PROGRADATIONAL-TO-RETROGRADATIONAL STYLES OF PALEOGENE FLUVIAL FAN SUCCESSIONS IN THE SAN JUAN BASIN, NEW MEXICO

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**ABSTRACT**

Basin-scale outcrop analyses of fluvial architecture in the Paleogene San Juan Basin, New Mexico document lateral and vertical trends in channel, floodplain and paleosol characteristics. Herein, the uppermost part of the Paleocene Nacimiento Formation and lower Eocene Cuba Mesa and Regina Members of the San Jose Formation are identified as deposits of large fluvial fans based on trends observed across the basin. Stratigraphic trends suggest two packages of fan progradation. Progradation of the lower fan system provides a new explanation for the transitional nature of a disconformity at the Nacimiento-San Jose Formation contact, previously thought to be a low-angle unconformity. The two fan systems are separated by a retrogradational interval that culminates in a depositional hiatus at the contact between the Cuba Mesa and Regina Members. This, combined with poor age-constraints, indicates that the duration of the disconformity at the base of the Cuba Mesa Member may have been overestimated. Furthermore, the succession is interpreted as deposits of variable discharge rivers, based on a combination of an abundance of upper-flow-regime and high-deposition-rate sedimentary structures indicative of intense flooding events, preservation of in-channel bioturbation and pedogenic modification indicating periods of prolonged dryness, bar strata, and alternations of poorly drained and well-drained floodplain deposits and/or slickensides indicating alternating wet-dry cycles.

This dataset adds to a growing body of evidence that the formation of large fluvial fans is promoted by discharge variability, and thus their link to hydroclimates with inter- and intra-annual precipitation variability and intense rainfall. A long-term stratigraphic shift from poorly drained to well-drained floodplain deposits across both progradational fan successions indicates that a predictive model suggesting downstream decreases in soil drainage conditions is not encompassing of all large fan systems, and instead suggests a transition to a more arid climate across the Paleocene-Eocene boundary.

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1. **INTRODUCTION**

Fluvial fans are extensive fan-shaped sediment accumulations built by river avulsions (Shukla et al., 2001; Leier et al., 2005; Chakraborty et al., 2010; Latrubesse et al., 2012; Sinha et al., 2012; Weissmann et al., 2015; Ventra and Clarke, 2018). Because they are predominantly aggradational landforms, fluvial fans have the potential to archive important information on the paleoclimate, local tectonic history, and landscape response to various allogenic and autogenic factors. Perhaps most importantly, fluvial fans are proposed to form the bulk of continental fluvial records, as they are the principal aggradational fluvial systems able to accumulate significant stratigraphic thicknesses in contrast to non-fan or tributary river systems that are confined to fluvial valleys and transfer sediment as bypass systems (Weissmann et al., 2010; Ventra and Clarke, 2018 but c.f. Fielding et al., 2012). Recent empirical and modeling efforts have led to the development of criteria used to recognize fluvial fan successions in the geologic record (e.g. Singh et al., 1993; Shukla et al., 2001; Weissmann et al., 2010, 2013; Plink-Björklund, 2021). These developments have improved our ability to predict proximal-distal trends in fan-deposit architecture, in addition to stratigraphic changes indicative of prograding systems. As a result, ancient fluvial fans are increasingly being identified from stratigraphic investigations (e.g. Kukulski et al., 2013; Weissmann et al., 2013; Gulliford et al., 2014, 2017; Lawton et al., 2014; Owen et al., 2015, 2017; Burnham and Hodgetts, 2018; Aliyuda et al., 2019; Wang and Plink-Björklund, 2019; Martin et al., 2021). Nevertheless, major gaps still exist in our knowledge of these depositional systems including recognition criteria for progradational-retrogradational architectural trends and related controls (Ventra and Clarke, 2018).

Commonly, tectonism is invoked as being responsible for upward coarsening and cyclical sedimentation associated with all types of terrestrial fan successions (e.g. Blair, 1987; Mack and Leeder, 1999; Jones, 2004; Luzón, 2005; Hirst and Nichols, 2009). While it is well-accepted that tectonism provides the opportunity for fan development through the creation of topographic relief at the basin margin, increasing gradients of river systems supplying sediments, and the creation of accommodation for storage of sediment and preservation of fan successions (Frostick and Steel, 1993; Jones, 2002), climate is increasingly regarded as a significant control on fluvial fan development (Harvey et al., 2005; Leier et al., 2005; Pope and Wilkinson, 2005; Weissmann et al., 2005; Quigley et al., 2007: Hansford and Plink-Björklund, 2020). In particular, rivers affected by variable discharge regimes resulting from strong precipitation variability at seasonal to interannual scale are suggested to promote fan formation because large discharge fluctuations contribute to the instability of channels, in turn favoring frequent avulsions that ultimately create distinctive fan-shaped sediment bodies (Sinha and Friend, 1994; Horton and DeCelles, 2001; Leier et al., 2005; Assine et al, 2014; Hansford and Plink-Björklund, 2020).

The laterally and vertically extensive exposure of Paleogene rocks in the San Juan Basin, New Mexico, provides an opportunity for a 3D basin-scale analysis of fluvial fan architecture. The objective of this research is to combine channel lithosome and floodplain paleosol characteristics to better understand the depositional processes and forcing mechanisms that may account for evolving fluvial deposition styles. This paper 1) quantifies the lateral and stratigraphic trends in channel lithosome and floodplain deposits and paleosols, including grain size, channel size, and the channel-to-floodplain ratio of deposits preserved in the stratigraphy; 2) identifies the depositional environment of the uppermost part of the Paleocene Nacimiento Formation and lower Eocene Cuba Mesa and Regina Members of the San Jose Formation as a fluvial fan; 3) explores the style and potential controls on fan progradation and retrogradation; 4) explores the implications that our findings may have for improved understanding of Paleogene San Juan Basin landscape evolution; and 5) discusses signatures of progradation-retrogradation and climate changes in fluvial fan depositional models.

In order to signify that the studied sedimentary succession was built by fluvial processes and lacks sedimentological signatures of gravity-flow and unconfined-flow processes that are common of high-gradient, piedmont alluvial fans (see Blair and McPherson, 1994), we adopt the term ‘fluvial fan’, with reference to fan-shaped bodies built by river avulsions (see Moscariello, 2018; Ventra and Clarke, 2018), rather than the ‘distributive fluvial system’ (DFS) terminology which includes alluvial fans as a part of a continuum of subaerial fan-shaped landforms (Hartley et al., 2010; Weissmann et al., 2010, 2015).

1. **GEOLOGICAL SETTING AND BACKGROUND**

The San Juan Basin (SJB) is in the Four Corners region of northwestern New Mexico and southwestern Colorado (Fig. 1a) and is one of several intraforeland (broken foreland) basins formed during the laramide orogeny (Dickinson et al., 1988; Cather, 2004). Laramide tectonics during the late Campanian (Late Cretaceous) through the Eocene caused subsidence of the SJB in response to uplift of surrounding areas (e.g. Smith, 1988; Cather, 2004). During the late Paleocene through early Eocene, the SJB was bound to the east by the Nacimiento and Brazos-Sangre de Cristo uplifts, to the west by the Defiance uplift, and to the north by the San Juan uplift (Fig. 1b; Cather, 2004). Today, the SJB has the form of an asymmetrical syncline with an arcuate axis that dips to the north with steeply dipping northern and eastern limbs and shallowly dipping southern and western limbs. The central, southern, and western sectors of the SJB are relatively undeformed, with regional dips of <5° (Woodward, 1987).

It has been suggested that the SJB received most of its sediments from highlands to the north and the early San Juan uplift (Baltz, 1967; Donahue, 2016), although source areas in the Brazos-Sangre de Cristo, Nacimiento, Zuni, and Defiance uplifts are also suspected (Smith, 1992; Cather, 2004). Past research has linked long-term evolution of the Cretaceous–Eocene sedimentary succession to three subsidence episodes in response to the Laramide orogeny: inception and early phase (~78-75 Ma), middle phase (~74-67 Ma), and late phase occurring during the Paleogene (Cather, 2004). Intraformational angular unconformities and reverse faults in the eastern outcrop area show that the Paleogene units in the SJB were deposited simultaneously with deformation along the basin-bounding Nacimiento fault (Woodward, 1987; Smith, 1988).

* 1. **Stratigraphy**

This study focuses on the uppermost part of the Nacimiento Formation and the Cuba Mesa and Regina Members of the overlying San Jose Formation.

**2.1.1 Paleocene Nacimiento Formation**

The Paleocene Nacimiento Formation is composed primarily of fluvial deposits consisting of sandstone and varicolored mudrocks that attain a thickness of as much as 525 m (Baltz, 1967; Lucas and Williamson, 1992). Throughout most of the San Juan Basin, the Nacimiento Formation is divided into three members based on lithologic and sedimentological features: The Arroyo Chijuillita Member (oldest), the Ojo Encino Member, and the Escavada Member (youngest) (Fig. 1c; Williamson and Lucas, 1992; Cather and others, 2019). A general north-to-south decrease in grain size and paleocurrent measurements from cross strata indicate a prevailing north-to-south paleoflow (Baltz, 1967; Klute, 1986; Sikkink, 1987; Smith, 1992), and a major regional paleodrainage (the Tsosie paleoriver) has been suggested to flow from the southwest to northeast (Cather et al., 2019). Across the southern SJB, the thickness of the Escavada Member varies from 19 to 88 m due to intraformational thinning (Butler and Lindsay, 1985) and channel scouring at the base of the San Jose Formation (Lucas et al., 1981).

The early Paleocene age of the Arroyo Chijuillita and Ojo Encino Members is well constrained by biostratigraphy, magnetostratigraphy, and radiometric dating (Lucas and Williamson, 1992; Leslie et al., 2018; Flynn et al., 2020). The age of the Escavada Member, however, is poorly constrained, with the only age indicator being a zone of normal magnetic polarity in the western SJB that has been correlated to chron 26, suggesting a late Paleocene age (Fig. 1c; Lindsay et al., 1981; Williamson and Lucas, 1992). If this correlation is correct, the Escavada Member extends to at least the lower part of chron 25 in the western SJB (Lucas and Williamson, 1992), suggesting that that the deposits of the uppermost part of the Nacimiento may be younger than 58.9 m.y.a. when correlated to the geomagnetic polarity time scale (GPTS - Ogg, 2012) (Fig. 1c). A summary of previous work and results of recent investigations of the Paleocene Nacimiento Formation in the SJB can be found in Hobbs (2016), Leslie et al. (2018), Cather and others (2019), Flynn et al. (2020), and Hobbs and Fawcett (2021; 2022).

**2.1.2 Lower Eocene San Jose Formation**

The San Jose Formation is the most extensively preserved and exposed Eocene stratigraphic unit in New Mexico (Smith and Lucas, 1991; Smith, 1992). Like the underlying Nacimiento Formation, it is composed of terrestrial fluvial deposits with a prevailing north-to-south paleoflow (Fig. 1d; Smith, 1988). Previous geological investigations of the southern and southeastern outcrop areas of the San Jose Formation include descriptions of fossils, local physical stratigraphic studies (e.g. Simpson, 1948; Lucas et al., 1981; Smith and Lucas, 1991), and regional stratigraphy and mapping (Baltz, 1967; Mytton, 1983; Manley et al., 1987; Smith, 1988; Smith and Lucas, 1991). Sandstone vs. mudrock dominance is the primary characteristic used to distinguish between the members within the San Jose Formation (Fig. 1c; Baltz, 1967; Smith, 1992). The Cuba Mesa and Regina Members are the focus of this study.

The Cuba Mesa Member at the base of the San Jose Formation in the SJB is a distinct 40 to 240 m thick, sandstone-dominated succession that overlies the Paleocene Nacimiento Formation through a stratigraphic contact of uncertain nature (see below) (Baltz, 1967; Smith and Lucas, 1991). It consists of medium- to very coarse-grained, buff-colored tabular sandstones that thicken locally in vertically stacked (amalgamated) channel belts that can attain thicknesses up to 100 m, with width-to-thickness ratios ranging from 20 to >1000 (Smith, 1988). The basal sandstone of the Cuba Mesa Member is continuous nearly basin-wide over an area of 8000 km2 (Smith, 1988). In some parts of the basin, the contact between the Nacimiento Formation and the Cuba Mesa Member of the San Jose Formation can be difficult to distinguish because the Escavada Member of the Nacimiento Formation contains arkosic sandstones that are petrographically similar to those of the overlying Cuba Mesa Member (Baltz, 1967; Smith and Lucas, 1991) and are composed of similar channel-fill facies (Zellman et al., 2020). Like the underlying Escavada Member, no age-diagnostic fossils or dateable materials have been discovered in the Cuba Mesa Member, leaving the deposits of both the upper part of the Nacimiento Formation and the lower part of the San Jose Formation poorly constrained in time (Fig. 1c).

The Regina Member of the San Jose Formation that overlies the Cuba Mesa Member ranges from 150 to 460 m in thickness and is composed of varicolored gray, purple and red mudrock and interbedded sandstone. The sandstone beds are lenticular over scales ranging from a few meters to many kilometers (Smith, 1992). The early Eocene age of the Regina Member is determined by Wasatchian (North American Land Mammal Age - NALMA) vertebrate fossils found in the middle to upper parts of the Regina Member (Fig. 1c; see Lucas and Williamson, 1992 and references within), which constrains the age of the deposits between 55.8–50.3 m.y.a. (Alroy et al., 2000).

**2.1.3 Nacimiento-San Jose Formation contact and the Paleocene-Eocene boundary**

It has long been propagated in the literature that there is a large unconformity of ≥5.6 m.y. (Fassett et al., 2010) that separates the Nacimiento and San Jose Formations in at least the southern SJB (Barnes et al., 1954; Baltz, 1967; Smith and Lucas, 1991, Cather et al., 2019). Some researchers have interpreted the contact as an angular unconformity (Baltz, 1967; Smith and Lucas, 1991; Williamson and Lucas, 1992; Cather et al., 2019) due to the abrupt change from mudrock-dominated lithofacies to sandstone-dominant lithofacies and localized observations of angular discordance between the Nacimiento mudrock layers and the base of the overlying Cuba Mesa channels. During our investigations, we have not observed an angular discordance at the Nacimiento-San Jose contact. However, the erosional base of the laterally continuous Cuba Mesa Member basal sandstone is a composite erosion surface of amalgamated channel bases and can thus create the illusion of a discordance locally. Nevertheless, the top of the basal Cuba Mesa sandbody and the overlying mudrock deposits appear geometrically conformable to the underlying Nacimiento mudrock deposits and channel tops.

It has also been suggested that the Nacimiento-San Jose Formation contact may be transitional in nature due to interpretations that the contact is conformable in the northern SJB (Barnes et al., 1954; Stone, 1983; Smith and Lucas, 1991; Cather et al., 2019) and either unconformable or disconformable in the southern SJB (Barnes et al., 1954; Stone, 1983; Smith and Lucas, 1991; Cather et al., 2019) (Fig. 1c). Evidence cited for a conformable contact in the northern SJB include intertonguing of the Nacimiento and lowermost part of the San Jose Formation (Cuba Mesa Member) with the upper part of the upper Paleocene Animas Formation, where the presence of Tiffanian strata (61.7 - 56.8 m.y.a.; Alroy et al., 2000) indicates that the upper Paleocene strata are preserved below and/or laterally adjacent to the San Jose Formation (Fig. 1c; Smith, 1988; Smith and Lucas, 1991; Cather et al., 2019). Evidence cited for an unconformable or disconformable contact in the southern SJB include a fossil gap of at least 6 m.y. between the stratigraphically highest Paleocene mammal find (Torrejonian, 63.3 - 61.7 m.y.a.) and the stratigraphically lowest lower Eocene mammal find (Wasatchian, 55.8 - 50.3 m.y.a.) (Fig. 1c). However, the fossil localities are separated by a minimum of 90 m of stratigraphy (Lucas et al., 1981).

Because of the uncertainty over the nature of the contact, and a lack of biostratigraphic evidence in the Escavada Member of the Nacimiento Formation and the Cuba Mesa Member of the San Jose Formation, the precise location of the Paleocene-Eocene boundary cannot be determined through the studied successions (Smith and Lucas, 1991). The Paleocene-Eocene boundary in the south-central SJB is located somewhere between the base of the Escavada Member of the Nacimiento Formation and the top of the Cuba Mesa Member of the San Jose Formation (Fig. 1c; Tsentas and Lucas, 1980; Lucas et al., 1981). Despite this uncertainty, the Paleocene-Eocene boundary is commonly inferred in the literature to reside within the suggested unconformity at the Nacimiento-San Jose contact (e.g. Dickinson et al., 1988). In summary, the nature of the Nacimiento-San Jose contact and the placement of the Paleocene-Eocene boundary in the SJB remains unresolved and requires further investigation.

1. **DATASET AND METHODS**

For this study, we conducted detailed investigations in three locations where the upper part of the Nacimiento, Cuba Mesa, and Regina deposits are well-exposed in outcrop: Arroyo Chijuilla (AC) and Continental Divide (CD) in the southern SJB, and Cañon Largo (CL) in the central SJB (Fig. 1d). Approximately 720 m of stratigraphic sections were measured between these three sites. Sandstones were described at approximately 10 cm resolution based on bedsets, sedimentary structures, biogenic structures, and grain characteristics (size, shape, sorting, and composition). Mudrock deposits were described based on texture and color of the matrix and mottles at approximately 1 to 1.5 m resolution.

A regional investigation was also conducted to better understand lateral variability in the deposits across the basin. Data collected in the regional investigation include outcrop photomosaics, channel dimensions (thickness and width), channel-fill characteristics, degree of channel amalgamation (qualitative assessment), and paleocurrent measurements (Fig. 1d). Paleocurrent directions were measured from dip directions of cross strata and laminae using a pocket transit. The collection of paleocurrent measurements in fluvial deposits commonly relies on the presence of regular cross-stratification, deposited under lower-flow-regime (LFR, Froude subcritical flow) conditions. In Zellman et al. (2020) we identified the dominant sedimentary structures in the study area as upper-flow-regime (UFR) features deposited under Froude supercritical flow conditions. These low-angle and scour and fill structures are commonly confused for regular cross strata (Alexander et al., 2001; Plink-Björklund, 2015) and can result in paleocurrent directions that do not represent true paleoflow when measured using traditional techniques. Due to the paucity of LFR structures (cross strata), our current measurements are few, therefore we combine our paleoflow measurements with vector means from Smith (1988) (Fig. 1d). Smith recognized the complexity of collecting paleoflow measurements through the Cuba Mesa Member, and used vector means of random cross strata attitudes to indicate average paleoflow directions throughout the basin.

Channel measurements were taken from outcrops using a laser rangefinder mounted to a tripod. The width of laterally extensive channel-bodies was measured by collecting GPS coordinates at channel terminations. Because many outcrop faces in the Cañon Largo (CL) study area are oblique to the true channel orientation (paleoflow vector mean = 128°), we later adjusted the channel geometry measurements to account for average paleoflow direction using the following equation:

*WT = Wosin*(|128° − *β*|)

where *WT* is the adjusted channel width, *WO* is the outcrop width, 128° is the vector mean paleocurrent direction, and *β* is the directional trend of the outcrop face (heading).

Channel measurements in the southern SJB were collected from east-to-west oriented outcrops, which is approximately perpendicular to the prevailing north-to-south paleoflow direction, therefore the measurements were not adjusted.

1. **FACIES ASSOCIATIONS**

Sandstone and mudrock sedimentary facies are described in Table 1 (for more detailed descriptions see Zellman et al., 2020). These sedimentary facies occur in fluvial channel and floodplain lithosomes described below.

**4.1 Channel facies associations**

A majority of sandstone and some of the mudrock facies (Table 1) occur in erosionally based, lenticular or amalgamated lithosomes. These channel lithosomes are organized into facies associations defined by lithology, channel size, channel architecture, and degree of channel amalgamation (Table 2) (for details see Zellman et al., 2020).

Sandy channel lithosomes (FA 1) are composed of thick, erosionally bound sandstones that are both vertically and laterally amalgamated. The extensive amalgamation results in sandstone cliffs up to 100 m in height that have a massive or uniform appearance in outcrop, except for thick mud-clast conglomerates that occur at the bases of channels and between some sandstone deposits. Channel fills are dominantly composed of poorly organized sandstone and conglomerate facies with planar to low-angle, concave- to convex-up laminae or devoid of structure (~96% - S1.1, S1.2, S1.3, S1.4, S1.5, S1.6 in Table 1) and lacking discernible in-channel macroforms. The remaining parts of channel fills (~4%) comprise sandstones with steeply dipping, downstream-oriented, cross strata and laminae (S2.1, S2.5 in Table 1). Large, low-angle (<10°) downstream- or upstream-dipping accretion sets are observed in outcrops oriented approximately parallel to the prevailing flow direction (north to south). Some deposits are bioturbated from the top down or from accretion set boundaries with vertical burrows.

Heterolithic channel lithosomes (FA 2) also consist of amalgamated sandstone deposits; however, they contain mudrock strata along accretion set boundaries that result in a less amalgamated appearance in outcrop than those of FA 1. Channel fills are dominantly composed of sandstones and conglomerates with planar to low-angle, concave- to convex-up laminae or devoid of structure (~89% - S1.1, S1.2, S1.3, S1.4, S1.5, S1.6 in Table 1), but there is a larger proportion of sandstones with steeply dipping downstream-oriented cross strata and laminae (~11% - S2.1, S2.3 in Table 1) than in FA 1. Accretion sets dip downstream at a low angle (<10°) in outcrops oriented parallel to general paleoflow (north to south). The in-channel mudrock facies consist of gray (M1.3 and M1.5) or purple mudrock (M2.1).

Lenticular channel lithosomes (FA 3) are isolated and bounded by floodplain mudrock deposits. These channel deposits range from sandy to heterolithic with mud layers separating sandy accretion sets. Although still abundant, the content of sandstones and conglomerates with planar to low-angle, concave- to convex-up laminae or devoid of structure is considerably lower (~50% - S1.2, S1.3, S1.4, S1.5, S1.6 in Table 1) and sandstones with steeply dipping downstream oriented cross strata and laminae are more abundant (~50% - S2.1, S2.3, S2.4 in Table 1) than in FA 1 and FA 2. The in-channel mudrock facies consist of gray mudrock (M1.3 and M1.5 in Table 1) or purple mudrock (M2.1 in Table 1).

**4.1.1 Interpretation of channel facies associations**

The facies displaying scour and fill structures (S1.2), planar to low-angle laminae (S1.3), and convex-up long-wavelength laminae (S1.4) resemble experimentally produced sedimentary structures from Froude supercritical flow (e.g. Alexander et al., 2001; Cartigny et al., 2014; Ono et al., 2021, as well as corresponding examples of modern river flood deposits (e.g. McKee et al., 1967; Williams, 1971; Stear, 1985; Billi, 2007) and interpreted outcrop examples of Froude super- and trans-critical or UFR flow deposits of ancient rivers (e.g. Stear, 1985; North and Taylor, 1996; Fielding, 2006; Fielding et al., 2009, 2011; Allen et al., 2014; Plink-Björklund, 2015). The preservation of these structures has been attributed to high-deposition-rates (Cartigny et al., 2014; Plink-Björklund, 2015; Vellinga et al., 2018; Slootman and Cartigny, 2019; Ono et al., 2021). Both soft-sediment deformation (S1.5) and structureless sandstones (S1.6) have various proposed origins, including movement and deposition in a liquefied state, post-depositional liquefaction processes that modify or obliterate stratification, high-deposition-rates and horizontal shear, and local gravitational collapse at scour or channel margins (Lowe, 1982; Talling et al., 2013; Postma and Cartigny, 2014; Carling and Leclair, 2019). Based on their stratigraphic proximity to other planar to low-angle sedimentary structures, and on their appearance, we hypothesize that the deposits of facies S1.5 are likely the result of early post-depositional deformation of facies S1.2 - S1.4. The occurrence of some structureless sandstones (S1.6) may also be the result of rapid sediment fallout under high-deposition-rates. However, primary sedimentary structures in some strata may be poorly recognizable at outcrop due to weathering and erosion, especially where poorly cemented, and thus it is likely that the structureless facies is over represented in our dataset. Thick mud-clast conglomerates have been linked to bank undercutting and collapse due to high streamflow and rapid lowering of water level during the waning stage of floods (e.g., Coleman, 1969; Gohain and Parkash, 1990; Singh et al., 1993; North and Taylor, 1996; Tandon and Gibling, 1997). In summary, the sandstones and conglomerates with planar to low-angle, concave- to convex-up laminae or devoid of structure (facies S1.1, S1.2, S1.3, S1.4, S1.5 and S1.6) are likely indicative of deposition under Froude supercritical, upper-flow-regimes (UFR) and possibly high-deposition-rates (HDR).

Conversely, planar or trough cross-stratification (Facies S2.1) is formed by migration of dunes under subcritical flow conditions (Simons et al., 1965; Allen, 1984). Climbing cross-stratification (Facies S2.2) indicates highly aggradational dune migration under subcritical flow combined with high-deposition-rates (Allen, 1984). Climbing cross laminae (Facies S2.3) are linked to ripple migration under high-deposition-rates (Allen, 1984). Overturned cross strata or laminae (Facies S2.4) are interpreted as the product of deformation of an overriding current (Mills, 1983), since the vergence of laminae overturning is consistent with prevailing southward paleoflow direction measured from primary cross-bedding. Collectively, we interpret the facies with steeply dipping cross strata and lamina as indicative of Froude subcritical, LFR conditions.

The dominance of UFR and HDR structures (~96%), the presence of thick mud-clast conglomerates at the base of sandy deposits, and a general lack of transitions from UFR to LFR structures suggest that the FA 1 channels consist entirely of high-magnitude flood deposits or flood event beds (see e.g. Stear, 1985; Abdullatif, 1989; Chakraborty and Gosh, 2010, Plink-Björklund, 2015). Deposition during high-magnitude flood events generates distinct deposits that are bounded by erosion surfaces, or by an erosion surface below and a mud drape above (see flood units of Plink-Björklund, 2015). The dominance of UFR and HDR sedimentary structures (~89%) in the FA 2 channels also suggests that most deposition occurred at high flow velocities and deposition rates. Vertical transitions from UFR to LFR structures in FA2 indicate significant deposition also during the waning phase of floods (Jones, 1977). The in-channel mud layers capping flood units may result from the final stages of flood events, as observed in modern river systems in dryland and monsoonal settings after major floods (e.g. Stear, 1985; Abdullatif, 1989; Singh et al., 1993; Billi, 2007). The presence of LFR structures in FA 3 channels indicates a less rapid decline in flood strength and greater preservation of waning phase deposits (e.g. Abdullatif, 1989; Plink-Björklund, 2015) or a greater degree of post-flood reworking of sediment under subcritical flow conditions. The presence of in-channel bioturbation in the FA 1 and FA 2 lithosomes and in-channel pedogenic modification in the FA 2 lithosomes implies that the channels were seasonally or inter-annually dry or had low perennial base flow (Hasiotis et al., 2007).

An abundance of UFR and HDR sedimentary structures, in-channel bioturbation and pedogenic modification of in-channel mud layers, thick mud-clast conglomerates, soft-sediment deformation structures, and the lack of preserved large-scale strata indicative of bars are key features that can be linked to deposition in river channels with strongly variable discharge, characterized by pronounced fluctuations between high-magnitude floods and periods of little to no discharge (see reviews by Fielding, 2006; Fielding et al., 2009, 2018; Plink-Björklund, 2015; 2019 and references therein). Thus, we identify the FA 1, FA 2, and FA 3 channel facies associations as deposits of variable discharge rivers (see also Zellman et al., 2020).

**4.2 Floodplain facies associations**

A majority of the mudrock and some sandstone facies (Table 1) occur in floodplain lithosomes that are organized into facies associations defined by dominant matrix colors, ped structure, and presence of mottling and/or nodules as indicators of soil drainage conditions (Table 2) (for more detailed descriptions see Zellman et al., 2020).

Poorly drained floodplain lithosomes (FA 4) consist of multiple sets of vertically stacked mudrock deposits interbedded with thin, tabular or lenticular, and poorly cemented structureless sandstone (2% - S1.6 in Table 1). The mudrock deposits contain dominantly gray-brown-black facies (95% - M1.1, M1.2, M1.3, M1.4, M1.5 in Table 1). Rare purple deposits are also observed (3% - M2.1 in Table 1). Vertical successions show alternations of mudrocks lacking visible evidence of pedogenic modification and commonly exhibiting preserved organic matter and/or relict lamination (M1.3 and some deposits of M1.5) with more strongly developed paleosols displaying soil structure (peds) and/or mottling (M1.2, M1.4, and deposits of M1.5 with weak to moderate angular blocky peds).

Variably drained floodplain lithosomes (FA 5) also consist of multiple sets of vertically stacked mudrock deposits interbedded with thin, tabular or lenticular, and poorly cemented structureless sandstone (32% - S1.6 in Table 1). However, the mudrock consists of alternating horizons of gray-brown-black (46% - M1.3, M1.4, M1.5 in Table 1) and purple-red facies (22% - M2.1, M2.2, M2.3 in Table 1). Similar to FA 4, these vertical successions show alternations of mudrock deposits lacking visible pedogenic modification (M1.3 and some deposits of M1.5) and paleosols. However, the paleosols in this facies association contain moderately to strongly developed peds and abundant slickensides.

Well drained floodplain lithosomes (FA 6)consist of multiple sets of vertically stacked mudrock deposits interbedded with thin, tabular or lenticular, and poorly cemented structureless sandstone (28% - S1.6 in Table 1) and a high occurrence of purple-red mudrock facies (42% - M2.1, M2.2, M2.3 in Table 1) and lesser gray-brown-black facies, which are almost all classified as mudrock lacking pedogenic modification (30% - M1.5 in Table 1). The palesols in this facies association contain blocky to wedge-shaped peds, abundant slickensides, mottling, and carbonate nodules.

**4.2.1 Interpretation of floodplain facies associations**

Black (Facies M1.2) and dark brown colors (Facies M1.3) are commonly attributable to the presence of organic matter or manganese oxide minerals (Vepraskas, 2016; Tabor et al., 2017). Gray or green colors (Facies M1.1, M1.4 and M1.5) are the result of reduction of ferric minerals or removal of organic matter and oxides, which are processes associated with water saturation and anoxia (Farnham and Kraus, 2002; Vepraskas, 2016; Tabor et al., 2017). Deposits exhibiting weak to moderate blocky peds (Table 1) are interpreted as former soil horizons (paleosols) of varying maturity (Retallack, 1988). Many of the structureless deposits that contain visible plant fragments and quartz granules (Facies M1.5) were likely buried before pedogenesis could take place (Mack et al., 1993; Tabor et al., 2017). In summary, the gray-brown-black mudrock deposits are consistent with poorly drained soil conditions and/or lesser degrees of pedogenic modification in floodplain mudrocks.

The coloring of the purple-red deposits is attributed to the presence of hematite, an iron oxide mineral resulting from the soil being moderately to well drained and oxidizing (Retallack, 1988). Deposits with a purple matrix are interpreted as having weaker hematite impregnation compared to deposits with a red matrix (Kraus et al., 2013). Mottles are redoximorphic features produced by soil gleying, and they indicate that the soils were episodically saturated (Farnham and Kraus, 2002). Gray mottles are also attributed to root traces and are thought to be a redoximorphic depletion feature formed when stagnating surface water seeps downward along root channels and, in the presence of organic matter, iron is reduced and removed (Kraus and Hasiotis, 2006). The presence of slickensides indicates repeated shrinking and swelling of clays due to fluctuations in the water table (e.g., Bigham et al., 2002; Kraus and Riggins, 2007). Most deposits of these facies are interpreted as paleosols based on the presence of peds, and in some cases, mottling indicative of root traces (Retallack, 1988) (Table 1). Deposits with well-developed structure are interpreted as mature paleosols, formed over longer intervals of time, in stable landscapes, or under intense weathering conditions (Marriott and Wright, 1993; Kraus, 1999; Tabor et al., 2017). The wedge-shaped peds that are common in these deposits are thought to form only in soil profiles where seasonal precipitation and abundant fine clay combine to induce shrink-swell processes (Tabor et al., 2017). In summary, the purple-red mudrock deposits indicate moderate- to well-drained soil conditions in floodplain environments.

The dominantly gray-brown-black deposits of FA 4 indicate a frequently wet depositional environment. The interbedding of gray-brown-black and purple-red paleosols in FA 5 suggests alternating wet and dry periods on the floodplain. The high proportion of purple-red paleosols and a lack of gray-brown-black paleosols in FA 6 indicates that the floodplain was sustainably dry. Alternations between paleosols and mudrock lacking pedogenic modification, as seen in FAs 4-6, indicate variations in the balance between sediment accumulation and the rate of pedogenesis (Marriott and Wright, 1993; Kraus, 1999). The poorly cemented structureless sandstones (S1.6) are interpreted as crevasse splays where thin and tabular, and channel deposits where thick and lenticular. The crevasse splay deposits indicate partial avulsions, which causes channels to shift their positions on the floodplain (Bridge and Leeder, 1979; Jones and Schumm, 1999). This process can terminate sedimentation to part of the floodplain for a period of time, leading to pedogenic modification of surface deposits (Kraus, 1999). Meanwhile, the location occupied by the overbank flow of the partial avulsion experiences a high rate of sedimentation that prevents pedogenic development (Kraus, 1999).

1. **PALEOCURRENT MEASUREMENTS**

Paleocurrent directions for this study were measured from the maximum dip direction of cross strata. Combined with vector means from Smith (1988), the dataset indicates a dominantly southward (ranging from southwest to southeast) fluvial sediment transport direction in the Escavada Member of the Nacimiento Formation and San Jose Formation (Fig. 1d). In the northern and central SJB, the paleoflow measurements show a clear dominance of sediment transport to the southeast. In the southern SJB, paleocurrent measurements are more variable with southwest to southeast transport. Textural and sorting trends are another indicator of a generally north to south paleoflow. In general, grain size is overall coarser and the sorting is poorer in both channel fill and floodplain deposits in the northern sector of the basin than in the southern sector (Fig. 3) (Zellman et al., 2020).

Some of the measurements collected show a bimodal distribution of paleoflow directions (Fig. 1e). The deposits from which these measurements were collected have the appearance of ‘regular’ cross strata (Fig. 2a), but when these structures are traced laterally, it is apparent that they grade into near-horizontal or low-angle laminasets, which distinguishes them from sets of regular cross strata (Fig. 2b). In the absence of evidence for other depositional environments commonly associated with bimodal paleoflow directions (e.g. tidal), and by comparison with experimentally produced upper-flow-regime (UFR) sedimentary structures (Cartigny et al., 2014), these measurements that are 180 degrees offset from the prevailing flow directions were likely collected from backsets that record upstream migration of antidune and/or cyclic step bedforms under Froude supercritical flow conditions (see Cartigny et al. 2014; Ono et al. 2020).

1. **ARCHITECTURAL AND STRATIGRAPHIC RELATIONSHIPS**

**6.1 Architectural styles**

Vertical changes in the proportion of sandstone and mudrock deposits have long been used to distinguish the Escavada, Cuba Mesa, and Regina Members in the San Juan Basin (Fig. 3) (Baltz, 1967). The principal differences between the members are the ratio of sandstone to mudrock lithofacies, channel size, degree of channel amalgamation, and facies composition. Based on these differences, we have identified three major depositional architectural styles: 1) amalgamated channels and minor (<20%) floodplain, 2) heterolithic channels and (20-60%) floodplain, and 3) isolated channels and dominant (>60%) floodplain (Fig. 4).

The amalgamated channels and minor floodplain deposits architectural style (AS 1) consists of vertically and laterally amalgamated sandy channel lithosomes (FA 1) ~10-50 m thick and 172-1564 m wide, separated by 2-20 m thick successions of floodplain lithosomes (FA 5 or FA 6) (Fig. 4a). The lateral and vertical amalgamation of the channel lithosomes results in thick (up to ~100 m) and laterally extensive packages of this architectural style that can be traced in some outcrops for >1 km. The associated floodplain deposits consist of variably drained lithosomes (FA 5) in the Cuba Mesa Member and well-drained floodplain lithosomes (FA 6) in the Regina Member. The overall thickness of units with this architectural style ranges from 15-100 m.

The heterolithic channels and floodplain deposits architectural style (AS 2) consists of complexes of heterolithic channel lithosomes (FA 2), 5-13 m thick and 94-312 m wide, separated by relatively thicker successions (10-25 m) of floodplain lithosomes (FA 4 or FA 5) compared to AS 1 (Fig. 4b). The associated floodplain deposits consist of poorly drained lithosomes (FA 4) in the Escavada Member of the Nacimiento Formation and variably drained floodplain lithosomes (FA 5) in the Cuba Mesa Member of the San Jose Formation. Crevasse splay deposits make up approximately 17% of the floodplain lithosomes.

The isolated channels and dominant floodplain deposits architectural style (AS 3) consists of isolated and lenticular channels (FA 3), 2-17 m thick and 27-282 m wide, bound laterally and vertically by thick floodplain deposits (10-34 m) (FA 4 or FA 6) (Fig. 4c). The associated floodplain deposits consist of poorly drained lithosomes (FA 4) in the Nacimiento Formation and well drained floodplain lithosomes (FA 6) in the Regina Member of the San Jose Formation. Crevasse splay deposits make up approximately 30% of the floodplain lithosomes.

**6.2 Lateral trends**

Flow perpendicular (east to west) trends are evaluated by comparing the Arroyo Chijuilla and Continental Divide measured sections (Fig. 3), field mapping, and oblique aerial photos (Fig. 5) collected along outcrops in the southern San Juan Basin. The Continental Divide study area is located approximately 9 km west of the Arroyo Chijuilla study area (Fig. 1d). The exposure of the outcrops is poor between the two study areas, making it challenging to trace channel complexes laterally across the whole distance. Therefore, lithologic similarities in sand-to-mudrock ratio, sandstone and paleosol facies assemblages, facies associations and architectural styles are used to correlate the sections, which are hung from a datum placed at the contact between the Cuba Mesa and Regina Members (Fig. 3). Due to the somewhat limited outcrop exposure in the Continental Divide study area, comparisons between deposits of the Nacimiento Formation are not possible. The Continental Divide study area contains a greater abundance of mudrock lithofacies in the Cuba Mesa and Regina Members of the San Jose Formation (46%) than in Arroyo Chijuilla (39%) (Fig. 3). The AS 1 and AS 2 deposits display reduced thicknesses in the Continental Divide study area compared to the Arroyo Chijuilla section (decreases of 53% and 56%, respectively). The AS 3 deposits show an increased abundance of floodplain and crevasse splay deposits (Fig. 5). Due to the increased abundance of mudrock and the decreased volume of sandstone deposits, the Continental Divide section appears thinner in comparison, with a total of 40.75 m of Cuba Mesa and 116.67 m of Regina outcrop measured in Continental Divide and 158.38 m of Cuba Mesa and 127.49 m of Regina outcrop measured in Arroyo Chijuilla (Fig. 3).

Lateral trends in the flow parallel direction (north to south) are evaluated by comparing the detailed measured sections from Cañon Largo study area in the central SJB with the Arroyo Chijuilla and Continental Divide study areas, located approximately 80 km to the southeast (Fig. 3), and from channel measurements (Fig. 6) and photomosaics collected in the northern, central, and southern San Juan Basin (Figs. 1 and 7). Through these comparisons, significant changes are observed in sandstone/mudrock ratio, grain size (Fig. 3), average channel size (Fig. 6), and degree of channel amalgamation from north to south (Fig. 7).

The percentage of sandstone vs. mudrock is calculated from the measured sections from the Cañon Largo, Arroyo Chijuilla, and Continental Divide study areas (Fig. 3). Due to the limited amount of the Nacimiento Formation that could be measured from outcrop, we only include data from the Cuba Mesa and Regina Members. These data show a decrease in the percentage of sandstone from north to south, and thus an increased abundance of mudrock. The Cuba Mesa and Regina deposits in Cañon Largo are composed of 72% sandstone lithofacies (22% mudrock, 6% covered), compared to 55% sandstone (39% mudrock, 6% covered) in Arroyo Chijuilla and 50% sandstone (46% mudrock, 4% covered) in Continental Divide.

Grain sizes in the sandstone deposits are overall coarser in northern and central SJB than in the southern study areas, with most common grain sizes in channels changing from an abundance of very coarse to coarse sand in Cañon Largo to a wider range of grain sizes spanning from very coarse to fine sand in the southern Continental Divide and Arroyo Chijuilla study areas (Fig. 3). In addition, the floodplain deposits show a greater abundance of silt in Cañon Largo and a dominance of clay in Continental Divide and Arroyo Chijuilla (Fig. 3).

The thickness and width of channel lithosomes also decreases from north to south (Fig. 6). Channel fills in the upper part of the Nacimiento decrease from an average depth of 19.8 m and average width of 358.8 m in Cañon Largo to an average depth of 6.0 m and average width of 138.9 m in Arroyo Chijuilla (average decrease of 69% in height and 61% in width). The Cuba Mesa channels decrease from an average depth of 26.9 m and average width of 979.2 m in Cañon Largo to an average depth of 11.9 m and average width of 300.7 m in Arroyo Chijuilla (average of 56% decrease in height and 69% decrease inwidth). The Regina channels decrease from an average depth of 8.7 m and average width of 378.0 m in Cañon Largo to an average depth of 7.3 m and average width of 118.2 m in Arroyo Chijuilla (average decrease of 16% in height and 69% in width).

There is an overall decreasing trend in channel amalgamation from north to south that is best observed in the photopanels of the Cuba Mesa Member (Fig. 7). The most laterally and vertically amalgamated channel complexes are in the northern SJB (Fig. 7a) and are dominated by AS 1. In Cañon Largo (central SJB), the channel complexes are still laterally amalgamated, but there is a visible decrease in the degree of vertical amalgamation (Fig. 7b). These channel complexes still meet the recognition criteria for AS 2, but they are separated by significant intervals of floodplain deposits (~2-4 m thick). In the southern SJB, channel complexes are still laterally and vertically amalgamated, but typically separated by thicker floodplain deposits (~10-25 m) (Fig. 7c). These channel complexes are composed of both the AS 1 and AS 2. In addition, a relative increase in the volume of crevasse splay deposits is observed in the southern SJB, in association with the increased abundance of floodplain deposits (Fig. 7c).

**6.3 Vertical Stratigraphic trends**

The Escavada Member of the uppermost part of the Nacimiento Formation is characterized by an upward shift from AS 3 to AS 2 (Fig. 8a; Fig. 9a). In the northern and central San Juan Basin, this change is observed as a gradual increase in channel size and degree of amalgamation (Fig. 9a). In the southern San Juan Basin, the shift appears more abrupt (Fig. 8a). The floodplain deposits within the Escavada member consist of poorly drained floodplain lithosomes (FA 4).

The base of the Cuba Mesa Member of the San Jose Formation is characterized by a shift to AS 1 (Fig. 8a; Fig. 9a; Fig. 10a,b). The abrupt lithologic change characterizes the Nacimiento-San Jose Formation contact in the southern San Juan Basin (Baltz, 1967) (Fig. 10b). The transition in the central and northern San Juan Basin is gradational, making it more difficult to pinpoint the precise location of the contact (Fig. 10a). In the southern Arroyo Chijuilla and Continental Divide study areas, the Cuba Mesa Member comprises three sandstone intervals (lower part of the Cuba Mesa, middle part of the Cuba Mesa, and upper part of the Cuba Mesa) separated by thick mudrock deposits (Fig. 8a,b,c; Fig. 11a). In these southern SJB study areas, only the lower part of the Cuba Mesa channel complex consists of AS 1 (Fig. 8a). The middle and upper channel complexes are more heterolithic (FA 2), and consist of AS 2 (Fig. 8b,c; Fig. 11a). In Cañon Largo, located in the central SJB, the Cuba Mesa Member is dominated by AS 1, and lacks the up section increase in channel-fill heterogeneity and floodplain abundance (Fig. 9a). In all three study areas, the floodplain deposits within the Cuba Mesa Member consist of the variably drained floodplain lithosome (FA 5), which is observed between channels and channel complexes (Fig. 8b,c; Fig. 9a; Fig. 11a).

The transition from the Cuba Mesa Member to the overlying Regina Member of the San Jose Formation is characterized by an initial shift to AS 3. However, the bounding floodplain deposits consist of well-drained facies associations (FA 6) (Fig. 8c; Fig. 9b), which contrasts with the poorly drained floodplain deposits (FA 4) observed bounding the similarly isolated channels in the Escavada Member of the Nacimiento Formation. In the Cañon Largo and Continental Divide study areas, another upward shift to AS 1 occurs higher in the Regina Member (Fig. 9b and 11b). This shift is abrupt in both study areas. In the Continental Divide study area, this amalgamated sandy channel complex is overlain by another succession of well-drained floodplain deposits (FA 6), although outcrop exposure is very limited (Fig. 11b).

In summary, there are at least two large-scale transitions from AS 3 to AS 1 that can be observed basin wide (Fig. 12). The first one extends from the Ojo Encino and Escavada Members of the Nacimiento Formation into the Cuba Mesa Member of the San Jose Formation. The second one is observed in the Regina Member of the San Jose Formation. In the southern SJB, the stratigraphic interval from the middle to upper part of the Cuba Mesa Member shows a reverse trend to increased heterogeneity and a return to AS 2. This trend is observed up to the Cuba Mesa-Regina contact where the second AS 3 to AS 1 package begins (Fig. 12b). In the central SJB, this reversal is not observed (Fig. 12a). Outcrop exposure of the upper Regina Member is limited, therefore it is not possible to determine if additional upward-coarsening successions were present. The bounding floodplain deposits transition from poorly drained (FA 4) in the uppermost part of the Nacimiento Formation to variably drained (FA 5) in the Cuba Mesa Member of the San Jose Formation. The floodplain deposits become increasingly well drained through the remainder of the Cuba Mesa Member and into the Regina Member, where purple-red mudrock facies are the most abundant (FA 6) (Fig. 12).

1. **DISCUSSION**

**7.1 Interpretation of Architectural styles**

The high degree of channel amalgamation, the cross-cutting channel relationships, and absence of lateral accretion sets in AS 1 and AS 2 indicates high avulsion rates (Jones and Hajek, 2007). The high degree of channel amalgamation is a function of high channel return frequency (Hajek and Wolinsky, 2012; Hajek and Edmonds, 2014). Avulsions are most commonly driven by high channel bed aggradation rates (Bryant et al., 1995; Mohrig et al., 2000; Berendsen and Stouthamer, 2001; Makaske, 2001; Jerolmack and Mohrig, 2007; Sinha and Sarkar, 2009; Hajek and Edmonds, 2014), supported in this study by the abundance of HDR structures and the preservation of UFR structures in the channel deposits. This high channel return frequency is likely also the reason for low preservation of floodplain facies in AS 1. Conversely, the lower degrees of channel amalgamation and higher preservation of floodplain facies in AS 2 and AS 3 suggest either less frequent avulsions and/or a lower channel return frequency.

Such architectural styles have also been linked to changes in accommodation, especially in sequence stratigraphic framework (*sensu* Shanley and McCabe, 1994). Later work has, however, shown that these architectural characteristics alone do not permit accommodation-based interpretations and have criticized sequence stratigraphic practice in application to fluvial successions (e.g., Colombera et al., 2015). Moreover, modern fluvial fans have shown to be landforms that build up to 100 m of topography above the surrounding floodplain, rather than fill accommodation (Chakraborty et al., 2010: Chakraborty and Ghosh, 2010). While lateral space availability is critical for fan formation (North and Warwick, 2007), subsidence is important for preservation but not accumulation of fans (Frostick and Steel, 1993; Jones, 2002). We thus do not interpret the architectural style changes in terms of accommodation or subsidence, especially as Holocene fans have been documented to accumulate stratigraphy in the order of 100 m at millennial timescales (Chakraborty et al., 2010; Assine et al., 2014). Our approach is further supported by the lateral relationships in architectural styles.

**7.2 Interpretation of Lateral Trends**

The most significant basin-scale changes in sandstone vs. mudrock percentage, grain size (Fig. 3), average channel size (Fig. 6), and degree of channel amalgamation (Fig. 7) are observed in the flow-parallel direction from north to south. This spatial trend indicates a proximal to distal relationship between the depositional styles and the location of deposits within the fluvial system. The observed downstream decrease in channel size suggests that distal channels transported lesser discharge than channels in the more proximal parts of the system. Such decreases in discharge may result from high rates of water loss to the floodplain, infiltration, or through evaporation (Singh et al., 1993; Shukla et al., 2001; Fisher et al., 2007; Nichols and Fisher, 2007; Weissmann et al., 2013; 2015). The downstream decrease in channel size differs from what is expected of tributive river systems where increasing amounts of water are added to the trunk and the channel capacity increases accordingly (see also Weissmann et al., 2015). These interpretations are further corroborated by the prevailing north-to-south paleoflow direction (Fig. 1d).

While we observe distinct lateral trends in channel architecture, there are no lateral trends in floodplain paleosols, as have been suggested to occur in some other fluvial fan systems, where well-drained soils predominate in proximal areas, with decreasing drainage through medial and poor drainage in distal areas as a function of the spring line (water table) on the fan (e.g. Weissmann et al., 2013; Hobbs and Fawcett, 2022).

In addition to the proximal to distal changes in channel size and degree of amalgamation, we have observed other characteristics that diverge from tributary river systems, including the large lateral extent of the system. The lateral extent of the Cuba Mesa Member of the San Jose Formation covers at least 8000 km2, based on calculations of the area of the basal Cuba Mesa channel complex (Smith, 1988). Furthermore, the abundant crevasse splay deposits throughout the study interval suggest local avulsions and unconfined flow were the key process of lateral river mobility and sediment distribution within the system (Bryant et al., 1995; Mohrig et al., 2000; Berendsen and Stouthamer, 2001; Makaske, 2001; Jerolmack and Mohrig, 2007; Sinha and Sarkar, 2009; Hajek and Edmonds, 2014).

**7.3 Comparison to Modern and Ancient Fluvial Fans**

The sedimentary and hydraulic geometry trends described above are indicative of successions accumulated by fluvial fans (sensu. DeCelles and Cavazza, 1999; Leier et al., 2005; Hartley et al., 2010; Weissmann et al., 2010; Latrubesse, 2015; Ventra and Clarke, 2018; Martin et al., 2021). The diagnostic sedimentological attributes of ancient fluvial fan successions include 1) a progressive downstream decrease in grain size, 2) a decrease in channel depth and width, 3) an increase in overbank preservation, crevasse-splay or sheetflood deposition on a basin scale, and 4) a decrease in lateral and vertical connectivity of channel deposits (DeCelles and Cavazza, 1999; Horton and DeCelles, 2001; Shukla et al., 2001; Nichols and Fisher, 2007; Cain and Mountney, 2009; Weissmann et al., 2010; Martin et al., 2021). These trends have been documented in modern (Singh et al., 1993; Shukla et al., 2001; Chakraborty et al., 2010) and ancient fluvial fans (Kukulski et al., 2013; Owen et al., 2015, 2017; Chesley and Leier, 2018; Batezelli et al., 2018; Aliyuda et al., 2019; Wang and Plink-Björklund, 2019; Martin et al., 2021), and are included in fluvial (mega)fan and DFS depositional models (Singh et al., 1993; Shukla et al., 2001; Weissmann et al., 2013, 2015). Below we compare our observations from fluvial facies and architecture styles with documented modern and ancient examples of proximal, medial, and distal large fluvial fans.

The amalgamated channels and minor floodplain deposits architectural style 1 (AS 1) (Fig. 4a) is preserved in the greatest abundance in the northern and central SJB. The proximal deposits of modern large fluvial fans (Singh et al., 1993; Shukla et al., 2001; Chakraborty et al., 2010) and ancient large fan systems (Kukulski et al., 2013; Owen et al., 2015, 2017; Batezelli et al., 2018; Aliyuda et al., 2019; Wang and Plink-Björklund, 2019; Martin et al., 2021) have commonly been documented as consisting of amalgamated channel belts with relatively coarse-grained infills and limited preservation of fine-grained floodplain material. The degree of channel amalgamation is highest in the most proximal fan where the fan area is smallest (Fig. 4d), and the aggradation rates and channel return frequency are highest (Chakraborty and Ghosh, 2010; Hajek and Wolinsky, 2012; Weissmann et al., 2013, 2015; Ventra and Clarke, 2018). Thus, the intervals that are dominated by amalgamated channels (AS 1) are herein interpreted as proximal fan facies (Fig. 4a).

The heterolithic channels and floodplain deposits architectural style 2 (AS 2) (Fig. 4b) closely resembles descriptions of medial fan deposits in that they characteristically show increased spacing between channel deposits and decreased channel belt size (Singh et al., 1993; Shukla et al., 2001; Weissmann et al., 2013; Owen et al., 2015, 2017; Batezelli et al., 2018; Chesley and Leier, 2018; Aliyuda et al., 2019; Wang and Plink-Björklund, 2019; Martin et al., 2021). These proximal to medial changes are attributed to losses from infiltration and the fan covering a wider area. In addition, a higher percentage of fine-grained material is deposited and has the potential to be preserved as a result of lower coarse sediment supply and decreased flow strength (Weissmann et al., 2013), creating more complex, heterolithic internal architecture (Moscariello, 2018) (Fig. 4b).

The isolated channels and dominant floodplain deposits architectural style 3 (AS 3) is consistent with observations of distal fan facies (Fig. 4c). Distal fan deposits commonly consist of isolated channel fills within dominantly muddy floodplain deposits (Shukla et al., 2001; Weissmann et al., 2013; Chesley and Leier, 2018; Moscariello, 2018; Martin et al., 2021). The more isolated channels are thought to result from a continued widening of the area covered by the fan and additional losses from infiltration (Singh et al., 1993; Shukla et al., 2001; Weissmann et al., 2015). ~~These interpretations are further corroborated by the prevailing north-to-south paleoflow direction (Fig. 1d).~~

**7.4 Interpretation of Vertical Stratigraphic Trends**

The general stratigraphic trend in which dominantly fine-grained overbank deposits with minor volumes of isolated, coarser channel fills (distal AS 3 fan facies) are progressively overlain by more sand rich, larger, and increasingly amalgamated channel bodies, with lesser volumes of preserved fine-grained overbank strata (medial AS 2 to proximal AS 1 facies) resembles the progradational packages that have been documented in modern (Shukla et al., 2001; Chakraborty et al., 2010; Sinha et al., 2014) and ancient (Willis, 1993; DeCelles and Cavazza, 1999; Nakayama and Ulak, 1999; Uba et al., 2005; Weissmann et al., 2013; Wilson et al., 2014; Owen et al., 2015, 2017; Batezelli et al., 2018; Wang and Plink-Björklund, 2019) fluvial fans. This trend is also a key recognition criterion in the prograding DFS stratigraphic model (Weissmann et al., 2013). Furthermore, the lateral extent of these large-scale stratigraphic trends suggests that they reflect whole fan progradation. Based on this interpretation, we document at least two of these whole fan progradational packages: the first extending from the Ojo Encino and Escavada Members of the Nacimiento Formation into the Cuba Mesa Member of the San Jose Formation (Fig. 12), and the second in the Regina Member of the San Jose Formation. However, proximal to distal changes in the gradational vs. abrupt nature of these progradational packages (Fig. 10, Fig. 12) suggests additional depositional complexity. There is an interval in the southern study areas between the progradational packages that extends from the middle to upper parts of the Cuba Mesa Member to the Cuba Mesa-Regina contact that appears to show a reversal of the progradational trend, with increased heterogeneity and floodplain deposits (a shift from proximal to medial fan facies) (Fig. 12b). This reversal could reflect a phase of retrogradation of the fan system, however this trend is not observed in the central SJB (Fig. 12a), and an alternative explanation could be lobe switching (see below).

**7.5 Fluvial Fan Progradation and Retrogradation**

Prograding fluvial fan successions are common in the geological record (e.g. Willis, 1993; Nakayama and Ulak, 1999; Shukla et al., 2001; Uba et al., 2005; Nichols and Fisher, 2007; Wilson et al., 2014; Owen et al., 2015, 2017; Batezelli et al., 2018; Wang and Plink-Björklund, 2019). However, the occurrence of stacked progradational packages, such as we propose in the San Juan Basin (Fig. 12), are rarely recognized in the literature (Luzón, 2005; and possibly Schneider et al., 2006 as hypothesized by Weissmann et al., 2013; Leary et al., 2015; Wang and Plink-Björklund, 2019), and recognition criteria for retrograding fluvial fans have not been established (Ventra and Clarke, 2018) due to a paucity of identified retrogradational successions in the geological record (exceptions include Luzón, 2005; Kukulski et al., 2013). In addition, causal mechanisms for fan progradation-retrogradation remain one of the major unanswered questions about fluvial fans.

The stacked progradational packages characterized by a sharp change from proximal fan facies associations to distal fan facies associations with no depositional evidence of fan backstepping, as observed in the northern and central San Juan Basin (Fig. 12a), may suggest a period of fan inactivity followed by reactivation. The stacked progradational packages with an intervening gradual decrease in channel amalgamation observed in the middle and upper part of the Cuba Mesa Member in the southern study areas (Fig. 12b) may suggest progradation, followed by backstepping toward the hinterland. Alternatively, this proximal to medial variability may be the result of lobe avulsions. Modern fans commonly consist of several aggradational lobes, which are formed by spatial clustering of channel avulsions (Assine and Silva, 2009; Chakraborty et al., 2010; Chakraborty and Ghosh, 2010; Assine et al., 2014) and show the concomitant presence of active lobe and abandoned older lobes on fan surfaces (Assine, 2005; Chakraborty and Ghosh, 2010; Weissmann et al., 2013). Wang and Plink-Björklund (2019) suggest that avulsion- and lobe-scale progradation may explain some intermediate-scale upward thickening trends and lateral variations.

Regardless of the cause of the decreasing trend in channel amalgamation in the middle and upper parts of the Cuba Mesa Member, the overlying relatively sharp transition to isolated channels in the basal Regina Member may suggest that the fan became inactive around the same time that activity ceased in the northern to central San Juan Basin. These lateral differences may indicate that the downstream extent of the fan reached a maximum point of progradation with the deposition of the lower Cuba Mesa Member in the southern San Juan Basin and that sediment delivery decreased prior to fan deactivation, whereas the upstream portions of the fan may have remained active until fan deactivation. This portion of the fan was later reactivated, resulting in a second episode of whole fan progradation that deposited the Regina Member of the San Jose Formation.

The limited amount of literature on stacked prograding fluvial fan systems provides little basis of comparison with other ancient systems. In the Oligocene to Miocene Ebro Basin, Spain, Luzón (2005) interpreted that two coarsening- to fining-upward packages record two cycles of fan progradation-retrogradation. In the central portions of the basin, these trends are characterized by either gradual changes from coarsening-upward to fining-upward or by sudden shifts suggesting upstream facies belt shifts. In addition, similar observations of finer-grained deposits overlying coarser-grained deposits have been made in the Kosi megafan in the Himalayan foreland basin, India (Sinha et al., 2014). This trend differs from other Quaternary fluvial fans that commonly indicate a period of fan inactivity and incision capping prograding fan packages (Weissmann et al., 2002; Gibling et al., 2005; Latrubesse et al., 2012; Roy et al., 2012; Assine et al., 2014; Fontana et al., 2014).

**7.6 Controls on Fan Progradation-Retrogradation**

While tectonic subsidence is certainly relevant to the long-term preservation of thick stratigraphic records, and fluvial fan formation is linked to high sediment supply common in orogenic belts (North and Warwick, 2007), there is a lack of evidence for tectonic controls on the episodes of fan progradation in the Paleogene San Juan Basin. For example, the size of extrabasinal clasts does not change markedly through the stratigraphic column (Fig. 3), and there is no evidence of tectonic unconformities. However, the size of channels, degree of amalgamation, and the abundance of UFR and HDR sedimentary structures linked to supercritical flow conditions fluctuate considerably. While channel size scales with discharge, and thus with drainage basin size (e.g. Syvitsky and Milliman, 2007), and could be controlled by tectonic processes, the proportion of supercritical flow sedimentary structures is a function of hydroclimate and independent of tectonic processes.

Examples from Quaternary fluvial fans also suggest that climate is a key control on fan progradation and retrogradation. Progradation of fans is commonly linked to conditions of high precipitation variability and associated high discharge variability, such as during the Pleistocene middle to late pleniglacial period (Latrubesse and Kalicki, 2002; Latrubessee, 2003; Latrubesse and Franzinelli, 2005; Latrubesse et al., 2012; Valente and Latrubesse, 2012; Assine et al., 2014) or due to variable discharge from glacial outwash during the last glacial maximum (Weissmann et al., 2002; Fontana et al., 2008; 2014). In contrast, fan retrogradation in the form of abrupt shifts towards the hinterland and periods of fan inactivity and incision have been suggested as responses to: 1) a change from a highly seasonal to more arid climate (Valente and Latrubesse, 2012), 2) a change from semiarid and flashy precipitation to more sustained rainfall and increased vegetation cover (Assine et al., 2014), 3) an increase in monsoon intensification (Roy et al., 2012), or 4) a decrease in sediment supply due to glacial retreat (Fontana et al., 2014). Despite the differences, all these interpretations suggest that fan activity is largely controlled by changes in discharge variability ultimately linked to millennial-scale changes in climate.

In the Paleogene San Juan Basin, the stratigraphic transition from poorly drained floodplain deposits to increasingly well-drained floodplain deposits reflects an overall trend toward increased aridity into the early Eocene (Zellman et al., 2020 and references within). These changes become more pronounced in the Regina Member of the San Jose Formation, where an increased abundance of purple-red paleosols suggests increased aridity over the underlying deposits of the Cuba Mesa Member. By combining evidence from channel and floodplain facies associations, we hypothesize that the stratigraphic trends in the San Juan Basin suggest a shift from an overall more monsoonal precipitation regime during deposition of the Escavada Member of the Paleocene Nacimiento Formation to fluctuating subhumid and semiarid during deposition of the Cuba Mesa Member of the lower Eocene San Jose Formation, to semiarid to arid during deposition of the Regina Member (see also Zellman et al., 2020). These findings suggest that the stratigraphic patterns observed in the study interval likely resulted from fluctuations in geomorphically effective discharge attributed to changing magnitudes of precipitation variability and changing climatic conditions. Progradation of the Cuba Mesa may be linked to a system clearing event that we hypothesize may have occurred as the climate shifted toward more arid conditions, by which reduction in vegetative cover, erosion of soils, and an increase in sediment yield resulted in a pulse of more efficient clastic transport basinward (Zellman et al., 2020). The second episode of fan progradation observed in the Regina Member may have resulted from long-term cycles of monsoon variability at millennial or orbital timescales, but the lack of time constraints precludes more detailed analysis at this time.

**7.4 Climate controls on fluvial fan development**

The link between fluvial fan occurrence and specific climate conditions remains a topic of active debate. Some researchers have suggested that the formation of large fluvial fans requires seasonal and highly variable precipitation (e.g. Singh et al., 1993; Shukla et al., 2001; Leier et al., 2005), citing evidence that modern and ancient examples of large fluvial fans have been linked to moderate to extreme seasonal fluctuations in discharge that result from highly seasonal precipitation patterns. The tendency for rivers with large fluctuations in discharge to construct large fluvial fans is thought to be related to the instability of channels, which results in rapid channel mobility and frequent avulsions that ultimately create distinctive fan-shaped landforms (Sinha and Friend, 1994; Horton and DeCelles, 2001; Leier et al., 2005; Hansford and Plink-Björklund, 2020). Leier et al. (2005) observed that the global distribution of modern megafans is primarily restricted to 15°-35° latitude in the Northern and Southern Hemispheres, corresponding to climatic belts that fringe the tropical climatic zone. Rivers in this climatic zone receive more than 80-90% of their annual precipitation during the summer monsoon season (Wang and Ding, 2008). The intense summer rainfall causes high-magnitude flooding in rivers that otherwise transmit a relatively low base flow (Sinha and Friend, 1994; Sinha and Jain, 1998; Alexander et al., 1999; Latrubesse et al., 2005; Fielding et al., 2009, 2011, 2018; Plink-Bjorklund, 2015). As a result, these rivers have been observed to deliver most of their water discharge and sediment load during the summer monsoon season as only the flood discharge is geomorphically effective and able to transport sediment (Alexander et al., 1999; Goodbred, 2003; Plink-Björklund, 2015). Others challenge the linkage between large fluvial fan development and climate, observing that large DFSs and their catchments are developed in all climatic regimes and are not restricted to any specific latitudinal belt (Hartley et al., 2010, 2013). However, this hypothesis is based on broad climate zones defined by temperature and mean annual precipitation, rather than accounting for precipitation range and variability.

We interpret the deposits of the study area to have resulted from deposition of variable discharge river systems (see details in Zellman et al., 2020). We attribute the occurrence of variable discharge river systems to highly variable interannual to seasonal precipitation patterns that may resemble those of the modern semiarid to arid subtropics and monsoonal domains (e.g. Latrubesse et al., 2005; Wang and Ding, 2008; Henck et al., 2010), suggesting that the occurrence of a large fluvial fan in the Paleogene San Juan Basin is linked to, and perhaps indicative of, these climatic conditions.

1. **IMPLICATIONS FOR SAN JUAN BASIN LANDSCAPE EVOLUTION AND FLUVIAL FAN DEPOSITIONAL MODELS**

The deposition of a north to south prograding large fluvial fan may provide a new explanation for the proposed transitional nature of the Nacimiento-San Jose contact in the SJB (Smith and Lucas, 1991). In the northern and central SJB, where the contact is thought by some researchers to be conformable (Barnes et al., 1954; Stone, 1983; Smith and Lucas, 1991), the gradual upward transitions from distal to medial to proximal fan facies are coincident with observations of stratigraphic trends from other ancient fans and with prograding fluvial fan depositional models (Willis, 1993; DeCelles and Cavazza, 1999; Nakayama and Ulak, 1999; Uba et al., 2005; Weissmann et al., 2013; Wilson et al., 2014; Owen et al., 2015, 2017; Batezelli et al., 2018; Wang and Plink-Björklund, 2019). However, in the southern SJB the change from distal fan to proximal fan facies associations is more abrupt where previous researchers have called the contact a large unconformity (Baltz, 1967; Lucas et al., 1981; Smith and Lucas, 1991). This seemingly abrupt downstream shift of proximal fan facies is not consistent with other examples of prograding fans (e.g. examples in Weissmann et al., 2013; Owen et al., 2015; 2017) and the associated depositional models (Weissmann et al., 2013) and raises questions about how prograding fan stratigraphic patterns change from upstream to downstream. A possible explanation is that as the fan system prograded basinward, younger deposits may have sequentially overlain the older deposits of the distal fan, potentially creating a depositional hiatus and time gap that increased in time with distance from the fan apex, and thus creating a more abrupt stratigraphic change (Fig. 13). This wedge-shaped time gap in deposition, combined with the laterally extensive erosional base of the channel complex at the lowermost part of the Cuba Mesa channel complex may have contributed to the interpretation of an angular unconformity by past researchers. Because our research has found no evidence of an angular discordance between the floodplain deposits that underlie and overlie the contact in our study areas, we classify the contact between the Nacimiento and San Jose Formations as a possible disconformity or hiatus. In the Oligocene to Miocene deposits of the Ebro Basin, stacked prograding fluvial fan intervals contain surfaces previously interpreted as angular unconformities at the top of coarsening-upward (prograding) intervals (Luzón, 2005). Major unconformities with soil formation and valley incision have also been observed at the top of Quaternary prograding fan deposits (Weissmann et al., 2002 and references within; Fontana et al., 2014). This may suggest that a previously unrecognized significant disconformity is present at the contact between the Cuba Mesa and Regina Members of the San Jose Formation, separating the two packages of whole fan progradation (Fig. 12). Because the only time constraints on the depositional age of these deposits comes from lower in the Nacimiento Formation and higher in the Regina Member of the San Jose Formation (Fig. 1c), identification of additional disconformities in the succession would suggest that the depositional time gap at the Nacimiento-San Jose Formation contact estimated to be ≥ 5.6 m.y.; Fassett et al., 2010) has been overestimated.

The lateral (i.e. across strike) change over ~9 km from relatively thick channel deposits in the Arroyo Chijuilla study area to thinner channel deposits in the Continental Divide study area may indicate that the deposits in Arroyo Chijuilla accumulated closer to the fan axis than those of Continental Divide. Lateral variability seen across larger distances within the SJB could result from differences in deposition between individual lobes. Thus, in addition to a potentially large depositional hiatus between whole fan progradation packages, the shifting areas of deposition may result in multiple lesser-magnitude depositional hiatuses throughout the succession, and the timing and duration of the hiatuses may vary laterally in the flow perpendicular direction across the basin, adding further to the stratigraphic complexity. The geometries created by such autogenic dynamics may explain some of the lateral variability in channel thickness and sandstone to mudrock ratio seen across the outcrops in the southern SJB, but further research is needed to test this hypothesis.

The improved soil drainage conditions suggested by the floodplain deposits that correspond with the first whole fan progradational package (FA 4 in the Nacimiento Formation - FA 5 in the Cuba Mesa Member of the San Jose Formation) is similar to observations from the stratigraphic records of some ancient prograding fan systems (Trendell et al., 2013; also see examples in Weissmann et al., 2013; Hobbs and Fawcett, 2022). Some researchers have linked proximal to distal reduction in soil drainage to shallow water tables in distal fans (e.g. Hartley et al., 2010), leading to the hypothesis that the stratigraphic trends observed in prograding fans are the result of changes in topographic position of paleosols and the proximity of deposits to the water table, rather than changing climatic conditions (Weissmann et al., 2013). Thus, the existing depositional model used for recognition of prograding fans in the stratigraphic record suggests an up-section change from ‘drab’ floodplain deposits associated with distal facies overlain by increasingly variegated floodplain deposits associated with medial and proximal facies (Weissmann et al., 2013). However, in the San Juan Basin, the distal deposits in the second fan progradational package (Regina Member) consist entirely of well-drained floodplain deposits (FA 6) (Fig. 12), suggesting an overall trend toward increased aridity. By comparison with the prograding fan model (Weissmann et al., 2013), we would expect to see a return to gray-brown-black poorly drained soils accompanying the retrogradation of the fan system, but instead the floodplains show signs of being increasingly well drained (Fig. 12). This contrast suggests that the existing predictive model which indicates a downstream increase in soil moisture variability in fan depositional systems (Weissmann et al., 2013) is not encompassing of all large fan systems. Combined with evidence for changing variable discharge conditions, we conclude that the stratigraphic trend in increasingly well-drained soil conditions was likely the result of changing climatic conditions spanning the Paleocene-Eocene boundary, and that climate was a significant control on the fluvial system in the Paleogene San Juan Basin.

1. **CONCLUSIONS**

This study identifies the deposits of the upper part of the Paleocene Nacimiento Formation and the Cuba Mesa and Regina Members of the early Eocene San Jose Formation as deposits of a large fluvial fan system. We recognize two vertically stacked packages of fluvial fan progradation. Abrupt shifts from proximal fan facies to distal fan facies suggest that a period of fan inactivity occurred between the progradational packages. The interpretation of stacked prograding fans suggests that a previously unrecognized depositional hiatus separates the fan packages at the contact between the Cuba Mesa and Regina Members of the San Jose Formation. Furthermore, evidence that the deposits were accumulated by variable discharge river systems, combined with a lack of evidence that the deposits resulted from tectonic pulses and comparisons with Quaternary and modern fans suggests changes in discharge variability linked to climate could have been a key control on fan activity in the Paleogene San Juan Basin.

The hypotheses presented in this study may have implications for improved understanding of San Juan Basin landscape evolution and the development of fluvial fan depositional models, including: 1) The San Juan Basin provides a dataset to study multiple packages of fan progradation, and the intermediate surfaces and deposits may improve our understanding of recognition criteria for retrograding fan systems in the ancient record. 2) The identification of a north to south prograding large fluvial fan that may have deposited progressively younger deposits basinward could provide a new explanation for the previously proposed transitional nature of the Nacimiento-San Jose contact in the San Juan Basin. 3) Lateral changes in the thickness of deposits and sandstone to mudrock ratio may be due to shifting areas of deposition between multiple fan lobes, which may have resulted in multiple lesser-magnitude depositional hiatuses throughout the succession. If these hypotheses are correct, the suggested depositional time gap (estimated to be ≥ 5.6 m.y.) at the contact between the Nacimiento and San Jose Formations is likely overestimated, as the depositional age of the entire study interval is loosely constrained between fossil localities. 4) Distal fan facies associated with both poorly drained and well-drained floodplain facies suggests that the existing predictive model which suggests topographically controlled downstream decreases in soil drainage conditions is not necessarily applicable to all fluvial fan successions and adds further evidence for a transition to a more arid climate across the Paleocene-Eocene boundary, emphasizing the possible role of long-term climate change in controlling pedogenic modification.

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