Touring Pikes Dome - Deformation of the Rocky Mountain Erosion Surface and Its Effects on Landscape Evolution and Drainage Reorganization across the Colorado Piedmont and Front Range.

Field trip guide for the Colorado Scientific Society

September 9-10, 2023

Co-Leader and field guide author: Ned Sterne (Independent)

Co- Leaders: Cal Ruleman (USGS), Bob Raynolds (DMNS), and Steve Keller (CGS)

Introduction

Since the 1870's when Archibald R. Marvine, geologist extraordinaire with the Hayden Expedition, recognized the accordant summits of the Front Range were beveled by erosion, geologists have pondered the evolution of what we now call the Rocky Mountain Erosion Surface (RMES). The surface formed between the end of Laramide contraction at ~45Ma and the advent of extension and voluminous volcanism of the Ignimbrite Flareup that blanketed it by ~37 Ma. These events bracket a period of stasis in the trajectory of the subducting Farallon Plate relative to the overriding crust of North America, once the plate reached its easternmost excursion due to flattening of its subduction angle, and it began to roll back to the west or founder.

The RMES is a surface of variable relief. What caused the relief and when it developed have long been debated by geologists and will be the focus of our field trip. Luminaries such as Thomas S. Lovering and Francis M. Van Tuyl explained the relief solely by erosion with the oldest of 14 surfaces preserved at high elevations and the youngest at low elevations. In contrast, illustrious pioneers such as Samuel H. Scudder, Arthur Lakes and George H. Stone recognized relief on the RMES was also due to later deformation by studying the ancestral rivers that once flowed across it.

During this trip we will be traversing Pikes Dome, a post-Laramide uplift that extends some 500 km from west of Pikes Peak east into western Kansas. Since its initial rise in the latest Eocene, the dome diverted the southerly flows of the ancestral South Platte and extinct Castle Rock rivers first to the east into the extinct Hayden-Divide-Arikaree River and finally to the northeast into the current course of the South Platte River. We will also ponder the Arkansas River that flowed south through the Wet Mountain Valley during the middle to upper Eocene and was diverted east during the Oligocene-Miocene between the rising Pikes Dome on the north and the Raton Dome on the south. Our discussion will be framed by a new structure map of the RMES across Colorado and parts of neighboring states compiled by past CSS president, Ned Sterne, and ongoing cosmogenic, detrital zircon and detrital sanidine dating of the various ancestral river gravels that rest on the RMES.

Our travels will take us south of Denver to Jackass Hill, Daniels Park, Castle Rock, Castlewood Canyon State Park, the Paint Mines Interpretive Park at Calhan, the Florissant Fossil Beds National Monument, Lake George, Tarryall Creek, Divide, Woodland Park, the Rampart Range and back to Littleton via Deckers and the South Platte River (Fig. 1). Join us as we follow the path forged by a host of CSS past presidents who have grappled with the evolution of our Cenozoic landscape, including Matt Morgan, Vince Matthews, Emmett Evanoff, Jack Reed, Rudi Epis, Wally Hansen, Tom Steven, Glen Izett, Glenn Scott and Ogden Tweto.

The principal themes of this trip are:

1) Mapping relief on the RMES, a composite unconformity overlapped by upper Eocene to basal Pleistocene deposits.

2) Characterizing relief on the RMES as depositional, structural or some combination of the two using past and present rivers to detect drainage reorganization and reversals, or where low-temperature thermochronologic data are available, using isochron surface mapping to detect deformation.
3) Dating enigmatic high-level gravels using cosmogenic, detrital zircon, and detrital sanidine techniques constrain timing for the development and deformation of the RMES.

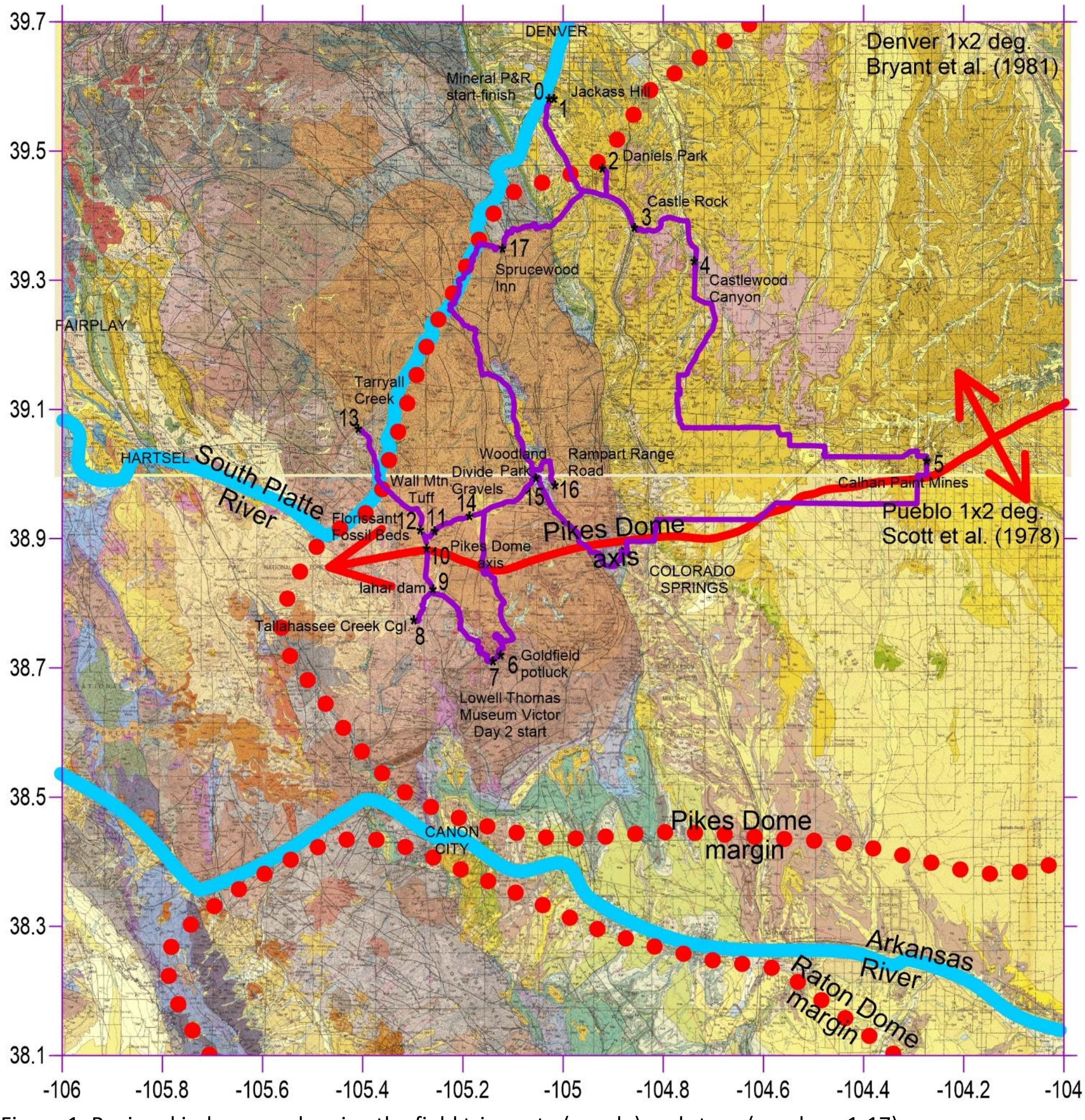


Figure 1. Regional index map showing the field trip route (purple) and stops (numbers 1-17).

Regional overview

The Rocky Mountain Erosion Surface (RMES) is a surface of variable relief that bevels the Laramide basement uplifts and basins of Colorado. It formed during a period of relative tectonic quiescence between the end of Laramide contraction at ~45 Ma and the advent of the ignimbrite flareup at ~37 Ma. Relative to Farallon Plate behavior, the RMES developed during the incipient stages of slab rollback or foundering, after the plate had reached its easternmost excursion due to flat-slab subduction (Fig. 2)

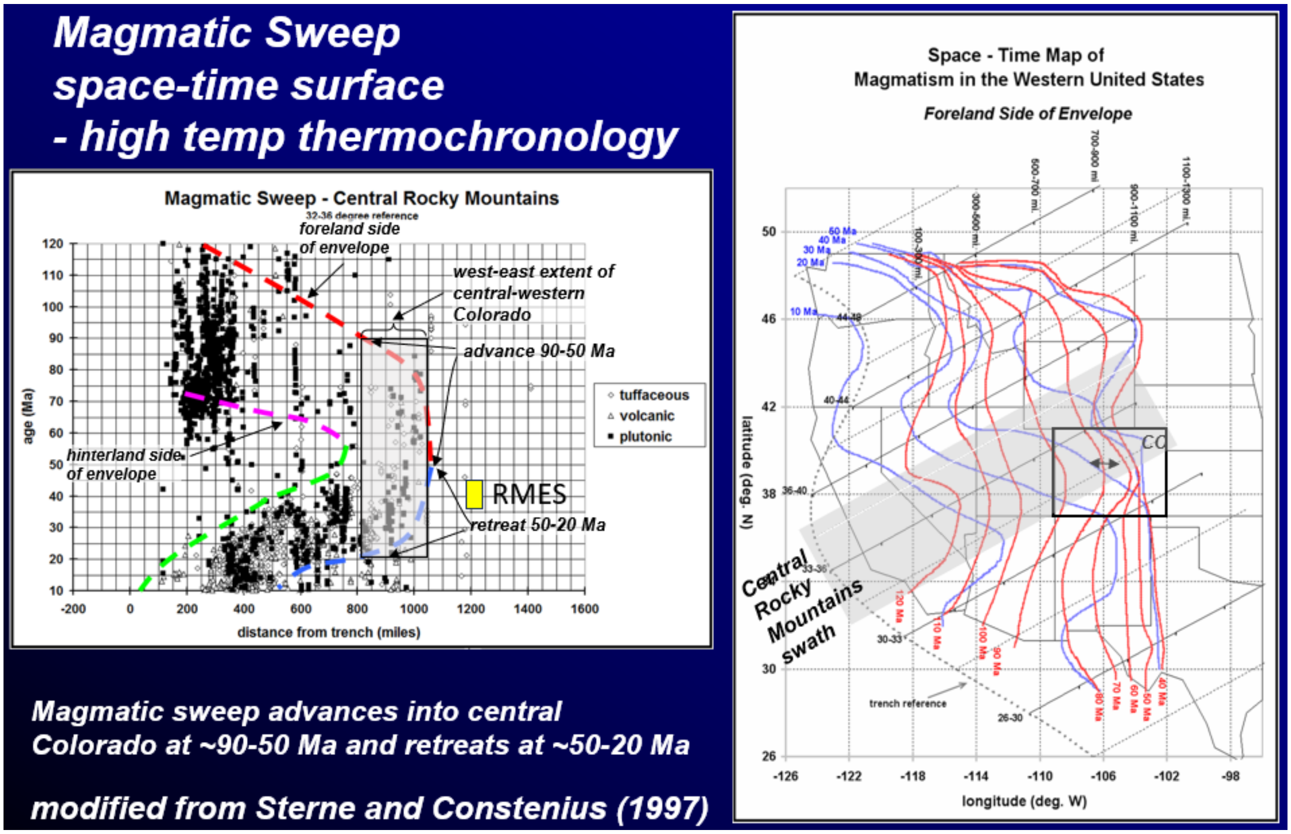


Figure_2. Magmatic sweep diagram for the central Rocky Mountains showing the development of the RMES between ~45 Ma and 37 Ma after the Farallon Plate had reached its easternmost excursion and during its incipient rollback or foundering.

Mapping structure of the RMES across Colorado and parts of neighboring states necessitated treating it as a “composite surface” (Evanoff and Chapin, 1994) involving multiple unconformities overlapped by strata of upper Eocene to earliest Pleistocene age. Three types of datums on the RMES were used to define the surface: 1) base of overlap deposits from geologic maps, 2) subsurface points from wells, gravity and seismic, and 3) “supersurface” points at or above current topography in areas devoid of overlap deposits (Fig. 3).

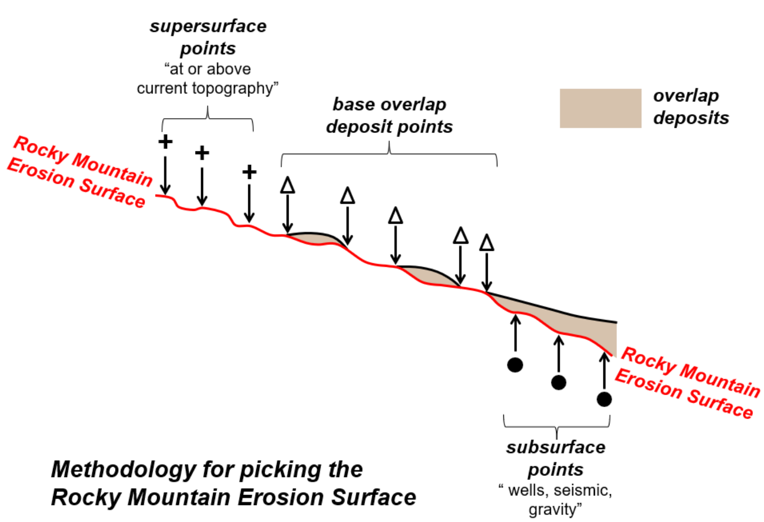


Figure 3. Methodology for picking datums on the RMES that results in a continuous “composite surface” across Colorado and parts of neighboring states.

The resultant RMES structure map for Colorado shows approximately 9000 meters of relief, with highs across the peaks of central Colorado, the San Juans and the Sangre de Cristo Range, a pronounced low in the San Luis Basin, and broad interfluve highs across the eastern piedmont (Fig. 4). Its shape is familiar to us because it mirrors the current topography of Colorado. While the Ancestral Rockies and Laramide orogenies built the first-order structure of our state, we inhabit a landscape shaped in large part by later forces that created relief on the RMES.

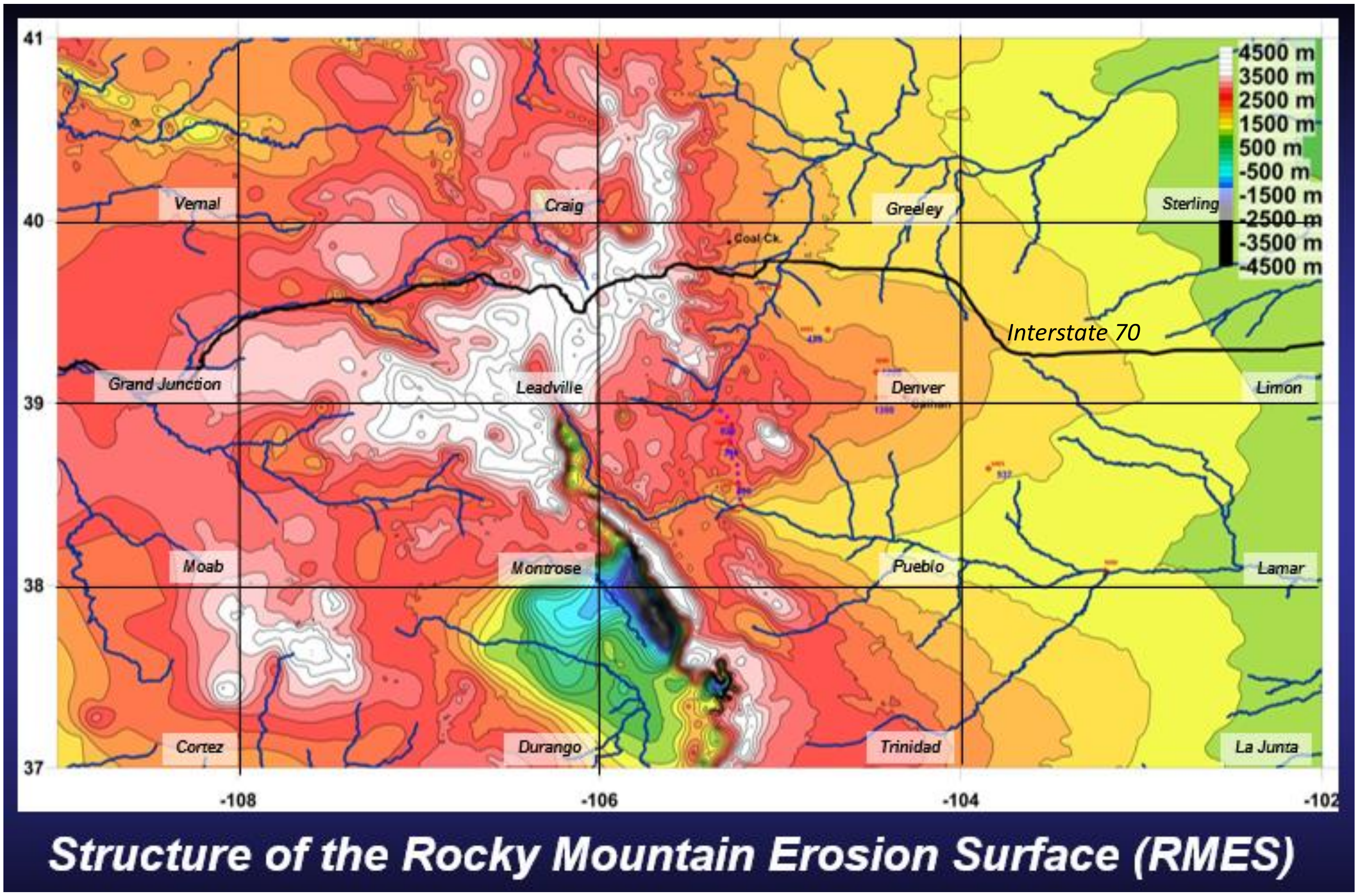


Figure 4. RMES structure map for Colorado showing major river courses, 1°x2° quadrangles, and Interstate 70.

Relief on the RMES is a function of differential erosion and Cenozoic tectonics. Deformation of the RMES is manifest in a variety of structures, including extensional basins, evaporite dissolution basins, flank uplifts along the Rio Grande Rift, laccoliths, and broad interfluve domes across the eastern piedmont. The focus of our field trip will be Pikes Dome, an interfluve high between the South Platte and Arkansas rivers that extends from west of Pikes Peak eastward off the map into western Kansas (Fig. 5).

Regional maps of relief on the RMES and closely associated surfaces have been done by several authors. The eastern plunge of Pikes Dome was mapped by Smith (1940). Leonard (2002) mapped the base of the Ogallala across eastern Colorado. McMillan et al. (2006) mapped the top of basin fill or top of the overlap deposits on the RMES across much of Colorado and parts of neighboring states. Karlstrom et al. (2012) and a similar author group, Lazear et al. (2013) mapped a 10 Ma paleosurface across Colorado. Regional studies of the overlap deposits and their paleo-drainages have been done by Epis and Chapin (1975), Epis et al. (1976), Scott (1975), Taylor (1975), Scott and Taylor (1986), Steven et al. (1997), and Condon (2005).

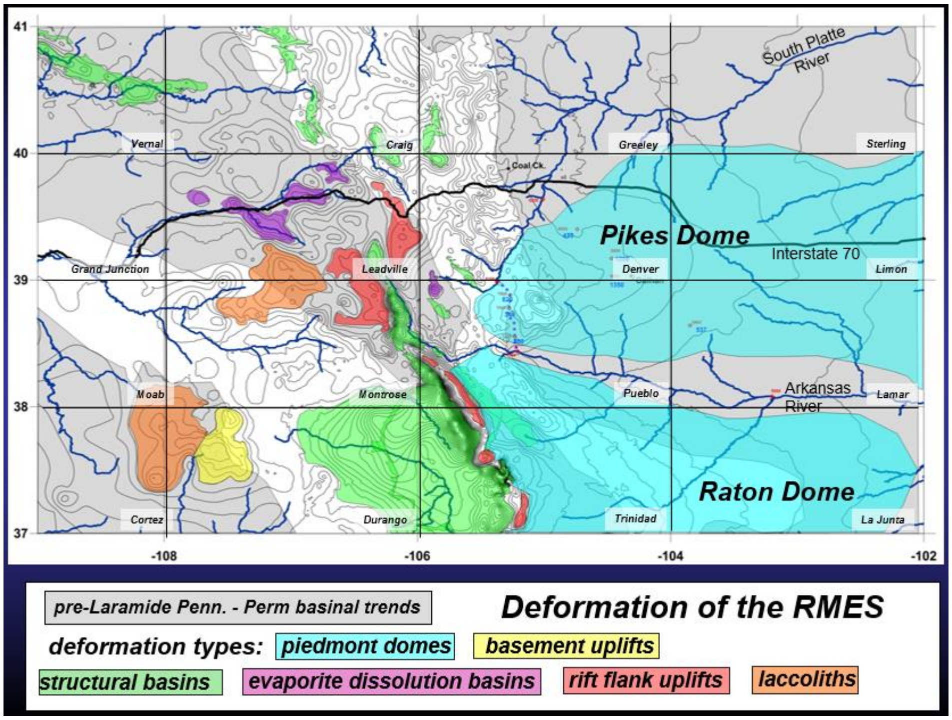


Figure 5. Types of deformation impacting the RMES. Gray areas show basins flanking Pennsylvanian to Permian uplifts of the Ancestral Rocky Mountains. Post-Laramide deformation of the RMES takes a variety of forms including basement uplifts, extensional basins, evaporite dissolution basins, rift flank uplifts, laccoliths, and the principal focus of our field trip, piedmont interfluve domes.

Smoothed topography across Colorado and neighboring states reveals the Southern Rocky Mountain epeirogen (SRMe) of Eaton (2008), a post-Laramide uplift centered on the high peaks of Colorado. Our field trip will focus on Pikes Dome, one of the second-order noses that populate the eastern flank of the uplift (Fig. 6). By extending the mapping beyond Colorado into parts of neighboring states it becomes apparent how closely current topography mirrors relief on the RMES (Fig. 7).

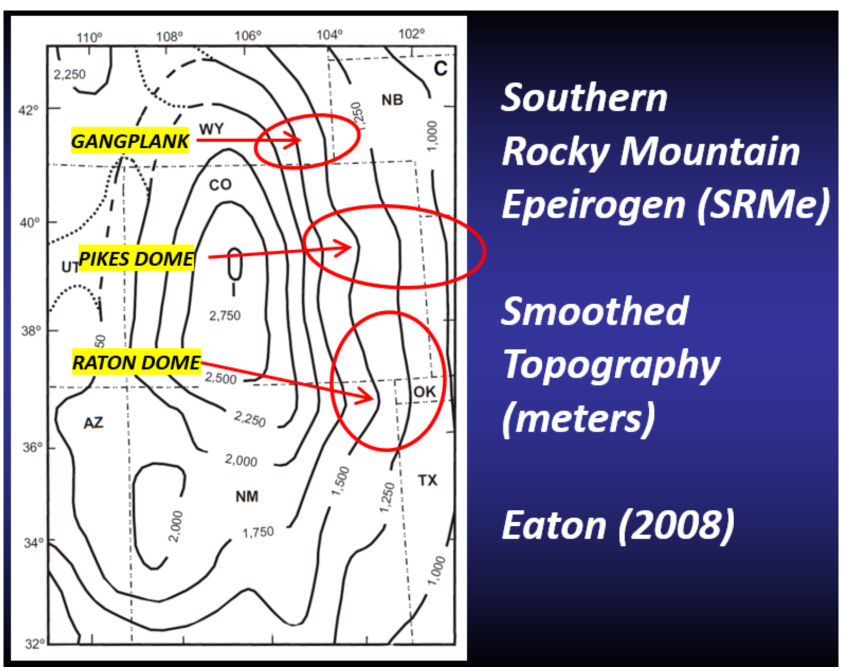


Figure 6. Smoothed topography defining the Southern Rocky Mountain Epeirogen (Eaton, 2008) showing second-order noses along its eastern flank, including Pikes Dome.

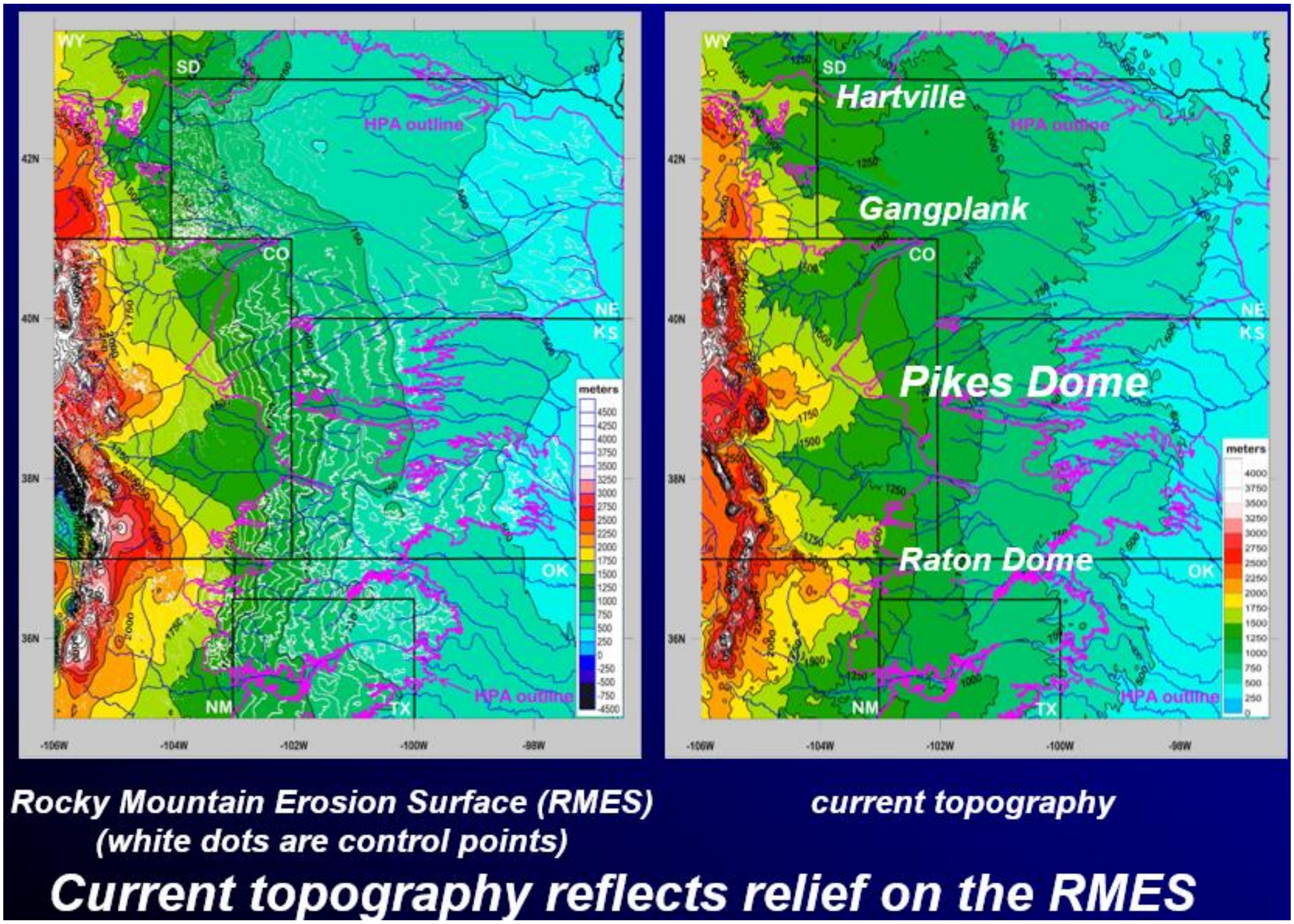


Figure 7. Comparison of the RMES with current topography showing current topography reflects relief on the RMES.

To better understand the relief and extent of the second-order noses along the eastern flank of the SRMe, we treat the first-order SRMe as a regional trend surface and subtract it from the RMES. This approach is similar to the way regional trends are subtracted from potential field data (gravity and magnetics) to highlight local anomalies. The first-order regional trend surface is based on RMES datums sampled along the major rivers that flank the piedmont interfluve highs (Fig. 8). Once the regional trend surface is subtracted from the RMES, the resulting residual thickness map (Fig. 9) shows Pikes Dome extends ~500 km from central Colorado into western Kansas and has 800 meters of relief independent of Pikes Peak proper (with its additional 1000 meters of relief). Raton Dome is centered on the laccolith at the Spanish Peaks and exhibits 900 meters of relief. Several smaller piedmont structures occur north of Colorado into southeastern Wyoming, western Nebraska and southwestern South Dakota.

Having framed the piedmont domes, the question remains whether their relief represents erosion or deformation. During the field trip we will visit three ancestral rivers on Pikes Dome that exhibit drainage reversal or inversion. Rivers don't flow uphill, so such drainage reversals show the dome is a structural high rather than a monadnock. Tracking these ancestral rivers through the Cenozoic allows us to see the evolution of the piedmont structure as it reroutes the rivers flowing across the RMES. During the upper Eocene, the major piedmont rivers including the Castle Rock, the ancestral South Platte and the ancestral Arkansas flowed to the south or southeast (Fig. 10).

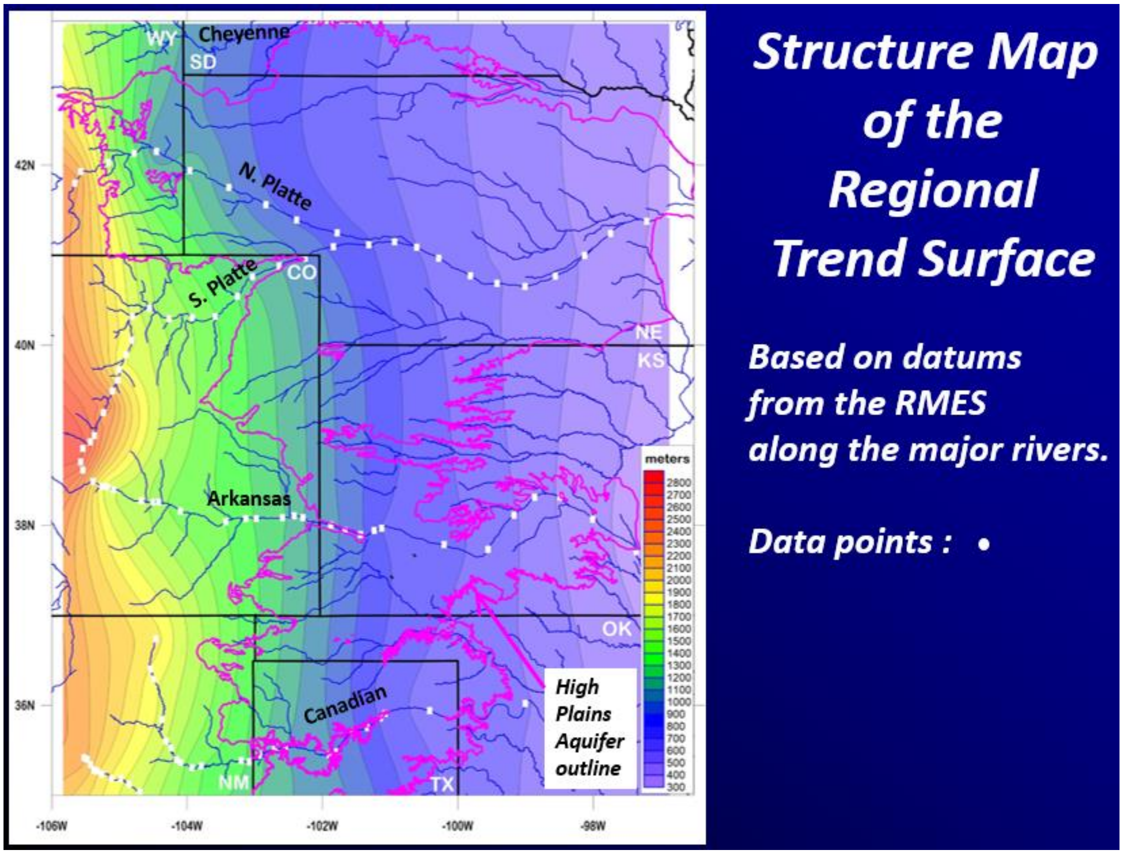


Figure 8. Regional trend surface based on RMES datums sampled along major rivers. Fuchsia outline shows the limits of the High Plains Aquifer.

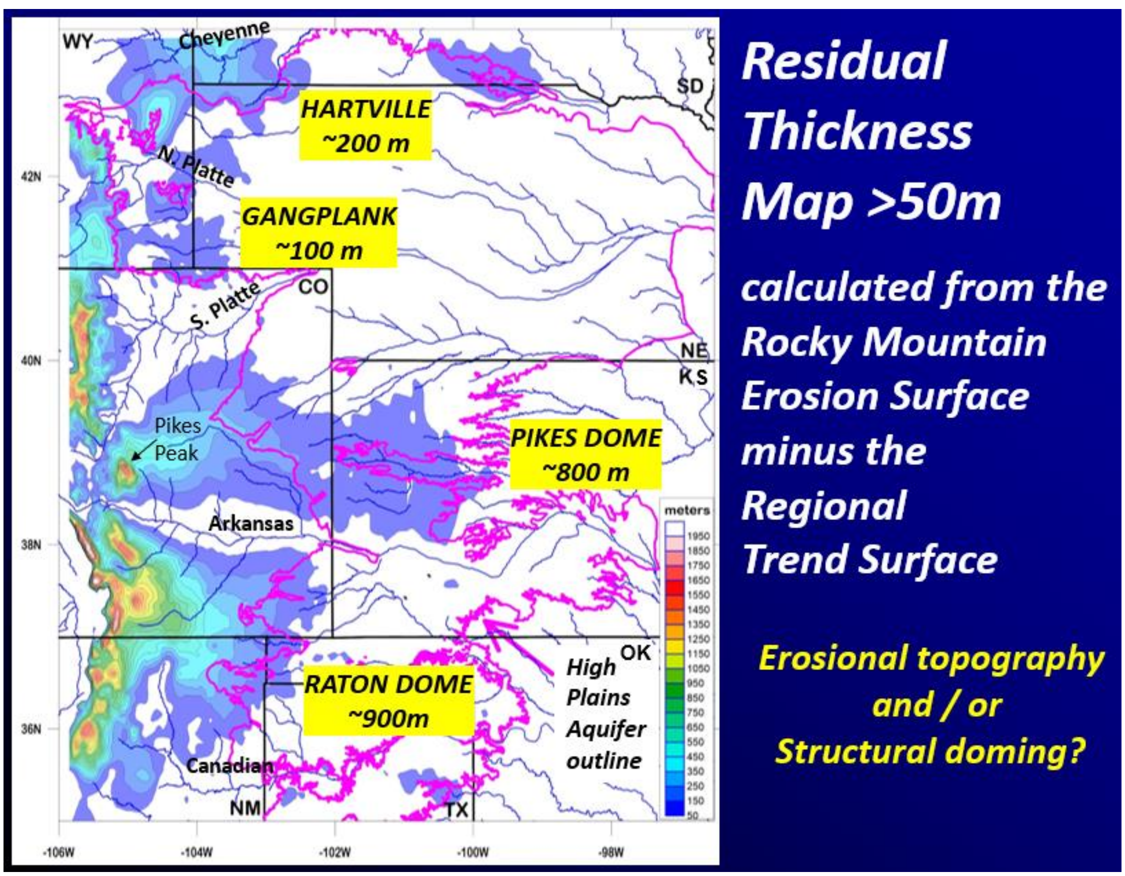


Figure 9. Residual thickness map showing piedmont domes is calculated by subtracting the regional trend surface from the RMES.

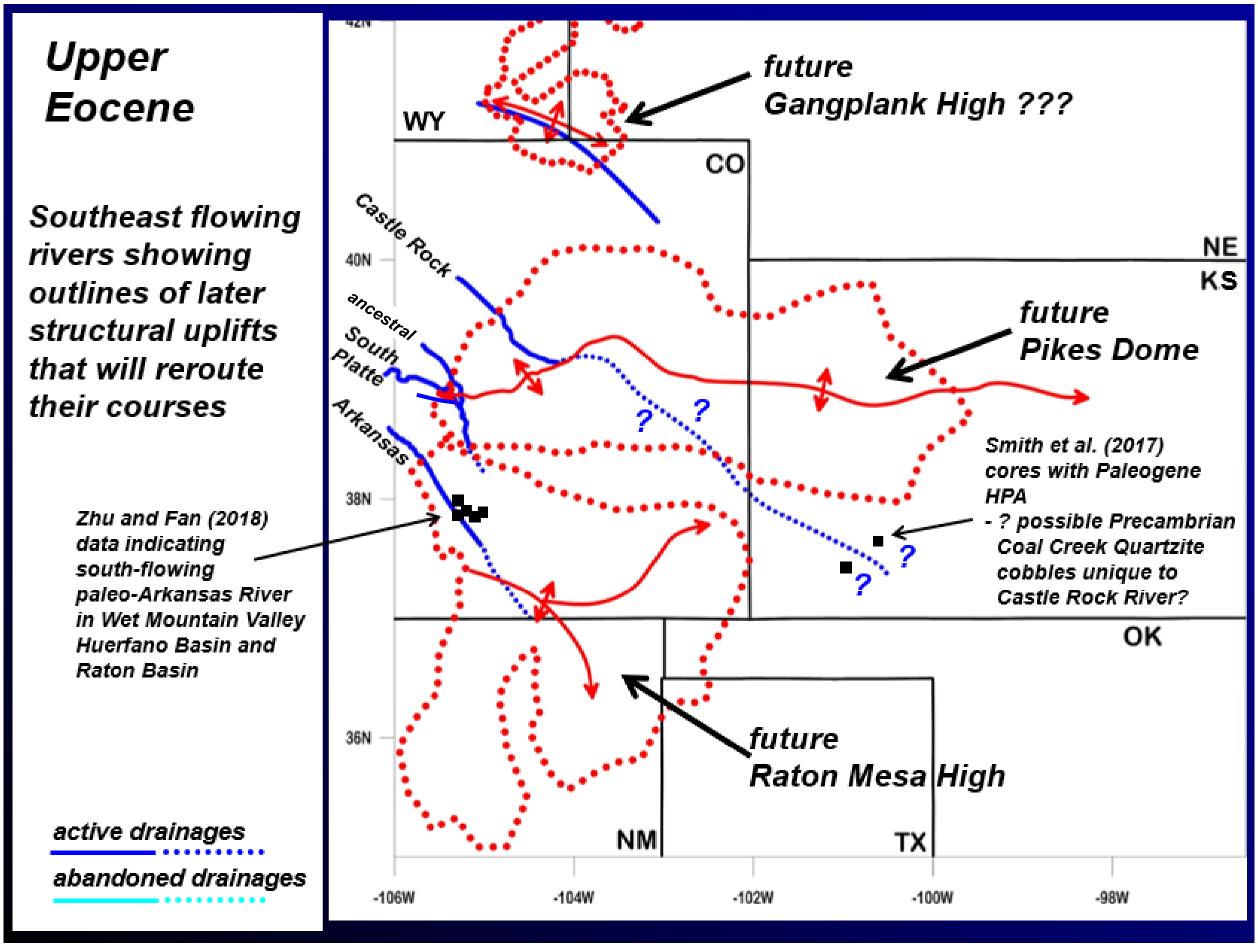


Figure 10. South- to southeast-directed piedmont river courses during the upper Eocene and locations of future piedmont domes.

At the Eocene-Oligocene boundary, initial growth of the Pikes and Raton domes destroys or reroutes the Castle Rock River, reverses the Ancestral South Platte River causing, along with the Thirtynine Mile Volcanics, the Florissant and Antero lakes to form as South Park becomes internally drained, and shifts the Ancestral Arkansas River from the Wet Mountain Valley to its present course between the rising domes (Fig. 11). During the Oligocene to Miocene, continued growth of Pikes Dome and regional eastward tilt due to uplift of the SRMe reroute the Ancestral South Platte to the east-northeast to become the variously named Extinct Hayden River of Stone (1900), the Ancestral-Arikaree River of Pearl (1971) or the Divide River of Steven et al. (1997) (Fig. 12). Here it will be called the Hayden-Divide-Arikaree River. During the Miocene to Present renewed uplift in the western part of Pikes Dome centered on Divide and Cripple Creek and encompassing Pikes Peak proper destroyed the Hayden-Divide-Arikaree River, thereby diverting the ancestral South Platte River to its present course along the northern margin of Pikes Dome (Fig. 13). These doming events are the reason the current South Platte River flows southeast across South Park, then makes a 90-degree left turn at the Pikes Dome margin and flows northeast to Denver and beyond.

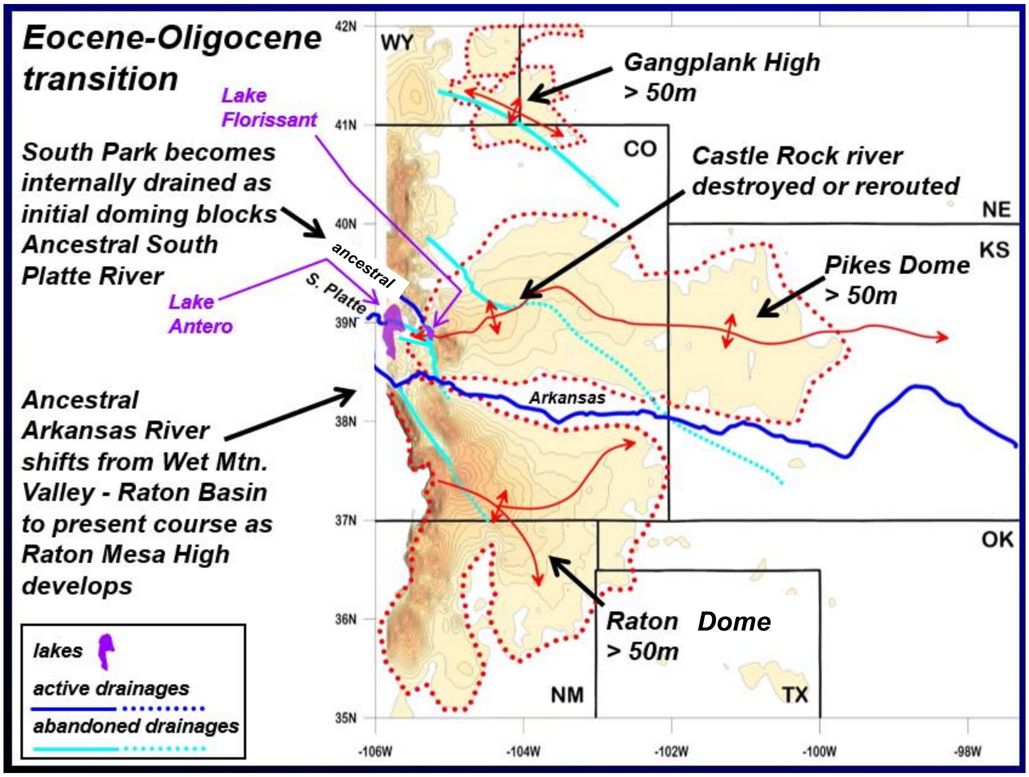


Figure 11. Initial growth of the Pikes and Raton domes at the Eocene-Oligocene transition. Lahar dams and initial uplift of Pikes Dome disrupts the tributaries of the ancestral South Platte River causing South Park to become internally drained. Uplift of Raton Dome diverts the Arkansas River from the Wet Mountain Valley to its present course between the rising Pikes and Raton domes.

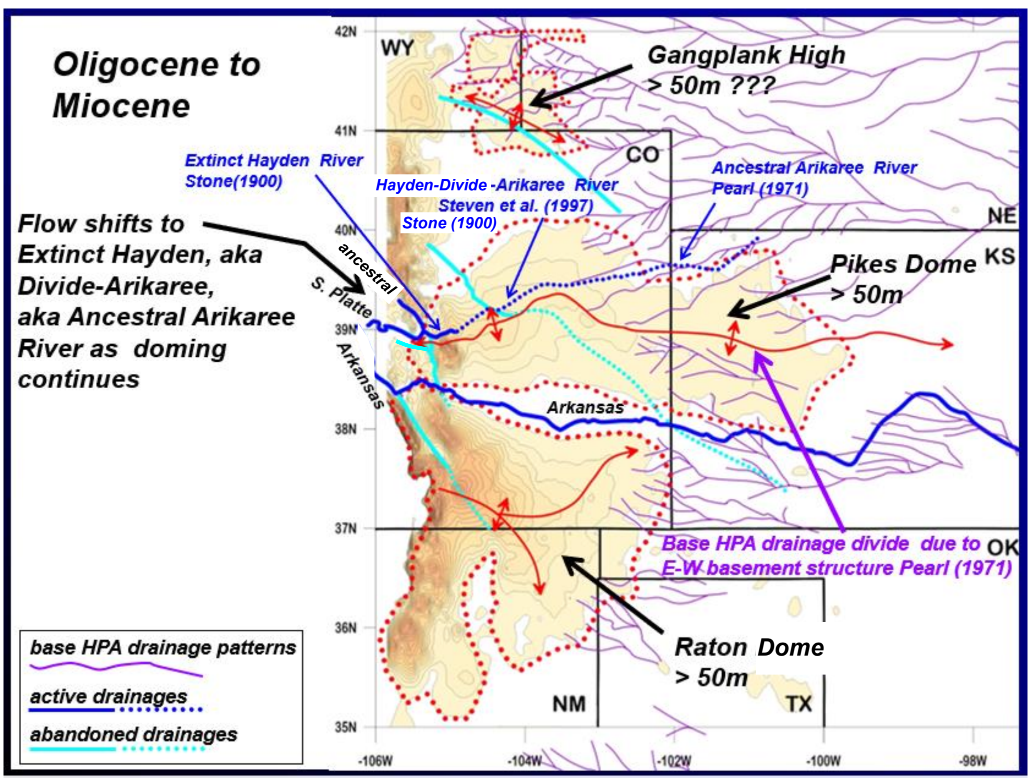


Figure 12. Continued uplift of Pikes Dome during the Oligocene to Miocene diverts the ancestral South Platte River to the east-northeast north of the Pikes Dome axis into the Hayden-Divide-Arikaree River. Purple lines show the pre-Ogallala drainage patterns. Prominent drainage divide in western Kansas is coincident with the Pikes Dome axis and shows the dome was active before the Ogallala was deposited.

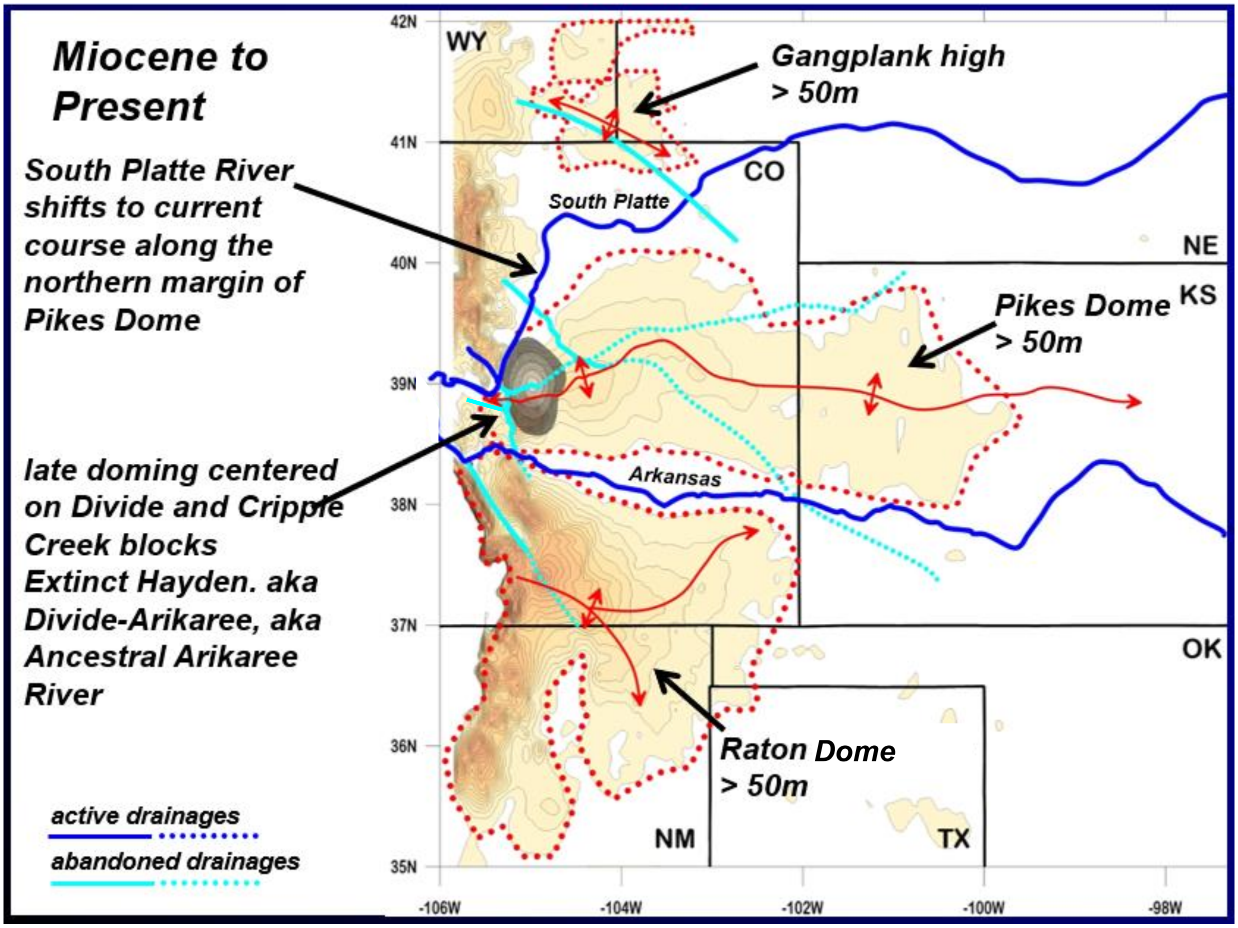


Figure 13. Miocene to Present uplift in the western reaches of Pikes Dome diverts the Ancestral South Platte River into its current course along the northern margin of Pikes Dome.

Descriptions of the field trip stops

Day 1 Overview.

The first day of this trip will start with a discussion of the implications of working with a composite surface, formed during multiple erosional cycles. By starting on the north, we are seeing, based on recent cosmogenic dating, a relatively young part of the RMES capped by early Pleistocene deposits. As we head south, we will encounter older parts of the RMES overlapped by a variety of upper Eocene, Oligocene, and Pliocene strata. This difference may reflect the current high elevations across much of the northern Front Range compared to the south with its single high area around Pikes Peak (Fig. 4). The northern areas are more glaciated, so it makes sense that there the RMES has been stripped of its older overlap deposits and is now capped by early glacial deposits.

Figure 14 depicts the stratigraphy of South Park, Florissant, the Front Range and the Denver Basin we will visit or discuss during the trip. The Cretaceous to middle Eocene portion of the chart shows marine units deposited in the Laramide foreland basin and later synorogenic deposits shed off the Laramide contractional basement uplifts. The blue lines show portions of the RMES capped by deposits of various ages. On Saturday we will discuss the Central City Gravels and Rocky Flats Alluvium that lie on the northern, younger part of the RMES in the central Front Range and adjacent Denver Basin. As we head south, our focus will shift to Paleogene Wall Mountain Tuff (36.7 Ma) and Castle Rock Conglomerate (~35 Ma) deposited in the southeast-flowing extinct Castle Rock River. At Calhan we will cross the axis of Pikes Dome. On its southern flank, the RMES is capped by

Nussbaum Alluvium, that has been attributed variously to the Miocene, Pliocene and Pleistocene (Scott, 1963). Detrital zircon dating of Nussbaum samples from Baculite Mesa near Pueblo are currently in progress. To the east at the longitude of Limon, the northern and southern flanks of the Pikes Dome are overlapped by upper Eocene to Oligocene deposits, while rocks immediately above the RMES astride the dome axis at Cedar Point yield a youngest single zircon grain of 23 Ma, indicating the "Ogallala" in this locale may be as old as the Arikareean (Matt Morgan, pers. communication). Sunday will find us traversing from the Florissant area to the Rampart Range. There we will see units deposited in tributaries of the ancestral South Platte River including upper Eocene units of the Wall Mountain Tuff, the Tallahassee Creek Conglomerate, the Thirtynine Mile Volcanics, and the Florissant lake beds and valley fill. During the final part of this trip we will follow the course of the extinct Hayden-Divide-Arikaree River that marked a major drainage reorganization as the earlier south-flowing rivers were rerouted into this northeast-flowing river by the rising Pikes Dome. Initial dates from detrital zircons and sanidines yield a youngest grain of 28.9 Ma showing the Divide Gravels in this extinct river may date to the middle Oligocene rather than the to the Miocene (Steven et al., 1997) or the Plio-Pleistocene (Pearl, 1971).

Stop 1. Jackass Hill, Littleton. (39.580641, -105.018266)

We will start the trip on Jackass Hill in Littleton, which provides a Front Range panorama that stretches from Pikes Peak on the south to Longs Peak and beyond on the north. Note the flat tops of these two peaks, interpreted here as remnants of the RMES. Below us the South Platte River exits the range at Waterton Canyon and notably flows to the northeast. This wasn't always the case, and tomorrow we will be tracking changes in the course of the South Platte back to the upper Eocene. We are not the first to enjoy this spectacular vantage point. Scattered "debitage" or stone flakes show Native peoples used this perch to fashion projectile points as they scouted for game and took in the view.

This spot is a good place to talk about the utility and pitfalls of treating the RMES as a "composite surface". Ideally, we would like to define a single post-Laramide surface across Colorado that is capped by rock of a single age. However, creating a continuous regional structure map necessitated combining current topography with unconformities overlain by a variety of post-Laramide deposits spanning the upper Eocene to the lowest Pleistocene. Areas where overlap deposits are present and dated, allow the elevation and the age of the underlying unconformity to be determined with confidence. If overlap deposits are present but not dated, the elevation but not the age of the RMES will be known. Where overlap deposits are absent, the best we can say is the RMES lies at or above current topography. By including supersurface points the map depicts total relief on the RMES with the surface running over the highest topography in areas stripped of overlap deposits and along the base of the overlap deposits in the subsurface where such data are available.

From Jackass Hill we can see the low in the range front just south of Red Rocks Park cut by Bear Creek, one of the canyons incised into basement along this part of the Front Range. Within these valleys are scattered high-level gravels that have been considered Miocene (Steven et al., 1997) or possibly Miocene (Kellogg et al., 2008), but may be Pleistocene, as discussed below. Clearly, changing the age of the overlap deposits by up to 20 Myr will change whether we link these gravels to formations preserved east on the piedmont such as the White River, Arikaree or Ogallala, and how we interpret the evolution of the landscape and the RMES in this part of the Front Range.

Current CSS president, Cal Ruleman, will discuss recently acquired Pleistocene cosmogenic ages of high-level gravels in the Clear Creek drainage thought traditionally to be Miocene, which shows the importance of using new techniques to date the gravels for the first time, and reveals incision of some of the Front Range canyons is a relatively recent modification of the RMES. Cosmogenic ages of 1.76-0.56 Ma for the Central City Gravels (Sortor

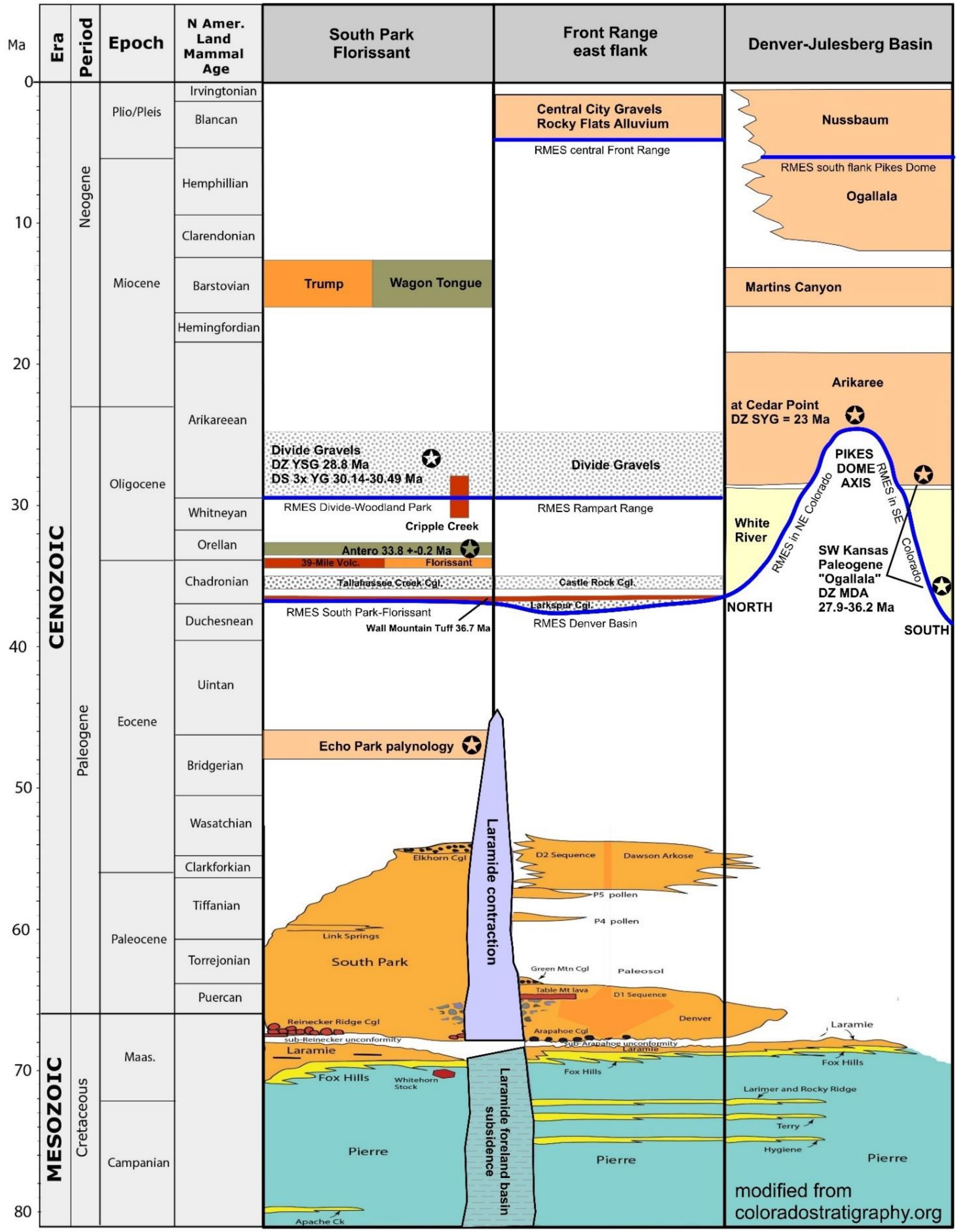


Figure 14. Stratigraphy of South Park and Florissant, the eastern flank of the Front Range, and the Denver-Julesberg Basin (modified from https://www.coloradostratigraphy.org).

et al., 2019; Ruleman et al., 2022) (Fig. 14.) overlap with ages of 1.5-0.4 Ma determined for the Rocky Flats Alluvium (Riihimaki et al., 2006). Assuming other high-level gravels in this part of the Front Range and the Rocky Flats Alluvium span the same time interval, a surface can be contoured that approximates the base of Pleistocene valleys sloping off the eastern Front Range to the piedmont (red contours, Fig. 16). Note the surface is defined differently than the RMES. It includes only points on the base of the overlap deposits and excludes supersurface points, which means the surface can be below current topography where overlap deposits are absent. Subtracting this surface from current topography permits the interpretation, if we assume no local deformation, that the high-level gravels were deposited in valleys with up to 700 meters of relief (positive values on Fig. 16, Fig 17), and up to 350 meters of incision has occurred since the gravels were deposited (negative values on Fig. 16, Fig. 17). We don't know how old the valleys are in which the high-level gravels reside; however, they could date to the upper Eocene, Oligocene or Miocene and could have been the provenance for piedmont formations of these ages (Fig. 17). There remain other enigmatic high-level gravels across the northern Front Range that should be dated using cosmogenic (for rocks with ages < 3 Myr), and detrital zircon or detrital sanidine dating techniques. Efforts are ongoing to date speleothems occurring in the canyons incised below the high-level gravels. Adam Hudson (USGS) has obtained a 240.1 +- 7.2 Ka date on cave ornamentation occurring approximately 100 meters below the inferred Pleistocene level of erosion (Figs. 16-17). He is also dating samples collected from Crystal Cave (see description by Reed,1991) by past CSS president, Pete Modreski that lies approximately 250 meters below the inferred base level (Figs. 16-17).

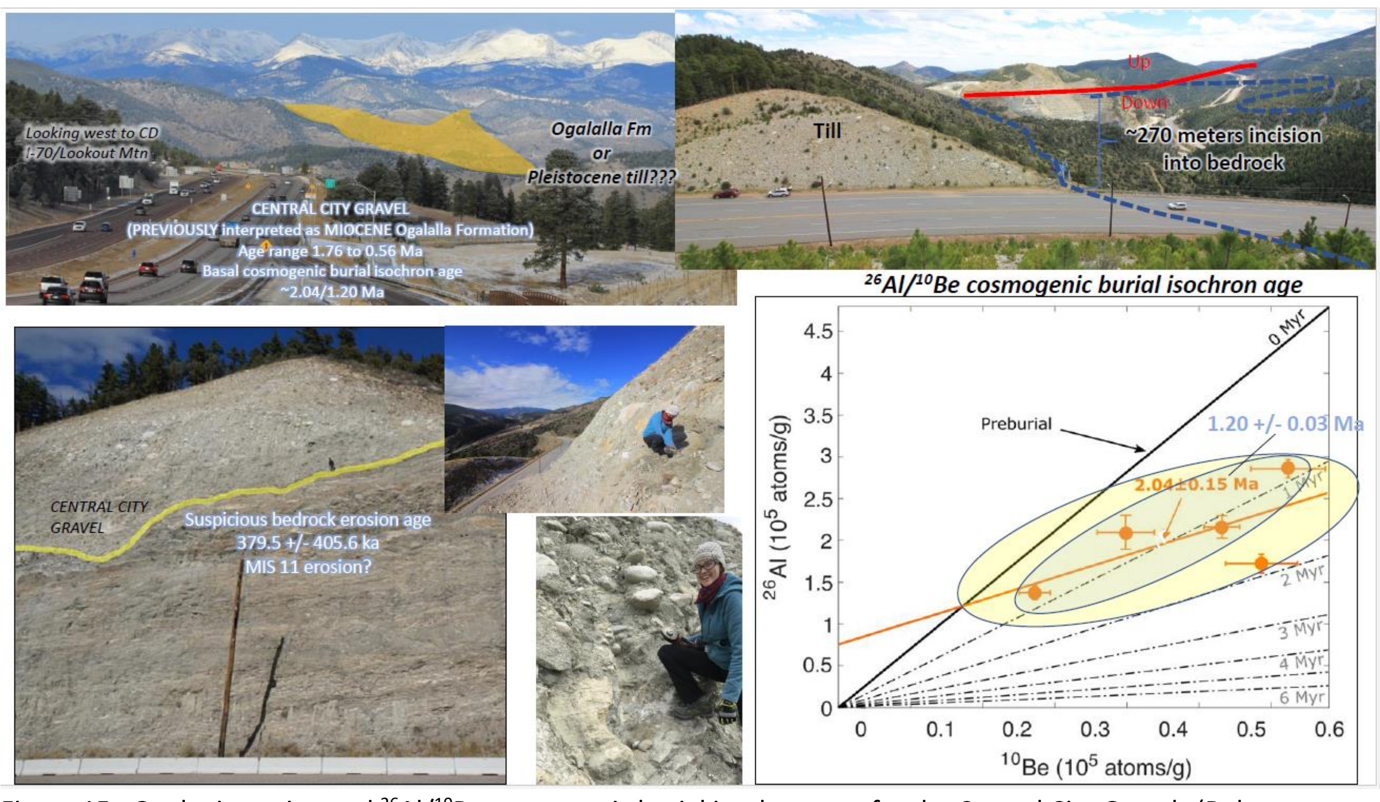


Figure 15. Geologic setting and $^{26}Al/^{10}Be$ cosmogenic burial isochron age for the Central City Gravels (Ruleman et al., 2022). Upper left is the scene looking west on I-70 from Lookout Mountain at the high-level Central City Gravels in the Clear Creek drainage. Pictures on the upper right and lower left show roadcuts through the gravels along the Casino Parkway connecting I-70 to Central City. The cross plot in the lower right shows the aluminum beryllium burial isochron analysis for five cobbles ranging in age from 0.56 to 1.76 Ma. A burial isochron age from all samples is 1.26 +\-0.13 Ma, but a 2.04 +\- 1.5 Ma isochron fits all data with compensation for potential reworked deposits. The sample with an age of 1.76 Ma shows a low $^{26}Al/^{10}Be$ ratio relative to the others, indicating possible reworking of the sample. An isochron age without the potentially reworked clast is 1.20 +/- 0.03 Ma. The basal contact of the gravels returned a spurious 0.3795 Ma age with an error larger than the age date of +- 0.405.6 Ma. Quarrying may offer opportunities to obtain better dates on the basal contact.

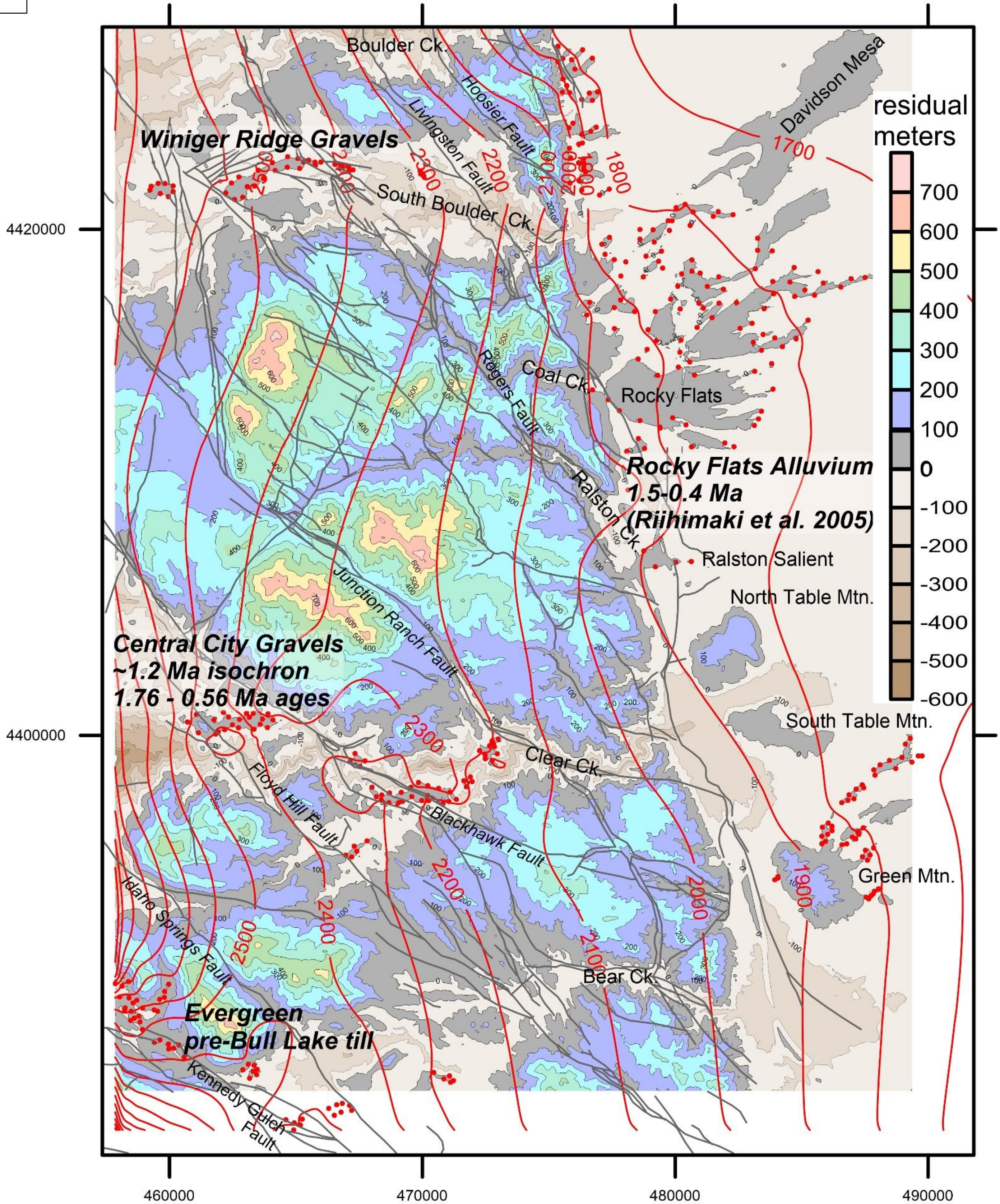


Figure 16. Residual based on structure map on the base of the Rocky Flats Alluvium and Front Range high-level gravels (red dots and contours) subtracted from topography. Positive residual (positive color-fill) shows up to 700 meters of relief in valleys occupied by the high-level gravels. Negative residual (negative color-fill) shows up to 350 meters of incision below the high-level gravels. Faults (gray lines) from Kellogg et al. (2008).

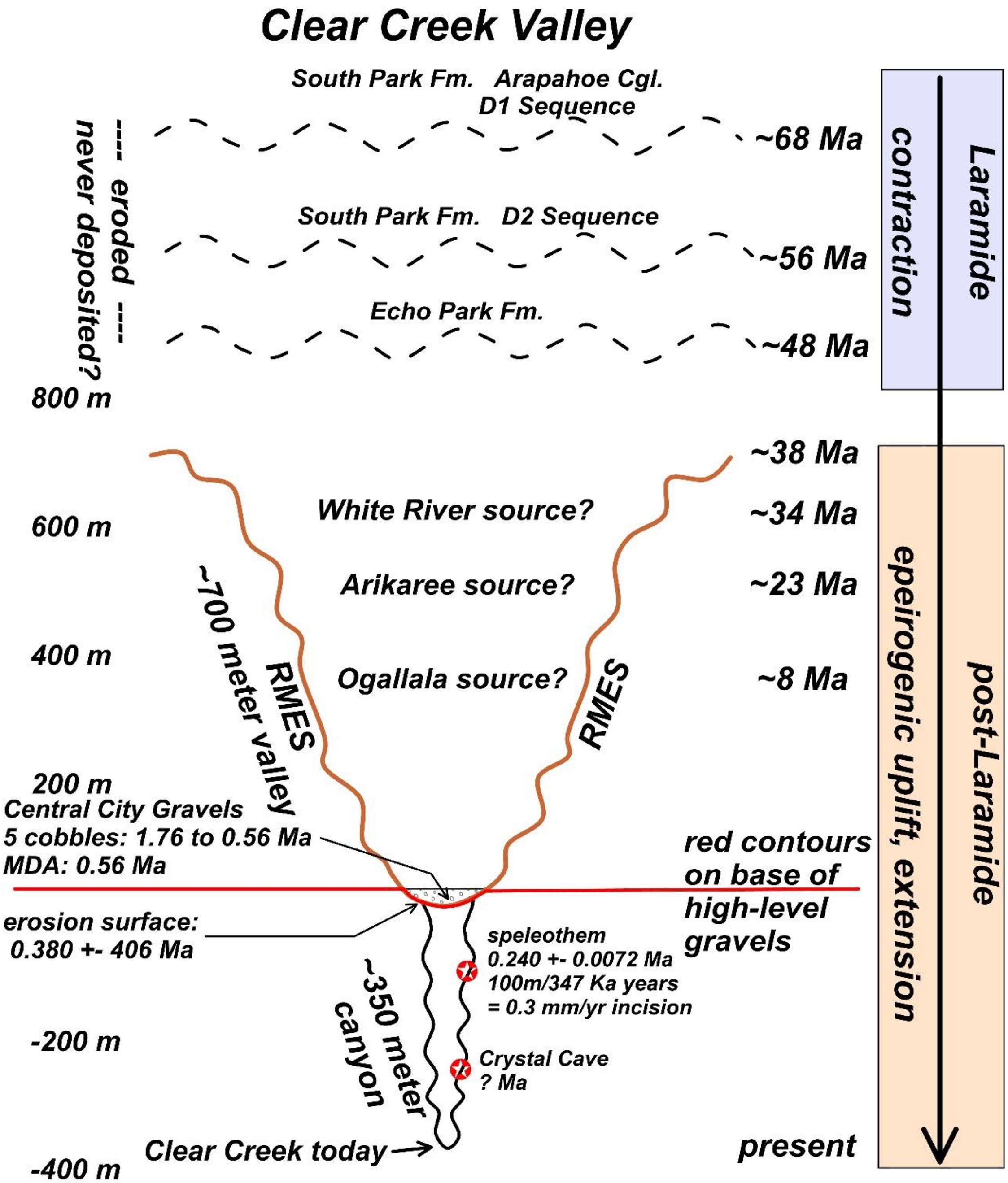


Figure 17. Clear Creek valley schematic showing progression of erosion through time. Central City Gravels rest in the base of a 700-meter-deep valley that may have been one of the source areas for the White River, Arikaree and Ogallala. Canyons cut below the Central City Gravels are up to 350 meters deep and efforts are ongoing to date speleothems that may further constrain the timing and rates of canyon incision.

Together, these analyses may constrain incision rates of the Front Range canyons since the Pleistocene. The computer contouring of the inferred Pleistocene base level shows what appear to be offsets of up to 100 meters across the Blackhawk Fault. Even when the datums are hand-contoured to reflect apparent valley walls (not shown), swings in the contours approaching Clear Creek indicate the Blackhawk Fault either controlled the location of the valley in which the gravels were deposited or the faulting offsets the gravels and is recent. Finding evidence of recent activity on faults in this part of the Front Range would have consequences for projects like the current expansion of Gross Reservoir above Boulder, so these deposits deserve more study. Regardless of the age, if there is faulting offsetting the RMES, it foreshadows the relationships across the Ute Pass Fault we will see tomorrow.

Stop 2. Daniels Park (39.473112, -104.921683)

Our stop at Daniels Park provides a commanding view of Plum Creek, which notably flows north, the “Big Flat” (Wobus, 2022) or Rampart surface, which is a low-relief portion of the RMES, and the Pikes Peak massif that rises above the Rampart surface and dominates the southern skyline.

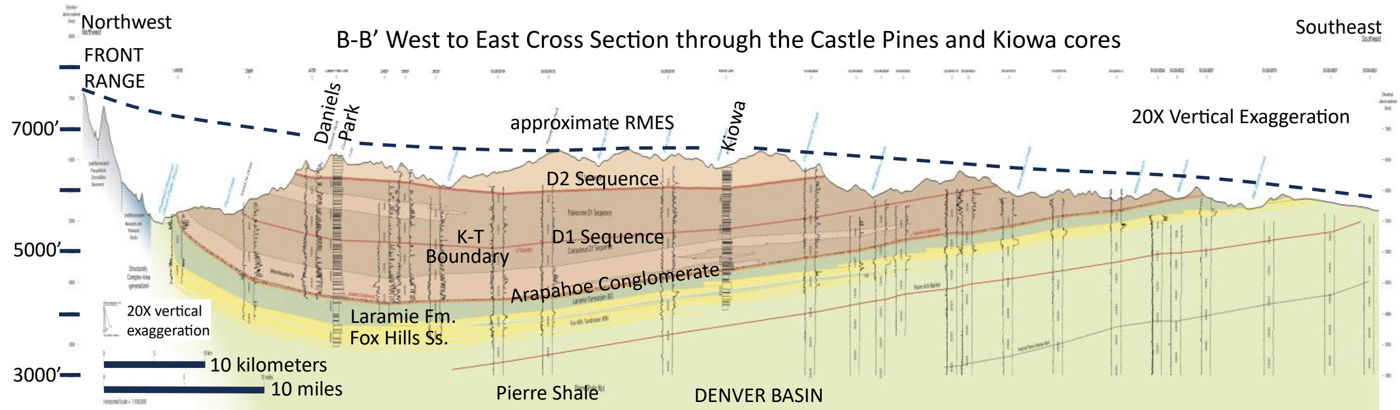


Fig 18. West to east cross section through Daniels Park and the Castle Pines and Kiowa cores (modified from Dechesne et al., 2011).

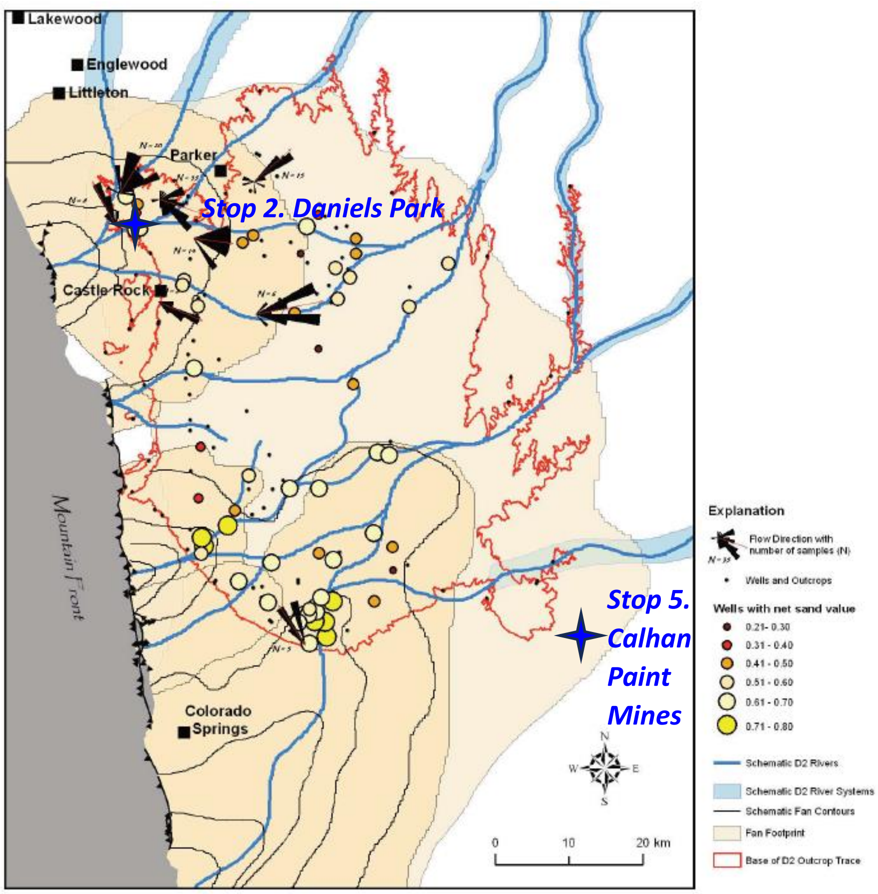


Fig. 19. Map showing the elements used to construct the fan distribution map for the Denver Basin Group D2 Sequence. Ratios of net sand thickness to total formation thickness (net/gross) aided delineation of the fans. Paleo-rivers and drainage patterns were drawn to match paleo-flow direction measurements, where available. Net/gross sand-ratios were obtained from 106 wells deeper than 300 feet that had the base of D2 present (Dechesne et al., 2011).

This stop gives us a chance to step back before development of the RMES to the Cretaceous to lower Eocene Laramide synorogenic deposits of the Denver Basin investigated by Marieke Dechesne, Kirk Johnson and past CSS presidents Peter Barkmann and Bob Raynolds (Dechesne et al. 2011). Their cross section (Fig. 18.) shows the marine Pierre Shale overlain by the coastal Fox Hills Sandstone and nonmarine Laramie Formation deposited during the last retreat of the Interior Cretaceous Seaway. The Arapahoe Conglomerate marks the initial basement unroofing during the Laramide Orogeny and is followed by the synorogenic D1 and D2 sequences. The approximate position of the RMES has been added based on outcrops along and to the south of the section. We are standing on the lower Eocene D2 Sequence. The sequence is dominated by fans flowing east to northeast off the Front Range (Fig. 19), a drainage vector different from what we will see in the upper Eocene rivers.

Both Sears and Beranek (2022) and Blum et al. (2017) show a wider context for the late Paleocene to earliest Eocene including a prominent drainage divide crossing the Front Range in the vicinity of Pikes Peak with east to northeast flows north of the divide consistent with the current directions seen here at Daniels Park, and southerly flows south of the divide (Fig. 20). The rivers north of the divide are shown to join northward with a "California- Platte River" or "paleo-Platte River" that drained the northern Great Basin before arcing to the east and southeast to flow into the paleo-Mississippi system. It is fair to say the details of such paleo-drainage maps are still in question, but the Blum et al. (2017) version suggests multiple rivers emanating from a high in central Colorado during this time. They also show a "paleo-Arkansas River" emanating from the Pikes Peak area north of the drainage divide, which is odd given it current course fits better into their "paleo-Colorado-Brazos" drainage system.

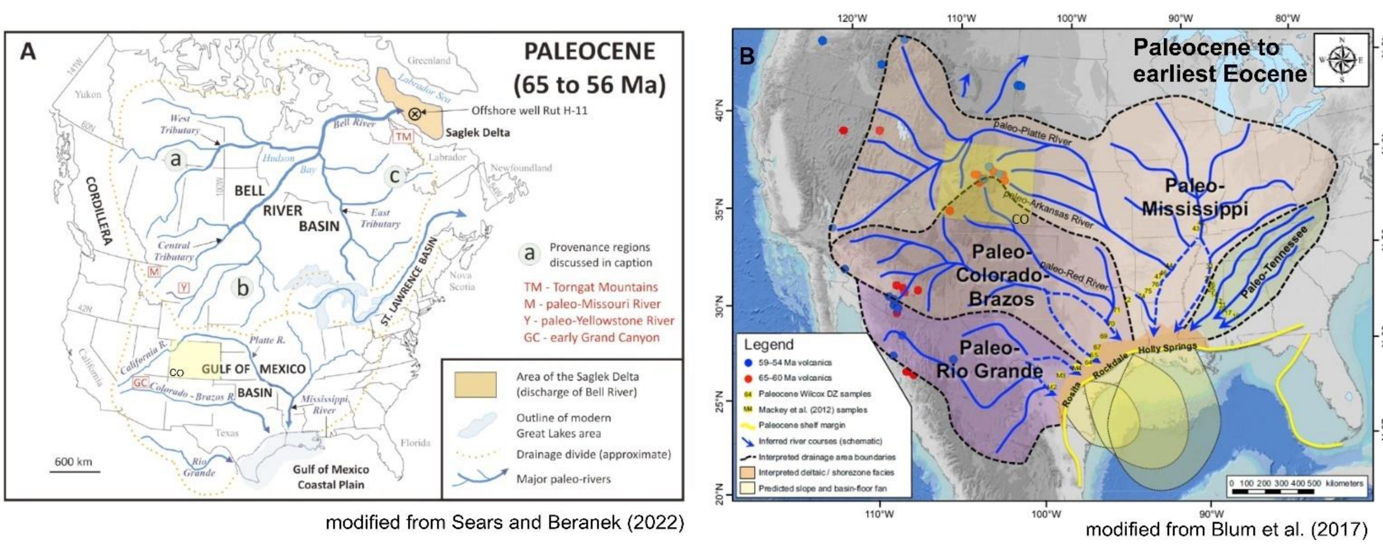


Figure 20. Paleocene drainage systems of North America by Sears and Beranek (A), and for the Paleocene to earliest Eocene by Blum et al. (2017) (B).

The Eocene stratigraphic record in the Denver Basin and South Park ends in the lower Eocene (Dechesne et al., 2011, Barkmann et al., 2016), which may mark the end of accommodation space creation and, therefore, the end of Laramide contraction in the Front Range at approximately 55 Ma. However, younger, middle Eocene strata of the Echo Park Formation present in the Tallahassee Creek Mining District in the southern Front Range are cut by an exposed thrust at the Mary L Mine indicating Laramide contraction persisted in the wider area to at least circa 47 Ma (Hon, 1984). This indicates strata as young as the middle Eocene should be considered synorogenic deposits related to Laramide contraction (Fig. 14). It also means that the development of the RMES took place over an 8 Myr period between approximately 45 and 37 Ma.

Stop 3. Castle Rock (39.381653, -104.857757)

Ascending Castle Rock we will see buttes to the west and south made up of the D2 Sequence and capped by Wall Mountain Tuff, an ignimbrite erupted at 36.7 Ma from the Mount Princeton-Mount Aetna area of the Sawatch Range that blanketed the RMES across the southern Front Range and into the Denver Basin (Epis and Chapin, 1975) (Fig. 21). Because of this and various Oligocene and Miocene overlap deposits the remainder of the trip will see us traversing one of the best-constrained parts of the RMES. On Castle Rock proper, the upper Eocene Castle Rock Conglomerate has cut through the Wall Mountain Tuff and rests unconformably on the D2 Sequence, as beautifully exposed at the top of the hiking trail. The conglomerates were deposited by the Castle Rock River, the first of three paleo-rivers that flowed across the RMES we will encounter during this trip. Tomorrow will find us in the upper Eocene ancestral South Platte River system, that was separated from the Castle Rock River by an interfluve coincident with the Front Range (Fig.21).

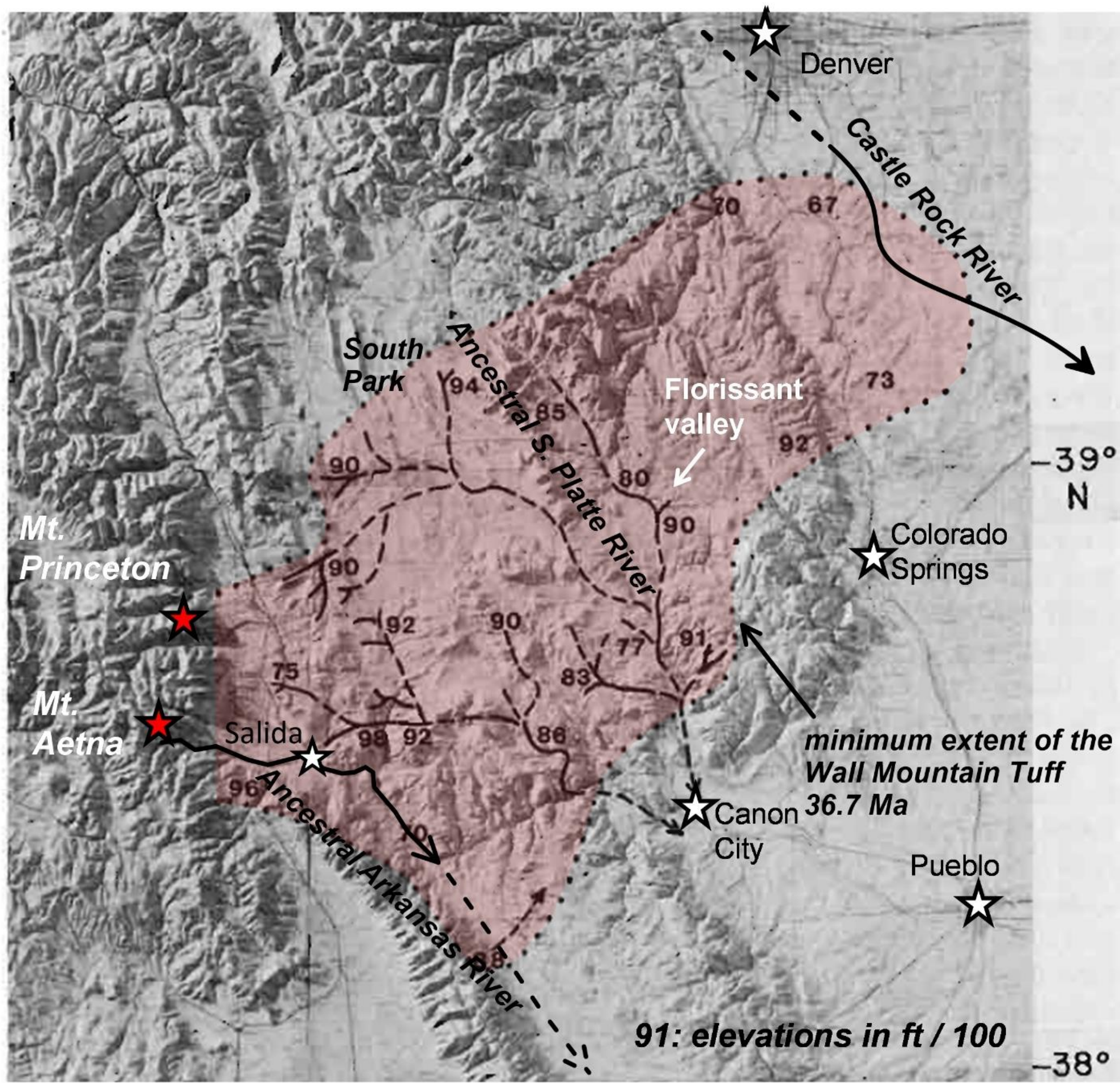


Figure 21. Extent of the Wall Mountain Tuff (36.7 Ma) and upper Eocene paleovalleys of the southern Front Range (modified from Epis and Chapin, 1975).

Based on current directions and clast-size distributions the main channel of the Castle Rock River flowed 130 kilometers southeast from Coal Creek to Calhan (Malin 1979: Evanoff, 2007; Keller and Morgan, 2016; Koch et al.,

2018) (Fig. 20), and possibly as far as southwest Kansas based on core samples radiometrically dated to the upper Eocene by Smith et al. (2017) (Fig. 10). The Castle Rock River carried meter-scale boulders of the Wall Mountain Tuff, Proterozoic Coal Creek Quartzite and Proterozoic Pikes Peak Batholith, that along with multi-meter scale trough cross beds attest to the torrential flows typical of this age rivers across Colorado and Wyoming (Evanoff, 2007). Cobbles of the blue gray Coal Creek Quartzite, which can include distinctive stretched-pebble conglomerates were sourced from outcrops in Coal Creek and Eldorado canyons and are found southeast to the preservation limits of the Castle Rock Conglomerate in Calhan (our Stop 5).

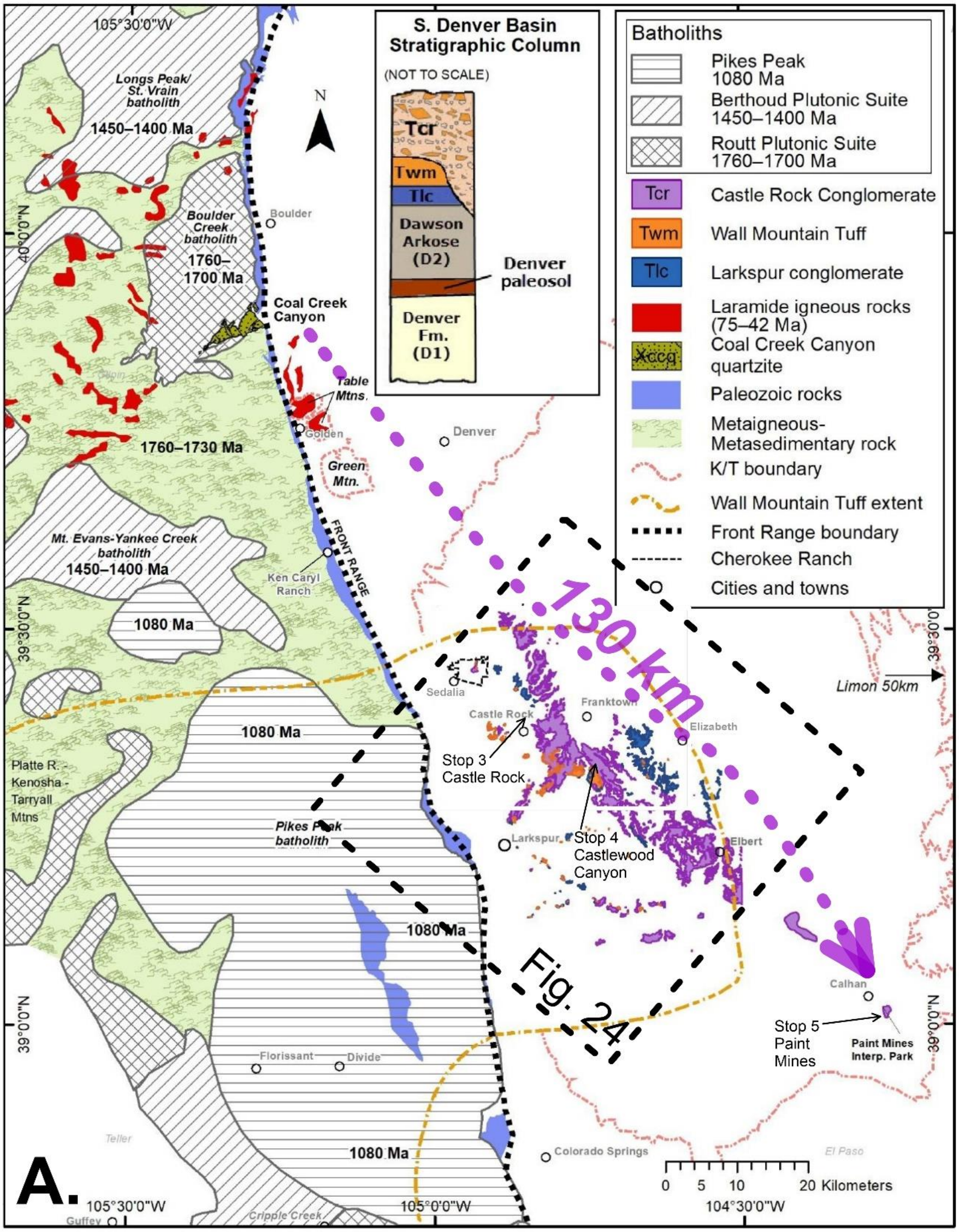


Figure 22. Map of the Castle Rock Conglomerate (Tcr), Wall Mountain Tuff and Larkspur Conglomerate outcrops in the south Denver Basin and key plutonic rocks of their Front Range provenance. Note the locations of Coal Creek Canyon and Calhan, at opposite ends of the Castle Rock Conglomerate belt (modified from Koch et al, 2018).

From the top of the hiking trail, we get another spectacular view of the RMES across the Rampart surface with Pikes Peak rising above it. From this vantage point it is apparent that the tops of the buttes to the southwest, which preserve the RMES capped by a thin veneer of Wall Mountain Tuff, are coplanar with the RMES across the Rampart Range and not separated by significant faulting (Leonard and Langford, 1994). Whether Pikes Peak is a monadnock or a structural uplift rising above the RMES will be discussed later in our travels.

Stop 4. Castlewood Canyon State Park (39.329797, -104.738258)

The walls of Cherry Creek's Castlewood Canyon beautifully expose the Castle Rock Conglomerate that caps the RMES in this area. Here we see excellent exposures of the large-scale trough cross-beds formed in the powerful upper Eocene Castle Rock River as it flowed 130 km southeast from the area between Golden and Boulder to Calhan (Fig. 23). In contrast, the canyon that later created these exposures has been carved by Cherry Creek, a creek that flows notably to the northwest. Clearly the drainage systems in this area have been reversed sometime between the upper Eocene and the present. Rivers don't flow uphill, so such drainage reversals are the hallmarks of landscape inversion due to structural deformation. Previous authors have noted outcrops of the Castle Rock Conglomerate are up to 300 meters higher at the southeast limits of the outcrop belt relative to its northwest limits, showing the southern part of the Denver Basin has been tilted to the north since the upper Eocene (Morse, 1979; Leonard and Langford, 1994; Evanoff, 2007; Koch et al., 2018)

Figure 23. Trough cross-bed sets in longitudinal section, northeast side of Cherry Creek, Castlewood Canyon State Park, showing curved beds and asymptotic lower contacts and a flow direction from left to right or southeast (photograph from Keller and Morgan (2016). Cherry Creek, at the bottom of the canyon, flows in the opposite direction from right to left or northwest showing the drainage of the Castle Rock River has been reversed since the upper Eocene.

The Castle Rock River exhibits bimodal current directions with the main paleochannel trends directed to the southeast and trends in the JA Ranch and Bucks Mountain tributaries directed to the northeast (Fig. 24). The tributary paleocurrents likely reflect northeast flow off the Front Range interfluve that separated the Castle Rock and ancestral South Platte drainages.

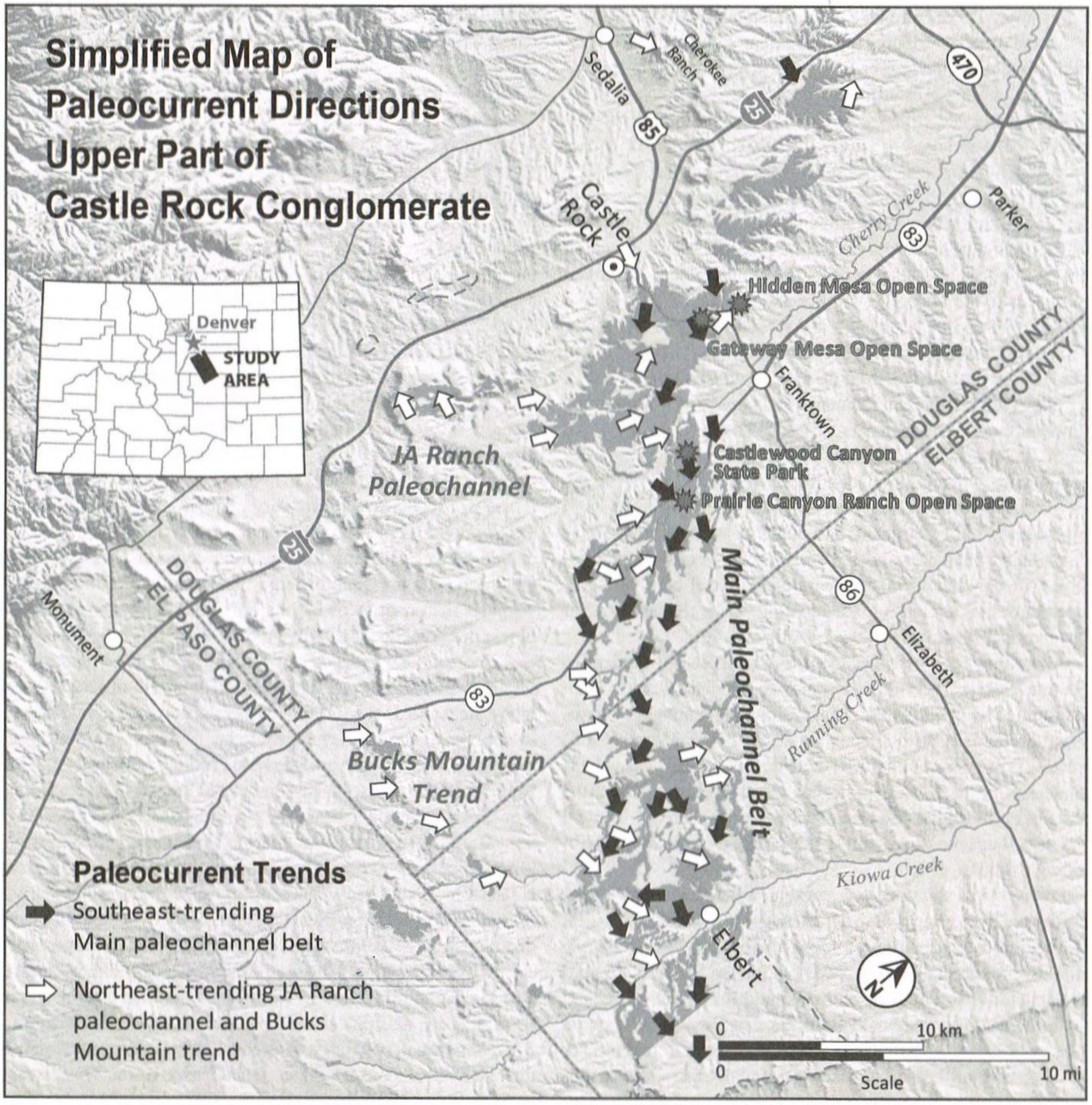


Figure 24. Current directions of the upper part of the Castle Rock Conglomerate from Keller and Morgan (2016) showing bimodal current directions due to northeast flows from tributary channels into the southeast flows of the main channel. Note clockwise rotation of map.

Stop 5. Calhan Paint Mines Interpretive Park (39.020488, -104.274258) and (38.996574, -104.293995

The Calhan Paint Mines give us another opportunity to think about the physiography of the Colorado piedmont before development of the RMES during the upper Eocene. Here we can see the more distal parts of the Cretaceous to Paleocene D1 and Paleocene to lower Eocene D2 sequences separated by the brightly colored shales of a paleosol, which have been mined for pigments. Our walk will also take us to a large boulder of Castle Rock Conglomerate containing clasts of upper Eocene Wall Mountain Tuff and Proterozoic Coal Creek Quartzite and Pikes Peak granite, that is typical of remnant blocks of the formation let down across the landscape at its distal and highest preservation limits.

C-C' West to East Cross Section from Colorado Springs through Calhan

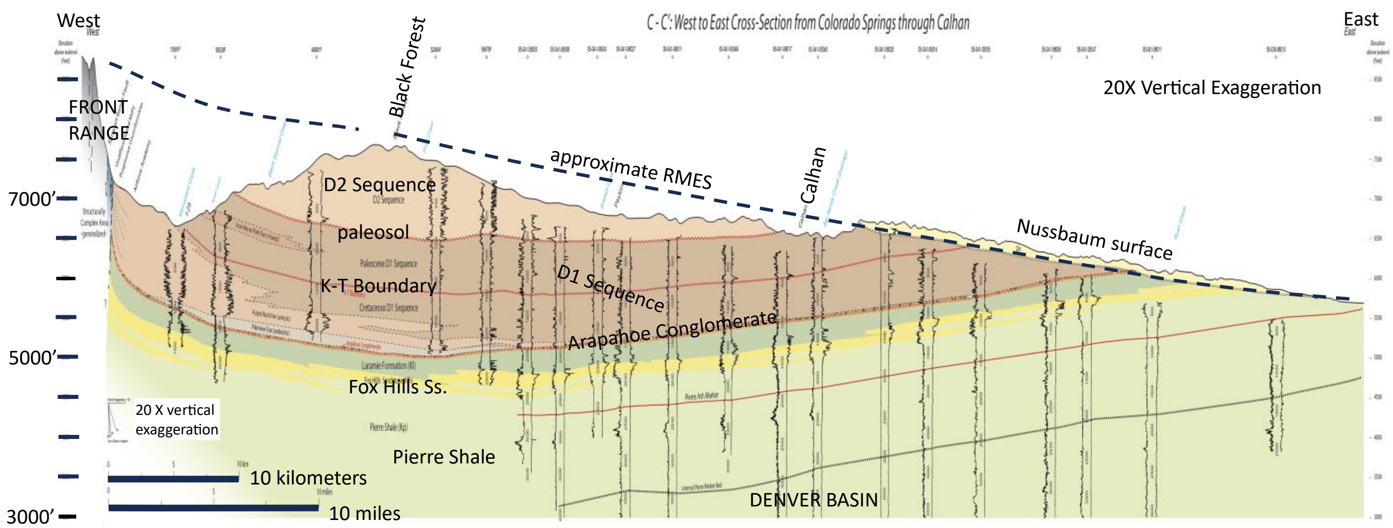


Figure 25. West to east cross section from Colorado Springs through Calhan (modified from Dechesne et al., 2011), showing the approximate level of the RMES above the Black Forest on the west and following the base of the Nussbaum on the east.

Similar to the D2 Sequence, the current directions in the D1 Sequence exhibit (Fig. 26) generally east to northeast flows off the Front Range, possibly transitioning to northerly flows as anticipated by Blum et al. (2017) (Fig. 20). Again, such northeast to north current directions contrast with the southeast flows in the main channel of the Castle Rock River suggesting either the northerly flows of the D1 Sequence are tributary to southeasterly flows farther to the east, or the drainage systems of the Colorado piedmont were reorganized between lower and upper Eocene time.

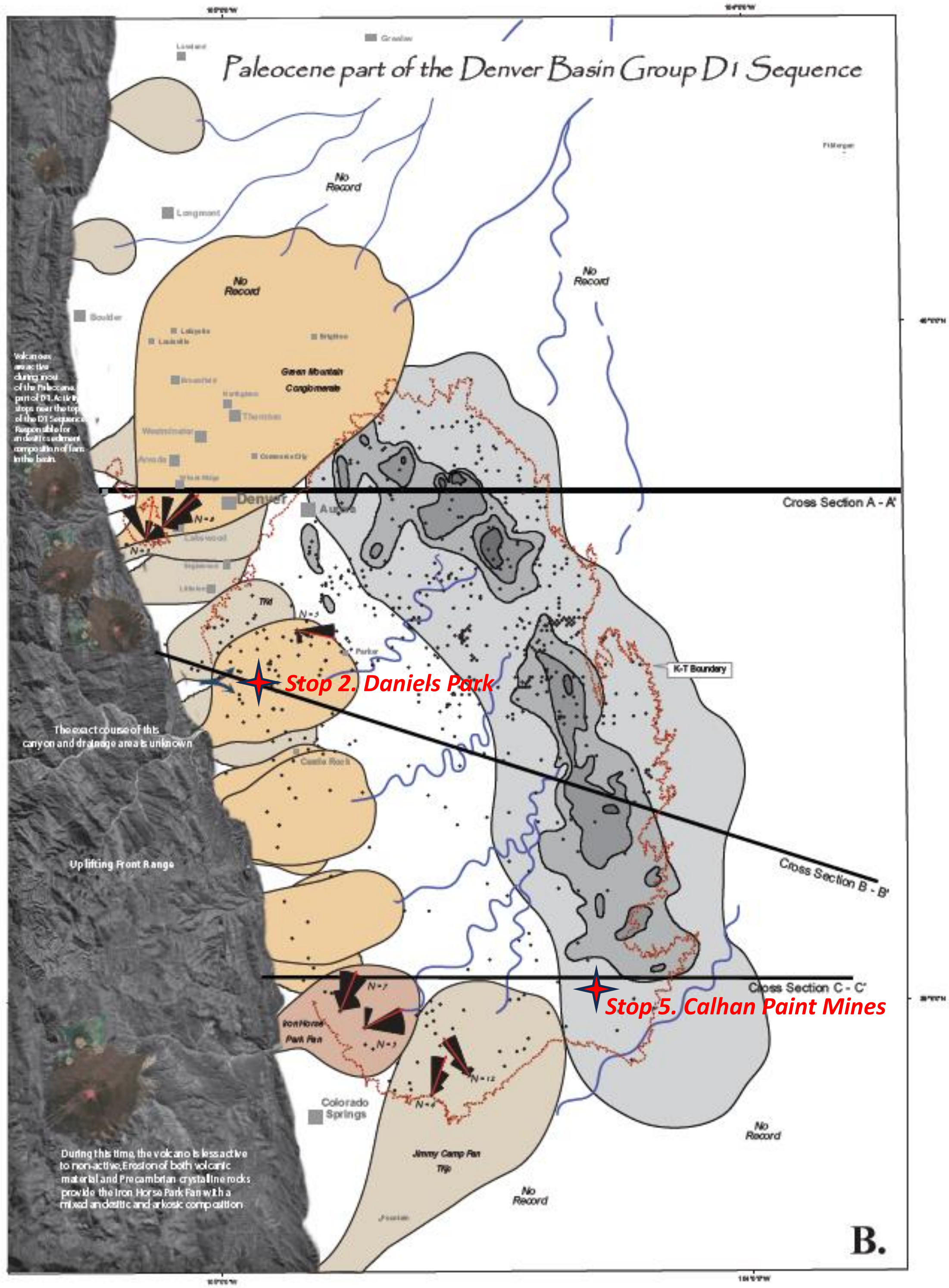


Figure 26. This interpretive map depicts fluvial systems active over the first 3 million years of the Paleocene. During this time interval smaller fans developed along the western margin of the basin. Near Green Mountain these fans were at first andesitic in composition; near Colorado Springs some fans were andesitic as well, or mixed in character. Elsewhere the fans were predominantly arkosic. Near the end of D1 Sequence deposition, the arkosic Green Mountain conglomerate was deposited as the proximal portion of a large fan. The coarse pebbles and boulders found in this fan suggest it may have been larger than most other fans deposited during this time interval. Coal swamps developed at the eastern and distal margin of the basin, near and following the end of the Cretaceous. The swamps suggest ponding near the eastern side of the foreland basin. River systems are inferred to have been isolated, low gradient and meandering (modified from Dechesne et al., 2011).

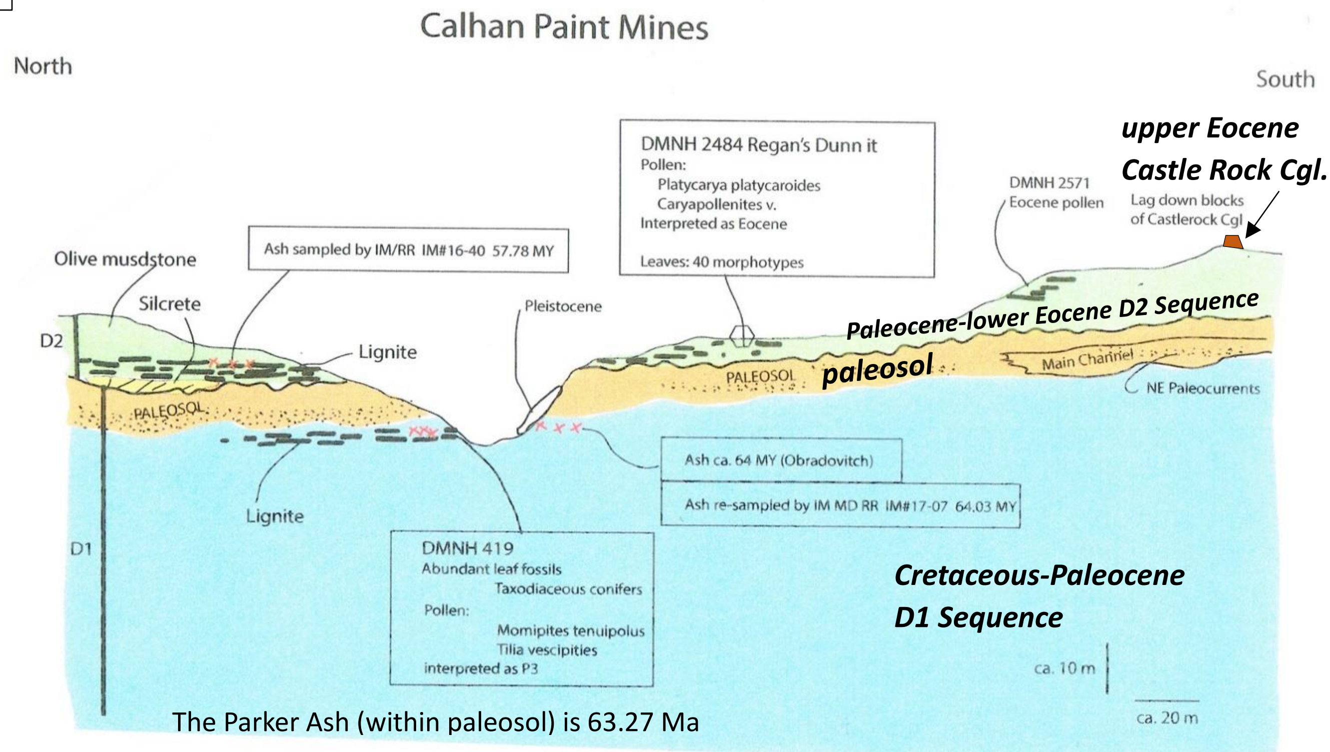


Figure 27. Sketch of the Calhan Paint Mines Interpretive Park showing allochthonous blocks of the Castle Rock Conglomerate mantling the D2 Sequence. The section approximates the walk we will take to look at the large block of Castle Rock Conglomerate let down onto the D2 Sequence (modified from a diagram by Bob Raynolds.)

After leaving the Paint Mines Interpretive Park we will drive south and east to an overlook at the Pikes Dome axis. From this vantage point we can see the topography drop north toward the South Platte River and south toward the Arkansas River. Just north of Calhan lies the valley of the upper part of Big Sandy Creek. Pearl (1971) noted its east-northeast trend and proposed it could have been the locus of his Ancestral Arikaree River that flowed from the vicinity of Colorado Springs to northwest Kansas. We will revisit this aspect of his work tomorrow when we discuss the third of the extinct rivers, the Hayden-Divide-Arikaree River, we will see during this trip.

A longitudinal section following the Castle Rock River reveals this once southeast-flowing river has been reversed due to uplift of the Pikes Dome axis (Fig. 28). The section shows approximately 500 meters of uplift at the dome axis relative to the regional trend surface and 400 meters of difference between the RMES elevation at the South Platte River in Denver and the dome axis near Calhan. Again, rivers don't flow uphill, so seeing such drainage reversal shows the relief on the RMES between Denver and Calhan is the result of deformation not erosion.

As we will see, this picture of the RMES or closely associated Cenozoic surfaces is not shared in the more recent literature. However, already by 1940, H.T.U. Smith aptly described the eastern plunge of Pikes Dome in a manner very similar to the approach taken here. He recognized the Ogallala had been warped by an uplift between the South Platte and Arkansas rivers that stretched from western Kansas into the Rocky Mountain front (Fig. 29). His structure map on the base of the Ogallala lumped the Nussbaum in eastern Colorado and the Oligocene Wolf Park lahars near Canon City with the Ogallala, which while incorrect, simply means he lumped overlap deposits of different ages to define the RMES, the approach taken here. He clearly recognized the surface capped by the Ogallala was a composite unconformity, likely formed during several cycles of erosion. The axis of his dome followed the drainage divide between the South Platte and Arkansas rivers with the magnitude of the arch increasing westward to 460 meters at the mountain front. These are all observations we will reiterate during this trip.

Surprisingly, Smith's (1940) framing of the eastern part of Pikes Dome has been largely forgotten in the more recent literature. Based on the thousands of water wells drilled through the Ogallala High Plains Aquifer, Pearl (1971) noted a prominent drainage divide evident from the trends of valleys carved into the surface below the Ogallala (see purple drainage patterns on Fig. 12) he attributed to an east-west basement structure active prior to Ogallala deposition. While Pearl references Smith's paper, he doesn't point out that the axis of the basement structure responsible for his drainage divide is the axis of Smith's piedmont dome, called here Pikes Dome (an attribution that would have helped the author of this field guide). By the time Leonard (2002) published his treatment of the base Ogallala surface, Smith's work would be henceforth no longer cited. While Leonard's base Ogallala surface conforms to Smith's in most areas, across the Arkansas River Valley Leonard shows a prominent high rather than a low, an interpretation at odds with Smith's base Ogallala surface and the RMES surface mapped here (Fig. 30). Essentially, Leonard connects the southern flank of Raton Dome with the northern flank of Pikes Dome without recognizing the pronounced low along the Arkansas River, an interpretation echoed in subsequent treatments of piedmont structure. McMillan et al. (2006) defined a top of basin fill or top of overlap deposit surface that closely tracks the RMES in most areas except across the Arkansas River valley where they follow Leonard's (2002) lead and show a high rather than a low. Karlstrom et al. (2012) define a 10 Ma paleosurface by connecting topographic profiles drawn along the axes of interfluve highs. Their model attributes piedmont relief to differential erosion meaning the Arkansas and South Platte valleys were filled to the level of their interfluve highs at 10 Ma with the now-phantom fill subsequently stripped out. Some of the same authors wrote Lazear et al. (2013), which added additional relief to their 10 Ma paleosurface along the major rivers anticipating their perceived differential erosion would cause isostatic rebound to build river anticlines along the South Platte and Arkansas rivers. However, the remnant overlap deposits in the South Platte and Arkansas valleys show synclines rather than anticlines along the rivers.

As stated previously, current topography closely mirrors relief on the RMES. By comparing the various proposed Cenozoic surfaces to current topography it becomes apparent where they track topography and where they diverge. Figure 31 shows the proposed surfaces within a box common to all of the studies. Although the map shown for Karlstrom et al. (2012) was constructed from their supplementary materials, its surface lies above rather than at current topography along the interfluve highs, likely not the picture intended by the authors, but because the shape of their published surface is similar to their intended surface, the residual map described below will still show anomalies in the correct location (requests for a corrected map were not answered). Subtracting the surfaces from current topography creates residuals showing how well the surfaces match topography. The RMES proposed here shows consistently small residuals indicating the RMES and topography track each other everywhere except in the headwaters of the Huerfano River on the deeply incised northern flank of Raton Dome. In contrast, the surfaces proposed by Leonard (2002) and McMillan et al. (2006) mirror topography everywhere except along the Arkansas River, indicating their treatment of the Cenozoic surface along the river is anomalous. The surfaces proposed by Karlstrom et al. (2012) and Lazear et al. (2013) are internally consistent in that they anticipate highs in their 10 Ma paleosurface wherever the topography is low. However, their models predict structural plateaus or anticlines across the major river valleys, whereas the preserved overlap deposits demonstrate structural lows in the RMES across the major river valleys.

Several lines of evidence support the low in the RMES at the Arkansas River. First, the 2200 to 2400-meter contours on the base of the RMES seen astride the Pikes Dome axis east of the mountain front swing some 75 kilometers to the southwest based on exposures of the RMES along the lower reaches of Fourmile Creek, thus defining the northern flank of the syncline in the RMES along the Arkansas River. If there were a high in the RMES along the Arkansas River the contours would swing to the southeast rather than to the southwest. Second, the Nussbaum surface (Figs. 29 and 32) dips at least 600 meters south from the Pikes Dome axis to the Arkansas River. The Nussbaum, originally thought to correlate with the Ogallala, caps an old remnant surface incised by modern streams that appears to be a continuation of the Ogallala-High Plains Aquifer surface as shown by the

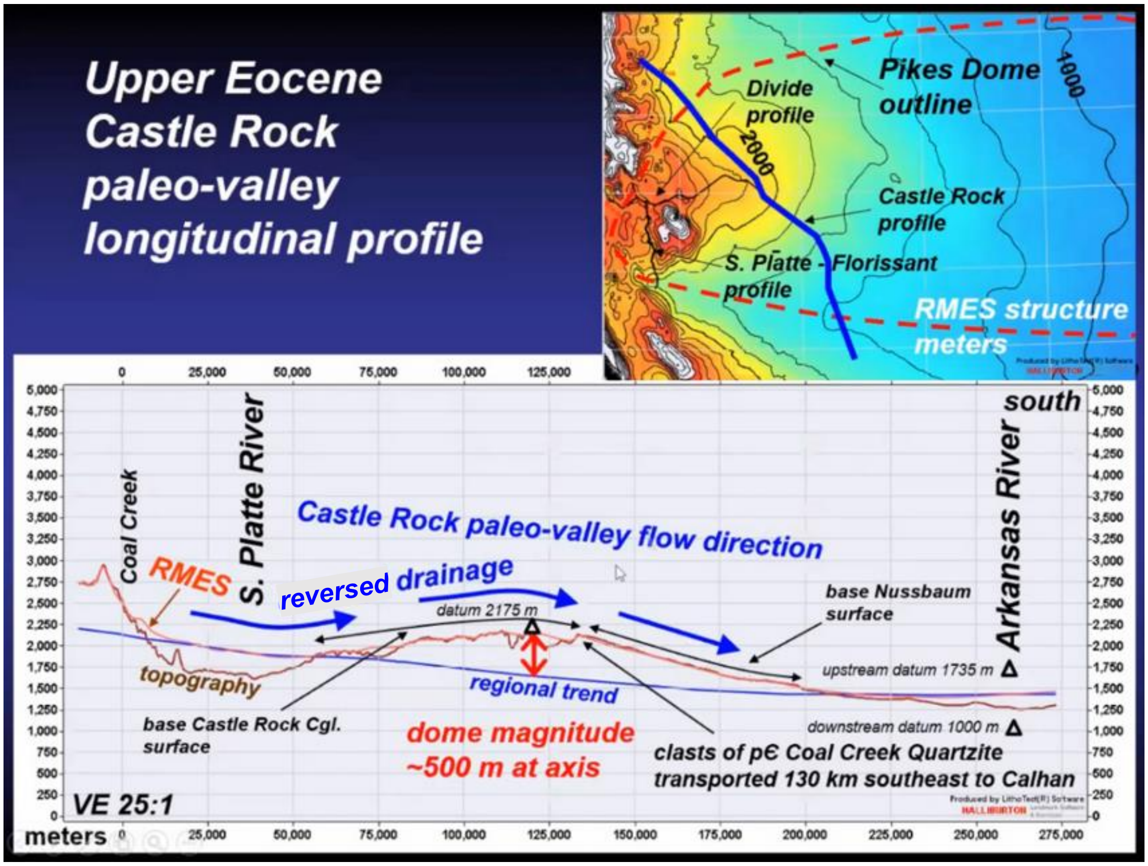


Figure 28. Castle Rock River longitudinal profile showing drainage reversal across the northern flank of Pikes Dome

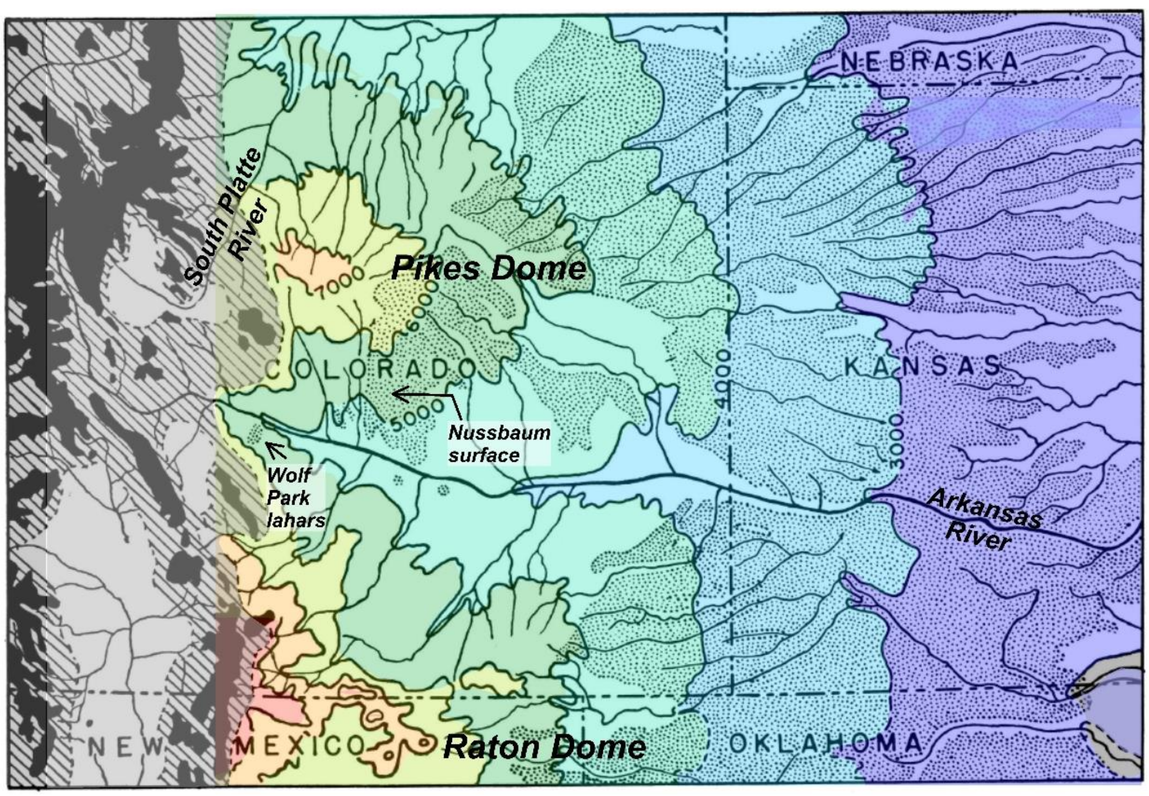


Figure 29. Physiography of the Ogallala formation from Smith (1940). Contour interval 1,000 feet. Stippled areas represent the Ogallala and Nussbaum formations. Areas in solid black represent mountain ridges and peaks above 10,000 feet, and crosshatching indicates lower altitude mountainous areas (modified from Smith, 1940).

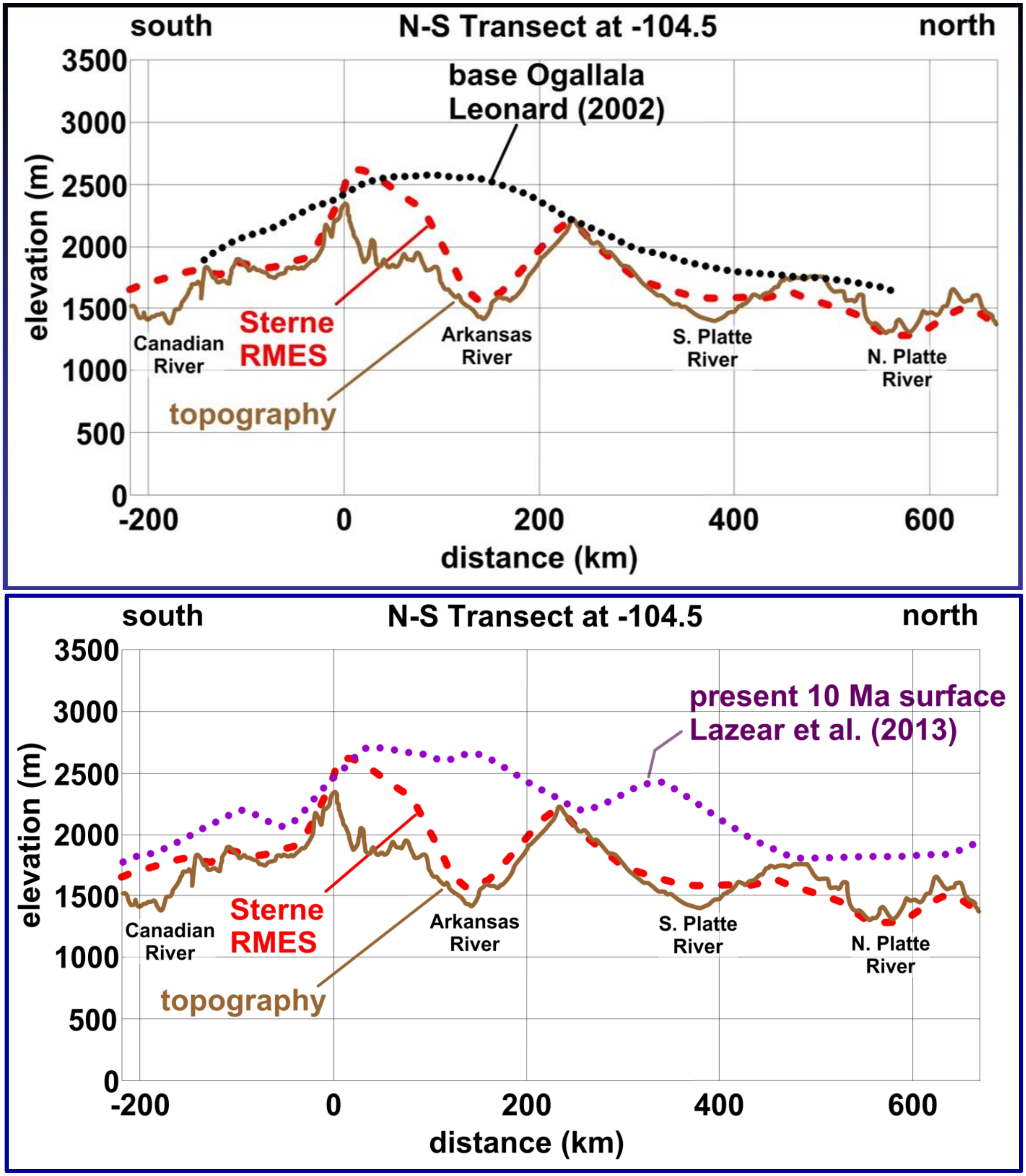


Figure 30. Comparison of Leonard (2002) base Ogallala and Lazear et al. (2013) 10 Ma surface with RMES proposed here along a north-south transect at -104.5° longitude. Note base Ogallala high across the Arkansas River from Leonard (2002) and highs in the 10 Ma surface across the Arkansas and South Platte rivers from Lazear et al. (2013). Based on datums on the base of existing overlap deposits, there are lows in the RMES across both the Arkansas and South Platte rivers and the rivers currently flow along these structural lows.

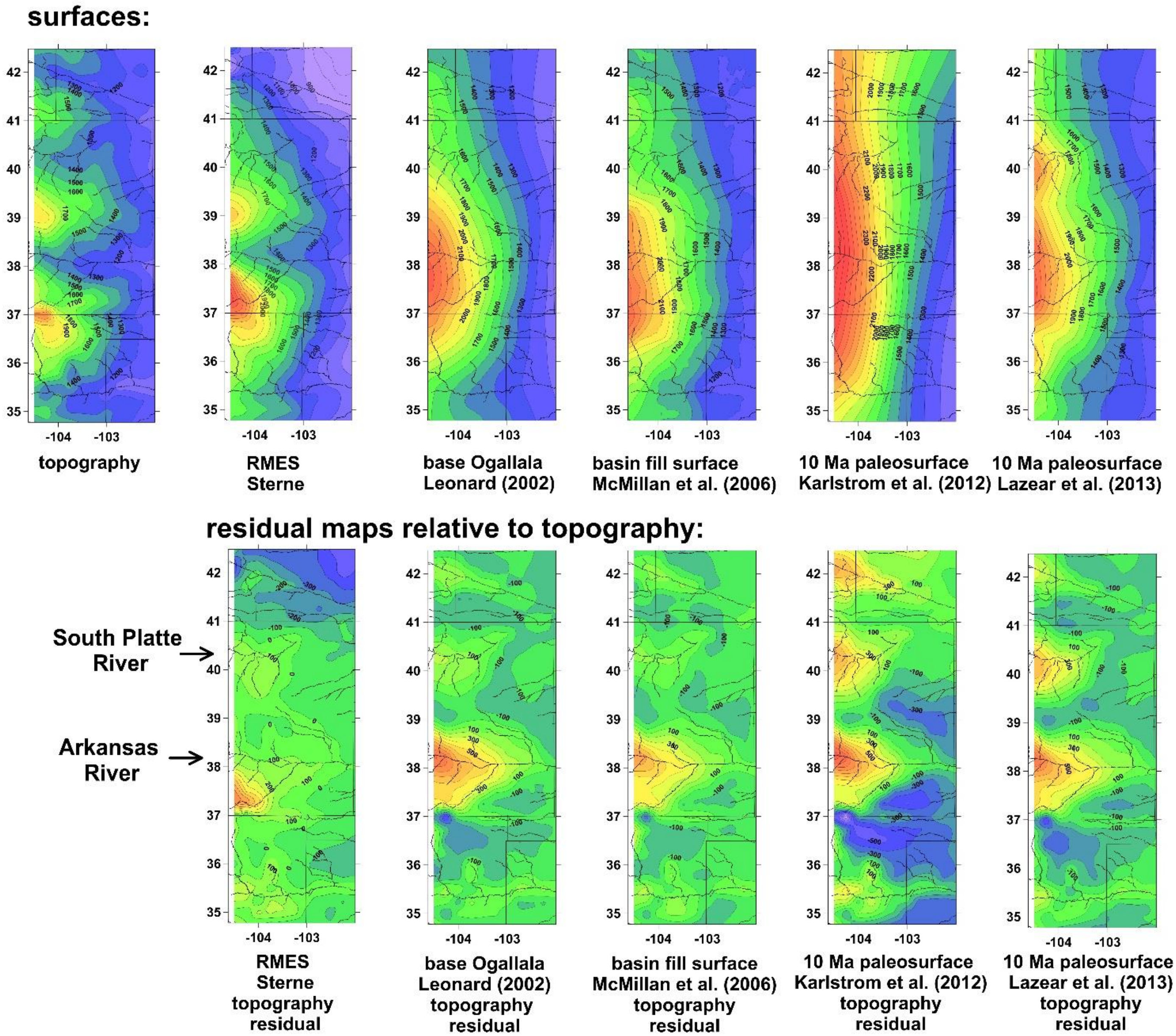


Figure 31. Top panels compare piedmont topography with Cenozoic surfaces proposed by various authors. Bottom panels show residual of topography subtracted from the proposed surfaces. Hot colors indicate larger differences between topography and the proposed surface. Note small residual along the Arkansas for RMES proposed here versus surfaces proposed by other authors. Large residuals along the Arkansas River for surfaces proposed by Leonard (2002) and McMillan et al. (2006) show their treatment of this area is anomalous. The surfaces proposed by Karlstrom et al. (2012) and Lazear et al. (2013) show highs across each of the river valleys, which results in high residuals in these areas.

shaded relief map of Colorado (Fig. 32). While, the Nussbaum is thought to be Pliocene in age Scott (1963), it may be older and is currently being dated using detrital zircons by the Colorado Geological Survey. Third, the major drainage divide marked by channels cut in the surface below the Ogallala that Pearl (1971) attributed to a structural high coincident with the axis of Pikes Dome lies north of rather than at the Arkansas River and thereby pointing to a low rather than a high along the river. Lastly, two isolated outcrops of lahar in Wolf Park just south of the Arkansas River near Canon City (Figs. 33 and 34; Leonard et al., 2002) contain clasts of Gribbles Park Tuff dated at 33.22 +-0.08 Ma and are intruded by basalts dated at 31.08+-0.11 Ma (dating by Dan Miggins, Oregon State University Argon Geochronology Lab) showing these deposits are definitively Oligocene as originally mapped by Taylor et al. (1975). These outcrops are key datums on the RMES surface because they show the magnitude of the structural low that controls the current course of the Arkansas River. The exposed contact between the lahars and the underlying weathered Pierre Shale lies at 1735 meters, providing a hard constraint for the synclinal axis in the RMES along the Arkansas River.

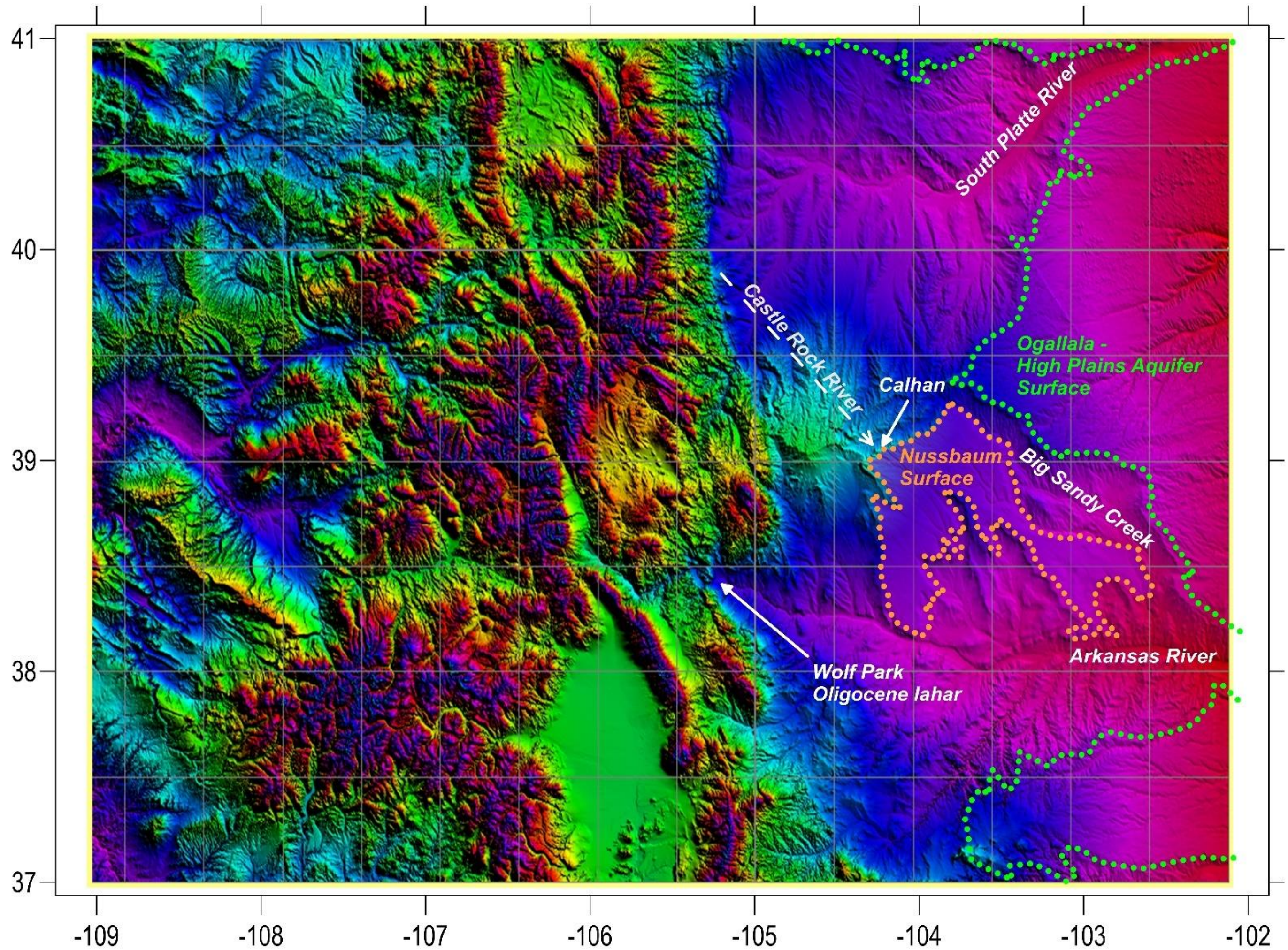


Figure 32. Shaded relief map of Colorado showing the Ogallala-High Plains Aquifer Surface, the adjacent Nussbaum Surface, the location of the Oligocene lahars in Wolf Park south of Canon City, and the course of the Castle Rock River. Noteworthy is the Nussbaum surface that has the identical physiographic appearance as the Ogallala-High Plain Aquifer Surface supporting its inclusion in the RMES. Both the Nussbaum Surface and the Oligocene lahars in Wolf Park show increasing relief of Pikes Dome heading west into the mountain front and provide critical support for the southern margin of Pikes Dome and the presence of a synclinal low in the RMES that controls the course of the Arkansas River.

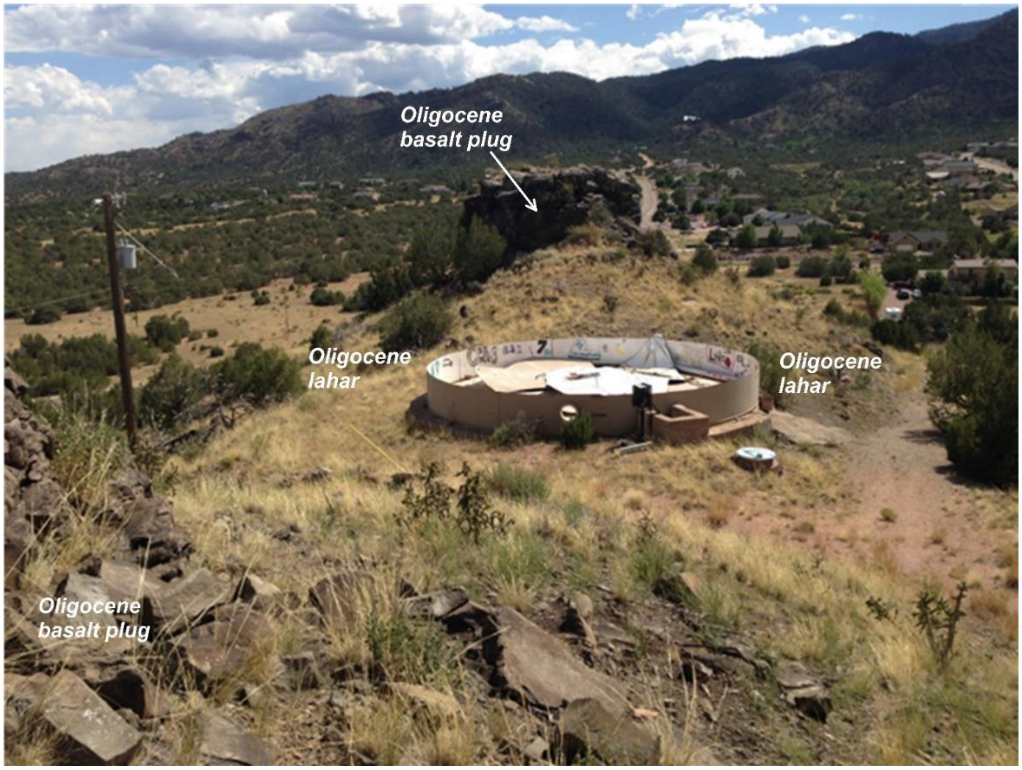


Figure 33. Photograph looking southeast at Oligocene lahar on Pierre Shale intruded by basalt plug in Wolf Park just south of Canon City. RMES datum at this locale is 1735 meters confirming the pronounced low in the RMES that controls the course of the Arkansas River. The basalt intruding the lahar has been dated at 31.08 +- 0.11 Ma by Dan Miggins at Oregon State University.

Figure 34. Large clast of Gribbles Park Tuff entrained in the Oligocene lahar in Wolf Park south of Canon City. The tuff has been dated at 33.22+-0.08 Ma by Dan Miggins at Oregon State University. This date and the basalt date noted above bracket the age of the lahar to a 2.1 Myr window in the lower Oligocene.

Stop 6. Goldfield Potluck (38.719981, -105.124512)

Stop 7 Lowell Thomas Museum – Victor (38.710031, -105.140097)

Day 2 Overview.

The second day of this trip will be spent exploring two phases of deformation that rerouted precursor rivers to the current South Platte River. The first, involving initial uplift of Pikes Dome, rerouted tributaries of the ancestral South Platte River, that once flowed south out of South Park to Canon City, eastward to form the Hayden-Divide-Arikaree River (Figs. 10-12) This east-flowing river was in turn rerouted by a more localized uplift called Peak Dome, encompassing the western parts of Pikes Dome, into the current northeasterly course of the South Platte River that tracks the northern margin of Pikes Dome (Fig. 13). The stops will feature the abundant outcrops of overlap deposits carried by rivers flowing across this part of the RMES. The destruction of these ancient rivers is what allows us to discern deformation of this landscape during the Cenozoic. We will discuss initial results of detrital zircon and sanidine dating of gravels carried by the Hayden-Divide-Arikaree River that help us refine our understanding of the timing of these different deformation phases. The last geologic stop of the trip on the Rampart Range will give us a chance to question whether the Pikes Peak massif is a monadnock or a localized structural uplift, and to discuss how low-temperature thermochronologic data provide another way to discriminate between erosional and tectonic relief on the RMES.

Stop 8. Tallahassee Creek Conglomerate (38.802321, -105.276945)

This stop will start our tour of the RMES overlap deposits in the Florissant area (Fig. 14). Here we are looking at the upper Eocene Tallahassee Creek Conglomerate with its cobbles of Proterozoic basement, pale green-weathered quartzite, Wall Mountain Tuff, and volcanics derived from early phases of the nearby Thirtynine Mile Volcanics Field. By the time the Tallahassee Creek Conglomerate was deposited, much of the slightly older Wall Mountain Tuff had been stripped out of upper Eocene valleys (Epis et al. 1976). The Tallahassee Creek Conglomerate is age equivalent with the Castle Rock Conglomerate seen yesterday in the Denver Basin. In places it carries massive boulders up to 5 meters in diameter (Olson and Wobus, 2019) that attest to the high carrying capacity of rivers of this age across Colorado and Wyoming (Evanoff, 2007). Do these raging rivers reflect renewed tectonism (Olson and Wobus, 2019), increased rainfall, or the breaching of short-lived volcanic dams? At Wright Reservoir we are located near the confluence of three tributaries of the ancestral South Platte River: the Tarryall-Florissant, the Slater, and the West Fourmile (Figs. 10, 35 and 36). The drainages were the headwaters of the ancestral South Platte River during the upper Eocene as it drained from South Park south through Fourmile Canyon to Canon City, and likely continued south beyond the current Arkansas River. The two map versions below (Figs. 35 and 36) show the utility of incorporating lithology information from water wells in the mapping of the RMES. In this area the drillers distinguish between sedimentary rocks (typically shales and sandstones), volcanic rocks, and granite. The sedimentary and volcanic rocks reside within the Cenozoic valleys, while the Proterozoic granite marks the base of the valley and thereby the RMES. In the contouring, wells that reached total depth while still in the valley fill established minimum depths for the RMES, while wells that tagged the granite provided datums on the RMES. The lithologic calls are based on well cuttings and are often very generalized; however, the hundreds of wells drilled into the Cenozoic valley fills of the Florissant area show repeating patterns that reveal aspects of the valley systems not apparent from surface data alone. Figures 35 and 36 contrast RMES structure maps made from surface data alone (Fig. 35), and from surface and subsurface

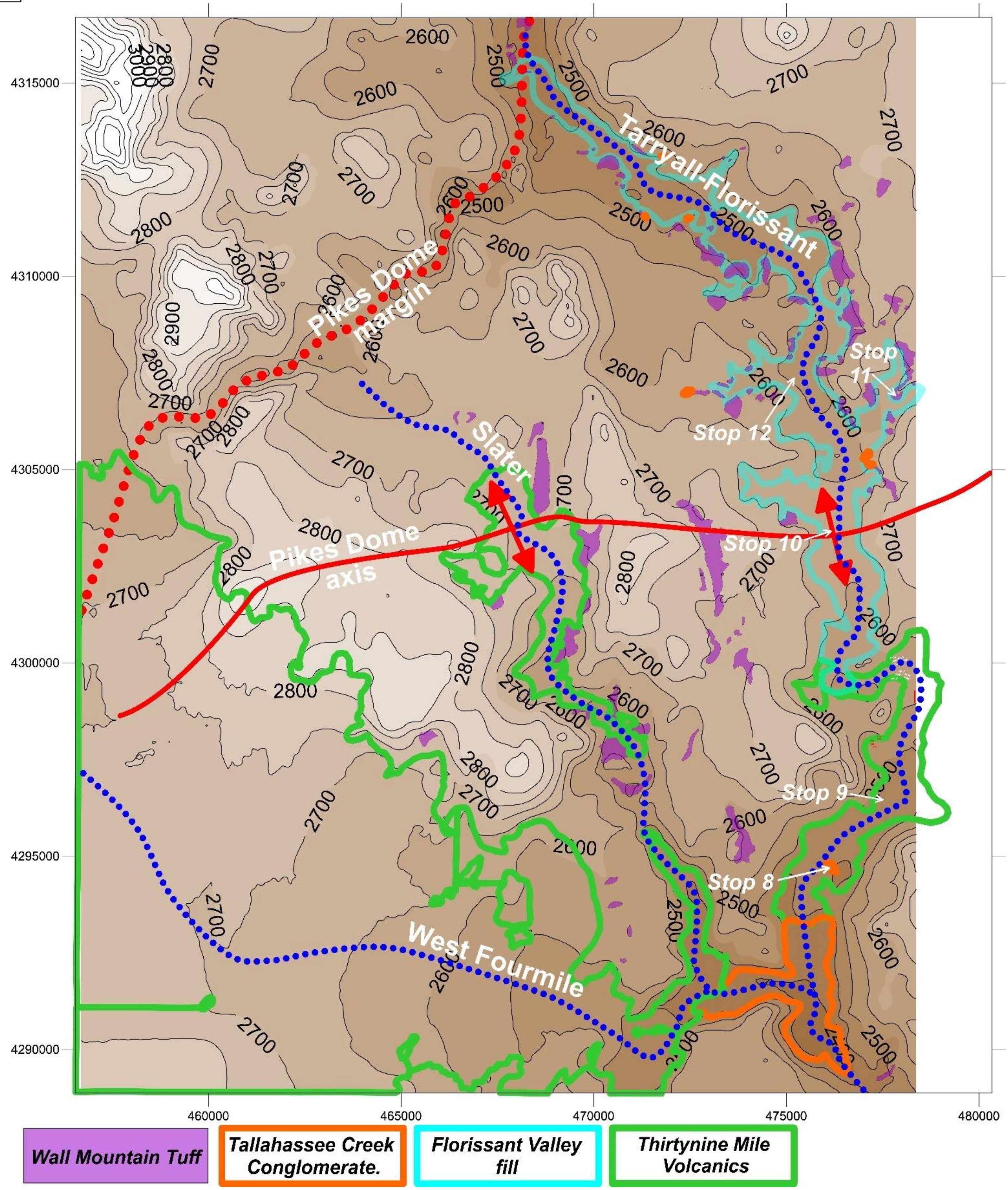


Figure 35. Map of the RMES contoured from datums on the base of overlap deposits and supersurface seed points only (brown spectrum). Outcrops of Cenozoic overlap deposits include the Wall Mountain Tuff (purple fill), Tallahassee Creek Conglomerate (orange outline), Florissant valley fill including lake deposits (cyan outline), and Thirtynine Mile Volcanics (green outline).

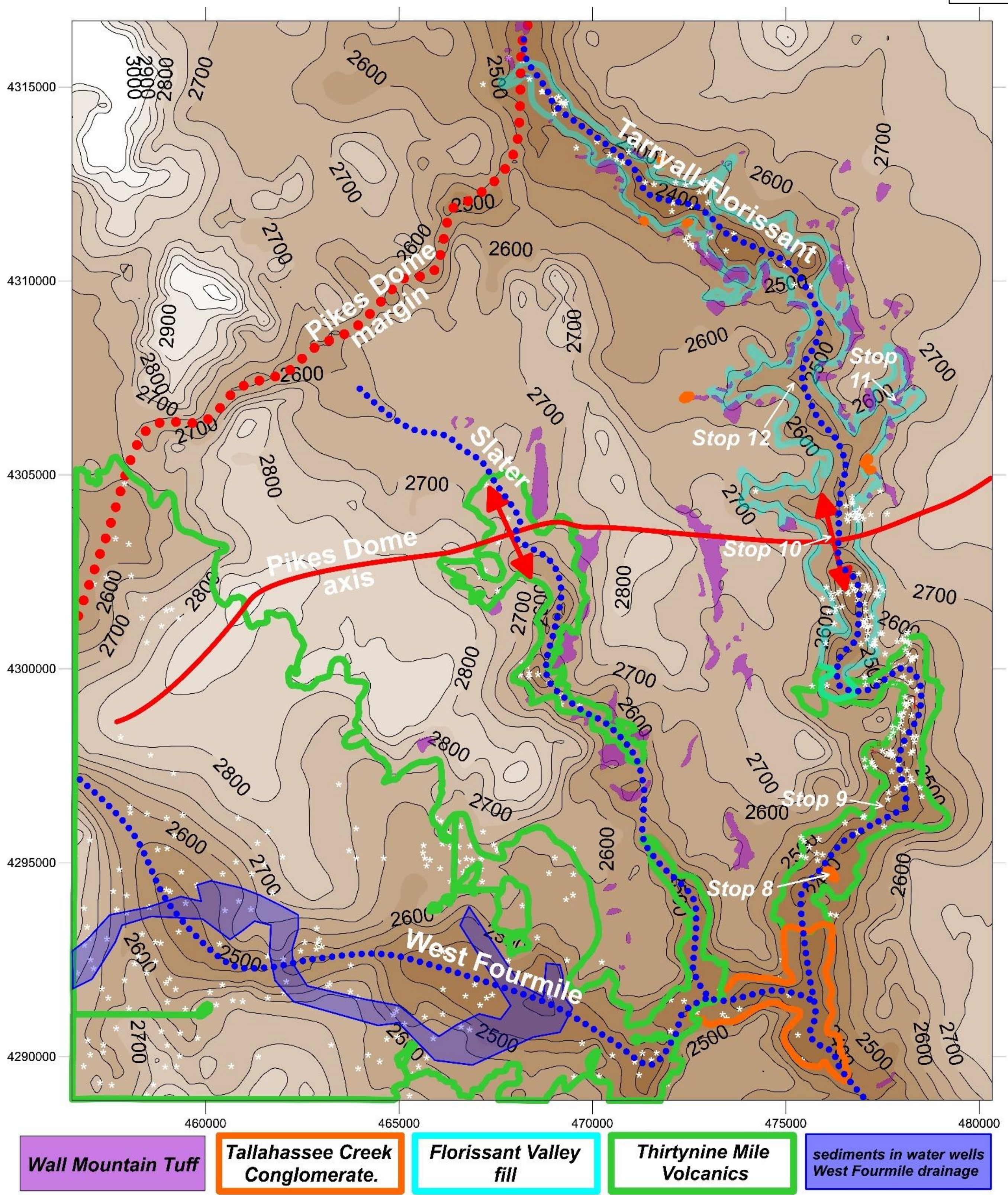


Figure 36. Map of the RMES contoured from datums on the base of overlap deposits, supersurface seed points and subsurface seed points (brown spectrum). Outcrops of Cenozoic overlap deposits include the Wall Mountain Tuff (purple fill), Tallahassee Creek Conglomerate (orange outline), Florissant valley fill including lake deposits (cyan outline), and Thirtynine Mile Volcanics (green outline). Water wells with lithologic logs that penetrate Cenozoic strata are shown with white dots. Water wells in the West Fourmile drainage that report sedimentary rocks other than volcanics are shown by the blue fill. Note better definition of the West Fourmile drainage when water well data are included.

data from water wells (Fig. 36). While the maps are similar, the water wells do a better job defining geometries of the West Fourmile drainage, including the presence of sedimentary rocks within the volcanic-rich section filling this valley, suggesting the presence of lake deposits similar to those seen in the Florissant Valley.

Colorado College professor, Christine Siddoway, and students have analyzed detrital zircon age distributions in two quartzite clasts from nearby Tallahassee Creek Conglomerates along Teller CR 112. They found one is sourced from the Sawatch Quartzite, very similar to samples from the Manitou area, and one is possibly Cambrian or Proterozoic with affinities to samples from more westerly sources in Utah and the Mohave Desert. More analyses of this type are needed as we try to understand the age and provenance of the many enigmatic high-level gravels across this part of Colorado.

From Wrights Reservoir we will head north into the Florissant valley where we will again cross the east-west trending axis of Pikes Dome we stood on yesterday some 60 miles to the east near Calhan. Similar to the structural inversion of the Castle Rock River, here the rise of Pikes Dome reversed the headwater tributaries of the ancestral South Platte River starting likely at the end of the Eocene. The main difference is the ancestral South Platte River is gone and its old valley is occupied by piddling, underfit streams. As we head north through the Florissant Valley there are enough remnants of Cenozoic overlap deposits on the RMES it will be evident we are traveling through topography that is very similar to what existed in the upper Eocene. In contrast, looking east from the relatively subdued landscape west of our perch at Wrights Reservoir, the topography rises over 2000 feet toward Cripple Creek and Victor. As we will discuss at later stops, this break in the topography marks the western margin of a late-stage, north-south trending uplift centered on Cripple Creek, Divide and Pikes Peak that impacted the western part of Pikes Dome.

This stop is on private land surrounding Wrights Reservoir and permission for our entry has been graciously given by Colorado Outdoor Sports. Additional exposures of the Tallahassee Creek Conglomerate are exposed in roadcuts 1.5 miles south of here, just east of the junction between CR 11 and CR 112, but that don't have safe pullouts for a large number of cars.

Stop 9. Lahar Dam and Incised Canyon below the Florissant Valley (38.821846, -105.259688)

In an outgrowth of the 15' quadrangle mapping by the USGS covering a wide area between South Park and the Wet Mountains, Epis et al. (1976) mapped the ancestral headwaters of the South Platte and Arkansas rivers. They recognized the Thirtynine Mile Volcanic Field played a role in damming preexisting drainages to create the Antero lakes of South Park and Lake Florissant (Fig.37). Here, we are standing within what has been called the lahar dam by staff at the nearby Florissant Fossil Beds National Monument (FFBNM). This admixture of large and small clasts of basement and volcanic rocks dammed the Florissant Valley to create Lake Florissant. I drew a series of transverse sections to better understand the geometries of the Florissant Valley including the relationship between the lahar dam and the upstream valley fill (Fig. 38). Lines were drawn between the highest outcrops preserved along the flanks of the valley using the assumption these lines proxy for the water level of Lake Florissant or the top of valley fill within the Florissant Valley. The bottom of the valley was inferred by connecting the bases of outcropping overlap deposits. To this were added lithologic picks from numerous water wells, revealing the unexpected result that the Florissant Valley is underlain by a canyon that in places is over 500' deep. Note the contrast between the widely-spaced black 100' contours of the RMES based on surface datums and the closely-spaced blue 100' contours of the RMES based on the water well data. The deepest valley fill was found in a well that drilled 520' of volcanics without reaching granite at the base of the valley (Fig. 39). This well was drilled 400' from a well drilled in granite outside of the valley, indicating a valley wall sloping in excess of 55 degrees. The transverse sections were then combined to create a longitudinal section of the valley, using the assumed water level as a flat datum. This exercise revealed the lahar dam did impound the upstream fill of the Florissant Valley, and suggests there may have been thinning of the valley fill coincident with the Pikes Dome axis indicating it may have been rising at this time (Fig. 40).

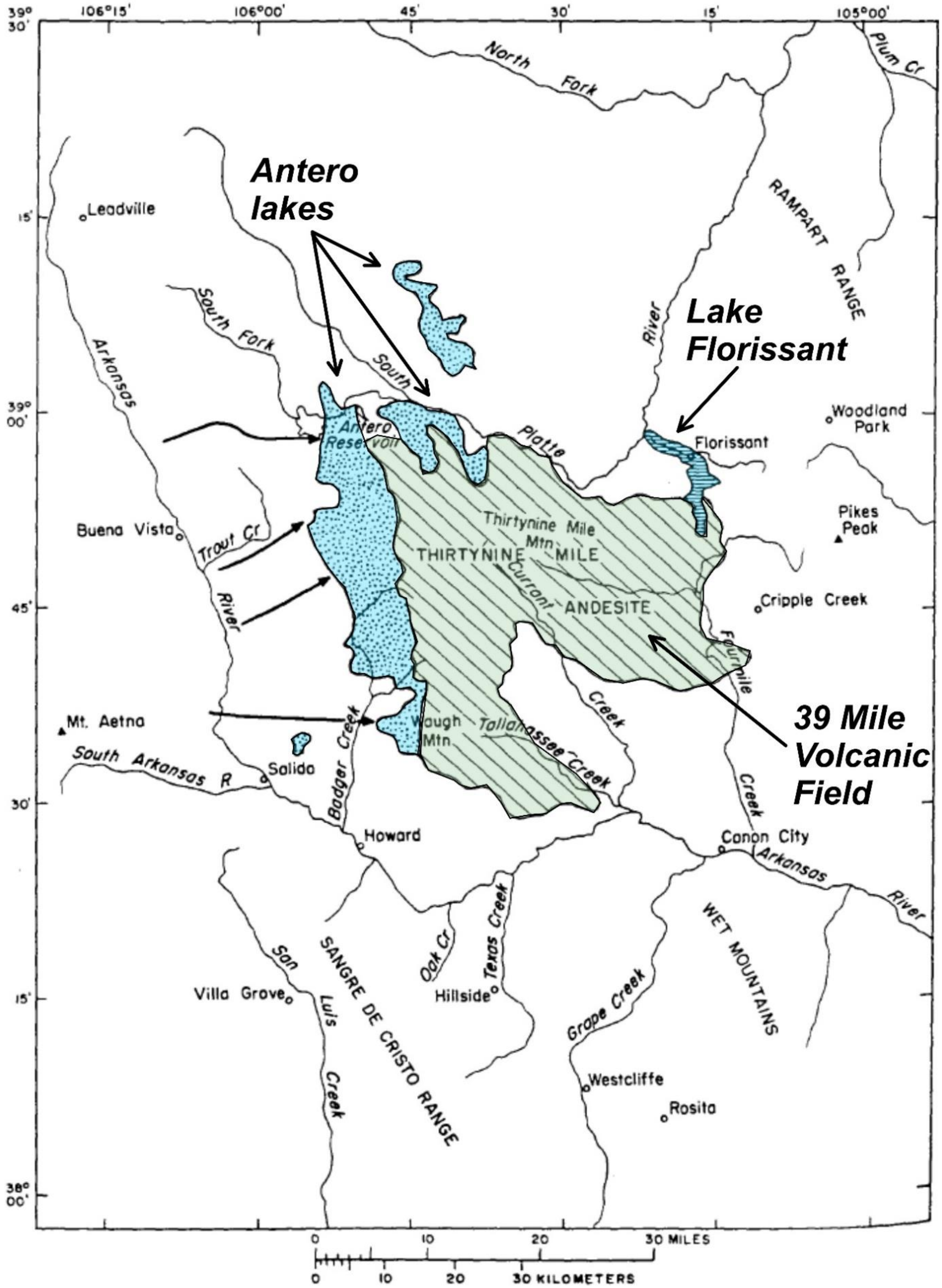


Figure 37. Present extent of the Thirtynine Mile Volcanics showing how the Florissant Lake (horizontal lines) and the Antero Formation (stippled) were deposited in water impounded by laharic breccias. Arrows show trends of paleovalleys (Epis et al., 1976).

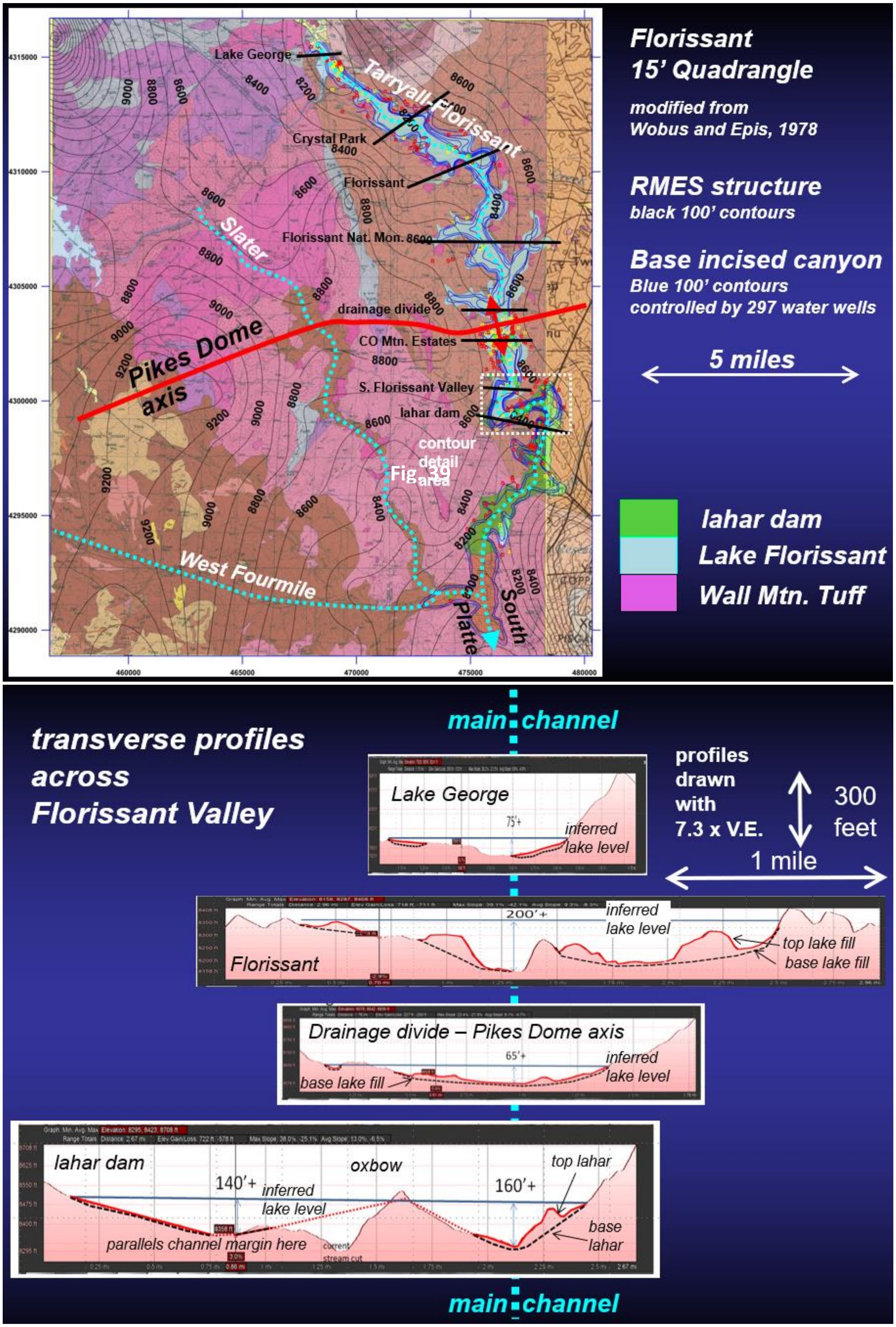


Figure 38. Serial sections transverse to the Florissant Valley connecting the highest points of preserved section across the valley and estimating the base of the valley fill from outcrop relationships. Contour map contrasts the widely-spaced RMES contours (black) based solely on outcrop data with the closely-spaced contours (blue) based on water wells showing a hidden, deeply-incised canyon beneath the Florissant Valley. Water wells are shown by red dots on the map of the Florissant Quadrangle modified from Wobus and Epis (1978).

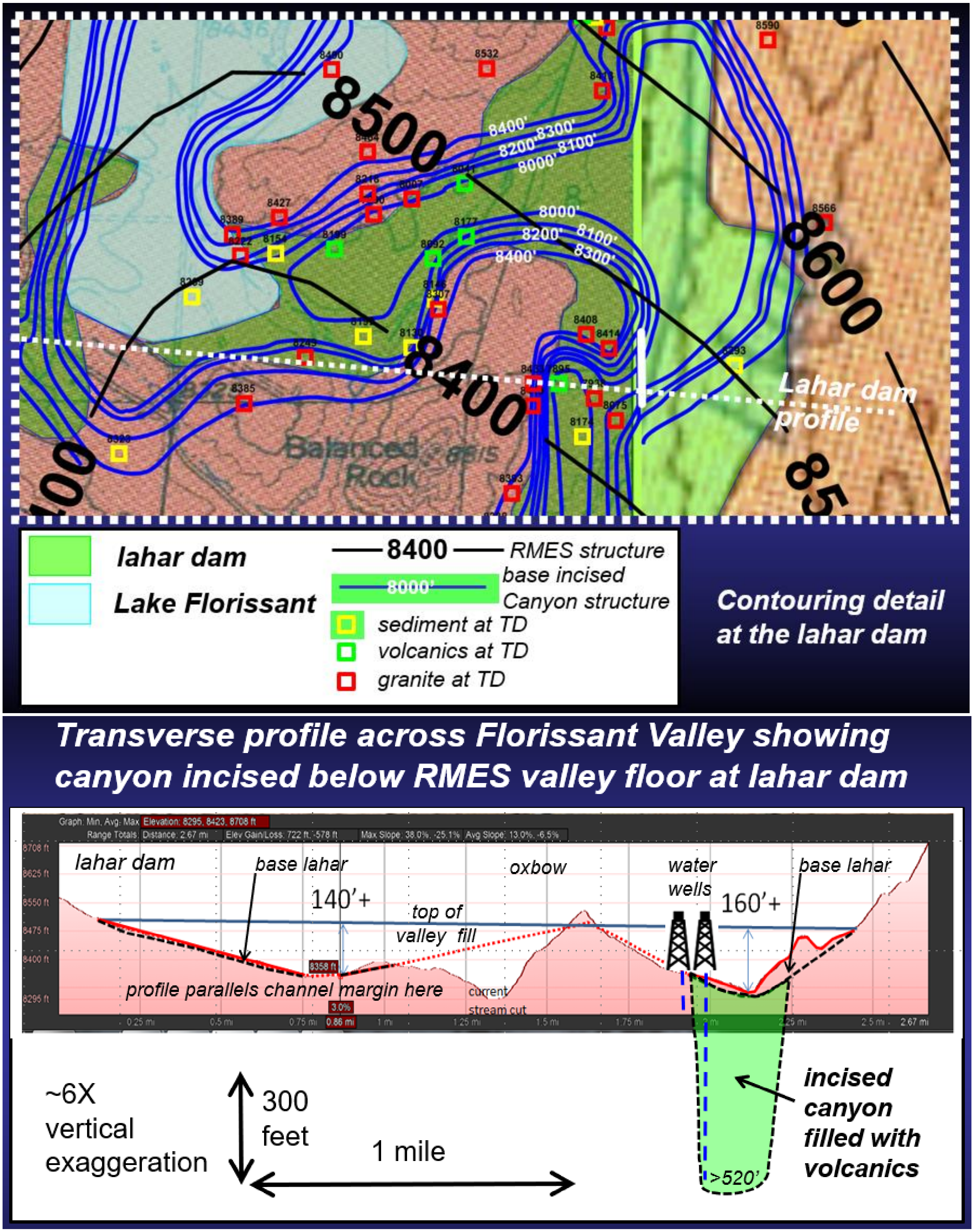


Figure 39. Detail of the lahar dam in the incised oxbow around Balanced Rock at the south end of the Florissant valley. Widely-spaced black contours based on surface datums contrast with closely-spaced contours based on numerous water wells. The water wells reveal a canyon beneath the Florissant Valley that in places is over 500' deep.

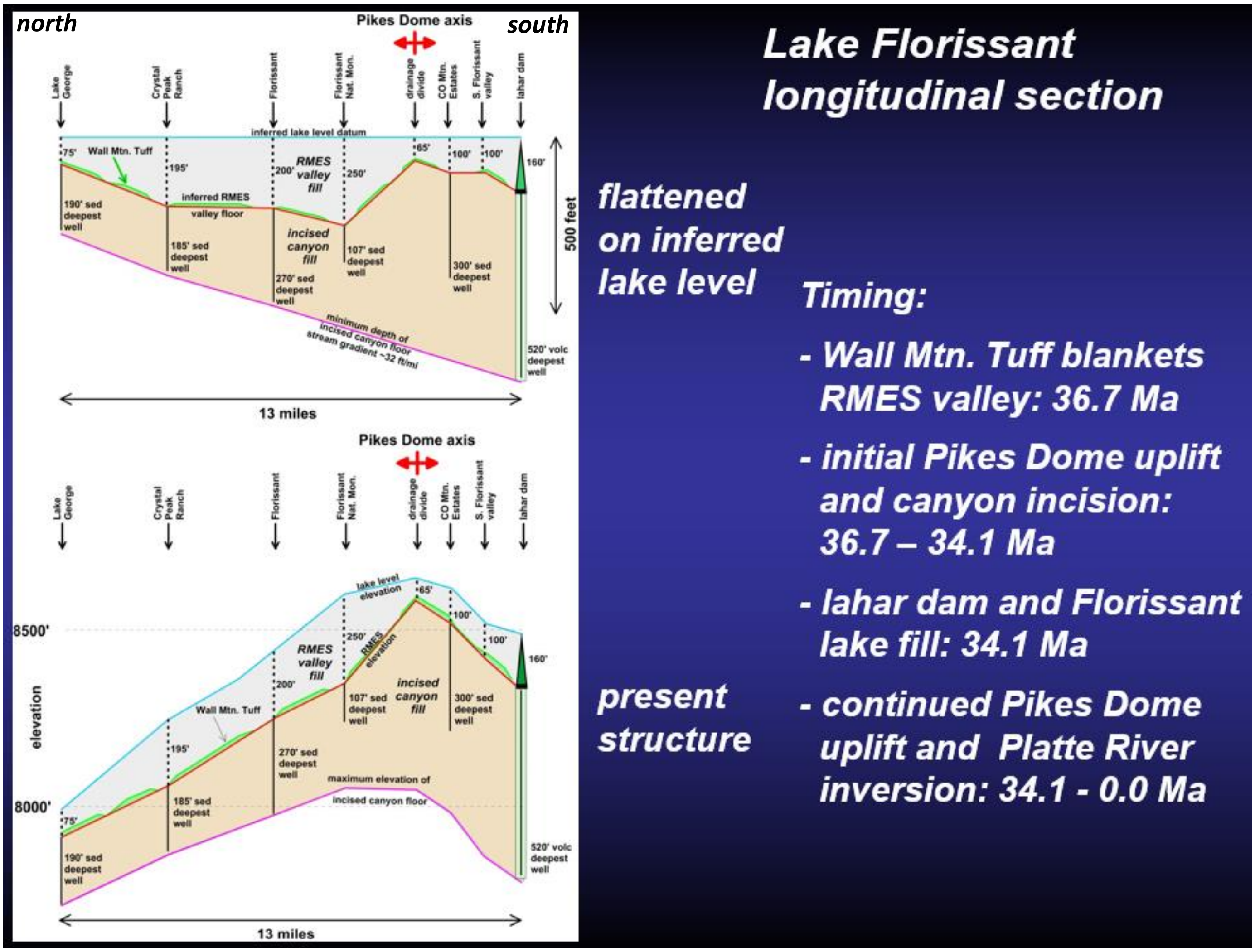


Figure 40. Longitudinal section of the Florissant Valley based on serial transverse sections (Fig. 38). Upper section is flattened on the assumed water level in Lake Florissant. The tan polygon shows deepest water well penetrations along the valley with the bottom of the polygon indicating the minimum depth of the canyon that underlies the Florissant Valley. The lower section is hung structurally, revealing the axis of Pikes Dome.

Stop 10. Pikes Dome axis- South Platte-Arkansas drainage divide (38.884808, -105.272848)

From the lahar dam we drove 450’ uphill and are now standing for the second time during this trip on the drainage divide between the South Platte and Arkansas rivers, which again marks the axis of Pikes Dome. From this point, the topography drops 31 miles south to the Arkansas River and 9 miles north to the South Platte River attesting to the width of the dome approaching its western terminus. Figure 41 is a vertically-exaggerated Google Earth oblique view showing the dome axis extending 60 miles east to yesterday’s stop near Calhan. The curvature along the dome axis is accentuated due to the foreshortening of the image. With the help of some posted datums, it is apparent the ancestral South Platte River between Lake George and the area below Cripple Creek shows over 500’ of drape across the axis of Pikes Dome.

Figure 42 is a longer, longitudinal section of the ancestral South Platte River crossing Pikes Dome from the current South Platte River at Lake George through the Florissant Valley and Fourmile Canyon to the current Arkansas River. From the margin of Pikes Dome at the current South Platte River in Lake George, the RMES rises over 500’ to the dome axis just south of the Florissant Fossil Beds National Monument (Stop 10), then drops through Fourmile Canyon to the Oligocene lahars in Wolf Park constraining the low in the RMES that controls the course of the current Arkansas River. The pronounced incision of the RMES through Fourmile Canyon reflects

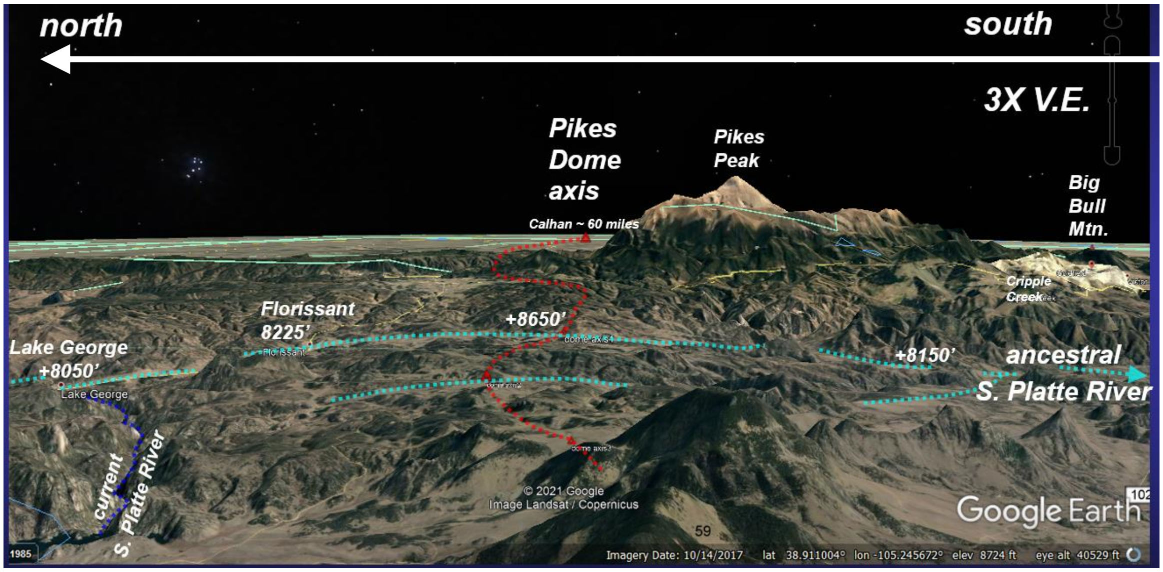


Figure 41. Google Earth oblique view looking east along the axis of Pikes Dome and showing tributaries of the ancestral South Platte River draped across the dome axis.

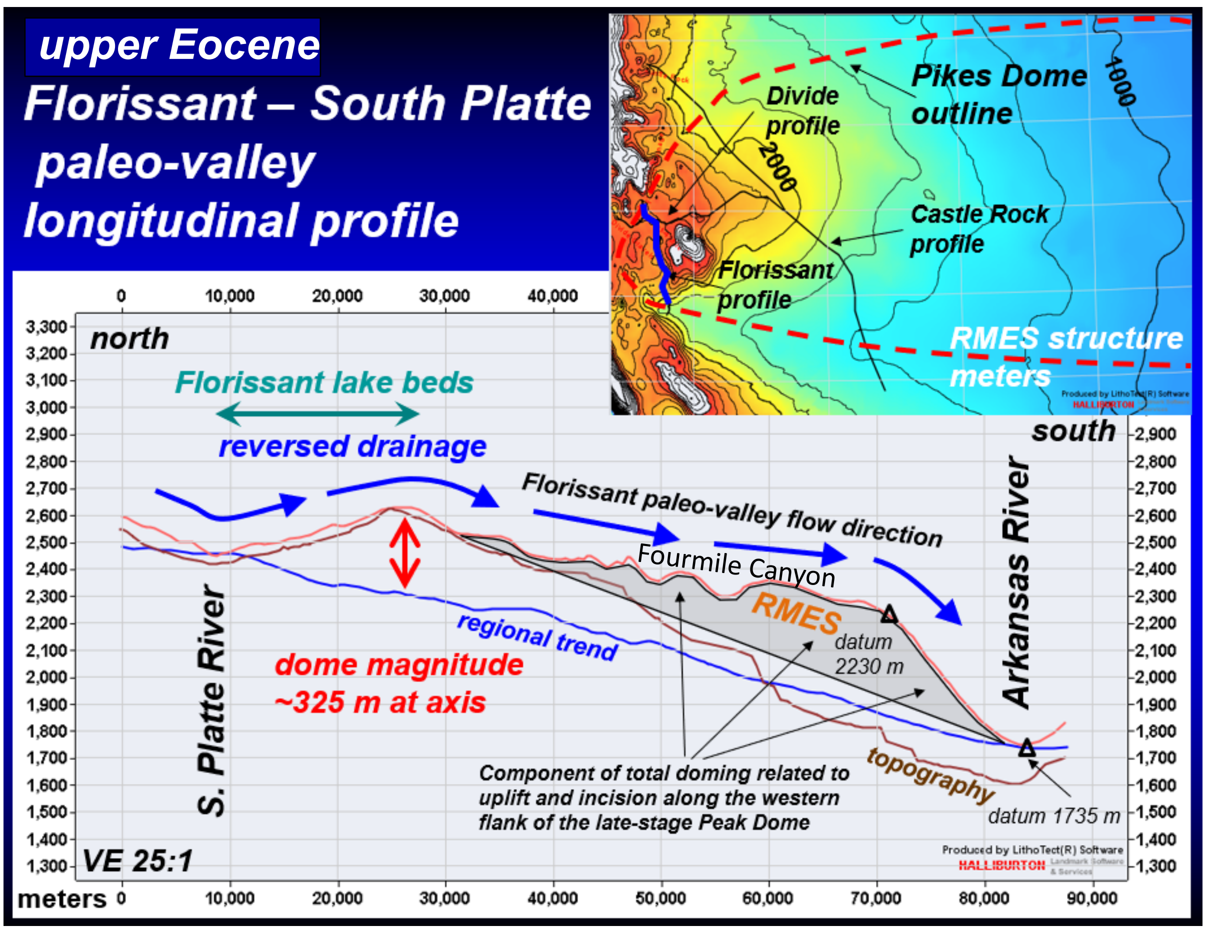


Figure 42. Longitudinal section of the Florissant tributary of the ancestral South Platte. RMES rises 175 meters (575') from the current South Platte River at Lake George to the Pikes Dome axis. Because the ancestral South Platte River flowed south, this stretch of the Florissant Valley is reversed due to the uplift of Pikes Dome. Relative to the regional trend surface the dome has 325 meters (1050') of relief at the dome axis. South of the dome axis, the RMES drops to the current Arkansas River as constrained by datums from the Oligocene Wolf Park lahars (Figs. 33 and 34). The RMES in the lower reaches of the valley is deeply incised due to uplift along the western flank of the late-stage Peak Dome that uplifted the Cripple Creek, Divide and Pikes Peaks areas.

uplift along the western margin of the late-stage Peak Dome that encompasses Cripple Creek, Divide, Pikes Peak, and the Rampart Range we will discuss later today.

Stop 11. Wall Mountain Tuff: Barksdale Picnic Area (38.911911, -105.255959)

We started this trip at the Littleton Downtown RTD station in front of the historic Littleton train depot that was made of Wall Mountain Tuff quarried near Castle Rock. There, the tuff is a fine-grained, varicolored welded tuff containing biotite and sanidine crystals. Here at the Barksdale Picnic Area on the margin of the Florissant Valley we are closer to the eruptive source of the tuff in the Sawatch Range and the tuff is much coarser-grained with larger biotite and sanidine crystals (Figs. 21 and 43). The RMES in the Florissant area is covered by numerous remnants of the Wall Mountain Tuff, which make it apparent that the topography of this area is much the same as it was in the upper Eocene (Figs. 35 and 36).

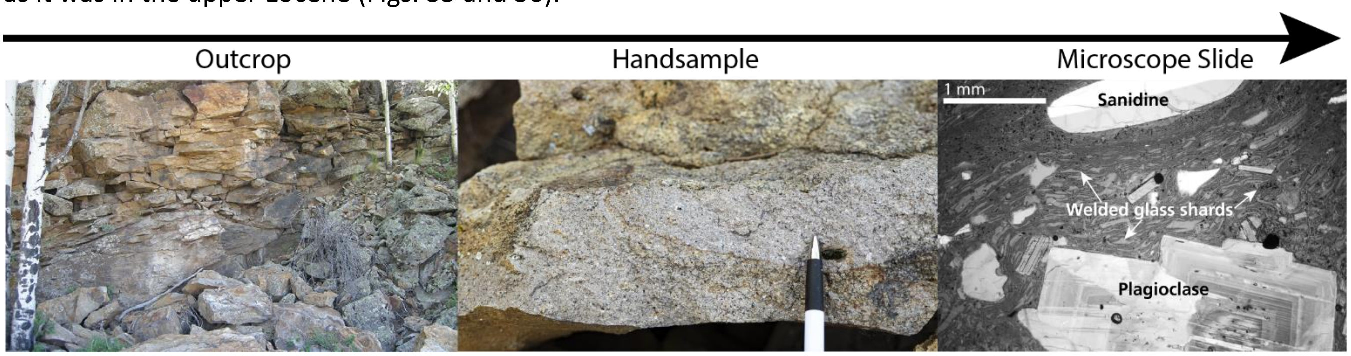


Figure 43. Outcrop, hand sample and microscopic views of the Wall Mountain Tuff (National Park Service by Michael Kelly, Bud Wobus and Christian Lockwood)

Stop 12. Florissant Fossil Beds National Monument (38.913556, -105.285388)

In 1878 Arthur Lakes and Samuel H. Scudder rode horses to Florissant where they spent 4.5 days studying the lake deposits and a half day chasing down a lost horse. Upon their return to civilization, Lakes crafted the first map of Lake Florissant (Fig. 44), which now resides at the Monument headquarters. Scudder (1878) went on to describe hundreds of insect species quarried from the valley fill and make the following statement regarding

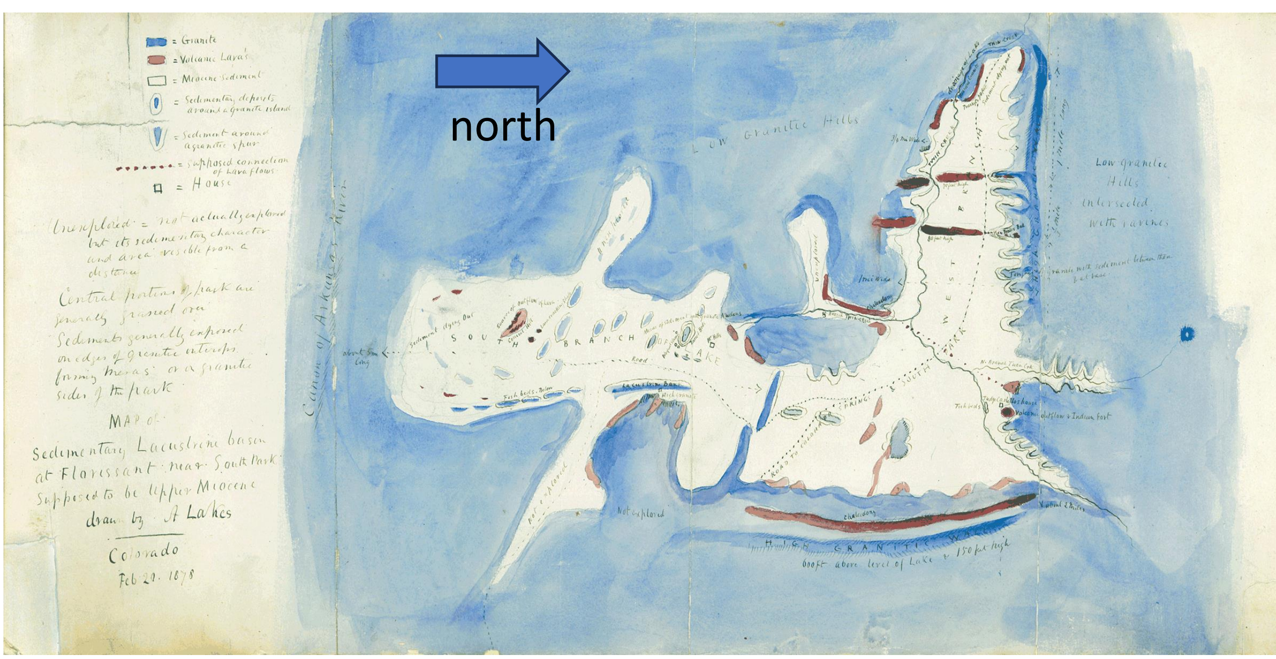


Figure 44. Arthur Lakes' 1878 map of Lake Florissant painted after his foray to the area with Samuel Scudder.

the formation of the lake: *" The ancient outlet of the whole system was probably at the southern extremity; at least the marks of the lake-deposits reach within a few meters of the ridge which now separates the waters of the Platte and Arkansas; and the nature of the basin itself, the much more rapid descent of the present surface on the southern side of the divide, with the absence of any lacustrine deposits on its slopes, lead to this conclusion. At the last elevation of the Rocky Mountains chain, the drainage flow of this immediate region was reversed; the elevation coming from a southerly or southeasterly direction (perhaps Pikes Peak), the lake, or series of lakes, was drained dry by emptying at the northwestern extremity. The drainage of the valley now flowed into a brook which followed the deeper part of its former floor, and the waters of the region have since emptied into the Platte and not the Arkansas, passing in their course between Topaz Butte and Castello's Mountain."*

Scudder (1878) thought the southern margin of Lake Florissant was controlled by a ridge at the current drainage divide between the South Platte and Arkansas rivers. While subsequent mapping showed the lake continued south of the drainage divide to the lahar dam (Epis et al., 1976; Wobus and Epis, 1978), what Scudder correctly recognized was the southerly flow in the Florissant Valley had been reversed by the uplift of Pikes Dome and replaced by an underfit "brook" flowing to the northwest to the current South Platte River.

Scudder's (1878) and Epis et al.'s (1976) ideas can be combined to explain the evolution of Lake Florissant as follows (Fig. 45):

1) The ancestral South Platte River begins as a low-gradient, meandering river flowing south within a valley that becomes mantled by the Wall Mountain Tuff at 36.7 Ma.
2) Initial uplift of Pikes Dome causes the river to erode a deep canyon – the river is now antecedent.
3) Lahars emanating from the Thirtynine Mile Volcanic Field block the canyon, causing Lake Florissant to form.
4) Continued uplift of Pikes Dome reverses the drainage of the ancestral South Platte River. Lahar and Florissant Valley fill are preserved as the river is replaced by an underfit stream.

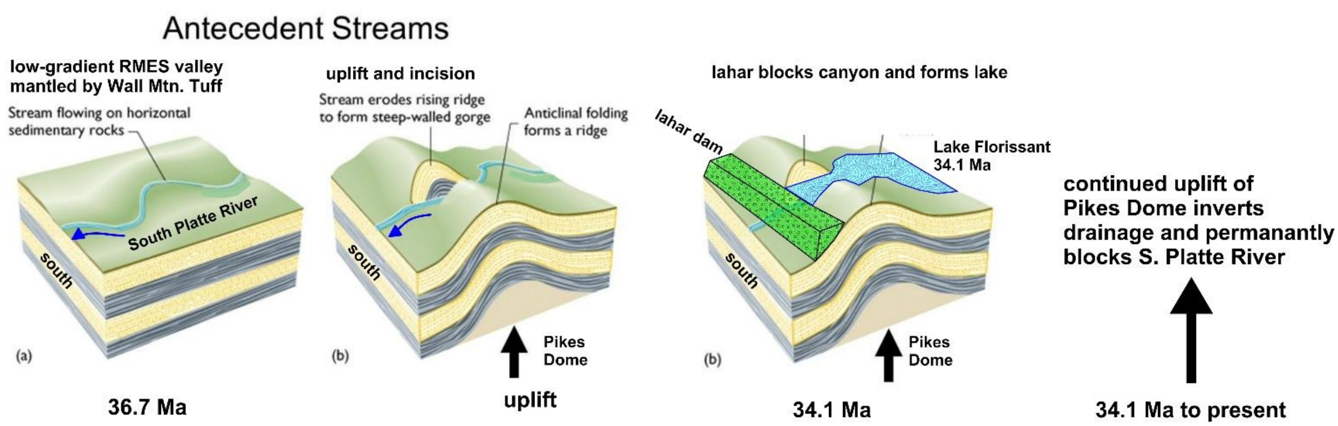


Figure 45. Evolution of the Florissant Valley showing the ancestral South Platte became an antecedent river during the initial rise of Pikes Dome. The resultant incised canyon was dammed by lahar flows causing Lake Florissant to form. Continued rise of Pikes Dome reversed the river, allowing the lahar dam and lacustrine valley fill to be preserved (block diagrams modified from Adam C. Simon, Research Associate University of Maryland).

Our visit to the Florissant Fossil Beds National Monument would be incomplete without seeing the exposures of the valley fill sequence at Big Stump Ridge (Fig. 46). The geology of the Monument has been mapped by past CSS president and University of Northern Colorado Emeritus Professor Emmett Evanoff and is currently being mapped in greater detail by him, Herbert Meyer, National Park Service Paleontologist Emeritus, and Robert Anderson, University of Colorado Boulder Distinguished Professor. There is also an effort by past CSS president

Ned Sterne to determine ages of various gravel deposits within and adjacent to the Monument using detrital zircon and sanidine dating.

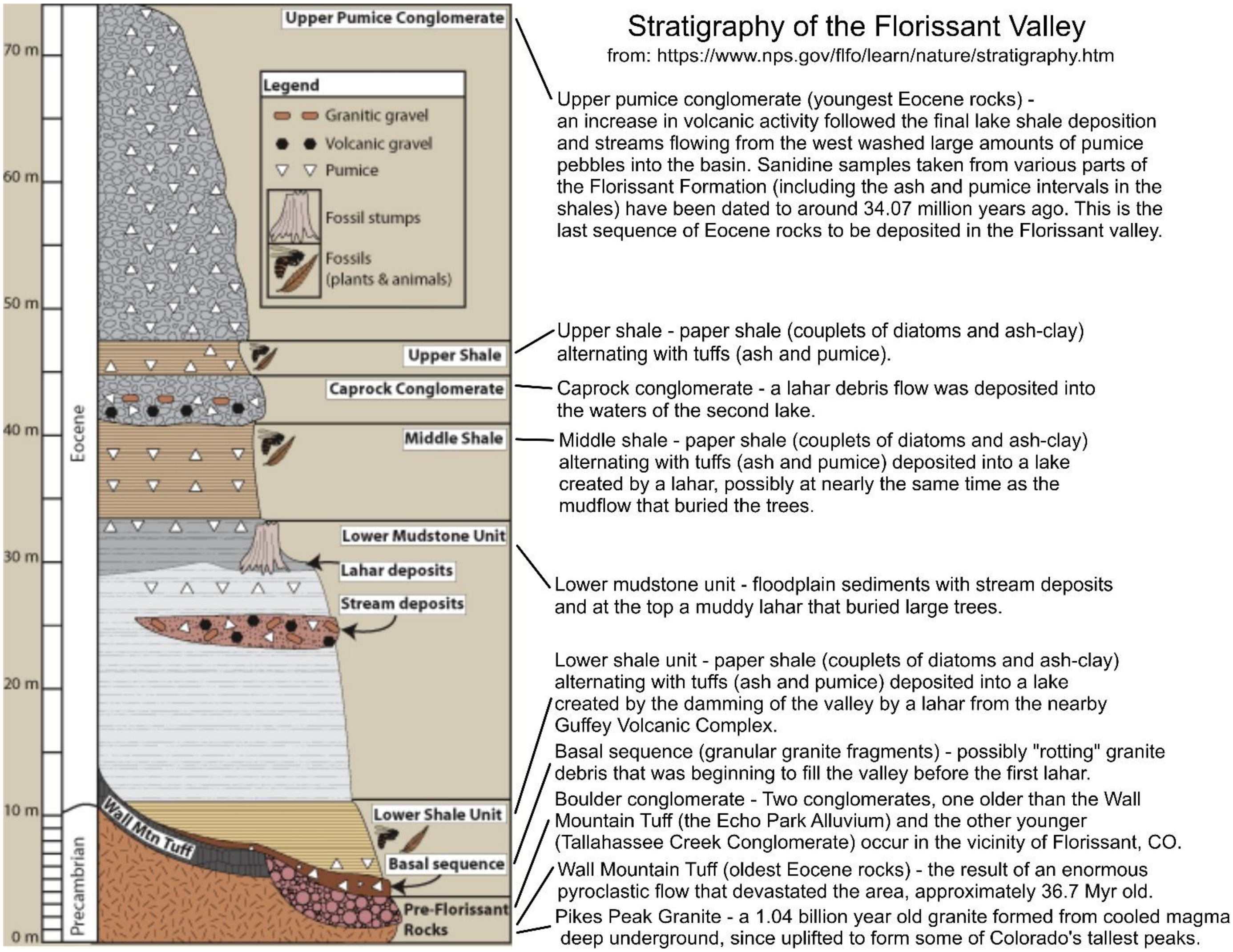


Figure 46. Stratigraphy of the Florissant Valley modified from: https://www.nps.gov/flfo/learn/nature/stratigraphy.htm

Stop 13. Tarryall Creek structural diversion (39.069699, -105.408660)

After leaving the Florissant Fossil Beds National Monument we will see a smaller example of tectonics reversing drainages and rerouting rivers. We will follow a tributary of the ancestral South Platte River in what was once the upstream direction from Florissant to Lake George and north to Tarryall Creek (Fig. 47). In the upper Eocene this tributary flowed south from its headwaters in northern South Park at Hoosier Pass and Georgia Pass, down the current Tarryall Creek Valley to Lake George, Florissant, through the Florissant Valley and Fourmile Canyon to Canon City. Currently Tarryall Creek follows its original course south to point B where it encounters an uplift and makes a lefthand turn, leaving its original course, to flow northeast joining the current South Platte River several miles upstream from Cheeseman Reservoir. This diversion of Tarryall Creek as it encounters an uplift is a good analog for the diversion of the more westerly tributaries of the ancestral South Platte River as they encountered the margin of Pikes Dome at Elevenmile Reservoir. The uplift that diverted Tarryall Creek crests at point C and the drainage between points B and C is reversed and is now occupied by an underfit stream. At point C, George C. Stone (unpublished excursion accounts archived at Colorado College) reported the presence of shales similar to those in Lake Florissant suggesting the lake originally extended 6 miles north of Lake George or multiple lakes developed along the valley. Between points C and D the original gradient of the Tarryall tributary has been accentuated by the structural uplift and the valley is again occupied by an underfit stream. Point D marks a structural low and is the margin of Pikes Dome. Between points D and E the current South Platte River follows the Pikes Dome margin and is flowing north or upstream along what was once one of its south-flowing tributaries – a clear example of drainage reversal. Between E and the town of Florissant at H the original southeast-flowing tributary has been reversed by uplift of Pikes Dome and replaced by northwest-flowing Twin Creek. Twin Creek follows the original valley except where it encounters an uplift that crests at F, where is cuts a new course through Twin Creek Canyon to join the current South Platte River at the margin of Pikes Dome. One explanation for the uplifts cresting at points C and F is rejuvenation along the margins of the Precambrian Lake George Intrusive Center, although the origins of these higher-order structures deserve more study.

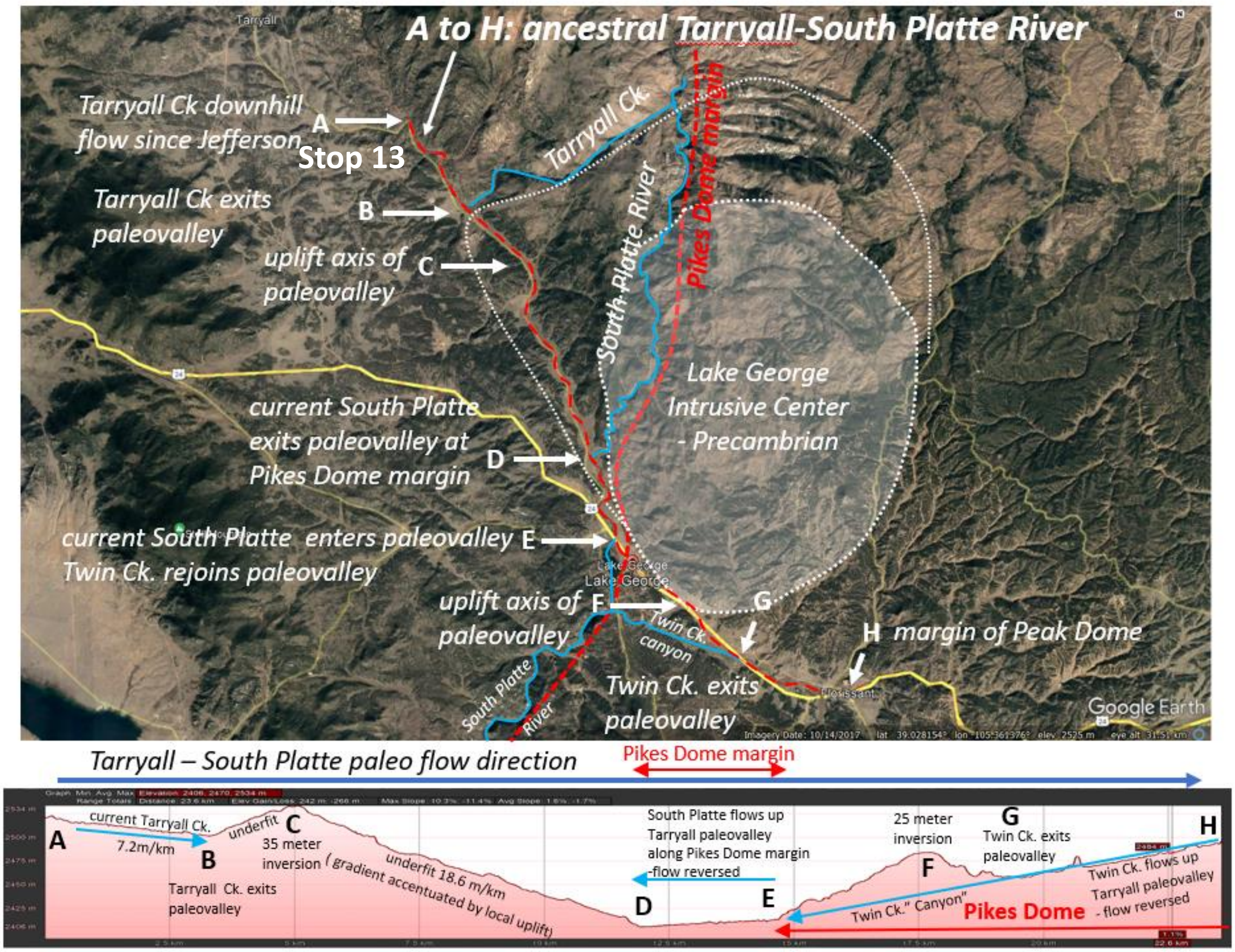
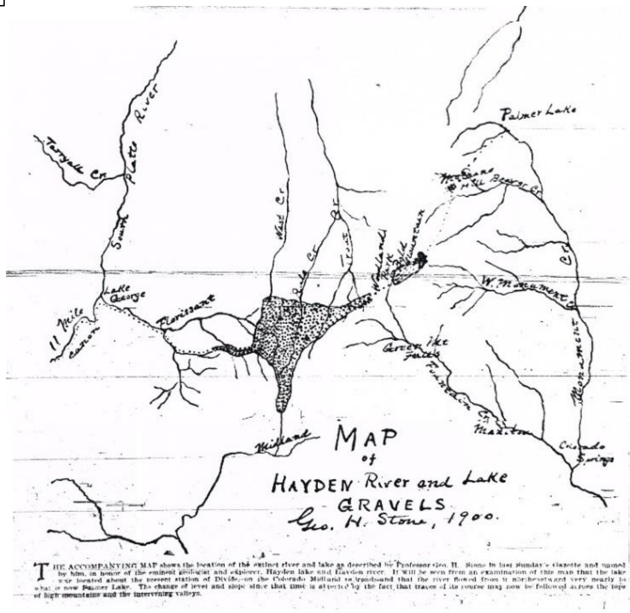


Figure 47. Tectonic drainage reversals and diversions of the Tarryall tributary of the ancestral South Platte River.

Stop 14. Divide Gravels – Hayden-Divide-Arikaree River (38.934680, -105.186490)

On March 18th 1900 George H. Stone, first geology professor at Colorado College, published an article in the Colorado Springs Gazette describing what he called the "extinct Hayden River". His full-page article detailed occurrences of what we now call the Divide Gravels extending from west of Divide to the Rampart Range. The article was not accompanied by a map, a possible oversight that was corrected by the appearance of a rough sketch map in the next Sunday's paper on March 25 (Fig. 48). Stone, while collaborating with Arthur Lakes on unpublished accounts of railroad excursions archived at Colorado College, later expanded his description of the Hayden River to include outcrops west of Florissant above the confluence of Wagon Tongue Gulch and



Colorado Springs Gazette March 25, 1900

Figure 48. George H. Stone's (1900b) sketch map of the Hayden River and Lake Gravels

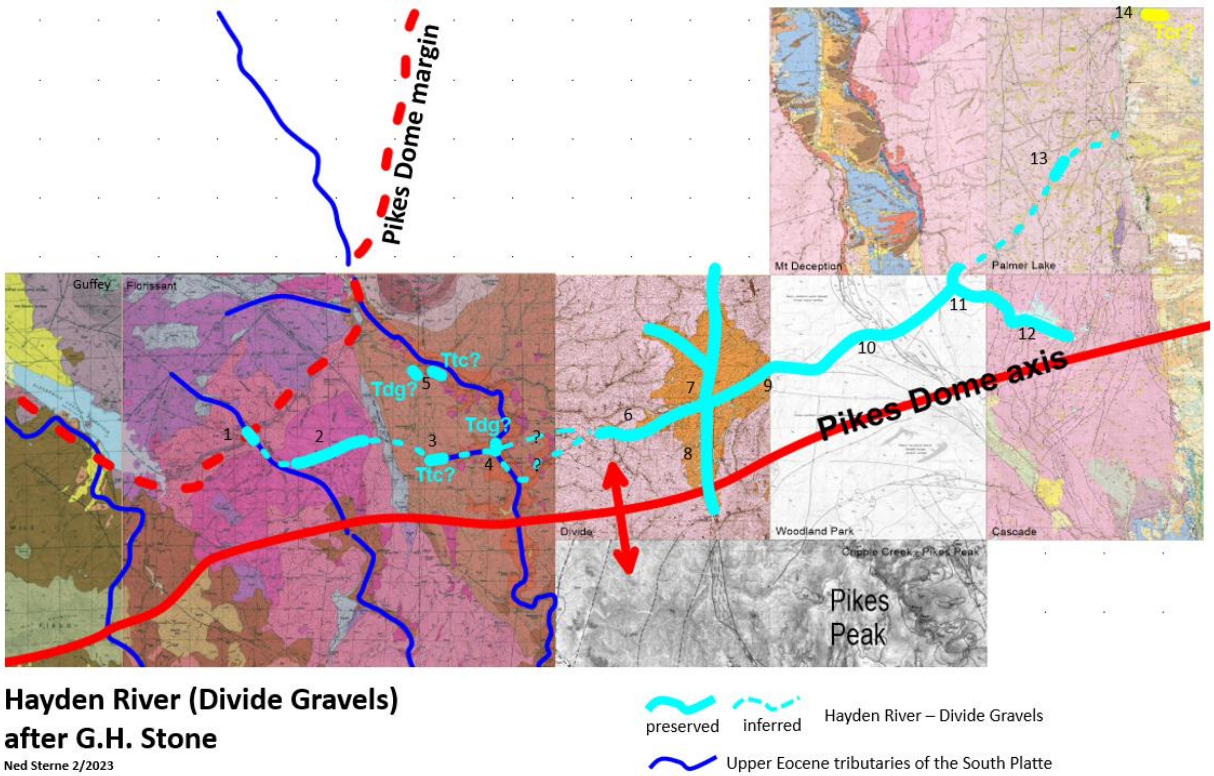


Figure 49. Tracking the Extinct Hayden River of G.H. Stone. Locations include: 1) Wagon Tongue Gulch and Elevenmile Canyon, 2) Lone Chimney Ranch, 3) Tallahassee Creek Conglomerates (?) just west of the FFBNM; 4) Tallahassee Creek Conglomerates (?) south of Lower Twin Rocks Rd. in the FFBNM; 5) Tallahassee Creek Conglomerates 2 miles west of Florissant (Olson and Wobus, 2019); 6) Divide Gravels on Daniwood Grove St.; 7) Divide Gravels at Divide; 8) Divide Gravels along Rt 67; 9) Divide Gravels on Rt 24; 10) Divide Gravels at Woodland Park; 11) Divide Gravels at Bald Mtn.; 12) Divide Gravels at Rampart Reservoir; and 13) Divide Gravels (?) on Palmer Lake Quadrangle. Quadrangles: Mount Deception: Temple et al. (2007); Palmer Lake: Keller et al. (2007); Cascade: Morgan et al. (2003); Woodland Park: Wobus and Scott (1977); Divide: Temple and Busacca (2009); Cripple Creek-Pikes Peak: Wobus et al. (1976); Florissant: Wobus and Epis (1978); Guffey: Epis et al. (1979).

Elevenmile Canyon (Location 1 on Fig.49), and at Lone Chimney Ranch (location 2 on Fig. 49). Unfortunately, no map from Stone's later writings has been located, although his wonderfully detailed field descriptions have made it possible to locate the western gravel occurrences. Pearl (1971) found unweathered clasts of Pikes Peak batholith in cores in northwest Kansas and proposed this material derived from the Divide area west of Colorado Springs and were transported to the northeast via his "Ancestral Arikaree River", part of which he thought would have flowed along the upper reaches of Big Sandy Creek we saw yesterday north of Calhan (Fig. 50). Scott (1982) notes fragments of amazonite, smokey quartz, and volcanic rocks similar to the Thirtynine Mile Volcanics in the Ogallala at Cedar Point near Limon he thought derived from the Divide area. Lastly, Bob Raynolds and I have found numerous clasts of grey quartzite reminiscent of the Proterozoic Coal Creek Quartzite possibly recycled from the Castle Rock River into the Ogallala in a gravel quarry just east of Limon along Interstate 70 and again at Cedar Point. Here at the intersection of Twin Rocks Road and Rt 24 is one of the best exposures of the Divide Gravels showing abundant clasts of Thirtynine Mile Volcanics and sanidine-rich sandstone lenses.

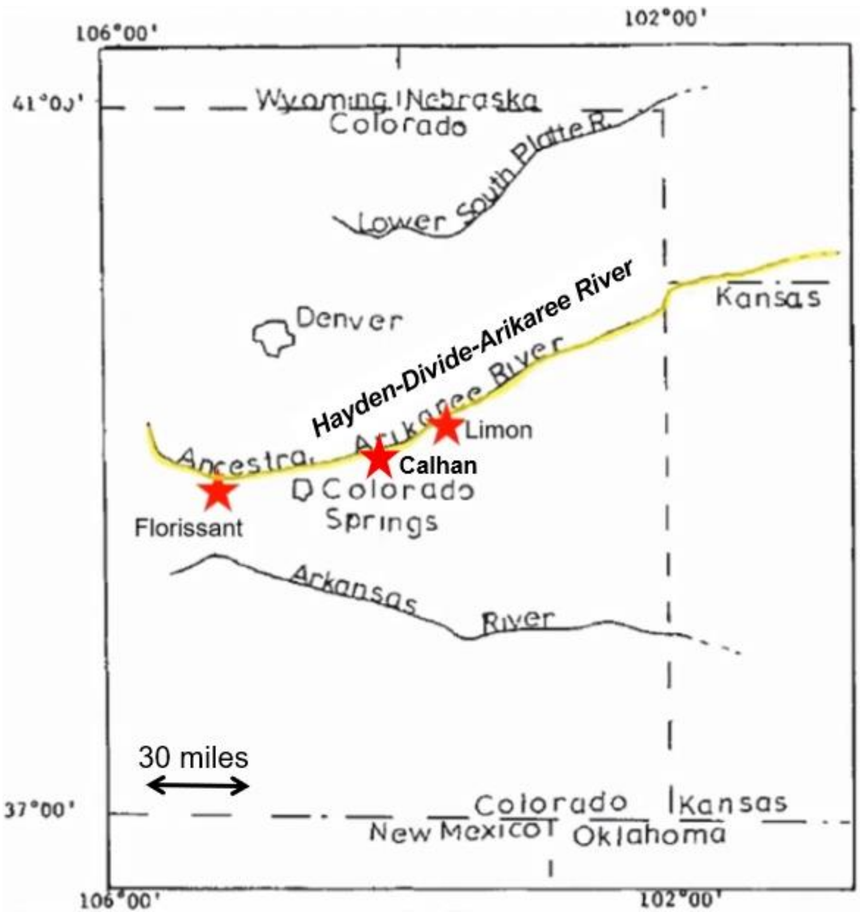


Figure 50. Map modified from Pearl (1971) showing the course of Hayden-Divide-Arikaree River.

The age of the Hayden-Divide-Arikaree River is an open question, with Cal Ruleman thinking it could be Pleistocene in part, Pearl (1971) dating the river to the late Pliocene to very early Pleistocene, Scott (1975), Epis et al. (1976) and Steven et al. (1997) assigning it to the Miocene, and my suspicion it could be as old as the Oligocene (Fig. 12). In collaboration with Matt Morgan at the Colorado Geological Survey, we have a 137-grain detrital zircon analysis for the gravels in a quarry at Divide returning a single youngest grain of 28.8+-1.66 Ma, and a 30-grain detrital sanidine analysis for gravels from our stop at the intersection of Twin Rocks Road and Rt 24 west of Divide yielding three youngest grains of 30.14+-0.03 Ma, 30.62+-0.03 Ma, and 31.49+-0.04 Ma. These early results indicate the Hayden-Divide-Arikaree River could be as old as the lower Oligocene, and we are currently analyzing additional samples from the far western outcrops (Points 1 and 2 on Fig. 49) and from the Rampart Range (Point 11, on Fig. 49).

What all of this points to is a major reorganization, starting as early as the lower Oligocene, with the south-flowing upper Eocene drainage systems replaced by the northeast-flowing Hayden-Divide-Arikaree River (Fig. 12). This came in response to the initial rise of Pikes Dome with the tributaries of the ancestral South Platte River diverting to the northeast north of the dome axis. The other indication of this early movement comes from the drainage divide in western Kansas noted by Pearl (1971) that is coincident with the axis of Pikes Dome. The drainage divide is seen in channels incised into the RMES below the Ogallala High Plains Aquifer in thousands of water wells (purple lines on Fig. 12).

Stop 15. Woodland Park Rest Area, Pikes Peak vista (38.994051, -105.054477)

Stop 16. Rampart Range Rd. – Ute Pass Fault offsets the Hayden-Divide-Arikaree River (38.982708, -105.016377)

Our final stop finds us on volcanic-rich Divide Gravels at Mount Baldy on the Rampart Range with a commanding view of Pikes Peak above and Woodland Park below. In his paper on Neogene tectonism, Taylor (1975) noted the significant offset of the Divide Gravels between Woodland Park and the Rampart Range due to extensional overprint on the Ute Pass Fault. My cross section (Fig. 51) shows the Manitou Park "graben" as an inlier caught between the east-directed Ute Pass Fault and the blind, west-directed Mount Deception Fault (my requisite triangle zone included). The Ute Pass Fault has experienced repeated movements including the Neoproterozoic

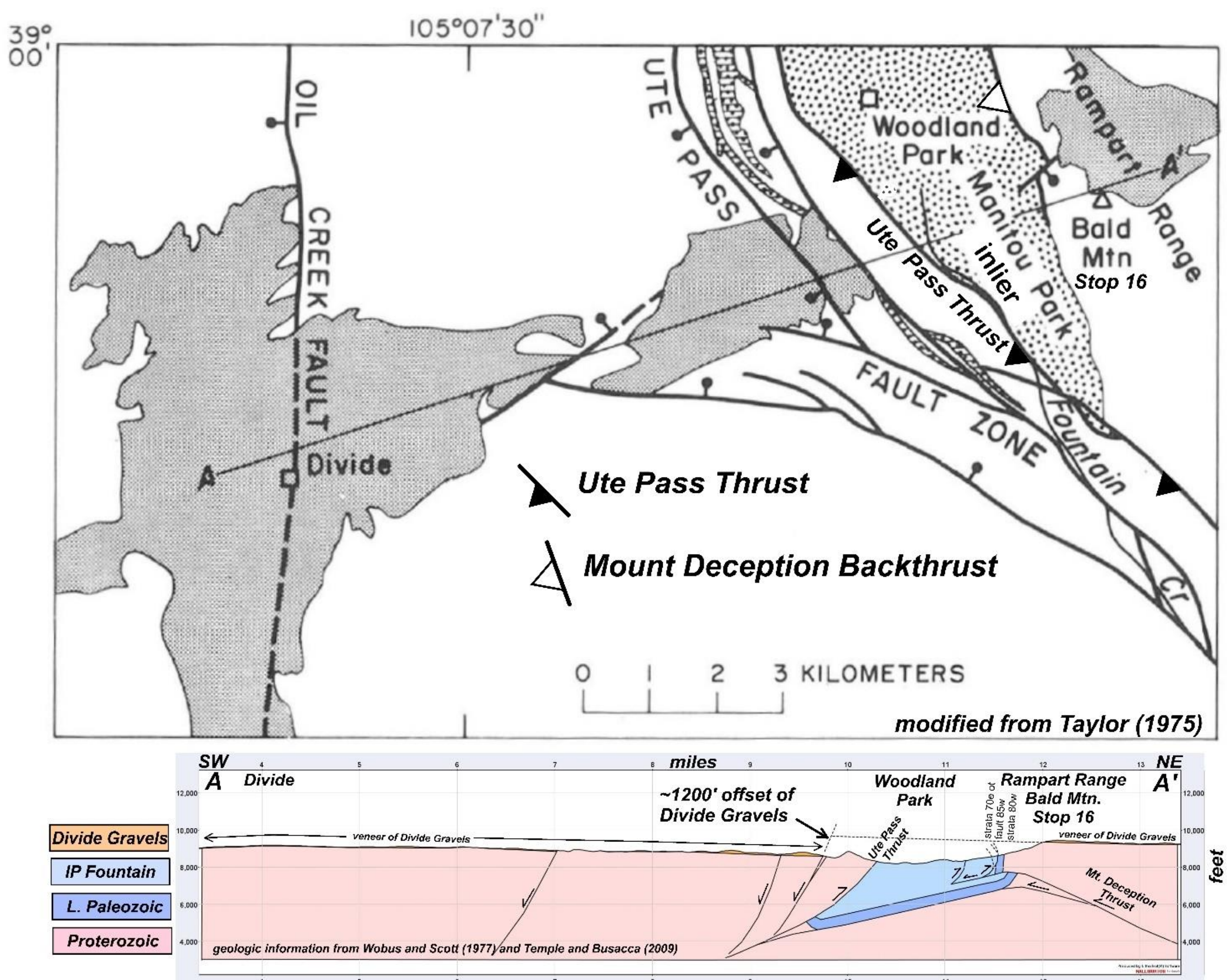


Figure 51. Map modified from Taylor (1975) showing distribution of the Divide Gravels (grey fill), Pennsylvanian rocks in the Manitou Park inlier (stippled fill), and Proterozoic Tava sandstone dikes (lined fill) surrounded by Proterozoic Pikes Peak batholith (white fill). Cross section by the author shows 1200' of offset of the Divide Gravels and the RMES by Cenozoic extensional overprint of the Ute Pass Thrust.

The Hayden-Divide-Arikaree River was in turn destroyed by deformation of the RMES due to uplift of the north-south trending Peak Dome that encompasses Cripple Creek, Divide, Pikes Peak and the Rampart Range. A longitudinal profile along the course of the river shows it reversed between the margin of Pikes Dome at the current South Platte River and Divide, and offset by the Ute Pass Fault (Fig. 52). Once again, rivers don't flow uphill, so the relief on the RMES is the result of deformation and not original erosional topography.

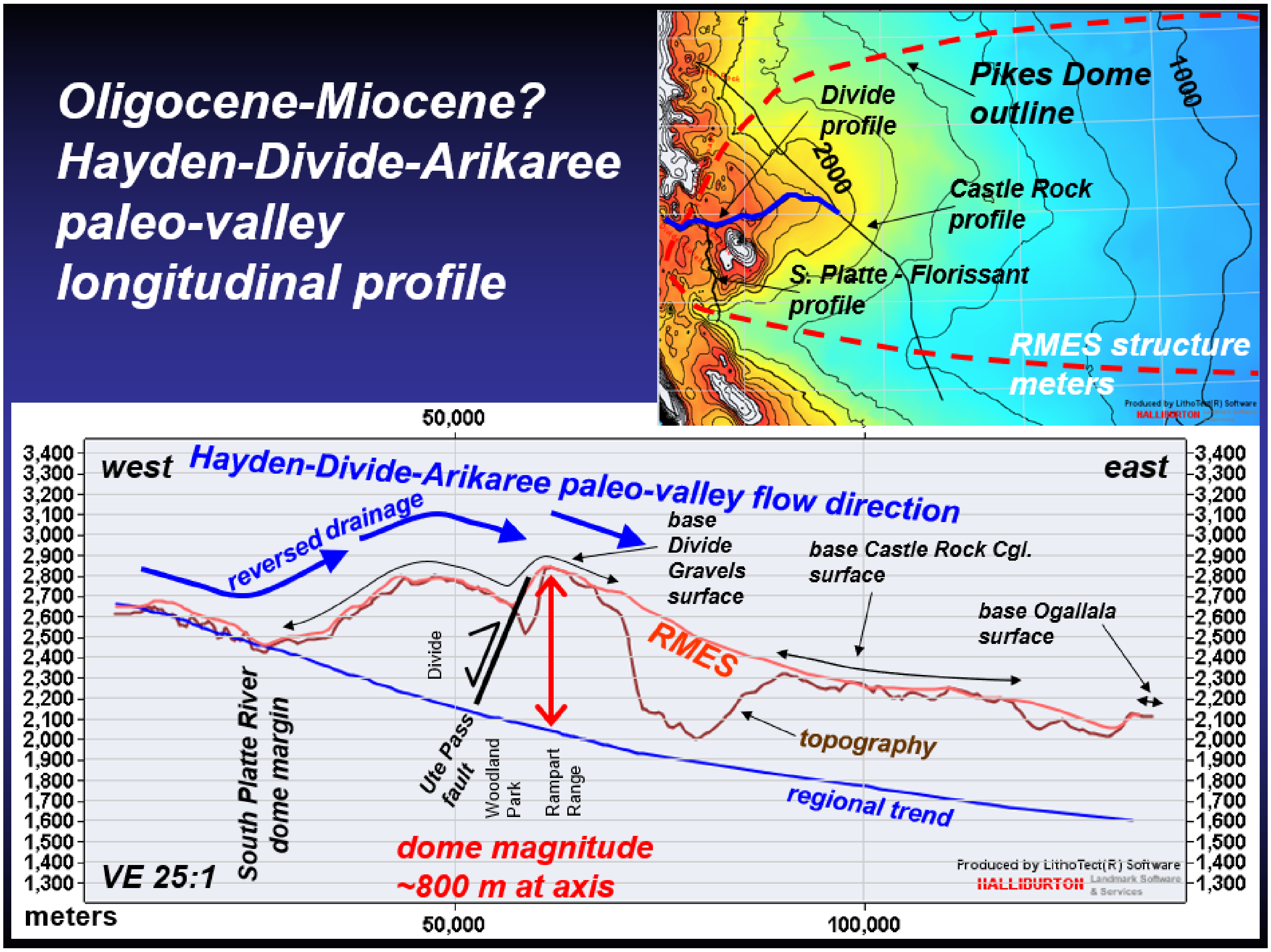


Figure 52. Longitudinal profile of the Hayden-Divide-Arikaree River showing doming of the RMES centered on Divide and offset of the RMES by Cenozoic extension on the Ute Pass Fault.

The preservation of two generations of rivers in this part of Colorado allows us to break apart the magnitudes and extents of two phases of superimposed doming by contouring two surfaces. The first surface corresponds to the dome magnitude attributable to only Pikes Dome and is built by putting a zero contour around the dome signifying the limits of uplift, then adding dome magnitude values (RMES minus the regional trend surface) along each of the south-flowing upper Eocene Rivers (Castle Rock, Tarryall-Florissant and Slater) (Fig. 53). Note this involved the interpretive step of apportioning magnitudes to different doming phases along the Florissant tributary of the ancestral South Platte River (Fig 42.). The second surface captures doming seen along all of the rivers by adding dome magnitude values along the Hayden-Divide-Arikaree River to the first surface. Subtracting the first surface from the second surface reveals the grey late-stage Peak Dome seen on Figure. 13. There are no paleo-drainages on Pikes Peak, but assuming the massif is a structure (more evidence for this to follow), subtracting the first surface from the RMES reveals the magnitude and extent of the late north-south trending Peak Dome centered on Cripple Creek, Divide, Pikes Peak and the Rampart Range (Fig. 54). Note the southern plunge of Peak Dome trends toward the Royal Gorge, suggesting this uplift may have played a role in the formation of that spectacular canyon.

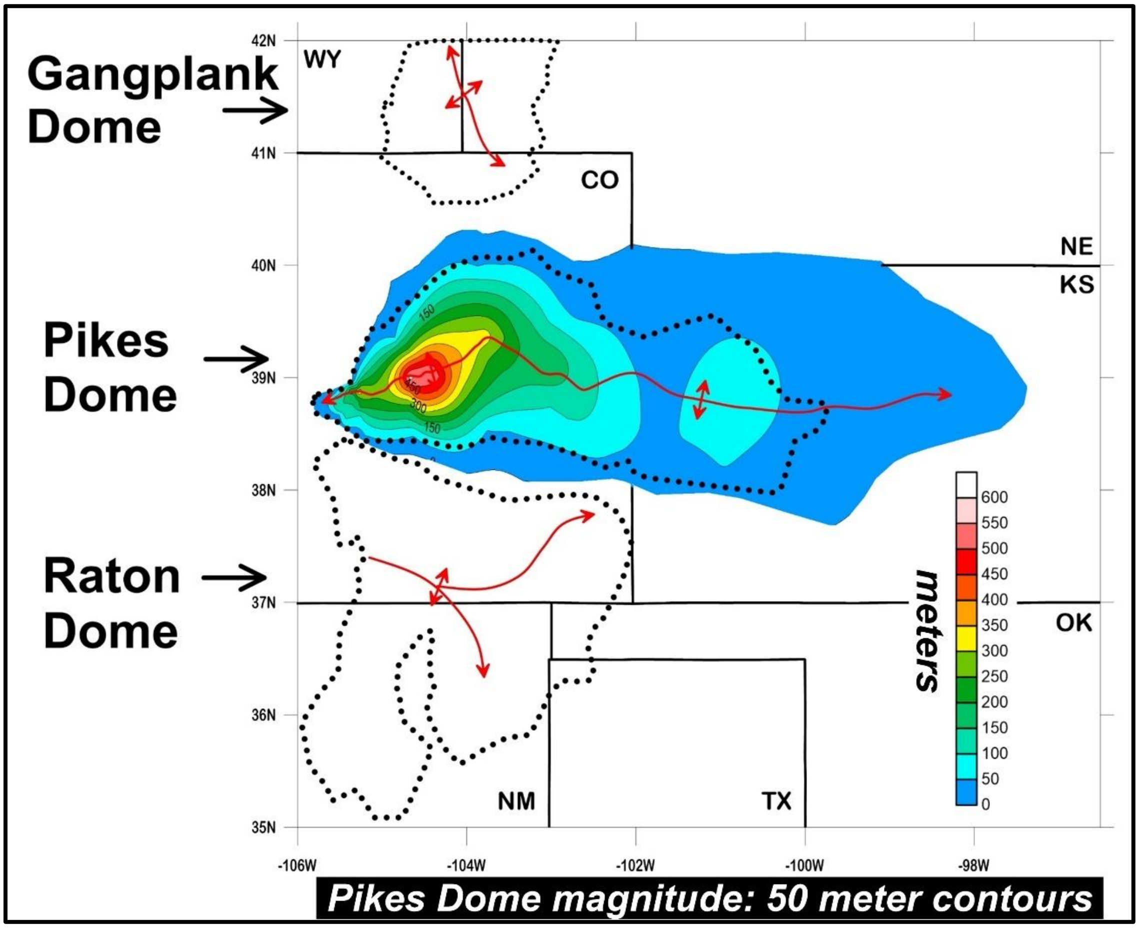


Figure 53. Dome magnitude attributed to Pikes Dome.

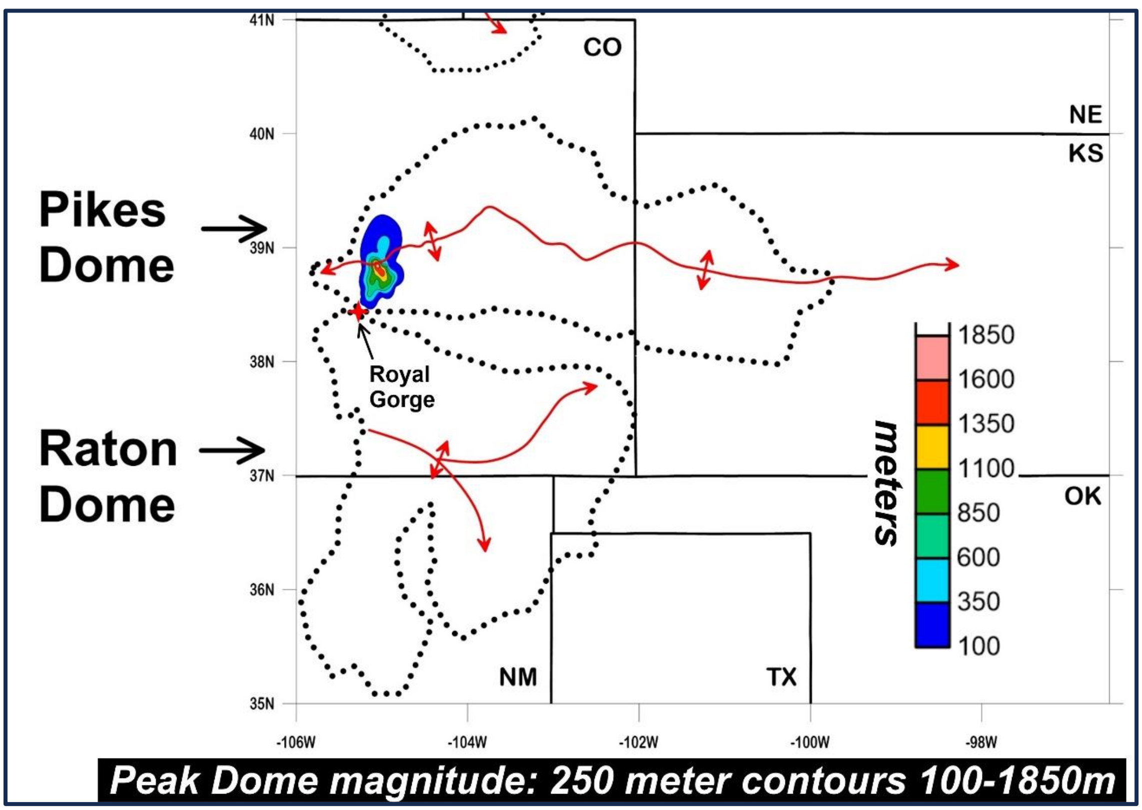


Figure 54. Dome magnitude attributable to the late-stage Peak Dome encompassing Cripple Creek, Divide, Pikes Peak and the Rampart Range. Southern plunge may have played a role in formation of the Royal Gorge.

So far during this field trip, our ability to distinguish between erosional and structural relief on the RMES has been limited to areas with preserved paleo-drainages. However, the increased availability of low temperature thermochronology (LTT) data in the form of apatite fission track (AFT) and apatite (U-Th)/He or A(He) analyses offers another way to understand relief on the RMES. The AFT and A(He) techniques use radiometric clocks that start recording time when rock temperatures cool below ~60-120° C and ~30-90° C, respectively. Such low closure temperatures are ideally suited for understanding burial and exhumation processes in the upper few kilometers of the crust, and are, therefore, tools we can use to decipher Cenozoic landscape evolution. AFT studies of central Colorado started with the work of Chuck Naeser (Naeser et al., 2002) and were greatly expanded by Shari Kelley (Kelly and Chapin, 1997; Kelley and Chapin, 2004). The A(He) technique is newer with central Colorado studies being conducted by Becky Flowers and coworkers at CU Boulder (Landman and Flowers, 2013; Kainz et al., 2022; Abbott et al., 2022; Abbott et al., 2023), and Allysa Abbey and coworkers at the University of Michigan and California State University Long Beach (Abbey and Niemi, 2018; Abbey et al., 2017).

Ideally, LTT data would be collected from wellbores that provide true vertical profiles, thereby showing a two-component system of age versus elevation. Figure 55 shows a true vertical profile of AFT data from closely spaced wellbores at the MWX site in the Piceance Basin (Kelley and Blackwell, 1990). In this case, burial

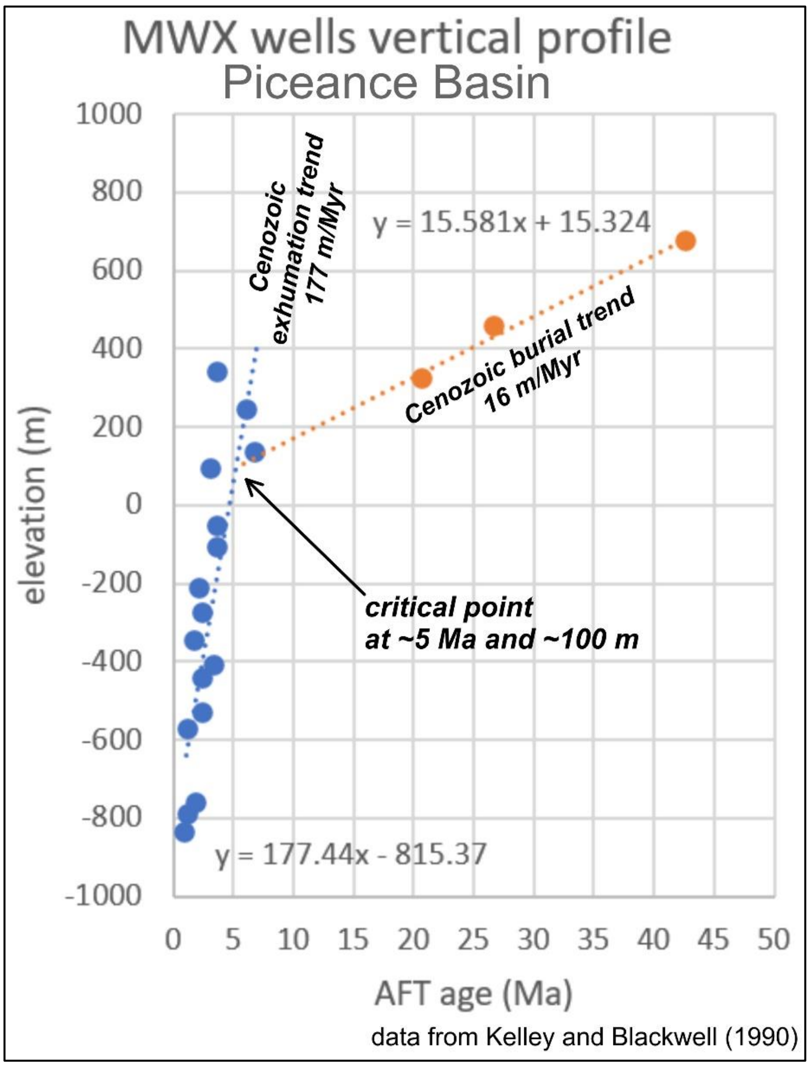


Figure 55. True vertical profile based on wellbore data from the MWX site in the Piceance Basin. Well-defined burial and exhumation trends indicate a critical point at ~5 Ma and 3850 m marking the switch from burial to exhumation (data from Kelley and Blackwell, 1990).

(16 m/Myr) and exhumation (177m/Myr) trends defined by multiple samples intersect at a critical point of ~ 5 Ma and 100 meters marking the change from burial to exhumation. Note the critical point is the only point common to both the burial and exhumation trends. The burial trend represents a Cenozoic partial annealing zone (PAZ), which for AFT data is the zone where fission tracks are progressively annealed, leading to decreasing AFT ages at lower elevations. The Cenozoic exhumation trend is made up of samples that cool to their closure temperatures at different times, leading to progressively younger AFT ages at lower elevations.

In practice, such wellbores are rarely available and geologists by necessity gather samples across the landscape that don't lie on true vertical profiles, thereby, introducing a third component of areal distribution or location to the analysis. LTT data then comprise a three-component system of age, elevation and location. However, typically the data are displayed on two-component plots with either LTT ages posted on maps, which don't capture elevation (Fig. 56), or with LTT ages cross-plotted relative to elevation, which don't capture location (Fig 57.). In either case, losing one component of the LTT system can hamper structural interpretation or lead to incorrect interpretations.

In contrast to the well-defined burial and exhumation trends exhibited by the true vertical profile from the Piceance wellbores (Fig. 55), AFT data from the Front Range show scatter even when parsed locally (Fig. 58). This pattern is reminiscent of the scatter shown by pressure versus elevation data in hydrodynamic systems. In those cases, the water density gradient is used to normalize each data point to a new elevation datum at pressure zero and the normalized datums are contoured to create a sloping or undulating potentiometric surface. By analogy, the data scatter in the Front Range may reflect deformation that has disrupted and complicated surfaces of

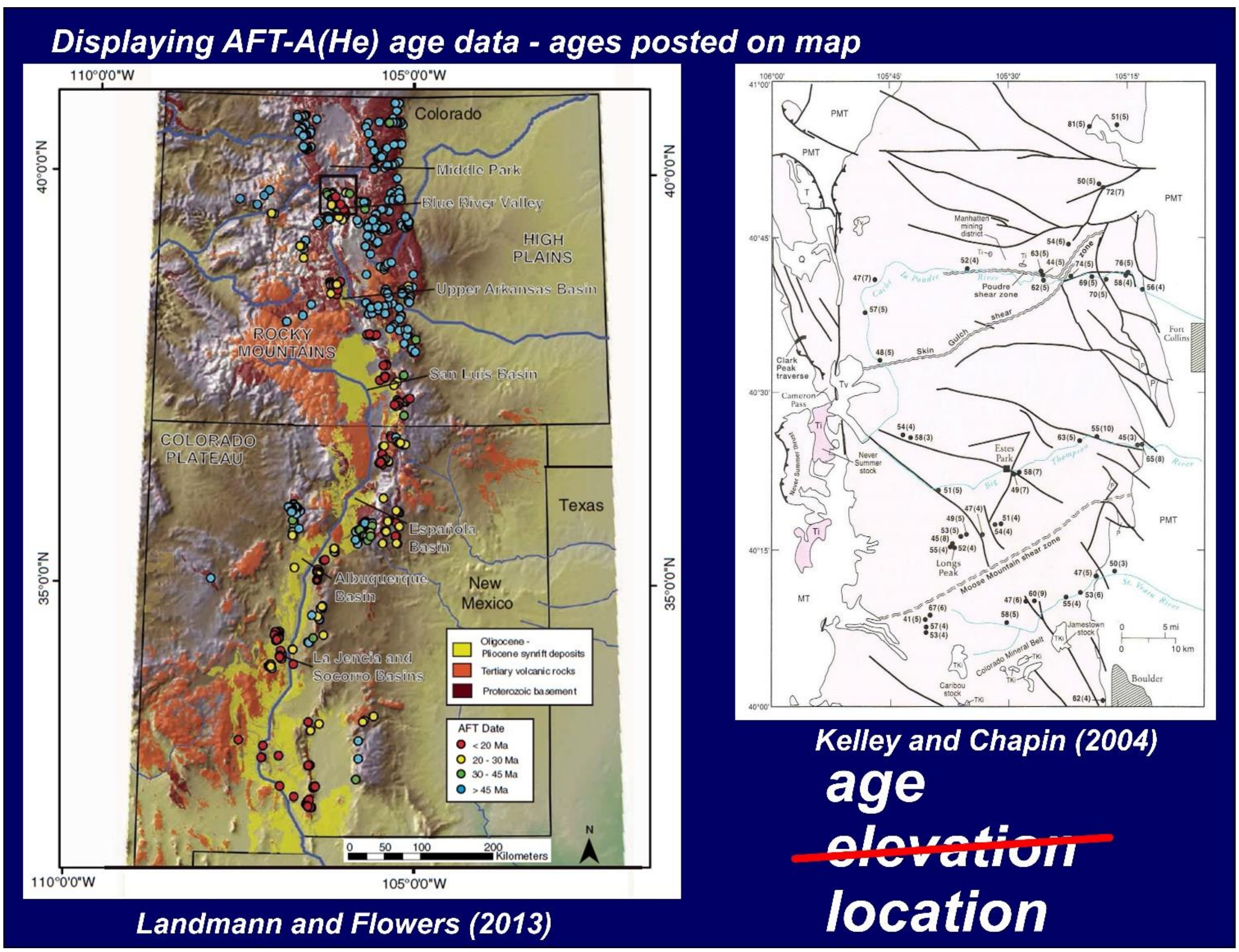


Figure 56. LTT ages versus map view or areal distribution. Such plots lose the elevation component of the LTT data.

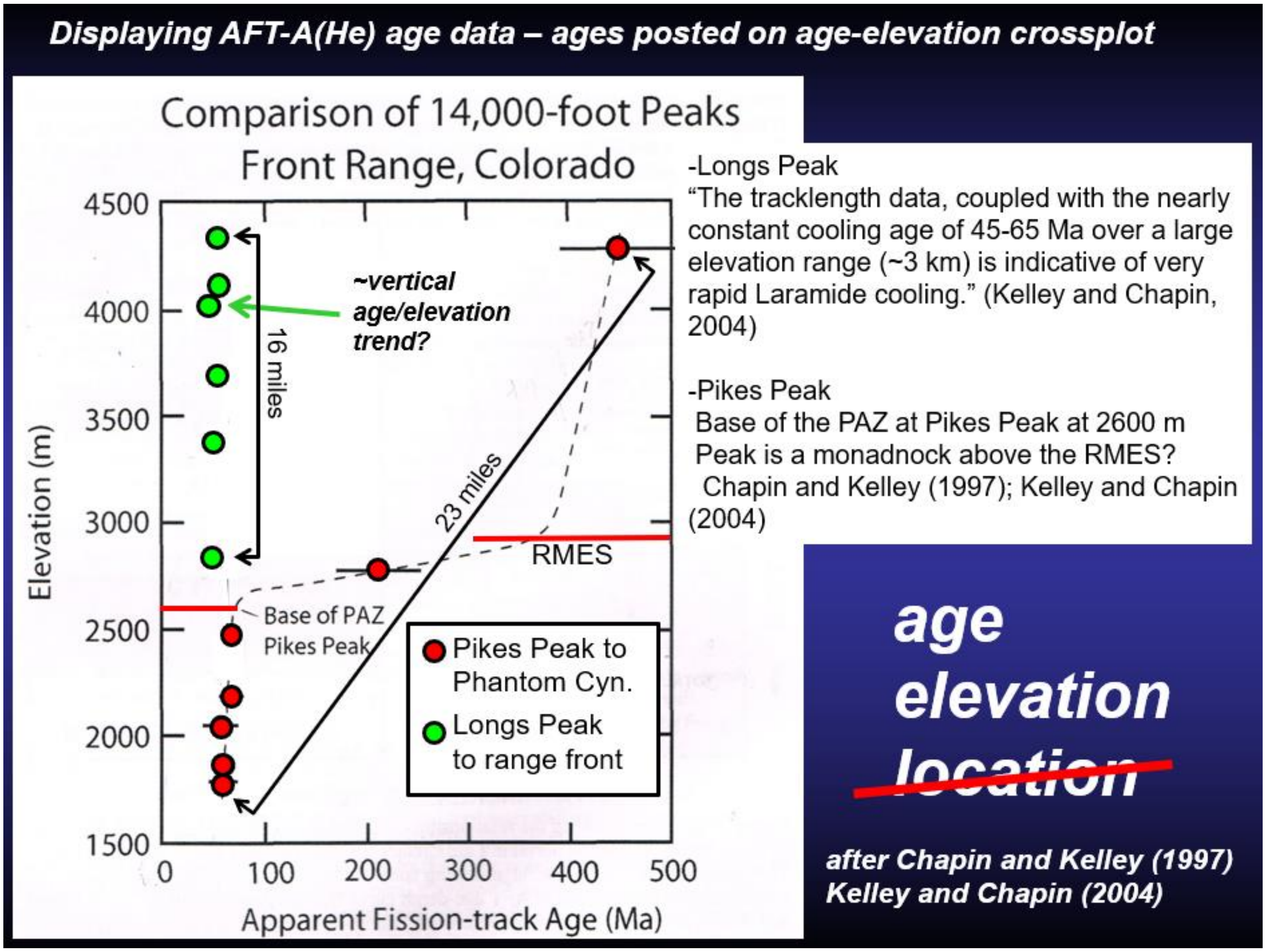


Figure 57. Age versus elevation plot for Longs Peak and Pikes Peak using data from Chapin and Kelley (1997) and Kelley and Chapin (2004) to show the lateral distances over which the samples were taken. Such plots lose the map view or areal distribution component of the LTT data, which can lead to incorrect interpretations.

constant LTT age or isochron surfaces. Going back to the true vertical profile example (Fig. 55), if we knew the critical point occurred at 5 Ma and knew the gradients of the burial and exhumation trends, it would be possible to calculate the elevation of the critical point given any point along either of the burial or exhumation tends. This would be a redundant exercise if applied to the MWX wells; however, given a surface sample some distance from the wells and the age of the critical point, the burial and exhumation gradients from the MWX wells could be used to calculate an elevation of the critical point at the location of the surface sample. If this elevation differed from the elevation of the critical point at the MWX wells it would indicate structural changes between the locations, or changes in either the critical point age, the burial gradient or the exhumation gradient used to calculate the new critical point elevation.

The technique proposed here (Sterne, 2019) follows the above example by adopting constant values for the critical moment, the burial gradient and the exhumation gradient to create an isochron structure map that incorporates all three components of the LTT system, age, elevation and location, in a single display (Fig. 59). In the Front Range we can assume a critical moment of 67 Ma marking the switch from burial in the foreland basin to Laramide basement exhumation based on the stratigraphic record of the Denver and South Park basins (Raynolds, 1997; Barkmann et al., 2016). Calculating a normalized critical point elevation for each sample at this critical moment of 67 Ma was done using a burial or PAZ gradient of 1.75 m/Myr for AFT ages greater than 67 Ma, and a Laramide exhumation or uplift gradient of 50 m/Myr for AFT ages between 40 and 67 Ma. By normalizing to 67 Ma and only including AFT data showing ages greater than 40 Ma, the expectation is the resulting isochron map will reflect deformation of the base of the Laramide PAZ during the Laramide or post-

Laramide. The burial gradient was chosen to create smooth transitions between points with ages on either side of the 67 Ma critical moment. The exhumation gradient was taken from data in the White River Range (Naeser et al., 2002). Using constants for the critical moment and the gradients over a wide area is an obvious oversimplification; however, as more data become available it should be possible to vary the gradients areally. Even with these questionable assumptions, the normalized datums created a 67 Ma isochron surface showing smooth transitions between highs and lows defined by multiple points, a somewhat surprising result that suggests the map has geologic import. Doubling or halving the gradients alters the dynamic range

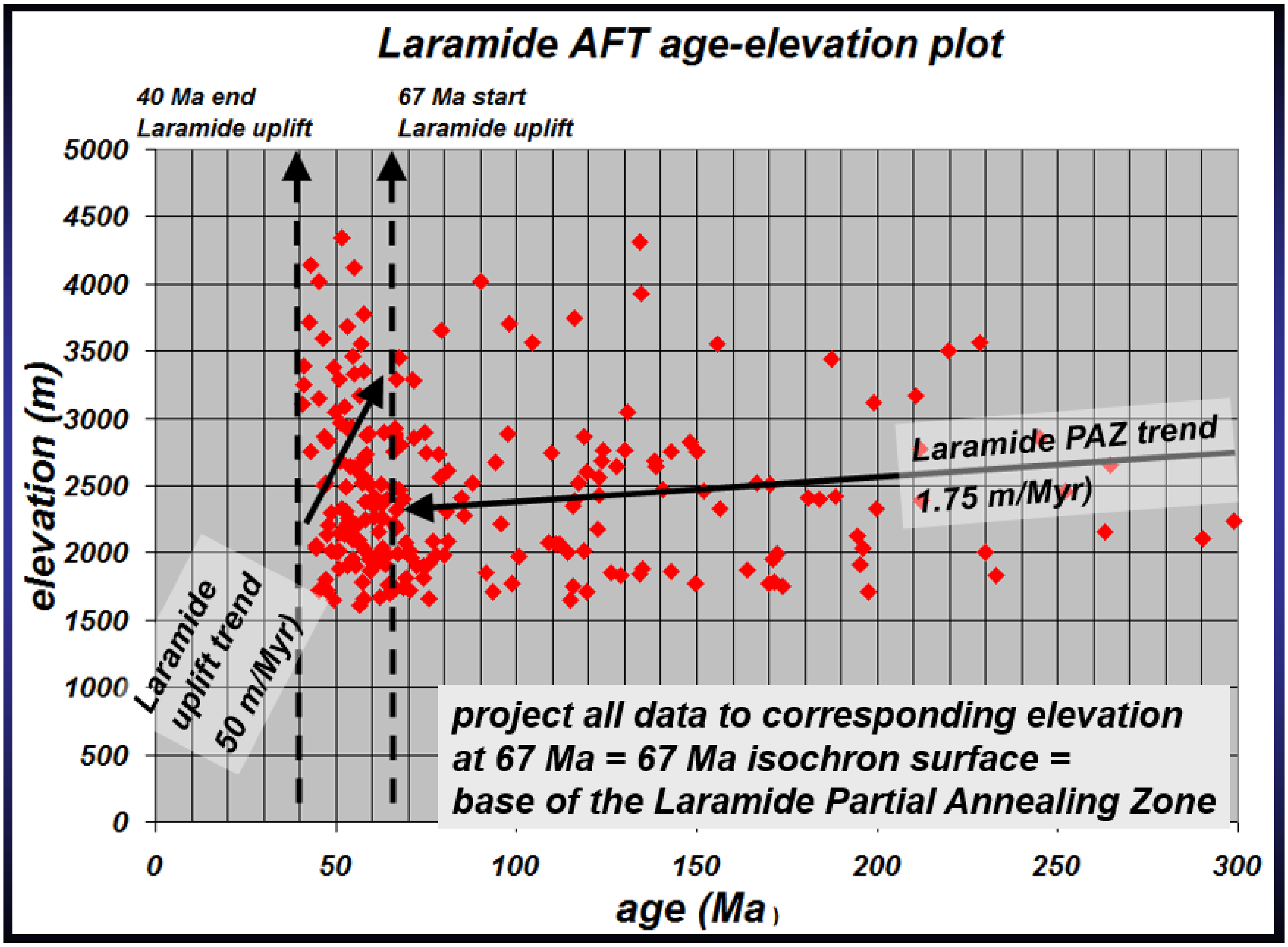


Figure 58. Front Range AFT data from Naeser et al. (2002) and Kelley and Chapin (2004) showing a cloud rather than defined trends of data. This pattern suggest deformation. Assumed Laramide Partial Annealing Zone (PAZ) or burial trend and Laramide uplift or exhumation trend were used to calculate a normalized datum for each sample at a critical moment of 67 Ma marking the onset of Laramide basement contraction. The new datums were used to contour the 67 Ma isochron surface shown below.

of the surface, but doesn't markedly change the position of highs and lows on the map. One less intuitive aspect of the map is highs can either represent structural highs or areas with elevated heat flow, a lateral change that affects the gradients that is accentuated on the map by the use of the constant gradients. An example of this are the three northeast trending highs on the eastern flank of the northern Front Range and the small high along the southern margin of the Front Range. These align with Proterozoic shear zones (not shown) mapped by Sims et al. (2001) that are favorably oriented to be opening, and therefore, high heat flow trends during northeast-directed Laramide contraction. The technique can also be applied to areas such as the Southern Gore Range (Landmann and Flowers, 2013) where a flank uplift to the Rio Grande Rift has exhumed rocks starting at a critical moment of 25 Ma that exhibit LTT ages less than 40 Ma.

As noted previously, age-elevation plots populated by samples collected across large lateral distances lose the location or areal distribution component, which can lead to incorrect interpretations. Figure 57 is an age-elevation plot for Longs Peak and Pikes Peak modified from Kelley and Chapin (2004). The Longs Peak data show an apparent vertical age-elevation trend, which they interpreted as showing very high exhumation rates across the northern Front Range. However, the data were collected across a lateral distance of 16 miles between the top of Longs Peak and the eastern range front, and as shown by the 67 Ma isochron map (Fig. 59) were sampled down an east-dipping isochron surface approximately paralleling the dip of the Great Unconformity. By sampling along a dipping isochron surface, ages stay the same, but elevations vary, thereby creating a vertical trend on the age-elevation plot, that does not indicate rapid exhumation. For Pikes Peak, Kelley and Chapin (2004) show data collected along a 23-mile traverse from the southern reaches of Phantom Canyon to the top of Pikes Peak (Fig. 56). They show the base of the Laramide PAZ at 2600 m and the top of the PAZ and the RMES at 2900 m. A

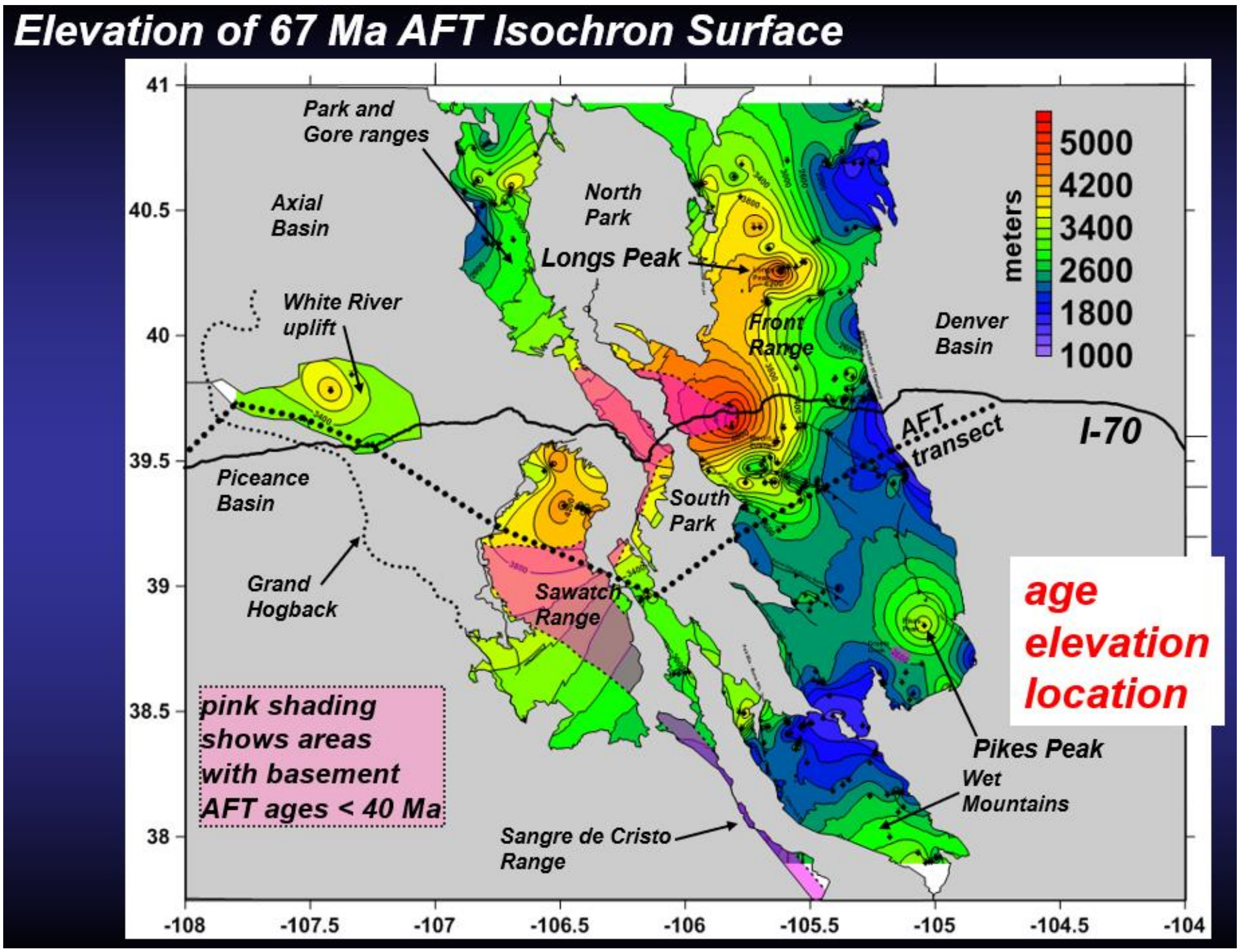


Figure 59. 67 Ma isochron structure map for the basement uplifts of central Colorado. Black dots show the locations of AFT samples sampled from Proterozoic basement.

burial gradient of ~0.7 m/Myr is shown within the PAZ, but is unconstrained given there is only one point within the PAZ. Another unconstrained gradient of ~20 m/Myr is drawn through the single point at the top of Pikes Peak, suggesting there is an Ancestral Rocky Mountain exhumation trend preserved on Pikes Peak. Given the RMES at 2900 m and the top of Pikes Peak at 4300 meters, their age-elevation plot implies Pikes Peak is a monadnock rising 1400 m above the RMES and there is no deformation in the 23 miles between the southern reaches of Phantom Canyon and Pikes Peak. It also implies the 1400-meter monadnock was present beneath a corresponding thin in the Cretaceous section during foreland basin burial that created the base of the PAZ in the southern reaches of Phantom Canyon. The 67 Ma isochron structure mapped here presents a different possibility with Pikes Peak as a structural high relative to the southern reaches of Phantom Canyon. Support for this interpretation comes from Bud Wobus, who mapped the faults around Pikes Peak, and past CSS president Tom Steven, who recognized the RMES is preserved up the west flank of Pikes Peak to its summit. Both interpreted Pikes Peak as a structure uplifted 1000 meters relative to the surrounding areas.

Figure 60 shows LTT samples of Proterozoic rocks superimposed on the RMES structure of Colorado and the location of section A-A', a transect across Pikes Dome from near the Arkansas River, then north over Pikes Peak to the South Platte River. Two versions of the section are shown in Figure 61. The first compares the RMES to the 67 Ma isochron surface as sampled along the transect. The second version shows the distribution of LTT points that control the surface and a reinterpretation of parts of the 67 Ma isochron surface showing fault offsets permissible given the sparse control. Data is sparse in this area because the Pikes Peak Batholith is largely devoid of apatite (Kelley and Chapin, 2004); however, Chuck Naeser obtained the lone sample we have from the summit of Pikes Peak, suggesting a deliberate search could yield more rock suitable for AFT or A(He) analysis. The 67 Ma isochron surface tracks several hundred meters below the RMES along the transect, indicating the surfaces have been deformed together and showing Pikes Peak as a structural high. If it were a monadnock, the 67 Ma isochron surface would remain at the same elevation across the peak. Given the deformation of the RMES demonstrated by drainage reversal along the upper Eocene rivers and the later Hayden-Divide-Arikaree River around Pikes Peak, the relief on the RMES and the 67 Ma isochron surface across the peak is best explained as post-Laramide deformation. Clearly, more data are needed to test this hypothesis.

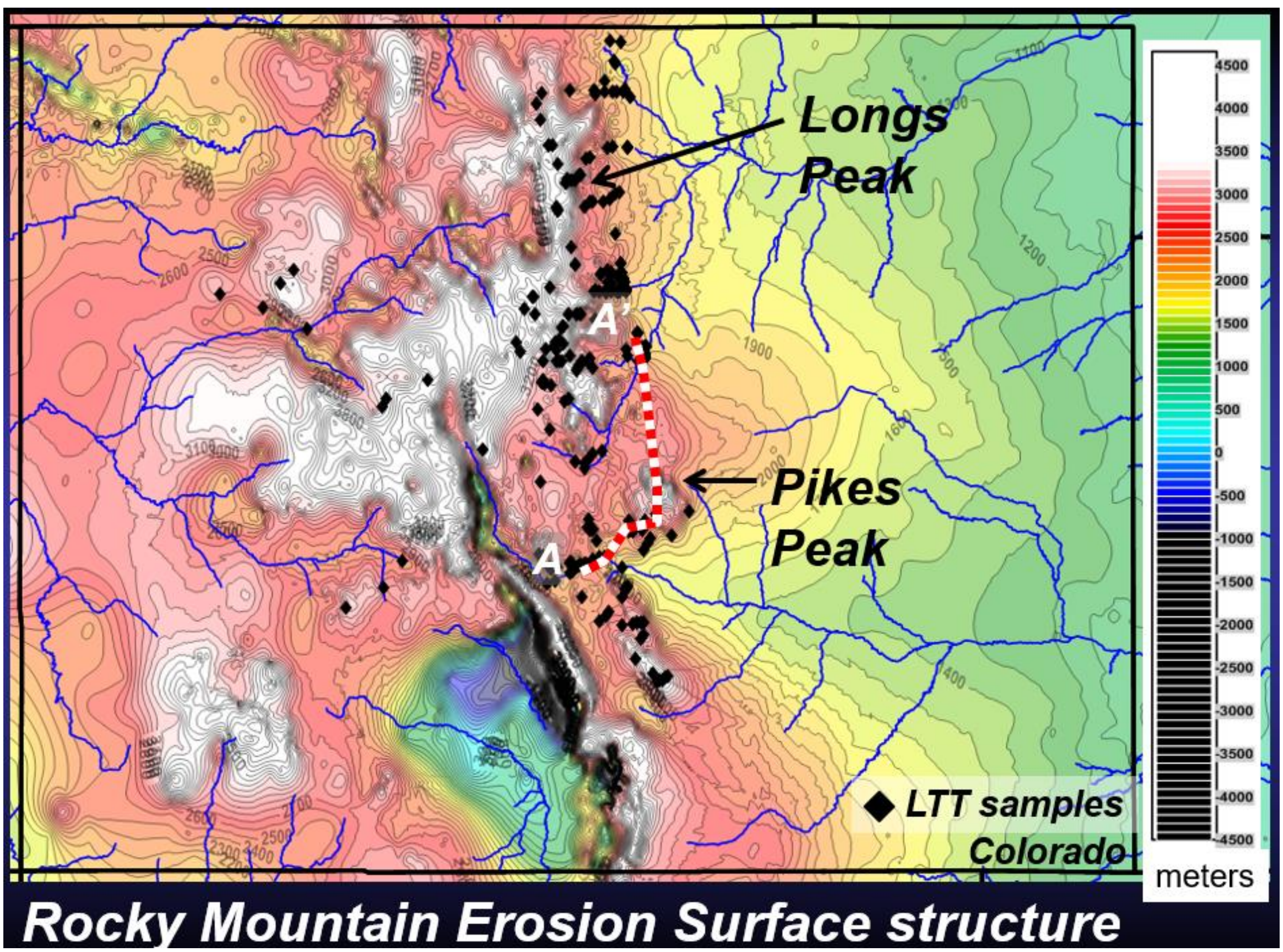
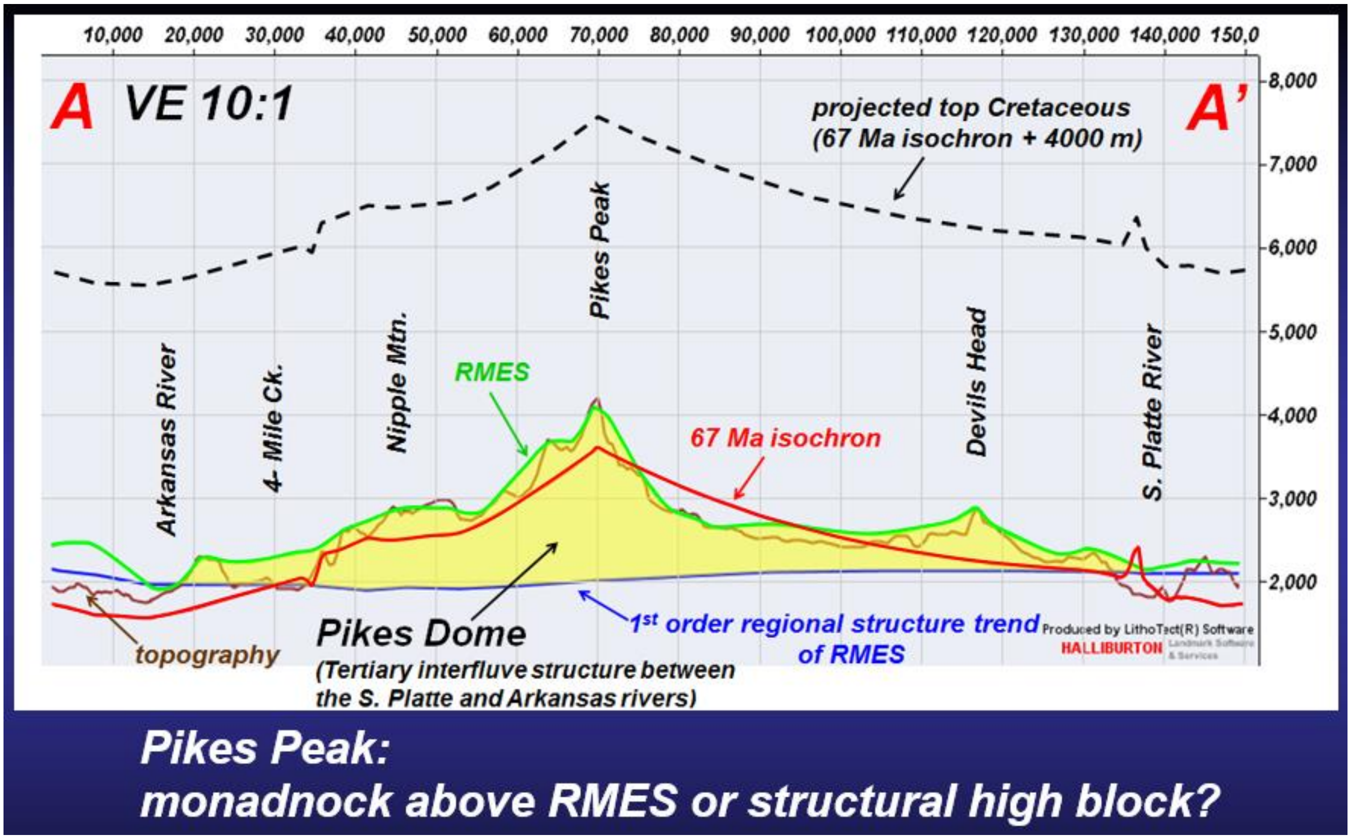


Figure 60. RMES structure map of Colorado showing the distribution of LTT samples of Proterozoic rocks from the basement uplifts of central Colorado (black diamonds), major rivers (dark blue lines), and the location of traverse A-A'.



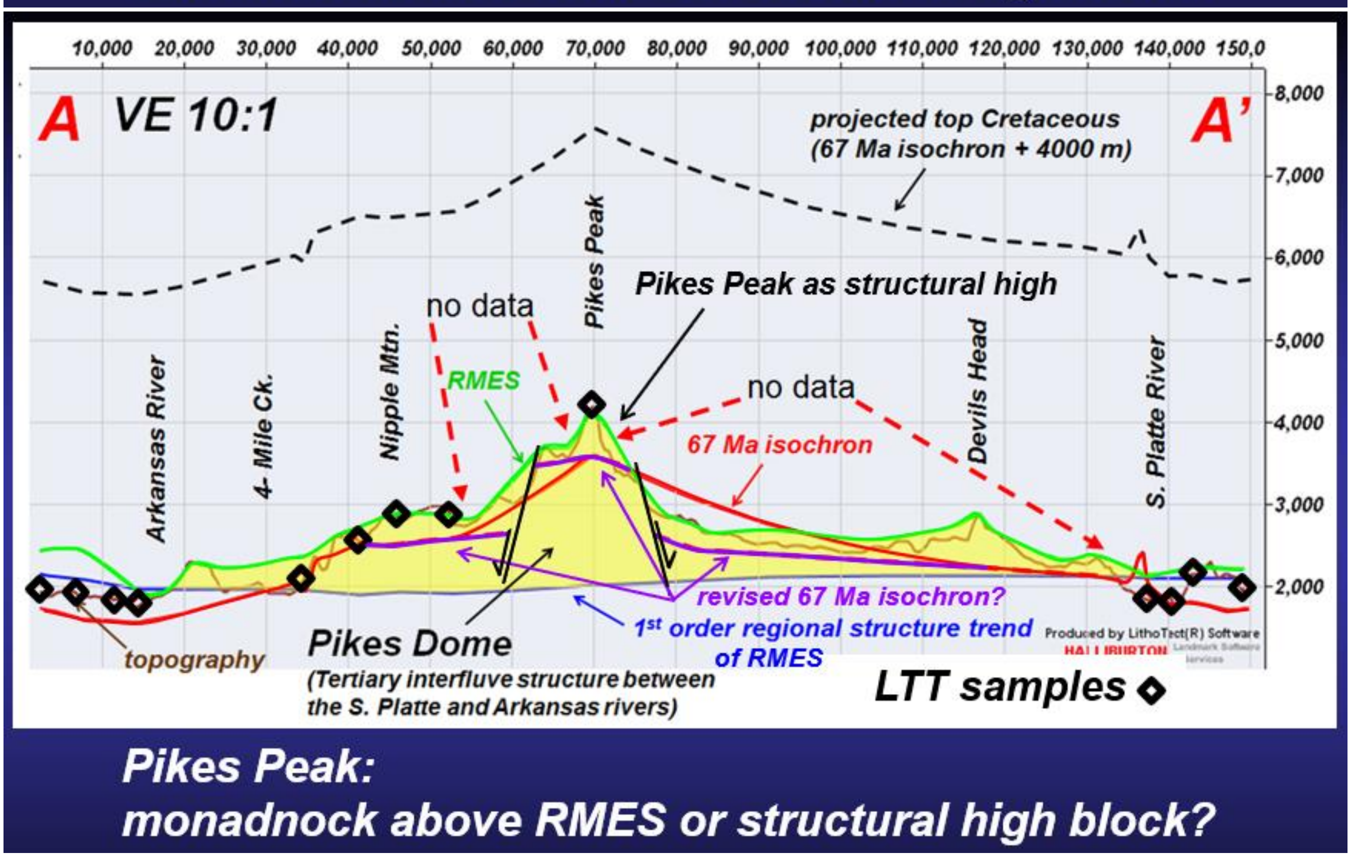


Figure 61. Two versions of A-A'. This first shows lines sampled from the RMES (green) map and the 67 Ma isochron map (red). The second shows samples controlling the surfaces (black diamonds) and faulted revisions of the 67 Ma isochron surface permissible given the sparse data (purple lines). Note Pikes Peak appears as a structural high rather than an erosional remnant or monadnock.

Stop 17. Sprucewood Inn (39.349052, -105.120926)

Join us for beers and discussion or head home.

Conclusion

While the Ancestral Rocky Mountain and Laramide orogenies shaped the structural underpinnings of Colorado, we inhabit a landscape formed largely in post-Laramide time. To understand the evolution of this landscape, we have mapped relief across Colorado on the Rocky Mountain Erosion Surface, a composite unconformity formed during multiple erosion cycles in post-Laramide time. To understand when that relief developed and whether it was the product of erosion or structural deformation, we have studied the birth and death of the everchanging paleo-rivers that flowed across the surface – and more dating of their gravels is needed. Where paleo-rivers are absent, low-temperature thermochronologic data provided another way to track the timing and extent of structural deformation – and more samples need to be analyzed, especially from the Pikes Peak Batholith. Over the past two days we have traversed Pikes Dome, a post-Laramide uplift that stretches 500 km from the Front Range into western Kansas. Uplift of the dome. starting at the end of the Eocene, diverted the southerly flows of the Castle Rock and ancestral South Platte rivers first to the east-northeast into the Hayden-Divide-Arikaree River, then to the northeast into the current course of the South Platte, as late doming impacted the western part of the dome.

Acknowledgements

Special thanks for help with this project go out to Dr. Bob Raynolds of the Denver Museum of Nature and Science, Cal Ruleman of the USGS, and consulting geologist Steve Cumella. Dr. Dan Miggins at the Oregon State Argon Geochronology Laboratory dated the tuff clast in the Wolf Park lahar, the basalt plug that intrudes the lahar, and sanidines from the Divide Gravels. Colorado State Geologist, Dr. Matt Morgan has helped in the collection and dating of detrital zircons from the Divide Gravels and the Nussbaum Formation. Dr. Herb Meyer, paleontologist emeritus with the National Park Service has facilitated pending dating of various gravels within the Florissant Fossil Beds National Monument. Colorado College professor, Dr. Christine Siddoway and her students provided detrital zircon analyses and regional provenance for quartzites clasts from the Tallahassee Creek Conglomerate. Colorado Mesa University professor, Dr. Andres Aslan facilitated pending detrital sanidine dating from the Divide Gravels through Dr. Matthew Heizler of the New Mexico Bureau of Geology and Mineral Resources. Dr. Bud Wobus, formerly of the USGS and professor emeritus at Williams College is thanked for his years of mapping that have made this project possible and for his continued encouragement.

References

Abbey, A.L., and Niemi, N.A., 2018, Low-temperature thermochronometric constraints on fault initiation and growth in the northern Rio Grande rift, upper Arkansas River valley, Colorado, USA: Geology, Vol. 46, No. 7, p. 627-630, https://doi.org/10.1130/G400232.1.

Abbey, A.L., Niemi, N.A., Geissman, J.W., Winkelstern, I.Z., and Heizler, M., 2017, Early Cenozoic exhumation and paleotopography in the Arkansas River valley, southern Rocky Mountains, Colorado: Lithosphere Vol. 10, No. 2; p. 239-266, https://doi.org/10.1130/L673.1.

Abbott, L.; Flowers, R., Metcalf, J., Falkowski S.,2 Niazy, F., 2022, Post-Laramide, Eocene epeirogeny in central Colorado - The result of a mantle drip?: Geosphere, https://doi.org/10.110/GES02434.1

Abbott, L., Flowers, R., and Metcalf, J., 2023, What mechanism created the Miocene-aged Gothic exhumation Dome in Colorado’s Elk Mountains?: Geological Society of America Abstract with Programs Rocky Mountain Section – 73rd Annual Meeting, Paper No. 17-3.

Blum, M.D., Milliken, K.T., Pecha, M.A., Snedden, J.W., Frederick, B.C., and Galloway, W.E., 2017, Detrital-zircon records of Cenomanian, Paleocene, and Oligocene Gulf of Mexico drainage integration and sediment routing: Implications for scales of basin-floor fans: Geosphere, Vol. 13, No. 6, p. 2169-2205, doi:10.1130/GES01410.1.

Bryant, B., McGrew, L.W., and Wobus, R.A., 1981, Geologic Map of the Denver 1°x2° Quadrangles, north-central Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-1163.

Chapin, C.E., and Kelley, S.A., 1997, Internal structure of the southern Front Range, Colorado, from an apatite fission-track perspective, in D.W. Bolyard and S.A. Sonnenberg, eds. Geologic history of the Colorado Front Range field trip guidebook: Denver, Rocky Mountain Association of Geologists. P. 19-30.

Condon, S.M., 2005, Geologic studies of the Platte River, south-central Nebraska and adjacent areas – geologic maps, subsurface study, and geologic history: U.S. Geological Survey, Professional Paper 1706, 63 p.

Dechesne, M, Raynolds, R.G., Barkmann, P.E., and Johnson, K.R., 2011, Notes on the Denver Basin geologic map2: bedrock geology, structure, and isopach maps of the upper Cretceous to Paleogene strata between Greeley and Colorado Springs, Colorado: Colorado Geological Survey OF-11-01, 35 p.

Epis, R.C. and Chapin, C.E., 1975, Geomorphic and tectonic implications of the post-Laramide, late Eocene erosion surface in the southern Rocky Mountains: Geological Society of America Memoir 144, p. 45-74.

Epis, R.C., Scott, G.R., Taylor, R.B., and Chapin, C.E., 1976, Cenozoic volcanic, tectonic, and geomorphic features of central Colorado: Colorado School of Mines Professional Contributions, no. 8, p. 323-338.

Epis, R.C., Wobus, R.A., and Scott, G.R., 1979, Geologic map of the Guffey Quadrangle, Park County, Colorado: U.S. Geological Survey Miscellaneous Investigations Series I-1180.

Evanoff, E., 2007, The Castle Rock Conglomerate: Geological Society of America Abstracts with Programs, Vol. 39, No. 6, p. 26.

Evanoff, E., and Chapin, C.E., 1994, Composite nature of the "late Eocene surface" of the Front Range and adjacent regions, Colorado and Wyoming: Geological Society of America Abstracts with Programs Rocky Mountain Section, no. 18711, p. 12.

Hon, K., 1984, Geology of volcanogenic uranium deposits within the Tallahassee Creek Conglomerate, Tallahassee Creek uranium district, Colorado: U.S. Geological Survey Open-file Report 84-219, 53 p.

Kainz, S.; Abbott, L.; Flowers, R., Olsson, A.; Fernandez, S.; and Metcalf, J., 2022, Cenozoic exhumation in the Great Plains of Colorado from (U-Th)/He Thermochronology: Geological Society of America GSA Connects Paper No. 163-16.

Karlstrom, K.E., Coblentz, D., Dueker, K., Ouimet, W., Kirby, E., Van Wijk, J., Schmandt, B., Kelley, S., Lazear, G., Crossey, L.J., Crow, R., Aslan, A., Darling, A., Aster, R., MacCarthy, J., Hansen, S.M., Stachnik, J., Stockli, D.F., Garcia, R.V., Hoffman, M., McKeon, R., Feldmn, J., Heizler, M., Donahue, M.S., and the CREST Working Group, 2012, Mantle-driven dynamic uplift of the Rocky Mountains and Colorado Plateau and its surface response: Toward a unified hypothesis; Lithosphere, Vol. 4, No. 1, p. 3-22.

Keller, J.W., Morgan, M.L., Thorson, J.P., Lindsey, N.R., and Barkmann, P.E., 2007, Geologic map of the Palmer Lake Quadrangle, El Paso County, Colorado: Colorado Geological Survey Open-File 06-06.

Keller, S.M. and Morgan, M.L., 2016, Overview of the Eocene Castle Rock Conglomerate, east-central Colorado, Remapping the fluvial system, and implications for the history of the Colorado Piedmont and Front Range: *in* Keller, S.M. and Morgan, M.L., eds, Unfolding the Geology of the West: Geological Society of America Field Guide 44, p. 125-141, doi:10.1130/2016.0044(05).

Keller, S.M. and Morgan, M.L., 2016, New paleocurrent measurements, clast population data, and age dates in the late Eocene Castle Rock Conglomerate, east-central Colorado: Colorado Geological Survey Open-file OF-16-01, 587 p.

Kelley, S.A., and Blackwell, D.D., 1990, Thermal history of the multi-well experiment (MWX) site, Piceance Creek Basin, northwestern Colorado, derived from fission-track analysis: Nuclear Tracks and Radiation Measurements, Vol. 17, p. 331-337.

Kelley, S.A., and Chapin, C.E., 2004, Denudation history and internal structure of the Front Range and Wet Mountains, Colorado, based on apatite fission-track thermochronology: New Mexico Bureau of Geology and Mineral Resources, Bulletin, Vol. 160, p. 41-68.

Morgan, M.L., Thorson, J.P., Lindsey, N.R., and Barkmann, P.E., 2007, Geologic map of the Palmer Lake

Quadrangle, El Paso County, Colorado: Colorado Geological Survey Open-File 06-06.

Kellogg, K.S., Shroba, R.R., Bryant, B., and Premo, W.R., 2008, Geologic map of the Denver West 30' x 60' Quadrangle, north-central Colorado: U.S. Geological Survey Scientific Investigations Map 3000.

Koch, A.J., Coleman, D.S., Sutter, A.M., 2018, Provenance of the upper Eocene castle Rock Conglomerate, south Denver Basin, Colorado, U.S.A.: Rocky Mountain Geology, Vol. 53, No. 1, p. 29-43, doi:10.24872/rmgjournal.53.1.29.

Landman, R.L., and Flowers, R.M., 2013, (U-Th)/He thermochronologic constraints on the evolution of the northern Rio Grande Rift, Gore Range, Colorado: Geosphere, Vol. 9, No. 1, p 170-187, doi:10:1130/GES00826.1

Scott, G.R., 1975, Cenozoic surfaces and deposits in the southern Rocky Mountains: *in* Curtis, B.F., ed., Cenozoic History of the Southern Rocky Mountains: Geological Society of America Memoir 144, p. 227-248.

Lazear, G., Karlstrom, K., Aslan, A., and Kelley, S., 2013, Denudation and flexural isostatic response of the Colorado Plateau and southern Rocky Mountains region since 10 Ma: Geosphere, Vol. 9, No. 4, p. 792-814.

Leonard, E.M., 2002, Geomorphic and tectonic forcing of late Cenozoic warping of the Colorado piedmont: Geology, vol. 30, no. 7, p. 595-598.

Leonard, E.M., Hubbard, M.S., Kelley, S.A., Evanoff, E., Siddoway, C.S., Oviatt, C.G., Heizler, M., and Timmons, M., 2002, High Plains to Rio Grande Rift: Late Cenozoic evolution of central Colorado: Geological Society of America, Field Guides 2002;3, p. 59-93.

Leonard, E.M. and Langford, R.P., 1994, Post-Laramide deformation along the eastern margin of the Colorado Front Range, A case against significant faulting: Mountain geologist, Vol. 31, p. 45-52.

McMillan, M.E., Heller, P.L., and Wing, S.L., 2006, History and causes of post-Laramide relief in the Rocky Mountain orogenic plateau: Geological Society of America Bulletin, vol. 118, no. 3/4, p.393-405, https://doi.org/10.1130/B25712.1.

Morgan, M.L., Siddoway, C.S., Rowley, P.D., Temple, J., Keller, J.W., Hawkins Archuleta, B., and Himmelreich, J.W., Jr., 2003, Geologic map of the Cascade Quadrangle, El Paso County, Colorado: Colorado Geological Survey Open-File Report 03-18.

Morse, D.G., 1979, Paleogeography and tectonic implications of the late Cretaceous to middle Tertiary rocks of the southern Denver Basin, Colorado: p. Ph.D. Dissertation, Baltimore, Maryland Johns Hopkins, 344 p.

Naeser, C.W., Bryant, B., Kunk, M.J., Kellogg, K., Donelick, R.A., and Perry, W.J., Jr., 2002, Tertiary cooling and tectonic history of the White River uplift, Gore Range, and western Front Range, central Colorado: Evidence from fission-track and $^{40}Ar/^{39}Ar$ ages: *in* Kirkham, R.M., Scott, R.B., and Judkins, T.W., eds. Late Cenozoic evaporite dissolution and volcanism in west-central Colorado: Boulder, Colorado, Geological Society of America Special Pare 366, p. 31-53.

Olson, E.R. and Wobus, R.A., 2019, Geomorphology and tectonism in Colorado's southern Front Range: implications of boulder and volcanic deposits on the late Eocene surface: Geological Society of America Abstracts with Programs Vol. 51, No. 5, doi:10.1130/abs/2019AM-331776.

Pearl, R.H., 1971, Pliocene drainage of east-central Colorado and northwestern Kansas: The Mountain Geologist Vol. 8, No. 1, p. 25-31.

Raynolds, R.G., 1997, Synorogenic and post-orogenic strata in the central Front Range, Colorado: *in* Bolyard, D.W., and Sonnenberg, S.A., eds. Geologic History of the Colorado Front Range: Rocky Mountain Association of Geologists Field Trip 7, AAPG Rocky Mountain Section, p. 43-47.

Reed, J.C., Jr., 1991, Geology of a fault-controlled cave in Precambrian crystalline rocks in Clear Creek Canyon, Jefferson County, Colorado: U.S Geological Survey Open-file Report 91-144, 7 p..

Riihimaki, C.A., Anderson, R.S., Safran, E.B., Dethier, D.P., Finkel, R.C., and Bierman, P.R., 2006, Longevity and progressive abandonment of the Rocky Flats surface, Front Range, Colorado: Elsevier Geomorphology, Vol. 78, Issues 3-4, p. 265-278, https://doi.org/10.1016/j.geomorph.2006.01.035.

Ruleman, C.A., and Hudson, A.M., 2016, The Central Colorado Icefield, a mechanism for inception of regional exhumation and deep-canyon incision during the Pleistocene?, Geological Society of America Abstracts with programs, v. 48., no. 7, doi: 10.1130/abs/2016AM-282920

Ruleman, Cal, Hudson, A.M., Caffee, M.W., and Brugger, K.A., 2018, MIS 12-11 (478-374 ka) ~ Middle Pleistocene glaciation of the central and southern Rocky Mountain-Colorado Plateau region: links to landscape evolution of major western North American rivers, Geological Society of America Abstracts with Programs, v. 50, no. 5, doi: 10.1130/abs/2018RM-314061

Ruleman, Cal, Hudson, A.M., Caffee, M.W., and Brugger, K.A., 2019, The middle Pleistocene unconformity and MIS 12-11 (~478-385 ka): Glaciofluvial processes override late Miocene-middle Pleistocene (~6 Ma-500 ka) tectono-magmatic capture and deep-canyon incision, western Great Plains-Southern Rocky Mountains-Colorado Plateau region, North America, Geological Society of America Abstracts with Programs, v. 51, no. 5, doi: 10.1130/abs/2019AM-339129

Ruleman, Cal, Hudson, A.M., Caffee, M.W., Goehring, B.M., Sortor, R.N.*, Brugger, K.A., Frothingham, M.G.*, and Nicovich, S.R.*, 2019, MIS 12-11 (478-374 ka) ~ Middle Pleistocene glaciation of the Southern Rocky Mountain-Great Plain region: Links to landscape evolution of major central North American rivers, Geological Society of America Abstracts with Programs, v. 51, no. 2, ISSN 0016-7592, doi: 10.1130/abs/2019SC-326957

Ruleman, Cal, Sortor, R.N., Hudson, A.M., Brugger, K.A., Goehring, B.M., and Caffee, M.W., 2021, New chronologic, stratigraphic, and geomorphic relationships indicating Neogene tectono-magmatic fragmentation of western North American fluvial systems and middle Pleistocene (MIS 12-11, ~480-370 ka) glaciofluvial integration and establishment of modern river systems, Geological Society of America Abstracts with Programs. Vol 53, No. 6, 2021, doi: 10.1130/abs/2021AM-36530

Ruleman, Cal, Goehring, B.M., Sortor, Rachel, Hudson, A.M., Reheis, Marith, and Caffee, Marc, 2022, The Central City Gravel-Rocky Flats-Colorado Icefield connection and middle Pleistocene erosion of the Front Range-Denver Basin region, Colorado, U.S.A., Geological Society of America Abstracts with Programs. Vol. 54, No. 5, 2022, doi: 10.1130/abs/2022AM-381787.

Ruleman, Cal, Hudson, Adam, Sortor, Rachel, Goehring, B.M., Brugger, Keith, Caffee, M.C., Frothingham, Michael, Nicovich, Sylvia, Rogers, John B., Reheis, Marith, Turner, K.J., and Thompson, Ren, 2022, The Central Colorado Icefield and MIS 12-11 (~480-370 ka): A mechanism for protracted fluvial integration of fragmented watersheds, and ~250-300 meters of Landscape Relief, northern Rio Grande rift-southern Rocky Mountains, Colorado and New Mexico, U.S.A., Geological Society of America Abstracts with Programs, doi: 10.1130/abs/2022CD-373878

Scott, G.R., 1963, Nussbaum alluvium of Pleistocene (?) age at Pueblo Colorado: U.S. Geological Survey: U.S. Geological Survey Professional Paper 475-C, p. C49-C52.

Scott, G.R., and Taylor, R.B., 1986, Map showing late Eocene erosion surface, Oligocene-Miocene paleovalleys and Tertiary deposits in the Pueblo, Denver, and Greeley 1°x2° quadrangles, Colorado: U.S. Geological Survey Miscellaneous Investigation Series Map I-1626.

Scott, G.R., Taylor, R.B., Epis, R.C., and Wobus, R.A., 1978, Geologic Map of the Pueblo 1°x2° Quadrangle, south-central Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-1022.

Scudder, S.H., 1883, The Tertiary lake-basin at Florissant, Colorado: U.S. Geological Survey 12th Annual Report, p. 271-293.

Siddoway, C.S. 2014, Basement-hosted sandstone injectites of Colorado: A vestige of the Neoproterozoic revealed through detrital zircon analysis: Lithosphere August 27, 2014, doi:10.1130/L390.1.

Sims, P.K, Bankey, V., and Finn, C.A., 2001, Preliminary Precambrian basement map of Colorado- A geologic interpretation of an aeromagnetic anomaly map: U.S. Geological Survey Open File Report 01-0364, http://pubs.usgs.gov/of/2001/ofr-01-0364/colo_of_text.html.

Smith, J.J., Ludvigson, G.A., Layzell, A., Moller, A., Harlow, R.H., Turner, E., Platt, B., and Petronis, M., 2017, Discovery of Paleogene deposits of the central High Plains aquifer in the western Great Plains, U.S.A.: Journal of Sedimentary Research, vol. 87, p. 880-896.

Sorter, R.N., Ruleman, Cal, and Goehring, B.M., 2019, Cosmogenic nuclide dating of the Central City Gravel, a mid-Pleistocene perched glacial till in the Front Range, Colorado, Geological Society of America Abstracts with Programs, v. 51, no. 5, doi: 10.1130/abs/2019AM-334111

Sortor, R.N., Ruleman, C., Goehring, B.M., and Caffee, M.W., 2019, The Central City Gravel: Cosmogenic nuclide dating of a mid-Pleistocene glacial till in the Front Range, Colorado: Geological Society of America Abstracts with Programs, Vol. 51, No. 2, doi: 10.1130/abs/2019SC-326076.

Sterne, E.J., 2019, Isochron structure maps bring new insights to low-temperature thermochronology – combining low-temperature thermochronology data with surface and subsurface data across Colorado: Geological Society of America Abstracts with Programs, Vol. 51, No. 5, doi: 10.1130/abs/2019AM-334027.

Sterne, E.J., and Constenius, K.N., 1997, Space-time relationships between magmatism and tectonism in the western United States between 120 Ma and 10 Ma: a regional context for the Front Range of Colorado, *in* Bolyard, D.W., and Sonnenberg, S.A., eds. Geologic History of the Colorado Front Range: Rocky Mountain Association of Geologists Field Trip 7, AAPG Rocky Mountain Section Meeting, p. 85-100.

Steven, T.A., Evanoff, E., and Yuhas, R.H., 1997, Middle and late Cenozoic tectonic and geomorphic development of the Front Range of Colorado, *in* Bolyard, D.W., and Sonnenberg, S.A., eds. Geologic History of the Colorado Front Range: Rocky Mountain Association of Geologists Field Trip 7, AAPG Rocky Mountain Section Meeting, p. 115-124.

Stone, G.H., 1900a, The Hayden extinct river and lake: Colorado Springs Gazette March 18, 1900, p. 9.

Stone, G.H., 1900b, Map of Hayden River and Lake gravels: Colorado Springs Gazette March 25, 1900.

Taylor, R.B., 1975, Neogene Tectonism in south-central Colorado: Geological Society of America Memoir 144, p. 211-226.

Taylor, R.B., Scott, G.R., Wobus, R.A., and Epis, R.C., 1975, Reconnaissance geologic map of the Royal Gorge Quadrangle, Fremont and Custer counties, Colorado: U.S. Geological Survey Miscellaneous Investigation Map I-892.

Temple, J. and Busacca, A., 2009, Geologic map of the Divide Quadrangle, Teller County, Colorado: Colorado Geological Survey OF-09-02.

Temple, J., Madole R., Keller, J.W., and Martin, D., 2007, Geologic map of the Mount Deception Quadrangle, Teller, and El Paso counties, Colorado: Colorado Geological Survey Open-File Report 07-07.

Wobus, R.A., 2022, The Big Flat: A geological and personal traverse from Colorado Springs to South Park across Colorado's subalpine erosion surface: Colorado Outdoor Education Center, Florissant, Colorado,75 p.

Wobus, R.A., and Epis, R.C., 1978, Geologic map of the Florissant Quadrangle, Park and Teller counties, Colorado: U.S. Geological Survey Miscellaneous Investigations Series I-1044.

Wobus, R.A., and Epis, R.C., and Scott, G.R., 1976, Reconnaissance geologic map of the Cripple Creek – Pikes Peak area, Teller, Fremont and El Paso counties: U.S. Geological Survey Miscellaneous Field Studies Map MF-805.

Wobus, R.A. and Scott, G.R., 1977, Reconnaissance geologic map of the Woodand Park Quadrangle, Teller County, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-842.