ANNUAL REVIEWS

Annual Review of Earth and Planetary Sciences

Tectonics of the Colorado Plateau and Its Margins

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Annu. Rev. Earth Planet. Sci. 2022. 50:295–322

First published as a Review in Advance on February 7, 2022

The *Annual Review of Earth and Planetary Sciences* is online at earth.annualreviews.org

https://doi.org/10.1146/annurev-earth-032320-111432

Keywords

Colorado Plateau, tectonics, Cenozoic uplift, physiographic provinces, geophysical provinces

Abstract

The Cenozoic Colorado Plateau physiographic province overlies multiple Precambrian provinces. Its ∼2-km elevation rim surrounds an ∼1.6-km elevation core that is underlain by thicker crust and lithospheric mantle, with a sharp structural transition ∼100 km concentrically inboard of the physiographic boundary on all but its northeastern margin. The region was uplifted in three episodes: ∼70–50 Ma uplift above sea level driven by flat-slab subduction; ∼38–23 Ma uplift associated with voluminous regional magmatism and slab removal, and less than 20 Ma uplift associated with inboard propagation of basaltic magmatism that tracked convective erosion of the lithospheric core. Neogene uplift helped integrate the Colorado River from the Rockies at 11 Ma to the Gulf of California by ∼5 Ma. The sharp rim-to-core transition defined by geological and geophysical data sets suggests a young transient plateau that is uplifting as it shrinks to merge with surrounding regions of postorogenic extension.

- The Colorado Plateau's iconic landscapes were shaped during its 70-million-year, still-enigmatic, tectonic evolution characterized by uplift and erosion.
- Uplift of the Colorado Plateau from sea level took place in three episodes, the youngest of which has been ongoing for the past 20 million years.

- Tectonism across the Colorado Plateau's nearest plate margin (the base of the plate!) is driving uplift and volcanism and enhancing its rugged landscapes.
- The bowl-shaped Colorado Plateau province is defined by ongoing uplift and an inboard sweep of magmatism around its margins.
- The keel of the Colorado Plateau is being thinned as the North American plate moves southwest through the underlying asthenosphere.

INTRODUCTION

The Colorado Plateau is a region of the southwestern United States known for its iconic physiography. The term Colorado Plateau first appeared in the earliest geologic reports of the region (Ives 1861, Powell 1875) but was used to label the Permian Kaibab Limestone surface south of the Grand Canyon now referred to as the Coconino Plateau. Dutton (1882) used the term Colorado plateaus, which was the origin of its use for the wider region. An early formal definition of the term Colorado Plateaus was as a physiographic province (**Figure 1**). "Its characteristic topography is determined in the main by greatly elevated, nearly-horizontal, strong strata, locally covered by lava flows" (Fenneman 1928, p. 338). Kelley (1955, p. 10) named and accurately described it:

> The physiographic province herein termed the Colorado Plateau is often referred to as the Colorado Plateaus in as much as the region embraces or is possibly dominated by many plateaus. However, there may be more area in the form of valleys, plains, mesas, buttes, and mountains than in plateaus and there is a growing tendency on the part of workers in the region to speak of the Plateau or the Colorado Plateau for the large province outlined by Fenneman (1930) even though it is not in a strict sense a single plateau. It is difficult to find a single feature of physiography, climate, or structure that would characterize the area as a whole, for it is a province of considerable diversity.

The goal of this review is to link the physiographic character of the Colorado Plateau province to its tectonic underpinnings and geologic evolution. This is motivated by the need for a synthesis of numerous new geophysical and geologic data sets and by geodynamic questions about the origin, longevity, and demise of the Colorado Plateau and its margins. We also discuss the relative importance of each of the three main uplift episodes that raised the surface elevation of the Colorado Plateau–Rocky Mountains region from sea level starting in the Late Cretaceous to current 2–3-km elevations. This region provides an important field laboratory for understanding the geodynamics of intracontinental tectonism and magmatism, the response of landscapes to the long-wavelength uplift of plateaus (epeirogeny), and their eventual collapse.

DESCRIPTIVE ELEMENTS

Each margin of the Colorado Plateau is itself a unique laboratory for understanding intracontinental tectonism. To the east is a world-class continental rift (Rio Grande rift); to the northeast is an intraplate thick-skinned orogen (Rocky Mountains); to the west is the Sevier fold-thrust belt and collapsed backarc hinterland (Nevadaplano and Great Basin); to the south is the extensionally collapsed Mogollon Highlands (Arizona Transition Zone and southern Basin and Range).

Physiographic Provinces and Subprovinces

Figure 1 shows the Colorado Plateau region with labeled physiographic provinces and subprovinces. A generalization of this topography is that the Colorado Plateau has a bowl shape with ~2-km-high rims surrounding an ~1.6-km-high core and an ~3-km average elevation in the

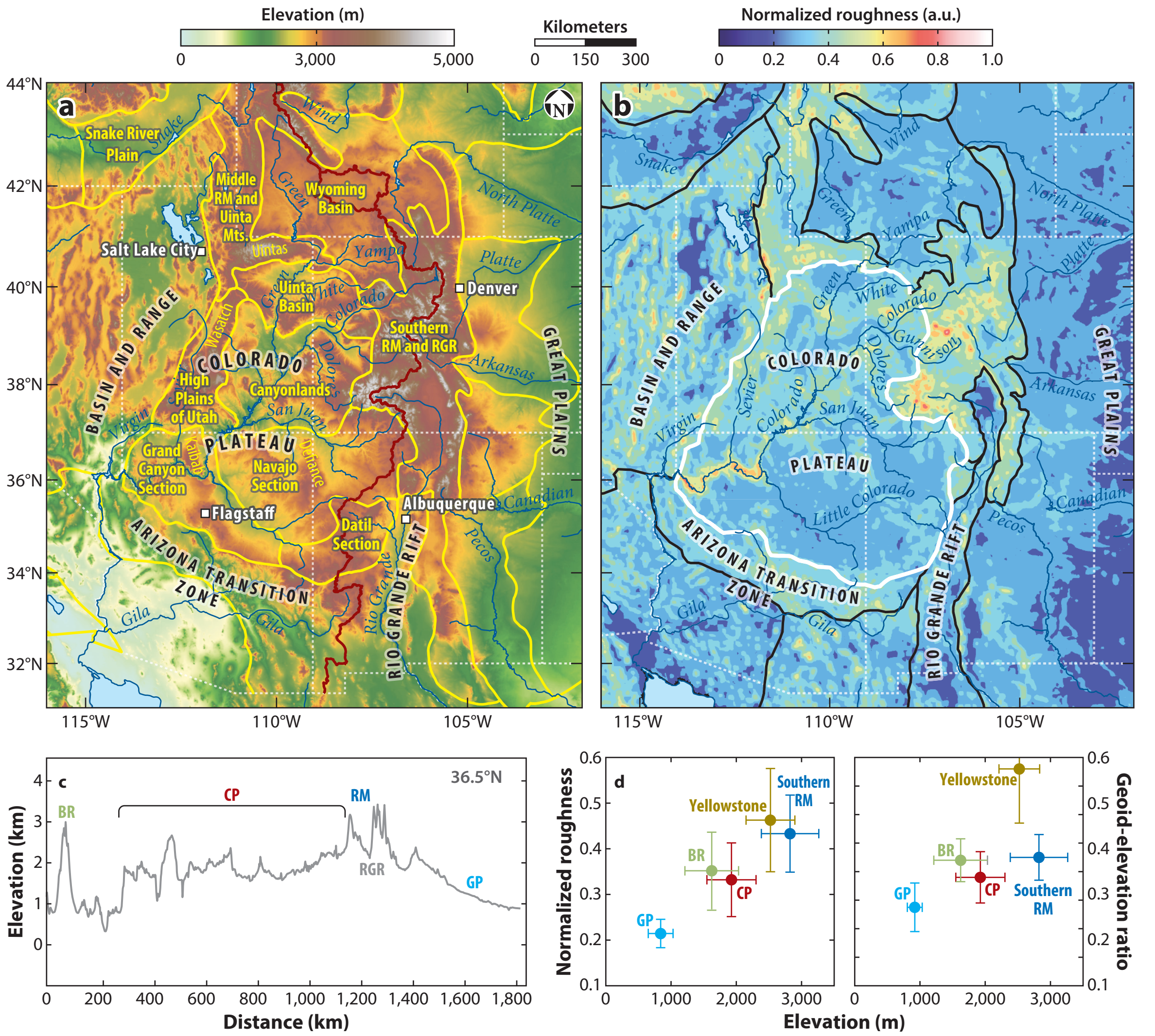

Figure 1

(*a*) CP physiographic province boundaries and subprovinces (Fenneman 1928) superimposed on a digital elevation model showing the general bowl shape of the CP. Most drainages exit via the Colorado River system through the Grand Canyon. The dark red line is the continental divide. (*b*) Topographic roughness (Coblentz & Karlstrom 2011) quantifies topography of physiographic provinces and subprovinces. (*c*) Topographic profile along 36.5°N showing that the CP is within a wide uplifted region that also includes the BR, RGR, southern RM, and GP. (*d*) Elevation of provinces plotted against roughness showing higher elevations are rougher. Geoid-elevation ratio showing crustal buoyancy supports elevation of the GP; crust plus some upper mantle buoyancy supports elevations of the CP, BR, and RM; and dynamic mantle buoyancy supports Yellowstone (Coblentz et al. 2011). Abbreviations: a.u., arbitrary units; BR, Basin and Range; CP, Colorado Plateau; GP, Great Plains; RGR, Rio Grande rift; RM, Rocky Mountains.

adjacent Rocky Mountains. This entire region was the foreland of the Cordilleran orogeny and was uplifted from sea level in several stages since the Late Cretaceous (Karlstrom et al. 2011, Cather et al. 2012). **Figure 1*b*** shows the spatial distribution of the topographic roughness (Coblentz & Karlstrom 2011) in the Colorado Plateau and demonstrates that higher roughness values occur in the higher elevation west and northeast margins and within canyons of the Colorado River system, versus low topographic roughness in lower elevation south and southeast subprovinces. **Figure 1*c*** shows that the Colorado Plateau and adjacent provinces are part of a broader western US uplifted region (epeirogen) (cf. Eaton 2008, figure 3).

Faults of different ages in and around the Colorado Plateau (**Figure 2**) lead to a first-order impression that the Colorado Plateau core is somewhat less faulted than its margins and adjoining provinces. The faults correspond in age to different uplift episodes. Late Cretaceous–Paleogene (Laramide) structures are reverse faults and folds of diverse orientations that delineate the Rocky Mountain arches and smaller amplitude but similar-style reverse-fault-cored monoclines that extend across the margins of the Colorado Plateau and that formed during contractional reactivation of Mesoproterozoic and Neoproterozoic normal faults (Marshak et al. 2000, Timmons et al. 2001). The Basin and Range to the west and south and the Rio Grande rift to the east are dominated by Miocene to ongoing normal faults and magmatism related to extensional collapse of earlier highlands. Quaternary faults are relatively pervasive across the region but less abundant in the core of the Colorado Plateau.

The Colorado Plateau is characterized by relatively flat-lying, but high elevation, Paleozoic and Mesozoic sedimentary strata compared to more highly deformed strata in the adjacent Rocky Mountain and Basin and Range provinces. The lowest elevation core of the plateau is deeply dissected by the Colorado River and its tributaries that have sculpted its high relief landscapes that include the Grand Canyon, Canyonlands, and the Grand Staircase. As noted by Powell (1875), deep canyons locally cut at high angles across 100-km-wavelength plateaus such as the Uinta Mountains and Kaibab uplift, which are fault-cored Laramide monoclinal and anticlinal structures. Laramide arches on the western Colorado Plateau are dominantly east-vergent monoclines above west-up reverse faults in the basement (e.g., Walcott 1889); some arches have oppositely vergent monoclines above reactivated Precambrian grabens creating flat-topped anticlines (e.g., Defiance uplift). Quaternary faulting generally reflects reactivation of older structures. The Colorado Plateau is bounded on the west by the Sevier fold-thrust front and both the Laramide (thick-skinned) and Sevier (thin-skinned) structures formed due to retroarc and foreland contraction across the Farallon-Kula and North America Late Cretaceous–Paleogene plate margin (Yonkee & Weil 2015).

The Rio Grande rift forms a tectonically well-defined eastern side of the southeastern Colorado Plateau. It is one of the classic continental rifts of the world with similar size and geometry of half-graben basins, rift flanks, and transfer zones as the East African rift (Keller et al. 1991). Parts of the rift have been shown to be collapsed Laramide highlands (e.g., Cather 1983). The Rio Grande rift expands southward into the southern Basin and Range and dies out northward into the Rocky Mountains. Rift extension began in the Oligocene, the main phase of uplift and unroofing of rift flanks and subsidence of half-grabens took place 20–10 Ma (Ricketts et al. 2016, van Wijk et al. 2018), and still-active extension is shown by Quaternary normal faulting (Ricketts et al. 2014) (**Figure 2**).

The Colorado Rocky Mountains are an unusual mountain belt in being greater than 1,000 km from the convergent plate margin and having no thick crustal root (Hansen et al. 2013). Rocky Mountain arches are thick-skinned basement-cored features similar in structural style but larger in amplitude than Colorado Plateau monoclinal structures. Paleozoic and Mesozoic strata generally bend and/or are faulted upward as they enter the Rocky Mountains from both the Colorado Plateau and Great Plains sides, and major frontal reverse faults verge outward toward the Great Plains and Colorado Plateau.

The Great Plains form the eastern piedmont slope of the Rocky Mountains. **Figure 1*c*** shows the broad topographic swell of the southern Rocky Mountains that Eaton (2008, figure 2) suggested was more similar to thermal uplift of oceanic rifts than to shorter piedmont flanks of

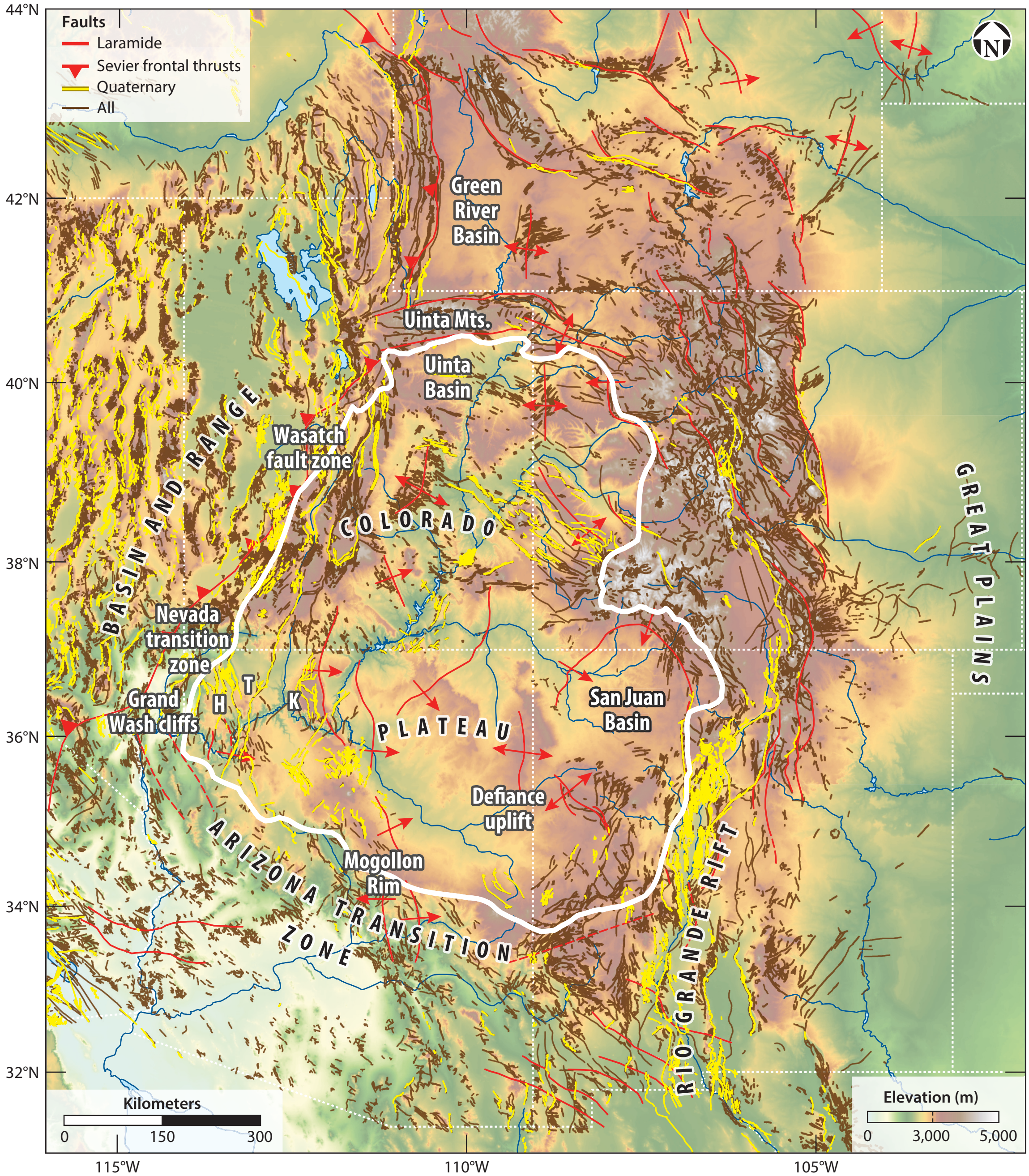

Figure 2

Cenozoic faults of the Colorado Plateau region. Red lines indicate major Laramide reverse faults and monoclines, the arrows point toward the downthrown block, yellow lines indicate Quaternary faults, red lines with teeth indicate Sevier frontal thrusts, and brown lines indicate all other faults. Abbreviations: H, Hurricane fault; K, Kaibab uplift; T, Toroweap fault. Figure adapted from USGS (2018).

major mountain ranges. Three topographic swells between major rivers (**Figure 1*a***) ramp up from the Great Plains to the Rocky Mountains; this topography represents a combination of differential erosion and differential uplift along the mountain front (Leonard 2002, Cather et al. 2012). Establishment of the Great Plains–Rocky Mountain boundary was partly by Laramide faulting, partly Oligocene (Eaton 2008), partly Neogene (Leonard 2002, McMillan et al. 2006, Cather et al. 2012), and ongoing (Nereson et al. 2013).

The Uinta Mountains form the northern margin of the Colorado Plateau, with the boundary drawn approximately at the break in slope between the mountains and adjacent basins. East-west-striking faults with kilometer-scale displacement separate the uplifted plateau from the Laramide Green River and Uinta Basins on the north and south sides, respectively. The unusual east-west orientation of the Uinta Mountains reflects reactivation of older Precambrian structures (Yonkee & Weil 2015). The Uinta boundary was further accentuated in the middle to late Cenozoic due to extensional collapse of the eastern Uinta Mountains that led to Neogene drainage integration across the uplift (Hansen 1986, Aslan et al. 2018).

The Wasatch fault zone forms a sharp western margin of the Colorado Plateau and is defined by a Miocene to Recent fault breakaway zone of segmented west-down normal faults and the related Intermountain Seismic Belt (Smith & Bruhn 1984). **Figure 2** shows a 100-km-wide highly faulted transition zone in Utah between the Colorado Plateau and Basin and Range (Wannamaker et al. 2008). This is similar to the Nevada transition zone that records inboard migration of faulting from 17 to 0 Ma (Faulds et al. 2016), leaving isostatically uplifted footwall blocks above a west-down breakaway zone (Wernicke & Axen 1988). Grand Wash cliffs, the retreated footwall of this fault zone, forms the physiographic edge of the Colorado Plateau, but the neotectonic margin is well inboard of the physiographic edge (Brumbaugh 1987, Kreemer et al. 2010) (**Figure 2**). Deep incision of the Grand Canyon and Virgin Canyon and related northward retreat of cliffs of the Grand Staircase (Dutton 1882) have erosionally removed about 2 km of Mesozoic strata from the southwestern edges of the Colorado Plateau (Winn et al. 2017).

The Arizona Transition Zone forms the transitional southern tectonic boundary of the Colorado Plateau. During the Late Cretaceous–Paleogene, this zone (Arizonaplano of J.B. Chapman et al. 2020) was the southern extension of the high elevation Nevadaplano orogenic plateau (DeCelles 2004) and basement-cored Kingman uplift (Beard & Faulds 2011). Extensional slip was transferred around the southwestern corner of the Colorado Plateau such that highly extended lower plates have been pulled out from beneath the Colorado Plateau to form metamorphic core complexes in Arizona. The Mogollon Rim defines a large portion of the Colorado Plateau's southern physiographic boundary and roughly coincides with the drainage divide that marks the northern edge of the Arizona Transition Zone. Topographic roughness is higher in the Arizona Transition Zone (**Figure 1*b***), reflecting exposure of Precambrian basement in normal fault uplifts and basins that record the collapse of the Mogollon Highlands.

Interpretation of the Physiography of the Colorado Plateau and Its Margins

The spectacular landscapes of the Colorado Plateau owe their origin to the Colorado River system deeply eroding into uplifted and currently uplifting terrain. The Colorado Plateau is far from flat and comprises six subprovinces with different mean topographic elevation, relief, and roughness. Different fault orientations and densities show a less faulted core, but the styles and timing of deformation, as well as physiography, are transitional with adjacent provinces. Thus, an understanding of the Colorado Plateau also requires understanding its margins. The east and west margins are sharpest and are defined by Miocene to Recent normal fault systems of the Rio Grande rift and Basin and Range. The northeast and southwest margins are gradational and defined by topographic gradients into the Laramide and still-deforming Colorado Rocky Mountains and Arizona Transition Zone, respectively. The physiography is built on a template of Laramide arches and basins, but it is young (Neogene), fault influenced, and enhanced by deep erosion.

GEOPHYSICAL UNDERPINNINGS

Geophysical methods help address the structure of the lithosphere and asthenosphere and the question of whether the Colorado Plateau is a lithospheric-scale tectonic province that behaved differently—for example, as a microplate—due to fundamentally different structure than adjacent provinces (**Figures 3** and **4**). Multiple lines of evidence indicate that the Colorado Plateau has relatively thick cold lithosphere compared to its neighboring provinces except the Archean Wyoming province to the north (e.g., Coblentz et al. 2007). Colorado Plateau heat flow values, ~45–75 mW/m^2, are higher than those of typical Archean cratons but lower than those of magmatically active provinces such as the Basin and Range and Rio Grande rift (Blackwell et al. 2011). Topography and gravity, in the context of elastic thickness of the lithosphere (Lowry & Pérez-Gussinyé 2011) (**Figures 3*a***), similarly isolate the Colorado Plateau, suggesting that a transition to a ductile rheology occurs at greater depth than in all adjacent provinces except Wyoming (Lowry & Pérez-Gussinyé 2011). Gravity and heat flow evidence for a thicker thermal boundary layer and consequently stronger lithosphere has long been recognized (Reiter et al. 1979, Thompson & Zoback 1979, Lowry & Smith 1995) and is consistent with seismic studies of the Colorado Plateau lithosphere (e.g., Beghoul & Barazangi 1989, Gao et al. 2004, West et al. 2004).

Spatially continuous seismic coverage of the EarthScope Transportable Array, in conjunction with other networks, provides a wealth of 3D constraints on upper mantle structure across the Colorado Plateau region. Resulting P- and S-wave tomography and scattered wave imaging of lithospheric interfaces all suggest that there is thicker lithosphere in the Colorado Plateau interior and that the high-velocity keel in the core of the province locally extends to greater than 150 km (Schmandt & Humphreys 2010, Levander et al. 2011, Obrebski et al. 2011, Lekić & Fischer 2014, Hansen et al. 2015) (**Figure 3*b–d***). The edges of the keel show a sharp transition to lower-velocity upper mantle beneath its west, south, and east margins, with boundaries that lie concentrically within the physiographic boundary. The mantle boundary on the northwestern edge of the Colorado Plateau is particularly sharp with ~10% sheer velocity (Vs) contrast over less than 100 km horizontally at about 100 km depth (Sine et al. 2008, Schmandt & Humphreys 2010). The sharpness of the transition and its position inward from the physiographic boundary suggest young modification by convective removal of lithosphere or extensive infiltration of partial melt (Roy et al. 2009, Crow et al. 2011, Roy et al. 2016). Magnetotelluric imaging also finds a sharp transition from electrically resistive Colorado Plateau interior lithosphere to high conductivity beneath the western margin, supporting lithospheric thinning or infiltration of melt from the asthenosphere (Wannamaker et al. 2008). The asthenosphere of the broader western US Cordillera is anomalously low in seismic velocity among global continental settings (Simmons et al. 2021), which likely indicates ascent to the base of thinned lithosphere of volatiles and partial melts due to a long history of subduction (Hansen et al. 2015, Plank & Forsyth 2016).

At shallower depths, the seismic structure and thickness of the Colorado Plateau crust further highlight its distinctive properties compared to surrounding regions (Keller et al. 1979, Wolf & Cipar 1993). The crust exhibits higher Vs (mid-lower crust), lower crustal (Lg) attenuation, and greater mean thickness, ~40–47 km, relative to the ~30–36-km-thick crust of the Basin and Range and Rio Grande rift provinces (Zandt & Ammon 1995, Sheehan et al. 1997, Bashir et al. 2011, Gilbert 2012, Phillips et al. 2014, Schmandt et al. 2015, Shen & Ritzwoller 2016) (**Figure 4**). The northeast transition to the southern Rockies also coincides with decreased seismic velocities and increased attenuation but similar or thicker crust, ~42–50 km (Hansen et al. 2013, Schmandt et al. 2015, Shen & Ritzwoller 2016). At the northern boundary high velocities extend into the Wyoming province, which has similar or thicker crust near the boundary (Schmandt et al. 2015, Shen & Ritzwoller 2016) (**Figure 4*a*,*d***). Crustal thickness estimates are locally variable despite

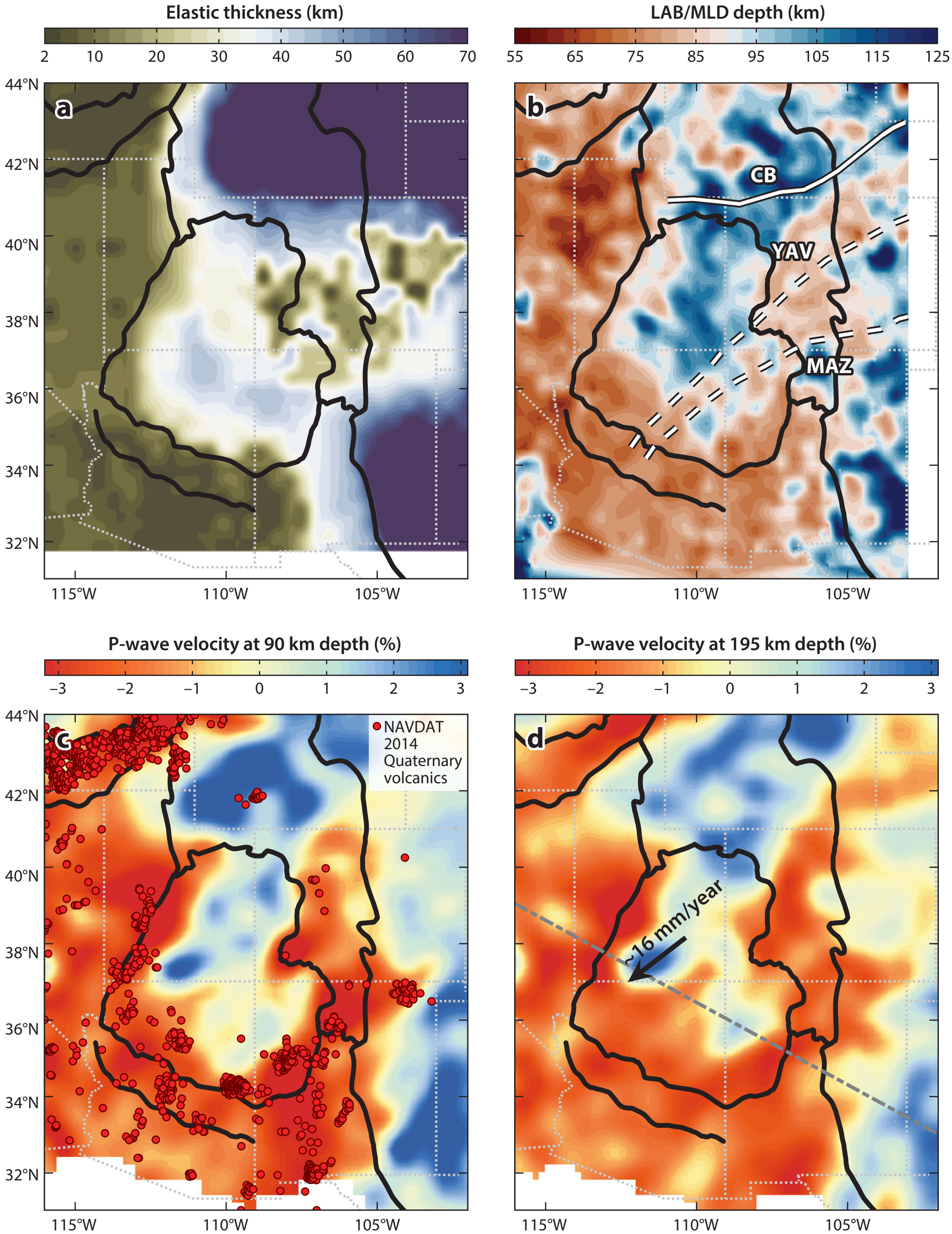

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Figure 3 (*Figure appears on preceding page*)

Lithospheric-scale properties that delineate the Colorado Plateau. (*a*) Elastic plate thickness, which is rooted in analysis of topography and gravity to optimize an elastic plate model for supporting topographic loads (Lowry & Pérez-Gussinyé 2011). (*b*) Depth to LAB or MLD (Lekić & Fischer 2014). These abrupt velocity decreases with depth align well with expectations for the LAB in magmatically active high heat flow areas such as the Basin and Range, but some deeper discontinuities may be MLDs located within the lithosphere beneath relatively stable and lower heat flow areas such as the Colorado Plateau and Wyoming. Thus, MLDs could be broadly considered as lower bounds on lithosphere thickness where the actual LAB may be too gradual for localized seismic detection. (*c*,*d*) P-wave tomography at 90 and 195 km depths (Schmandt & Lin 2014). The black arrow in panel *d* represents North American absolute plate direction and velocity of ∼16 mm/year (Kreemer et al. 2014). The gray dashed line in panel *d* is the line of tomographic cross section for **Figure 5*d***. Abbreviations: CB, Cheyenne belt (Archean–Proterozoic suture); LAB, lithosphere–asthenosphere boundary; MAZ, Mazatzal crustal province (1.7–1.6 Ga); MLD, mid-lithospheric discontinuity; YAV, Yavapai crustal province (1.84–1.7 Ga).

the general trend of thicker crust than surrounding extensional provinces (**Figure 4*a*,*c***). Variability is attributed to lithologies (e.g., mafic intrusions) that have smaller impedance contrasts with the upper mantle (Zandt & Ammon 1995, Sheehan et al. 1997, Schmandt et al. 2015, Shen & Ritzwoller 2016) and to the heterogeneous presence of multiple seismic interfaces due to delamination of dense lower crust (Levander et al. 2011). Modeling of crustal Vs, thickness, and heat flow suggests that Colorado Plateau crust has a composition that is slightly more buoyant (∼40–60 kg/m^3) than crust east of the Rocky Mountain front, which may partially explain its combination of high elevation and cool geotherm (Levandowski et al. 2014, Porter et al. 2017). However, upper mantle thermal buoyancy appears necessary to reconcile elevations across the western US Cordillera (Becker et al. 2014, Levandowski et al. 2014, Schmandt et al. 2015). A role for mantle buoyancy is particularly clear for the Colorado Plateau's elevated rim (Becker et al. 2014), which is generally underlain by thinner crust (**Figure 4**).

TECTONIC AND MAGMATIC EVOLUTION

Figure 5 depicts the prevailing paradigm for the tectonic and magmatic evolution of the Colorado Plateau–Rocky Mountain region. The 90–40 Ma Laramide orogeny is generally attributed to flat-slab subduction of the Farallon plate (**Figure 5*b***), the 38–23 Ma ignimbrite flare-up was due to delamination and sinking of parts of the Farallon slab (**Figure 5*c***), and post-20 Ma epeirogeny is due to small-scale mantle convection in the aftermath of the previous events (**Figure 5*d***).

Laramide Orogeny (ca. 90–40 Ma)

The Colorado Plateau region was amagmatic from late Cambrian (Oklahoma rift–related magmatism; Hansen et al. 2013) until the Late Cretaceous (Gonzales 2015). Following an arc flare-up ∼90 Ma (**Figure 5*a***), magmatism at the Sierra Nevada arc waned and the locus of magmatism migrated eastward across southern Arizona–New Mexico as the subducting Farallon plate flattened (Coney & Reynolds 1977) (**Figure 5*b***). Flat-slab subduction caused an ∼1,200-km-wide volcanic gap across most of the Colorado Plateau except within the Colorado Mineral Belt (Saleeby 2003, Chapin 2012). Uplift of the Colorado Plateau and Rocky Mountain provinces was exhibited by a change from marine to nonmarine facies across the foreland region after ∼75 Ma.

Similar to basement crustal age provinces (Whitmeyer & Karlstrom 2007) (**Figure 3*b***) and Pennsylvanian uplifts of the Ancestral Rocky Mountains (Leary et al. 2017), Laramide-style structures extend beyond the Colorado Plateau physiographic boundaries, suggesting little distinction between provinces during these times. For example, the Uncompahgre uplift had 4–5 km of structural relief with the adjacent Paradox Basin in the Pennsylvanian, whereas the Laramide Uncompahgre was only modestly reactivated, despite its favorable orientation. Total structural relief on arch-basin pairs (**Figure 6**) is lowest in the southwestern Colorado

Plateau (1–3 km), increases near the northeastern margins of the Colorado Plateau (∼5 km), and is greatest in the northern Rocky Mountains (10–15 km). Crustal shortening accomplished by Laramide structures is ∼5–15%, as opposed to ∼50% in the Sevier fold-thrust belt (Chapin & Cather 1981, Erslev 1993), and is insufficient to explain uplift of the province via

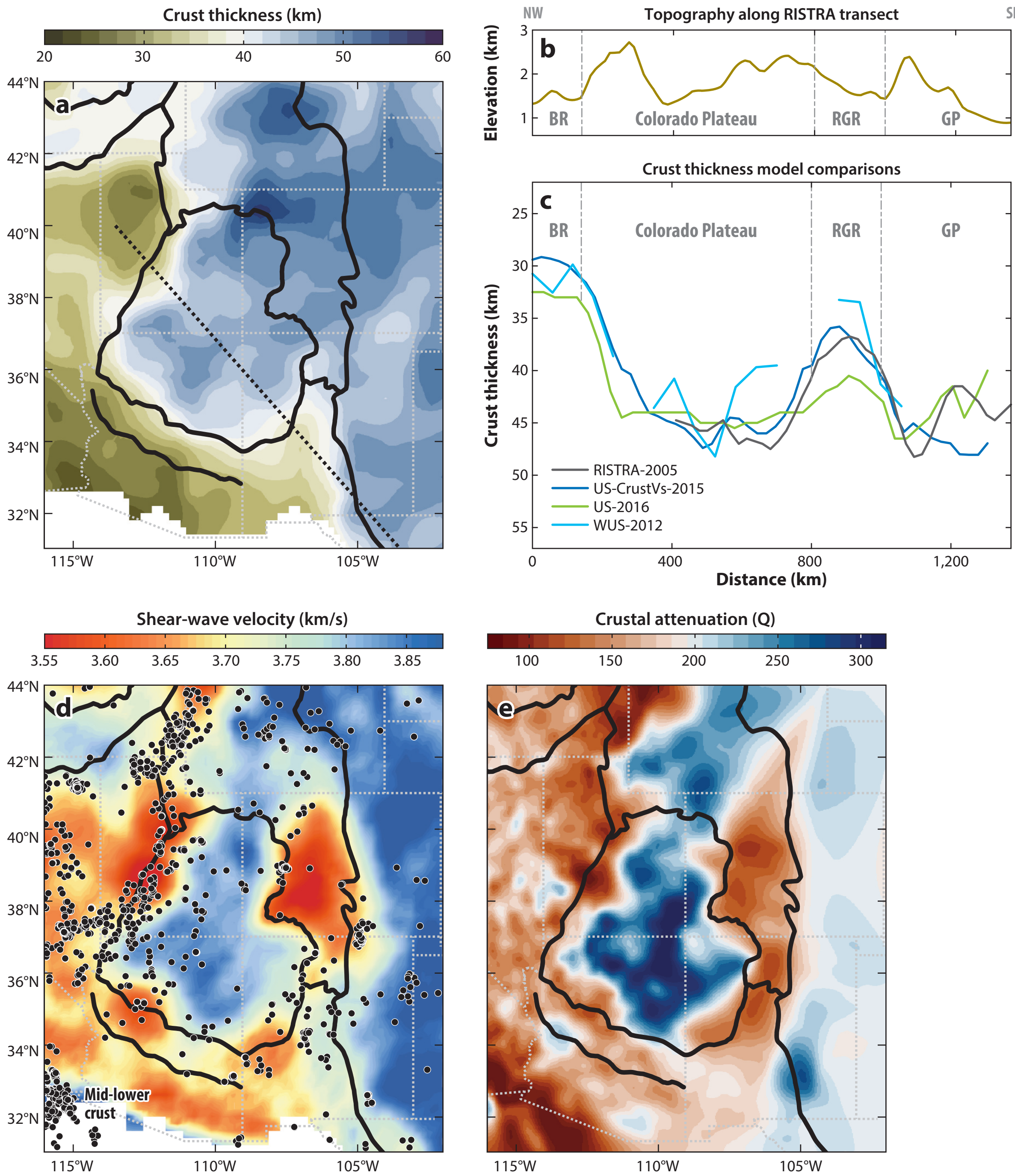

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Figure 4 (*Figure appears on preceding page*)

Crustal-scale properties that delineate the Colorado Plateau. (*a*) Crustal thickness from multimode receiver function stacking and surface wave dispersion constraints (Schmandt et al. 2015). The black dashed line delineates a cross section along the LA RISTRA experiment (Wilson et al. 2005) shown in panels *b* and *c*. (*b*) Smoothed topography along the LA RISTRA line. Vertical dash-dotted lines indicate physiographic provinces and extend into panel *c*. (*c*) Crustal thickness estimates from multiple models along the LA RISTRA line. RISTRA-2005 data from Wilson et al. (2005), US-CrustVs-2015 data from Schmandt et al. (2015), US-2016 data from Shen & Ritzwoller (2016), and WUS-2012 data from Gilbert (2012). (*d*) Shear velocity averaged through middle and lower crustal depths [11 km to Moho (Schmandt et al. 2015)] and estimated earthquake hypocenters from the Array Network Facility catalog developed during uniform seismograph coverage from the EarthScope Transportable Array [*black dots* (Astiz et al. 2014)]. Only local nighttime hours are used for plotted earthquakes to reduce (but not perfectly eliminate) mining seismicity that can bias views of natural tectonic processes (Astiz et al. 2014). (*e*) Crustal attenuation from inversion of Lg waves at 1 Hz (Q) (Phillips et al. 2014). Abbreviations: BR, Basin and Range; GP, Great Plains; LA RISTA, Colorado Plateau/Rio Grande Rift Seismic Transect; RGR, Rio Grande rift.

crustal thickening (Morgan 2003). Timing of Laramide-style tectonism also suggests continuity rather than separation of the Colorado Plateau–Rocky Mountain provinces. Onset of Laramide-style tectonism on the Colorado Plateau and Rocky Mountains was not synchronous at ca. 75 Ma ± 5 Ma (Dickinson et al. 1988, Davis & Bump 2009). Rather, thermochronologic data (Thacker et al. 2021) suggest onset of tectonism at 90–85 Ma in the western Colorado Plateau, ca. 80 Ma in the eastern Colorado Plateau, and 75–70 Ma in the southern Rocky Mountains. This is in general agreement with volcanism that swept eastward across southern Arizona–New Mexico until about 50 Ma (Coney & Reynolds 1977, Copeland et al. 2017).

The Colorado Mineral Belt is a belt of magmatism that cuts across Laramide structures from the northeastern Colorado Plateau into the Central Rocky Mountains (**Figure 6**). Chapin (2012) summarized three main magmatic stages: Late Cretaceous to mid-Eocene (75–43 Ma), mid-Cenozoic (43–18 Ma), and late Cenozoic (18–0 Ma). Laccolithic intrusions of 68–72 Ma extend this magmatic trend to the Four Corners area (**Figures 6** and **7**). Extrusive rocks are not preserved in most of the Colorado Mineral Belt or within the interior of the Colorado Plateau due to deep erosion. This magmatic belt has been attributed to ascent of magmas along Precambrian shear zones (Tweto & Sims 1963) and/or along a tear in the Farallon flat slab (Chapin 2012). There is no obvious younging trend within the Colorado Mineral Belt (Mutschler et al. 1987), and the zone has been a locus of magmatism since the Late Cretaceous.

The Mogollon Highlands were part of an orogenic plateau present along the southwest margin of the Colorado Plateau from the Jurassic (Dickinson & Lawton 2001, Chapman & DeCelles 2021) to the Late Cretaceous. The presence of high topography along this margin is geologically recorded by northeast-flowing paleorivers (Young & Hartman 2014). Gastil et al. (1992) suggested a highland on the order of 5 km high based on remnants of these paleorivers (Rim Gravels) on the northern flank of the highland and unconformities in southern California. J.B. Chapman et al. (2020) utilized whole-rock La/Yb ratios from continental arc rocks in southern Arizona and northern Sonora to estimate crustal paleothickness of 62–48 km from 76 to 61 Ma.

Ignimbrite Flare-Up (38–23 Ma)

An ignimbrite flare-up is a style of arc volcanism that results from removal of the subducting slab after a period of flat slab subduction under thick, nonextended crust that contrasts with steady-state, near-trench arc volcanism (Best et al. 2016). In the western United States, such magmatism from 38 to 23 Ma involved silicic caldera-forming supereruptions exceeding 10^2 to 10^3 km^3, little or no basalt lava extruded, ash flow sheets that covered 10^5 km^2, and continental-scale ash fall deposits. Major ignimbrite volcanic fields in and around the Colorado Plateau occur in the Great Basin, including the Marysvale volcanic field, southern Rocky Mountains, and Mogollon-Datil volcanic fields. The ignimbrite flare-up in the southern Great Basin progressed from north to

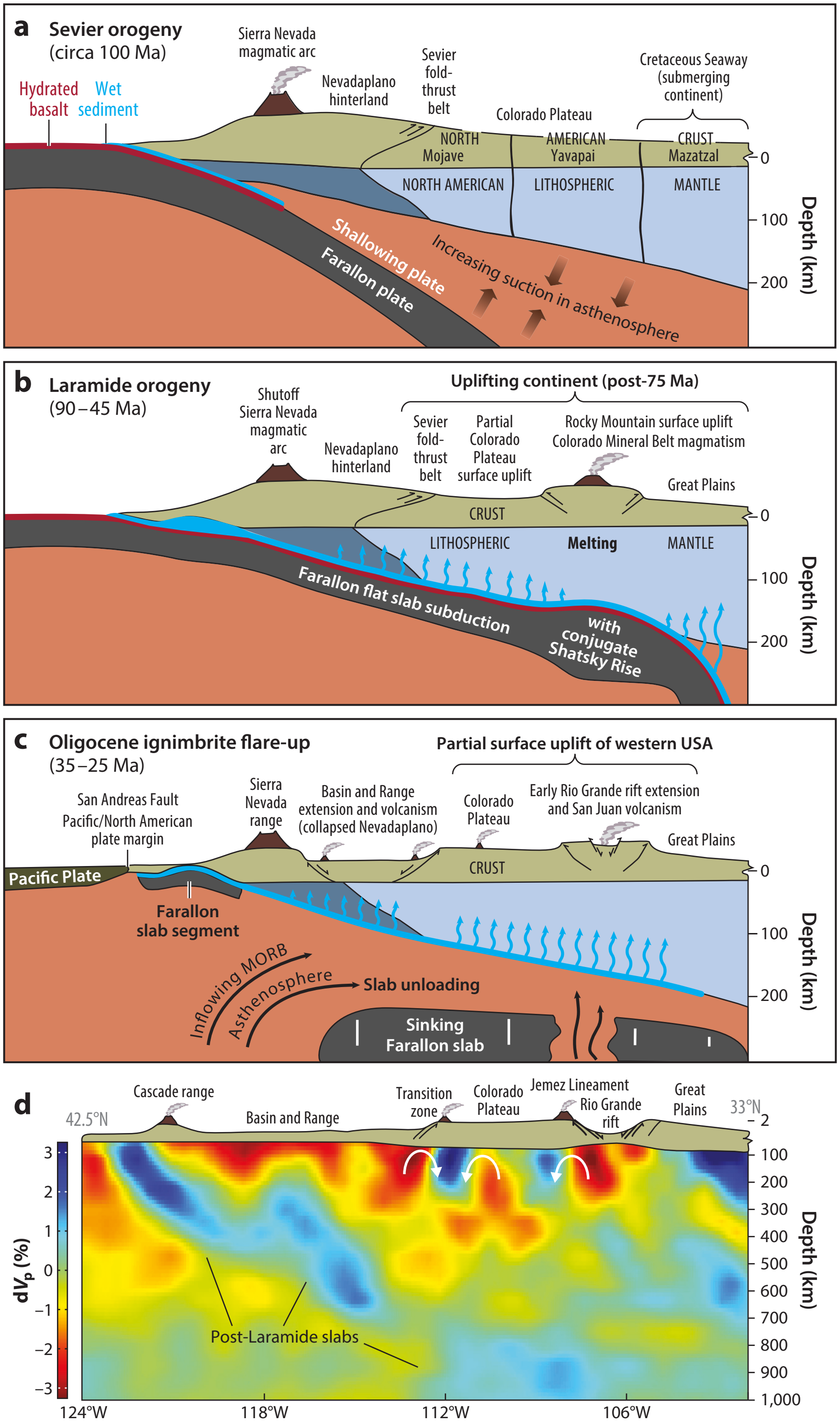

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Figure 5 (*Figure appears on preceding page*)

Time slice tectonic model for evolution of the Colorado Plateau region, Late Cretaceous to present day. (*a*) The Sierra Nevada arc formed above a moderately dipping downgoing Farallon slab. (*b*) Shallowing of the dip of the subducting Farallon slab transferred lithospheric hydration, tectonism, and magmatism progressively eastward. (*c*) Removal of the Farallon slab by drips and delamination caused warming of the lithosphere and the ignimbrite flare-up. (*d*) Modern mantle tomographic image along the cross section line shown in **Figure 3*d*** shows post-Laramide slabs, subducted since the ~40 Ma initiation of the Cascades arc, imaged from the uppermost mantle to ~1,000 km depth beneath the Cordillera (Schmandt & Lin 2014). At depths less than ~200 km, the Colorado Plateau is mainly expressed as a relatively high-velocity province between the Basin and Range and Rio Grande rift. Arrows denote interpreted locations of vigorous uppermost mantle convection eroding thermal lithosphere and driving melt infiltration near the edges of the Colorado Plateau. The high-velocity anomaly near the western edge has low-velocity mantle encroaching from both sides and may represent a larger volume of delaminating and downwelling cold mantle lithosphere plus dense lower crust. Abbreviation: MORB, mid-ocean ridge basalt. Figure adapted from Humphreys et al. (2003) and Crossey et al. (2015).

south between 36 and 18 Ma (Humphreys 1995, Henry & John 2013). Caldera complexes that began to define the Colorado Plateau are the southern Rocky Mountain 38–23 Ma (Lipman 2021), Mogollon-Datil 36–24 Ma (McIntosh et al. 1992), and Marysvale 28–19 Ma (Best et al. 2016) volcanic fields. Lower-volume magmatism affected the core of the Colorado Plateau at the same time period in the form of laccoliths and the Navajo volcanic field diatremes (**Figure 7**). Migration of the caldera eruptions through time (**Figure 7**) may be a proxy for progressive exposure of the base of the plate to upwelling asthenosphere as the Farallon slab was peeled back or dripped off (Ricketts et al. 2016).

Collectively, western US ignimbrite flare-up magmatism records a whole-lithosphere overturn (Farmer et al. 2008) that profoundly modified lithospheric structure. This event has been modeled as a mechanism for regional epeirogenic uplift (Spencer 1996) due to a combination of conductive heating (Roy et al. 2009), differentiation of crust and formation of deep crustal dense roots (J.B. Chapman et al. 2020), and convective removal (delamination) of lithosphere and crust (Levander et al. 2011, Hansen et al. 2013, A.D. Chapman et al. 2020). Evidence for significant surface uplift of the entire region during and following the ignimbrite flare-up includes (*a*) ~1.2 km of erosion of the central Colorado Plateau ~27–16 Ma between the time of the Chuska sandstone and the Bidahochi Formation (Cather et al. 2008), (*b*) thermochronologic data suggesting the 25–15 Ma carving of the East Kaibab paleocanyon across the Kaibab uplift (Karlstrom et al. 2014, 2020), (*c*) 20–10 Ma rapid uplift and denudation of rift flanks of the Rio Grande rift (Ricketts et al. 2016), (*d*) thermochronologic data from the Colorado Plateau and Rocky Mountains showing a widespread cooling pulse about 25 Ma (Flowers et al. 2008, Karlstrom et al. 2011, Rønnevik et al. 2017), and (*e*) deep erosion prior to and during ignimbrite magmatism in the San Juan Mountains (Lipman 2021).

Extensional Tectonism and Magmatism (≤20 Ma)

Cessation of the ignimbrite flare-up at about 17–16 Ma and the onset of basaltic volcanism coincided with a change to regional extensional strain (Camp et al. 2015, Best et al. 2016). Late Cenozoic basalt fields rim the western and southern margins of the Colorado Plateau and extend out into adjacent provinces. The locus of basaltic magmatism swept inboard (Wenrich et al. 1995, Roy et al. 2009), and the Nd composition of the basalts became more asthenospheric through time (Livaccari & Perry 1993, Crow et al. 2014), suggesting progressive shrinking of the Colorado Plateau by destabilization of mantle lithosphere. In the southwestern Colorado Plateau, the magmatic sweep rate of 18 km/Ma to the northeast (Walk et al. 2019) (**Figure 7**) is interpreted

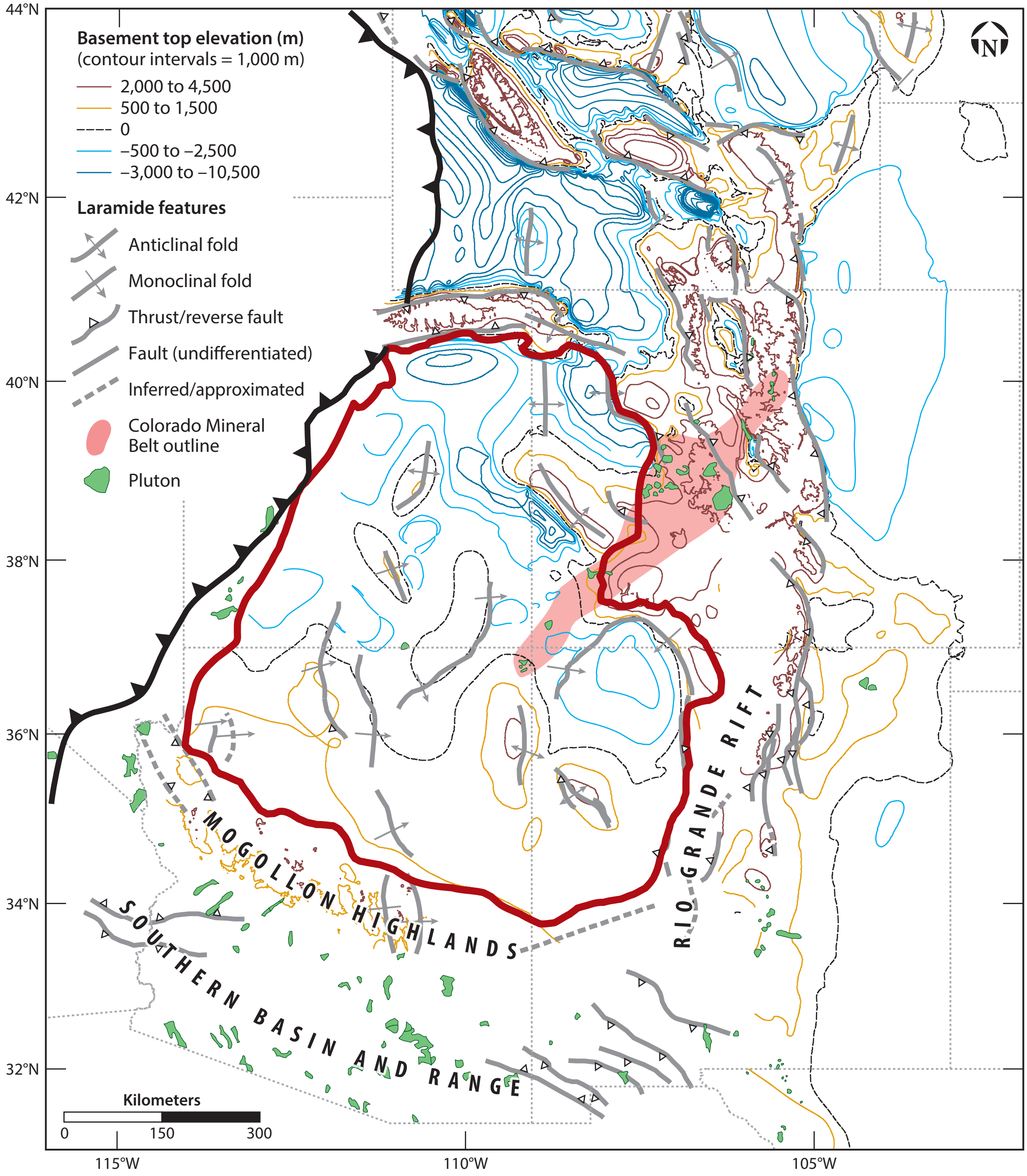

Figure 6

Modern elevation of the top of Precambrian basement (the Great Unconformity) in comparison to Late Cretaceous–Paleogene tectonic and magmatic features; note that greater than 1–2 km of Phanerozoic strata overlie this basement contact in much of the Colorado Plateau, giving a mean surface elevation of ~2 km (Pederson et al. 2002). Structural relief between arch-basin pairs increases from southwest (1–2 km) to northeast (>5 km) across the Colorado Plateau; this pattern was established in the Laramide, but structural relief has been accentuated by subsequent fault reactivation. The collapsed Mogollon Highlands remain relatively high. Data from Marshak et al. (2017).

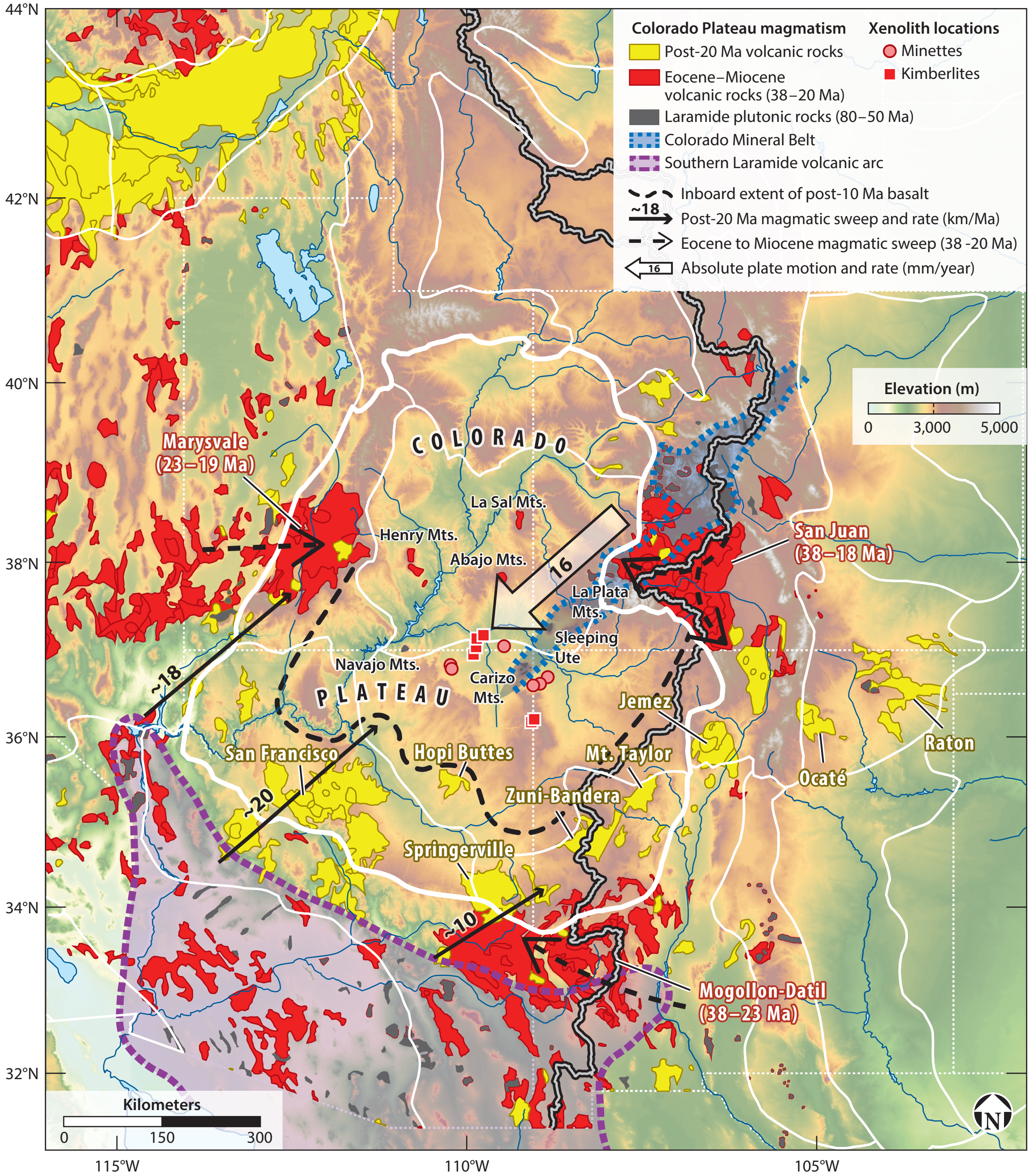

Figure 7

Cenozoic volcanism in and surrounding the Colorado Plateau. Purple indicates the locus of the southern Laramide volcanic arc; gray indicates Laramide intrusions; red indicates Eocene–Miocene (38–20 Ma) caldera complexes, laccoliths, and diatremes; and yellow indicates Neogene (20–0 Ma) volcanic fields (dominantly basalt). The Oligocene ignimbrite flare-up was the time when the Colorado Plateau was first geographically delineated—melt extraction from the mantle was likely related to prior hydration and geometry of removal of Farallon slab. Post-20 Ma sweep of basaltic magmatism (*black vectors*) is opposite absolute plate motion and tracks convective modification of lithosphere at the base of the plate.

as the surface manifestation of North American absolute plate motion of ~16 km/Ma (Kreemer et al. 2014) to the southwest through underlying asthenosphere (**Figure 3*d***). Intermediate to felsic plutons were emplaced and unroofed in the past 3–7 Ma in the southwestern San Juan Mountains (Gonzales 2015).

The northeast alignment of volcanic fields from Springerville to Raton is known as the Jemez lineament (Aldrich 1986) (**Figure 7**). It was proposed as a possible plume track because of its general alignment parallel to North American absolute plate motion (Suppe et al. 1975), but there is no apparent age trend along its length (Dunbar 2005). It has been linked to a Proterozoic suture zone at depth (Magnani et al. 2004). The volcanic fields are basaltic to intermediate in composition except the Jemez volcanic field that is located at the intersection of the Jemez lineament and Rio Grande rift and had ignimbrite eruptions at 1.61 and 1.23 Ma and rhyolite flows as young as 75 ka (Zimmerer et al. 2016). The Huegoten CO_2-rich gas field in the Great Plains may be a northeast continuation of the lineament that is allowing degassing of mantle fluids along the same trend (Crossey et al. 2016). Teleseismic imaging shows low velocities beneath the lineament in the upper mantle, but it does not have clear evidence for deeper upwelling based on mantle transition zone imaging and the geoid (Schmandt et al. 2012).

Contemporary Crustal Deformation

Relative stability of the Colorado Plateau within the slowly deforming western US Cordillera is constrained by satellite geodesy (Berglund et al. 2012, Murray et al. 2019, Broermann et al. 2021). Earthquake activity is tracked by sparse regional seismographs, except near the Wasatch Front where more extensive monitoring exists and strain rates are an order of magnitude greater (Murray et al. 2019). The interior of the Colorado Plateau (Colorado Plateau Interior Block of Broermann et al. 2021) is deforming more slowly than its margins but exhibits dilatation strain rate near the margin of detectability, −0.5 +/− 0.5 nanostrain/year, indicating slight compression or a nondeforming block embedded among adjacent extensional provinces (Broermann et al. 2021). The region spanning from the western rim of the Colorado Plateau to the western Great Plains shows broadly distributed slow extension of 1.2 (+/− 0.2) nanostrain/year (Berglund et al. 2012). It is noteworthy that multidecadal geodetic observations can detect some deformation within the Colorado Plateau, but its magnitude is small compared to the surrounding Cordillera (Murray et al. 2019). Relative stability of the Colorado Plateau interior is further supported by the concentration of seismicity near its margins (Lockridge et al. 2012, Nakai et al. 2017) (**Figure 4*d***), especially if mining-related seismicity is culled (Astiz et al. 2014). The western rim hosts the most frequent seismicity and dominantly exhibits normal faulting mechanisms (Brumbaugh 1987, 2019; Herrmann et al. 2011). However, the interior is not aseismic and occasionally hosts deep crustal, greater-than-20-km events that bolster the evidence of cold and strong lithosphere (Wong & Humphrey 1989, Lockridge et al. 2012).

LANDSCAPE EVOLUTION

The paleoelevation history of the Colorado Plateau–Rocky Mountain region as estimated by various proxy data sets currently yields ambiguous results. As summarized by Cather et al. (2012), Huntington et al. (2010), Zaborac-Reed & Leopold (2016), and Heitmann et al. (2021), a wide range of paleoelevation proxies have been applied. $\delta^{18}O$ stable isotope analyses of carbonates apply the concept that carbonates may preserve $\delta^{18}O$ of waters they precipitated from, which decreases with increased elevation, although factors that complicate $\delta^{18}O$-elevation relationships for precipitation are numerous. Paleotemperature proxies can be used to estimate mean annual surface temperature, which can be combined with lapse rate estimates (decrease of temperature with elevation) to estimate paleoelevation. Such studies include paleobotanical analyses of fossils such as leaf morphologies and nearest living relatives. Clumped isotope studies evaluate the ratio of carbonate molecules that contain heavy isotopes of both ^{13}C and ^{18}O, for example compared to sea water, to derive paleotemperature, and then an estimated lapse rate is applied to derive paleoelevation. Basalt vesicle paleobarometry is based on the concept that vesicle size distributions will vary from base to top of a sequence of flows depending on atmospheric pressure, hence elevation. So far, these methods give conflicting results both within and between methods, and reported error bars are large. Important examples include the well-studied 34 Ma Flourissant fauna lake deposits of the Front Range of the Colorado Rocky Mountains that are at a modern elevation of 2.5 km. Conflicting results suggest that the paleoelevation at 34 Ma could have been between 0.5 and 4 km depending on approach and assumed lapse rate (Heitmann et al. 2021). However, application of the coexistence approach using overlapping climatic requirements for different Flourissant taxa and their nearest living relatives suggests a mean annual temperature between 14.3 and 18.2°C and a warm temperate to subtropical flora deposited at 1–1.5 km elevation (Zaborac-Reed & Leopold 2016). This is in general agreement with pollen studies from several caldera lakes (Leopold & Zaborac-Reed 2019) and tectonic studies (Raynolds et al. 2007, Cather et al. 2012, Karlstrom et al. 2011) in suggesting ~1–1.5 km of surface uplift of the southern Rockies in the past 34 Ma.

For the younger uplift component and the core of the Colorado Plateau, clumped isotopes suggest that the Miocene Bidahochi Formation of the southern Colorado Plateau was deposited at a paleoelevation of ~1.9 km, near its modern elevation, but the error bars for this and other clumped isotope analyses are hundreds of meters to a kilometer, such that this method cannot yet evaluate proposed uplift of 40 m/Ma over the past 6 Ma (Karlstrom et al. 2017). Vesicle paleoelevation results (Sahagian et al. 2002) propose large magnitude post-10 Ma uplift that is compatible with 1,500 m of denudation in the western Rockies (Aslan et al. 2019) and significant young relief generation in the Grand Canyon (Darling & Whipple 2015), but the vesicle paleoelevation studies have been questioned (Bondre 2003, Libarkin & Chase 2003) and have not been independently reproduced. Existing paleoelevation data do seem to support the concept of multistage uplift (Heitmann et al. 2021), but relative magnitudes remain poorly constrained.

Another paleoelevation proxy involves calculating long-term differential bedrock incision of the Colorado River system from base level to headwaters. The modern river systems that drain the entire western Rocky Mountains and Colorado Plateau have developed in the past ~11 Ma, with the oldest paleoriver deposits beneath the 11 Ma Grand Mesa basalt near Grand Junction, Colorado, in the northeastern Colorado Plateau (Aslan et al. 2019). Drainage was presumably internal (Aslan et al. 2018) until the river system extended its length southward via a combination of mechanisms such as lake spillover (Douglass et al. 2009, 2020; but cf. Dickinson 2013) and groundwater sapping (Crossey et al. 2015) through older paleocanyons (Karlstrom et al. 2014) and reached the Gulf of California between 4.8 and 4.65 Ma (Crow et al. 2021). The river may have achieved a near-equilibrium concave up profile in 0.1 to 1.0 Ma (Pazzaglia et al. 1998) and was graded to sea level by 4.6 Ma (Crow et al. 2021). Thus, upstream changes in incision rate across faults and other geophysical and tectonic boundaries may be a proxy for differential surface uplift. Hamblin (1984) and Walk et al. (2019) argued for the Virgin River that both upthrown and down-dropped fault blocks (for example, of the Hurricane fault) record net incision relative to the basalt-preserved paleochannel profiles and that steady differential incision has taken place in each reach, suggesting ~1,000-m uplift of the upthrown Colorado Plateau blocks relative to sea level in the past 5 Ma rather than lowering of the elevation of Basin and Range blocks. Using similar reasoning, Karlstrom et al. (2008) and Crow et al. (2014) suggested ~700 m of differential uplift of eastern Grand Canyon relative to western Grand Canyon in the past 5 Ma. Karlstrom et al. (2011) and Rosenburg et al. (2014) proposed ~500 m of uplift of the Rockies relative to the

Colorado Plateau, suggesting a net uplift of 1–1.5 km of the Colorado Rockies relative to sea level in the past 5 Ma (similar to Raynolds et al. 2007). The observation that incision is steady at the 1–2 Ma timescale in a given reach but differs between reaches (Karlstrom et al. 2008, Crow et al. 2014, Aslan et al. 2019) implies differential uplift (Anderson et al. 2021) rather than passage of knickpoint transients (Cook et al. 2009) or other climate and geomorphic forcings.

Alternatively, some researchers have argued that Neogene uplift is not required to explain the observed differential incision data in some locations (Ott et al. 2018). The alternative no-young-uplift hypothesis is that climatically and geomorphically driven integration of the Colorado River system took place in a region that was already fully uplifted (Pederson et al. 2002, Huntington et al. 2010, Wernicke 2011). Some researchers question or de-emphasize any association between geomorphic features and modern mantle velocity patterns, neotectonic faulting, or magmatic trends and explain the ~2 km of post-5 Ma differential incision data in terms of knickpoint transients and isostatic rebound from differential erosion (Pederson et al. 2013, Bursztyn et al. 2015; but cf. Lazear et al. 2013).

GEODYNAMICS AND SYNTHESIS

The Colorado Plateau, and much of the Cordillera, was near sea level ~75 Ma, and it has been uplifted to its present ~2-km average elevation in three episodes described above, but the relative importance of each uplift episode is unresolved. Uplift, however, is not the only consideration regarding emergence of the Colorado Plateau as a distinctive lithospheric and physiographic province. There is also ambiguity regarding the physical origins of the Colorado Plateau's modern buoyancy and strength. Surrounding post-Laramide (Oligocene to present) magmatism and extension helped define the Colorado Plateau because they were suppressed or subdued across the peninsula of thicker lithosphere extending from the Colorado Plateau and into the Wyoming province (**Figure 3*c*,*d***). This keel as a whole, and the Colorado Plateau individually, crosscut major Precambrian province boundaries so their distinct modern structure is not easily linked to inheritance from Precambrian continental assembly. To synthesize major events leading to the emergence of the Colorado Plateau and its ongoing and gradual outside-in demise, we consider geodynamic linkages among modern constraints on deep structure and geological constraints on spatiotemporal evolution.

Geophysical imaging and geodynamic studies of the modern Colorado Plateau indicate that its core, with a mean elevation of ~1.6 km, is nearly stable from the perspectives of geodetic surface horizontal displacements (Murray et al. 2019, Broermann et al. 2021), isostatic support (Becker et al. 2014), and the ongoing presence of thick lithosphere (Schmandt & Humphreys 2010, Shen & Ritzwoller 2016). How and when did this stable, high-standing core emerge? For analyses of topography that is isostatically compensated at wavelengths greater than the flexural wavelength (conditions that are generally applicable), the geoid/topography ratio (GTR) can be used to estimate the depth of compensation (Coblentz et al. 2011). The Colorado Plateau has a moderate GTR of ~4 m/km (**Figure 1*d***), which is intermediate between provinces with strong evidence for focused deep mantle buoyancy (e.g., Yellowstone's ~7.5 m/km GTR) and provinces that are fully compensated at crustal depths (e.g., Great Plains average of ~2 m/km). These observations support the notion that most of the Colorado Plateau's buoyancy is within the uppermost ~100 km, thus highlighting the importance of ~75 Ma to present evolution of the crust and shallow mantle lithosphere. Modest Laramide shortening affected a broader region and swept across the Colorado Plateau from ~90 to 75 Ma (Thacker et al. 2021). More focused effects on the Colorado Plateau and Wyoming province are plausible following the model that subduction of the conjugates of known Pacific oceanic plateaus traversed the base of the lithosphere along this corridor [the conjugate Hess Rise (Livaccari et al. 1981), but more likely the conjugate Shatsky Rise (Liu et al. 2010)]. The thick thermal boundary layer and altered oceanic crust could cause cooler temperatures and hydration to propagate into the overlying lithosphere. Cooling would transiently increase density and viscosity until the effects are gradually reversed following slab removal. The first episode of uplift associated with the Laramide is likely important to modern properties of the province's core, but insufficient to delineate it within the Cordillera or raise it to its present elevation.

The subsequent ignimbrite flare-up produced voluminous eruptions around the margins of the Colorado Plateau with smaller eruptions and intrusions in its core, thereby spatially isolating it within the Cordillera. Large ignimbrite eruptions in the peripheral San Juan, Mogollon-Datil, and Great Basin volcanic fields suggest the interior possessed sufficiently thick and cold lithosphere to prevent such voluminous inputs of upper mantle melt (e.g., Farmer et al. 2008). Nonetheless, increased thermal buoyancy is expected through the Oligocene due to intense magmatism at the edges and more subdued magmatism in the province's core, consistent with evidence for increased exhumation (Lazear et al. 2013). Upward propagation of volatiles from the former Laramide slab would decrease the density of mineral assemblages in the lithospheric mantle and lower crust (Levandowski et al. 2018), consistent with evidence from xenoliths (Humphreys et al. 2003, Smith et al. 2004, Jones et al. 2015, Schulze et al. 2015, Hoover et al. 2020). Crustal extension would have further defined the Colorado Plateau as a distinct province by the mid-Miocene on account of Basin and Range and Rio Grande rift extension.

An outstanding question is why were magmatic and extensional events suppressed in the core of the Colorado Plateau? Thicker and stronger lithosphere is necessary, but the source is unclear. Possibilities include maintenance of thicker lithosphere above the flat slab, which is plausible for areas to the southwest where basal erosion of North America lithosphere by the flat slab is estimated to be more severe based on exhumation and xenolith constraints (Saleeby 2003). On the east side, reactivation of earlier structures is likely, perhaps driven by steepening of the flat slab beneath the Rocky Mountain front region that amplified weakness in the upper plate and helped control the position of the Rio Grande rift (Ricketts et al. 2016). An additional hypothesis is that removal of the flat slab from the base of North America was delayed and may still be incomplete beneath portions of the Colorado Plateau and Wyoming province (Schmandt & Humphreys 2010). At the conclusion of the second episode of uplift, the Colorado Plateau would have been tectonically and magmatically distinct, but key modern features such as its deeply incised river network and tectonically active rim were still developing.

The Neogene to modern rim of the province exhibits higher elevations, inward-propagating magmatic activity, extensional deformation, and high rates of landscape evolution. A spatial map of geoid-elevation ratio (Coblentz et al. 2011, figure 8) suggests that the more active rims on the south, east, and west sides are compensated at slightly greater depths, implying a stronger role for young structural evolution of the uppermost mantle (**Figure 1*d***). Geodynamic modeling incorporating crust and mantle properties from EarthScope seismic data along with complementary geophysical constraints such as gravity and heat flow indicate that the core of the Colorado Plateau appears stable, but there is an increased role for ongoing mass redistribution due to small-scale convection beneath the rim (Becker et al. 2014). Thermal edge convection, melt infiltration, and lithospheric delamination may all be shrinking the stable core. Edge convection operates at any step in thermal boundary layer thickness such as the margins of the Colorado Plateau by creating a localized convection cell (van Wijk et al. 2010, Ballmer et al. 2015) (**Figure 5*d***). Additionally, the flow of partially molten asthenosphere around the leading edge of the Colorado Plateau lithosphere, as it moves southwest with North America, can drive melt infiltration that accelerates erosion of the thermal lithosphere (Crow et al. 2014, Plank & Forsyth 2016, Roy et al. 2016). Finally, spatially isolated and deeper protruding high-velocity anomalies may represent larger volumes of dense foundering lithosphere (**Figure 3*c*,*d***). The high-velocity anomaly beneath central-southern Utah is linked to disrupted seismic interfaces near the regional Moho and lithosphere–asthenosphere boundary that could indicate a delamination-style instability (Levander et al. 2011). Thus, there is evidence for a spectrum of small-scale convective processes that destabilize Colorado Plateau lithosphere and increase mantle buoyancy at its edges. Mantle flow modeling and crustal stress orientations suggest the advancing front of small-scale convection drives the crustal transition to active intraplate extension (Becker et al. 2015). By this interpretation, adjacent provinces (except Wyoming) variously represent more advanced stages of lithospheric thinning and transition to postorogenic extension.

CONCLUSIONS

The association of young physiography, modern geophysics, young magmatism, and young differential incision warrants the conclusion that the Colorado Plateau is a less than 10 Ma physiographic province with a central bowl being carved by the post-11 Ma Colorado River system and uplifting rims defined by young faults and volcanic fields. Most researchers agree that its overall uplift history involved several stages: Late Cretaceous–Paleogene, mid-Tertiary, and post-20 Ma. Its margins include a series of older reactivated structures such as the Paleozoic Cordilleran miogeocline hingeline and frontal thrusts of the Sevier thrust belt on the west and various Laramide faults and monoclines on the north and east. But we suggest that the Colorado Plateau province was first crudely defined during the mid-Tertiary ignimbrite flare-up. This event set the stage for Neogene to ongoing extension that propagated inward from the southwest and was separately initiated on the east side by steepening and break off of the Farallon flat slab. The Colorado Plateau is geophysically defined by a cold and thick lithospheric core. Sharp transitions in most geophysical data sets are observed about 100 km inboard of the physiographic boundaries on all but the northeast margin. These transitional domains contain post-20 Ma basaltic magmatism that extends beyond the plateau's uplifted edges and results from an inboard sweep of small-scale mantle convection that is thinning the lithosphere on the west, southwest, and eastern margins.

This summary has led us to the hypothesis that the Colorado Plateau is not a separate microplate but rather the present manifestation of lithospheric thinning and magmatic modification taking place at the leading prow as the North American plate moves southwest through the asthenosphere. Young tectonism within the interior of the Colorado Plateau further challenges the notion of a stable Colorado Plateau microplate and motivates the need to better quantify the magnitudes of the different uplift events. Although prominent and geologically intriguing, the Colorado Plateau, relative to cycles within plate tectonics, appears to be a transient feature that is best defined by dynamic activity along its margins and thus may vanish as quickly as it appeared.

FUTURE OUTLOOK

Critical data needed to address unresolved issues about the Colorado Plateau and its margins include the following: (*a*) Paleoelevation data using multiple proxies need to be cross calibrated to track differential uplift through time and across the region. (*b*) The role, scale, and timing of lithospheric delamination in driving differential uplift remain unquantified; improved structural imaging of the lithospheric keel and its internal interfaces could provide key constraints to advance geodynamic models. (*c*) The extent that Neogene differential river incision tracks differential surface uplift remains controversial within geomorphic and neotectonic communities. (*d*) Refined dating and geochemistry of Neogene basaltic volcanism is needed to resolve the rate and directions of the volcanic sweeps across different margins of the Colorado Plateau compared to North

American absolute plate motion. (*e*) Quantifying the youngest component of Colorado Plateau uplift (past 10 Ma) will allow geodynamic models to work backward to understand the processes and relative magnitudes of Oligocene and Laramide uplift components.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

We thank National Science Foundation awards for partial support (EAR-1348007 and EAR-1347990 to K.E.K.; and EAR-1554908 to B.S.). We thank the following students for compilations and discussions contributed during a University of New Mexico graduate seminar: Jordan Anderson, Roselyn Hurlow, Kory Kirchner, Sarah Nolt-Caraway, Brionna O'Connor, Brynna Siluk, Carmen Winn, and Daniel Young.

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Annual Review
of Earth and
Planetary Sciences

Volume 50, 2022

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Errata

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