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NEW STRATIGRAPHIC AND PROVENANCE CONSTRAINTS FROM LOWER(?) EOCENE SYNOROGENIC STRATA OF THE SAN JOSE FORMATION, SOUTHEASTERN SAN JUAN BASIN, NEW MEXICO

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Abstract—Sedimentologic, stratigraphic, and provenance data from siliciclastic nonmarine strata of the lower(?) Eocene San Jose Formation provide new insights on the depositional style, stratigraphic relationships, and sandstone modal composition trends across four key members of the San Jose Formation that crop out in the southeastern part of the San Juan Basin in northwestern New Mexico. Presented here are new measured stratigraphic sections and sandstone modal composition trends from N = 18 samples (n = 7,200 point counts) from the Cuba Mesa, Regina, Llaves, and Tapicitos Members. New measured sections record near-continuous sedimentation during deposition of the basal Cuba Mesa Member and overlying Regina Member as well as in the younger Llaves and overlying Tapicitos Members. The Cuba Mesa Member marks the base of the San Jose Formation and shares similar sedimentologic characteristics with the overlying Regina Member. Both members consist largely of laterally extensive lenticular and tabular fluvial sandstone bodies (up to 10 m thick) that are encased in tabular floodplain siltstones that preserve isolated fossil wood including entire fossil tree trunks near the base of the Regina. The younger Llaves and Tapicitos Members exhibit laterally extensive lenticular and tabular fluvial sandstone bodies that are similar to the Cuba Mesa and Regina Members with thicknesses not exceeding 5 m. Both upper members preserve thick succession (up to 15 m) of floodplain siltstone and isolated claystone. The sandstone bodies within all four members of the San Jose Formation have regular occurrences of horizontal and ripple cross-stratification, small-scale planar cross-stratification (<0.25 m thick), and soft-sediment deformation. We note that occurrences of larger-scale cross-stratification and evidence for in-channel bar forms throughout the San Jose Formation are extremely rare as are occurrences of conglomerate (not including mudstone rip-up clasts). The Cuba Mesa and Regina Members share similar detrital sandstone modes and consist primarily of arkosic to lithic-arkosic sandstone (quartz [Q]: 67%, feldspar [F]: 26%, lithic fragments [L]: 7%), whereas the Llaves and Tapicitos Members record higher relative percentages of quartz and consist largely of subarkose to sublitharenite sandstone (Q: 85%, F: 9%, L: 6%). Based on new data presented here, we favor a model for the San Jose Formation where sedimentation was uniform and characterized primarily by vertically aggrading channels (with little to no lateral migration) that avulsed onto adjacent well-developed, vegetated floodplains. Detritus in the Cuba Mesa and Regina Members was likely derived from a combination of recycled orogen and arc sources (Sevier fold-and-thrust belt and Cordilleran arc) and Laramide basement uplifts. Quartz-rich detritus in the Llaves and Tapicitos Members has very little arc signature and was likely derived primarily from Precambrian basement-cored Laramide uplifts.

INTRODUCTION

The Laramide orogeny marks the final Late Cretaceous–middle Eocene stages of mountain building associated with ocean-continent convergence and subduction of the Farallon plate beneath western North America (e.g., Dickinson and Snyder, 1978; Seager, 1981; Seager et al., 1986; Dickinson et al., 1988; Seager et al., 1997; DeCelles, 2004; Dickinson, 2004; Cather, 2004; Nummedal, 2004; Seager, 2004) and was characterized by shallowly dipping subduction and the eastward stepping of thick-skinned, basement-involved deformation, arc magmatism, and basin subsidence and sedimentation (e.g., Snyder et al., 1976; Dickinson and Snyder, 1978; Seager, 2004; McMillan, 2004; Amato et al., 2017). The southwestern United States preserves an excellent record of Laramide deformation, erosion, and sedimentation in the form of numerous basement uplifts and adjacent sedimentary basins throughout central and eastern Utah, northern Arizona, and central and western Colorado and New Mexico (Fig. 1). In northwestern New Mexico and southwestern Colorado, key Laramide basement uplifts include the Uncompahgre, Zuni, Defiance, Carthage-La Joya, Baca, El Rito-Galisteo, Needle Mountains, and Nacimiento uplifts, the latter of which are in closest proximity to the San Juan Basin (Fig. 1).

The focus of this study was on the sedimentology, stratigraphic relationships, and provenance of lower(?) Eocene siliciclastic nonmarine strata of the San Jose Formation in the southeastern part of the San Juan Basin in northwestern New Mexico (Figs. 1 and 2). Although there has been a considerable amount of previous work on Jurassic through earliest Paleogene strata in the San Juan Basin (e.g., Cather, 2003; Cather, 2004; Dickinson and Gehrels, 2008; Donahue, 2016; Hobbs, 2016; Pecha et al., 2018, 2022; Cather et al., 2019), only a few previous studies have focused on the Eocene stratigraphic history and evolution of the San Juan Basin (e.g., Baltz, 1967; Smith and Lucas, 1991; Smith, 1992). Presented here are new measured stratigraphic sections and modal composition trends from eighteen sandstone samples from each of the four members (Cuba Mesa, Regina, Llaves, and Tapicitos) of the San Jose Formation. New measured stratigraphic sections help further constrain the overall depositional style of the San Jose Formation as well as refine the stratigraphic relationships among the four members, whereas sandstone modal composition provides insight into source areas that were being uplifted and eroded during the Eocene development of the San Juan Basin.

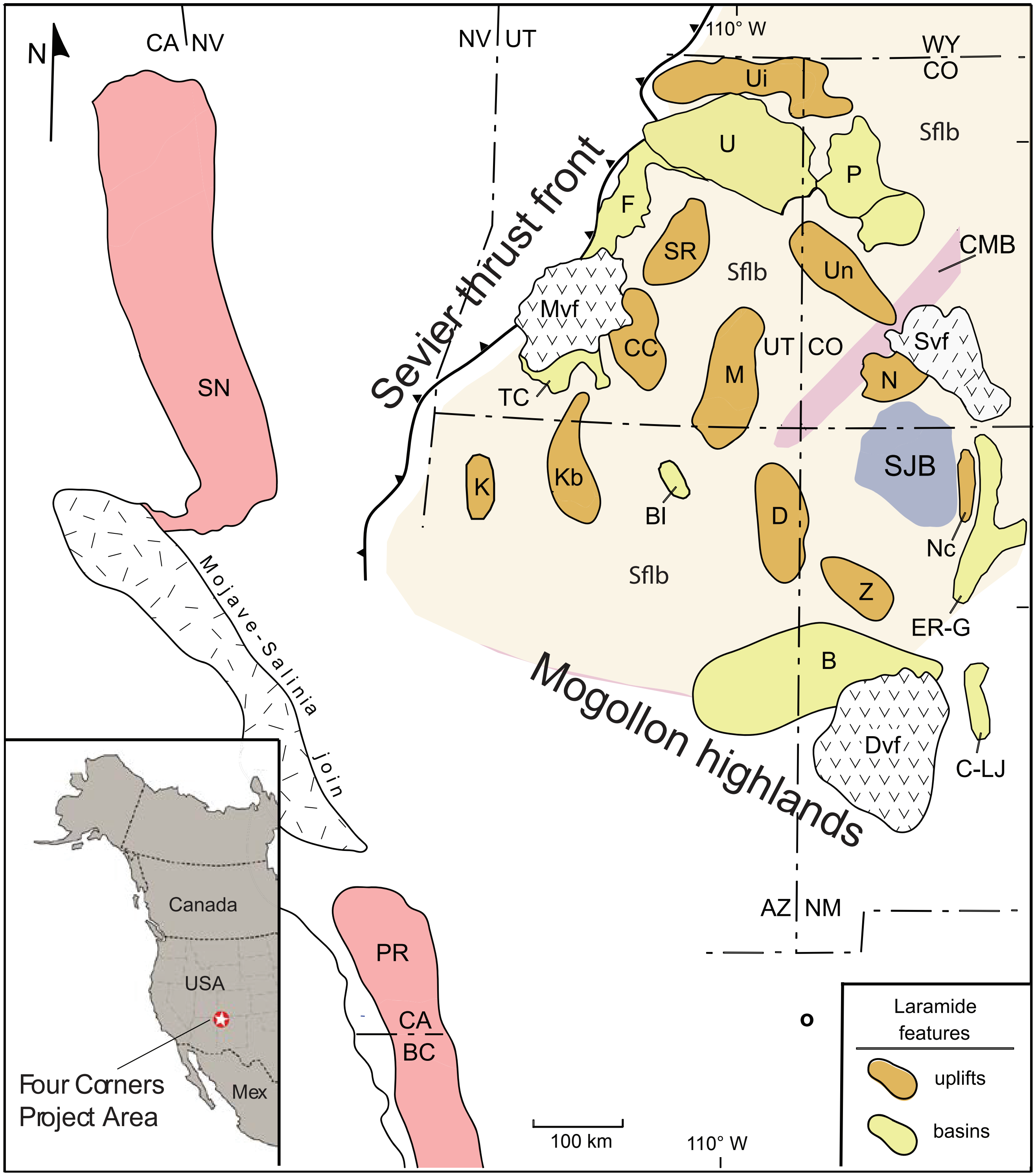

Figure 1. Tectonic map of southwestern North America. SJB—San Juan Basin (highlighted in blue) in relation to structural features of the North American Cordillera; PR—Peninsular Ranges; SN—Sierra Nevada; GVfab—Great Valley forearc basin; Sflb—Sevier foreland basin. Laramide basins (Maastrichtian–Paleogene): B—Baca; Bl—Black Mesa; C-LJ—Carthage-La Joya; ER-G—El Rito–Galisteo; F—Flagstaff; P—Piceance; SJB—San Juan; TC—Table Cliff; U—Uinta. Laramide uplifts: CC—Circle Cliffs; D—Defiance; Kb—Kaibab; K—Kingman; M—Monument; N—Needle Mountains; Nc—Nacimiento; SR—San Rafael; Ui—Uinta; Un—Uncompahgre; Z—Zuni. Purple line denotes approximate boundary between dominantly Cretaceous (K) arc plutons (westward) and dominantly Jurassic (J) and older arc plutons (eastward) (Dickinson et al., 2012). Laramide-age magmatism: CMB—Colorado mineral belt; LPCP— Laramide porphyry copper province. Oligocene (post-Laramide) volcanic fields: Mvf—Marysvale; Dvf—Mogollon-Datil; Svf—San Juan. (Modified from Pecha et al., 2018).

STRATIGRAPHIC OVERVIEW

Cenozoic strata in the San Juan Basin consist primarily of the Ojo Alamo Formation sensu Baltz (1967), Animas Formation, Nacimiento Formation, the Eocene San Jose Formation, and upper Eocene–Oligocene Chuska Sandstone (Fig. 3A). Previous work on Paleocene–Eocene strata throughout the San Juan Basin constrained the depositional histories and stratigraphic relationships between the Nacimiento and Animas Formations, obtained the first (and only) biostratigraphic age constraint and identified five stratigraphic members of the San Jose Formation (Fig. 3B; Baltz, 1967; Smith and Lucas, 1991; Smith, 1992). The San Jose Formation is thought to be early Eocene based on the occurrence of vertebrate fossils and has been interpreted to represent a nonmarine, fluvial environment with well-developed, vegetated floodplains (Smith, 1992; Smith and Lucas, 1991). The five members of the San Jose Formation are (1) the basal Cuba Mesa Member, which overlies the Nacimiento Formation, (2) the overlying Regina Member, (3) the Llaves Member, (4) the Ditch Canyon Member (not included in this study), and (5) the uppermost Tapicitos Member (Fig. 3B). The following provides a brief overview of these five members.

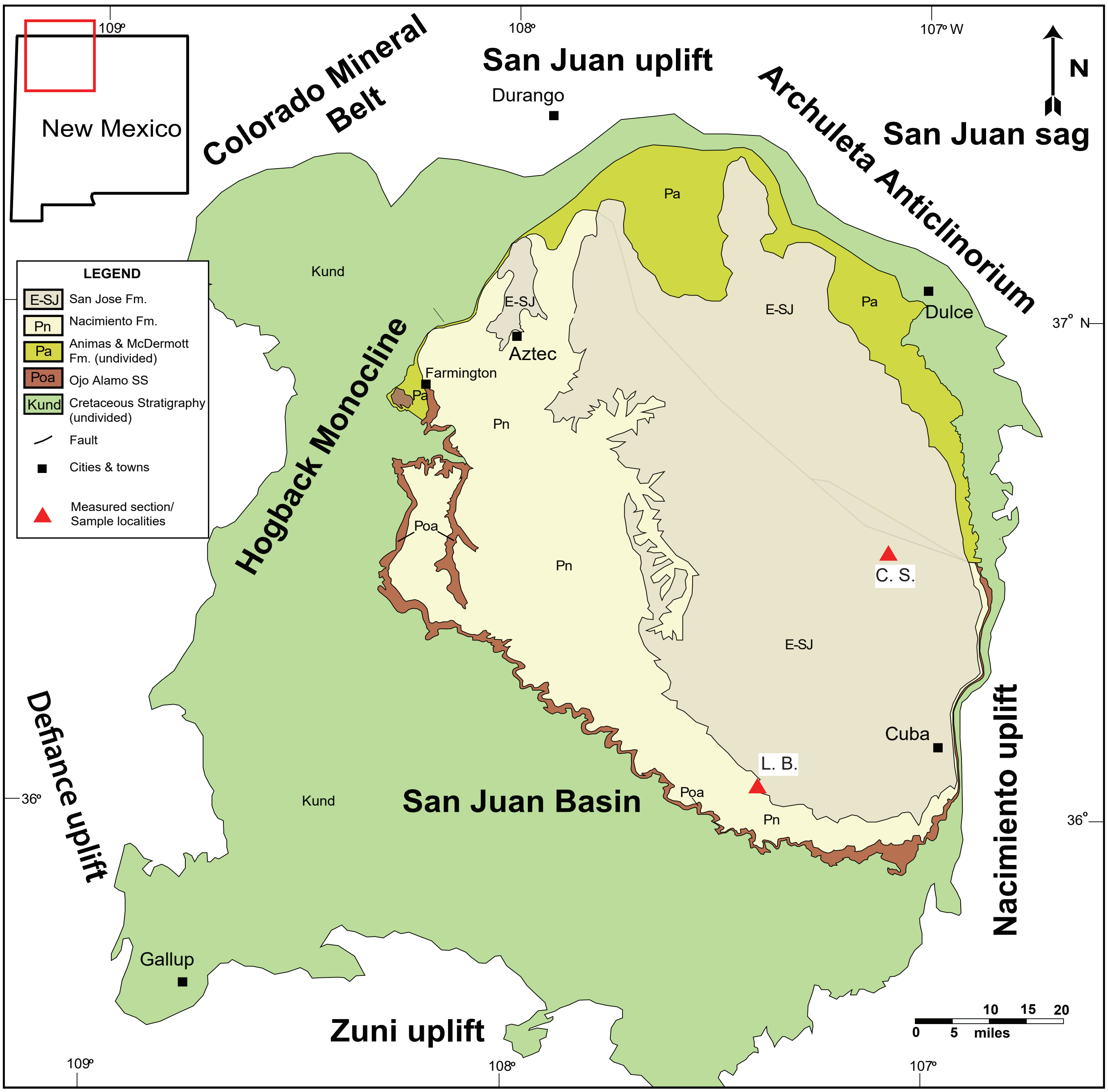

Figure 2. Geologic map of the San Juan Basin of northwestern New Mexico and southwestern Colorado. Surrounding Laramide features indicated in bold print. Modal composition and measured section sample localities indicated by red triangles (L.B—Lybrook Badlands measured section; C.S—Cañada Simon measured section). Base geologic map modified from New Mexico Bureau of Geology and Mineral Resources (2003) and Pecha et al., (2018).

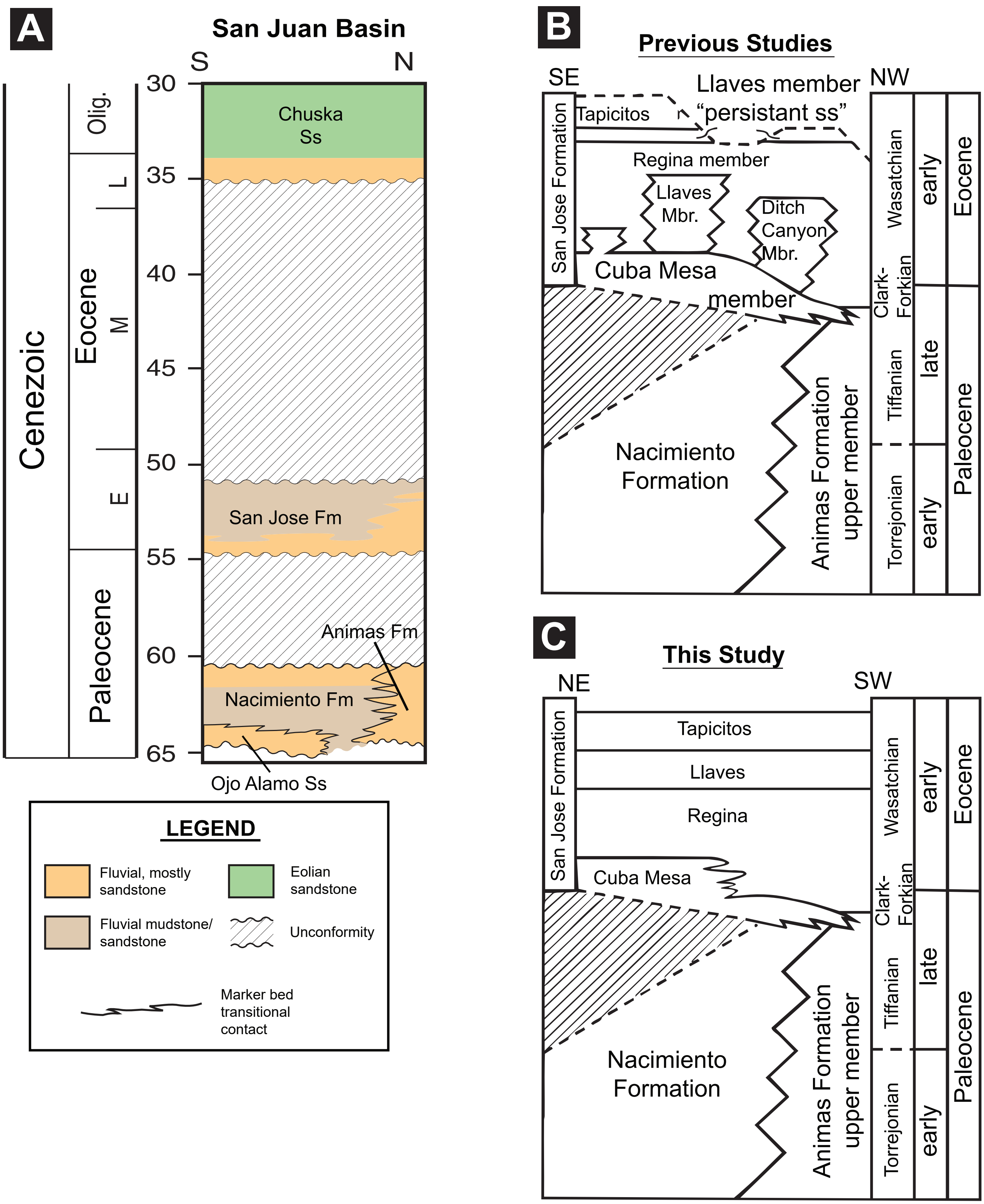

Figure 3. A: Generalized stratigraphic column of the Paleocene–Oligocene strata in the San Juan Basin (modified from Cather, 2004). B: Schematic stratigraphic column of the San Jose Formation subdivided into five individual members (Smith and Lucas, 1991). C: Schematic stratigraphic column of the San Jose Formation in the southeastern San Juan Basin subdivided into four stratigraphically continuous individual member (this study).

Cuba Mesa and Regina Members

The type locality in the San Juan Basin for the basal Cuba Mesa Member is referred to as Mesa de Cuba and crops out just west of the town of Cuba, New Mexico, in the southeastern part of the basin (Fig. 2). Here, and throughout the San Juan Basin, the Cuba Mesa Member consists largely of medium- to coarse-grained arkosic and quartzose sandstone, siltstone, claystone, with rare occurrences of pebble conglomerate (Baltz, 1967; Smith and Lucas, 1991; Smith, 1992). Locally, the Cuba Mesa is up to 240 m thick. It has been interpreted to represent laterally extensive fluvial sandstone bodies and well-developed floodplain deposits (Smith and Lucas, 1991), but was more recently interpreted to represent sedimentation in a distributive fluvial fan environment (Zellman et al., 2020, 2024). The Cuba Mesa Member is thought to thin toward the northwest and center of the San Juan Basin (Fig. 3B; Baltz, 1967; Smith and Lucas, 1991; Smith, 1992). The nature of the contact between the Cuba Mesa and the Nacimiento Formation has been debated and was originally proposed as an unconformable contact with possibly several million years missing in the central and southeastern parts of the basin (Figs. 3B and 4A; Baltz, 1967).

The Regina Member exhibits some of the best and most widespread exposure throughout the San Juan Basin, especially in the southern part, and is reported to consist largely of multicolored floodplain siltstone and claystone with isolated occurrences of fine- to coarse-grained channel sandstone with the total thickness estimated to be anywhere from 50 to 200 m (Baltz, 1967; Smith and Lucas, 1991; Smith, 1992). Many of the vertebrate fossils used to constrain the age of the San Jose Formation occur in the Regina Member and consist largely of nonmarine vertebrate fossil fragments of multiple small mammals (including *Phenacodus primaevus*, *Coryphodon* sp., *Hyracotherium angustidens*, and *Hyopsodus miticulus*), reptiles (including Crocodilia and *Echmatemy*), and fish (Gar family of Lepisosteidae; Smith and Lucas, 1991). Some of these taxa are correlative to specimens found in nonmarine Eocene strata in Wyoming and elsewhere in the western United States and place the strata at ~53 Ma in the Wasatchian–Lysitean (Smith and Lucas, 1991). Previous studies have reported that the Regina Member is conformable with the underlying Cuba Mesa Member (Fig. 4A) and may interfinger with the Cuba Mesa in the southeastern part of the San Juan Basin (Fig. 3B; Smith and Lucas, 1991). The Regina shares fluvial characteristics with the Cuba Mesa Member and both have been interpreted to represent a fluvial fan environment (Zellman et al., 2020, 2024).

Ditch Canyon Member

The Ditch Canyon Member is the most localized of the five members of the San Jose Formation. It occurs in the northernmost parts of the San Juan Basin along the border between New Mexico and Colorado in its type locality of Ditch Canyon, New Mexico (Smith, 1992). The member has been estimated to be up to 220 m thick and consist primarily of medium- to coarse-grained fluvial sandstone and less abundant floodplain siltstone and claystone (Smith, 1992). The Ditch Canyon is thought to conformably overlie the Cuba Mesa Member and may be stratigraphically equivalent to and interfinger with the lower and middle parts of the Regina Member (Fig. 3B). The Ditch Canyon Member was not analyzed for this study given the focus on the southeastern part of the San Juan Basin.

Llaves and Tapicitos Members

The Llaves and Tapicitos Members are perhaps the most poorly understood members of the San Jose Formation due largely to limited prior study and lack of outcrop in the central and western part of the San Juan Basin. The Llaves Member has been described as a cliff-forming unit consisting primarily of medium- to coarse-grained, white and gray fluvial sandstone, brown floodplain siltstone, and claystone (Baltz, 1967; Smith and Lucas, 1991; Smith, 1992). The Llaves has been interpreted to interfinger with the lower and middle parts of the underlying Regina Member along the eastern side of the San Juan Basin (Figs. 3B and 4B; Baltz, 1967; Smith and Lucas, 1991; Smith, 1992). It is thought to be conformably overlain by the Tapicitos Member, which is made up largely of fine- to medium-grained white and pink fluvial sandstone, and deep red floodplain siltstone and claystone (Fig. 4C). The estimated combined thickness of both members is 135 m. To date, no fossils have been reported from either of these members.

METHODS

Two field localities in the southeastern San Juan Basin of northwestern New Mexico were selected for measured stratigraphic sections and sandstone sample collection (Fig. 2). Field localities were chosen based on excellent regional exposure of the Cuba Mesa, Regina, Llaves, and Tapicitos Members as well as exposure of the underlying Nacimiento Formation. Two stratigraphic sections were measured: the Lybrook Badlands section and the Cañada Simon section (Fig. 2). The purpose of measuring the Lybrook Badlands section was to document the basal contact of the Cuba Mesa Member with the underlying Nacimiento Formation and the contact between the Cuba Mesa and Regina Members. The section includes the uppermost 35 m of the Nacimiento Formation and extends into the Regina Member of the San Jose Formation. The purpose of the Cañada Simon section was to document the nature of the contact between the Llaves and Tapicitos Members. This section extends through the upper Llaves and lower Tapicitos Member.

Principal data collection for sedimentologic and stratigraphic analyses of the San Jose Formation consisted of detailed measured stratigraphic sections at two field localities where contacts between the Cuba Mesa and Regina and the Llaves and Tapicitos Members could be directly observed. Data collected included lithofacies, grain size, thickness, and bed geometries. All strata were measured with a standard 1.5-m-long Jacob's staff and recorded on standard measured section sheets.

A total of eighteen medium-grained sandstone samples were collected from each measured section. Sandstones were prepared for thin section by cutting hand samples into billets and staining for feldspars to distinguish plagioclase and K-feldspar. For each thin section, a total of 400 sand-sized grains were identified using the Gazzi-Dickinson method (Dickinson et al., 1983; Ingersoll et al., 1984). All thin sections were counted using a polarizing microscope equipped with a Conwy stepping stage. All raw data were recalculated for provenance analysis. Raw and recalculated data are in Appendix 1. Ternary plots were created using the plotting program TRI-PLOT (Graham and Midgley, 2000).

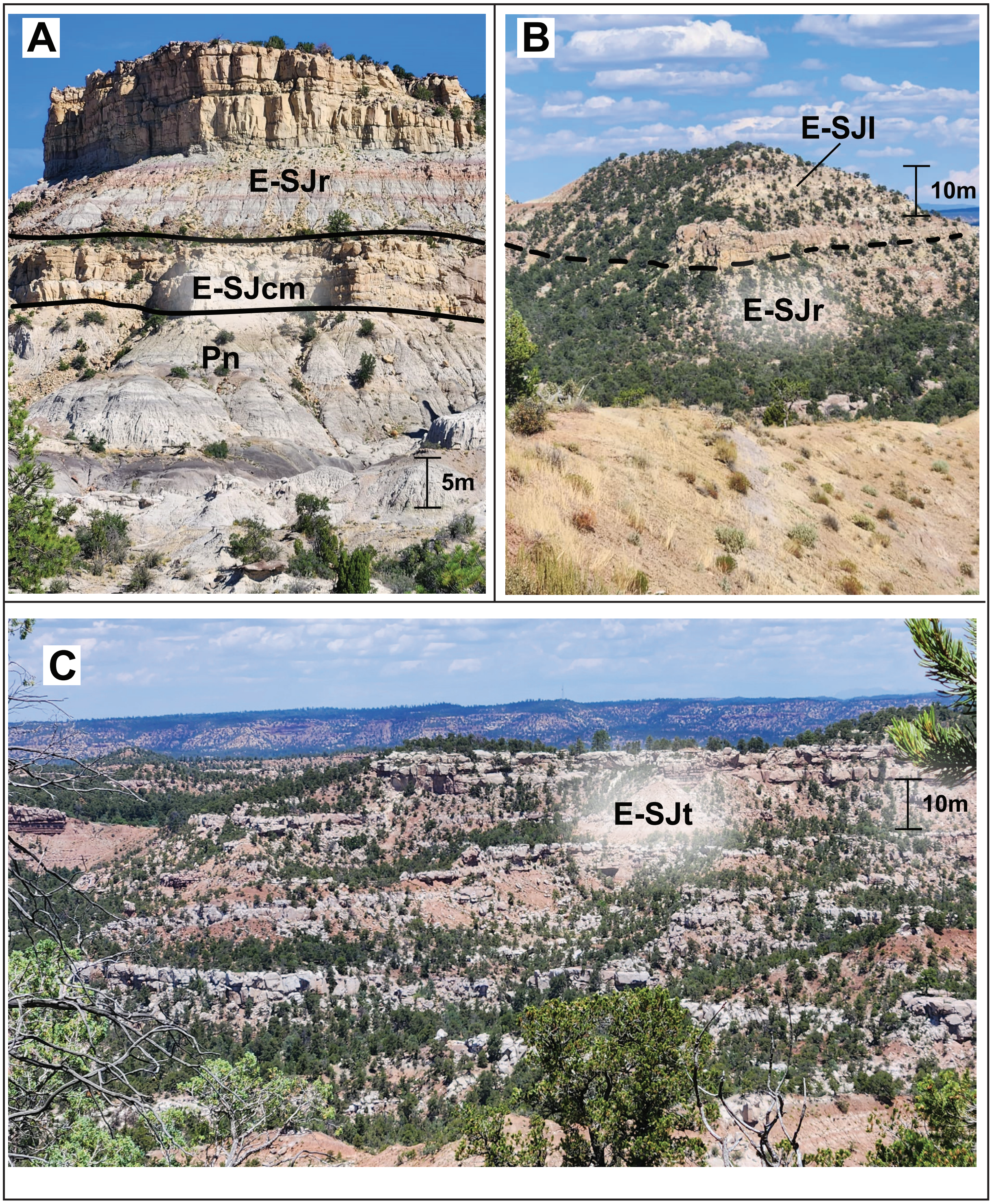

Figure 4. Annotated field photographs of each member of the San Jose Formation in the southeastern San Juan Basin. A: The Nacimiento Formation unconformably(?) underlying the Cuba Mesa Member, which underlies the Regina Member at the Lybrook Badlands field locality. B: The Llaves Member of the San Jose Formation overlying the Regina Member at the Cañada Simon field locality. C: Regional view to the north of the Tapicitos member of the San Jose Formation.

RESULTS

Sedimentology and Stratigraphy

The Lybrook Badlands measured section totaled 111.5 m, including the uppermost 35 m of the Paleocene Nacimiento Formation (Figs. 4A and 5). Although not the primary focus of this study, the uppermost Nacimiento at Lybrook Badlands consists primarily of tabular sheets of massive sandstone and conglomerate units that range in thickness from 0.25 to 2.0 m that are interbedded with siltstone beds between 2 and 5 m thick (Fig. 5). A lenticular sandstone in the Cuba Mesa appears to scour into siltstone at the top of the Nacimiento (Fig. 5). The Cuba Mesa Member is 24 m thick and consist primarily of lenticular sand bodies that average ~2 m thick that are interbedded with massive siltstones (Fig. 5). Siltstone rip-up clasts are present at the base of lenticular sandstone units. Pebble conglomerate occurs but is rare and isolated. Sedimentary structures are abundant in the Cuba Mesa and consist largely of ripple cross-stratification, horizontal stratification, and rare planar and trough cross-stratification (Fig. 5). Soft-sediment deformation is common in sandstone units near the top of the Cuba Mesa.

The contact between the Cuba Mesa and Regina Member is marked by a siltstone unit at the top of the Cuba Mesa and a claystone at the base of the Regina Member. Just above this claystone is a 6-m-thick siltstone that contains an abundance of small fossil wood fragments as well as several >3-m-long fossil tree trunks (Fig. 5). Overall, the Regina Member consists of tabular sandstone bodies that range in thickness from 1 to 5 m that are interbedded with massive siltstones and claystones (Fig. 5). Similar to the underlying Cuba Mesa Member, pebble conglomerate is rare and isolated. Sandstone units are massive in the lower part of the Regina and exhibit ripple cross-stratification, horizontal stratification. Soft-sediment deformation structures are present in upper parts of the member (Fig. 5).

The Cañada Simon measured section totaled 150 m, including 86 m in the lower Llaves Member and 64 m in the Tapicitos Member (Fig. 5). The Llaves Member is characterized by tabular sandstone bodies that range in thickness from 1 to 5 m and are interbedded primarily with massive siltstone, with one pebble conglomerate bed observed near the top of the Llaves

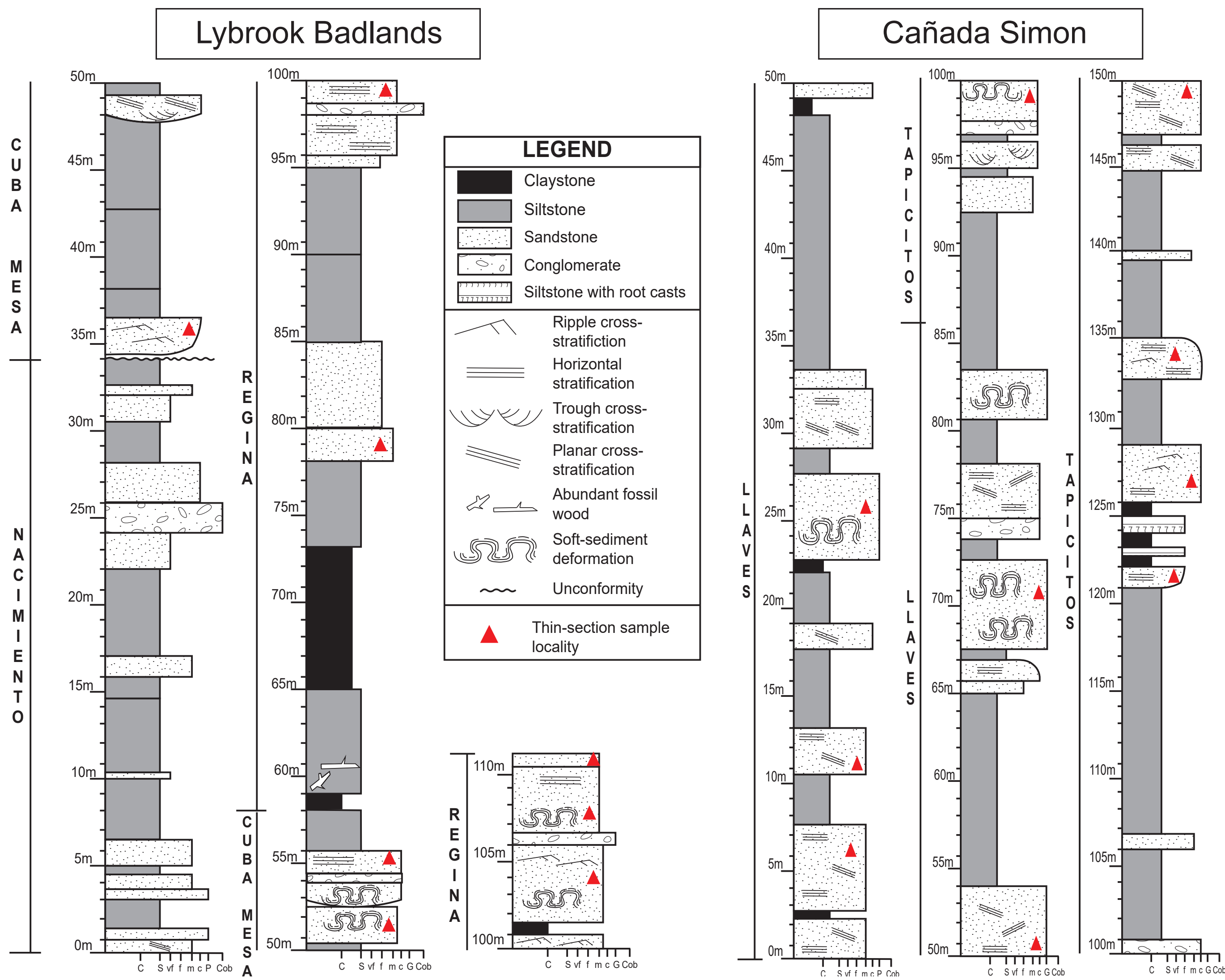

Figure 5. Measured stratigraphic section for all four members of the San Jose Formation in the Lybrook Badlands and the Cañada Simon sample localities.

Member (Fig. 5). Sedimentary structures are common in the Llaves and consist primarily of extensive horizontal stratification, small-scale planar cross-stratification (<0.2 m thick), and soft-sediment deformation (Fig. 5). The contact between the Llaves and Tapicitos Members is thought to be conformable (Baltz, 1967; Smith and Lucas, 1991; Smith, 1992) and is marked by a siltstone unit. The Tapicitos Member consists largely of tabular sandstone bodies that range in thickness from 0.75 to 3.0 m thick along the measured section that are interbedded with siltstones and minor claystones that contain isolated root casts (Fig. 5). Lenticular sandstone bodies are rare and contain siltstone rip-up clasts near the base of the unit. Several 1-m-thick beds of pebble conglomerate occur in the lower part of the Tapicitos Member. Common sedimentary structures in the Tapicitos include abundant horizontal stratification, small-scale planar cross-stratification, ripple cross-stratification, and isolated trough cross-stratification.

All four members of the San Jose Formation exhibit extensive horizontal stratification and ripple cross-stratification. Occurrences of larger bedforms such as large-scale planar cross-stratification and trough cross-stratification are rare (Fig. 5). The lack of any evidence for in-channel bar forms throughout all four members of the San Jose is notable.

Sandstone Modal Composition

Sandstone modal composition trends averaged across the four members of the San Jose Formation show relatively high percentages of quartz and feldspar, and only minor lithic fragments (Q: 76%, F: 17%, L: 6%). The quartz fraction is dominated by monocrystalline quartz and feldspar percentages are split near equally between plagioclase and K-feldspar (monocrystalline quartz [Qm]: 77%, P: 10%, K: 13%).

The Cuba Mesa and Regina Members contain some of the lowest relative abundance of quartz and highest relative abundance of feldspar in the San Jose Formation and share nearly identical percentages of quartz, feldspar, and lithic fragments (Fig. 6; Cuba Mesa: Q: 67%, F: 26%, L: 7%; Regina Member: Q: 67%, F: 25%, L: 8%). The Cuba Mesa contains a slightly higher relative abundances of plagioclase compared to K-feldspar (Qm: 65%, plagioclase [P]: 19%, K-feldspar [K]: 16%). The Regina member has slightly higher relative abundances of K-feldspar when compared to plagioclase (Qm: 68%, P: 14%, K: 18%). Lithic fragments in both members are minor constituents and exhibit slightly elevated relative percentages of lithic volcanic fragments to lithic metamorphic and sedimentary ones (Fig. 6; Cuba Mesa: lithic volcanic fragments [Lv]: 4%, lithic metamorphic fragments [Lm]: 1%, lithic sedimentary fragments [Ls]: 2%; Regina Member: Lv: 4%, Lm: 3%, Ls: 1%).

Both the Llaves and Tapicitos Members share very similar relative percentages of quartz, feldspar, and lithic fragments and are very quartz rich (Fig. 6; Llaves: Q: 85%, F: 10%, L: 5%; Tapicitos: Q: 85%, F: 9%, L: 6%). Both members also have slightly more K-feldspar relative to plagioclase (Llaves: Qm: 86%, P: 3%, K: 11%; Tapicitos: Qm: 89%, F: 5%, K: 6%). Lithic fragments in the Llaves are sparse and have slightly elevated relative abundances of lithic metamorphic fragments (Fig. 6; Lv: 1%, Lm: 3%, Ls: 1%), whereas lithic fragments in the Tapicitos have higher relative abundances of lithic volcanic fragments (Fig. 6; Lv: 4%, Lm: 1%, Ls: 1%).

DISCUSSION

Sandstone bodies throughout the San Jose Formation that exceed 0.5 m in thickness exhibit both lenticular and tabular geometries and are interpreted to represent poorly confined fluvial channels and unconfined sheetflood sedimentation. Sandstone and mudstone bodies that are less than 0.5 m in thickness are interpreted to represent unconfined floodplain crevasse splay deposits. These thin, fine-grained strata are interpreted to represent unconfined floodplain sedimentation where soil development occurred, and vegetation was abundant and mature. Horizontal stratification and ripple cross-stratification in all four members of the San Jose Formation are much more common than larger bedforms such as large-scale planar cross-stratification and trough cross-stratification, which are rare (Fig. 5). Due to the persistence of smaller-scale sedimentary structures such as horizontal stratification and ripple cross-stratification coupled with no evidence of in-channel bars, we prefer a model for the San Jose Formation where depositional style was characterized by laterally extensive channels that aggraded in place and later occupied adjacent areas of the floodplain through channel avulsion (rather than lateral migration across floodplain regions). It is also possible that channels may have remained in place for longer episodes of time, which promoted vegetation to mature on floodplain surfaces. This fluvial style has been observed and described in both modern and ancient settings (e.g., Hampton and Horton, 2007; Weismann et al., 2010; Ventra and Clark, 2018; Moscariello, 2018: Owen et al., 2015; Owen et al., 2017), and has been previously interpreted for the Cuba Mesa and Regina Members of the San Jose Formation (Zellman et al., 2024). The pervasive occurrences of sandy channel systems as opposed to coarser-grained pebble- or cobble-filled channels may imply that detritus was sourced regionally rather than from nearby areas. Soft-sediment deformation in channel sandstones is interpreted to represent either dewatering caused by rapid sedimentation or liquefaction due to syndepositional seismic events.

Baltz (1967) formally designated the members of the San Jose Formation. Prior to his work, the San Jose Formation was described inconsistently as unnamed sandstone units or correlated to and assigned as Wasatch Formation. Baltz (1967) designated the five members based on lithologic appearances and general thickness. He described the Cuba Mesa as being composed of arkosic sandstones interbedded with fine-grained units. He mapped the Regina Member as a siltstone/mudstone dominated unit with interbedded sandstones. He noted the similarities of sandstones and fine-grained units between the Cuba Mesa and Regina Members but kept them separate based on relative abundances of variegated siltstone/mudstone units and sandstone bodies. Based on our observations of lithologic trends across the Cuba Mesa and Regina Members, we present a model where these two members are combined because their

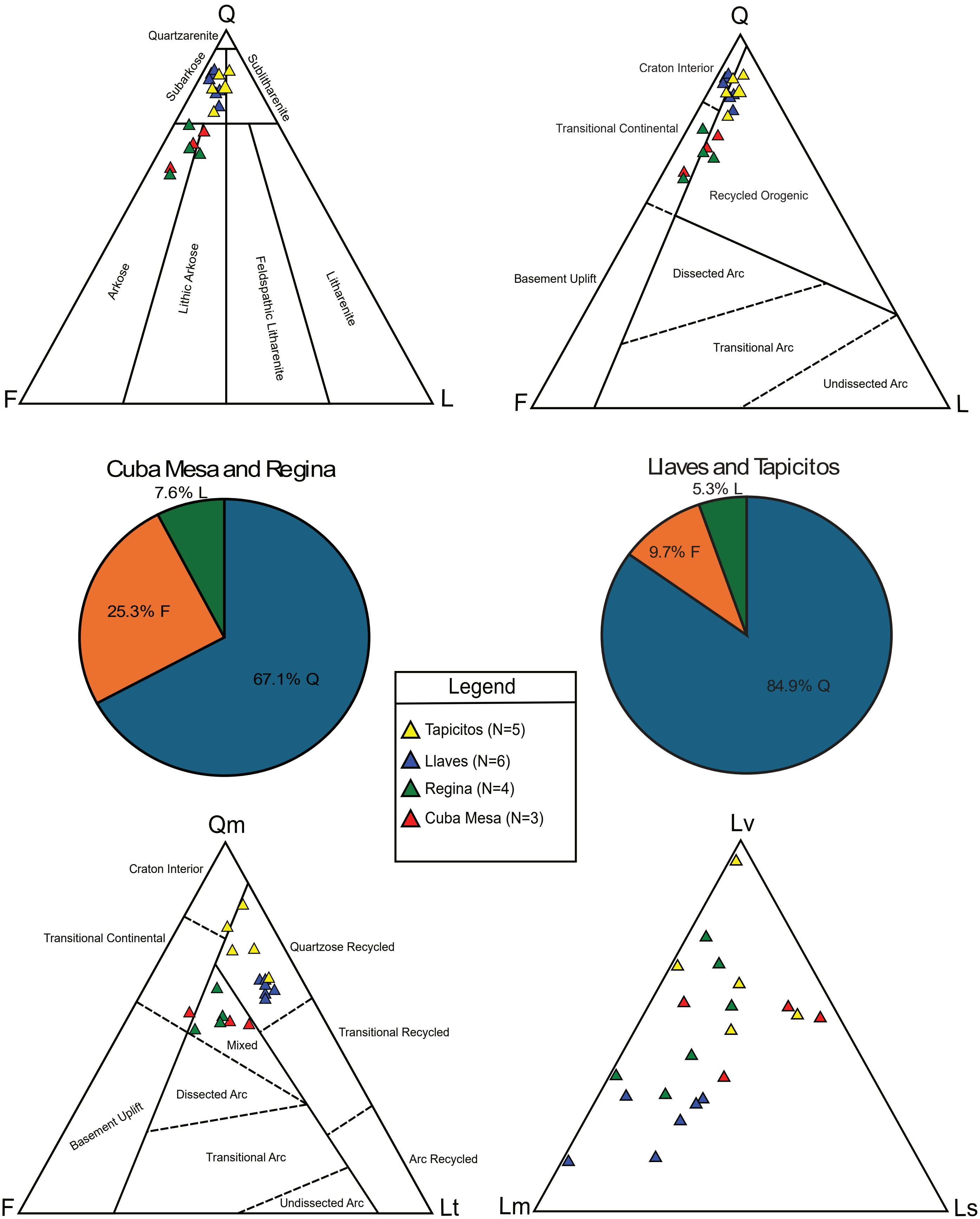

Figure 6. Ternary diagrams and pie charts summarizing the sandstone modal compositional trends of the San Jose Formation and its individual members.

lithologies are very similar. The sandstones of the Cuba Mesa are generally thicker than those of the Regina, but they still share similarities in grain size, composition, and sedimentary structures with those in the Regina. The siltstone/mudstone horizons of the Cuba Mesa are also similar in color, thickness, and grain size to those of the Regina Member. Relative percentages of sand bodies and fine-grained units in the Cuba Mesa and Regina only vary by a small margin (e.g., within 10%; Fig. 5).

Detrital sandstone modes from all four members of the San Jose Formation exhibit a range of quartz, feldspar, and lithic fragment percentages. Sandstone in the Cuba Mesa and Regina Members plot largely as arkosic to lithic arkosic and nearly all samples plot in the both the mixed and dissected arc provenance fields. Sandstone in the Llaves and Tapicitos Members plot as subarkosic to litharenitic and plot in quartzose recycled and craton interior provenance fields (Fig. 6). Based on these trends, the San Jose Formation appears to transition upsection from being derived from more recycled orogen and arc source areas to the upper members being derived from recycled orogen and craton interior sources. Craton interior sources areas likely reflected contributions from Laramide Precambrian basement blocks (rather than the true North American craton). Arc source areas seemed to have been present during deposition of the Cuba Mesa and Regina Members, but less so during the deposition of the Llaves and Tapicitos Members. Subtle changes in compositional trends between members suggest the introduction or removal of general source areas. Thus, the lower percentages of arc material within the Llaves and Tapicitos Members suggest that arc source areas contributed less to those units. This trend may also represent simply an increased input from basement sources (i.e., local basement cored uplifts), which would cause more muted concentrations of arc material. We suggest these compositional trends represent a combination of these two scenarios.

These compositional trends may also reflect spatial source area differences versus temporal ones. Limited paleocurrent data suggest that flow directions were from the west-northwest to the east-southeast, with minor differences on the eastern flank of the basin where flow directions were primarily to the south (Smith and Lucas, 1991). This difference could allow for slight variations in provenance. More detailed compositional data within individual members from different locations within the San Juan Basin will be necessary to determine the complexity of these trends.

Lithic compositions across all members and exhibit no discernable trends. Given the low percentages of lithics in the overall compositions, a larger sample size of compositional data may reveal trends that are herein undistinguishable.

CONCLUSIONS

Although much more work is needed to fully understand the stratigraphic history, sedimentation styles, basin provenance, and sediment dispersal trends during the early Eocene development of the San Juan Basin, several preliminary conclusions can be made for the San Jose Formation. First, the four members in this study exhibit very similar depositional styles that indicate a vertically aggrading fluvial system marked by little to no lateral migration, and well-developed, long-lived floodplain regions. Nearly uniform sedimentologic trends from the four members imply that intrabasinal and extrabasinal controls on sedimentation (e.g., discharge, sediment load, and subsidence rates) may have been consistent and little changed, and these promoted the distributive fluvial style during the early Eocene history of the San Juan Basin. At present, more work is needed to determine if tectonic and/or climatic drivers may have played a role in the distributive fluvial style. We note that distributive fluvial styles have been reported in basins undergoing rapid subsidence (e.g., Hampton and Horton, 2007) and in regions characterized by arid environments and marked by punctuated flooding events (e.g., Zellman et al., 2024).

Preliminary provenance trends from the San Jose Formation reveal very similar (to nearly identical) modal composition trends in the Cuba Mesa and Regina Members, and in the Llaves and Tapicitos Members. Recycled orogen, arc, and basement sources areas were likely contributing detritus to the San Juan Basin during the deposition of the Cuba Mesa and Regina Members. However, the Llaves and Tapicitos have very little to no evidence of arc detritus, implying at least some change in sediment routing for these members. Given the uniform fluvial style throughout the San Jose Formation, this may imply a regional, extrabasinal tectonic mechanism that reduced contributions from the Cordilleran arc and possibly Sevier fold-and-thrust belt. More provenance data may greatly advance our understanding on sediment routing during the early Eocene evolution of the San Juan Basin.

Finally, we would favor an approach that groups the more similar members of the San Jose Formation. Given the near identical lithologic traits and provenance tends in the Cuba Mesa and Regina Members, we would accept a merging these two members unless future data supports otherwise. At present, and despite the near identical provenance trends in the Llaves and Tapicitos Members, more data may be required to support merging these two members due to their lithologic dissimilarities.

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Appendix can be found at
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