



Proterozoic and Pre-Cenozoic History of the Sierra Grande Uplift and its margins: A Key Piece of the Ancestral Rocky Mountains

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PROTEROZOIC AND PRE-CENOZOIC HISTORY OF THE SIERRA GRANDE UPLIFT AND ITS MARGINS: A KEY PIECE OF THE ANCESTRAL ROCKY MOUNTAINS

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ABSTRACT — A new compilation of wells penetrating or approaching basement combined with a comprehensive review of existing literature result in new observations on Proterozoic, Late Paleozoic and later structures in northeastern New Mexico, southeastern Colorado and adjacent states. Proterozoic granitic rocks (1400-1340 Ma) underlie much of the area, forming a broad rim around the Panhandle volcanic rocks of the same age; this may represent differential uplift of a shallow batholith, which is overlain by its own volcanic cover under the Texas Panhandle, but has been eroded to the west and largely removed by 15 km of erosion in central New Mexico. Late Paleozoic uplift of the Ancestral Rocky Mountains formed a complex high with several prongs, bounded on one or both sides by major faults. The Cimarron-Bravo uplift on the south and Apishapa uplift on the north form a two-sided outward-verging high, with a shallow proto-Raton basin between them. A zone of isolated basins and uplifts lying to the south in the Tucumcari and Palo Duro basins may represent a wrench fault complex. Laramide formation of the Raton basin reactivated the western part of the Cimarron uplift as a north-verging structure and created the sharp-crested Sierra Grande uplift.

INTRODUCTION

Northeastern New Mexico, southeastern Colorado and surrounding areas form a key part of any tectonic analysis of southwest and south-central North America. During the Proterozoic, it lay at the northwest end of a broad area of 1400-1340 Ma igneous activity termed the “Southern Granite-Rhyolite Province” (Bickford et al., 2015). During the late Paleozoic, it lay in a central nexus of the Ancestral Rocky Mountains, where the eastern, northwestern and southern prongs of uplift and basin development met and interacted (Fig. 1). Laramide deformation (70-40 Ma) created the deep Raton and Denver basins and modified the structure of older units. This modified structure then hosted world-class carbon dioxide reserves, as well as the igneous centers of the Raton-Clayton volcanic field.

The area has been studied since the 1910s. The presence of Precambrian rocks below Permian redbeds, characteristic of Ancestral Rocky Mountain uplifts, was known by 1921 from scattered wells (Rich, 1921), and the name “Sierra Grande uplift” was used by 1933 (Heaton, 1933; Winchester, 1933). Continued drilling in search of oil, gas and carbon dioxide defined the uplifted area and its boundaries. Pre-Pennsylvanian and Pennsylvanian-Permian stratigraphy were studied in the producing areas to the east and northeast (Maher and Collins, 1949; Norman, 1956) and also in northern New Mexico exposures (Read and Wood, 1947). In the 1950s, the systematic lithologic and petrographic description of basement rocks began with the work of Flawn (1956) in Texas, followed by Foster and Stipp (1961) in New Mexico and Edwards (1966) in Colorado. Renewed exploration and discovery in the Dalhart and Tucumcari basins (McCasland, 1980; Montgomery, 1986; Broadhead and King, 1988), and frontier exploration in Mora

County (Baltz and Myers, 1999; Broadhead, 2008), advanced geologic understanding of these areas, as did the systematic exploration of carbon dioxide resources in the Bravo Dome field (Roberts et al., 1976; Broadhead, 1990, 1993; Cassidy et al., 2013).

The purpose of the present study is to assemble as complete a database as possible of wells penetrating or approaching basement in a broad study area (the ‘Area of Concern’ on Fig. 1). The area was drawn to include the Texas and Oklahoma panhandles, southwestern Kansas, Colorado to the Pueblo area, and New Mexico southwest to the Pederal Hills. The principal objective is to map the Ancestral Rockies structures at the highest possible regional resolution, while considering later Laramide or later reactivation or modification of those structures. This mapping extends northwestward the earlier work on the Texas panhandle published in Ewing (1991). An important secondary objective is to better define the Proterozoic lithologic distribution in the area and to understand the possible limits of the ca. 1350 Ma granitic and volcanic terrane against the older exposed rocks in the mountains of New Mexico and Colorado.

Within the area of concern, a search was made for records of wells penetrating basement or approaching basement (pre-Pennsylvanian penetrations). A total of 874 wells penetrating basement were used; 271 in New Mexico, 874 in Texas, 92 in Colorado, 11 in Oklahoma and 8 in Kansas. Precambrian tops, sample descriptions, overlying Paleozoic strata, and various stratigraphic tops were recorded based on well records and published sources (but not yet by direct log or sample examination). Published geochronologic data from subsurface sources have been compiled (Lidiak et al., 1993; Barnes et al., 2002; Amarante et al., 2015; Bickford et al., 2015) and tied to

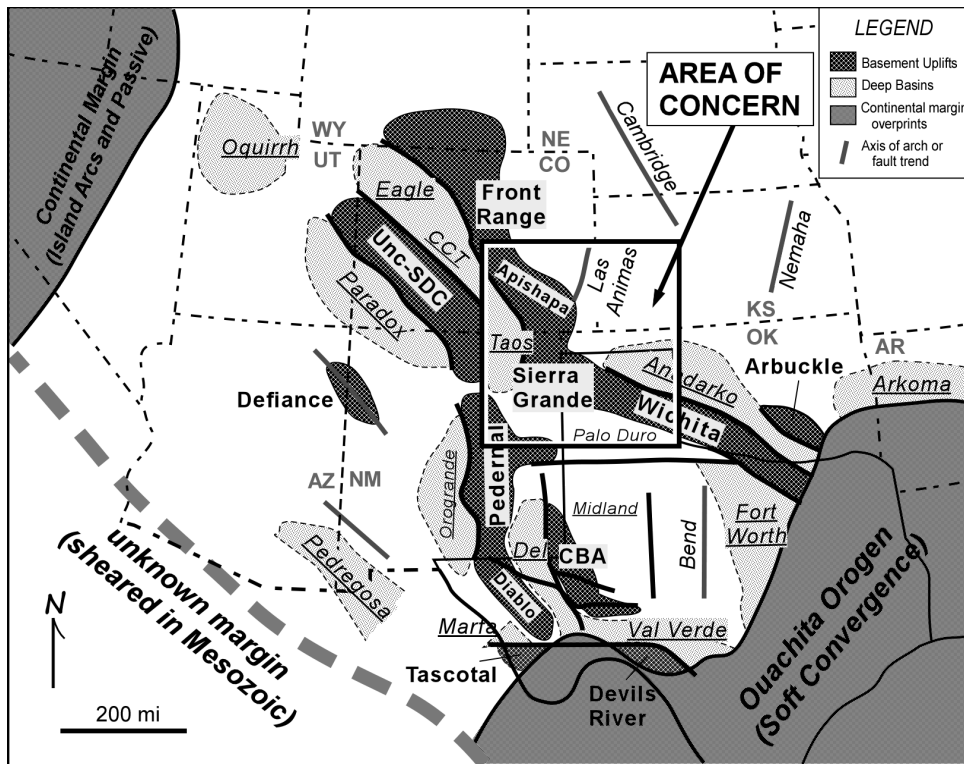


FIGURE 1. General map of the Ancestral Rocky Mountains, modified from Ewing (2016), with location of the present area of mapping shown. CBA = Central Basin Axis, Del = Delaware Basin, CCT = Central Colorado Trough, Unc-SDC = Uncompahgre-Sangre de Cristo uplift.

database entries. All entries and the maps derived from them are in English units, as they were measured in the subsurface.

In Colorado, principal sources of data are Norman (1956), Edwards (1966), and Hemborg (1996), supplemented with records at the Colorado Oil and Gas Conservation Commission (2019).

In New Mexico, principal sources of data are Baldwin and Muehlberger (1959) for Union County; Foster and Stipp (1961) statewide; Baltz and Myers (1999) for the Rainsville and Cimarron area; Broadhead and King (1988) and Broadhead et al. (2002) for the Tucumcari Basin area, and Broadhead (2008, 2010) for the Colfax-Mora area, supplemented with records at the New Mexico Oil Conservation Division (2019).

In Kansas, records at the Kansas Geological Survey (2019) were consulted.

In Oklahoma, records at the Oklahoma Corporation Commission (2019) were consulted; some information also was derived from McCasland (1980) and from Campbell and Weber (2006).

In Texas, the principal source of data is the published mapping of Ewing (1991), supplemented by the work of McCasland (1980) in the Dalhart Basin, and the study by Barnes et al. (2002) of wells in the area north of Amarillo. The pioneering work of Flawn (1956) also identified basement tests in Texas and New Mexico.

This database and the following maps represent a work in progress. The short text here will focus on significant observations and issues that have been identified to March, 2019.

PROTEROZOIC

The Proterozoic exposures in the mountain ranges of New Mexico and Colorado consist almost entirely of rocks assembled, metamorphosed, deformed and intruded during the complex mountain-building events of the Yavapai (1760-1700 Ma), Mazatzal (1700-1600 Ma) and Picuris (1460-1400 Ma) orogenies. Karlstrom et al. (2004) provide a comprehensive summary of these rocks in New Mexico; Daniel et al. (2013) subsequently identified the Picuris orogeny. Rocks of Yavapai and Mazatzal ages are also known from northern Kansas (Lidiak et al., 1994; Bickford et al., 2015). In the subsurface of the study area, rocks of these ages consist primarily of granitic gneisses with occasional amphibolite and locally abundant metasedimentary units. These rocks were then subjected to widespread amphibolite-grade metamorphism, intrusion of granites and deformation during the Picuris orogeny, 1460-1400 Ma (Shaw et al., 2005; Arnoff et al., 2016).

The most widespread materials encountered beneath Phanerozoic rocks are granitic and rhyolitic rocks of 1380-1330 Ma age (Fig. 2). In northeastern New Mexico and southeastern Colorado, these are nearly entirely biotite granite, occasionally showing some cataclasis but otherwise undeformed. Similar granites occur to the south (southeastern New Mexico) and to the east (southwestern Kansas), and may connect eastward with the Spavinaw Granite in northeastern Oklahoma. They have been dated by the zircon U-Pb method at two locations in New Mexico (the Labrador #1 Mescalero well, Guadalupe Co., 1332 Ma, Amarante et al., 2005; and the Amoco #1 Bueyeros, Harding Co., 1369 Ma; Barnes et al., 2002). An older Rb-Sr whole rock date in Baca Co., Colorado of 1280 Ma is consistent with being part of the same sequence, as is a feldspar Rb-Sr date in Mora Co., New Mexico of 1397 Ma. Other dates have been obtained in Cimarron Co., Oklahoma (1370 Ma), and in Stevens, Haskell and Scott counties, Kansas. In Texas, numerous dates from 1390 Ma to 1338 Ma by U-Pb dating on zircons have been obtained from complex rhyolite stratigraphy and related granites (Barnes et al., 2002). The granitic terrane appears to form a broad halo around the rhyolitic subcrops. The northern edge is defined by geochronologic control in Kansas and in Pueblo County, Colorado. However, granite of the same age (1371-1344 Ma) is exposed in the Wet Mountains (San Isabel pluton; Bickford et al., 1989, 2015), and other granites and mylonites of similar age occur farther north in Colorado (Shaw et al., 2005).

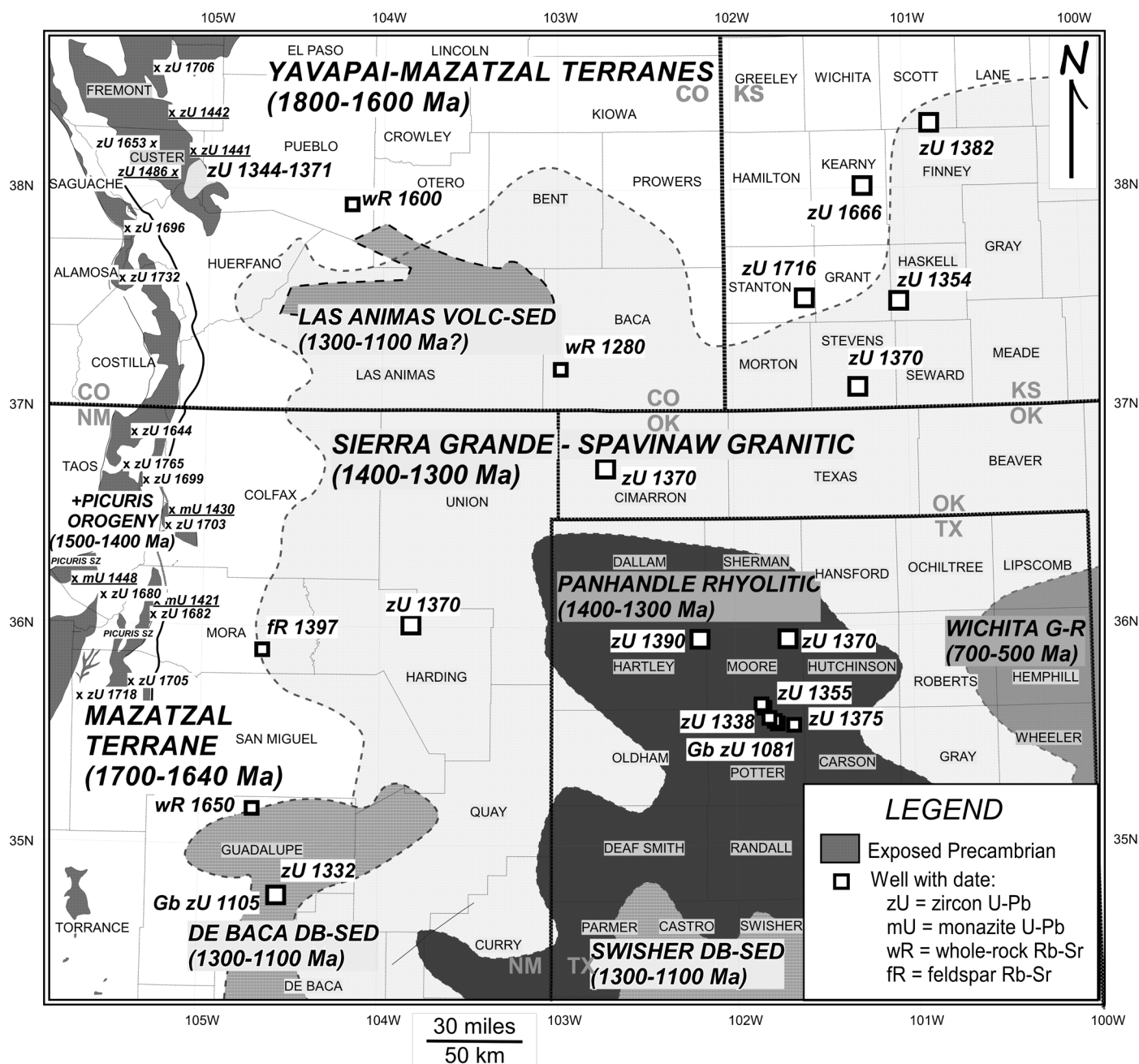


FIGURE 2. Basement lithologies at base of Paleozoic sediments, grouped into 'terrane' with age affiliation shown. DB-Sed = Diabase intruding sediments; G-R = Granite and rhyolite; gb = gabbro (or diabase); YMTR = Yavapai-Mazatzal Transitional (terrane). Las Animas configuration from Tweto (1983). Age information from Lidiak et al. (1993), Barnes et al. (2002), and Bickford et al. (2015). County names are shown.

From relationships in the Texas panhandle, it is reasonable to infer that the granitic rocks were emplaced at upper-crustal depths and may have had a rhyolitic volcanic cap over most of their extent. If so, the preservation of rhyolites in the Texas panhandle may indicate an area of relative subsidence and lesser erosion before deposition of younger rocks. In contrast, rocks in the Sangre de Cristo and Wet Mountains were at 15 km depths about 1450-1400 Ma. Different post-1400 Ma cooling histories suggest the presence of a north-south tectonic boundary on the east margin of the Sangre de Cristo range separating rocks of different crustal depths. Faulting may have caused the uplift of the

now-exposed rocks about 1000 Ma, and have been reactivated in all subsequent orogenic events (Sanders et al., 2005).

Younger sedimentary and igneous rocks overlie the granitic and rhyolitic sequence in southeastern Colorado and along the southern margin of the study area. The Labrador #1 Mescalero penetrated a thick sequence of indurated but nearly unmetamorphosed sediments below Mississippian strata and above a 1332 Ma granite (Amarante et al., 2005). These strata are correlated with the De Baca sedimentary terrane, which continues irregularly southward to the Van Horn area (where it is dated at about 1250 Ma; Ewing et al., 2019). To the east, sediments

are locally present in a broad band through Castro, Swisher and Briscoe counties, Texas, and may correlate to sedimentary or metasedimentary rocks in southernmost Oklahoma and adjacent Texas (Tillman Metasedimentary Group). In southeastern Colorado, Tweto (1983) defined a thick sequence of volcanic and phyllite-grade metasedimentary rocks as the Las Animas Formation. This unit has not been dated, but is inferred to be post-1300 Ma. The De Baca and Las Animas units have been correlated regionally with the Unkar Group in the Grand Canyon (Timmons et al., 2005).

Diabase and/or gabbro intrusions are widespread in the area, particularly in the areas of De Baca and Swisher sedimentary rocks and in the Panhandle rhyolitic area. Two U-Pb zircon dates from these intrusions are 1105 Ma (Guadalupe Co., New Mexico) and 1081 Ma (Potter Co., Texas; Barnes et al., 2002; Amarante et al., 2005). These dates are similar to those of the Pecos layered mafic intrusion in the Permian Basin to the south, and to basaltic 'Keweenawan' volcanics and intrusives of the Mid-Continent Rift System, suggesting regional extension and injection of magma.

The last igneous event in the basement is the rifting and rhyolitic volcanism and magmatism associated with the Wichita province and the Southern Oklahoma Aulacogen. At present, this material is inferred to underlie the deep Anadarko Basin on the eastern edge of the Texas panhandle, but outliers may be present elsewhere.

PALEOZOIC

Initial deposition over basement rocks consisted of transgressive sandstone and a thick carbonate platform sequence of Late Cambrian and Early Ordovician age, called the Arbuckle Group (Oklahoma, Kansas and Colorado) or the Ellenburger Formation (Texas). Arbuckle rocks overlie Precambrian throughout the Anadarko Basin and northwest to Colorado (Fig. 3). They were probably deposited over most of the area; however, later pre-Mississippian erosion has stripped them over a wide belt from northwest to southeast (the Texas Arch; Ewing, 1991). Mississippian carbonates were deposited on top of the eroded surface and overlie Precambrian rocks in Texas and New Mexico. Mississippian rocks were probably deposited over most of the area, but latest Mississippian and Early Pennsylvanian erosion removed them from large areas, where Precambrian rocks are now overlain by Pennsylvanian or Permian strata.

Faulting, uplift and basin development during the Pennsylvanian and Permian have profoundly shaped the five-state region, resulting in the complex pattern indicated on Figures 3 and 4. As shown in present-day structure on top of Precambrian (Fig. 4), shallow basement (largely overlain by Permian redbed sediments) occupies a large area trending north-northeast into southeastern Colorado, with a series of prongs or arms projecting to the southeast and west. There are three culminations along the high trend; the Cherryvale high in eastern San Miguel and Mora counties, bounded by the late Paleozoic Tucumcari basin to the south and the Rainsville Basin (Taos Trough) to the northwest; the Sierra Grande uplift, bounded

by the Dalhart Basin to the east and the Laramide Raton Basin to the west; and the Apishapa arch, bounded by the Laramide Denver and Raton basins, and a broad Late Paleozoic shelf to the northeast and east. The saddles between the high areas are relatively gentle; separation from the Pedernal uplift to the southwest is not evident on Figure 4 because of Laramide uplift, but is indicated by Pennsylvanian deposition (see Fig. 3). The two principal western prongs, the Cimarron arch and the Apishapa arch, are coaxial and continuous with two Laramide uplifts which appear to have reactivated the Late Paleozoic structures (Cimarron uplift and the Wet Mountains).

Faults are abundant, but can only be defined in the present study by differential uplift between wells in excess of regional gradients. There are more faults than shown, particularly in areas of sparse well control. Strike-slip faults are probably underrepresented as vertical uplift along them is limited and inconsistent; also, some faults shown may be monoclines. Seismic data would be required to fully image and delineate these fault systems.

The Apishapa arch or uplift extends southeast from the Wet Mountains to the west end of Baca County. Present mapping defines two fault zones on the northern flank; earlier maps by Tweto (1987) and Hemborg (1996) show several more, but they are hard to support in the present database. The eastern end is defined by a sharp break, the Freezeout Creek fault (Buehler, 1947), which well control indicates has a northwesterly trend. Parts of the east end of the arch are covered by a thin 'flap' of Arbuckle rocks underlying Pennsylvanian redbeds, suggesting lesser uplift in these areas (Fig. 2).

The north-south trending eastern boundary of the Sierra Grande uplift into the Dalhart Basin south of the Freezeout Creek fault, is a complex zone, informally called here the "Kenton zone" after Kenton, Oklahoma. It yields an oddly sinuous set of structure contours, suggesting a complex fault pattern. The well data identify primarily major northeast-trending east-down faults, but significant northwest-trending faults are likely to be present as well. Well control in this area is inadequate to define the structure.

The Bravo arch or "Bravo Dome" is the southeast-projecting prong of the Sierra Grande uplift. It is bounded on the northeast by a well-defined fault system, separating it from the Dalhart Basin (Broadhead, 1990; Johnson, 1983). Local Laramide reactivation of this system produced the Clapham anticline (Baldwin and Muehlberger, 1959). The southwestern side has less relief, but several northwest-trending faults are present; one transects the Bravo Dome CO₂ field (Cassidy et al., 2013). The arch dies out to the southeast in Oldham County, Texas where the deep Whittenburg trough separates it from the fault-bounded Amarillo Uplift (Budnik, 1986).

The southern margin of the Cherryvale high is a complex transition into the Tucumcari Basin, which consists of several subbasins and intervening highs (Broadhead and King, 1988; Broadhead et al., 2002). Numerous faults are present, the present mapping shows only those reliably inferred from well data. The Cuervo subbasin is a remarkably deep fault-bounded block, where wells drilled by Shell in the 2000s have found basement at depths of over 9000 ft subsea (twice as deep as pre-

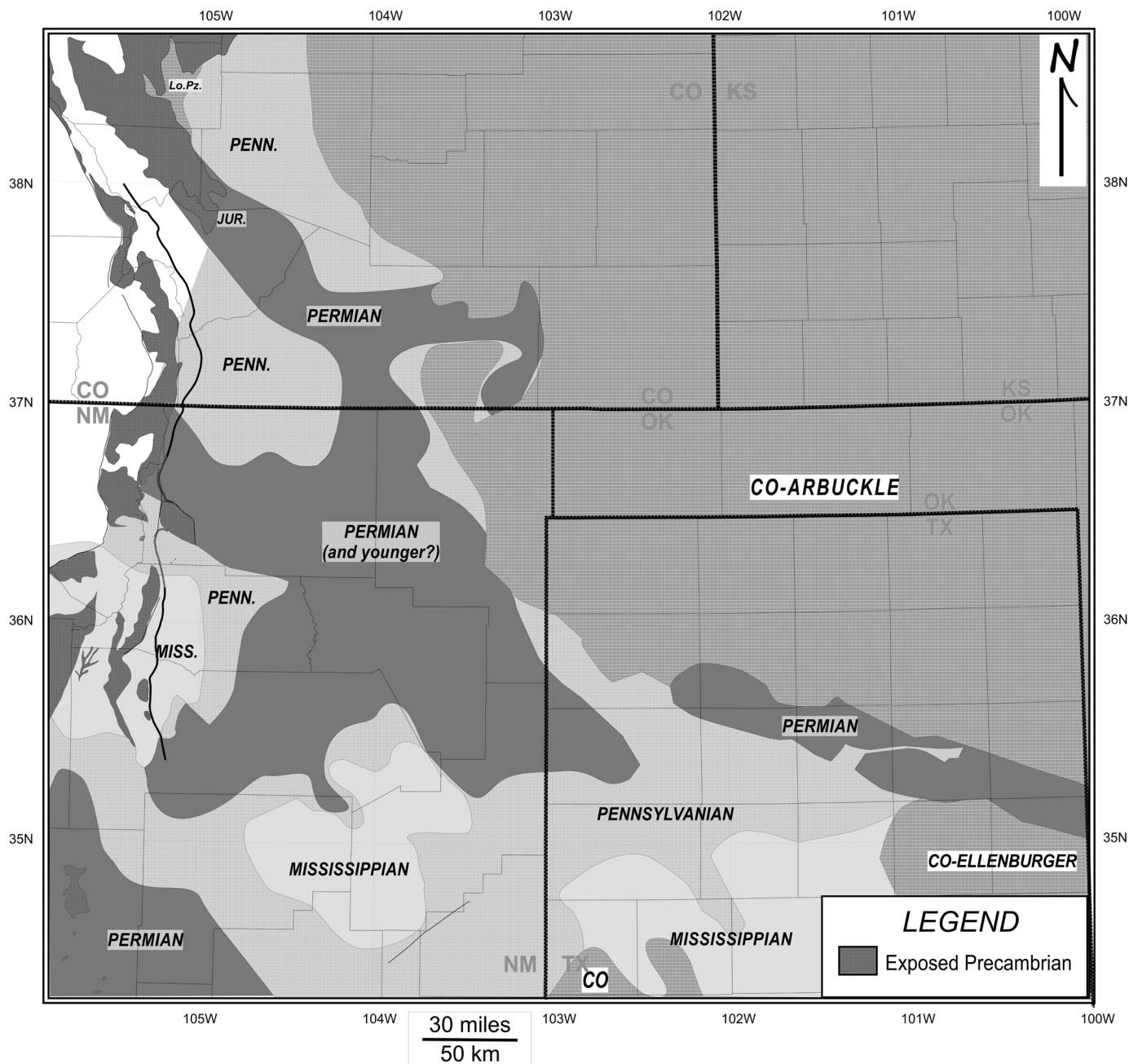


FIGURE 3. Map showing Paleozoic sediments overlying basement. Some data from Grant and Foster (1989) in New Mexico and Dutton et al. (1982) in Texas.

vious estimates). Adjacent to the deep basin is the high-standing Newkirk ridge. These local fault-bounded lows and highs suggest a zone of structural disturbance, as discussed below.

The western margin of the Cherryvale high is defined by an apparent homoclinal dip into the Rainsville Basin, where thick Pennsylvanian strata accumulated (Baltz and Myers, 1999). This basin is cut by Laramide uplift and faulting on its west and northwest (Ocate anticline), but originally connected westward to the Taos Trough, possibly with discontinuous north-trending faulted highs separating them. The northern margin of the Rainsville basin against the Cimarron Arch is a major fault zone (Saladon Creek fault of Baltz and Myers, 1999).

The northwest boundary of the Sierra Grande uplift is a gentle homocline into the Raton basin. This homocline is largely of Laramide origin; only thin Pennsylvanian strata have been found in parts of the basin (Fig. 3). The structural relations at the north end of the Raton basin against the Apishapa arch and Wet Mountains and the location of the margin of the deep Central Colorado trough are not clearly defined (Fig. 1).

Most of the uplifted zones appear to be primarily Late Pennsylvanian and Wolfcamp in age. The pattern of preservation of Mississippian strata (Fig. 3) indicates that a similar pattern of basins and uplifts was present in Early Pennsylvanian time as well, with the addition of an uplifted area east of the Tucum-

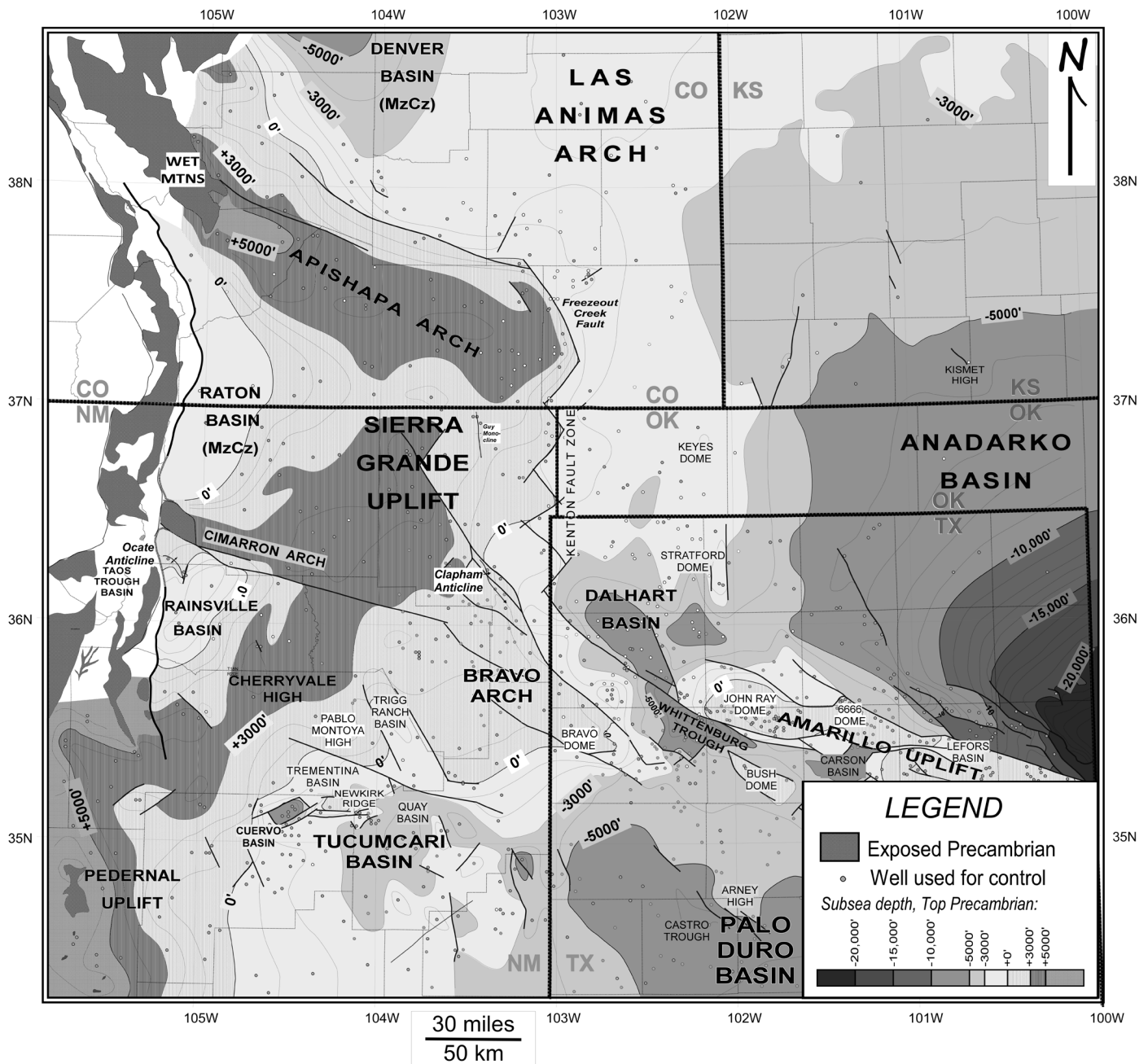


FIGURE 4. Structure map on base of Paleozoic. Contour interval = 1000 ft, color breaks every 5000 ft, secondary breaks at +3000' and -3000'. Texas section from Ewing (1991); Kansas after Cole (1976). For sources of well data see text.

cari basin (the “Frio uplift” of some authors) which is not well expressed in the Top Precambrian structure.

A preliminary tectonic interpretation of the Ancestral Rocky Mountains in the area is suggested on Figure 5. Uplift zones and surrounding basins generally trend northwestward, in continuity with the Amarillo-Wichita axis, and are bordered across major faults by areas of ‘granite wash’ (alluvial arkose) deposition. The Bravo and Cimarron prongs are likely parts of a “Cimarron-Bravo uplift”, with major faults on the south (in the west) and northeast (in the east). To the north, the Apishapa uplift has major faulting to the north and to the east along the complex Kenton trend. The area between the Cimarron-Bravo

and Apishapa uplifts is a gentle sag with limited deposition, which may be connected to the deep Central Colorado trough to the northwest (Baltz, 1965).

South of the main uplift, a WNW-ESE trending belt of structural disturbance, the “Cuervo-Castro zone” extends from central New Mexico into the Palo Duro basin of Texas. This includes not only the deep Cuervo mini-basin and the Newkirk ridge, but also several other areas of significant faulting and anomalous elevations. This zone of disturbance may represent a diffuse strike-slip fault zone, similar to the Matador fault zone (“Matador Arch”) that lies south of the study area (Fig. 1; Brister et al, 2002; Ewing, 1991, 2019). Faulting may connect this

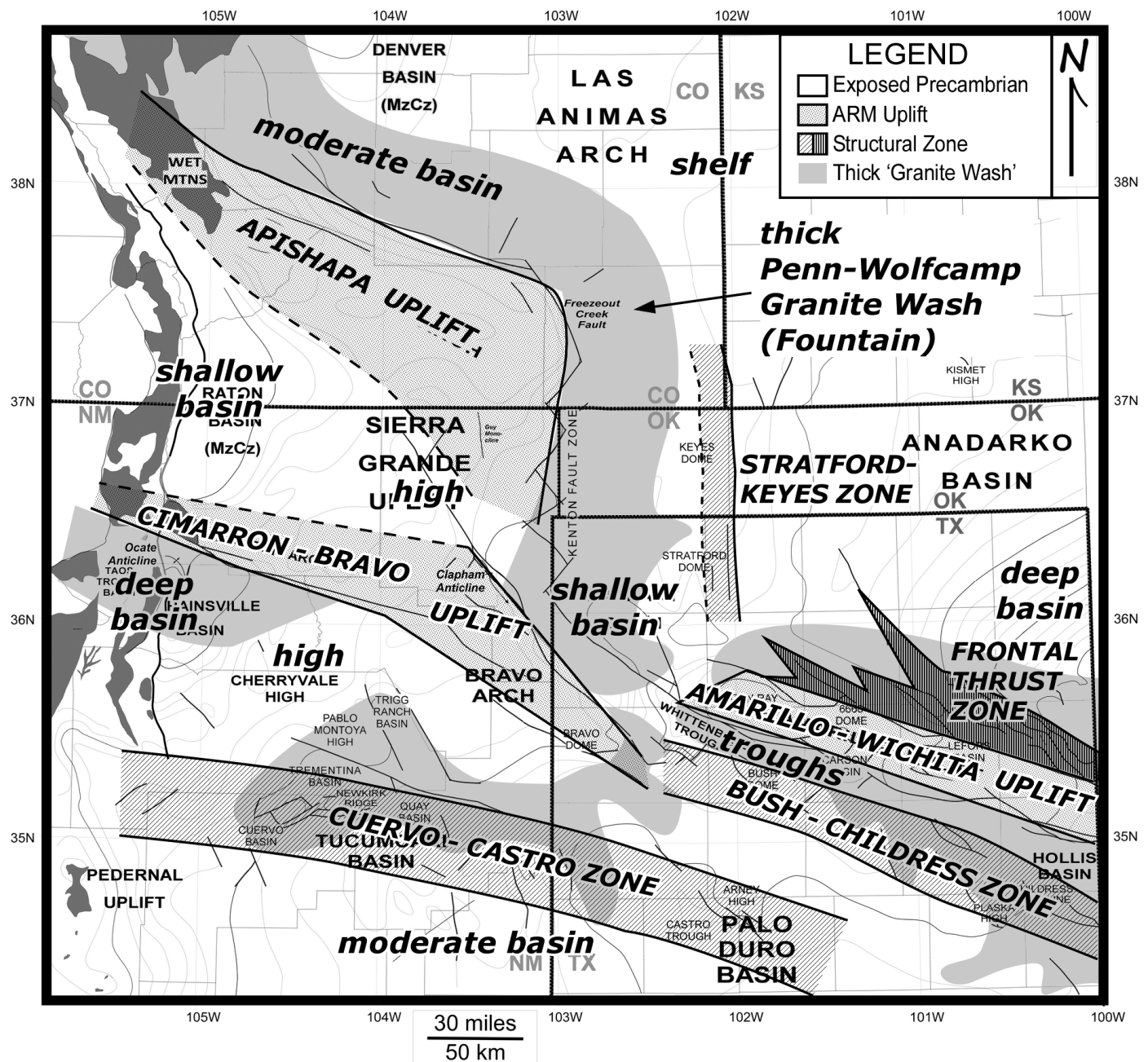


FIGURE 5. Major structural features of Late Paleozoic age overlaid on structure map of Figure 3. Shading - areas of thick 'granite wash' (arkosic alluvial and fan-delta) sedimentation, primarily of Pennsylvanian age. Texas information is from Dutton et al. (1982). New Mexico 'granite wash' information is from Roberts et al. (1976), Broadhead and King (1988) and Baltz and Myers (1999); only Pennsylvanian alluvial debris is indicated, as Wolfcampian debris is widespread. Colorado and Dalhart information is from De Voto (1980) and McCasland (1980).

zone northwest to the Cimarron-Bravo uplift, creating the Trigg Ranch subbasin. Similar discontinuous structures extend south of the Amarillo-Wichita uplift in a 'Bush-Childress zone', as noted by Budnik (1986). A north-south trending zone of structures extends parallel to the Kenton margin of the Apishapa uplift, the "Stratford-Keyes zone". West of the Cherryville high, north-south trends of uplifts and small basins predominate, as shown by Baltz and Myers (1999). What causes the Cherryville high itself is not understood at present.

A significant feature of eastern and southern arms of the Ancestral Rocky Mountains orogen are small but deep fault-bounded basins within the major uplifted zones. In the Amarillo uplift, these include the Lefors and Deep Lake basins; in the Permian Basin area there are multiple smaller uplifts and basins. Could such mini-basins be present in the broad Sierra Grande complex? There are a few wells with anomalously deep basement, but none yet have penetrated marine Pennsylvanian strata. But large areas remain undrilled. The zone between

the Trigg Ranch basin and the Cimarron-Bravo bounding fault in Mora and Harding counties, New Mexico could be a good place to find these.

MESOZOIC AND CENOZOIC

As mentioned above, the structure contouring of Figure 4 is also affected by Laramide basin development and uplift, as well as later uplift and regional tilting. To define these later events, a structure roughly at the base of the Cretaceous is useful (Fig. 6). Cretaceous strata are widely exposed in New Mexico and Colorado, but are eroded in Texas and the Tucumcari area; so the contouring there is inferred from regional work (Ewing, 2016, 2019). In general, there is a smooth eastward dip (probably post-Laramide in origin) countered by two westward-deepening Laramide basins, the Raton and Denver basins. West of these basins are complex faulted and uplifted areas, where contouring is not attempted.

Both the Sierra Grande and Apishapa high areas are evident on the map. The Sierra Grande and a subtle 'Las Animas arch' to the northeast can be considered as flexural outer highs related to basins subsiding to the west. The Apishapa arch separates the two basins and is a low-relief Laramide uplift, connected northwestward into the much higher Wet Mountains.

The Raton basin has a gently homoclinal southeast flank, a steeper northeast flank and a thrust western margin. The southern margin against the Cimarron arch is steep, and complexly faulted and folded with uplift of the Cimarron block on the Fowler Pass fault. The area south of the Cimarron uplift (the "Las Vegas Basin") shows only minor depression despite the distinct surface expression. It is of interest that the Cimarron arch is south-verging during the Late Paleozoic (with the large fault on the south), but north-verging during the Laramide (with the large fault on the north).

FUTURE DIRECTIONS

This work has shown the benefits of a broad, multistate study of geologic relationships. As stated, it is a work in progress, and more information on stratigraphic relationships and refinement with log and sample data will improve various aspects and correct the inevitable errors.

There is a need for additional geochronology of Proterozoic rocks in Colorado and New Mexico. The important Las Animas unit is undated and unstudied since Tweto's work, yet it has appeared as an element in regional correlations. The rocks of the De Baca unit also do not yet have firm dating in many areas. Restudy of the basement samples in the Sierra Grande and other units, particularly using modern geobarometry and geothermometry, would help in validating the shallow level of emplacement inferred for these rocks.

The present work has not relied on gravity or other potential field data, as basement variations seem to be as responsible for the anomaly patterns as the Late Paleozoic structures are. However, the data should be carefully examined with the present structure to assist in defining fault trends and perhaps searching for intra-uplift basins. Sims et al. (2001) presented an inter-

pretation in Colorado using magnetic data, and Andreasen et al. (1962) were a pioneering study in portions of New Mexico. Seismic data exist for several parts of the area, but are proprietary; access to some of this data would be most informative.

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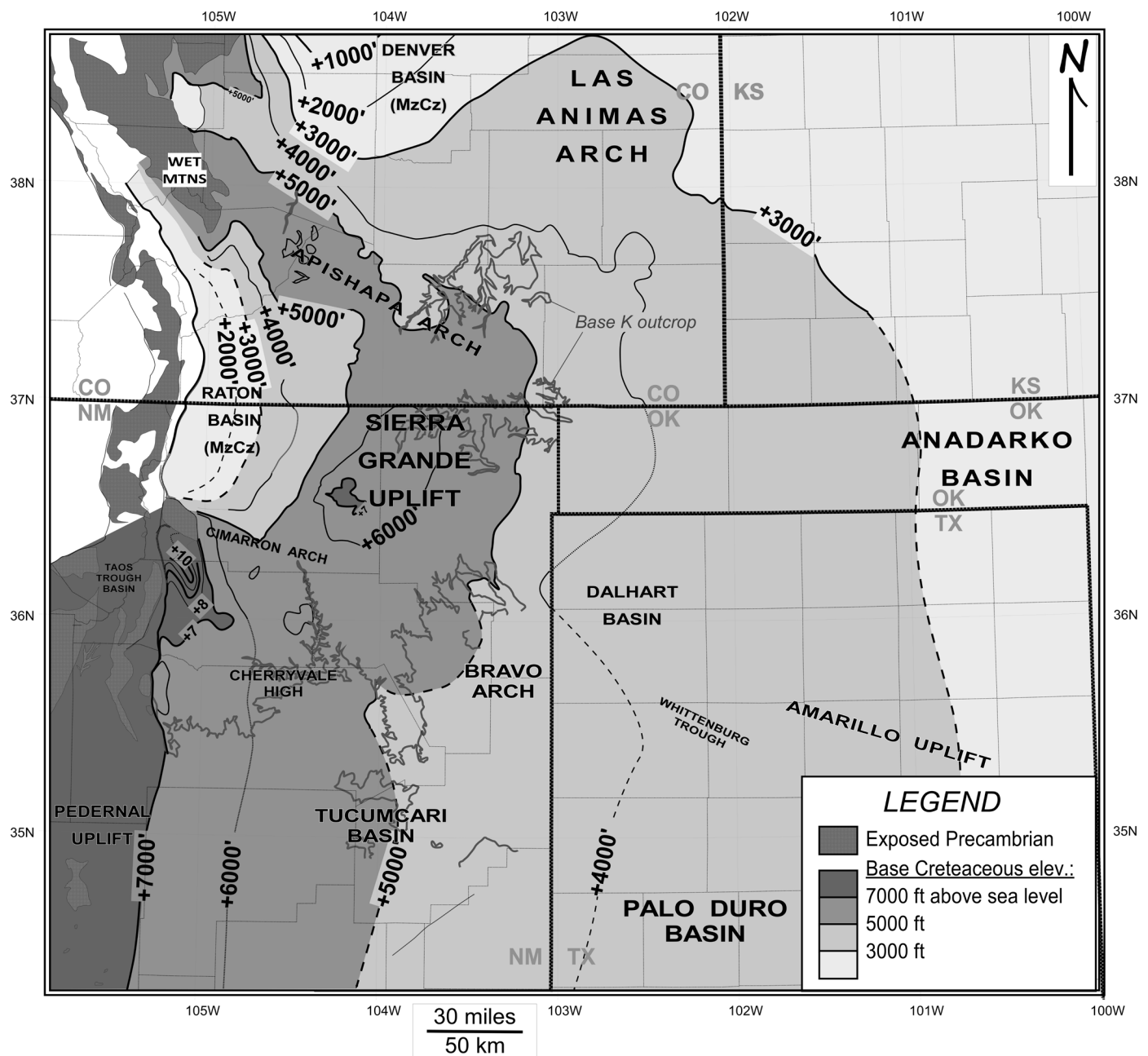


FIGURE 6. Structure map showing base of Cretaceous and/or Top Dakota. Contour interval = 1000 ft. Sources: Scott (1968), Johnson (1969), Scott et al. (1978) for Colorado; Scott (1986), Scott and Pillmore (1993), and Baldwin and Muehlberger (1959) for Union County, New Mexico.

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