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A comparison of sandstone modal composition trends from Early Permian (Wolfcampian) strata of the Abo Formation in the Zuni and Manzano mountains with age-equivalent strata throughout New Mexico

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A COMPARISON OF SANDSTONE MODAL COMPOSITION TRENDS FROM EARLY PERMIAN (WOLFCAMPIAN) STRATA OF THE ABO FORMATION IN THE ZUNI AND MANZANO MOUNTAINS WITH AGE-EQUIVALENT STRATA THROUGHOUT NEW MEXICO

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Abstract—Early Permian (Wolfcampian) nonmarine siliciclastic strata of the Abo Formation and age-equivalent units record exhumation, erosion, and sedimentation associated with the final orogenic phase of the Ancestral Rocky Mountains throughout New Mexico. Sandstone modal composition data and documentation of secondary feldspar alteration (albitization) from these strata are presented here to provide first-order constraint on the provenance and diagenetic changes that occurred during and after these strata were deposited. Overall, compositional trends from this study exhibit elevated occurrences of quartz and feldspar grains with minor lithic fragments (Q–56%, F–42%, L–2%) and are interpreted to have been derived from Precambrian continental-block/basement sources that consisted of the Yavapai, Mazatzal, and Granite-Rhyolite provinces and recycled strata of the Grenville foreland basin (i.e., DeBaca Group of southeastern New Mexico). Strata contain elevated occurrences of plagioclase and K-feldspar grains (Qm–52%, P–35%, K–13%) with isolated sedimentary, volcanic, and metamorphic fragments (Ls–41%, Lv–32%, Lm–27%). There is a noticeable change in the relative abundance of plagioclase and K-feldspar as well as lithic fragments when comparing data from the Zuni and Manzano mountains with samples collected further north with field localities in southern part of the state. Strata in the northernmost field locality exhibit the highest overall percentages of K-feldspar (Qm–48%, P–29%, K–23%) compared with strata in the Zuni and Manzano Mountains (Qm–47%, P–44%, K–9%) and southernmost New Mexico (Qm–63%, P–36%, K–1%). The relative decrease in K-feldspar occurrences from north to south accompanies an increase in the amount and degree of observed K-feldspar albitization. Nearly all K-feldspar grains are partially to completely albitized in all field localities south of the Zuni and Manzano Mountains. Although secondary feldspar alteration trends presented here warrant a more detailed and comprehensive study, K-feldspar replacement and albitization appears to be most pervasive in localities that have the thickest successions of evaporite-rich overburden (i.e., regions south of the Zuni and Manzano Mountains). Evaporative concentrations of salts in these basins could have provided sodium-rich brines that reacted with K-feldspar to produce albite. Albitization may have also occurred due to high heat flow associated with regional-scale tectonic subsidence events (e.g., Sevier and Laramide foreland subsidence, and/or Rio Grande rift subsidence) that buried strata to depths and temperatures that initiated K-feldspar albitization (i.e., ~2000–2500 m and ~60–70°C), or high heat flow associated with igneous activity related to the Rio Grande rift.

INTRODUCTION

The Ancestral Rocky Mountains were marked by thick-skinned, basement-involved, block uplifts that affected much of the south-central and southwestern continental United States during latest Mississippian–Early Permian time (Fig. 1A; e.g., Kluth and Coney, 1981; Ross and Ross, 1985; Kluth, 1986; Algeo et al., 1992; Soreghan, 1992; Devaney and Ingersoll, 1993; Ye et al., 1996; Hoy and Ridgeway, 2002; Barbeau, 2003; Dickinson and Lawton, 2003; Soreghan et al., 2012; Lawton et al., 2017; Leary et al., 2017). By the Early Permian, at least eight basement-cored block uplifts throughout New Mexico were thought to be exposed and possibly still tectonically active (Fig. 1A). Exhumation during this time resulted in some of the largest volume and coarsest fraction of nonmarine siliciclastic sediment associated with the Ancestral Rocky Mountains with strata reaching >1000 m thick in some localities (Kluth and Coney, 1981; Kottlowski, 1960a; Kues and Giles, 2004). It is thought that much of the Early Permian nonmarine strata throughout New Mexico were sourced primarily from the Uncompahgre uplift in southwestern Colorado and northern New Mexico and were transported southward to the Early Permian paleoshoreline (Fig. 1A; e.g., Mack and James, 1986; Mack et al., 2003a; Kues and Giles, 2004). The Pedernal and Sierra Grande uplifts may have also contributed detritus to nonmarine systems during this time (Fig. 1A; Kluth and Coney, 1981; Kues and Giles, 2004).

By the end of the Early Permian, clastic and carbonate strata onlapped and covered nearly all basement uplifts in New Mexico with the exception of parts of the Pedernal uplift (Kelley, 1971; Kottlowski, 1985; Kluth, 1986; Mack, 2003b). Ancestral Rocky Mountain orogenesis in New Mexico is thought to have terminated by Leonardian time, and the stratigraphic record of this transition is preserved primarily by marginal marine-dominated strata of the gypsum-rich Yeso Formation, wind-blown eolian sandstone of the Glorieta Formation, and limestone and gypsum-rich strata of the San Andres Formation (e.g., Kottlowski, 1985; Mack and Dinterman, 2002; Mack et al., 2003b).

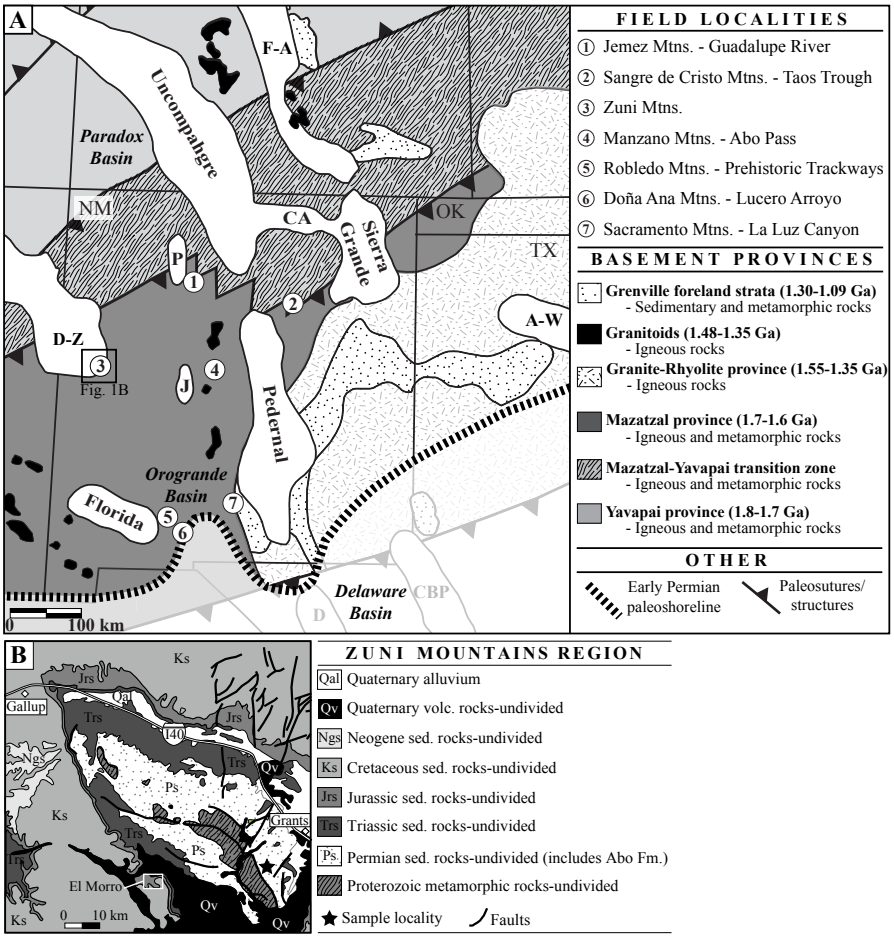


FIGURE 1. **A**) Early Permian (Wolfcampian) paleogeography and Precambrian province map of the southwestern U.S. with emphasis on late Paleozoic Ancestral Rocky Mountain (ARM) basement uplifts and adjacent basins in New Mexico and Colorado. Basement provinces and ages are from Karlstrom et al. (2004),Whitmeyer and Karlstrom (2007), and Mulder et al. (2017). Approximate location of ARM basement uplifts (gray pattern) from Kluth and Coney (1981), Ross and Ross (1985), Ye et al. (1996), Baltz and Myers (1999), Soreghan et al. (2012), and Leary et al. (2017). Abbreviated ARM basement uplifts include Peñasco (P), Joyita (J), Cimarron Arch (CA), Diablo (D), Central Basin Platform (CBP), and Amarillo-Wichita (A-W) uplifts. White circles denote project field localities for this study in northern, central, and southern New Mexico. **B**) Generalized geologic map of the Zuni Mountains region near Grants, New Mexico. Star denotes sample locality just east of El Morro National Monument. Modified from the New Mexico Bureau of Geology and Mineral Resources (NMBGMR) (2003) database and Kelley (2003).

The focus of this study is the provenance and secondary feldspar alteration trends of Early Permian (Wolfcampian), the coarse- to fine-grained, nonmarine, synorogenic strata of the Abo Formation in the Zuni and Manzano Mountains and age-equivalent nonmarine strata that crop out throughout New Mexico to the north and south. Presented here are new sandstone modal composition data and documentation of minor to extensive occurrences of secondary feldspar albitization from seven field localities from throughout New Mexico (Figs. 1A, 2). New provenance data and albitization trends from these strata provide first-order constraints on bedrock source areas that contributed detritus to Early Permian sedimentary basins and also provide insight into post-depositional diagenetic alteration that took place after erosion and sedimentation associated with the Ancestral Rocky Mountains.

FIELD LOCALITIES AND STRATIGRAPHY OF INTEREST

A total of seven field localities from across New Mexico were selected for this study and include sites in the Zuni and Manzano Mountains where nonmarine channel strata are exposed (Figs. 1A, 2). A summary of each field locality can be found in the online Data Repository (http://nmgs.nmt.edu/repository). The following text provides a general stratigraphic overview at each field locality and is presented in geographic order from north to south in New Mexico to provide a proximal-to-distal, source-to-sink context for south-flowing Early Permian (Wolfcampian) fluvial systems.

Northern New Mexico – Jemez and Sangre de Cristo Mountains

Early Permian (Wolfcampian) nonmarine strata of interest in north-central and northeastern New Mexico include (1) the Abo Formation in the Guadalupe River valley of the southwestern Jemez Mountains (Figs. 1A, 2) and (2) the Sangre de Cristo Formation in the Taos Trough of the southern Sangre de Cristo Mountains (Figs. 1A, 2). The Abo Formation in the Guadalupe River region ranges from 150–190 m thick (Lucas et al., 2013) and consists primarily of interbedded fine- to medium-grained massive and cross-stratified sandstone and massive and laminated siltstone (Figs. 2, 3A). Age-equivalent strata of the Sangre de Cristo Formation in the Taos Trough are characterized by interbedded clast-supported conglomerate, fine- to coarse-grained cross-stratified sandstone, and massive to laminated mudstone (Figs. 2, 3B) with an overall thickness that ranges considerably from 55–900 m (e.g., Soegaard and Caldwell, 1990; Baltz and Myers, 1999).

Central New Mexico – Zuni and Manzano Mountains

Two field localities in central and west-central New Mexico include the southeastern margin of the Zuni Mountains southwest of Grants (and due east of El Morro National Monument; Figs. 1B, 2) and the Abo Pass field locality in the southern Manzano Mountains (Figs. 1A, 2). In both localities, the Abo Formation consists primarily of interbedded fine- to medium-grained, massive and cross-stratified sandstone and massive and laminated mudstone (Figs. 2, 3C, D). In the Zuni Mountains, the Abo Formation ranges from 180–215 m

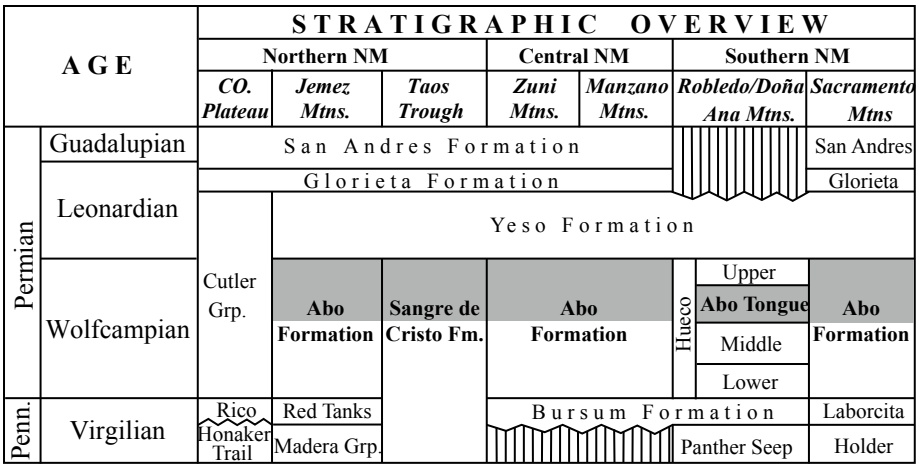


FIGURE 2. Generalized summary of Late Pennsylvanian and Early Permian stratigraphy throughout New Mexico. Stratigraphic interval of interest (shaded gray) includes the upper Abo and Sangre de Cristo Formations as well as the Abo Tongue of the Hueco Formation. Stratigraphy from Seager et al., (1976), Mack and James (1986), Mack et al. (1998), Kues and Giles (2004), Lucas et al. (2005) and Lucas et al. (2013).

thick and directly overlies Precambrian basement of the Defiance-Zuni uplift (Fig.1; Mack et al., 1998). The Abo in the Manzano Mountains is approximately 300 m thick (Lucas et al., 2013).

Southern New Mexico – Robledo, Doña Ana, and Sacramento Mountains

Early Permian (Wolfcampian) nonmarine strata of interest in south-central New Mexico include (1) siliciclastic portions of the Hueco Formation (Abo Tongue) near the Prehistoric Trackways National Monument along the eastern margin of the Robledo Mountains and in Lucero Arroyo along the western margin of the Doña Ana Mountains (Figs. 1A, 2), as well as (2) the Abo Formation near La Luz Canyon along the southwestern margin of the Sacramento Mountains (Figs. 1A, 2). Note that we use combined stratigraphic nomenclature from Kottlowski (1960a, 1960b, 1963) and Jordan (1971, 1975) when referencing Hueco-equivalent strata in the Robledo and Doña Ana Mountains (Fig. 2) and nomenclature from Pray (1961) for Wolfcampian strata in the southwestern Sacramento Mountains (i.e., Abo Formation; Fig. 2).

The coarsest nonmarine portions of the Abo Tongue in the Robledo and Doña Ana Mountains consist primarily of massive, laminated, ripple- and trough-cross stratified sandy siltstone and claystone (Figs. 2, 3E). In both the Robledo and Doña Ana Mountains, the Abo ranges from 120–300 m thick, and thins southward to 60–150 m where it is interbedded with Wolfcampian marine limestone units of the Hueco Formation (Needham and Bates, 1943; Mack et al., 1998, 2003b; Lucas et al., 2013). The coarsest parts of the Abo Formation in the Sacramento Mountains are characterized by interbedded, clast-supported conglomerate and medium- to coarse-grained cross-stratified sandstone (Figs. 2, 3F). Individual clasts consist primarily of quartzite and granite (Pray, 1961; Malone et al., 2017), and the thickness of the Abo in the Sacramento Mountains ranges from 80–335 m thick (Otte, 1959; Pray, 1961).

SANDSTONE MODAL COMPOSITION

Petrographic and compositional data were obtained from 16 sandstone samples (n=6400 grain counts) collected from Early Permian (Wolfcampian) nonmarine strata from seven field localities (Figs. 1A, 2). Samples were collected from the coarsest sand-size fraction preserved in fluvial-channel architectural elements at each field locality. Standard petrographic thin sections were cut and stained for plagioclase and potassium feldspar (K-feldspar). Thin sections were analyzed according to the modified Gazzi-Dickinson point-counting methods (Dickinson, 1970; Ingersoll et al., 1984). Modal composition was determined by identifying 400 grains from each thin section. Table 1 provides a summary of parameters used for sandstone point counts. A summary of all raw and recalculated point-count data collected from this study can be found in the online Data Repository (http://nmgs.nmt.edu/repository). Recalculated data are based on procedures defined by Ingersoll et al. (1984) and Dickinson (1985).

Overall, the modal composition of Early Permian (Wolfcampian) strata from throughout New Mexico is characterized by

Table 1. Summary of grain parameters for sandstone point counts.

Quartz (Q) = Qm + Qp + chert
- Monocrystalline quartz (Qm)
- Polycrystalline quartz (Qp)
- Chert (C)
Feldspar (F) = P + K
- Plagioclase (P)
- Potassium feldspar (K)
Lithic fragments (L) = Ls + Lm + Lv
- Lithic sedimentary (Ls)
- *Mudstone (Lsm)*
- *Sandstone (Lss)*
- *Limestone - micrite (Lslm)*
- *Limestone - non-micrite (Lsl)*
- Lithic metamorphic (Lm)
- *Phyllite (Lmp)*
- *Schist (Lms)*
- *Quartzite (Lmq)*
- *Gneiss (Lmg)*
- Lithic volcanic (Lv)
Lt = Ls + Lm + Lv + Qp + chert

*Grains of calcite, mica, and dense minerals also included in point-count totals

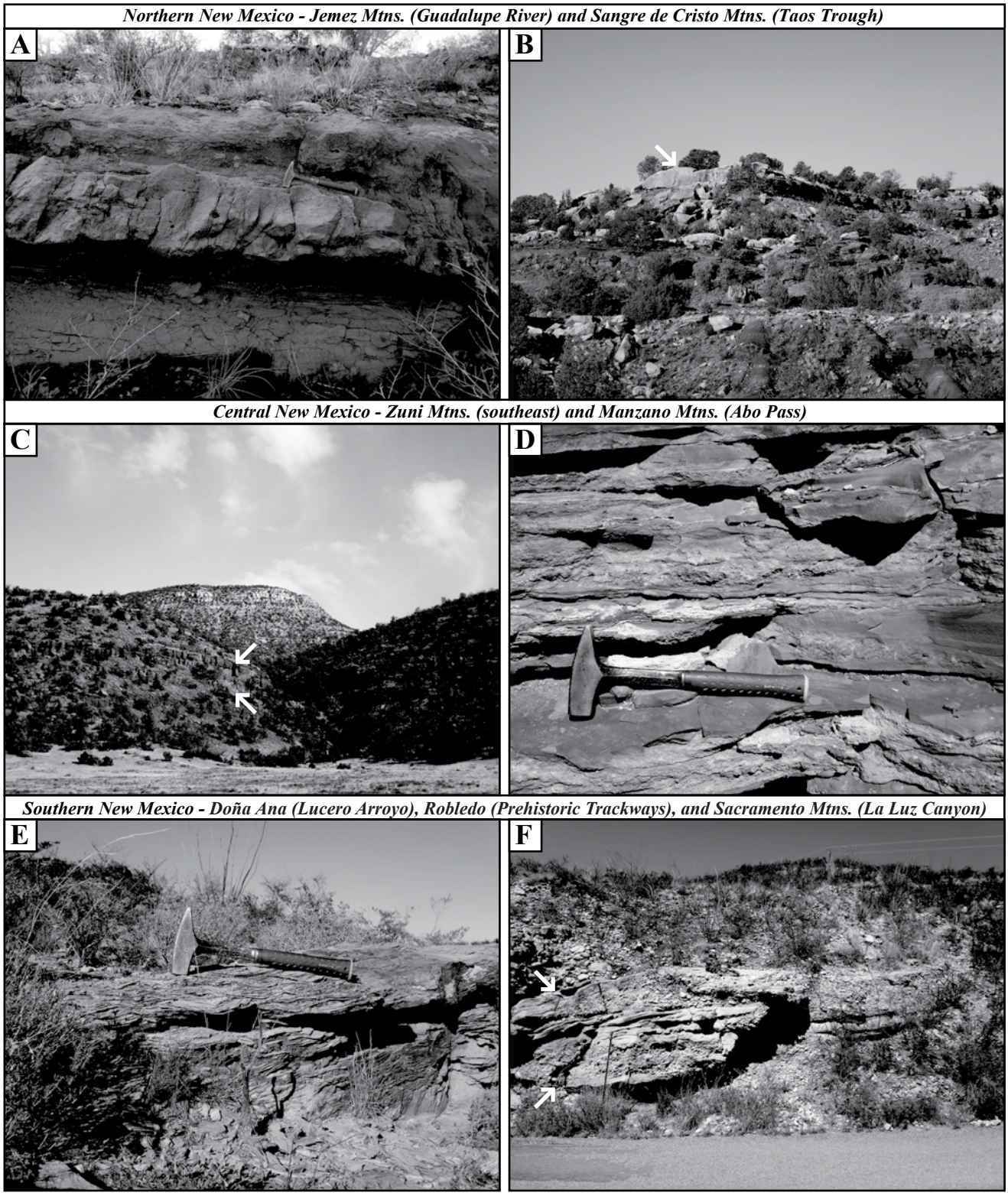


FIGURE 3. Field outcrop photos of nonmarine portions of the Abo, Hueco, and Sangre de Cristo Formations. **A**) Interbedded sandstone and siltstone of the Abo Formation in the southwestern Jemez Mountains (Guadalupe River region). Rock hammer for scale. **B**) Tabular and lenticular sandstone and mudstone deposits of the Sangre de Cristo Formation in the southern Sangre de Cristo Mountains (Taos Trough). White arrow denotes a channel sandstone unit that is 2–3 m thick. **C**) View to the north of the Abo Formation and gypsum-rich beds of the overlying Yeso Formation in the Zuni Mountains of west-central New Mexico. White arrows show base and top of a 2.5-m-thick sandstone. **D**) Thin, tabular beds of siltstone and fine-grained sandstone that make up the Abo Formation near Abo Pass in the Manzano Mountains (rock hammer for scale). **E**) Ripple-cross stratified siltstone and very fine-grained nonmarine sandstone of the Hueco Formation at Lucero Arroyo in the Doña Ana Mountains of southern New Mexico (rock hammer for scale). **F**) Lenticular bed made up primarily of clast-supported cobble-conglomerate in the southern Sacramento Mountains. White arrows show base and top of a~2.5-m-thick channel conglomerate.

predominantly quartz and feldspar with minor occurrences of lithic fragments (Q–56%, F–42%, L–2%; Figs. 4, 5, 6). Quartz grains consist of monocrystalline quartz (Qm) and polycrystalline quartz (Qp) with monocrystalline quartz being the most common constituent (Fig. 4). The feldspar population is made up largely of plagioclase (P) but does have a significant amount of K-feldspar (K; Qm–52%, P–35%, K–13%; Figs. 5A, B, 6). Lithic grains, in order of decreasing occurrences, consist of lithic sedimentary (Ls), lithic volcanic (Lv) and lithic metamorphic (Lm; Ls–41%, Lv–32%, Lm–27%; Figs. 4A, C, 5B, 6). Lithic sedimentary fragments consist of sandstone, mudstone (Fig. 4A), and limestone (micrite) grains. Lithic volcanic grains consist primarily of fragments with microphenocrysts of quartz and feldspar (Fig. 4B). The most common lithic metamorphic fragments are gneiss with subordinate occurrences of quartzite, schist, and phyllite (Fig. 4C). Calcite makes up ~3% of total grains counted whereas mica and dense mineral fragments make up ~1% of all grains counted.

Based on Q-F-L percentages, nearly all samples plot in the arkose field of Folk (1968) with the exception of southern samples from the Abo Formation in the Sacramento Mountains plotting in the subarkose field and a second southern sample from the Hueco Formation plotting in the quartzarenite field (Fig. 6). Similarly, all samples plot either in the Transitional-Continental or Basement-Uplift province of Dickinson et al. (1983) except for two samples from the Jemez Mountains of northern New Mexico and the two previously mentioned southern samples. These samples plot in the Craton (Q-F-L) or Quartzose Recycled (Qm-F-Lt) province fields of Dickinson et al. (1983), near the end of the path of increasing maturity from the Continental Block province (Qm-F-Lt). The following text provides a summary comparison of modal composition trends from Early Permian (Wolfcampian) strata from field localities in northern, central, and southern New Mexico.

Northern New Mexico – Abo Formation and Sangre de Cristo Formation

The Abo Formation in the Guadalupe River valley of the southwestern Jemez Mountains is characterized by elevated occurrences of quartz and feldspar (Fig. 6; Q–56%, F–43%, L–1%) with K-feldspar and monocrystalline quartz making up the highest percentage of total feldspar and quartz grains (Fig. 6; Qm–49%, P–22%, K–29%). Lithic fragments are dominated by metamorphic and volcanic grains (Fig. 6; Lv–48%, Lm–52%, Ls–0%). Calcite and mica grains make up ~9% and ~0.5% of total occurrences, respectively. To the east, the Sangre de Cristo Formation in the Taos Trough of the southern Sangre de Cristo Mountains is also dominated by occurrences of feldspar and quartz (Fig. 6; Q–48%, F–51%, L–1%) with monocrystalline quartz and plagioclase making up the highest quartz and feldspar percentages (Fig. 6; Qm–47%, P–44%, K–9%). Here, lithic grains consist largely of volcanic and sedimentary fragments (entirely micrite) and subordinate metamorphic fragments (Fig. 6; Lv–46%, Lm–17%, Ls–37%). Calcite and mica grains make up ~0.1% and ~0.5% of total grain occurrences, respectively.

Average relative feldspar percentages from the Abo Formation in the Guadalupe River valley of the southwestern Jemez Mountains total 51% with K-feldspar making up 29% (Fig. 6; Qm–49%, P–22%, K–29%). Samples from this field locality have the highest relative percentage of K-feldspar in this study and there is no evidence of any secondary textures or albitization of feldspar. The Sangre de Cristo Formation in the Taos Trough has an average relative feldspar of 44% with K-feldspar making up 9% (Fig. 6; Qm–47%, P–44%, K–9%). Worm-like vermicules (i.e., myrmekitic textures) are rare but do occur in isolated plagioclase grains and appear as irregular intergrowths of quartz in a single grain of plagioclase (Fig. 7A). Some plagioclase and K-feldspar from these samples show textural signs of partial to complete albitization with minor occurrence of red-brown Fe-oxide typical of albite alteration (Figs. 4C, 7B).

Central New Mexico – Abo Formation

The Abo Formation which crops out along the southeastern margin of the Zuni Mountains is made up primarily of feldspar and quartz (Fig. 6; Q–48%, F–50%, L–2%) with plagioclase and monocrystalline quartz making up the highest percentages of overall feldspar and quartz grains (Fig. 6; Qm–45% P–43% K–12%). Lithic grains consist entirely of metamorphic and volcanic fragments (Fig. 6; Lv–37%, Lm–63%, Ls–0%). There are no occurrences of calcite grains in these samples and mica makes up ~3% of total occurrences. To the east, the Abo Formation in the Abo Pass field locality of the southern Manzano Mountains is dominated by quartz and feldspar (Fig. 6; Q–53%, F–43%, L–4%) with monocrystalline quartz and plagioclase making up the highest percentages of total quartz and feldspar (Fig. 6; Qm–54%, P–46%, K–0%). Lithic fragments consist entirely of lithic sedimentary grains of micrite (Fig. 6; Lv–0%, Lm–0%, Ls–100%). Calcite and mica grains make up ~2% and ~0.25% of total grain occurrences, respectively.

Relative total feldspar from the Abo Formation in the Zuni Mountains is 55% with K-feldspar making up 12% (Fig. 6; Qm–45%, P–43%, K–12%). No granophyric or myrmekitic textures were observed in feldspars from these samples, but there is textural evidence on both plagioclase and K-feldspar grains of minor secondary albite alteration. Relative feldspar percentages from the Abo Formation in the Abo Pass field locality of the southern Manzano Mountains total 46% with plagioclase making up 100% of all feldspar grains (Fig. 6; Qm–54%, P–46%, K–0%). Feldspars exhibit minor secondary albitization, but no granophyric or myrmekitic textures were observed.

Southern New Mexico – Hueco Formation (Abo Tongue) and Abo Formation

Nonmarine portions of the Hueco Formation ("Abo Tongue"), which crops out along the eastern margin of the Robledo Mountains and in Lucero Arroyo along the western margin of the Doña Ana Mountains, consists primarily of quartz, subordinate feldspar, and rare lithic fragments (Fig. 6; Q–76%,

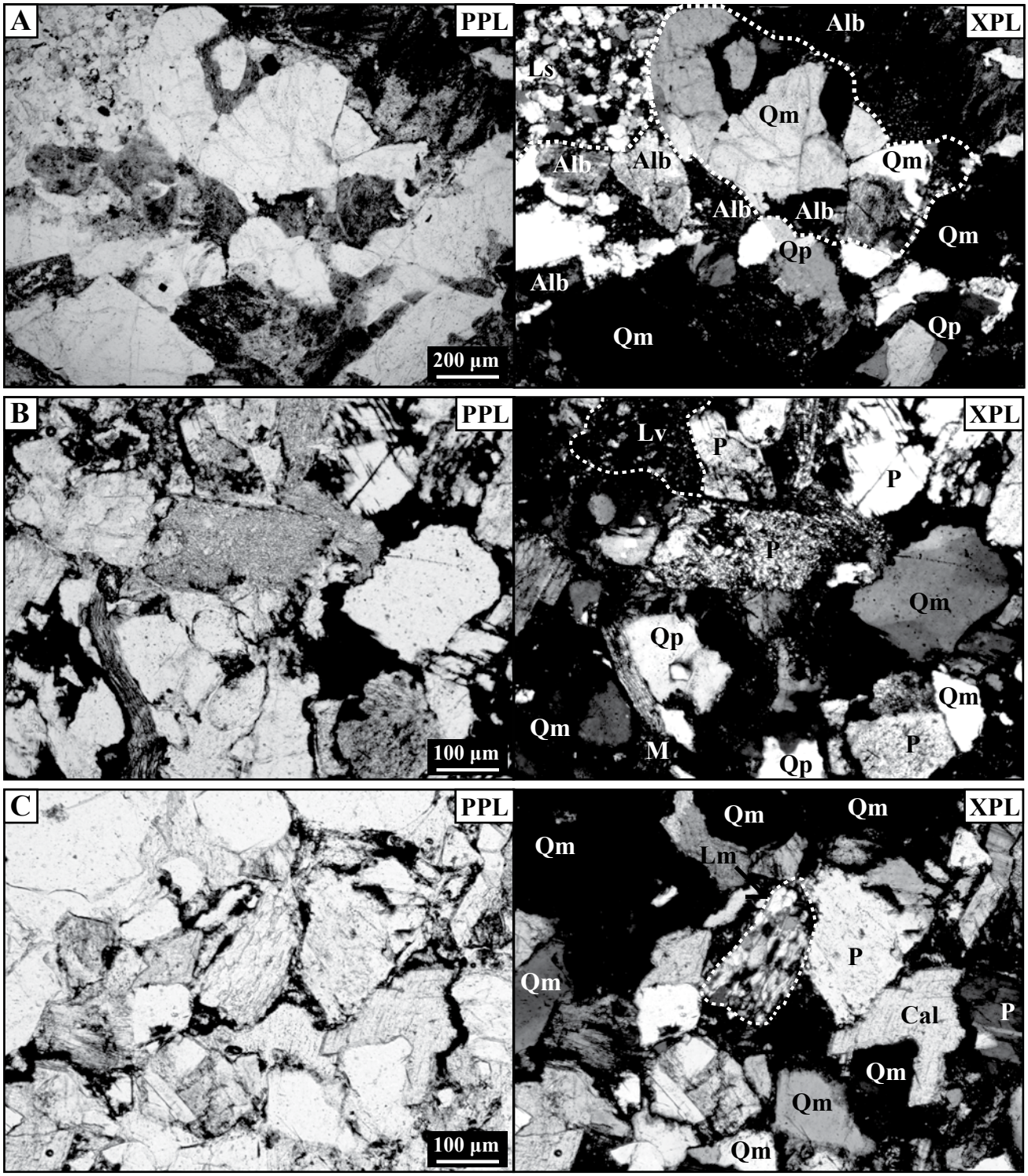


FIGURE 4. Photomicrographs of Early Permian, nonmarine sandstone with plane-polarized light (PPL) view on the left and identical polarized (XPL) view on the right. Dashed lines depict grain boundaries. **A**) Monocrystalline quartz (Qm), polycrystalline quartz (Qp), lithic sedimentary fragments (Ls), and albitized feldspar (Alb) from southern New Mexico. **B**) Monocrystalline quartz (Qm), polycrystalline quartz (Qp), lithic volcanic fragments (Lv), plagioclase (P), and biotite mica (M) from northern New Mexico. **C**) Monocrystalline quartz (Qm), metamorphic fragments (Lm), plagioclase (P), and calcite grains (Cal.) from northern New Mexico.

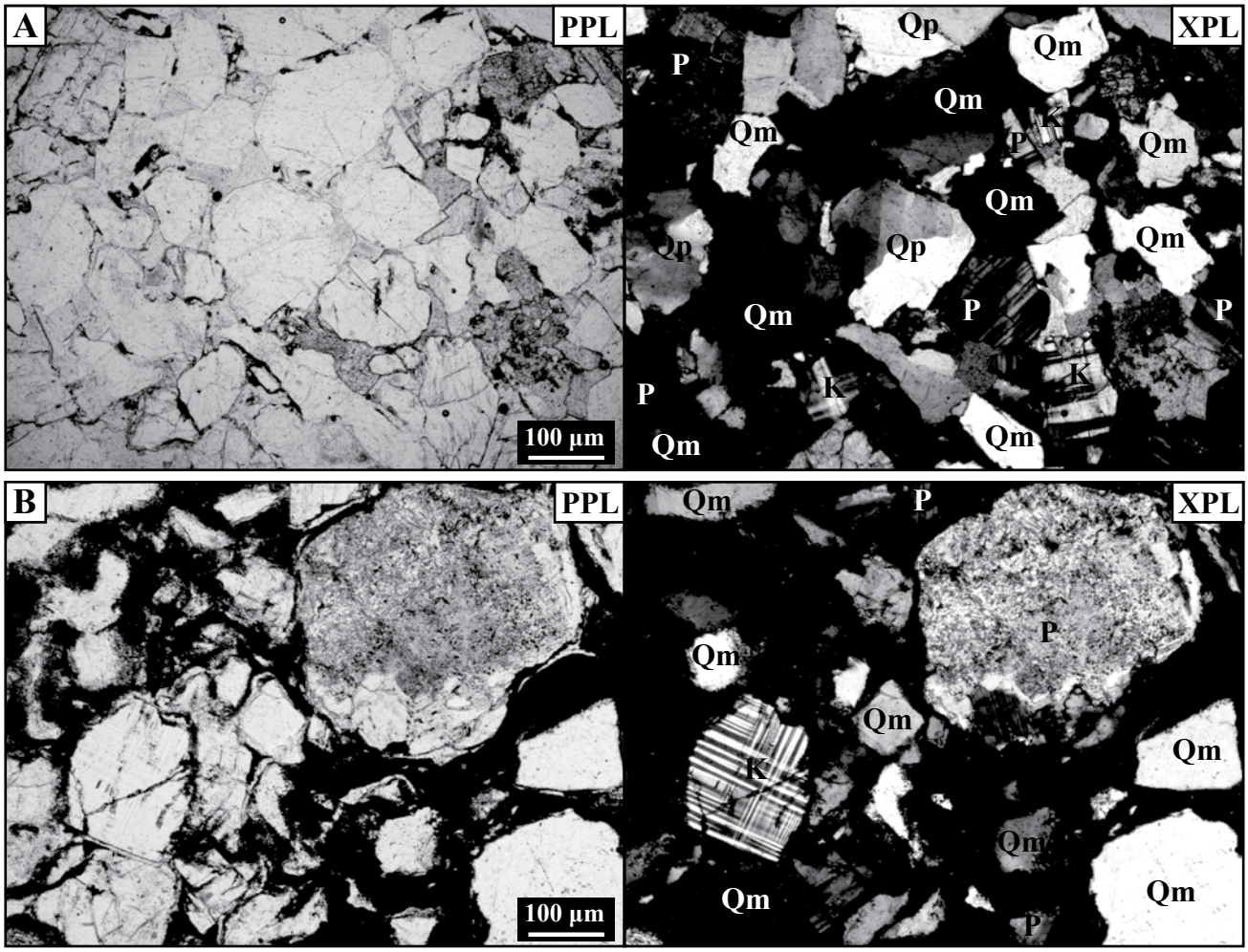


FIGURE 5. Photomicrographs of Early Permian, nonmarine sandstone from northern New Mexico with plane-polarized light view on the left and identical cross-polarized view on the right. **A**) Monocrystalline quartz (Qm), plagioclase (P), and K-feldspar (K) from northern New Mexico. **B**) Monocrystalline quartz (Qm), plagioclase (P), and microcline K-feldspar (K) from northern New Mexico.

F–23%, L–1%). Monocrystalline quartz makes up the majority of quartz grains and plagioclase makes up all feldspar grains (Fig. 6; Qm–76%, P–24%, K–0%). Lithic fragments consist of sedimentary and volcanic grains (Fig. 6; Lv–33%, Lm–0%, Ls–67%) with sandstone and siltstone making up ~63% of total lithic sedimentary fragments and micrite making up the other ~37%. Calcite and mica grains make up ~1% and just over 0.5% of total grain occurrences, respectively. The Abo Formation near La Luz Canyon along the southwestern margin of the Sacramento Mountains is characterized by elevated occurrences of quartz and feldspar and subordinate lithic fragments (Fig. 6; Q–57%, F–38%, L–5%) with monocrystalline quartz and plagioclase making up the majority of quartz and feldspar percentages (Fig. 6; Qm–54%, P–45%, K–1%). Lithic fragments are dominated by lithic sedimentary grains (Fig. 6; Lv–10%, Lm–2%, Ls–88%), of which sandstone and siltstone make up ~70% of total lithic sedimentary fragments and micrite makes up the other ~30%. Calcite makes up ~0.5% of total grain occurrences and there are no documented occurrences of mica.

Average relative feldspar percentages from nonmarine portions of the Hueco Formation in the Robledo Mountains and Doña Ana Mountains are the lowest in this study at 24% with plagioclase making up all feldspar grains (Fig. 6; Qm–76%, P–24%, K–0%). No granophyric or myrmekitic textures were observed in feldspars, but albite alteration is common and pervasive throughout these samples. Total relative feldspar percentages from the Abo Formation near La Luz Canyon along the southwestern margin of the Sacramento Mountains are 46% with K-feldspar only making up 1% (Fig. 6; Qm–54%, P–45%, K–1%). Nearly all plagioclase and K-feldspar grains from these samples exhibit albite-replacement textures with occurrences of Fe-oxide, and in some cases, albite overgrowths and cementation (Fig. 7B). Myrmekitic textures as well as fine-grained granophyric intergrowths of quartz on isolated feldspar grains (Fig. 7C) do occur but are rare.

DISCUSSION AND CONCLUSIONS

Spatial trends in sandstone modal composition and feldspar alteration from Early Permian (Wolfcampian) nonmarine strata of the Abo Formation in the Zuni and Manzano Mountains and age-equivalent strata from around New Mexico provide an op-

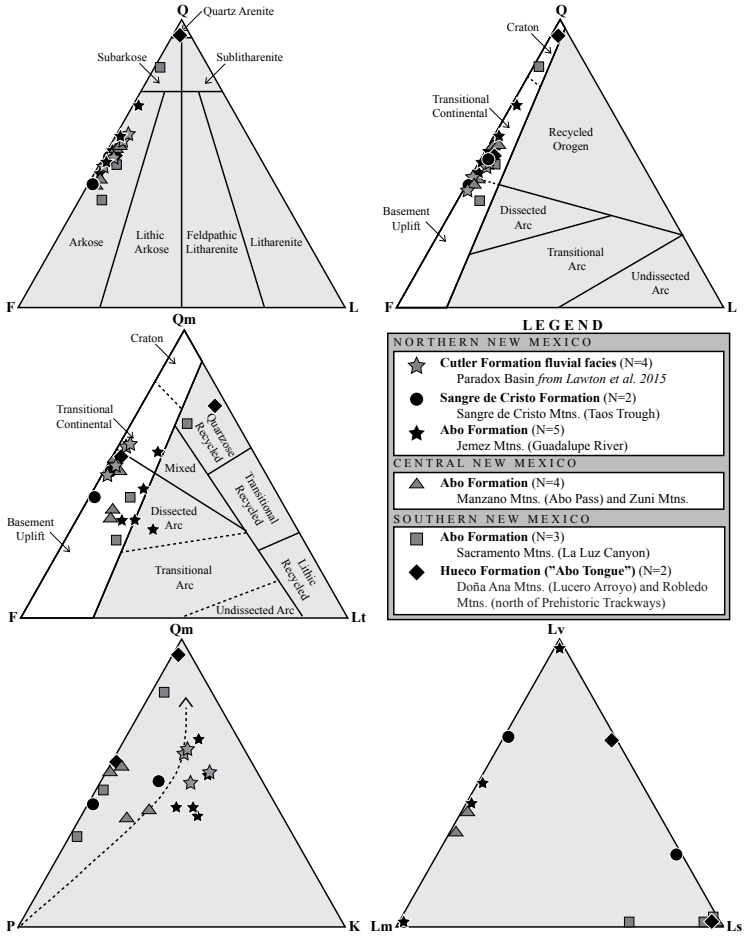


FIGURE 6. Q-F-L, Qm-F-Lt, Qm-P-K, and Lv-Lm-Ls ternary diagram plots for Early Permian, nonmarine strata from throughout New Mexico. Sandstone fields from Folk (1968) and provenance fields after Dickinson et al. (1983). Dashed line on Qm-P-K diagram reflects path of increasing sandstone maturity.

portunity to better constrain primary, original source provinces that shed detritus during the final phase of the Ancestral Rocky Mountain orogenesis in New Mexico, as well as diagenetic changes that took place after sedimentation. New data from this study support an interpretation wherein these strata were derived largely from a combination of basement-uplift, transitional-continental, and cratonic provinces (Fig. 6; Dickinson et al., 1983).

Elevated occurrences of feldspar, lithic volcanic and lithic metamorphic fragments, and mica in the Zuni Mountains and throughout central and northern New Mexico are interpreted to reflect detrital contributions from igneous and metamorphic basement rocks derived from the southern margin of the Uncompahgre basement uplift, and likely a combination of the Uncompahgre, Sierra Grande, and northern Pedernal uplift (e.g., Yavapai, Mazatzal, and Granite-Rhyolite provinces; Fig. 1A). Similar compositional trends have been reported from the Cutler Formation (Abo Formation equivalent; Fig. 2) of the Paradox basin in southwestern Colorado where the Cutler crops out proximal to rocks of the Uncompahgre uplift (Figs. 1A, 2, 6; Lawton et al., 2015). he Defiance-Zuni uplift was apparently not a major contributor of detritus given the fine-grained nature of the Abo directly adjacent to this uplift in the Zuni Mountains, rather than coarser, less texturally mature sediments expected closer to the source (Fig. 1B).

The Abo Formation and equivalent nonmarine strata in southern New Mexico contain variable proportions of feldspar and predominantly lithic sedimentary fragments consisting of mudstone, sandstone, and micrite with pedogenic floodplain origins. Isolated, fine-grained stratigraphic intervals with low occurrences of feldspar and elevated occurrences of quartz in the Robledo Mountains are interpreted to represent the distal-most fluvial systems that originated from the southern margin of the Uncompahgre and possibly the western margin of the Pedernal uplift (e.g., Yavapai, Mazatzal, Granite-Rhyolite, and Grenville foreland provinces; Fig. 1A). Strata in the Doña Ana and Sacramento Mountains were likely derived primarily from the western margin of the Pedernal uplift (e.g., Mazatzal, Granite-Rhyolite, and overlying, younger strata of the Grenville foreland provinces – DeBaca Group of southeastern New Mexico) and possibly the southern margin of the Uncompahgre and Sierra Grande basement uplifts (e.g., Yavapai, Mazatzal, and Granite-Rhyolite provinces; Fig. 1A).

Secondary alteration textures observed in this study include partial seritization reflecting normal breakdown of feldspar and widespread partial to complete secondary albitization of K-feldspar grains (Fig. 7B). Albitization increases considerably (at the expense of K-feldspar percentages) from north to south with the most extreme examples occurring in the southernmost field localities. Myrmekitic and granophyric textures observed in this study (Figs. 7A, C) are interpreted to reflect primary, original textures in basement source areas that formed prior to erosion and sedimentation. Although secondary albitization of K-feldspar grains does affect sandstone modal composition trends when comparing percentages of plagioclase and K-feldspar grains, it does not change the overall interpretation of these strata being derived from cratonic, transitional-continental, and basement-uplift source areas. It does, however, shed light on potential secondary processes that affected these strata after deposition. Although interpreting the exact timing and mechanisms responsible for secondary albitization in Early Permian nonmarine clastic strata throughout New Mexico is beyond the scope of this study, we do offer a brief review of potential drivers that could have played a role in influencing feldspar occurrence and albitization.

Secondary albitization is common during diagenesis of felsic, arkosic sedimentary strata (e.g., Boles, 1982; Walker, 1984; Gold, 1987; Saigal et al., 1988; Aagaard et al., 1990; Morad et al., 1990; Ramseyer et al., 1992; Parsons et al., 2005) and often involves the process of sodium metasomatism. Where felsic sedimentary strata react with available saline fluids, silt- and sand-size K-feldspar and plagioclase are partially to completely replaced by albite at a range of basin depth and temperature conditions (e.g., Land and Milliken, 1981; Boles, 1982; Walker, 1984; Land, 1984; Land and Fisher, 1987; Saigal et

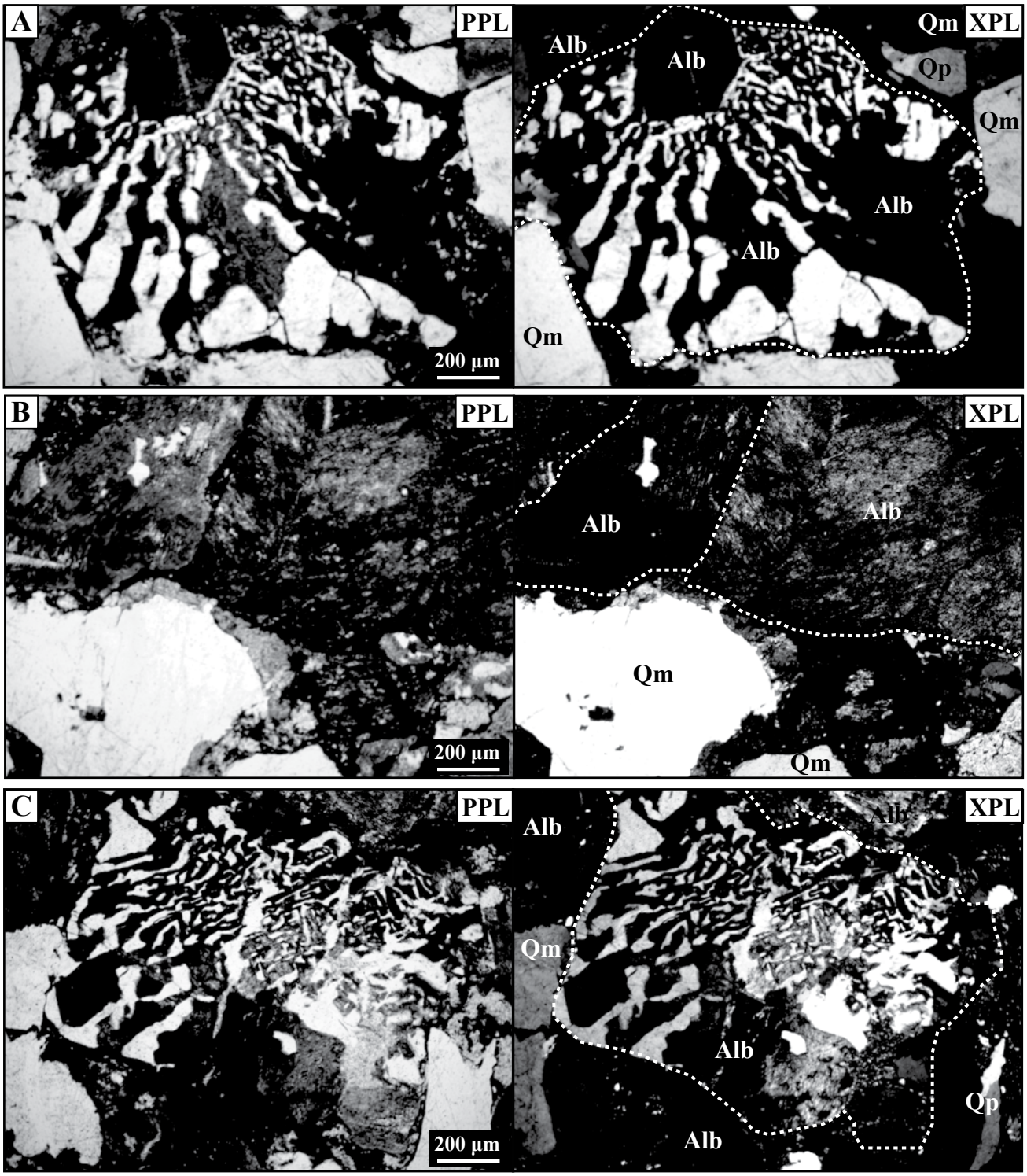


FIGURE 7. Photomicrographs of Early Permian, nonmarine sandstone from southern New Mexico with plane-polarized light view on the left and identical cross-polarized view on the right. Dashed lines depict grain boundaries. **A**) Rare, worm-like vermicules (i.e., myrmekitic textures) on quartz and albitized feldspar grains (Alb). **B**) Pervasive albite-replacement textures including albite overgrowths and cementation. **C**) Rare granophyric textures on quartz and albitized feldspar.

al., 1988; Gold, 1987). At the surface and at shallower basin depths, evaporative concentration of salts in the groundwater of a closed basin will yield Na-rich brines that can react with detrital silicates to develop authigenic albite. At depth, the onset of albitization of K-feldspar occurs around 60–70°C (near depths of ~2500 m) when formation waters transition out of the stability field of K-feldspar and begin to approach the stability field of albite (Aagaard et al., 1990).

During early-middle Leonardian–early Guadalupian time, much of southern, east-central, and northeastern New Mexico

experienced a marine transgression that is recorded by shelf and marginal marine, sandy-sabkha, and lagoon-evaporite strata of the lower to middle Yeso Formation and equivalent units, (e.g., Mack and Dinterman, 2002), nonmarine, eolian strata of the Glorieta Formation, and shelf carbonate strata of the interfingering and mostly overlying San Andres Formation (e.g., Kelley and Wood, 1946; Baltz, 1965; Kottlowski, 1969; Johnson 1973; Broadhead and King, 1988; Colpitts, 1989; Fig. 2). With the exception of the northernmost Jemez locality (Guadalupe River field site), which was marked by fluvial and eolian sedimentation (Baars, 1962; Stanesco, 1991; Huffman and Condon, 1993; Mack and Dinterman, 2002), all other field localities in this study experienced shelf-carbonate sedimentation with much of central and eastern New Mexico recording gypsum-, and anhydrite-dominated facies of the San Andres Formation. The occurrence and deposition of gypsum- and anhydrite-rich facies above the Abo Formation … corresponds to areas where increased degrees of albitization and lower percentages of K-feldspar are observed, thus pointing to a shallow basin environment during diagenesis.

In addition to the availability of large volumes of Late Permian, marginal-marine overburden and associated shallow, sodium-rich brines, it is worth noting the regional subsidence history throughout New Mexico since the Early Permian as tectonic burial events may have been partially responsible for generating moderate to deep basin depths and elevated heat flow. Much of New Mexico experienced long-wavelength flexure and subsidence during the Late Cretaceous associated with eastward propagation of the Sevier foreland basin (e.g., DeCelles, 2004). However, subsidence from the Sevier alone does not seem to account for the north-south variability observed in feldspar occurrence and alteration. Late Cretaceous–early Eocene subsidence associated with short-wavelength, "wedge-top" like basins that formed ahead of thick-skinned, basement-involved Laramide uplifts may also be partially responsible but also do not alone adequately account for feldspar trends in these strata. We also consider basin subsidence that developed as a result of the late Eocene–Present Rio Grande rift. Except for one sample area located just off-axis of the rift along the eastern margin of the Colorado Plateau (Zuni Mountains), all other field localities are within the rift axis. It is possible secondary alteration that occurred both within the rift axis and off rift axis was driven in part by elevated heat flow associated with early-to late rift volcanism (e.g., Zuni-Bandera volcanic field just east of the Zuni Mountains).

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Appendices can be found at http://nmgs.nmt.edu/repository/index.cfml?rid=2020004