 1986; DeCelles and Coogan, 2006). The western flank of the Sevier culmination makes up part of the eastern limb of a regional-scale, north-trending structural trough in westernmost Utah, the Confusion synclinorium (Hose, 1977). This structure has the subcrop pattern of an erosionally beveled open syncline that preserves subcrop levels as young as Triassic in its hinge zone. The axial trace of the Confusion synclinorium can be traced for a north-south distance of ~150 km.

Late Paleozoic to Mesozoic Subcrop Domain of Eastern Nevada

West of the Confusion synclinorium axis, and east of the CNTB, a southward-tapering region of eastern Nevada and westernmost Utah at least ~350 km long north-south, and between ~100 and 200 km wide east-west, is dominated by Mississippian and younger subcrop levels (Fig. 2 and Plate 2). This was first documented in early subcrop maps of east-central Nevada (Armstrong, 1972; Gans and Miller, 1983). Plate 2 expands on these pioneering studies by presenting subcrop patterns for a much larger area of eastern Nevada. In this region of the Sevier hinterland, the oldest Tertiary rocks overlie Palozoic-Mesozoic subcrop with an angular discordance typically <15° (e.g., Kellogg, 1964; Moores et al., 1968; Armstrong, 1972; Gans and Miller, 1983).

Paleogene subcrop in this region is dominated by approximately equal areas of Mississippian, Pennsylvanian, and Permian rocks. Two elongate, north-trending subcrop patterns are apparent; they define the map patterns of regional-scale, long-wavelength, low-amplitude synclines that have been beveled by erosion. These include the Butte synclinorium, a structural trough originally defined by Hose (1977), which preserves subcrop levels as young as Permian and Triassic for a north-south distance of ~250 km, and a previously unnamed synform north of the Snake Range core complex, referred to here as the Pequop synclinorium, which exhibits subcrop levels as young as Triassic, and in one locality Jurassic, for a north-south distance of at least 100 km.

Central Nevada Thrust Belt

Taylor et al. (2000) grouped thrust faults exposed between the Sheep and Grant Ranges together as the Garden Valley thrust system.

Taylor et al. (1993, 2000) suggested that the Garden Valley thrust system correlates with the Eureka thrust belt (Speed, 1983; Speed et al., 1988) ~100 km to the north, and grouped these two systems together as the CNTB, a north-trending zone of east-verging, Mesozoic(?) contractional structures that deform the Paleozoic section. Plate 2 presents the first regional-scale subcrop map of the CNTB, and is greatly aided by the thrust correlation scheme presented in Taylor et al. (2000). Subcrop data for the CNTB are compiled for an along-strike distance of >300 km, and an across-strike distance of ~50–75 km (Fig. 2 and Plates 1–2).

Garden Valley thrust system. Taylor et al. (2000) correlated isolated exposures of structures in the Garden Valley thrust system, and interpreted two main throughgoing thrust systems, the Golden Gate–Mount Irish–Pahranagat (GMP) thrust system on the east, and the Rimrock-Lincoln-Freiberg (RLF) thrust system on the west. Plate 2 shows that isolated exposures of these two thrust systems can be connected along strike based on their subcrop patterns.

The GMP thrust system is shown connecting southward with the Gass Peak thrust. This contrasts with the interpretation of Armstrong (1968), who suggested that the concealed trace of the Gass Peak thrust continues to the northeast into Utah. The northward correlation of the Gass Peak thrust with the GMP thrust system was initially suggested by Taylor et al. (2000), based on (1) the relative stratigraphic levels of the footwalls of the Gass Peak and Delamar thrusts at the same latitude, and (2) the left-lateral sense of offset on the Pahranagat shear zone, which would be predicted to offset the trace of the Gass Peak thrust to the southwest. Plates 1 and 2 show a north-trending subcrop pattern of Ordovician levels on the west juxtaposed against Devonian levels on the east, which is interpreted here as the map pattern of a concealed thrust trace that connects the Gass Peak and Pahranagat thrusts; this supports the correlation of Taylor et al. (2000). Stratigraphic separation across the Gass Peak–GMP thrust system generally decreases to the north, from Cambrian–Ordovician over Pennsylvanian rocks in the northern Sheep Range, to Devonian over Mississippian rocks in the Pahranagat and Timpahute Ranges, to its eventual tip-out in the Golden Gate Range (Armstrong and Bartley, 1993). This northward termination suggests that a component of slip on the Gass Peak–GMP thrust system may have been transferred to more frontal Sevier structures in southeast Nevada and southern Utah (Taylor et al., 2000).

Taylor et al. (2000) suggested that the RLF thrust system correlates southward across the Nevada Test Site to either the Pintwater anticline or the Spotted Range thrust. Subcrop data in Plates 1 and 2 support correlation with the Spotted Range thrust. The Lincoln thrust juxtaposes Ordovician over Devonian rocks at its southernmost exposure in the Timpahute Range (Taylor et al., 2000). Although a thrust fault has not been mapped in the Groom Range, subcrop data show a consistent north-trending pattern of Ordovician to Cambrian subcrop levels on the west, juxtaposed against Devonian to Mississippian subcrop levels on the east, that continues southward to the trace of the Spotted Range thrust, which places Cambrian over Mississippian rocks (Cole and Cashman, 1999). I propose that a previously unmapped thrust trace in the Groom Range is concealed by a combination of Tertiary normal faulting and cover by Tertiary rocks, and connects the Lincoln and Spotted Range thrusts. The approximate trace of this structure is shown as queried in Plate 2. The combined RLF–Spotted Range thrust system has a total along-strike length of ~185 km.

In the Grant and Quinn Canyon Ranges, the northernmost structures of the Garden Valley thrust system are (1) the Sawmill thrust, the westernmost and structurally highest of the system, which places Cambrian and Ordovician rocks over Devonian rocks along much of its length (Bartley and Gleason, 1990), and (2) the structurally lower Schofield Canyon thrust (and associated Timber Mountain hanging-wall anticline), which places greenschist facies Cambrian rocks over Ordovician rocks in the footwall of a Tertiary attenuation fault system (Fryxell, 1988, 1991).

Nevada Test Site. West of the RLF thrust system, two structurally higher thrust systems are exposed in the region of the Nevada Test Site. The Belted Range thrust is an east-vergent structure that places Neoproterozoic–Cambrian rocks over rocks as young as Mississippian (Cole and Cashman, 1999), and the CP thrust system (after the CP Hills, Nevada) is a zone of west-vergent thrusting and folding in the footwall of the Belted Range thrust, which places Cambrian rocks over Mississippian rocks, and postdates emplacement of the Belted Range thrust (Caskey and Schweickert, 1992; Cole and Cashman, 1999). Paleogene subcrop patterns of Cambrian against Mississippian rocks allow tracing of these two structures as far north as the Belted Range, but due to sparse subcrop data and extensive cover by Quaternary and Tertiary rocks, their map patterns become difficult to discern farther to the north. In Plate 2, both structures are shown cutting upsection to Ordovician levels in their hanging walls (Plate 1; Supplemental Fig. 1 [see footnote 1]), and the CP thrust is shown cutting the Belted Range thrust (e.g., Cole and Cashman, 1999). The Belted Range thrust is shown connecting to the north with the Big Cow thrust in the northern Hot Creek Range (McHugh, 2006; Cashman et al., 2008). The trace of this structure is shown as queried in the intervening region, due to minimal subcrop data.

The Belted Range and CP thrusts are correlated with similar foreland- and hinterland-vergent structures documented farther to the southwest in Nevada and southeast California (Snow and Wernicke, 1989; Caskey and Schwieckert 1992; Snow, 1992; Cole and Cashman, 1999). The Belted Range thrust is correlated with the Last Chance thrust system, which is interpreted as Permian (Snow and Wernicke, 1989; Snow, 1992). Because displacement on CNTB structures at this latitude can only be broadly constrained between Pennsylvanian and Late Cretaceous (e.g., Taylor et al., 1993, 2000), it is unclear how they may relate in time to the Belted Range and CP thrust systems.

Railroad Valley to Eureka. Between the Grant Range and the northern Pancake Range, the Paleogene surface expression of the CNTB transitions to a series of folds in Devonian–Permian subcrop levels (Plate 2) (e.g., Kleinhampl and Ziony, 1985; Perry and Dixon, 1993; Taylor et al., 1993; French, 1998; Thompson and Taylor, 2011). Regional-scale folds shown in Plate 2 include an anticline-syncline pair defined by drill holes under Railroad Valley (French, 1998), and the McClure Spring syncline in the southern Pancake Range (Perry and Dixon, 1993).

In the northern Pancake Range, Carpenter et al. (1993) described the east-vergent Moody Peak, Pancake, and Duckwater thrusts, which are supported by subcrop patterns in Plate 2. The Pancake thrust (Nolan et al., 1974; Carpenter et al., 1993) places Devonian over Mississippian rocks along the majority of its length, and in Plate 2 it is shown connecting to the south with the Moody Peak thrust (Carpenter et al., 1993), which places Ordovician rocks over Devonian to Mississippian rocks. The Duckwater thrust is exposed in the eastern Pancake Range, and places Devonian rocks over Mississippian rocks along the majority of its length (Carpenter et al., 1993).

In the Fish Creek and Diamond Ranges, near the town of Eureka, several structures interpreted as contractional have been grouped together as the Eureka thrust belt (e.g., Nolan et al., 1956, 1974; Nolan, 1962; Speed, 1983; Speed et al., 1988; Taylor et al., 1993; Lisenbee et al., 1995). However, several generations of structural interpretations have been made in the Eureka area, and the same large-offset structures have been interpreted as contractional or extensional in different studies. Two important examples include:

(1) the Hoosac fault (Nolan, 1962), which juxtaposes Cambrian and Ordovician rocks against Mississippian–Permian rocks, and has been interpreted as a thrust fault (Nolan, 1962; Taylor et al., 1993; Lisenbee et al., 1995) and a normal fault (Nolan et al., 1974); and (2) the Pinto Summit fault (Lisenbee et al., 1995; also called the Milk Ranch thrust by Taylor et al., 1993), which juxtaposes Silurian–Devonian rocks against Permian–Mississippian rocks, and has also been interpreted as a thrust fault (Taylor et al., 1993) and a normal fault (Nolan et al., 1974; Lisenbee et al., 1995).

In this paper, the following interpretations are used: (1) the Hoosac fault is an east-vergent thrust fault, and its hanging wall was translated eastward over much of the southern Diamond Range (Lisenbee et al., 1995); (2) the Pinto Summit fault is an east-vergent thrust fault (Taylor et al., 1993) that drops the upper plate of the Hoosac thrust sheet below the erosion surface toward the east (Lisenbee et al., 1995). Following these interpretations, the area of Mississippian to Permian subcrop between the Hoosac and Pinto Summit faults is shown as a tectonic window in Plate 2. A third thrust fault, the Moritz-Nager thrust (French, 1993), which places Devonian over Mississippian rocks, is present in the southern Diamond Range.

PALEOGENE EXHUMATION CONTOUR MAP

Western Utah and eastern Nevada were sites of relatively continuous sedimentation from the late Neoproterozoic to the Early Triassic (e.g., Stewart and Poole, 1974; Stewart, 1980). Major depositional events include: (1) late Neoproterozoic to Devonian deposition of the Cordilleran passive margin sequence, a westward-thickening section of clastic and carbonate sedimentary rocks deposited on the North American continental shelf, that approaches thicknesses of ~10 km in eastern Nevada (e.g., Stewart and Poole, 1974); (2) Late Devonian to Mississippian deposition of as much as ~3 km of coarse detritus in the Antler foreland basin (e.g., Poole, 1974; Poole and Sandberg, 1977) and Antler successor basins (Trexler et al., 2003); (3) Pennsylvanian to Early Triassic deposition of ~2–3 km of dominantly shallow-marine clastic and carbonate rocks on the continental shelf, with locally thick depocenters, including the ~6–7-km-thick Pennsylvanian–Permian Oquirrh Basin in northwest Utah and the ~3-km-thick Pennsylvanian Ely Basin in northeast Nevada (e.g., Rich, 1977; Stevens, 1977; Collinson and Hasenmueller, 1978).

By compiling thicknesses from hundreds of stratigraphic columns measured across Nevada and Utah, Stewart (1980) generated isopach maps that contour the thickness of sedimentary rocks deposited during the Neoproterozoic Era, and for each period from the Cambrian to the Triassic. By combining these detailed records of sedimentary thickness trends with the map of Paleogene erosion levels (Plate 2), I have generated a map that contours the vertical thickness of sedimentary rock eroded from a large area of the Sevier hinterland between the Triassic and the Paleogene (Plate 3).

Methods and Estimation of Error

The isopach maps of Stewart (1980) are compiled onto palinspastic base maps that are restored for estimated crustal shortening accommodated in the Antler and Sevier orogenic events. Because Plates 1–3 are not compiled on a restored base map, specific locations had to be estimated on these isopach maps. However, multiple spatial markers, including the restored positions of state and county boundaries, and the locations of major thrust faults, were available on the isopach maps to aid in matching locations. In addition, in the region between the Roberts Mountains thrust and the westernmost Sevier thrust system, Stewart (1980) restored deformation only in a few spatially limited areas, which further facilitated matching of locations.

To obtain exhumation magnitudes, the top of the Lower Triassic section was used as a datum (see following discussion, Considerations in Interpretation), and the cumulative thickness of rocks between the top of the Triassic section and the stratigraphic level of the Paleogene unconformity was measured by adding the thicknesses on the isopach maps of each relevant period. This was performed at 921 separate locations, which are shown individually in Supplemental Figure 1 (see footnote 1). Nearly all data locations were chosen along stratigraphic contacts between rocks of successive periods in Plate 2; this avoided the uncertainty of having to approximate the specific erosion level within the thickness of rock in the Paleogene subcrop period. However, in 28 localities where no stratigraphic contacts were exposed (marked with asterisks in Supplemental Fig. 1 [see footnote 1]), the Paleogene erosion level was approximated by assuming that half of the thickness of rock on the isopach map of the relevant period was eroded away.

If a measurement location plotted directly on or immediately adjacent to a contour line on one of the isopach maps, the thickness value of that contour line was used. If a measurement location was at a significant distance between two contour lines, a simple thickness interpolation halfway between the values of the adjacent contour lines was used. The contour intervals of the isopach maps of Stewart (1980) were 1000 ft (i.e., 305 m) for all periods between Cambrian and Triassic, except the Silurian map, which had a contour interval of 500 ft (152 m). The cumulative thickness values for each measurement location were calculated in feet, converted to kilometers, and interpolated and contoured in ArcGIS using inverse distance weighting. The thickness values for the 921 locations are shown in kilometers (reported to 0.1 km) in Supplemental Figure 1 (see footnote 1), and are contoured in Plate 3 with a blue (low exhumation) to red (high exhumation) color scheme and a 1 km contour interval.

Reasonable error estimates for the construction method described would be approximately half of the contour interval of the isopach map for each period, and thus error would propagate with deeper Paleogene subcrop level. Approximate cumulative error estimates for each period, rounded to the nearest 100 m, are ±0.2 km for Triassic, ±0.3 km for Permian, ±0.5 km for Pennsylvanian, ±0.6 km for Mississippian, ±0.8 km for Devonian and Silurian, ±1.0 km for Ordovician, and ±1.1 km for Middle–Late Cambrian subcrop levels. Because Paleogene erosion levels did not breach the base of the Neoproterozoic section in the map area, the Neoproterozoic–Early Cambrian isopach map of Stewart (1980) was not used to calculate exhumation values. At the only locality on the map area where map unit Zqs was exhumed in the Paleogene, a thickness of 1.6 km was estimated for map unit CZq (Cole and Cashman, 1999) to calculate exhumation at the Zqs-CZq contact (Plates 1 and 2). By adding half of this thickness value to the cumulative errors listed here, an approximate cumulative error of ±1.9 km can be estimated for Neoproterozoic–early Cambrian subcrop levels.

Considerations in Interpretation

Plate 3 contours the thickness of stratigraphic section that was between the top of the Early Triassic section and the Paleogene subcrop level. This is interpreted here as a first-order estimation of the thickness of rock that was removed by erosional exhumation between the Late Triassic and the Paleogene, and thus approximates synorogenic exhumation magnitudes in the hinterland of the Late Jurassic to Paleocene Sevier fold-thrust belt. This interpretation, and the tectonic significance of it discussed below, is subject to the following considerations.

1. Interpretation of the exhumation patterns requires assuming that the stratigraphic thick-

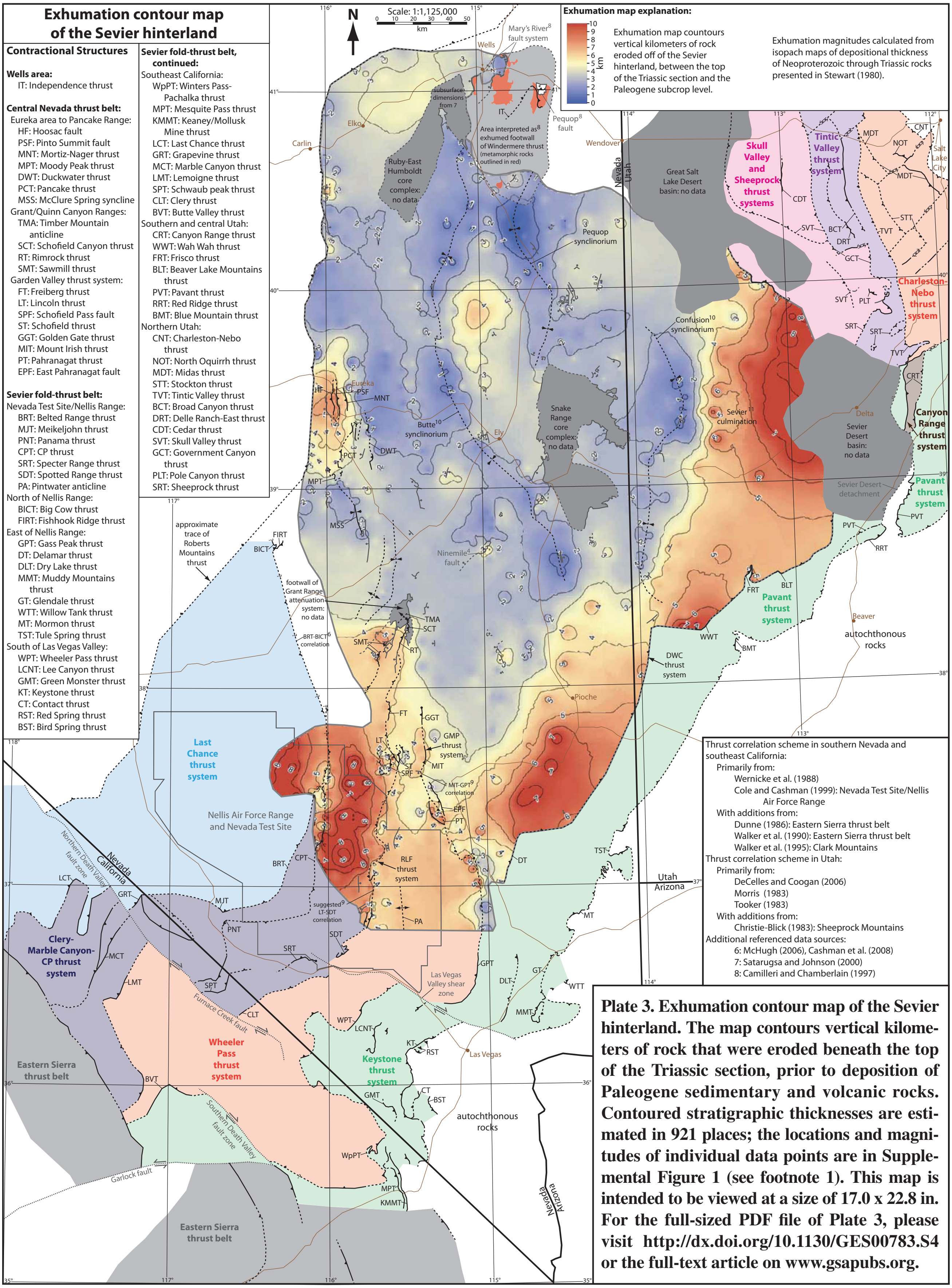

Plate 3. Exhumation contour map of the Sevier hinterland. The map contours vertical kilometers of rock that were eroded beneath the top of the Triassic section, prior to deposition of Paleogene sedimentary and volcanic rocks. Contoured stratigraphic thicknesses are estimated in 921 places; the locations and magnitudes of individual data points are in Supplemental Figure 1 (see footnote 1). This map is intended to be viewed at a size of 17.0 x 22.8 in. For the full-sized PDF file of Plate 3, please visit http://dx.doi.org/10.1130/GES00783.S4 or the full-text article on www.gsapubs.org.

nesses shown on the isopach maps of Stewart (1980) are correct. The isopach maps are based on interpolation of isolated data points, and thus have incomplete and variable data coverage. Thickness results compiled from additional stratigraphic columns would undoubtedly improve the accuracy and resolution of sedimentary thickness trends; however, I suggest that the extensive compilation of hundreds of stratigraphic columns performed by Stewart (1980) has defined all first-order, regional-scale thickness trends.

2. The contoured exhumation values should be interpreted as minima, because they measure the bedding-perpendicular thickness of strata that have been eroded above the Paleogene erosion surface, and do not account for areas of folding. The vertical exhumation magnitude in areas of folded or homoclinally dipping strata will always be greater than the bedding-perpendicular thickness of the dipping strata.

3. Interpretation of exhumation magnitudes in the immediate footwalls of CNTB thrust faults requires assuming that the leading edges of these thrust sheets were eroded as they passed upward through the erosion surface, and thus that footwall rocks east of their trace were never buried by the hanging-wall section. For this reason, the exhumation magnitudes in areas immediately east of the traces of CNTB structures should cautiously be interpreted as minima.

4. The contoured exhumation values should be interpreted as minima, because several studies have suggested that a mid-Mesozoic sedimentary section, possibly several kilometers thick, may have been deposited in eastern Nevada and western Utah, and subsequently eroded during Cretaceous thrust-related uplift (Royse, 1993; Bjerrum and Dorsey, 1995; Allen et al., 2000; DeCelles and Currie, 1996). Royse (1993) hypothesized that a Late Jurassic–Early Cretaceous foredeep that contained as much as 6 km of synorogenic sediment existed in western Utah, and was then completely eroded away during Cretaceous thrusting. Bjerrum and Dorsey (1995) and Allen et al. (2000) proposed that Middle Jurassic sedimentary units exposed in Utah represent distal flexural foreland basin sedimentation in response to crustal thickening in western Nevada and southeast California, and thus that eastern and central Nevada was the site of a Jurassic proximal foredeep. DeCelles and Currie (1996) and DeCelles (2004) proposed that Cordilleran foreland basin sedimentation began with accumulation of Late Jurassic strata in a back-bulge setting in Utah, and interpreted a Jurassic foredeep setting in eastern Nevada. Although these models differ in detail regarding timing and depositional setting, they all imply that a potentially thick (several kilometers) mid-Mesozoic sedimentary section may have existed in eastern Nevada and western Utah.

Across the entire map area, rocks interpreted as Late Triassic and Early Jurassic in age are preserved in only one locality in northeast Nevada (units Trch and JTra in Plates 1 and 2) (Stewart and Carlson, 1978). They consist of nonmarine sedimentary rocks that are possibly correlative with the Chinle Formation (Trch) and Aztec sandstone (JTra) of southern Nevada (Coats, 1987). Late Jurassic rocks are not preserved anywhere in the map area. Early Cretaceous rocks are limited to sparse exposures of the Newark Canyon Formation in the Eureka region, and unconformably overlie Paleozoic rocks (Plates 1 and 2) (Fouch et al., 1979; Vandervoort and Schmitt, 1990).

However, despite the existence of these isolated mid-Mesozoic outcrops, compilations of conodont alteration indices (CAI), which provide semiquantitative estimates of the maximum temperature a rock has undergone during metamorphism or diagenetic burial (e.g., Epstein et al., 1977), argue strongly against deep burial of Paleozoic strata under a thick Mesozoic sedimentary section (Harris et al., 1980; Gans et al., 1990; Crafford, 2005, 2007). Triassic, Permian, and Pennsylvanian rocks in a large part of the map area in eastern Nevada are characterized by CAI values of 1–1.5 (Harris et al., 1980; Crafford, 2005, 2007), which correspond to a maximum temperature range of ~<50–80 °C (Konigshof, 2003). These low maximum temperatures, combined with the ~2–3 km typical cumulative thickness of the Triassic, Permian, and Pennsylvanian section across much of the map area (Stewart, 1980), are very strong arguments against the presence of a thick, regionally continuous Mesozoic section. In particular, the deeper Pennsylvanian and Permian parts of the section would be expected to exhibit higher CAI values if buried deeper than ~3 km, at typical geothermal gradients. Deeper stratigraphic levels in eastern Nevada, most notably Devonian and Ordovician rocks, exhibit CAI values typically in the range of 2–3, which are commensurate with burial under observed overburden thicknesses for Triassic and older rocks, and indicate an average geothermal gradient (Crafford, 2005).

Recent thermochronologic studies also provide further evidence against a thick Mesozoic section. Colgan et al. (2010) obtained Jurassic apatite fission-track and apatite (U-Th)/He ages from plutons that intrude late Paleozoic rocks east of the Ruby Mountains, indicating a lack of burial beyond observed stratigraphic thicknesses. Druschke et al. (2011) obtained Pennsylvanian–Permian zircon (U-Th)/He ages from a Mississippian bedrock unit and from detrital thermochronology in the Late Cretaceous–Eocene Sheep Pass Formation in the Egan Range. The presence of late Paleozoic cooling ages is significant, because deposition of a thick mid-Mesozoic sedimentary succession would be predicted to result in mid-Mesozoic (or younger) cooling ages for these rocks (e.g., Druschke et al., 2011).

Though these CAI and thermochronologic data sets argue against the existence of a several kilometers thick, widely distributed mid-Mesozoic sedimentary section, the presence of locally thick, or thinner (<~1 km) yet widely distributed, mid-Mesozoic sedimentary basins within the map area cannot be ruled out. Therefore, the contoured exhumation values in Plate 3 should be cautiously interpreted as minima for the amount of total exhumation at any point in the map area, but they most likely represent a first-order approximation that is within ~1 km of the true exhumation amount.

Results: Spatial Patterns and Magnitudes of Exhumation, and Structural Relief

Exhumation patterns and magnitudes are distinct for the three subcrop domains defined here (Plate 3). In addition, because the subcrop map restores the Paleogene erosion surface to a flat reference plane, i.e., it assumes no Paleogene topography, the contoured exhumation values can be used to estimate structural relief within and between the three subcrop domains.

Highly Exhumed Leading Part of Delamar–Wah Wah–Canyon Range Thrust Sheet

The leading part of the DWC thrust system exhibits exhumation magnitudes between 4 and 8 km, which decrease systematically across strike toward the west-northwest to values as low as 1–2 km in the hinge zone of the Confusion synclinorium in western Utah, and as low as 2–3 km in southeast Nevada. This is consistent with the subcrop pattern of a gently west-northwest–dipping thrust sheet that is beveled by erosion.

Several areas with steep across-strike exhumation gradients are present between the highly eroded part of the DWC thrust sheet and the low-exhumation domain to the west. The steepest gradient is in the western part of the Sevier culmination, which exhibits a 5 km westward decrease in exhumation in a 13 km map distance, corresponding to a 38% gradient. A maximum lateral gradient of 4 km in a map distance of 25 km, corresponding to a 16% gradient, is observed in southeast Nevada. If this region is restored for ~50% extension (e.g., McQuarrie and Wernicke, 2005), these gradients increase to 58% and 24%, respectively.

Paleogene structural relief within the leading part of the DWC thrust sheet is as high as 7 km in western Utah, and as high as 5 km in southeast Nevada. Structural relief of the western part of the Sevier culmination is as high as 5 km.

Low Exhumation Region of Eastern Nevada and Westernmost Utah

The domain of late Paleozoic to Mesozoic subcrop between the CNTB and the leading part of the DWC thrust sheet yields exhumation values typically between 2 and 3 km. The map patterns of the Confusion, Pequop, and Butte synclinoria are easily traced as exhumation lows, with magnitudes locally <1 km in their hinges. Three isolated, spatially limited areas with exhumation magnitudes as high as 4 km are present. The largest of these areas is between the hinges of the Butte and Pequop synclinoria.

The total Paleogene structural relief for this entire ~350 km north-south by 100–200 km east-west region is between 3 and 4 km. However, excluding the isolated high- and low-exhumation areas, the characteristic structural relief for the majority of this region is 2 km.

Heterogeneous Exhumation in the CNTB

The CNTB exhibits heterogeneous along-strike and across-strike exhumation patterns. The two throughgoing structures of the Garden Valley thrust system can be traced along strike by their exhumation patterns. The Gass Peak–GMP thrust system exhibits 3–5 km magnitudes in its hanging wall, and 2–4 km magnitudes in its footwall. The hanging wall of the RLF–Spotted Range thrust system exhibits 5–10 km magnitudes at the Nevada Test Site that decrease to 4–5 km to the north in the Quinn Canyon Range. The hanging wall of the Belted Range thrust exhibits 6–8 km magnitudes. Northwest of the Grant Range, a sharp drop-off to 2–3 km magnitudes corresponds to late Paleozoic subcrop levels in Railroad Valley and the central Pancake Range. Farther to the north, the region between the northern Pancake Range and Eureka exhibits 3–6 km magnitudes. Under the structural interpretations of Lisenbee et al. (1995), the area of rock between the Hoosac and Pinto Summit faults represents a tectonic window, and thus the full thickness of the Hoosac thrust sheet was eroded off of the top of it. North of the Eureka area, exhumation decreases to ~2 km.

On the basis of these along-strike patterns, the CNTB can be divided into the high-exhumation Garden Valley and Eureka thrust systems, and an intervening low-exhumation area. Total structural relief in the Garden Valley and Eureka thrust systems is 7–8 km and 4–5 km, respectively. Total structural relief in the Railroad Valley–Pancake Range area is 2 km.

DISCUSSION

Implications of Structural Correlations Between the Central Nevada and Sevier Thrust Belts

By correlating the GMP thrust system southward with the Gass Peak thrust, Taylor et al. (2000) argued for a direct structural link, and thus an overlap in deformation timing, between the CNTB and the Sevier fold-thrust belt in southeast Nevada. The subcrop and exhumation data presented here support this correlation, and also argue for southward correlation of the RLF thrust system with the Spotted Range thrust. These correlations imply that (1) the CNTB is a more internal (hinterland) part of the Sevier fold-thrust belt; (2) surface-breaching contractional deformation bifurcated around a triangular-shaped region of eastern Nevada and western Utah; and (3) a component of the cumulative slip on the major Sevier thrust systems in southern Nevada was transferred northward into central Nevada.

Constraints on the timing of motion of CNTB structures are minimal. Structures in the Garden Valley thrust system can only be broadly bracketed between Pennsylvanian, the age of the youngest strata that they cut and fold, and Late Cretaceous (ca. 85–100 Ma), the age of crosscutting granite intrusions (Taylor et al., 2000). In the Eureka area, compressional deformation is also poorly dated, and this is further compounded by varying interpretations of the style of specific structures (see preceding discussion, Central Nevada Thrust Belt). Different studies have interpreted: (1) thrusting bracketed between the Permian and Early Cretaceous, based on the age of the youngest strata cut by thrust faults, and conglomerate of the Newark Canyon Formation overlapping thrust faults (Nolan, 1962; Taylor et al., 1993; Lisenbee et al., 1995); (2) Early Cretaceous thrusting and folding contemporaneous with deposition of the Newark Canyon Formation (Vandervoort and Schmitt, 1990); and (3) postdepositional folding of the Newark Canyon Formation, bracketed between the Early Cretaceous and Eocene (Vandervoort and Schmitt, 1990; Taylor et al., 1993).

Precise constraints for the timing of motion of structures in the Sevier fold-thrust belt in southern Nevada are limited to the frontal Keystone thrust system (Plates 1–3), where crosscutting relationships with synorogenic sedimentary units indicate Late Cretaceous (100–89 Ma; Cenomanian–Turonian) displacement (Fleck, 1970; Bohannon, 1983; Fleck and Carr, 1990; Carpenter and Carpenter, 1994). Minimal timing constraints exist for Sevier structures farther to the hinterland. The Gass Peak thrust is correlated southward with the Wheeler Pass thrust (Burchfiel, 1965; Burchfiel and Davis, 1971; Guth, 1981; Wernicke et al., 1988), which is further correlated with the Winters Pass–Pachalka thrust in the Clark Mountains in southeast California (Walker et al., 1995; Wernicke et al., 1988) (Plates 1–3). There are no precise timing constraints available for displacement on the Gass Peak or Wheeler Pass thrusts, but crosscutting relationships with plutons bracket displacement on the Winters Pass–Pachalka thrust between ca. 148 and 135 Ma (latest Jurassic to Early Cretaceous) (Walker et al., 1995). Farther to the hinterland, along-strike correlations between thrust systems in southern Nevada become less clear. The Spotted Range thrust could correlate southward to either the Clery thrust or Schwaub Peak thrust in the Funeral Mountains in southeast California (Wernicke et al., 1988; Cole and Cashman, 1999). No precise timing constraints exist for any of these structures. Assuming that deformation in this region progressed from hinterland to foreland, a lower age bound of Permian can be estimated for these three structures, based on the Permian displacement age interpreted for the Last Chance thrust and correlative Belted Range thrust (Snow and Wernicke, 1989; Snow, 1992) (Plates 1–3).

Correlation between the Sevier thrust belt in southern Nevada and the CNTB is compatible under the broad range of estimates of timing of motion currently available. However, these constraints do not allow for evaluation of space-time patterns of strain partitioning between the two thrust belts. The possible Early Cretaceous (or younger) deformation age at Eureka is particularly intriguing, because at this latitude the contractional deformation front is interpreted to have migrated into western Utah by the latest Jurassic (DeCelles and Coogan, 2006). This would indicate synchronous deformation partitioned between hinterland and foreland thrust systems. However, based on the varying structural interpretations in the Eureka area, the timing of CNTB deformation cannot be definitively interpreted as Early Cretaceous.

The thrust correlations supported by subcrop and exhumation patterns in this study indicate the need for more precise control on the age of contractional structures in the CNTB and in the Sevier thrust belt in southern Nevada in order to understand the relative timing relationships between foreland and hinterland deformation in the Cordillera.

Implications for the Map Pattern of the Windermere Thrust

In the East Humboldt Range, Wood Hills, and Pequop Mountains in northeast Nevada, emplacement of the regional-scale Windermere thrust sheet (Camilleri and Chamberlain, 1997) has been interpreted to explain the following observations: (1) high temperatures and pressures recorded by metamorphosed Precambrian and Paleozoic sedimentary rocks, which indicate burial depths as much as ~20 km greater than their original stratigraphic depth; (2) bedding-subparallel metamorphic mineral isograds indicating progressively higher grades downsection in rocks interpreted as part of the footwall of the thrust; and (3) ductile fabrics indicative of bedding-subparallel flattening strain in metamorphic rocks interpreted to be in the footwall (Camilleri, 1996, 1998; Camilleri and Chamberlain, 1997; Camilleri and McGrew, 1997). The Windermere thrust is interpreted to have carried the complete Paleozoic section in its hanging wall, and to have buried a complete Paleozoic section in its footwall, resulting in the observed Barrovian-style metamorphism and flattening strain (Camilleri and Chamberlain, 1997; Camilleri, 1998). A minimum of 69 km of top-to-southeast displacement is inferred on this structure. Emplacement of the Windermere thrust is bracketed between Late Jurassic and Late Cretaceous (ca. 154–84 Ma), and peak metamorphism of rocks interpreted to be in its footwall occurred in the Late Cretaceous (ca. 84 Ma) (Camilleri and Chamberlain, 1997). The Windermere thrust model is the most comprehensive model developed for the Mesozoic–Cenozoic development of this complex region of northeast Nevada. However, as is the case for much of the Great Basin, subsequent extensional deformation, which in this region is of an exceptionally high magnitude, has obscured the original deformation geometry.

The area interpreted by Camilleri and Chamberlain (1997) as the exhumed footwall of the Windermere thrust, as indicated by the maximum extent of Paleozoic rocks exhibiting Barrovian metamorphism, includes all rocks exposed at Spruce Mountain and in the southern part of the Pequop Mountains (Fig. 2 and Plates 2 and 3). However, because Pennsylvanian, Permian, and Triassic rocks in the southern Pequop Mountains yield CAI values indicative of burial depths that do not exceed observed stratigraphic thicknesses (Harris et al., 1980; Crafford, 2005, 2007), it is argued here that structural burial under the Windermere thrust sheet must have been minimal or absent by this point, and thus did not extend farther to the south. Thus, if the Windermere thrust model is correct, this dramatic southward gradient in burial depth could be explained by rapid thinning of the thrust sheet, termination at a lateral structure such as a tear fault, or a transition to a blind geometry.

In addition, a significant north-south gradient in burial depth has also been documented between highly metamorphosed Paleozoic rocks in the northern Ruby Mountains and correlative, unmetamorphosed strata in the southern Ruby Mountains that were never buried deeper than observed stratigraphic thicknesses (Colgan et al., 2010). East of the southern Ruby Mountains, a Jurassic pluton that intrudes late Paleozoic rocks in the Medicine Range yielded Jurassic apatite fission-track and apatite (U-Th)/He ages, indicating a lack of burial in excess of stratigraphic depths (Colgan et al., 2010).

The subcrop pattern of a surface-breaching structure with the stratigraphic offset proposed for the Windermere thrust would be comparable in scale to the leading part of the DWC thrust system. However, such a thrust trace is not observed south of the Pequop or Ruby Mountains in Plate 2. Thus, if the model of Camilleri and Chamberlain (1997) is correct, the deep structural burial and Barrovian-style metamorphism that resulted from emplacement of the Windermere thrust sheet are phenomenona that are localized to the northern Ruby Range, East Humboldt Range, Wood Hills, and northern Pequop Mountains.

Implications for the Timing, Magnitude, and Distribution of Upper Crustal Extension in the Nevadaplano

The Sevier hinterland has been interpreted as a tectonically quiescent, low-relief, externally drained plateau that persisted until regional extension began in the Middle Miocene (e.g., Henry, 2008; Colgan and Henry, 2009; Henry et al., 2011). This is based primarily on the presence of far-traveled Eocene and Oligocene ash-flow tuffs that flowed down east- and west-draining paleovalleys into Utah and California, respectively, indicating external drainage of a low-relief landscape (Henry et al., 2004, 2011, 2012; Faulds et al., 2005; Garside et al., 2005; Henry, 2008; Cassel et al., 2009; Henry and Faulds, 2010), and low-temperature thermochronology data indicating that rapid exhumation began in the Middle Miocene in north-central Nevada (Colgan and Henry, 2009; Colgan et al., 2010), eastern Nevada (Miller et al., 1999), and west-central Utah (Stockli et al., 2001).

In contrast, thermochronologic and thermobarometric data from metamorphic rocks in metamorphic core complexes (e.g., Hodges and Walker, 1992; McGrew and Snee, 1994; Camilleri and Chamberlain, 1997; Snoke et al., 1997; McGrew et al., 2000; Wells and Hoisch, 2008) argue for significant (in some places as much as 20 km; Hodges and Walker, 1992) exhumation of mid-crustal rocks as early as the Late Cretaceous. In addition, structural, sedimentologic, and provenance data from latest Cretaceous to Eocene strata in eastern Nevada and western Utah (e.g., Vandervoort and Schmitt, 1990; Fouch et al., 1991; Potter et al., 1995; Camilleri, 1996; Dubiel et al., 1996; Camilleri and Chamberlain, 1997; Druschke et al., 2009a, 2009b, 2011) are interpreted to represent a transition to a period of upper crustal extension, characterized by surface-breaching normal faulting, development of internally drained basins, and locally rugged topography in the Sevier hinterland as early as the latest Cretaceous, that continued through the middle Cenozoic. In addition, normal faults that are overlapped by Late Eocene to Oligocene volcanic rocks are documented in eastern Nevada (Taylor et al., 1989; Axen et al., 1993), and several studies argue for surface-breaking extensional faulting coinciding with (and being driven by) ignimbrite-flareup volcanism (e.g., Gans and Miller, 1983; Coney and Harms, 1984; Gans et al., 1989, 2001; Armstrong and Ward, 1991).

The subcrop and exhumation maps document minimal (~2 km) Paleogene structural relief in the hinterland region between the CNTB and the leading part of the DWC thrust system; this argues strongly against widely distributed, high-magnitude (kilometer-scale throw on normal faults), prevolcanic, surface-breaking normal faulting. Because of the limitations of the construction technique, the minimum resolution of detection of structures in Plate 2 is dictated by the thicknesses of strata within vertically adjacent time periods at or near the Paleogene subcrop level, which for late Paleozoic to Triassic rocks is typically ~1 km. Thus, many smaller scale (<1 km throw) structures may not be identified. However, the minimal structural relief that typifies this hinterland region, combined with angular discordance typically <15° between Late Eocene–Oligocene volcanic rocks and Paleozoic–Mesozoic rocks (Kellogg, 1964; Moores et al., 1968; Armstrong, 1972; Gans and Miller, 1983), and subcrop map patterns that are more compatible with beveled, long-wavelength, low-amplitude folds (e.g., Armstrong, 1972; Gans and Miller, 1983) than spaced normal faulting, all argue against high-magnitude, regionally distributed, prevolcanic upper crustal extension in this region. As an example, the ~10 km of present-day structural relief (estimated from Stewart and Carlson, 1978) within surface exposures in the Cherry Creek Range (Fig. 2) illustrates the dramatic difference between Paleogene and present-day structural relief.

The subcrop data presented here allow for synvolcanic and prevolcanic extension. Plates 2 and 3 show the traces of 70 structures (gray faults) that are overlapped by the Paleogene unconformity. These structures are shown on source maps as normal faults. Under the resolution of the construction technique, most of these structures can only be traced for along-strike distances of ~1–10 km. Because nearly all of these structures juxtapose rocks of chronologically adjacent periods, their throws must be ~1–2 km or less.

One notable exception is the Ninemile fault in the southern Egan Range, which exhibits Pennsylvanian hanging-wall subcrop levels, and footwall subcrop levels as deep as Ordovician (Druschke et al., 2009a) (Plate 2). This corresponds to a ~3 km difference in exhumation magnitude across this fault (Plate 3), which is similar to the 4 km throw estimated for this structure by Druschke et al. (2009a). Druschke et al. (2009a, 2009b) interpreted this structure as a normal fault that broke the surface during latest Cretaceous to Paleocene time, and formed the basin in which the type section of the Sheep Pass Formation accumulated.

Potentially large-throw, prevolcanic or synvolcanic, normal-sense structures are also observed in the CNTB. In the northern Quinn Canyon Range, five normal faults that are overlapped by the volcanic unconformity are shown (Plates 2 and 3). However, the subcrop patterns of these structures are interpreted as the result of synvolcanic normal faulting juxtaposing different parts of the Sawmill and Rimrock thrust sheets, followed by more significant postvolcanic normal faulting (Bartley and Gleason, 1990). Therefore, the resulting subcrop patterns represent the cumulative throws of CNTB thrust faults and synvolcanic normal faults, with complex overprinting of thrust geometries by postvolcanic normal faulting. In the Eureka area, the Hoosac and Pinto Summit faults have been alternatively interpreted as contractional or extensional (e.g., Nolan, 1962; Nolan et al., 1974; Taylor et al., 1993; Lisenbee et al., 1995). Although the thrust interpretations of Lisenbee et al. (1995) were used for the construction of Plates 2 and 3, subcrop and exhumation patterns in the Eureka area could represent the cumulative throws of older thrust faults and prevolcanic or synvolcanic normal faults.

High-magnitude (11 km throw), prevolcanic, surface-breaking extension juxtaposing the upper and lower plates of the Windermere thrust sheet and bracketed between Late Cretaceous and Late Eocene (ca. 84–41 Ma) has been interpreted on the Pequop fault in the northern Pequop Mountains (Fig. 2 and Plates 2 and 3) (Camilleri, 1996; Camilleri and Chamberlain, 1997). Under this interpretation, significant prevolcanic structural relief was a cumulative result of normal faulting and erosional exhumation superimposed over regional-scale thrust faulting. Constructing subcrop and exhumation maps for the northern Pequop Mountains was not possible because data on the stratigraphic level of the unconformity are sparse, and because of the difficulty in estimating exhumation using the methods described here in rocks interpreted as tectonically buried and exhumed to varying degrees (e.g., Camilleri and Chamberlain, 1997). The subcrop and exhumation maps do not yield evidence for comparable high-throw, prevolcanic normal faults in the southern Pequop Mountains (Plates 2 and 3), and CAI data from Pennsylvanian, Permian, and Triassic rocks across the southern Pequop Mountains and southern East Humboldt Range (Harris et al., 1980; Crafford, 2005, 2007) indicate minimal stratigraphic burial and exhumation (~1–2 km or less). Therefore, the high-throw (~11 km), surface-breaking, prevolcanic extension proposed for the Pequop fault may be localized to the region of significant tectonic burial and crustal thickening associated with the proposed emplacement of the Windermere thrust sheet, and thus is the exception rather than the rule for the Sevier hinterland.

In summary, the constraints on the magnitude, timing, and distribution of upper crustal extension indicated by the Paleogene erosion surface do not clearly preclude prevolcanic and synvolcanic extensional faulting (e.g., Gans and Miller, 1983; Gans et al., 1989, 2001; Armstrong and Ward, 1991; Axen et al., 1993; Druschke et al., 2009a), or the existence of geographically isolated, internally drained, latest Cretaceous to Eocene extensional basins surrounded by areas of locally rugged relief (e.g., Druschke et al., 2009a, 2011, and references therein). However, the subcrop and exhumation data indicate that prevolcanic and synvolcanic extension was of limited magnitude, and that the majority of extension that dismembered the orogenic highland and produced the high structural relief observed today had to be postvolcanic. This timing constraint further highlights the paradox of significant Late Cretaceous and Paleogene mid-crustal exhumation of rocks now exposed in metamorphic core complexes (e.g., Camilleri and Chamberlain, 1997; Wells et al., 1997; McGrew et al., 2000; Wells and Hoisch, 2008) without corresponding upper crustal extension (e.g., Hodges and Walker, 1992).

Altiplano versus Nevadaplano: Comparison of Exhumation Magnitudes and Patterns

Because of a similar tectonic setting, and evidence for an ancient, high-elevation (at least 3 km) orogenic plateau underlain by unusually thick (50–70 km) crust (e.g., Coney and Harms, 1984; Molnar and Lyon-Caen, 1988; Dilek and Moores, 1999; DeCelles, 2004; DeCelles and Coogan, 2006; Best et al., 2009), the Sevier hinterland region is often compared with the modern central Andean Altiplano-Puna plateau, which has an average elevation of 4 km and 60–70-km-thick crust (Beck and Zandt, 2002), hence the name Nevadaplano. For comparison of scale, Figure 3 shows maps of the Sevier and central Andean orogenic systems. When approximately restored for Cenozoic extension (using the palinspastic base map of DeCelles, 2004), the Sevier hinterland region forms a 300–350-km-wide, southward-tapering region between the 100-km-wide Sevier thrust belt and the Sierra Nevada magmatic arc (Fig. 3A).

The central Andes (Fig. 3B) can be divided into distinct physiographic provinces (e.g., Isacks, 1988; Sempere et al., 1990; Kley, 1996; Lamb and Hoke, 1997), including, from west to east: (1) the high-relief, high-elevation (peaks >6 km) Western Cordillera, the magmatic arc; (2) the Altiplano intermontane basin, a region of internal drainage and low topographic relief as much as 200 km wide, with an average elevation of 3.8 km; (3) the high-relief, high-elevation (peaks >6 km) Eastern Cordillera, a range as much as 200 km wide that represents an older, interior, bivergent part of the fold-thrust belt; and (4) the Interandean and Subandean zones, the younger, frontal, lower elevation parts of the fold-thrust belt, collectively as much as 200 km wide. The Andean orogenic plateau, when defined as the region above 3 km elevation (e.g., Isacks, 1988; Allmendinger et al., 1997), reaches a maximum width of 350–400 km in Bolivia (Fig. 3B). Under this definition, the plateau consists of the internally draining Altiplano basin, as well as much of the Western and Eastern Cordilleras. At the Eastern Cordillera–Interandean zone boundary, a distinct ~1 km downward topographic step delineates the eastern limit of the orogenic plateau (Fig. 3B) (Isacks, 1988; Allmendinger et al., 1997).

The equivalent eastern plateau boundary within the Sevier thrust belt can be approximated by a north-trending series of antiformal culminations in Utah, including the Wasatch, Santaquin, and Canyon Range culminations (e.g., DeCelles, 2004). The eastern flanks of the Wasatch and Canyon Range culminations delineate the eastern limit of high-magnitude exhumation and the western limit of the wedge-top depozone, and have been interpreted as the eastern limit of high paleotopography (DeCelles, 1994; DeCelles and Coogan, 2006). The position of these culminations was controlled by the basement step that marks the eastern limit of Neoproterozoic continental rifting, the Wasatch hingeline (DeCelles, 2004), and thus the position of the hingeline is shown as the approximate eastern limit of the Sevier plateau (Fig. 3A).

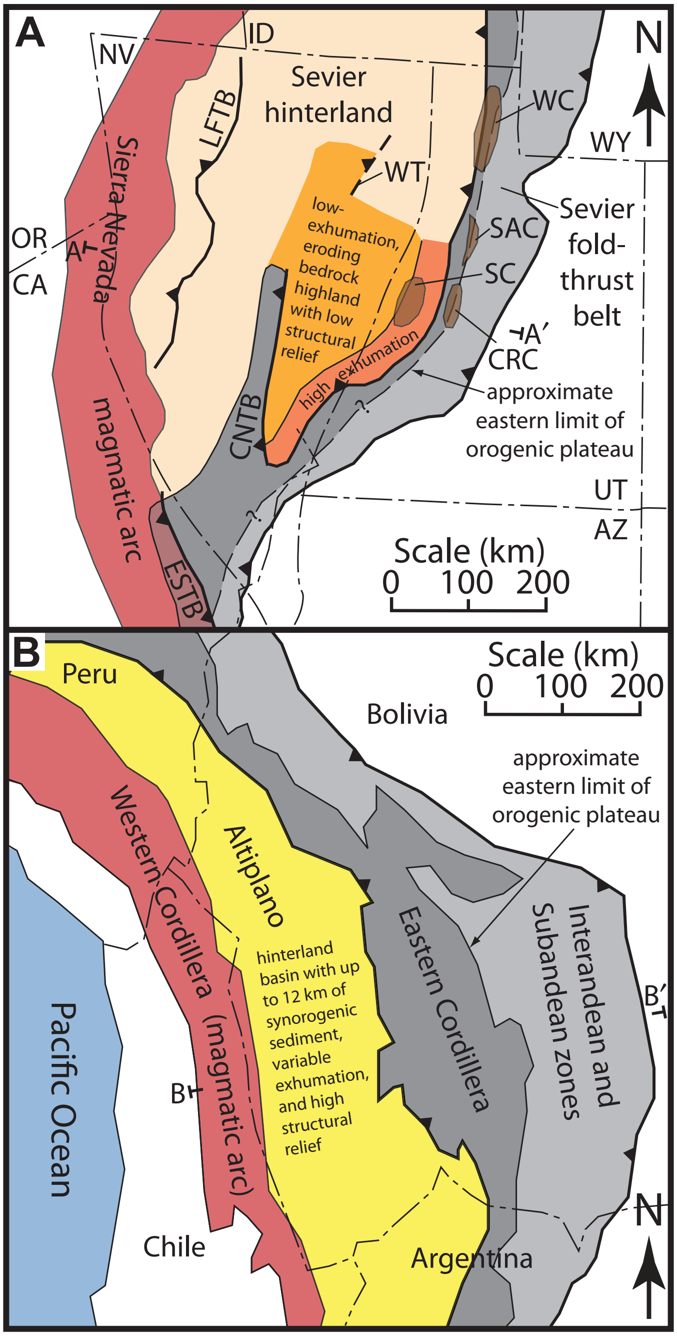

Figure 3. (A) Generalized geologic map of the Sevier orogenic belt, approximately restored for Cenozoic extension (base map modified from DeCelles, 2004). Mesozoic thrust systems: LFTB—Luning-Fencemaker thrust belt, CNTB—central Nevada thrust belt, ESTB—eastern Sierra thrust belt, WT—Windermere thrust. Structural culminations in Utah: SC—Sevier culmination, CRC—Canyon Range culmination, SAC—Santaquin culmination, WC—Wasatch culmination. Approximate eastern limit of orogenic plateau based on position of Wasatch hingeline and positions of culminations (queried where unknown) (e.g., DeCelles, 1994, 2004; DeCelles and Coogan, 2006). Line A–A′ delineates approximate cross-section line of Figure 4A. Note that exhumation magnitudes outside of the map area in this study are not quantified. (B) Generalized geologic map of the central Andean orogenic belt (modified from Coutand et al., 2001). The eastern boundary of the high Andean plateau, as defined by the region above 3 km elevation (e.g., Isacks, 1988; Allmendinger, 1997), corresponds approximately with the eastern boundary of the Eastern Cordillera. Line B–B′ delineates approximate cross-section line of Figure 4B.

For comparison of exhumation patterns, an analogy is drawn here between the Eastern Cordillera and the interior, high-elevation part of the Sevier fold-thrust belt, which includes the highly eroded leading part of the DWC thrust sheet. Erosional exhumation magnitudes in the Eastern Cordillera in Bolivia have been estimated between ~4 and 10 km, based on balanced cross sections (McQuarrie, 2002; McQuarrie et al., 2008a, 2008b) and low-temperature thermochronology (Barnes et al., 2006, 2008). These values are similar to the ~5–8 km exhumation magnitudes that characterize the leading part of the DWC thrust sheet.

Exhumation magnitudes drop sharply to ~2–3 km westward into westernmost Utah and easternmost Nevada, and these magnitudes persist for an across-strike distance as much as 150–200 km (Figs. 3A and 4A). Exhumation also decreases significantly between the Eastern Cordillera and the Altiplano basin. The Altiplano basin contains as much as 12 km of Late Cretaceous to Cenozoic synorogenic sediment (Horton et al., 2001) (Fig. 4B) that accumulated in a foreland basin setting (DeCelles and Giles, 1996; Horton et al., 2001, 2002) until an eastward jump of the deformation front into the Eastern Cordillera in the Eocene isolated the Altiplano as a large, internally drained piggyback basin (McQuarrie et al., 2005). It has since remained a repository for synorogenic sediment, which is sourced from both the Western and Eastern Cordilleras (Horton et al., 2002; DeCelles and Horton, 2003; Leier et al., 2010). Synorogenic sedimentary rocks within the Altiplano have undergone variable amounts of syndepositional and postdepositional uplift and erosion, as a result of compressional deformation on its western end (McQuarrie, 2002), within the eastern boundary region with the Eastern Cordilleran backthrust belt (e.g., Leier et al., 2010; Murray et al., 2010) and within internal parts of the basin (e.g., McQuarrie and DeCelles, 2001; Horton et al., 2002; McQuarrie, 2002). Thus, exhumation magnitudes in the Altiplano are highly variable, and are controlled by local structural relationships. Exhumation estimates from balanced cross sections range between ~0 and 8 km (McQuarrie, 2002; McQuarrie et al., 2008a), and estimates from thermochronometry range between ~2.5 and 4 km (Barnes et al., 2006, 2008).

Two important differences between the Andean and Sevier plateaus are emphasized here. One is that the Nevadaplano lacks an analogous synorogenic, compressional hinterland basin approaching a scale even an order of magnitude smaller than the Altiplano basin. In contrast, the Sevier hinterland was an uplifted, eroded highland composed of preorogenic rocks. Using

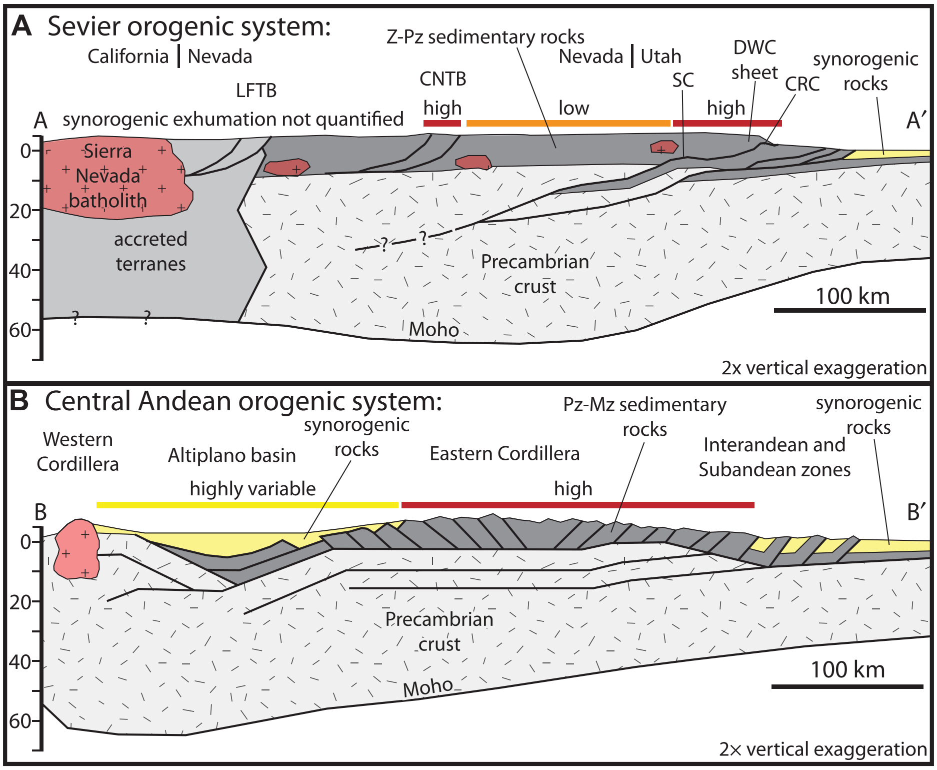

Figure 4. Schematic cross sections comparing deformation geometries and exhumation patterns between the Sevier and central Andean orogenic systems. Approximate cross-section lines are shown in Figure 3. (A) Schematic preextensional geometry of the Sevier orogenic system, modified from Allmendinger et al. (1987) and Best et al. (2009). Placements of individual structures and plutons are largely schematic, and are meant to show only general locations. Eastern limit of high topography is placed above the Canyon Range culmination (DeCelles and Coogan, 2006). Generalized exhumation magnitudes are shown by red and orange bars. LFTB—Luning-Fencemaker thrust belt, CNTB—central Nevada thrust belt, SC—Sevier culmination, CRC—Canyon Range culmination, DWC—Delamar–Wah Wah–Canyon Range, Z–Pz—Neoproterozoic–Paleozoic. (B) Schematic present-day geometry of the central Andean orogenic system (modified from Leier et al., 2010). Generalized exhumation magnitudes are shown by red and yellow bars. Pz–Mz—Paleozoic–Mesozoic.

the stratigraphic contact between preorogenic and synorogenic rocks as a datum, between the ~12-km-thick synorogenic section in the Altiplano and the ~2–3 km of exhumation below the top of the Triassic section in the Sevier hinterland, rock uplift differs by as much as 14–15 km between the interior parts of these two orogenic plateaus (Fig. 4). The second difference is that structural relief varies significantly in the interior parts of the two plateaus. The ~200-km-wide Altiplano, both at its margins and its interior, has undergone complex synorogenic deformation that has resulted in juxtaposition of preorogenic and synorogenic rocks, for a minimum structural relief of ~12 km. In contrast, the Sevier plateau exhibits an ~100–150-km-wide region of minimal (~2 km) structural relief.

The Puna plateau of northern Argentina is the southern topographic continuation of the Altiplano, and contains a thinner (as much as ~5 km) synorogenic section (Allmendinger et al., 1997). However, the Puna plateau consists of a series of basement ranges bound by high-angle reverse faults with no preferred vergence direction, with intervening Cenozoic intermontane basins (Coutand et al., 2001). This dramatic difference in structural style between the Puna and Sevier plateaus makes comparison between the two difficult.

Controls on Erosional Exhumation in the Sevier Hinterland

The lack of regionally distributed, high-magnitude (multiple kilometers of throw), surface-breaking extensional faulting prior to mid-Tertiary volcanism in the Sevier hinterland (section 5.3) indicates that erosion, not tectonic exhumation, was the primary mechanism for generating the observed exhumation patterns. Plate 3 illustrates a close spatial association of high exhumation magnitudes with the hanging walls of thrust faults, most notably the leading part of the DWC thrust sheet, and several CNTB structures. This highlights the first-order control that deformation has on exhumation patterns and suggests that erosional exhumation is a response to relief generation accompanying contractional deformation in orogenic systems (e.g., Ahnert, 1970; Willett, 1999; Willett and Brandon, 2002; Sobel and Strecker, 2003; Clark et al., 2005; Barnes et al., 2006, 2008; Garzione et al., 2006). In addition, similarity in exhumation magnitudes for ~350 km north-south within the proximal DWC hanging wall and the low-exhumation region of eastern Nevada implies that relief generation was relatively uniform along strike.

I suggest that the steep across-strike gradient in exhumation magnitude observed between the leading part of the DWC thrust sheet and the low-exhumation region of easternmost Nevada is the result of shielding of the western area from headward erosion by long-lived uplift, erosion, and eastward passive translation of the DWC thrust sheet. DeCelles and Coogan (2006) noted that erosion of the Canyon Range thrust sheet dominated the supply of synorogenic sediment through the full duration of Sevier shortening. Although motion on the Canyon Range thrust was completed in the Early Cretaceous, erosion of its hanging wall accompanied passive uplift and transport of the thrust sheet through the remaining history of Sevier shortening, by mechanisms including the growth of antiformal duplexes at depth and forward propagation of younger, frontal thrust faults (DeCelles and Coogan, 2006). This passive translation and uplift provided continued development of relief that effectively shielded the region to the west from significant erosional exhumation.

The timing and rates of erosional exhumation in the Sevier hinterland are unconstrained, and need future investigation. Establishing temporal relationships between exhumation rates and competing scenarios for the timing of surface uplift of the hinterland, including protracted Cretaceous surface uplift accompanying isostatically compensated crustal thickening in the Sevier fold-thrust belt (e.g., Coney and Harms, 1984; DeCelles and Coogan, 2006), rapid Eocene surface uplift following post-Laramide removal of dense lower lithosphere and/or the subducting Farallon slab (e.g., Platt and England, 1993; Humphreys, 1995; Sonder and Jones, 1999; Horton et al., 2004; Mix et al., 2011), and new models of Cordilleran orogenesis that predict multiple cycles of surface uplift and subsidence (DeCelles et al., 2009), would be of fundamental importance to understanding linkages between surficial and deep-seated processes in orogenic plateaus.

CONCLUSIONS

1. The Sevier hinterland can be divided into three across-strike subcrop domains: the highly eroded leading part of the DWC thrust sheet, with subcrop levels that young westward from Cambrian to Mississippian; a broad region of eastern Nevada and westernmost Utah devoid of surface-breaching thrust faults, with subcrop levels between Mississippian and Triassic; and the CNTB, which exhibits along-strike variation in subcrop levels between Neoproterozoic and Permian.

2. Synorogenic exhumation magnitudes vary between 4 and 8 km in the leading part of the DWC thrust sheet, and Paleogene structural relief is as high as 7 km. The CNTB can be divided into high-exhumation southern (4–10 km) and northern (4–6 km) segments, with an intervening low-exhumation (2 km) segment. Maximum along-strike and across-strike structural relief in the CNTB is 7–8 km. The broad, intervening region of easternmost Nevada exhibits typical exhumation magnitudes of 2–3 km, and is characterized by low (2 km) structural relief.

3. Isolated exposures of southern CNTB structures can be correlated by their subcrop and exhumation patterns into two throughgoing thrust systems, and both can be traced southward to connect with structures in the Sevier thrust belt in southern Nevada, which supports structural correlations suggested by Taylor et al. (2000). This implies a direct structural link between the CNTB and the Sevier fold-thrust belt, although available constraints on the timing of deformation do not allow for evaluation of space-time patterns of strain partitioning between these thrust systems.

4. Exhumation patterns corroborate CAI and thermochronometry data (Harris et al., 1980; Crafford, 2007; Colgan et al., 2010) that indicate that the deep structural burial and Barrovian-style metamorphism attributed to emplacement of the Windermere thrust sheet of Camilleri and Chamberlain (1997) does not continue south of the Pequop and Ruby Mountains. In addition, subcrop patterns do not reveal evidence for a surface-breaching thrust trace south of the Pequop or Ruby Mountains that would mark the southern continuation of the Windermere thrust. Thus, if the Windermere thrust model is correct, this implies rapid southward thinning of the thrust sheet, termination at a lateral structure such as a tear fault, or a transition to a blind geometry.

5. The ~2 km structural relief that characterizes much of the Sevier hinterland indicates that the majority of the high-magnitude (multiple kilometers of throw), regionally distributed, surface-breaching normal faults that dismembered the orogenic highland and produced the high structural relief observed today are post-Oligocene. The subcrop and exhumation data sets do not preclude synvolcanic and prevolcanic extension, and the traces of 70 normal faults that are overlapped by the Paleogene unconformity are identified. However, the throw on nearly all of these structures is limited to a maximum of 1–2 km. This further highlights the paradox of extensive Late Cretaceous–Paleogene exhumation of mid-crustal rocks now exposed in metamorphic core complexes without corresponding high-magnitude upper crustal extension (e.g., Hodges and Walker, 1992).

6. The older, uplifted, interior parts of the central Andean and Sevier thrust belts exhibit similar exhumation magnitudes (~4–10 km and ~5–8 km, respectively). However, an important difference between the Andean and Sevier orogenic plateaus is emphasized: the interior part of the Sevier plateau was an eroded (2–3 km exhumation) highland with low structural relief (2 km), composed of preorogenic rocks, while the interior part of the Andean plateau consists of a variably deformed and exhumed, synorogenic hinterland basin as much as 12 km thick, with very high structural relief. Thus, using the stratigraphic contact between preorogenic and synorogenic rocks as a datum, there is a difference of as much as 14–15 km in rock uplift between the interior parts of these two orogenic plateaus.

7. The spatial association of high exhumation magnitudes with the hanging walls of major thrust faults illustrates the first-order control that deformation has on exhumation patterns, and suggests that erosional exhumation is a response to relief generation accompanying contractional deformation in orogenic systems. The lack of significant along-strike exhumation variability within much of the map area implies that generation of relief was relatively uniform along strike. The high across-strike exhumation gradient between the proximal DWC hanging wall and the low-exhumation region to the west is interpreted as the result of shielding of the western area from headward erosion by long-lived uplift, erosion, and eastward passive translation of the DWC thrust sheet.

ACKNOWLEDGMENTS

I thank Chris Henry for helpful discussions that led to many of the ideas presented in this paper, and Andrew Hanson and Eric Christiansen for thoughtful reviews that greatly improved the manuscript.

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