New Mexico Geological Society

Downloaded from: https://nmgs.nmt.edu/publications/guidebooks/74

Structural geology of the Tierra Amarilla Anticline, New Mexico

John M. Bailey, Karl E. Karlstrom, Cameron C. Reed, and Matthew T. Heizler, [eds.]
2024, pp. 281-289. https://doi.org/10.56577/FFC-74.281

in:
Geology of the Nacimiento Mountains and Rio Puerco Valley, Karlstrom, Karl E.;Koning, Daniel J.;Lucas, Spencer G.;Iverson, Nels A.;Crumpler, Larry S.;Aubele, Jayne C.;Blake, Johanna M.;Goff, Fraser;Kelley, Shari A., New Mexico Geological Society 74 th Annual Fall Field Conference Guidebook, 334 p.

This is one of many related papers that were included in the 2024 NMGS Fall Field Conference Guidebook.

Annual NMGS Fall Field Conference Guidebooks

Every fall since 1950, the New Mexico Geological Society (NMGS) has held an annual Fall Field Conference that explores some region of New Mexico (or surrounding states). Always well attended, these conferences provide a guidebook to participants. Besides detailed road logs, the guidebooks contain many well written, edited, and peer-reviewed geoscience papers. These books have set the national standard for geologic guidebooks and are an essential geologic reference for anyone working in or around New Mexico.

Free Downloads

NMGS has decided to make peer-reviewed papers from our Fall Field Conference guidebooks available for free download. This is in keeping with our mission of promoting interest, research, and cooperation regarding geology in New Mexico. However, guidebook sales represent a significant proportion of our operating budget. Therefore, only *research papers* are available for download. *Road logs*, *mini-papers*, and other selected content are available only in print for recent guidebooks.

Copyright Information

Publications of the New Mexico Geological Society, printed and electronic, are protected by the copyright laws of the United States. No material from the NMGS website, or printed and electronic publications, may be reprinted or redistributed without NMGS permission. Contact us for permission to reprint portions of any of our publications.

One printed copy of any materials from the NMGS website or our print and electronic publications may be made for individual use without our permission. Teachers and students may make unlimited copies for educational use. Any other use of these materials requires explicit permission.

This page is intentionally left blank to maintain order of facing pages.

STRUCTURAL GEOLOGY OF THE TIERRA AMARILLA ANTICLINE, NEW MEXICO

JOHN M. BAILEY[1], KARL E. KARLSTROM[1], CAMERON C. REED[1], AND MATTHEW T. HEIZLER[2]

[1]Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131; kek1@unm.edu
[2]New Mexico Bureau of Geology and Mineral Resources, 801 Leroy Place, Socorro, NM 87801

Abstract—The Tierra Amarilla anticline of northwestern New Mexico is a well-exposed anticline in Mesozoic strata that lies near the boundary of the Colorado Plateau to the west and the Rio Grande rift to the east. Its axial trace appears to align with the southern extension of the Nacimiento fault zone, and its gentle south plunge mimics the south plunge of the Laramide Nacimiento uplift. This paper examines the relationship of the anticline to the apparent southern termination of the Nacimiento fault. New 1:6,000 mapping by the University of New Mexico Department of Earth and Planetary Sciences 2023 field camp suggests several new map interpretations that recognize three fault segments as a continuation of the Nacimiento fault system. The ~10-m-thick travertine carapace and aligned artesian carbonic springs in the western core of the fold are best explained by a concealed fault that we call the Tierra Amarilla segment. A Gypsum Hill segment is an east-side-up reverse fault in the center of the fold that repeats the Todilto Formation and has been partly inverted by east-side-down normal displacement during rifting. The East Limb segment is also an east-side-up reverse fault that repeats the Todilto and Summerville Formations. Both exposed fault zones are ~10 m wide and involve a dextral strike-slip displacement component. Recognizing that the strike-slip component precludes rigorous restoration of cross sections, we restore the dip-slip component and suggest that the Tierra Amarilla anticline is an inverted (collapsed) segment of the Nacimiento uplift. A second new interpretation is constraining the age of the angular unconformity that bevels the folded strata and fault zones. We call this erosional surface the San Ysidro surface, and we dated the Cenozoic sediments that overlie it. The basal travertine carapace that was deposited on this surface yields U-series ages as old as 269±3 ka, which we interpret to be a minimum age for the erosional beveling. A detrital sanidine age (n = 1) from the Cenozoic sediment above the unconformity yields a youngest ^{40}Ar/^{39}Ar age of 261±34 ka, which is a maximum depositional age for the sediment and a similar minimum age for the erosion. The San Ysidro surface slopes northward toward the Rio Salado and is approximately graded to a travertine-cemented river strath terrace that is 44 m above river level and gives a U-series age of 250±4 ka. The combined constraints suggest that the deposition on top of the San Ysidro surface took place 270–250 ka. The inception, duration, and rate of erosional beveling that created the angular unconformity are not constrained by our data but the formation of the San Ysidro surface may be related to rapid incision along the adjacent Rio Salado and Quaternary neotectonic uplift of the southern Nacimiento Mountains.

INTRODUCTION

The Tierra Amarilla anticline area attracts geology departments from across the country to teach field camp students geologic mapping because of its incredible exposure, distinct stratigraphy, and prominence in ancillary datasets such as satellite/aerial imagery and lidar digital elevation models. The original stewards of this landscape include the people of Zia Pueblo and Jemez Pueblo, and a synclinal part of the structure is situated on Zia Pueblo land. As mapped by Woodward and Ruetschilling (1976), the conspicuous anticline-syncline pair of folded Mesozoic strata is well exposed and plunges about 10–15° south. The anticline is cored by a significant travertine deposit, and the west limb has been eroded into an impressive hogback ridge that has a recreational trail with the suitable name Dragon's Back. Woodward and Ruetschilling (1976) showed this structure to be one of several folds that align with the southernmost extent of the Nacimiento fault, which is mapped to within ~2 km just north of the anticline (Fig. 1). At a larger scale, the Nacimiento fault zone aligns with the Sand Hill fault that forms the west side of the Albuquerque basin of the Rio Grande rift (Kelley, 1977; U.S. Geological Survey, 2016) and with the far west side of the Santo Domingo transfer zone between the Albuquerque and Española basins.

STRUCTURE OF THE TIERRA AMARILLA ANTICLINE

The structure of the Tierra Amarilla anticline has similarities to the contractional features of both the Rocky Mountains and the fault-cored monoclines of the Colorado Plateau. The Mesozoic stratigraphy in the anticline is that of the adjacent San Juan Basin and extends from the Triassic Petrified Forest Formation to the Cretaceous Mancos Shale. The Sierra Nacimiento just to the north is a west-verging, basement-cored uplift that has been thrust westward over San Juan Basin units (Baltz, 1967) and began to be unroofed during the Laramide orogeny (Kelley et al., 1992; Cather, 2004). At the easternmost edge of the San Juan Basin and flanking the west side of the Sierra Nacimiento are steeply dipping to locally overturned folded Paleozoic strata through Eocene strata.

The Woodward and Ruetschilling (1976) geologic map shows the Tierra Amarilla anticline as a pair of south-plunging anticlinal hinges cored by the Petrified Forest Formation of the Chinle Group that are separated by a ridge of Todilto Formation gypsum. Adjoining the anticline to the east and west are synclines that are cored by the Mancos Formation. Figure 2 shows our interpretation that the anticline is associated with three fault segments that we name the Tierra Amarilla, Gypsum Hill, and East Limb segments. The two eastern segments likely had a Laramide contractional origin that links the

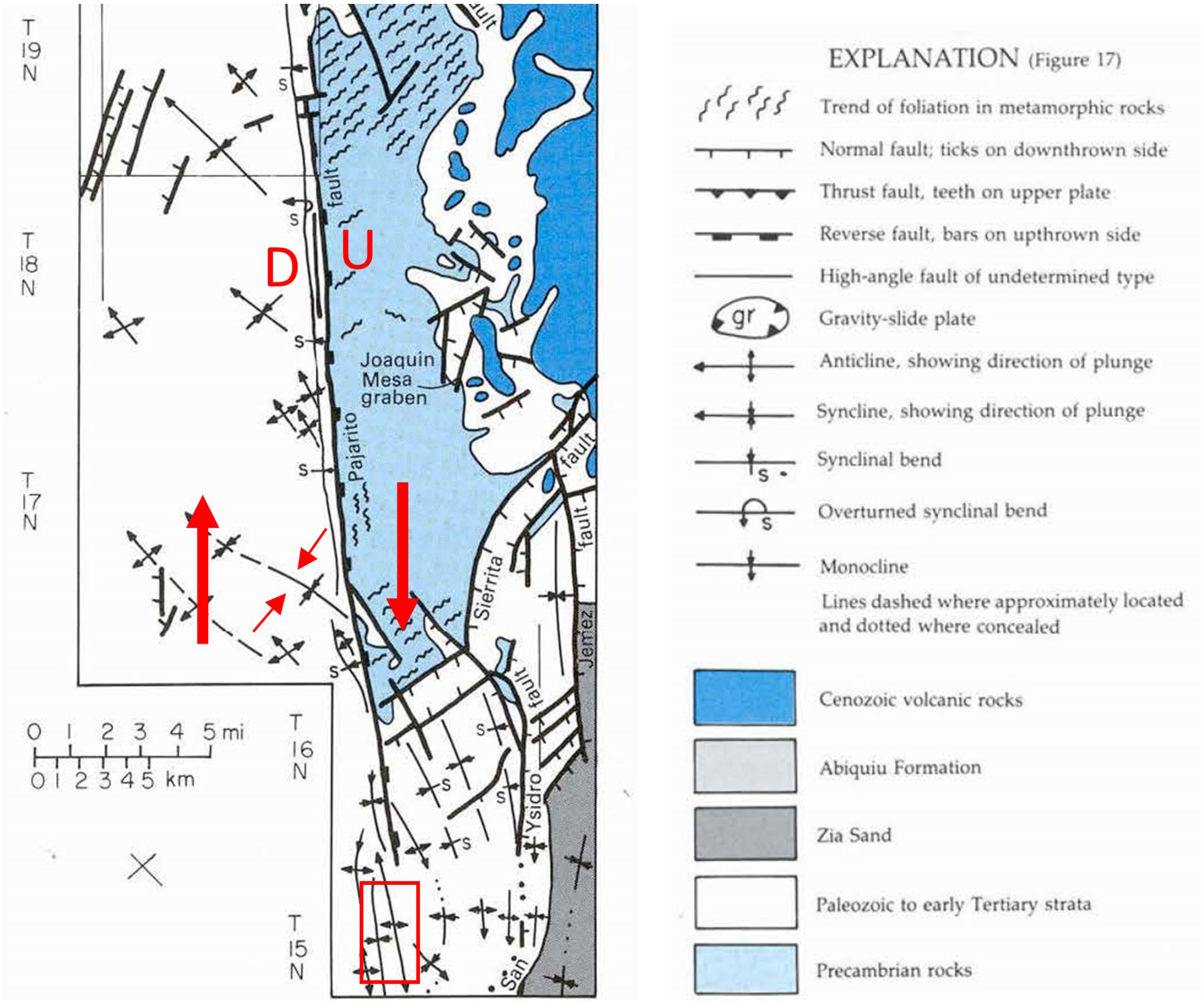

FIGURE 1. The southern Nacimiento uplift and Tierra Amarilla anticline (red box; modified from Woodward, 1987). The large red arrows display the dextral strike-slip component to the transpressional deformation during the Laramide orogeny. U and D indicate the dip-slip component with east-side-up reverse faulting. The smaller red arrows are the incremental shortening direction and a proxy for principal compressive stress (σ_1) during dextral strike-slip.

anticline to the Nacimiento uplift. The Cenozoic extensional reactivation of these faults links them to the Rio Grande rift. The use of the Tierra Amarilla segment by ascending artesian waters suggests Quaternary and ongoing neotectonics.

Figure 3 shows the Tierra Amarilla segment interpreted to form the core of the western anticline. A concealed but deeply penetrating fault likely explains the alignment of a series of travertine-depositing artesian springs that contain deeply sourced CO_2 and mantle-derived ^3He (Crossey et al., 2016; McGibbon et al., 2018). This segment provides a conduit for the fluids that are currently depositing travertine in the core of the anticline and which have done so for >270 ka (Cron et al., 2024; McGibbon et al., 2018). The north-south orientation of the springs and related travertine carapace suggest an underlying Tierra Amarilla fault segment that lines up with the southernmost mapped extent of the Nacimiento fault but has little displacement at this stratigraphic level. Figure 4 displays a roughly 0.5-m-wide crack in the travertine at "Fissure Ridge," just north of the map area in Figure 3A, which is an expression of this segment.

The Gypsum Hill segment is named for the topographic high point in the map area that sits at 6601 ft (1847 m) and is informally named Gypsum Hill because it exposes the upper Todilto Formation at a higher elevation than it is just to the west. This fault is structurally similar to the Nacimiento fault in that it is a west-verging reverse fault. The main hanging wall at Gypsum Hill is thrust over two slivers of the Jurassic Todilto and Summerville Formations. Figure 5 shows a northern exposure of the Gypsum Hill segment with the anticlinal bend of an east-side-up monocline that has been inverted by east-side-down normal faulting. Previous mapping by Woodward and Ruetschilling (1976) showed this structure with both east-side-down displacement (in their cross-section B-B') and east-side-up displacement near Gypsum Hill (in the area of Fig. 5). The fault zone dips east near Gypsum Hill, as shown in satellite imagery in terms of the way the fault "V"s across topography such that the along-strike ambiguity in displacement is best explained in terms of fault reactivation, shown in Figure 5.

New mapping suggests the presence of a reverse fault zone in the east limb of the anticline that we name the East Limb

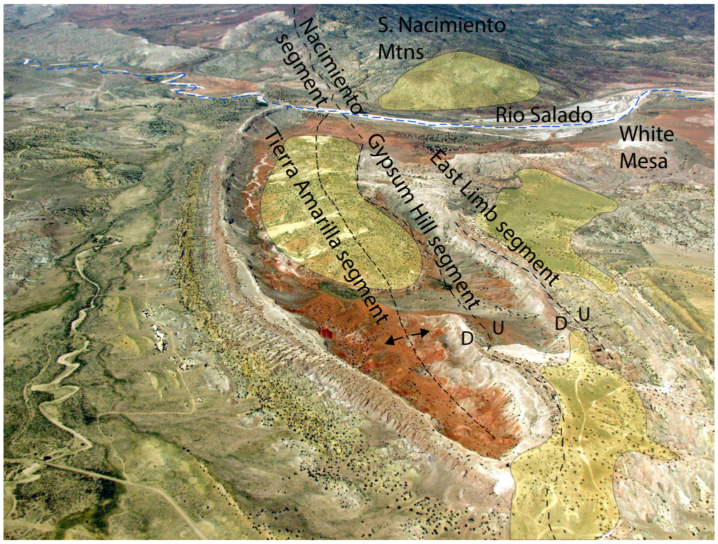

FIGURE 2. Aerial view of the Tierra Amarilla anticline with the south-plunging nose of the Sierra Nacimiento and the Rio Salado in the background. Laramide structural features are in black; note the general alignment of the fold axial plane trace with the southern exposed section of the Nacimiento fault. Other segments of the Nacimiento fault system exposed in the Tierra Amarilla anticline are called the Tierra Amarilla, Gypsum Hill, and East Limb segments. These had Laramide east-up reverse displacement and dextral strike-slip displacement, followed by east-down Rio Grande rift reactivation. Quaternary features are in yellow—travertines above the Tierra Amarilla segment, San Ysidro surface, and Rio Salado terraces on the nose of the Nacimiento Mountains. *Photo by Larry Crumpler*

segment that repeats the Todilto and Summerville Formations (Fig. 6A). Associated with this fault is a significant ductile deformation zone in the gypsiferous beds of the lower Summerville Formation, with west-verging asymmetric folds in the Summerville Formation that are consistent with the east-side-up thrust sense of displacement on the East Limb segment (Fig. 6B). This segment aligns with the core of the monoclinal flexure of Todilto gypsum along the escarpment west of White Mesa, as mapped by Woodward and Ruetschilling (1976). The deformation zone is spectacularly exposed below an angular unconformity that underlies the San Ysidro erosion surface.

In the cross section of Figure 3A, both Gypsum Hill and East Limb segments are shown to have 100–200 m of net reverse throw that has been partially inverted by normal displacement. Reverse throw is given by the ~100-m higher elevation of the Todilto-Summerville contact at Gypsum Hill relative to the gypsum ridge. Similarly, East Limb reverse throw of ~100-m scale is shown by mapped fault slices. In the restored cross section in Figure 3C, the Gypsum Hill segment is shown with east-side-down inversion to account for the steeply dipping bedding segments within the fault zone that are interpreted to be remnants of the steeply dipping limb of the Laramide monocline. The amount of extensional inversion of the East Limb segments is not known. Figure 3C depicts the combined Gypsum Hill and East Limb reverse faults as genetically related to an east-side-up, west-verging monoclinal uplift analogous to the Nacimiento uplift and fault system to the north, but the pre-extension elevation of the basement-Paleozoic contact, shown in Figure 3C as ~6000 ft in elevation, is speculative.

Gypsum veins are exposed in the Summerville Formation along both exposed fault zones. In both segments, ~75° east-dipping gypsum veins are subparallel to bedding in what we interpret to be steeply east-dipping monoclinal limb remnants (Fig 3A). Figure 7 shows evidence for dextral strike-slip associated with both fault segments. The low-strain examples have gypsum fibers that grew perpendicular to the vein, suggesting they may have initially developed in essentially flat-lying beds with high fluid pressure overcoming a vertical least compressive stress (σ_3). As folds and reverse faults grew, veins and beds were rotated to steep dips that would be unfavorable to continued vein opening, and the veins recorded the strike-slip component of regional transpression.

Laramide dextral strike-slip has long been invoked across the Nacimiento fault system and other rift faults (Kelley, 1955; Baltz, 1967; Karlstrom and Daniel, 1993; Pollock et al., 1998; Cather, 1999; Erslev, 2001), but estimates of lateral slip magnitude have varied from several to tens of kilometers (Woodward et al., 1997, 1999; Cather et al., 2006). A possible present consensus is that the strike-slip component exceeds the dip-slip component of ~2 km (Cather, 1999; Cather et al., 2006). The northwest-striking open folds in the eastern San Juan Basin adjacent to the Nacimiento faults are also compatible with a dextral shear couple (Fig. 1; Baltz, 1967; Woodward et al., 1999). Erslev (2001) included the Tierra Amarilla anticline area and Rio Puerco fault system in a paleostress analysis using minor faults and showed a set of west-northwest steeply dipping minor faults, locally with conjugate fault geometries. Similar east-west-oriented minor strike-slip faults are observed offsetting the Jackpile-Dakota contact on the east limb of the Tierra Amarilla anticline (Fig. 3). Paleostress analyses of these minor faults indicate a Laramide contraction direction with an azimuth of ~060° (Fig. 8). This orientation would cause dextral strike-slip on north-south striking faults and folds like the Nacimiento fault system and Tierra Amarilla anticline.

The various structures described above within the Tierra Amarilla anticline include reverse faults, fault-related folds (monoclines), strike-slip on north-south steeply dipping gypsum veins, and east-west- to northeast-striking conjugate

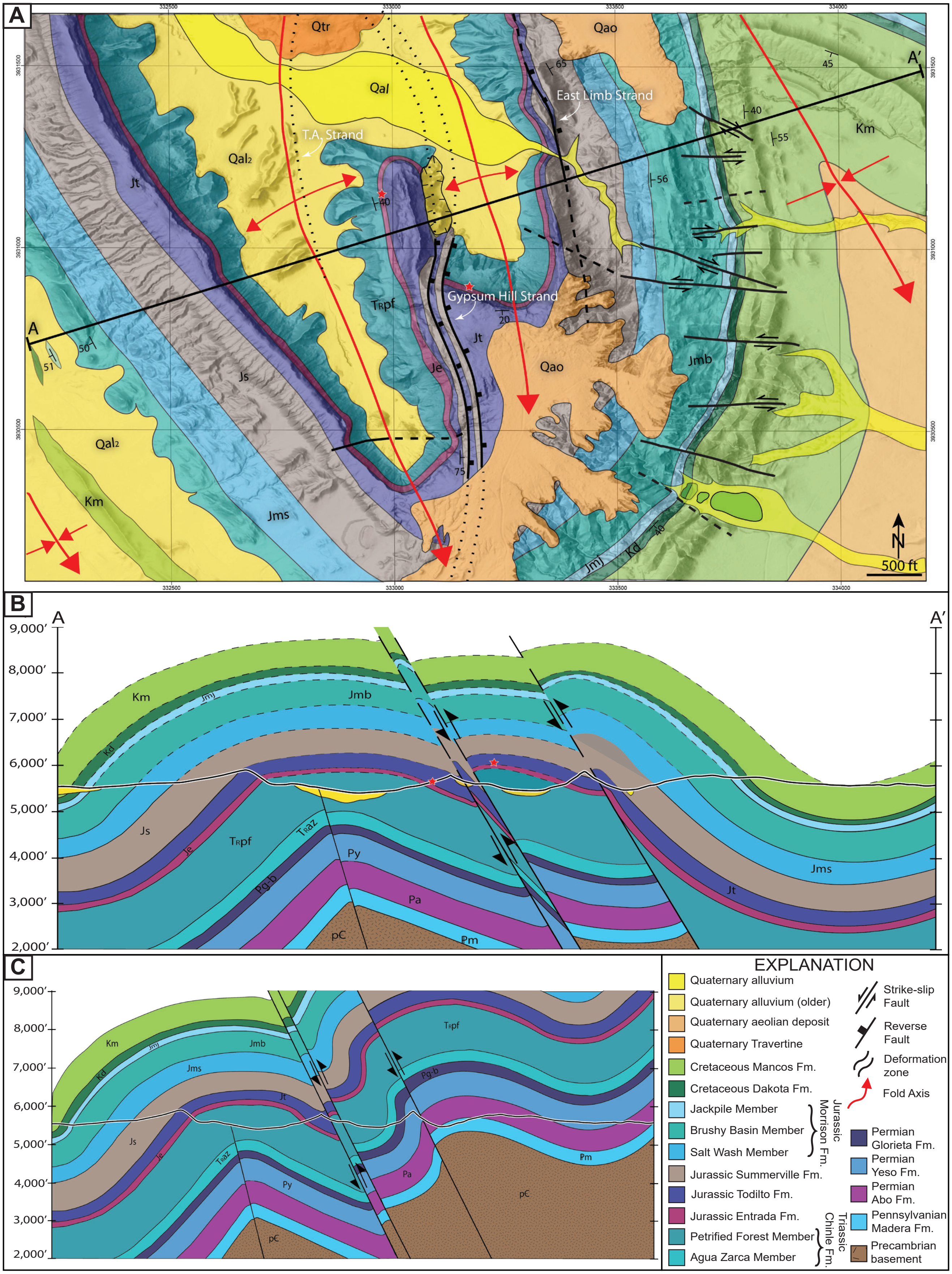

FIGURE 3. (A) Geologic map of the southern end of the Tierra Amarilla anticline area. Original mapping at 1:6,000 is shown at 1:12,000. (B) Geologic cross section from A to A′ that has a V/H ratio of 1. (C) Restored cross section to Laramide deformation ~50 Ma, with the current topographic profile for reference.

strike-slip faults on the limbs. The relative ages of these structures is not well constrained, but this combination of contractional and strike-slip across the north-south Nacimiento fault zone and Tierra Amarilla anticline likely formed during the progressive Laramide transpressive deformation, with potential for slip partitioning into zones of shortening and strike-slip (Cather et al., 2006, and references therein). Additional complexity farther north along the Nacimiento fault zone was reported by Pollock et al. (2004) and involves low-angle thrust segments that seem compatible with models for fault-propagation folding and tri-shear (Bump, 2003).

FIGURE 4. One of several artesian carbonic springs aligned in the core of the Tierra Amarilla anticline, with a view looking north to the Sierra Nacimiento. This roughly 0.5-m crack in the travertine at Fissure Ridge is inferred to be an expression of the Tierra Amarilla fault segment.

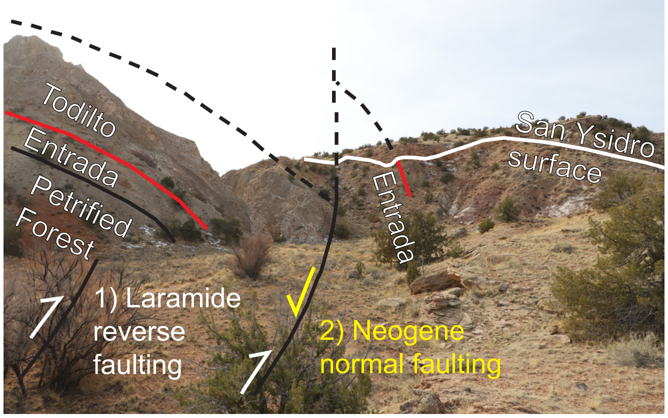

FIGURE 5. Looking south at the northern exposure of the Gypsum Hill segment of the Nacimiento fault zone. Initial east-up Laramide high-angle reverse movement folded the overlying stratigraphy into the west-facing Nacimiento monocline. The fault was later reactivated with east-down normal movement during Neogene extension. Photo taken just south of Highway 550 and the Rio Salado.

SAN YSIDRO SURFACE ANGULAR UNCONFORMITY

A second contribution is better understanding of the San Ysidro erosional surface that represents a time of local erosional beveling of the anticline to create the spectacular angular unconformity atop folded and faulted Mesozoic rocks (Fig. 9). Alluvial deposits just above this surface record the small streams that beveled the unconformity, and the calcic soil horizons and eolian sands between the modern topographic surface and the unconformity record a significant amount of time.

Detrital sanidine samples were taken from the back of the outcrop in the approximate stratigraphic positions shown in Figure 9. TA-1A and TA-1B are from the bottom and top of the thick calcic soil, and TA2 is from eolian sands just above. Figure 9C shows that the youngest detrital sanidine grain in TA2 constrains the deposition of the sediment overlying the San Ysidro surface to be ≤261±34 ka. Full detrital sanidine spectra show reworking of Paleozoic and Mesozoic strata (lower panel) with volcanic grains from the Mogollon Datil (MD), Latir Amalia Tuff (AT), and San Juan volcanic field (SJVF), specifically Thorn Ranch Tuff (TR) of SJVF.

The travertine carapace in the center of the Tierra Amarilla anticline was built on top of the San Ysidro erosional surface such that U-series dates on the overlying travertine can also constrain the age of the surface. This carapace has fractured, and huge blocks have slid downhill, exposing several places where you can see a cross section of most of the deposit. Sampling was done to test an oldest-at-the-bottom stratigraphy. This is generally confirmed with a 269 ka age nearer the base and 212 ka age nearer the top, indicating that the main carapace formed 269–212 ka, although younger infillings of flowstone travertine also crystallized at various levels into older layers. Modern travertine is still being deposited by artesian carbonic springs deposited near the top of the travertine ridge, documenting the longevity of the fault-influenced confined fluid conduit for artesian carbonic waters (Cron et al., 2024).

Our conclusion from combined U-series and detrital sanidine geochronology is that the erosion that formed much of the San Ysidro surface in this area was over by 260–270 ka, when travertines, soils, and eolian deposits developed on top of it. However, the erosion represented by this surface was likely long-lived in the Quaternary, and the inception, duration, and rates are not constrained by our data. Formento-Trigilio and Pazzaglia (1998) published a 272±24 ka U-series age for travertines interbedded with fluvial terrace deposits on the Arroyo Peñasco that drains the southwestern Nacimiento Mountains. Cron et al. (2024) dated the 44-m terrace travertine cap on the Rio Salado directly north of Tierra Amarilla as 250 ka. The numerous 270–250 ka dates suggest an important travertine-depositing interval within the alternating incision and aggregation events recorded by terraces of the Rio Salado and Rio Jemez system. If so, pulses of erosional beveling of the San Ysidro surface may have taken place in response to incisional periods on the Rio Salado. Reed et al. (2024) used terrace dates

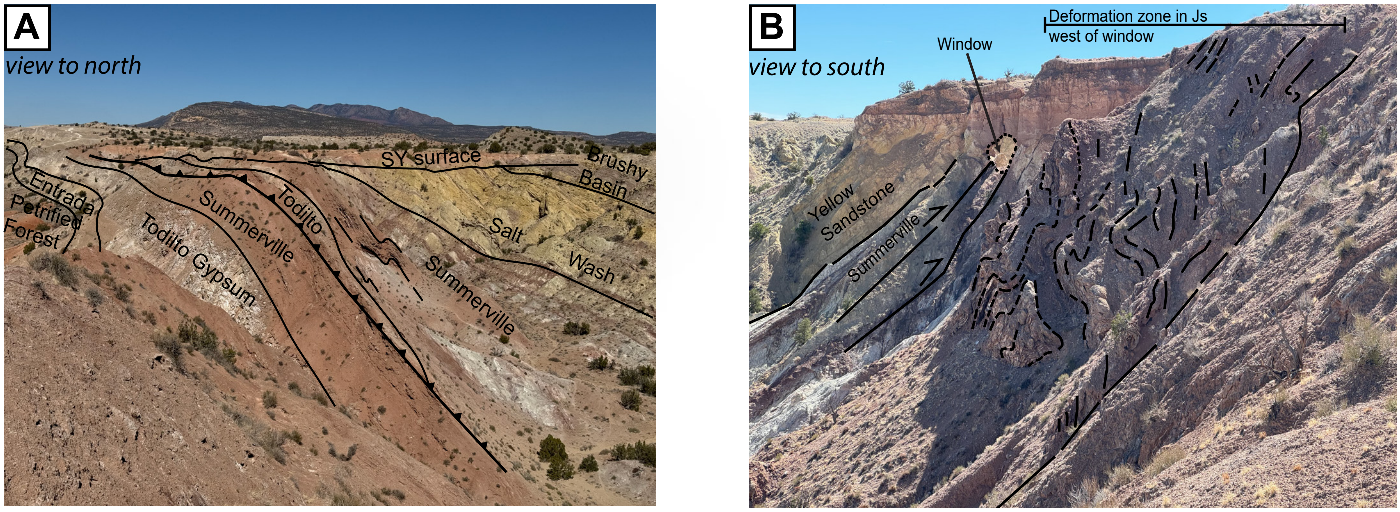

FIGURE 6. (A) East Limb fault strand repeats a sliver of Todilto gypsum and Summerville with east-side-up thrust movement. View is to the north with the Nacimiento Mountains in the background. (B) Deformation zone and minor west-verging folds associated with the East Limb fault below the angular unconformity created by the San Ysidro surface. View is to the south.

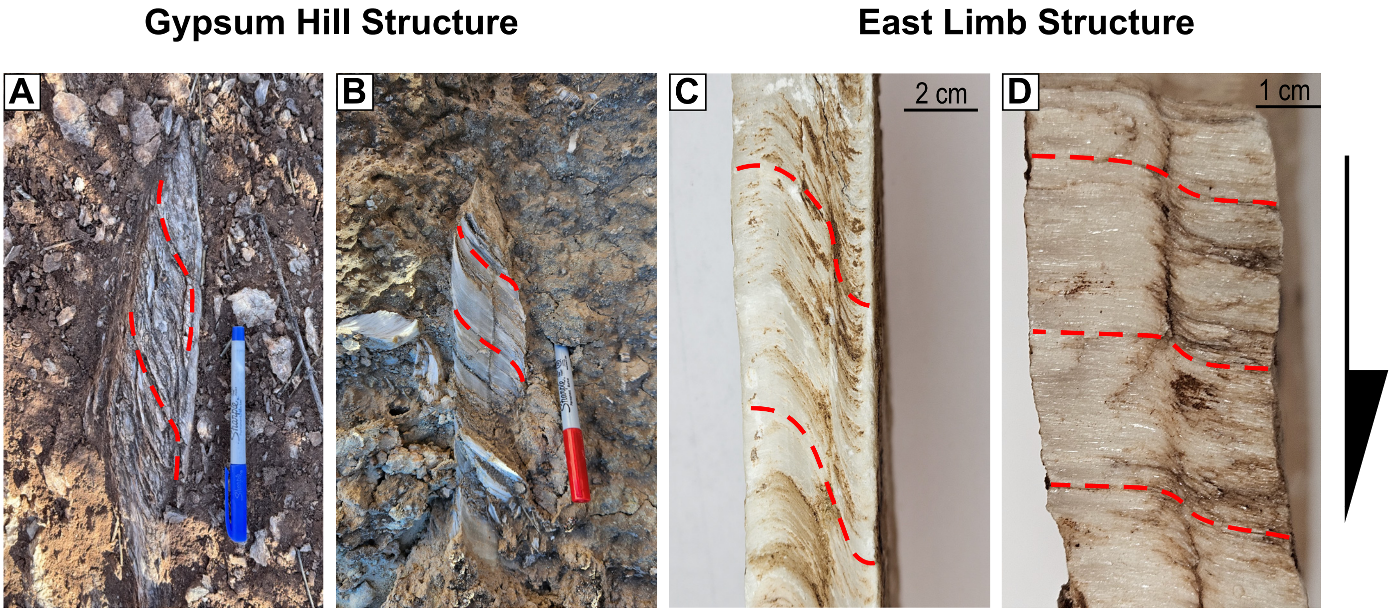

FIGURE 7. Map view of sheared gypsum veins in their present orientation within steeply east-dipping, north-south-striking bedding. Some (A and B) may have grown during dextral strike-slip. Others (C and D) may have formed in flat-lying beds before or early in the growth of the folds because their present fiber orientation indicates east-west opening, which is not compatible with east-west Laramide compression.

and heights to suggest that highest bedrock incision rates on this system of ~300 m/Ma averaged over the past 400–600 ka are recorded by terraces on the nose of the Sierra Nacimiento directly north of and across the Rio Salado from the Tierra Amarilla anticline (Fig. 2).

From these combined data and multiple studies, we propose that multistage beveling of the San Ysidro surface coincided with the long-term Quaternary bedrock incision of the Rio Salado-Rio Jemez system. Further, local high rates of bedrock river incision and extensive landscape erosion of the San Ysidro surface may reflect uplift of the Nacimiento fault block relative to the San Juan Basin to the west (e.g., Formento-Trigilio and Pazzaglia, 1998) and the Rio Grande rift to the east (Reed et al., 2024). These may be shorter-wavelength, fault-influenced,

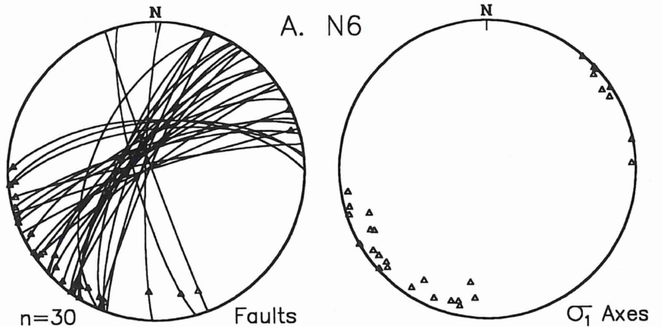

FIGURE 8. Stereonets showing faults (planes as great circles), slickenlines (triangle symbols), and ideal σ_1 axes for the N6 locality, which included minor faults in the Nacimiento and Rio Puerco fault systems, southwest of San Ysidro (Erslev, 2001).

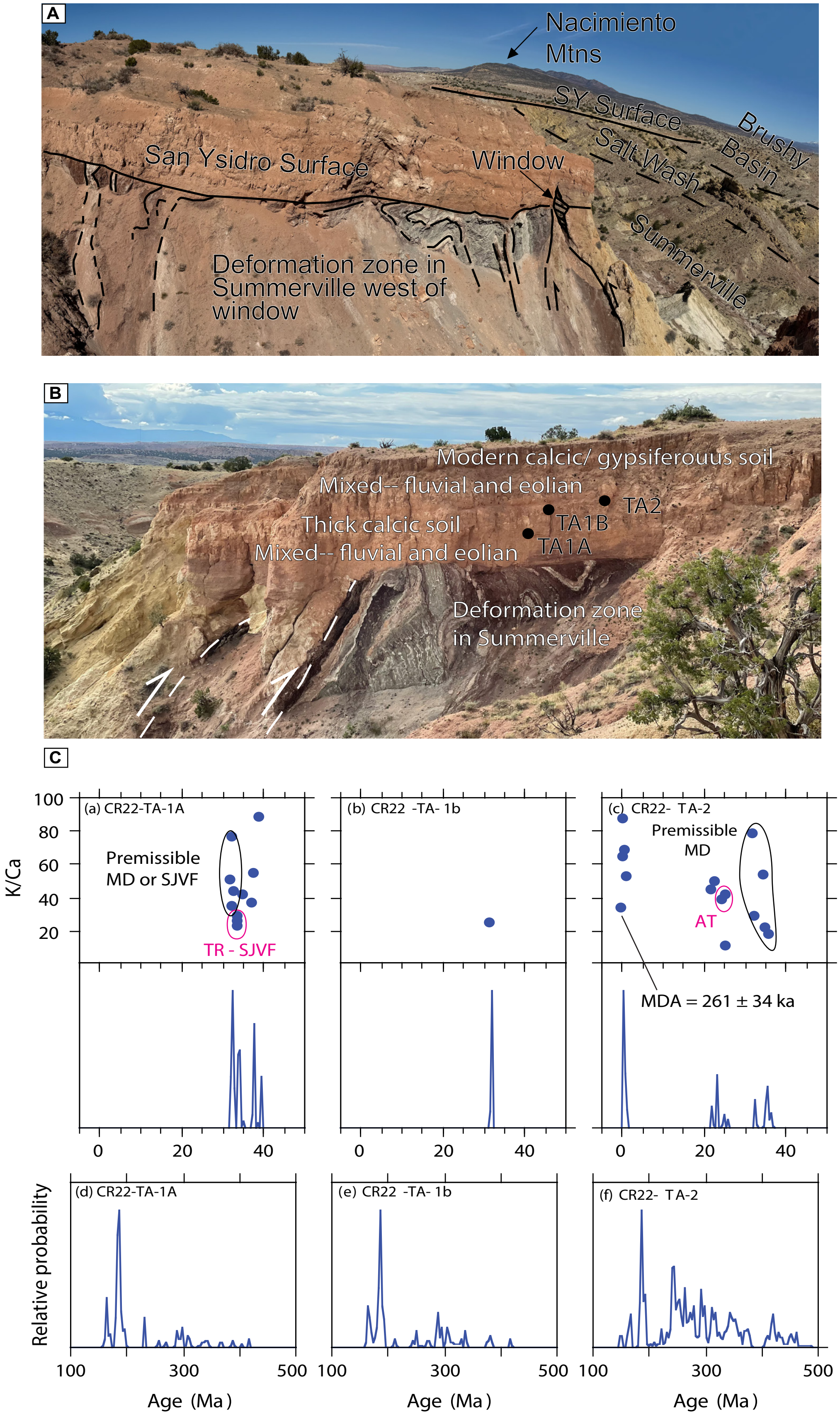

FIGURE 9. Ductile deformation zone in the Jurassic Summerville Formation and associated East Limb fault segment underlying the San Ysidro surface angular unconformity. (A) View to the north toward the Sierra Nacimiento; note the recumbent fold. (B) View to the south. (C) Age probability diagram for the single-crystal sanidine results from the deposits above the San Ysidro surface. The youngest detrital sanidine grain in TA2 constrains the deposits on top of the San Ysidro surface to be ≤261±34 ka.

upper-crustal responses to neotectonic, long-wavelength, mantle-driven epeirogenic uplift of the edges of the Colorado Plateau (Karlstrom et al., 2024).

CONCLUSIONS

This progress report on new mapping of the Tierra Amarilla anticline highlights new directions that require additional work to resolve the structural evolution of the Nacimiento fault zone, which forms parts of the boundary between the Colorado Plateau, Rocky Mountains, and Rio Grande rift. At present, the relative ages of the Laramide east-up reverse faulting, formation of the Tierra Amarilla anticline, strike-slip on the north-south fault segments, formation of syn-tectonic gypsum veins in the fault zones, and conjugate east-west strike-slip faults on the limbs of the fold are incompletely known but are all compatible with progressive regional east-northeast transpression during the Laramide orogeny. The magnitude of dextral strike-slip remains poorly constrained. Laramide structures are in part overprinted by Rio Grande rift–related east-down normal displacement on older Laramide faults.

The Quaternary San Ysidro surface in the Tierra Amarilla anticline area needs to be traced eastward and southward and better correlated with river terraces and surfaces to further understand not only the apparent end of the erosional beveling circa 250–270 Ma but also its earlier history. Our present hypothesis is that the Tierra Amarilla anticline area within the Nacimiento nexus region was part of a more extensive Laramide basement-cored uplift that is now collapsing and merging with the Rio Grande rift. The southern nose of the present Nacimiento uplift and the Tierra Amarilla anticline area may be neotectonically uplifting relative to the San Juan Basin and Rio Grande rift, and both the San Ysidro surface and high bedrock incision rates in the adjacent reach of the Rio Salado may record a component of this uplift.

ACKNOWLEDGMENTS

We acknowledge the generations of field camp and field class student mappers of the San Ysidro anticline area and encourage the next mapping contributions. We thank Adam Read, Tyler Mackey, and Larry Crumpler for reviews that helped improve this paper.

REFERENCES

Baltz, E.H., Jr., 1967, Stratigraphy and regional tectonic implications of part of Upper Cretaceous and Tertiary rocks, east-central San Juan Basin, New Mexico: U.S. Geological Survey Professional Paper 552, 101 p., https://doi.org/10.3133/pp552

Bump, A., 2003, Reactivation, trishear modeling, and folded basement in Laramide uplifts: Implications for the origins of intra-continental faults: GSA Today, v. 13, p. 4, 10.1130/1052-5173(2003)013<0004:RTMAFB>2.0.CO;2

Cather, S.M., 1999, Implications of Jurassic, Cretaceous, and Paleozoic piercing lines for Laramide oblique-slip faulting in New Mexico and rotation of the Colorado Plateau: Geological Society of America Bulletin, v. 111, no. 6, p. 849–868, https://doi.org/10.1130/0016-7606(1999)111<0849:IOJCAP>2.3.CO;2

Cather, S.M., 2004, Laramide orogeny in central and northern New Mexico and southern Colorado, *in* Mack, G.H., and Giles, K.A., eds., The Geology of New Mexico: A Geologic History: New Mexico Geological Society Special Publication 11, p. 203–248.

Cather, S., Karlstrom, K., Timmons, J., and Heizler, M., 2006, Palinspastic reconstruction of Proterozoic basement-related aeromagnetic features in north-central New Mexico: Implications for Mesoproterozoic to late Cenozoic tectonism: Geosphere, v. 2, no. 6, p. 299–323, https://doi.org/10.1130/GES00045.1

Cron, B., Crossey, L.J., Karlstrom, K.E., Polyak, V., Asmerom, Y., and McGibbon, C., 2024, Geochemistry and microbial diversity of CO_2-rich springs and U-series dating of travertine from the Tierra Amarilla anticline, New Mexico, *in* Karlstrom, K.E., Koning, D.J., Lucas, S.G., Iverson, N.A., Crumpler, L.S., Aubele, J.C., Blake, J.M., Goff, F., and Kelley, S.A., eds., Geology of the Nacimiento Mountains and Río Puerco Valley: New Mexico Geological Society Guidebook 74 (this volume), p. 225–235.

Crossey, L.J., et al., 2016, Continental smokers couple mantle degassing and unique microbiology within continents: Earth and Planetary Science Letters, v. 435, p. 22–30, https://doi.org/10.1016/j.epsl.2015.11.039

Erslev, E.A., 2001, Multistage, multidirectional Tertiary shortening and compression in north-central New Mexico: Geological Society of America Bulletin, v. 113, p. 63–74, https://doi.org/10.1130/0016-7606(2001)113<0063:MMTSAC>2.0.CO;2

Formento-Trigilio, M.L., and Pazzaglia, F.J., 1998, Tectonic geomorphology of the Sierra Nacimiento: Traditional and new techniques in assessing long-term landscape evolution in the Southern Rocky Mountains 1: The Journal of Geology, v. 106, p. 433–453, https://doi.org/10.1086/516034

Karlstrom, K.E., and Daniel, C.G., 1993, Restoration of Laramide right-lateral strike-slip in northern New Mexico by using Proterozoic piercing points: Tectonic implications from the Proterozoic to the Cenozoic: Geology, v. 21, p. 1193–1142, https://doi.org/10.1130/0091-7613(1993)021<1139:ROLRLS>2.3.CO;2

Kelley, V.C., 1955, Regional tectonics of the Colorado Plateau and relationships to the origin and distribution of uranium: Albuquerque, University of New Mexico Publications in Geology, no. 5, 120 p.

Kelley, V.C., 1977, Geology of the Albuquerque Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources Memoir 33, 60 p., https://doi.org/10.58799/M-33

Kelley, S.A., Chapin, C.E., and Corrigan, J., 1992, Late Mesozoic to Cenozoic cooling histories of the flanks of the northern and central Rio Grande rift, Colorado and New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 145, 39 p., https://geoinfo.nmt.edu/publications/monographs/bulletins/145/

McGibbon, C., Crossey, L.C., Karlstrom, K.E., and Grulke, T., 2018, Carbonic springs as distal manifestations of geothermal systems, highlighting the importance of fault pathways and hydrochemical mixing: Example from the Jemez Mountains, New Mexico: Applied Geochemistry, v. 98, p. 45–57, https://doi.org/10.1016/j.apgeochem.2018.08.015

Pollock, C.J., Stewart, K.G., Hibbard, J.P., Wallace, L., and Giral, R.A., 2004, Thrust-wedge tectonics and strike-slip faulting in the Sierra Nacimiento, New Mexico, *in* Cather, S.M., McIntosh, W.C., and Kelley, S.A, eds., Tectonics, Geochronology, and Volcanism in the Southern Rocky Mountains and Rio Grande Rift: New Mexico Bureau of Geology and Mineral Resources, Bulletin 160, p. 97–111.

Reed, C., Karlstrom K.E., Rodriguez, B., Iverson, N.A., Heizler, M.T., Rose-Coss, D., Crossey, L.J., Cox, C., Jean, A., Polyak, V.J., and Asmerom, Y., 2024, Differential river incision due to Quaternary faulting on the Río Salado-Jemez system at the million-year timescale, *in* Karlstrom, K.E., Koning, D.J., Lucas, S.G., Iverson, N.A., Crumpler, L.S., Aubele, J.C., Blake, J.M., Goff, F., and Kelley, S.A., eds., Geology of the Nacimiento Mountains and Río Puerco Valley: New Mexico Geological Society Guidebook 74 (this volume), p. 237–256.

U.S. Geological Survey, 2016, Sand Hill fault zone (Class A) No. 2039: Quaternary Fault and Fold Database of the United States, accessed 2024. https://earthquake.usgs.gov/cfusion/qfault/show_report_AB_archive.cfm?fault_id=2039&section_id=

Woodward, L.A., Hultgren, M.C., Crouse, D.L., and Merrick, M.A., 1992, Geometry of the Nacimiento-Gallina fault system, northern New Mexico, *in* Lucas, S.G., Kues, B.S., Williamson, T.E., and Hunt, A.P., eds., San Juan Basin IV: New Mexico Geological Society Guidebook 43, p. 103–108, https://doi.org/10.56577/FFC-43.103

Woodward, L.A., Anderson, O.J., and Lucas, S.G, 1997, Mesozoic stratigraphic constraints on Laramide right slip on the east side of the Colorado Plateau: Geology, v. 25, p. 843–846, https://doi.org/10.1130/0091-7613(1997)025<0843:MSCOLR>2.3.CO;2

Woodward, L.A., Anderson, O.J., and Lucas, S.G., 1999, Late Paleozoic right-slip faults in the Ancestral Rocky Mountains, *in* Pazzaglia, F.J., and Lucas, S.G., eds., Albuquerque Country: New Mexico Geological Society Guidebook 50, p. 149–153, https://doi.org/10.56577/FFC-50.149

Woodward, L.A., and Ruetschilling, R.L., 1976, Geology of San Ysidro Quadrangle, New Mexico: New Mexico Bureau of Mines and Mineral Resources Geologic Map 37, scale 1:24,000, https://doi.org/10.58799/GM-37

High Mound, looking west to Cabezon and Mesa Chivato, with perennial carbonic groundwater at the bottom that is tapped into the Tierra Amarilla spring and fault system. This is the turnaround point for the afternoon hike on the first-day field trip.