Geosphere

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Geosphere 2012;8;654-668
doi: 10.1130/GES00681.1

Notes

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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 paleohighlands has revealed landscapes dating from Permian time. These relationships suggest cessation of uplift followed by active subsidence 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 as that implied 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 intraplate orogenesis and epeirogenesis, including its potential role in hastening the reduction of regional elevation, and enabling the ultimate preservation of paleolandscapes.

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 paleohighlands 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 intraplate 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.

Geosphere; June 2012; v. 8; no. 3; p. 654–668; doi: 10.1130/GES00681.1; 11 figures; 1 supplemental file.

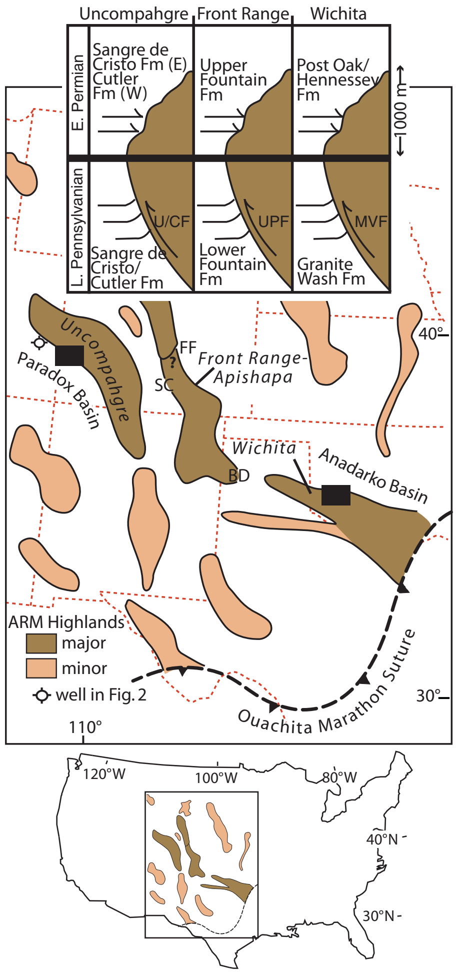


Figure 1. A schematic view of the Pennsylvanian–Permian Ancestral Rocky Mountains (ARM) system, highlighting locations noted in text (modified from G. Soreghan et al., 2008). Black rectangles denote areas shown in detail in Figures 4 and 7. ARM uplifts coded as major are those marked by >1000 m of adjacent 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 gabbroic complex (Glen Mountains Layered Complex) and associated shallow intrusives (Hogan and Gilbert, 1997). As much as 40,000 km^3 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; Arbenz, 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

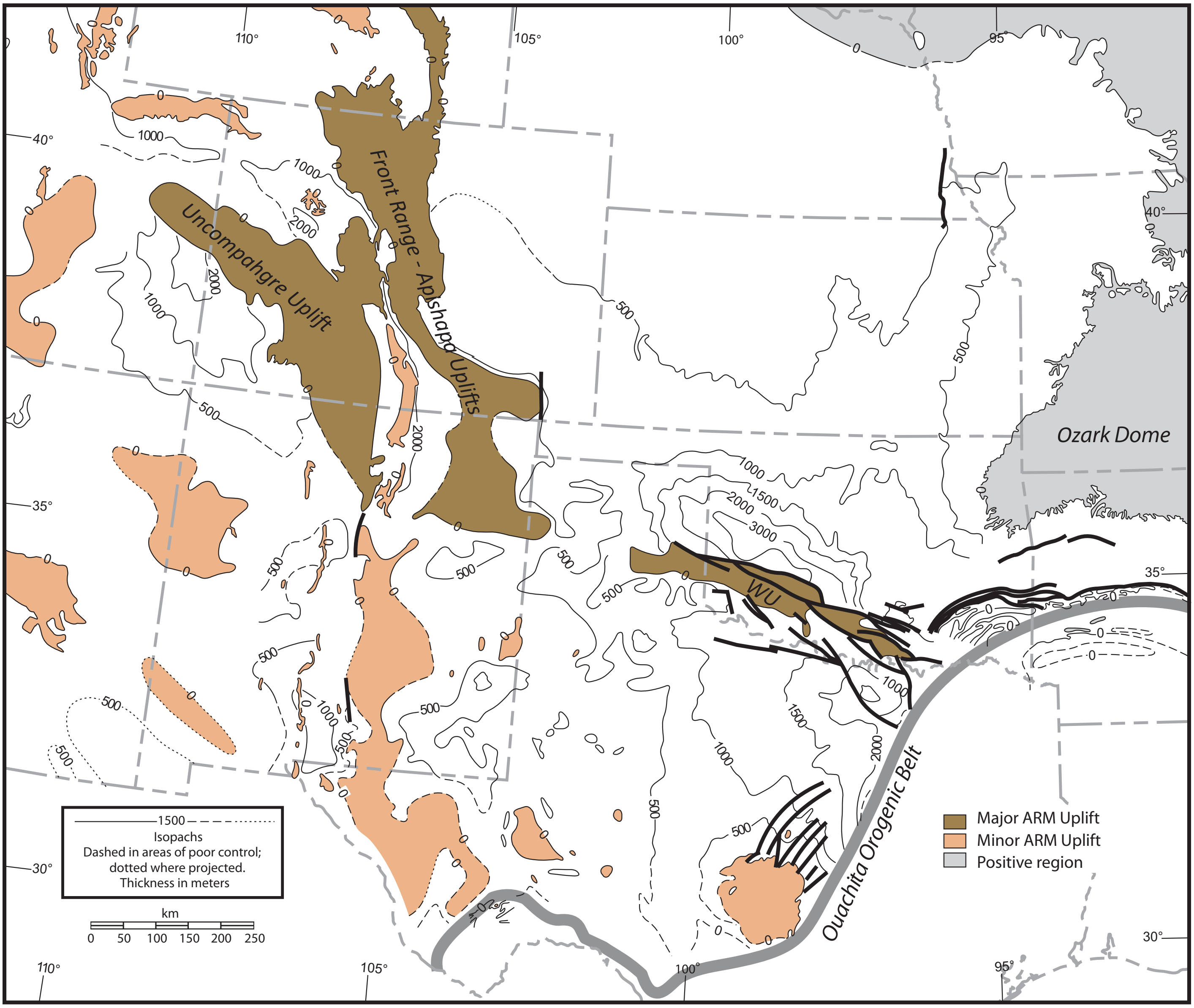


Figure 2. Isopach map showing preserved Pennsylvanian strata of the region shown in Figure 1. ARM—Ancestral Rocky Mountains. Note the large (>1000 m) thicknesses of Pennsylvanian strata adjacent to the Uncompahgre, Front Range–Apishapa, and Wichita uplifts (WU; see Fig. 1). Bold black lines are faults. Modified from McKee and Crosby (1975).

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

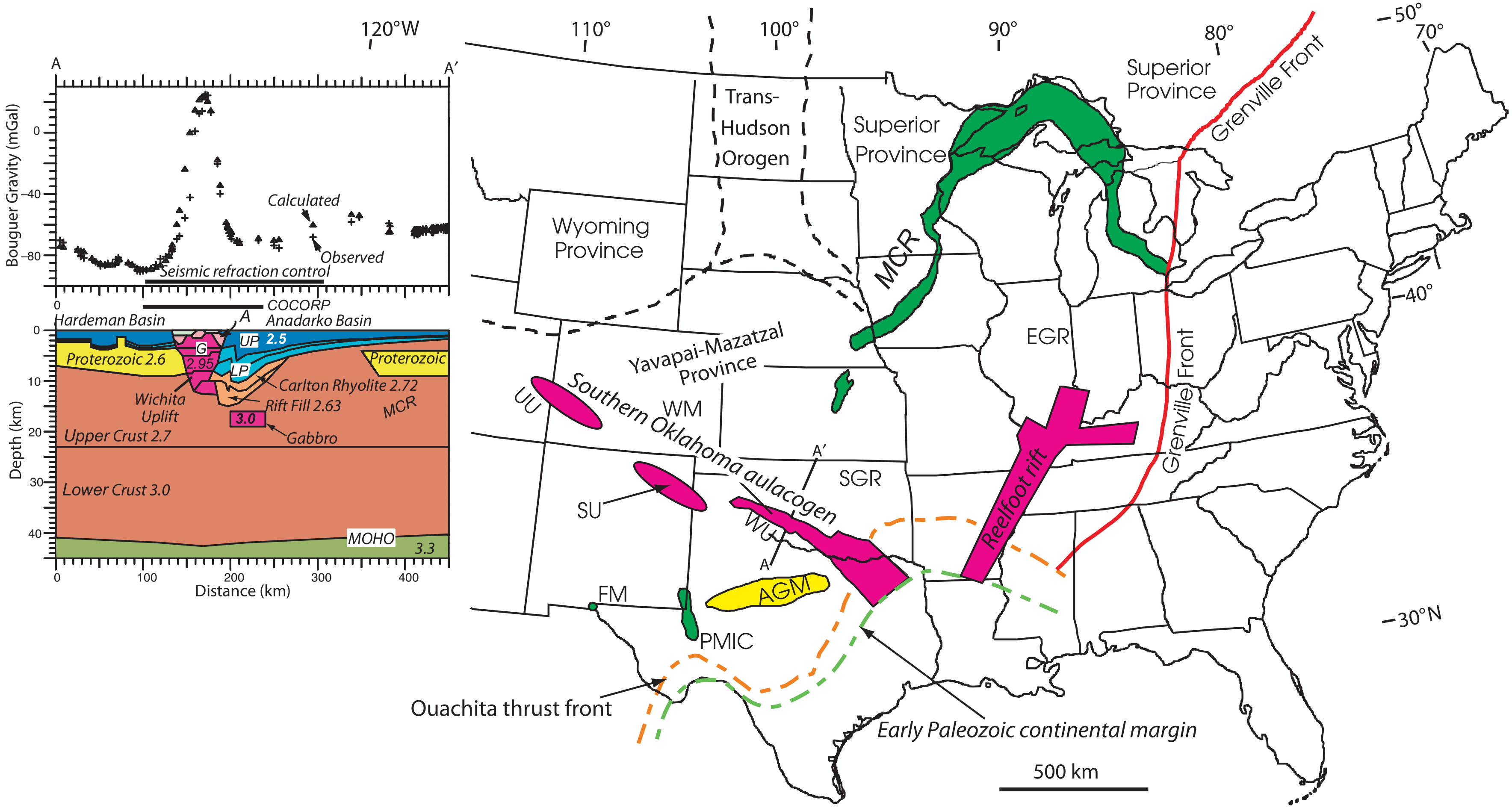


Figure 3. Regional tectonic index map of southern Laurentia showing features of interest in this study. Proterozoic terranes (Yavapai-Mazatzal Province, EGR—Eastern granite-rhyolite province; SGR—Southern granite-rhyolite province). Proterozoic rifts and mafic intrusives in green (MCR—Midcontinent Rift 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/m^3 × 10^{-3}; modified from Keller and Stephenson, 2007).

southwest Texas (Kluth and Coney, 1981; Kluth, 1986; Algeo, 1992; Trexler et al., 2004; Poole et al., 2005). Owing in part to this timing, which coincides with that of the Ouachita-Marathon orogeny, Kluth and Coney (1981), Kluth (1986), Dickinson and Lawton (2003), and others linked the intraplate deformation of the ARM to far-field effects of the Ouachita-Marathon orogeny, a model that seems particularly applicable for the Wichita-Anadarko system of Oklahoma. In this model, the ARM intracratonic deformation stems from activation of preexisting weaknesses by propagation of far-field stresses associated either with (south-dipping) subduction of promontories or wrenching of Laurentia as eastern parts of the Pangean suture locked (Kluth and Coney, 1981; Kluth, 1986; Algeo, 1992; Dickinson and Lawton, 2003; Poole et al., 2005). Marshak et al. (2000) reinforced the role of preexisting weaknesses by suggesting that faults associated with the ARM orogeny were formed initially by crustal rupturing during Proterozoic rifting. Others suggested a connection to events (convergence or megashear activity) along southwestern or western Laurentia (e.g., Ye et al., 1996; Trexler et al., 2004; Cashman et al., 2011), most notably for features in the far-western ARM system.

PERMIAN HISTORY OF THE CORE ARM: POSTOROGENIC SUBSIDENCE?

Permian Onlap of the Wichita Uplift, Oklahoma

Lower Cambrian magmatic rocks in the Wichita Mountains of southwest Oklahoma form the largest surface exposure of the SOA. These units, uplifted and eroded during ARM tectonism, now protrude through a mantle of Lower Permian redbeds (Fig. 4) that otherwise extend across the region. Relative to the Rocky Mountain region in general, Oklahoma has remained less disturbed by post-Paleozoic tectonism. As demonstrated by apatite fission-track and auxiliary data from the Wichita Mountains and neighboring Anadarko basin, the region records ~800 m to 1.5 km (1–3 km inferred by Lee and Deming, 1999) of Permian–Jurassic burial before denudation that began in the Late Jurassic, and ≤1.5 km of denudation in the late Mesozoic–Paleogene in response to tectonic and/or climatic influences (Schmoker, 1986; Cardott, 1989; Carter et al., 1998; Winkler et al., 1999; Hemmerich and Kelley, 2000; Eaton, 2008), but no reactivation of old uplifts, as occurred in the Rocky Mountains.

Geologic relationships in the Wichita Mountains demonstrate that Permian strata onlap paleorelief on the Cambrian basement (Fig. 4). At the surface, stream drainages are visible today carved into both Cambrian igneous basement and Cambrian–Ordovician carbonates, but these drainages commonly do not propagate headward into the superjacent Permian strata, despite the less competent nature of the latter. Rather, drainages appear to have been beheaded (crosscut) by horizontal Lower Permian strata (Gilbert, 1982; Donovan, 1986). Numerous shallow wells drilled in the 1950s (Ham et al., 1964) reveal a carapace of Permian strata as much as 1 km thick onlapping the basement of the Wichita highland, thus revealing the magnitude of the onlap.

Seismic data corroborate and expand upon these surface and well-bore observations. The Mountain View thrust fault, the main fault of the Frontal fault zone, marks the boundary between the uplift and adjacent basin (Brewer et al., 1983; McConnell, 1989). This fault zone is well imaged seismically (Fig. 5), and demonstrates profound displacement in the pre-Permian section, and an onlap by minimally deformed Early Permian strata that extend from the basin onto the uplift. These relationships have long been recognized and cited as evidence for a Pennsylvanian age for the deformation; however, the magnitude of the onlap (~1 km; Figs. 4 and 5) and the extension of the onlap from the basin up onto and across the uplift have not been highlighted.

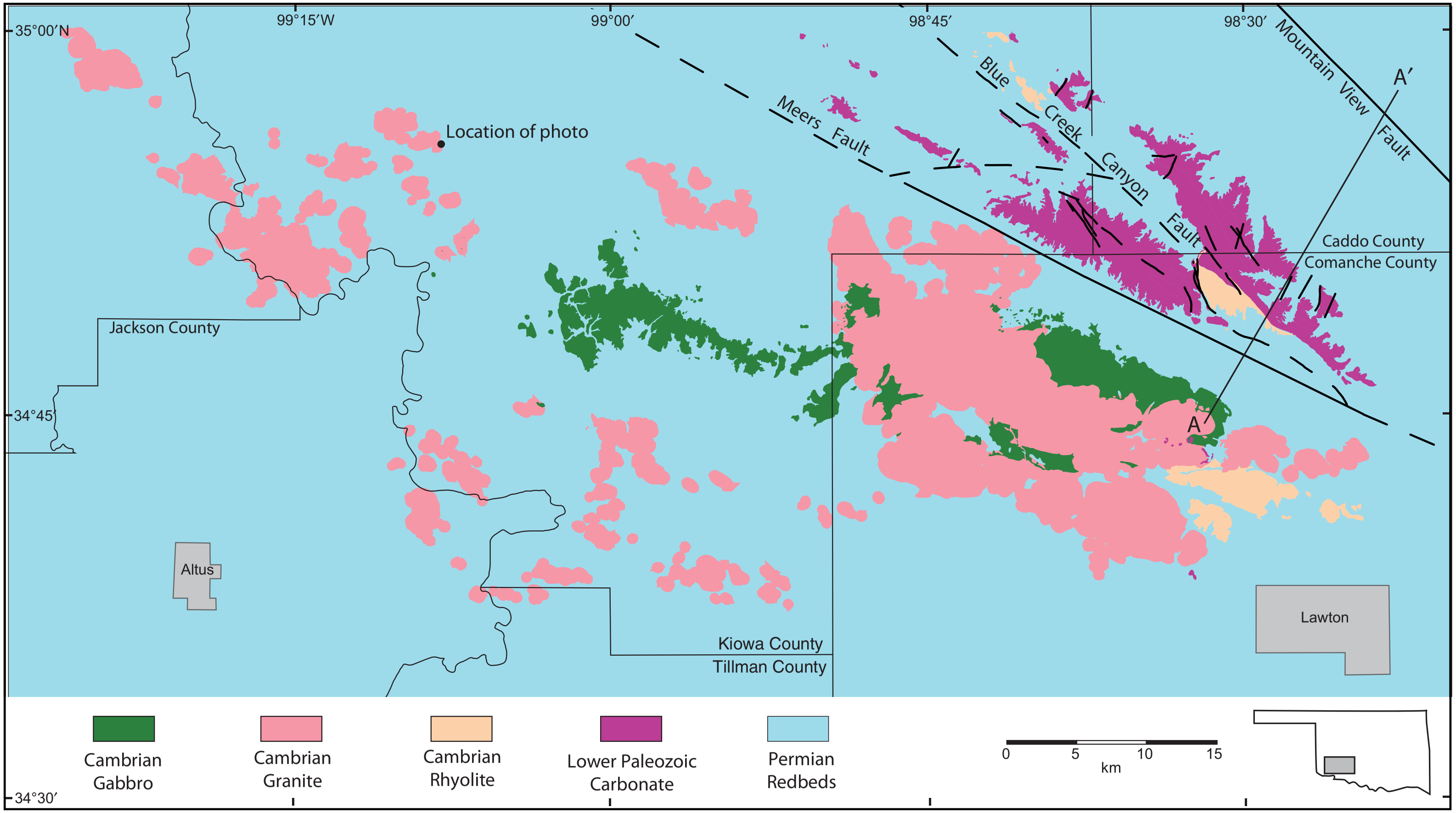
The subsidence history of the proximal Anadarko basin (Fig. 6) shows that subsidence associated with the late Paleozoic basin history continued into Permian time. This history depicts a rapid late Mississippian through late Pennsylvanian subsidence event, a less rapid but significant Early Permian event, and the eventual cessation of subsidence by middle Permian time. This subsidence analysis employs a composite stratigraphic section from wells in the foredeep of the basin, and includes a rare foredeep well with a complete log through the Permian section, thus capturing a subsidence event that is equivalent in age to the onlapping Permian strata previously documented (Fig. 6; Supplemental File[1]).

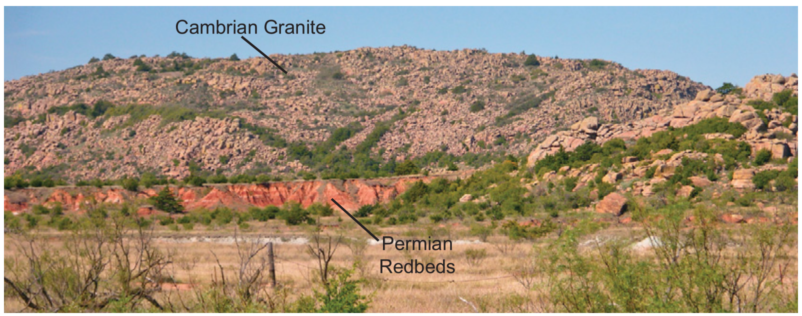
The surface observations of onlap of the Lower Permian strata onto Cambrian basement demonstrate that the Wichita Mountains as observed today represent a late Paleozoic (Early Permian) landscape undergoing exhumation for the first time since the Early Permian. That is, the paleomountains are being progressively exposed as erosion removes the friable Lower Permian mudstone units that mantle the paleolandscape (Fig. 4). The granitic hills of the Wichita Mountains display minimal evidence for modern erosion; for example, alluvial fan mantles of granitic material do not occur. Rather, the crosscutting relationships of Lower Permian strata across drainages carved into Cambrian basement date the landscape to the pre–Early Permian. This profound nonconformity has long been recognized (Ham et al., 1964; Johnson et al., 1988), but its tectonic significance has largely escaped notice. Taken together with the subsurface data, these relationships document Early Permian subsidence that (1) abruptly postdates compressional uplift, and (2) extends beyond the foredeep of the Anadarko basin and onto the Wichita uplift; that is, the core of the uplift subsided along with the flanking basinal regions.

Permian Onlap in the Uncompahgre Uplift, Colorado

In contrast to the minimally disturbed record of Permian burial in Oklahoma, the ARM paleouplifts 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

[1]Supplemental File. PDF file of information on the construction of the subsidence plot. The supplemental file includes data sources for stratal thicknesses and ages used, including well locations; procedure and equations used for subsidence calculations; lithologic porosity assumptions and sources; map locations of wells used for the subsidence plot; and cited references. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00681.S1 or the full-text article on www.gsapubs.org to view the Supplemental File.





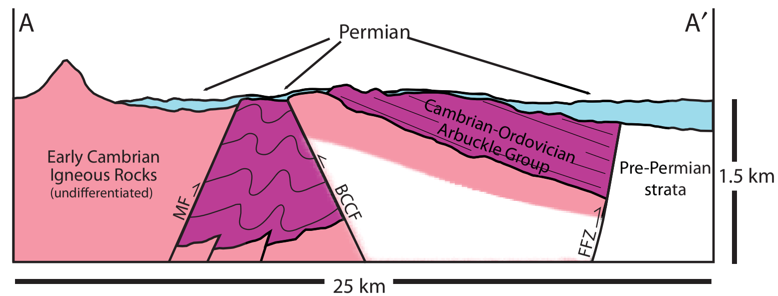


Figure 4. Map, cross section, and photo illustrating regional structure and burial of paleorelief and faults by Lower Permian strata in the Wichita Mountains, Oklahoma (map and cross section modified from Ham et al., 1964). Cross section (profile A–A′) extends across the center and north side of the 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.

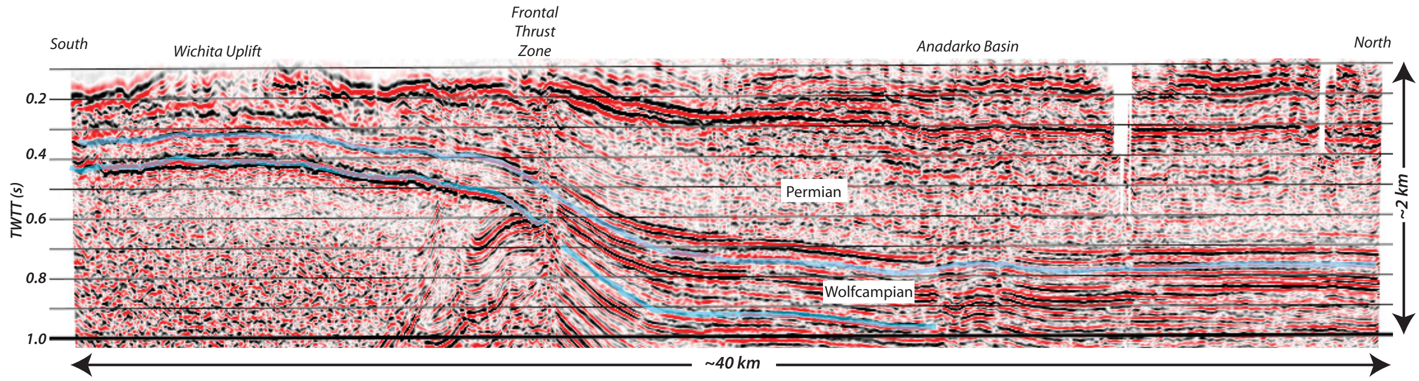


Figure 5. Seismic image of the Wichita Frontal fault zone and Permian overlap succession (line location is shown in Fig. 10). TWTT—two-way traveltime. The blue lines mark the approximate top and bottom of the Lower Permian (Wolfcampian) section. Note the presence of ~600 m of Permian strata preserved on top of the uplift and ~1500 m in the proximal basin in this view; these values do not include the Permian subsequently eroded during ongoing Cenozoic exhumation. This image was provided by Petroleum Geo-Services from their three-dimensional Wichita Mountain Front reflection surveys (modified from Rondot, 2009).

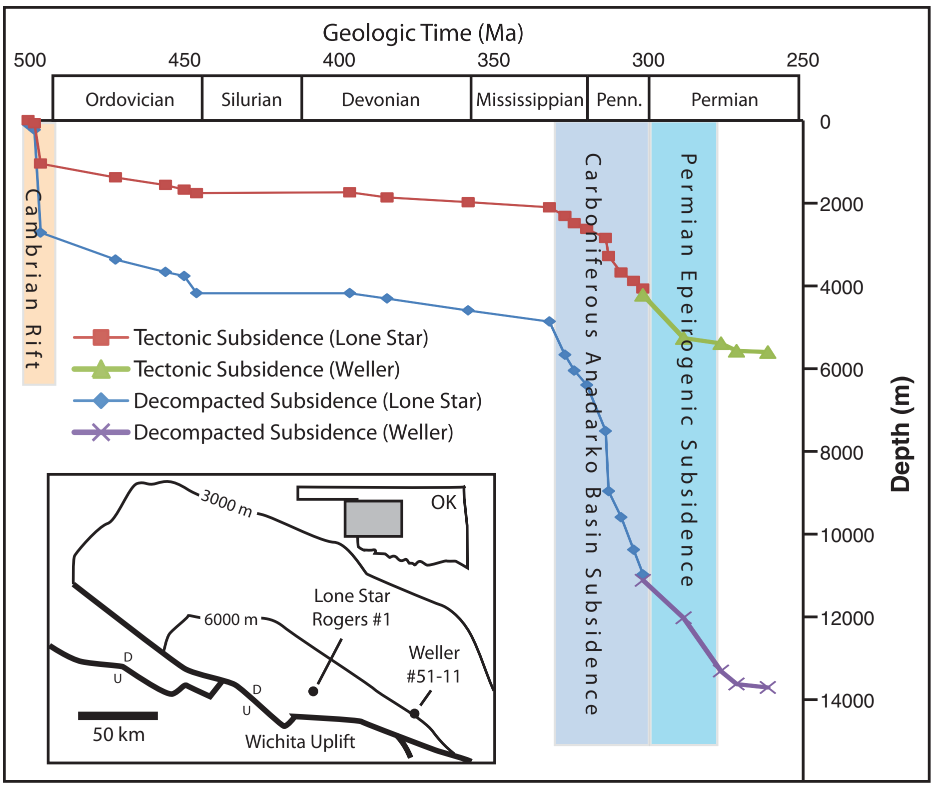


Figure 6. Paleozoic subsidence history of the Anadarko basin, illustrating the dual history of Cambrian rifting and thermal subsidence followed by late Paleozoic compressional subsidence. This analysis was constructed by compositing the Cambrian through Pennsylvanian (Penn.) record from the Lone Star Rogers #1 well and the Permian record from the Weller #51–11 well, both located in the foredeep of the Anadarko basin (Supplemental File [see footnote 1]). Note the significant subsidence through the Early Permian (see text). U—upthrown; D—downthrown. The amount of Permian (decompacted) sediment accumulation here in the foredeep of the basin is ~2.5 km. (For details of plot construction, see footnote 1.)

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 southwestern 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; 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.

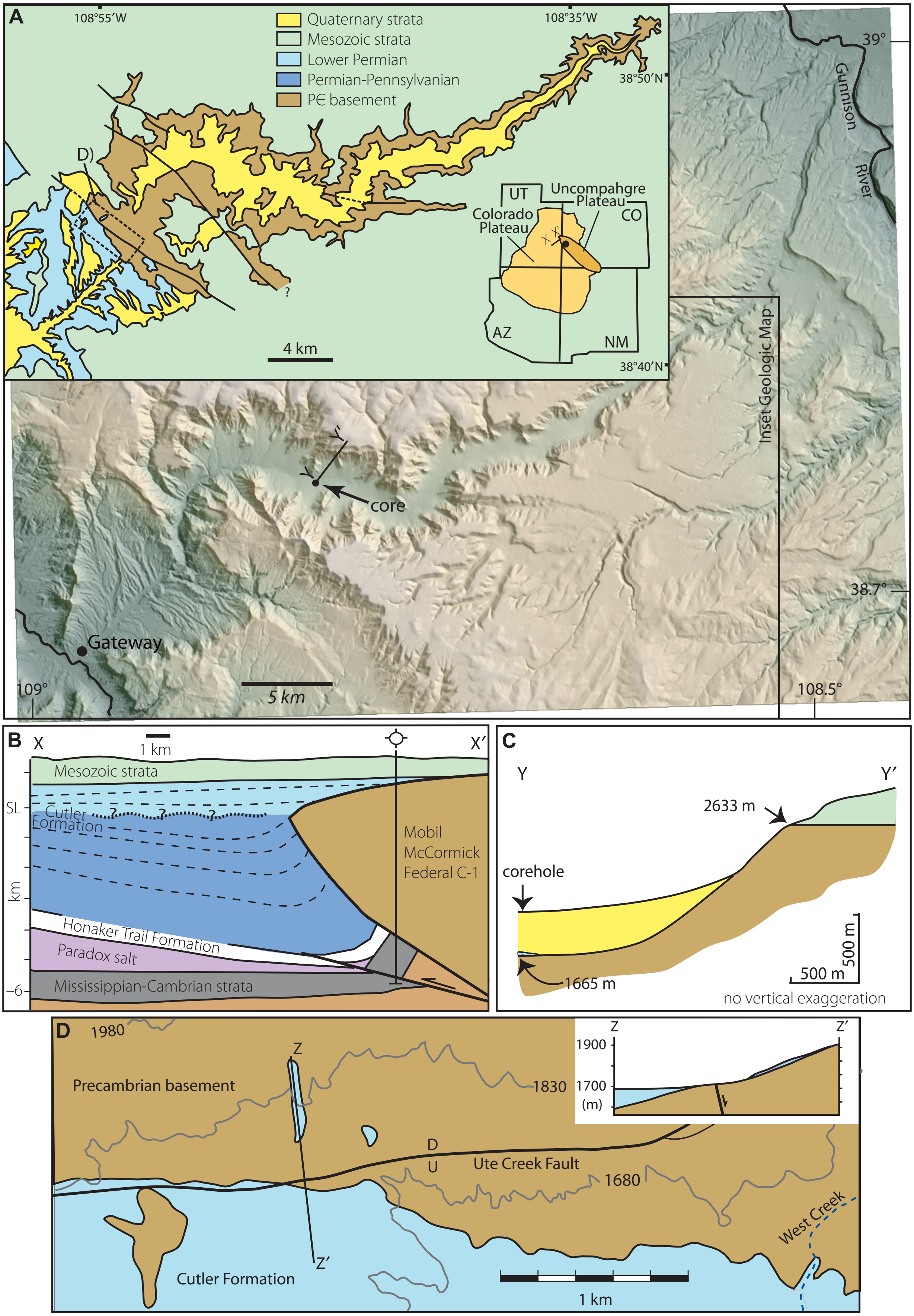
Passive post-tectonic erosional beveling of the highland was once thought to have produced the depositional onlap along the margin of the uplift. However, the burial extends on top of the paleo-uplift, well beyond the flanking regions, indicating that the highland must have been buried by at least 970 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 Moenkopi Formation between the Permian Cutler and Triassic Chinle 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 beveling of a highland that persisted to Triassic time; however, any such beveling 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 Moenkopi 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). Postorogenic 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.



A
108°55′W
108°35′W
Quaternary strata
Mesozoic strata
Lower Permian
Permian-Pennsylvanian
PЄ basement
38°50′N
38°40′N
D)
UT
Uncompahgre Plateau
Colorado Plateau
CO
AZ
NM
4 km
Gunnison River
39°
Inset Geologic Map
core
38.7°
Gateway
109°
5 km
108.5°
B
X
1 km
X′
Mesozoic strata
SL
Cutler Formation
km
Mobil McCormick Federal C-1
Honaker Trail Formation
Paradox salt
Mississippian-Cambrian strata
–6
C
Y
Y′
2633 m
corehole
1665 m
500 m
500 m
no vertical exaggeration
D
1980
Precambrian basement
Z
1830
Z
Z′
1900
1700
(m)
D
U
Ute Creek Fault
1680
West Creek
Cutler Formation
Z′
1 km

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 Pennsylvanian–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.

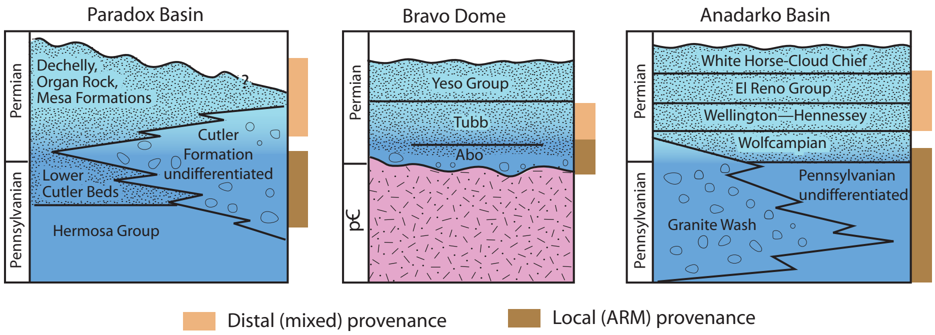


Figure 8. Schematic provenance relations in the Paradox and Anadarko basins, and intervening Bravo Dome area (see Fig. 1 for general locations). Dark blue denotes synorogenic strata, light blue denotes postorogenic onlap; the color gradation between these depicts the provisional nature of the age control. 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).

GEOPHYSICAL EVIDENCE FOR A CRUSTAL LOAD BENEATH THE CORE ARM

Gravity data provide a clear picture of the extent of the SOA and the impressive mafic magmatism associated with the Cambrian rifting (Fig. 9). In southwestern Oklahoma, both COCORP seismic reflection profiles (Brewer et al., 1983) and a large refraction, wide-angle reflection experiment (Chang et al., 1989; Keller and Baldridge, 1995; Rondot, 2009) were integrated with geologic, drilling, gravity, and magnetic data to produce the crustal model shown in Figure 10 (simplified in Fig. 3). Notably, the mafic complex exposed in the Wichita highland and associated with a >100 mGal gravity high occurs almost entirely within the upper plate of a large thrust zone manifested near the surface as the Mountain View fault (Fig. 10). Regional gravity anomalies (Fig. 9) show that this mafic mass extends northwestward, with slight (50 km) offset, for ~500 km, well into northeastern New Mexico, before being disrupted by features associated with the Rio Grande Rift. Farther northwest, the San Juan volcanic field dominates the gravity field, but Larson et al. (1985) presented evidence for Cambrian rifting extending to the Uncompahgre highland, and geophysical studies of this highland indicate that it also is underlain by a high-density, high-velocity body (Snelson et al., 1998; Casillas, 2004). The amplitude of the anomaly across the Uncompahgre highland is ~50 mGal, but flanking strata are of lower density than those flanking the Wichita highland, reducing the density anomaly needed within the Uncompahgre highland uppermost crust. Moreover, new field studies along this trend, in the Wet Mountains of southern Colorado (Pardo, 2009), reveal a 40 mGal gravity high associated with Cambrian mafic and ultramafic complexes. These results, when merged with regional gravity and magnetic data, indicate that a large (>1000 km^2) part of the Wet Mountains is cored by Cambrian mafic igneous rocks, an inference consistent with seismic refraction data (Rumpel et al., 2005). We thus infer that the northwest-trending gravity anomalies that begin in northeastern Texas, are most prominent in southern Oklahoma, and extend to the Uncompahgre highland of Colorado, represent a high-density upper crustal load, the total length of which is ~1500 km. The potential effects of this load have not been previously addressed.

MODELING THE EFFECTS OF A CRUSTAL LOAD

Today the Wichita highland is supported by a strong lithosphere that continues to support the load associated with an ~120 mGal Bouguer gravity anomaly high. Concentrating on geophysical manifestations of the SOA in southern Oklahoma (to avoid the Laramide complications of the Uncompahgre highlands), we vertically integrate the density structure derived from gravity observations and seismic velocity interpretations along the profile highlighted in Figure 9. We then quantify the lithospheric load and thus the flexure forced by the Cambrian mafic and ultramafic bodies underneath (Fig. 10). The nomenclature used here closely follows that of Turcotte and Schubert (2002).

Flexural Calculations: No Horizontal Stress

First we define the effective elastic thickness (T_{eff}) of the lithosphere as

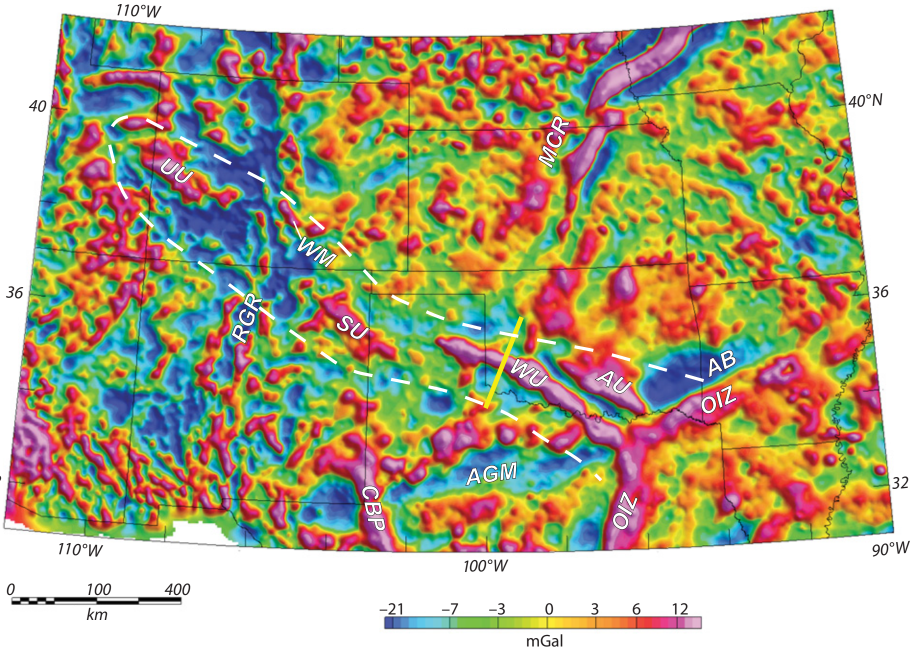


Figure 9. Residual gravity anomaly map calculated by subtracting a regional gravity field from the complete Bouguer anomaly values. The regional field was calculated by continuing upward (20 km) the complete (terrain corrected) Bouguer anomaly values. The yellow line is the location of the integrated 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.

$$T_{\text{eff}} = h = \left[\frac{12D\left(1-\nu^2\right)}{E}\right]^{1/3}, \qquad (1)$$

where h is elastic thickness (in m), E is Young's modulus (in Pa), ν is Poisson's ratio, and D is flexural rigidity (in Nm),

$$D = \frac{Eh^3}{12\left(1-\nu^2\right)}. \qquad (2)$$

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

$$D\frac{d^4w}{dx^4} = q_a(x) - \left(\rho_m - \rho_{in}\right)gw(x) - P\frac{d^2w}{dx^2}, \quad (3)$$

where w is vertical displacement (flexure, in m), g is gravitational acceleration (in m/s^2), x is horizontal ordinate (in m), q_a is applied external load (in N/m), ρ_m and ρ_{in} are mantle and infill density in (kg/m^3), 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 $P \sim 0$ is appropriate for the present-day situation.

With a further definition of the flexural parameter

$$\alpha = \left[\frac{4D}{\left(\rho_m - \rho_{in}\right)g}\right]^{1/4}, \qquad (4)$$

an unbroken elastic plate will behave as

$$w(x) = w_0 e^{-x/\alpha}\left[\cos\frac{x}{\alpha} + \sin\frac{x}{\alpha}\right], \qquad (5)$$

and

$$w_0 = \frac{V_0\alpha^3}{8D}, \qquad (6)$$

with $V_0 = q_a$ 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.

Flexural Calculations: Horizontal Stress Included

If the in-plane horizontal stress (P) is nonzero, then the flexural solution becomes more complicated, and the flexural parameter splits into two, labeled here as β and γ,

$$w(x) = \left[\frac{V_0}{4D\beta\left(\gamma^2+\beta^2\right)}\right]e^{-\beta|x|}\cos(\gamma x), \quad (7)$$

with

$$\gamma = \left\{\left[\frac{g\left(\rho_m - \rho_{in}\right)}{4D}\right]^{1/2} + \frac{P}{4D}\right\}^{1/2} \qquad (8)$$

and

$$\beta = \left\{\left[\frac{g\left(\rho_m - \rho_{in}\right)}{4D}\right]^{1/2} - \frac{P}{4D}\right\}^{1/2}. \qquad (9)$$

As P increases in size, β decreases until it approaches zero, at which time the square root in β becomes undefined on the real axis. This corresponds to buckling or the elastic limit (Fig. 10). The limit is

$$F_c = \left[\frac{Eh^3 g\left(\rho_m - \rho_{in}\right)}{3\left(1-\nu^2\right)}\right]^{1/2} \text{ as } \beta \to 0, \qquad (10)$$

which occurs at a wavelength λ_c of

$$\lambda_c = \left[\frac{Eh^3}{12\left(1-\nu^2\right) g\left(\rho_m - \rho_{in}\right)}\right]^{1/4}. \qquad (11)$$

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 paleohighlands, 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

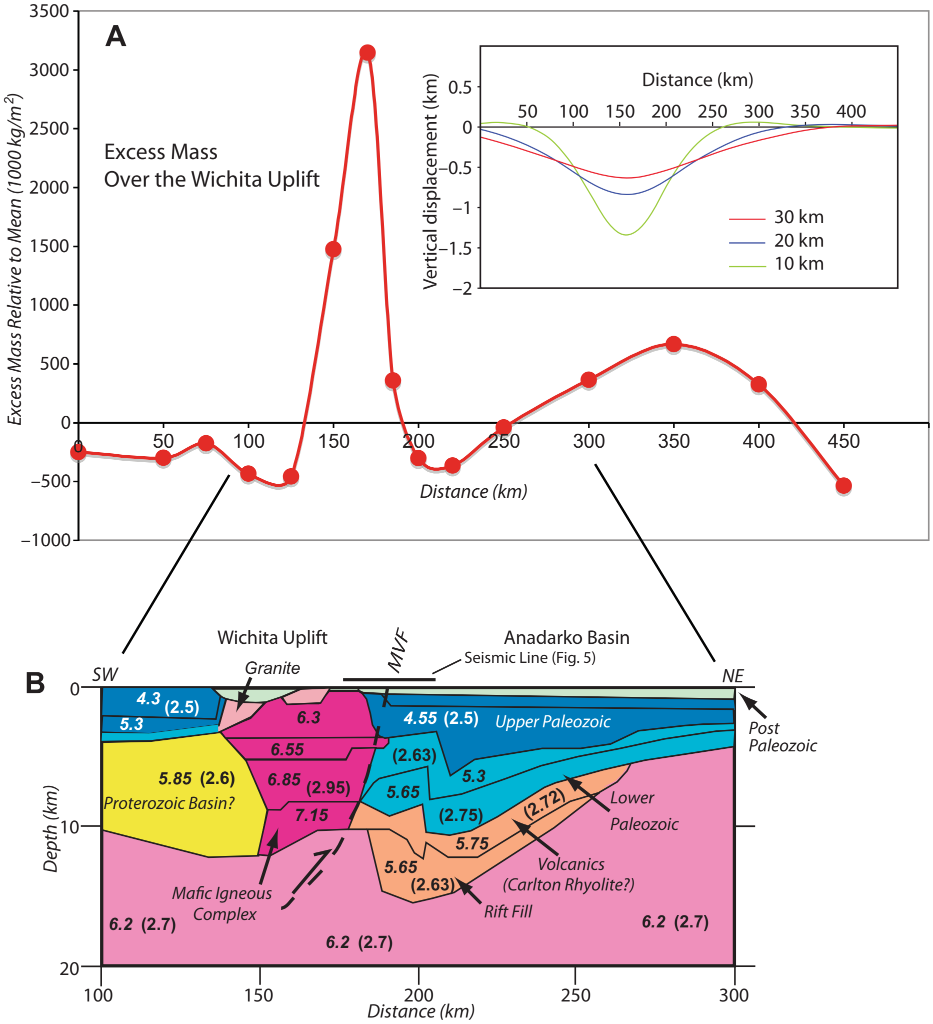


Figure 10. (A) Mass excess and flexure computation across profile A–A′ of Figure 3. The upper plot shows the vertically integrated mass along profile A–A′ using the density structure derived from the model below. Note also the location of the seismic reflection line shown in Figure 5. The zero point on the vertical axis of this profile was set to the mean value of lithospheric load in units of 1000 kg/m². The excess mass anomaly is no wider than 80 km, and has maximum amplitude of 3800 kg/m². The inset plot shows the flexure caused by the modeled lithospheric load. The curves here are labeled with effective elastic thicknesses (*h*) of 10, 20, and 30 km. In these flexural isostatic models, Moho deflection would not be detectable by seismic refraction unless *h* is <10 km. Other parameters in the inset models were held constant at Young's modulus 70 GPa, Poisson's ratio of 0.25, and infill density 2500 kg/m³. (B) Velocity and density model of central portion of profile A–A′ from Figure 3. Numbers in parentheses are densities (in kg/m³ × 10⁻³); other numbers are seismic P-wave velocities (in km/s).

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

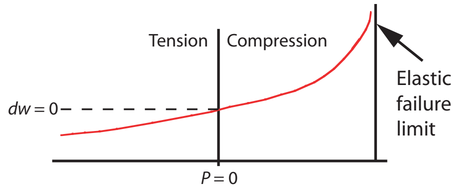


Figure 11. Amplification of flexure in response to in-plane stress. Increasing horizontal compressive stresses relative to a plate with no horizontal stress ($P = 0$) on an elastic lithosphere with applied vertical loads will increase flexure amplitudes until the elastic failure limit is reached and buckling occurs. Conversely, placing the lithosphere under relative tension will decrease the amplitude of flexure. This mechanism modulates load-induced flexures. Dashed line (*dw*; see text) represents position of loaded and flexed but uncompressed plate.

of horizontal stresses acting upon a markedly inhomogeneous crust is most consistent with both the data and modeling results from the ARM system. The mafic keel of the SOA-ARM system originated during the Cambrian rifting that produced the SOA, and underpins the core uplifts of the ARM discussed here. As reflected in the subsidence history of the earlier Oklahoma basin (Johnson et al., 1988; Gilbert, 1992), and the later-evolved Anadarko basin, the loads and cooling caused subsidence of the SOA region into Mississippian time, but these loads subsequently acted as foci for ARM uplifts. Geodynamic modeling results are consistent with the hypothesis that relaxation, or lessening, of the compressional stresses that accompanied ARM orogenesis resulted in the cessation of uplift of the mountains, and active subsidence of the greater ARM region in response to the changing horizontal stress field in the context of the preexisting crustal inhomogeneities.

This mechanism provides a means to hasten the removal of highlands by creating positive accommodation in the hinterland, thus leading to long-term preservation of ancient highlands otherwise destined for erosional eradication. The core ARM highlands did not succumb to isostatically induced erosional beveling that reduced relief over tens of millions of years, for example as in the Appalachian orogen, because this was not a plate-margin collision associated with major crustal thickening. Therefore, once the stresses that induced ARM orogenesis ceased, the effects of the underlying mass load acted to reduce elevation through subsidence and burial.

Landforms are traditionally taken as the result of geologically recent (late Cenozoic) activity, although landforms dating from the Mesozoic and even Paleozoic are increasingly well recognized (Twidale, 1998), especially from the Gondwanan 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 Pennsylvanian–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 Pennsylvanian 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.

ACKNOWLEDGMENTS

Research contributing to the ideas presented here was funded in part by grants from the National Science Foundation (EAR-0230332, EAR-0404500) and the U.S. Geological Survey National Cooperative Geologic Mapping Program (awards G10AC00329 and G11AC20217). The views and conclusions contained in this document are ours and should not be interpreted as representing the official policies, either expressed or implied, of the U.S. Government. We thank reviewers C. Kluth, R. Langford, *Geosphere* editor D. Harry, and the *Geosphere* Associate Editor for constructive comments on an earlier version of this manuscript. We are grateful to Petroleum Geo-Services for generously providing access to images from their three-dimensional Wichita Mountain Front reflection surveys. We thank T. Eccles, A. Shock, and D. Ambuehl for mapping assistance, and K. Johnson and R. Burkhalter for valuable discussions on the Permian of Oklahoma.

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Manuscript Received 3 March 2011
Revised Manuscript Received 19 December 2011
Manuscript Accepted 31 December 2011