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Load-induced subsidence of the Ancestral Rocky Mountains recorded by preservation of Permian landscapes

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ABSTRACT

The Ancestral Rocky Mountains (ARM) formed a system of highlands and adjacent basins that developed during Pennsylvanian–earliest Permian deformation of interior western North America. The cause of this intracratonic deformation remains debated, although many have linked it to far-field compression associated with the Carboniferous–Permian Ouachita-Marathon orogeny of southern North America. The ultimate disappearance of the ARM uplifts has long been attributed to erosional beveling presumed to have prevailed into the Triassic–Jurassic. New observations, however, indicate an abrupt and unusual termination for the largest of the ARM uplifts. Field evidence from paleohighlands in the central ARM of Oklahoma and Colorado indicates that Lower Permian strata onlap Pennsylvanian-aged faults and bury as much as 1000 m of relief atop the paleohighlands. In parts of Oklahoma and Colorado, late Cenozoic partial exhumation of these paleo-highlands has revealed landscapes dating from Permian time. These relationships suggest cessation of uplift followed by active subidence of a broad region that encompassed both basins and uplifted crustal blocks and that commenced in Early Permian time, directly following the Pennsylvanian tectonic apogee of the ARM. Independent from these geological observations, geophysical data reveal a regional-scale mafic load underpinning these paleohighlands, emplaced during Cambrian rifting associated with the southern Oklahoma aulacogen. Geophysical modeling of the effects of such a load in the presence of a horizontal stress field, such that implyed by ARM orogenesis, indicates that the amplitude of flexurally supported features is modulated nonlinearly. This leads to buckling and thrust formation with the application of sufficient compressive stress, and subsidence of topography formed by buckling upon relaxation of the high compressional stresses. We therefore infer that the core ARM highlands subsided owing to the presence of a high-density upper crustal root, and that this subsidence began in the Early Permian owing to relaxation of the in-plane compressional stresses that had accompanied the last phase of the Ouachita-Marathon orogeny of southern and southwestern Laurentia. Our results highlight the importance of tectonic inheritance in intra-plate orogenesis and epeirogenesis, including its potential role in hastening the reduction of regional elevation, and enabling the ultimate preservation of paleolands. 

INTRODUCTION

The Pennsylvanian–Permian Ancestral Rocky Mountains (ARM) of the west-central U.S. (Fig. 1) formed a collection of largely crystalline basement-cored highlands that shed debris into adjacent basins in western equatorial Pangea far from any recognized plate boundary (e.g., Kluth and Coney, 1981; Kluth, 1986). The term “Ancestral Rockies” arose nearly a century ago, in recognition of the thick, coarse-grained strata that wedge toward Precambrian basement regions of the modern Rockies (Lee, 1918; Melton, 1925). Many of these paleo-highlands are bounded by high-angle, Pennsylvanian-aged faults reflecting significant (several kilometer) dip-slip offset, as well as lateral displacements (e.g., McConnell, 1989; Thomas, 2007; Keller and Stephenson, 2007). The core ARM uplifts are characterized by large structural displacements and thick (≥2 km), proximally conglomeratic mantles, and extend beyond the immediate Rocky Mountains region into Oklahoma (Fig. 2). Here, ARM structures coincide spatially with much older structures linked to the Precambrian–Cambrian rifting of the Rodinian supercontinent (Ham et al., 1964; Perry, 1989; Fig. 3).

The ARM form a classic example of intra-plate orogeny and remain enigmatic, although several authors have linked the orogenesis to far-field effects of the Marathon-Ouachita convergent margin (e.g., Kluth and Coney, 1981; Kluth, 1986; Algeo, 1992; Dickinson and Lawton, 2003). New data and reanalysis of existing data indicate that even the termination of the ARM orogeny is enigmatic. It has been long accepted that the ARM highlands continued to rise from middle Pennsylvanian through at least Early Permian time, and that subsequent erosional beveling associated with isostatic adjustment over tens of millions of years ultimately obliterated the mountains by Triassic–Jurassic time (e.g., Lee, 1918; Mallory, 1972; Blakey, 2008); however, we present new observations of significant preserved paleorelief on top of ARM uplifts that challenge this view. This paleorelief preservation is remarkable because it archives landscapes of great antiquity, and appears to record subsidence of highland and adjacent regions not previously recognized. Here we combine geologic mapping, stratigraphic, petrologic, structural, and geophysical data from some of the largest-magnitude ARM highlands and intervening regions to document an episode of widespread subsidence that followed the tectonic apogee of the ARM orogeny. We then integrate these observations with documentation of a high-density crustal load underpinning the core ARM, and model the possible effects of this load in light of the changing stress fields associated with ARM orogenesis. Our analysis indicates that tectonic inheritance such as ancient mass loads in the crust or lithosphere should be considered as a previously unrecognized means to hasten the demise of orogenic highlands.

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Figure 1. A schematic view of the Pennsylvanian–Permian Ancestral Rocky Mountains (ARM) system, highlighting locations noted in text (modified from G. Soreghan et al., 2008). Black rectangles denote areas shown in detail in Figures 4 and 7. ARM uplifts coded as major are those marked by >1000 m of adjacent Pennsylvanian strata (see Fig. 2). Inset at top depicts deformed late Pennsylvanian (syntectonic) and onlapping Early Permian (post-tectonic) stratigraphic relations in the ancestral Uncompahgre, Front Range–Apishapa, and Wichita uplifts; the thick horizontal line schematically depicts the transition between syntectonic and post-tectonic strata (sources: data in Fig. 2 and DeVoto, 1980; Hoy and Ridgway, 2002; Sweet and Soreghan, 2010). Stratal names are shown for both the eastern (E) and western (W) regions of the Uncompahgre uplift. Other abbreviations denote outcrop areas of the Fountain Formation (FF) and Sangre de Cristo Formation (SC), and the subsurface location of Bravo Dome (BD), regions also mentioned in the text and figures. U/CF—Uncompahgre and Crestone faults, UPF—ancestral Ute Pass fault, MVF—Mountain View fault.

GEOLOGIC SETTING: EARLY AND LATE PALEozoIC GEOLOGIC EVENTS OF THE NORTH AMERICAN MIDCONTINENT

Major tectonic events that affected the North American midcontinent through Phanerozoic time include early Paleozoic (Early Cambrian) rifting associated with the breakup of the Rodinian supercontinent, and late Paleozoic (Pennsylvanian–Permian) compression associated with the assembly of the Pangean supercontinent (references following). Although the latter event forms the focus of this paper, the early Paleozoic events imparted a tectonic fabric that possibly influenced later deformation.

Early Paleozoic Southern Oklahoma Aulacogen

A series of igneous rocks and associated crustal-scale structures extending at least through Oklahoma and the Texas panhandle mark the trend of the so-called southern Oklahoma aulacogen (SOA) (e.g., Shatski, 1946; Hoffman et al., 1974; Kruger and Keller, 1986; Perry, 1989; Keller and Stephenson, 2007; Fig. 3). The SOA is a classic example of an intracontinental failed rift that was later tectonically inverted, and geologic studies indicate that a combination of thrusting and lateral movements occurred during its formation (e.g., Ham et al., 1964; Brewer et al., 1983; Thomas, 2011). Knowledge of the Cambrian extension is based on many studies of the bimodal igneous rocks exposed in the Wichita uplift of Oklahoma (summarized in Gilbert, 1983), regional relationships (Keller et al., 1983), and postrift subsidence (Hoffman et al., 1974). Cambrian igneous activity resulted in intrusion of a voluminous gabbror complex (Glen Mountains Layered Complex) and associated shallow intrusives (Hogan and Gilbert, 1997). As much as 40,000 km³ of metaluminous silicic magmas were generated ca. 530 Ma, producing the Carlton Rhyolite Group (and intrusive Wichita Granite Group; Ham et al., 1964). This assemblage of Lower Cambrian granite, rhyolite, and gabbro forms the basement of southwestern Oklahoma and the Texas panhandle (Fig. 3). Notably, Larson et al. (1985) suggested that the SOA extended to the Uncompahgre uplift region of Colorado on the basis of distributed, but limited, Cambrian mafic intrusives. Recent geophysical studies corroborate this inference (e.g., Smith, 2002; Casillas, 2004; Rumpel et al., 2005; Keller and Stephenson, 2007; Pardo, 2009; details in the following).

Extensive petroleum exploration of the southern Oklahoma region provides good constraints on the postrift thermal subsidence history, which includes ~3 km of predominantly Ordovician carbonate strata preserved in uplifted blocks and within the axis of the proto-Anadarko basin (Johnson et al., 1988). Following thermal subsidence and associated Ordovician sedimentation in the wake of Cambrian rifting, subsidence within the SOA region and greater interior North America slowed considerably. In southern Oklahoma, a relatively thin Silurian–lower Mississippian carbonate and shale section records this interval of tectonic quiescence (Feinstein, 1981). This period was followed by a Mississippian–Pennsylvanian subsidence event heralding the beginning of the present Anadarko basin and accompanying the Ouachita orogeny (Garner and Turcotte, 1984; Arbenn, 1989).

Late Paleozoic Ancestral Rocky Mountains

By latest Mississippian and Pennsylvanian time, the Ancestral Rocky Mountains orogeny commenced, as recorded by uplift of various highlands and major subsidence and sediment accumulation within highland-adjacent basins (e.g., Kluth and Coney, 1981; Kluth, 1986). The core ARM uplifts exhibiting the largest-magnitude fault displacements across basin-bounding faults, and thickest mantles of locally derived, coarse-grained conglomerate, occur in Colorado and Oklahoma, most notably in the Wichita–Anadarko and Uncompahgre-Paradox systems (Figs. 1 and 2).

Within southern Oklahoma, the Wichita uplift–Anadarko basin system formed as a result of late Mississippian–Pennsylvanian ARM compression that inverted the failed Cambrian rift (Larson et al., 1985; Gilbert, 1992). The inversion structures are unusually large, with at least 12 km of vertical separation between the Cambrian basement exposed in the Wichita Mountains and that present in the subsurface of the adjacent Anadarko basin (Perry, 1989; Keller and Stephenson, 2007). This 12 km displacement results from the dual-phase history of the SOA- Anadarko system, wherein the basin contains 4–5 km of rift-related lower Paleozoic section and an additional 7 km attributable to flexurally induced subsidence related to Mississippian–Pennsylvanian compressional deformation.
during the ARM orogeny (Johnson, 1989; Perry, 1989). The length of the SOA (~1500 km; Keller and Stephenson, 2007) approximates that of the Main Ethiopia and Kenya rifts combined, and the signature transects the prevailing northeast-southwest grain of the Mesoproterozoic basement of North America (Karlstrom and Bowring, 1998). Pennsylvanian strata are not well exposed in this region, but intense petroleum exploration has revealed the presence of thick uplift-adjacent conglomeratic units (e.g., Tomlinson and McBee, 1959; Dutton, 1982; Fig. 2). For example, the so-called Granite Wash within the subsurface along the Frontal fault zone (i.e., basinward of the Wichita uplift) of Oklahoma and the Texas panhandle reaches thicknesses of 2–3 km and exhibits a well-known reverse stratigraphy representing the active unroofing of the Wichita uplift during Pennsylvanian time (Edwards, 1959; Johnson et al., 1988). Minimal post-Paleozoic deformation in the craton region of the southern mid-continent has enabled nearly pristine preservation of this system. Therefore, the Anadarko basin area archives a complete record of early Paleozoic extensional to late Paleozoic compressional deformation.

Similar relationships exist in Colorado. ARM tectonism resulted in as much as 8 km of vertical displacement documented from drilling and seismic data bordering the Uncompahgre uplift (Frahme and Vaughn, 1983; White and Jacobson, 1983). Adjacent basins such as the Paradox basin accumulated several kilometers of syntectonic carbonate-clastic strata, and thick conglomeratic aprons mantling several uplifts (Mallory, 1972; DeVoto, 1980).

Judging by sedimentation rates and structural-biostratigraphic data, deformation that produced the Ancestral Rocky Mountains peaked in middle Pennsylvanian to earliest Permian time, albeit with some spatial variation, such as Permian ages of deformation in the Marathon region of Ozark Dome.

Figure 2. Isopach map showing preserved Pennsylvanian strata of the region shown in Figure 1. ARM—Ancestral Rocky Mountains. Note the large (>1000 m) thicknesses of Pennsylvanian strata adjacent to the Uncompahgre, Front Range–Apishapa, and Wichita uplifts (WU; see Fig. 1). Bold black lines are faults. Modified from McKee and Crosby (1975).
Figure 3. Regional tectonic index map of southern Laurentia showing features of interest in this study. Proterozoic terranes (Yavapai-Mazatzal Province, EGR—Eastern granite-rhyolite province; SGR—Southern granite-rhyolite province). Proterozoic rifts and mafic intrusives in green (MCR—Midcontinent Rift System; PMIC—Pecos mafic intrusive complex, underlain by the Central Basin Platform, an Ancestral Rocky Mountains [ARM] uplift; FM—Franklin Mountains outcrops). AGM—Abilene gravity minimum (ca. 1.4 Ga?). Cambrian rifts in magenta. ARM features: UU—Uncompahgre uplift; SU—Sierra Grande uplift; WU—Wichita uplift. WM—Wet Mountains. The approximate location of the Ouachita thrust front and the early Paleozoic continental margin are denoted by the orange and green dashed lines, respectively (from Keller and Stephenson, 2007; modified from Barnes et al., 1999). Inset at left shows a simplified crustal density model across the Wichita-Anadarko system (line A–A′; see Fig. 10 for a more detailed version of the central portion of this cross section; numbers are densities in kg/m³ × 10⁻³; modified from Keller and Stephenson, 2007).
Permian Onlap in the Uncompahgre Uplift, Colorado

In contrast to the minimally disturbed record of Permian burial in Oklahoma, the ARM paleo-uplifts of Colorado exhibit a complex history affected by Mesozoic burial, reactivation of uplifts during Cretaceous–Paleogene (Laramide) tectonism, and significant Neogene exhumation associated with landscape evolution and climate change in the Cenozoic Rocky Mountains (Eaton, 2008). Of the Colorado ARM uplifts, however, the Uncompahgre system of western Colorado is comparatively well preserved, with a carapace of relatively undeformed Mesozoic strata (Williams, 1964). This perhaps reflects its location within the larger Colorado Plateau, which was relatively undisturbed by Laramide tectonism (Marshak et al., 2000). The (ancient) Uncompahgre uplift was a large northwest-southeast–trending feature that formed during the ARM orogeny and was separated from the adjacent Paradox basin to the southwest by a seismically imaged subsurface reverse fault system that exhibits as much as 8 km of up-to-the-northeast vertical displacement (Fig. 1; Frahme and Vaughn, 1983; White and Jacobson, 1983; Trudgill and Paz, 2009). The modern Uncompahgre Plateau composes only a part of the ancient highland and consists of a Precambrian basement core mantled by Mesozoic strata, except where breached by Unaweep Canyon, a large gorge in the southwestern plateau (Fig. 7) that exposes the Precambrian crystalline core.
Figure 4. Map, cross section, and photo illustrating regional structure and burial of paleorelief and faults by Lower Permian strata in the Wichita Mountains, Oklahoma (map and cross section modified from Ham et al., 1964). Cross section (profile A–A') extends across the center and north side of the Wichita uplift. FFZ—Frontal fault zone (includes Mountain View fault), MF—Meers fault, BCCF—Blue Creek Canyon fault. The Frontal fault zone separates the Anadarko basin and the uplift, and is buried by Permian strata (seismically imaged in Fig. 5). Photo shows partially emergent paleolandforms in the western Wichita Mountains, where Cambrian igneous basement (unfaulted) protrudes through, and is onlapped by Permian strata.
of the plateau. Clastic detritus eroded from the highland during Carboniferous–Permian tectonism accumulated in the adjacent Paradox basin to form the Cutler Formation (Wengerd, 1962; Mallory, 1972; Campbell, 1980; Mack and Rasmussen, 1984; Condon, 1997; Dubiel et al., 2009; Soreghan et al., 2009a).

The contact between the Cutler Formation and Precambrian basement along the south-western front of the modern Uncompahgre Plateau is well exposed near Gateway, Colorado (Fig. 7). In this location, Cater (1955) mapped the contact as a depositional onlap; Frahme and Vaughn’s (1983) analysis of seismic data to the northwest revealed a zone of reverse faults in the subsurface. Recent detailed mapping (Moore et al., 2008; Eccles et al., 2010; Fig. 7) confirms Cater’s (1955) depiction of a Permian (Cutler) onlap contact, and expands the recognized extent of the onlap onto Precambrian basement. Furthermore, these mapping results indicate little deformation during the time recorded by the Cutler Formation now exposed at the surface, a point also emphasized by Cater (1970). These relationships indicate that motion on the subsurface Uncompahgre fault largely ceased before deposition of the youngest (Permian) Cutler strata, as Cater (1970) originally suggested.

At this location, the post-tectonic Permian Cutler Formation buries ~520 m of paleorelief on Precambrian basement, observable in outcrop as documented on published maps (Cater, 1955; Moore et al., 2008; Eccles et al., 2010; Fig. 7) confirms Cater’s (1955) depiction of a Permian (Cutler) onlap contact, and expands the recognized extent of the onlap onto Precambrian basement. Furthermore, these mapping results indicate little deformation during the time recorded by the Cutler Formation now exposed at the surface, a point also emphasized by Cater (1970). These relationships indicate that motion on the subsurface Uncompahgre fault largely ceased before deposition of the youngest (Permian) Cutler strata, as Cater (1970) originally suggested.

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At this location, the post-tectonic Permian Cutler Formation buries ~520 m of paleorelief on Precambrian basement, observable in outcrop as documented on published maps (Cater, 1955; Moore et al., 2008; Eccles et al., 2010; Fig. 7). Furthermore, the Cutler Formation here projects into Unaweep Canyon, a hypothesized exhumed landscape with remnant Pennsylvanian–Permian fill (Soreghan et al., 2007, 2009b). The age of the canyon fill is inferred from the combined evidence for its
exclusively Precambrian provenance, Pennsylvanian–Permian palynomorph content, and shallow (late Paleozoic) paleomagnetic inclinations (detailed in Soreghan et al., 2007, 2009b). A pre-Mesozoic age for the Precambrian (inner) gorge of Unaweep Canyon is also inferred from geomorphologic relationships wherein Mesozoic strata crosscut tributary valleys carved in Precambrian basement (Soreghan et al., 2007), analogous to the crosscutting relationships noted for the Wichita Mountains. Acceptance of the antiquity of Unaweep Canyon implies the preservation of at least 970 m of paleorelief, as measured between the Precambrian–Mesozoic nonconformity contact on top of the Uncompahgre Plateau and the nonconformity contact between the inferred Pennsylvanian–Permian canyon fill and Precambrian basement encountered in a corehole in the base of the canyon (Fig. 7).

The onlap of the uppermost (exposed) Permian Cutler Formation onto Precambrian basement of the (paleo) Uncompahgre uplift records Permian burial of the Uncompahgre highland. Cater (1970, p. 68) first reached this conclusion, noting, “After the [Uncompahgre] highland attained its maximum height and while the Cutler was being deposited, the highland began sinking—at least along its southwest flank” (brackets are ours). The inferred Pennsylvanian–Permian age of Unaweep Canyon is consistent with this conclusion, and increases the recognized magnitude of the onlap, from ≥500 m to nearly 1000 m.

Passive post-tectonic erosional bevelling of the highland was once thought to have produced the depositional onlap along the margin of the uplift. However, the burial extends on top of the paleo-uplift, well beyond the flanking regions, indicating that the highland must have been buried by at least 970 m of sediment to preserve the observed paleorelief. Accumulation of this stratal thickness on top of the highland and its paleorelief in the absence of subsidence is difficult to conceive for the active margin of a compressional orogen. The observations suggest that the highland subsided, and the onlapping Permian strata record burial of the uplift and of the fault along which the highland had been uplifted. That is, the uplift and surrounding regions underwent subsidence together. The thickness of the proximally exposed Cutler Formation, 965 m as indicated by the sequential measured sections of the Cutler Formation in its most proximal location against the uplift (Soreghan et al., 2009a), provides a minimum amount of subsidence on the Uncompahgre highland, and closely approximates the 970 m of preserved paleorelief within Unaweep Canyon. The inference of subsidence of the Uncompahgre uplift is also consistent with Cater’s (1970) observation that well data near the Gateway area show >2000 m of Cutler strata on top of Precambrian basement, and thus subsidence of the upthrown block.

These data indicate that the paleocanyon was backfilled by the end of deposition of the uppermost Cutler Formation in Early Permian time. The Triassic Moenikop Formation between the Permian Cutler and Triassic Chinele units in the proximal Paradox basin thins to almost nothing toward the highland with a slight angular (<5°) unconformity between the Cutler and Moenkopi units (Cater, 1955). These relationships could reflect gradual erosional bevelling of a highland that persisted to Triassic time; however, any such bevelling should have produced a coarse clastic apron, yet no known strata exist that record this later (post-Cutler) history. Rather, the coarse-grained, locally derived conglomeratic aprons persist only into earliest Permian time. Alternatively, these relationships could reflect reduction (via subsidence) of the highland to a low-elevation surface, against which the Moenikop Formation onlapped, and the ultimate disappearance of the uplift as a significant eroding source by middle Permian time. Taken together, the geologic relationships are most consistent with the interpretation that the proximal Cutler Formation records cessation of ARM uplift in the region, followed by ~1 km of subsidence of the greater region, encompassing both the proximal Paradox basin and the adjacent Uncompahgre highland.

PERMIAN ONLAP AND PROVENANCE RELATIONSHIPS IN THE GREATER ARM REGION

Structural relationships analogous to those documented for the Uncompahgre and Wichita systems also exist in the intervening ARM regions (Fig. 1). In southern Colorado, Pennsylvanian–Permian strata bury ARM faults and adjacent basement by 800–1000 m (DeVoto, 1980; Hoy and Ridgway, 2002). Farther to the north, 315 m of the (Lower Permian) upper Fountain Formation record sedimentologic, structural, and stratigraphic relationships that indicate that these strata postdate movement of the local basin-bounding fault, thus requiring a regional mechanism for accommodation (Sweet and Soreghan, 2010; Fig 1). Postorogenetic burial of the piedmont of an orogen (e.g., Tertiary strata of the modern Front Range) can simply reflect strong erosion in the hinterland. However, preservation of substantial paleorelief in the hinterland, rather than piedmont, of both the Wichita and Uncompahgre systems precludes an explanation linked to denudation of the highland. Rather, the relationships documented here demonstrate Permian burial extending across the ARM highlands and recording ~1 km of accommodation space (conservatively ignoring compaction effects). This implies that uplift of the mountains in this compressional orogen ceased, and the core highlands, even beyond faulted flanking regions, underwent subsidence beginning in Early Permian time.

Figure 7 (on following page). Map and cross-section data illustrating regional structure and burial of paleorelief and faults by Permian strata in the Uncompahgre uplift (Colorado, CO) (see Fig. 1 for additional location information). AZ—Arizona; NM—New Mexico; UT—Utah. (A) Simplified geologic map (inset) and digital elevation model of a part of the Uncompahgre Plateau (CO), focused on Unaweep Canyon; inset (lower right) on the geologic map shows the regional location on the Colorado and Uncompahgre Plateaus, and location of the cross-section X′–X′ (detailed in B). The Pennsylvanian–Permian Cutler Formation (blue) onlaps Precambrian basement of Unaweep Canyon and projects into the canyon. Geologic map data from Cater (1955), Moore et al. (2008), Eccles et al. (2010), and G. Soreghan (our data). (B) Subsurface profile across the Uncompahgre front in Utah (along cross-section X′–X′ in A), showing Permian onlap onto Precambrian basement (modified from Moore et al., 2008). SL—sea level. (C) Transverse cross section across Unaweep Canyon, showing the paleorelief on the nonconformity surface. (See text for detailed discussion.) (D) Detailed geologic map of the area shown in box in A. This map highlights the onlap relationship of the Permian Cutler Formation onto the Permian paleorelief of the Precambrian basement, originally documented by Cater (1955). The minimum amount of paleorelief buried here, observable in outcrop, is 370 m, measured between the highest elevations of the Cutler outlier and the lowest elevation of the Precambrian onlap contact. However, these contacts are separated by a fault estimated (from Cater, 1955) to exhibit ~115–150 m of (down-to-the-north) offset. Palinspastically restoring this offset increases the observed paleorelief here to ~520 m. Note that this is a minimum, because this onlap relationship continues for an unknown extent into the subsurface. U—upthrown; D—downthrown.
Provenance data for Pennsylvanian–Permian strata flanking many ARM uplifts shed additional light on the timing of active uplift and erosion. For example, the well-documented Pennsylvanian–Lower Permian conglomeratic strata that mantle many of the core ARM uplifts of Colorado and Oklahoma are the hallmarks of ARM tectonism, cited for nearly a century as the basis for recognition of the ARM system (e.g., Lee, 1918; Melton, 1925). However, these conglomeratic units, which record local highland erosion, persist only into the Lower Permian section. Their subsequent disappearance aligns with detrital zircon provenance results from sandstone and siltstone of the greater region. If the ARM uplifts persisted as significant sediment sources into Triassic–Jurassic time, then Mesozoic strata in ARM-proximal regions should exhibit a significant provenance signature reflecting an ARM source, but they do not (Dickinson and Gehrels, 2009, 2010). Rather, these Mesozoic strata reflect a dominant source from eastern Laurentia (e.g., Grenville basement exposed in the Appalachian-Ouachita system), and lack a significant signature from the crystalline basement (either the Yavapai-Mazatzal or Wichita provinces) coring the ARM uplifts, excepting a minor and inferred recycled population (Dickinson and Gehrels, 2009, 2010). Gehrels et al. (2011) documented this provenance shift in Paleozoic strata of the Grand Canyon, which exhibit an evolution from a significant ARM source in the Pennsylvania–earliest Permian to an Appalachian-Ouachita source in the later Permian. This shift is also captured in Lower Permian siltstone units of New Mexico and Oklahoma (M. Soreghan et al., 2002, 2008; Templet and Soreghan, 2010; Fig. 8).

The age and provenance of the continental strata onlapping the ARM faults and burying the hinterland paleorelief provide approximate constraints on the timing of subsidence. As illustrated in Figures 4–7, faulting ceased in the late Pennsylvanian and post-tectonic onlap began by Early Permian time. Furthermore, structural restoration of the Paradox basin fill indicates that, for the Uncompahgre front, faulting had largely ceased and onlap initiated in earliest Permian time (between 293 and 284 Ma according to Trudgill and Paz, 2009). More accurate constraints on timing await higher resolution dating of these continental units.

GEOPHYSICAL EVIDENCE FOR A CRUSTAL LOAD BELOW THE CORE ARM

Gravity data provide a clear picture of the extent of the SOA and the impressive mafic magmatism associated with the Cambrian rift-

![Figure 8. Schematic provenance relations in the Paradox and Anadarko basins, and intervening Bravo Dome area (see Fig. 1 for general locations). Dark blue denotes synorogenic strata, light blue denotes postorogenic onlap; the color gradation between these depicts the provisional nature of the age control. Fine stippled pattern signifies generally fine-grained (mudstone to sandstone) redbed units; conglomeratic pattern denotes coarse clastic wedges along active basin margins. Dark brown denotes proximal Ancestral Rocky Mountains (ARM) sources, whereas light brown bars denote regional sources, as inferred from published detrital zircon data. Sources for provenance data: Paradox basin—M. Soreghan et al. (2002), Dickinson and Gehrels (2003); Bravo Dome region—M. Soreghan et al. (2008); Anadarko basin—Giles et al. (2009), Templet and Soreghan (2010).](image-url)

First we define the effective elastic thickness ($T_e$) of the lithosphere as
Figure 9. Residual gravity anomaly map calculated by subtracting a regional gravity field from the complete Bouguer anomaly values. The regional field was calculated by continuing upward (20 km) the complete (terrain corrected) Bouguer anomaly values. The yellow line is the location of the integrated geophysical model shown in Figure 10, and the central portion of this line is the location of the seismic section shown in Figure 5. Abbreviations for tectonic elements: UU—Uncompahgre uplift, WU—Wichita-Amarillo uplift, AU—Arbuckle uplift, WM—Wet Mountains, CBP—Central basin platform, AB—Arkoma basin, MCR—Midcontinent Rift, RGR—Rio Grande Rift, SU—Sierra Grande uplift, AGM—Abilene gravity minimum, OIZ—Ouachita orogenic belt interior zone that marks the Cambrian margin of Laurentia.

\[ T_{\text{eff}} = h \left[ \frac{12D(1 - v^2)}{E} \right]^{1/2}, \]  
\[ D = \frac{Eh^3}{12(1 - v^2)}, \]  
\[ \frac{d^2w}{dx^2} = q_e(x) - (\rho_m - \rho_a)gw(x) - P \frac{d^2w}{dx^2}, \]  

where \( h \) is elastic thickness (in m), \( E \) is Young’s modulus (in Pa), \( v \) is Poisson’s ratio, and \( D \) is flexural rigidity (in Nm).

With these definitions, the governing equation for two-dimensional cylindrical flexure is

\[ D \frac{d^2w}{dx^2} = q_e(x) - (\rho_m - \rho_a) gw(x) - P \frac{d^2w}{dx^2}, \]  

where \( w \) is vertical displacement (flexure, in m), \( g \) is gravitational acceleration (in m/s²), \( x \) is horizontal ordinate (in m), \( q_e \) is applied external load (in N/m), \( \rho_m \) and \( \rho_a \) are mantle and infill density in (kg/m³), and \( P \) is horizontal (in plane) force in (N).

Initially, we set \( P = 0 \) and later examined the effect of varying values of \( P \). Appropriate values of mid-continental stress are difficult to establish. Large-scale patterns are sometimes quite clear, but second- and third-order patterns may depend on local geologic histories and density heterogeneities (Coblentz and Richardson, 1995; Heidbach et al., 2007). In the region of the SOA, the World Stress Map database release 2008 (Heidbach et al., 2008) shows a variety of directions of the horizontal maximum stress \( S_h \), but they are dominantly perpendicular to the main structure in the vicinity of the Anadarko basin. A smoothed stress field (Heidbach et al., 2010) shows a similar northward trend near 34°N, 95°W, but more eastward trends north and south of that location. The implication of these observations is that the present-day stress field in the central SOA is roughly isotropic and only weakly affected by the Cambrian and Pennsylvanian structures underneath, and an in-plane stress value \( P \approx 0 \) is appropriate for the present-day situation.

With a further definition of the flexural parameter

\[ \alpha = \left[ \frac{4D}{(\rho_m - \rho_a) g} \right]^{1/2}, \]  

an unbroken elastic plate will behave as

\[ w(x) = w_0 e^{-\gamma x} \left[ \cos \frac{x}{\alpha} + \sin \frac{x}{\alpha} \right], \]  

and

\[ w_0 = \frac{V_e \alpha}{8D}. \]  

where

with \( V_e = q_e \) from Equation 3.

In Figure 10 we used seismic, gravity, and density data to calculate the load placed on the SOA area by the excess mass of the mafic Cambrian rift structure rocks. We can now calculate the amount of lithospheric flexure that should result from application of Equations 5 and 6, varying the elastic thickness from 10 to 30 km. Although the mass excess may seem large, the narrowness of the mass anomaly results in very modest amounts of Moho deflection. The high peak amplitude of the load (consistent with the ~100 mGal gravity anomaly) combined with its narrowness produces a peak Moho deflection of ~1.4 and 0.6 km at effective elastic thicknesses of 10 and 30 km, respectively. In practice, this amount of deflection is barely detectable by seismic means. A similar gravity anomaly is observed in the Uncompahgre uplift region, but the amount of subsidence is smaller than that in the Wichita uplift region; this is consistent with the smaller modeled mafic core of the Uncompahgre region, and its more distal location relative to the southeastern part of the SOA.
\[
F_i = \left[ \frac{Eh^2 g(\rho_m - \rho_m)}{3(1 - \nu^2)} \right]^{1/2} \text{ as } \beta \to 0, \quad (10)
\]

which occurs at a wavelength \( \lambda_c \) of

\[
\lambda_c = \left[ \frac{2Eh^2 g(\rho_m - \rho_m)}{12(1 - \nu^2) g(\rho_m - \rho_m)} \right]^{1/4}. \quad (11)
\]

Thus, the result of changing in-plane stresses is that the amplitude of flexurally supported features is modulated in a nonlinear fashion, leading to buckling and thrust formation with sufficient compressive stress, and subsidence of topography formed by buckling upon relaxation of the high compressional stresses. The relaxation need not proceed as far as deviatoric tension, because most of the flexural relaxation occurs within the compressional field (Fig. 11).

**DISCUSSION: WHY DID THE ANCESTRAL ROCKY MOUNTAINS STOP RISING?**

The disappearance of highland elevation in the core ARM, as recorded by preservation of Permian landscapes on top of the paleo-highlands, records cessation of uplift, followed by significant subsidence over a broad region. Mechanisms possibly capable of inducing such vertical motion include orogenic collapse, negative dynamic topography, or the influence of horizontal stresses. Any mechanism invoked to explain such motion must account for the significant vertical and areal extent of the subsidence, and the geologically abrupt onset following the apogee of ARM tectonism. Orogenic collapse is well recognized as an important process in the evolution of mountain belts (Dewey, 1988; Menard and Molnar, 1988; Rey et al., 2001; Dilek, 2006). Orogenic collapse, however, implies a large orogen with thick crust, usually accompanied by partial melting to weaken the thick crust, and typically postdates thickening by many millions of years. Such collapse involves gravity-driven flow that counteracts crustal thickening, reducing lateral contrasts in gravitational potential energy, and is commonly associated with extensional structures in the thickened crust and shortening in the foreland (see preceding references). These attributes do not occur in the ARM system, calling into question any role of orogenic collapse as traditionally defined.

Dynamic topography refers to elevation differences caused by mantle flow, and has been invoked to explain large-scale continental flooding and exposure (Gurnis, 1993; Lithgow-Bertelloni and Gurnis, 1997). Uplift and subsidence of large continental areas resulting from dynamic topography relate to mantle flow linked to the initiation and cessation of subduction. The potential appeal of dynamic topography for the ARM system derives from the presumed importance of the Ouachita-Marathon subduction system in ARM orogenesis; however, the system records southward-dipping subduction (Viele and Thomas, 1989; Loomis et al., 1994; Dickinson and Lawton, 2003; Poole et al., 2005), such that any potential influence of dynamic topography should have affected the Gondwanan, rather than the Laurentian, plate.

In-plane stress acting on an inhomogeneous crust provides an additional mechanism to explain large areas of vertical motion of the crust, including modulation of sedimentary basin formation (Cloetingh, 1988; Cloetingh and Kooi, 1992; Heine et al., 2008). The mechanism...
although landforms dating from the Mesozoic and even Paleozoic are increasingly well recognized (Tiwade, 1998), especially from the Gondwana continents. We hypothesize that Early Permian landscapes from the upland Uncompahgre and Wichita systems were preserved as a result of active regional subsidence in Early Permian time that affected both the uplifts and surrounding regions. Exhumation of these landscapes occurred in the Cenozoic, associated with Laramide and more recent orogenesis and auxiliary drainage evolution in Colorado, and the distal effects of the Rio Grande Rift that extended to Oklahoma (Eaton, 2008). Our hypothesis predicts that Lower Permian postorogenic strata should thicken toward the core ARM highlands, along a trend perpendicular to that of the gravity anomaly and inferred mass load.

CONCLUSIONS

Geologic data from the core ARM system, both long known and newly documented, indicate preservation of Early Permian landscapes that exhibit paleorelief of as much as 1000 m, and record subsidence extending over a length scale of nearly 1500 km. In addition, geophysical data buttressed by geological data reveal a regional-scale mafic load underpinning these same regions. The correspondence of the gravity data with direct observation of high-density Cambrian mafic intrusives from the Wichita Mountains (Oklahoma) and Wet Mountains (Colorado) indicates that this signal relates to the formation of the early Paleozoic SOA. Geodynamic modeling of the effects of such a load in the presence of a horizontal stress field, such as that implicated in Pennsylvania–Permian ARM orogenesis, indicates that the amplitude of flexurally supported features is modulated nonlinearly. This leads to buckling and thrust formation with the application of sufficient compressive stress, and subsidence of topography formed by buckling upon relaxation of the high compressional stresses. We use these results to suggest that the core highlands of the Ancestral Rocky Mountains, uplifted in Pennsylvania time, ceased to rise and ultimately succumbed to load-induced subsidence in Early Permian time, spatially associated with high-density bodies in the upper crust. Unlike orogenic collapse, this phenomenon formed unassociated with any significant upper crustal structural or magmatic activity. Like orogenic collapse, however, this subsidence likely reflects readjustment of horizontal stresses. Dickinson and Lawton (2003) hypothesized that the termination of ARM deformation was related to stress release associated with closure of the Marathon segment of the Ouachita orogenic belt. We hypothesize that this shift in the regional stress field and associated cessation of northeast-oriented compressive stresses (Cloetingh and Kooi, 1992; Cloetingh, 1988) precipitated the geologically abrupt reversal from orogenic uplift to epeirogenic subsidence tied to the existence of an upper crustal mafic load, as documented in our data set and modeling. These results underscore the roles of inheritance and crustal inhomogeneity in erecting and ultimately eradicating a classically enigmatic intraplate orogenic system.

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