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Research Article

The evolution and degradation of Quaternary fossil fluvial fans in Brazilian semi-arid regions

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Abstract

Alluvial fans associated with eolian fields are common geomorphic features that reflect complex interactions in which the alluvial or eolian system acts as both a sedimentary source and a modifier. The semi-arid region of the São Francisco River is notable in Quaternary studies for its alluvial system and the largest Quaternary inland eolian field in Brazil. Fluvial fans are present on the western margin of the river and to the south of the eolian field. To characterize these fans, we used remote sensing, fieldwork, sedimentology, and OSL dating. We identified three fluvial fans: two asymmetric (> 185 km^2) and one circular (8.5 km^2). The eolian deposits played a critical role in both sediment supply and formation of the fluvial fans. Fan spreading occurred due to the difference in gradient between the eolian field and the river terraces. Fan deposits were dated to 4.5 ± 0.6 ka, and overlap with other systems, which suggests the system was active before 4 ka. Currently, these fans are degrading and being reworked by wind, and the drainages that exist across them are ephemeral. The Xique-Xique fluvial fans are now fossil systems, preserving evidence of past increased rainfall and base level lowering in the Late Holocene.

Keywords: São Francisco River; Xique-Xique dune field; Fluvio-eolian interaction; Inland eolian system

Introduction

Semi-arid environments are consistently associated with the presence of eolian dune fields; however, dunes are just one of many geomorphological features found in such environments. Alluvial fans associated with eolian fields are common and may reveal a record of complex interactions, such as the alluvial system being both the source of sediments to the dunes and their modifying agents (Al-Masrahy and Mountney, 2015). Interactions between different depositional systems in semi-arid regions result in a large amount of available sediment due to sparse vegetation on these deposits, which provides an important influence on the geomorphology of the area (Wainwright and Bracken, 2011).

Alluvial fans are cone-shaped deposits formed where there is a distinct break in topography between the high ground of the drainage basin and the flatter sedimentary basin floor. In this situation. the valley opens and there is a change in gradient that allows water and sediment to spread out, forming a distinct cone morphology (Assine, 2008). Fan type is determined by slope variation: fans dominated by gravity flow (slope $> 1.5°$ and gradient > 0.026 m/m; e.g., Trollheim Fan, EUA) and fluvial fans (slope $< 0.4°$ and gradient < 0.007 m/m; e.g. Okavango fan, Botswana) (Assine, 2008). Fluvial fans can reach tens to 100 kilometers in length, whereas gravity-flow-dominated fans are usually smaller (reaching only a few kilometers in length; Assine, 2008).

In Brazil, the alluvial fans of Alto Paraguai are sedimentary features that have been the subjects of several geomorphological studies (Zani et al., 2012; Assine et al., 2015; Pupim et al., 2017; Merino and Assine, 2020). These fans typically form in a region with a seasonal tropical climate (according to the Köppen–Geiger climate classification), where evapotranspiration rates exceed precipitation rates within the plain (McGlue et al., 2011); examples include the Pantanal, one of the world's largest wetlands. Among them, the Taquari megafan stands out as a large, rounded deposit covering an area of 49,000 km^2 (Zani et al., 2012).

Although alluvial fans are globally common landforms, their study is best conducted in arid or super-arid environments, where fan surfaces are better preserved, and minimal vegetation enhances their visibility (Hedrick et al., 2013). In Brazil, alluvial fans are infrequently associated with arid and semiarid environments, and the studied fans from the middle course of the São Francisco River represent one of few examples in the country. However, similar systems are prevalent in the deserts of southern South America, particularly Argentina, Bolivia, and Chile (Mather and Hartley, 2005; Sancho et al., 2008; Hedrick et al., 2013; Terrizzano et al., 2017).

In northwest Argentina, near the Bolivian border, the Tilcara alluvial fan comprises deposits that span 5 km^2 and were formed by the Huasamayo River, which drains an area of nearly 120 km^2. The Tilcara fan is primarily composed of conglomeratic facies, originating from compressive tectonic forces during the Pleistocene (84.5 ± 7 ka; Sancho et al., 2008). Closer to the Chilean border, the Masquerado, Loma Negra, and Carpintería alluvial fans display conglomeratic to coarse-sand facies and yield OSL ages of 17 ka, 50 ka, and 5 ka, respectively. These formations are situated in a tectonically active zone characterized by peaks rising 1000–2000 m above sea level, contributing to their form and distribution (Hedrick et al., 2013).

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The largest desert in South America, the Atacama Desert in Chile, includes alluvial fan deposits within tectonically active areas, a prominent example of which is the Tambores Fan. Encompassing an area of 8 km^2, this fan is primarily composed of conglomeratic material, with finer-grained muds, silts, and evaporites found at lower elevations (Mather and Hartley, 2005). All South American fans described are located within tectonically active regions and are primarily composed of conglomeratic material due to their proximity to source areas. However, the alluvial fans in the middle reaches of the São Francisco River are situated within the tectonically stable São Francisco Craton.

The São Francisco River is considered the largest entirely Brazilian river (Silva et al., 2003); as such, it plays a fundamental role in the distribution of fauna and flora and in the socioeconomic activities of the local communities. The river is important in the semi-arid region of Brazil which, despite its low rainfall and high evaporation rates, remains perennial throughout the dry season. The river's perennial flow is primarily sustained by waters from its upper course, which is situated in a semi-humid climatic area and contributes approximately 65% of the total discharge (Mescolotti et al., 2021).

The semi-arid region within the middle reaches of the São Francisco River has received increasing attention in Quaternary geomorphological studies, either through investigation of the alluvial system of this important river (e.g., Mescolotti et al., 2021) or by virtue of its status as the largest continental Quaternary dune field in Brazil (Barreto, 1996; Oliveira et al., 1999; Giannini et al., 2005, Ab'Sáber, 2006; Bartorelli et al., 2010; Tripaldi and Zárate, 2016; Mescolotti et al., 2023). The area exhibits alluvial fans, documented for the first time in this study, that are thought to be associated with regional eolian and alluvial systems (Fig. 1).

The middle São Francisco River region and its associated Quaternary dunes are of significant environmental and climatic relevance, both in the present and the past. In the past, palynological data indicate that this region acted as a corridor for southern montane forest taxa to migrate northward during the Heinrich Stadial 1 (HS1; 18–15 ka) event, resulting in biological connections between the Amazon and Atlantic forests (Pinaya et al., 2019). Additionally, pollen studies in the area were key to interpreting the expansion of the Caatinga biome in Brazil over the past 4,000 years (Oliveira et al., 1999). Today, the area hosts a diverse herpetofauna with a high level of endemism, including several species adapted to sandy substrates (Rodrigues, 1996; Rodrigues, 2003; Recoder and Rodrigues, 2020).

In this context, the middle São Francisco deposits serve as an essential geological archive for reconstructing the Quaternary environmental and landscape history of northeastern Brazil. This work outlines the geomorphologies of alluvial fans that occur in association with the middle reaches of the São Francisco River and the Xique-Xique eolian fields and aims to understand the geomorphological relationships between the alluvial fans and the Xique-Xique continental dune field. To achieve this, remote sensing, sedimentology, and OSL dating were used.

Environmental setting

São Francisco River

South America hosts six of the 10 largest rivers in the world in terms of water discharge (Latrubesse et al., 2005a, 2005b; Latrubesse, 2008). However, these rivers are all located either on wetlands in the Amazon or in south-central South America (Parana River). The São Francisco River is the easternmost large river of South America and the largest river flowing through the semi-arid region of northeastern Brazil.

The São Francisco River is one of the main rivers that flows exclusively in Brazilian territory, with a length of 2,900 km and a watershed with an area of 631,133 km^2, corresponding to 7.4% of the Brazilian territory (Fig. 1; Knoppers et al., 2006; de Andrade e Santos et al., 2012). Consequently, it is crucial to human activities because it provides water resources for five states from southeast to northeast Brazil, and its waters are currently being artificially rerouted to reach several other states facing water supply shortages. Although the headwaters of the São Francisco River lie in the transition between the Atlantic rainforest and Cerrado biomes in the Serra da Canastra highlands, southeastern Brazil, for most of its course, it drains high, dissected landscapes in the domain of tropical Caatinga dry forests. Thus, the São Francisco River also plays an important role in sustaining neotropical ecosystems in Brazil.

The São Francisco drainage basin can be divided into four distinct geomorphological domains: upper, medium, sub-medium, and lower (Pereira et al., 2007). Stabilized parabolic dunes occur in association with the São Francisco River plain, primarily in its middle reaches, and are particularly well represented in the Xique-Xique dune field (Oliveira et al., 1999; Barreto et al., 2002; Ab'Sáber, 2006; Bartorelli et al., 2010; Fig. 2).

Fluvial incision events were triggered by increased fluvial discharge produced by intensification of the South Atlantic Convergence Zone (SACZ), which has significant influence on precipitation over the upper São Francisco River (Mescolotti et al., 2021).

Study area

The alluvial fans presented in this study occur in the middle reaches of the São Francisco River, northwest Bahia, in the city of Barra (Fig. 1). The area is classified as dryland due to its P/E rates (± 50) (Thornthwaite, 1948) and as semi-arid (BSh) according to the Köppen climate classification scheme (Beck et al., 2018), exhibiting an average annual precipitation below 700 mm, which falls primarily between December and March. The Xique-Xique region has an average annual wind speed of 3.5 m/s, with a seasonal wind pattern marked by higher speeds during the dry seasons, reaching 4.1 m/s in winter and 3.7 m/s in spring (Mescolotti et al., 2023).

The alluvial plain in the study area is well developed and the main tributary of the São Francisco River is the Grande River, with its mouth in the city of Barra, whereas the other tributaries are intermittent or have low flow rates. The river plain in the area is located within the north-northwest portion of the São Francisco Craton (Almeida, 1977). It is bordered to the east by Proterozoic metasedimentary rocks from Chapada Diamantina (mostly low-grade metasandstones and metaconglomerates; Schobbenhaus, 1984; Moraes and Amaral; 2001) and to the west by Neoproterozoic quartzites from Serra do Estreito (Northern Espinhaço; Fig. 2), a narrow and elongated NS-oriented ridge.

Several alluvial geomorphological zones have been recognized in the middle reaches of the São Francisco River (Mescolotti et al., 2021). Two zones are represented by degraded terraces and three zones comprise the confined active aggradational plain of the river. Four phases of fluvial aggradation (> 90 ka, 65–39 ka, 18–9.5 ka, and 380 years to recent) and three phases of incision (85–65 ka, 39–18 ka, and 9.5–1.0 ka) were recognized. Another zone includes the Xique-Xique eolian dune field, characterized by stabilized parabolic landforms (simple megadunes, compound dunes,

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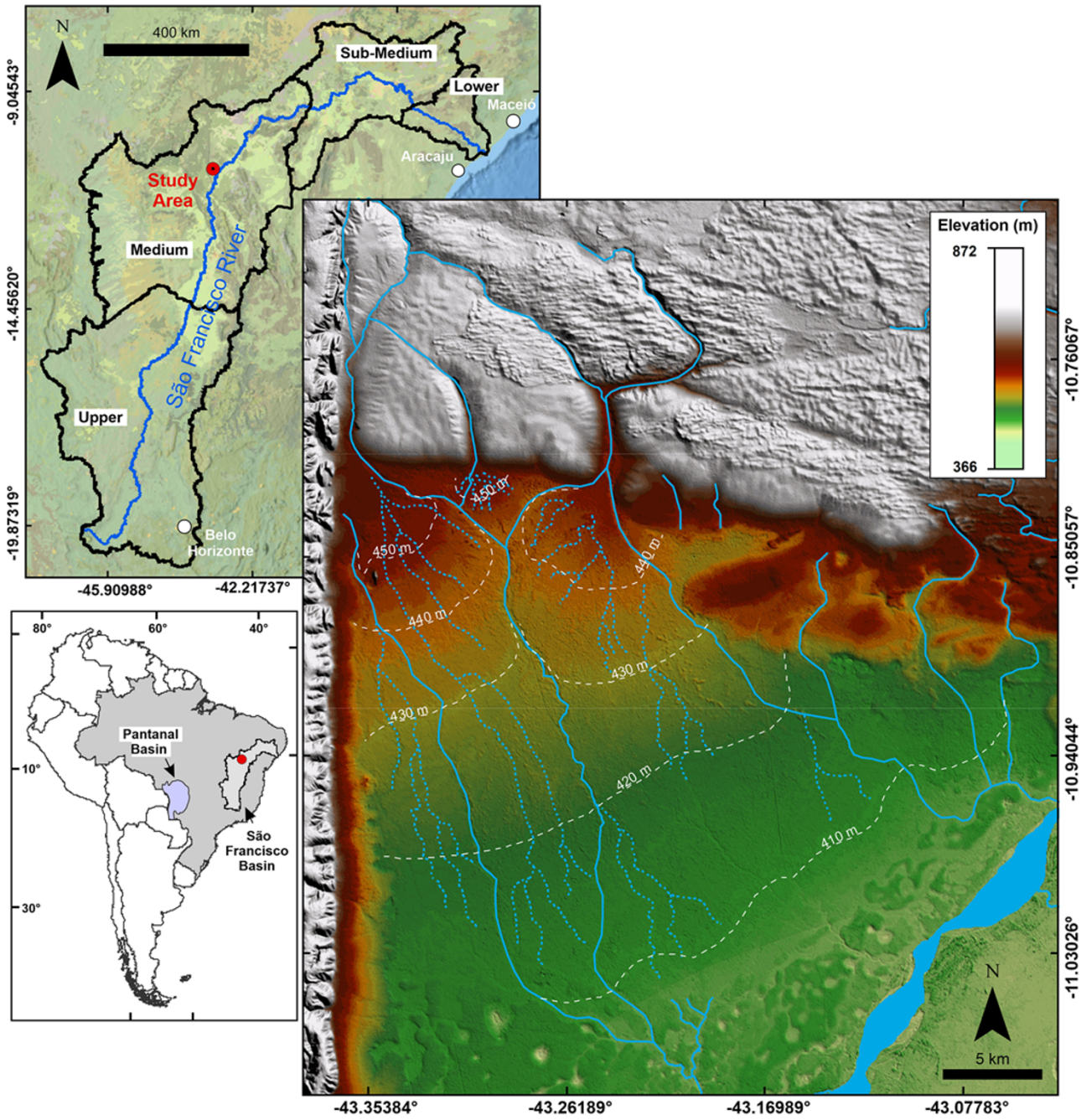

Figure 1. Map of the location of the alluvial fans of Xique-Xique. Digital elevation model/Shuttle Radar Topography Mission (DEM/SRTM) 30 m; thick black line = delimitation of the São Francisco River Basin and four distinct geomorphological domains: upper, medium, sub-medium, and lower; dashed white lines = fan-contour lines in meters; blue lines = current drainages (perennial and ephemeral); dashed blue lines = paleochannels.

and perched dunes) and active parabolic dunes. Mescolotti et al. (2021) conducted OSL dating of the eolian deposits and identified two phases of eolian deposition: the first ranging from 45.1 ± 5.2 ka to 25.5 ± 4.4 ka, and the second from 14.3 ± 2.6 ka to 5.2 ± 1.4 ka.

Methods

Geomorphological mapping

Geomorphological mapping was carried out through the recognition and characterization of terrain and drainage elements based on the visual analysis of remote-sensing-generated images aided by satellite image interpretation criteria described by Soares and Fiori (1976) and Veneziani and Anjos (1982). Such procedures allowed the recognition of patterns and the delimitation of zones with similar morphological elements, later interpreted as geomorphological compartments. Prior recognition of different morphological dune patterns within an eolian system environment is essential to guide sampling for geochronological studies (Stone and Thomas, 2008; May, 2013; Thomas, 2013).

Images from optical sensors (Landsat 8 OLI/TIRS Level-2) and digital elevation models (DEM) from Shuttle Radar Topography Mission (SRTM/C-band, 30-m resolution) (all acquired from the

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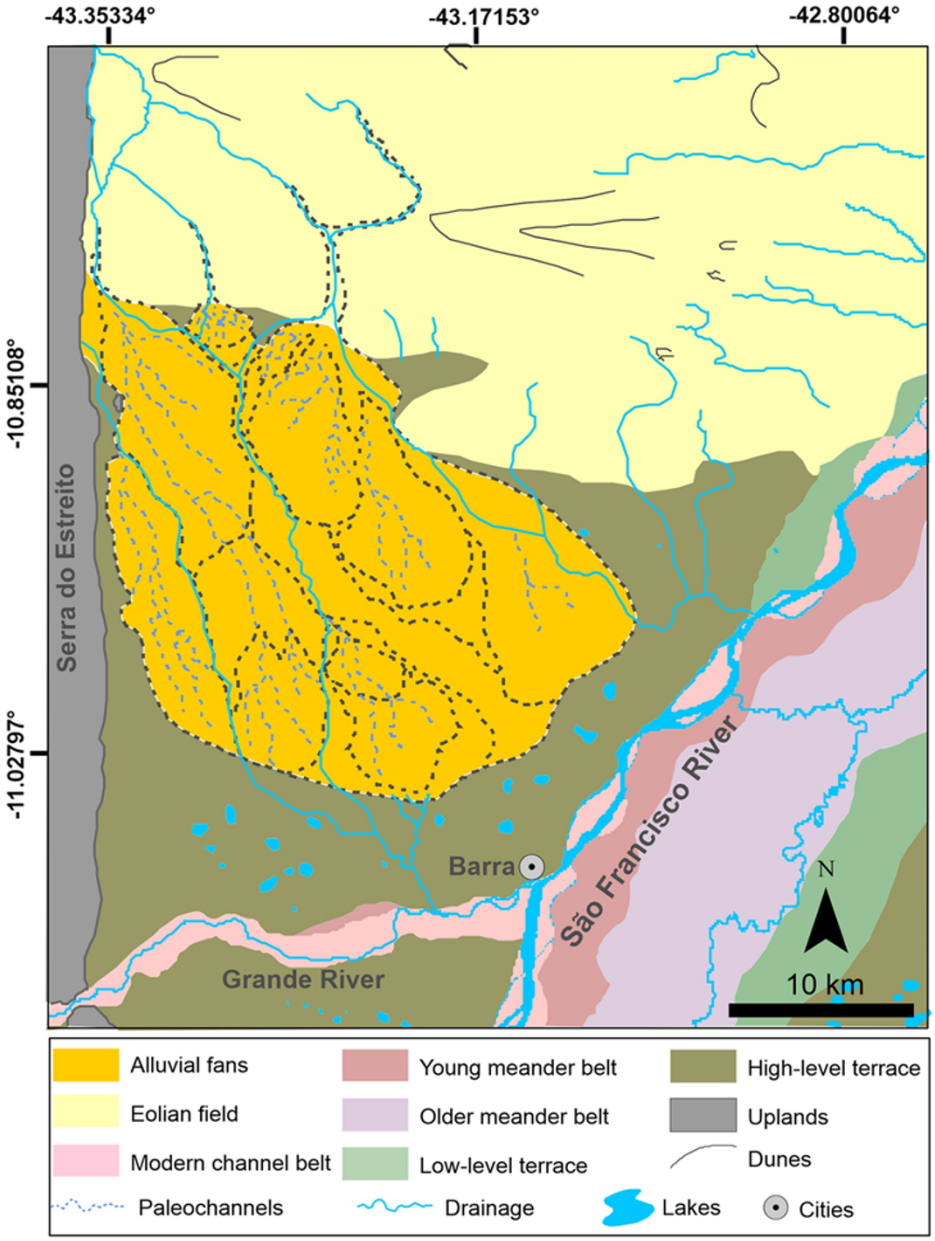

Figure 2. Geomorphological map of the area (modified from Mescolotti et al., 2021). Black dashed lines delimit the alluvial fans and their depositional lobes.

website https://earthexplorer.usgs.gov/) were used for recognition and mapping of landforms. The remote sensing applied on Landsat 8 OLI images aimed to obtain false-color composite mosaics of the bands 743, 753, and 432 (RGB) for images from November 2017. The DEMs were presented based on the customization of color palettes with intervals ranging 1–15 meters, aiming to highlight low topographic amplitude geomorphological features (Merino et al., 2015). The DEMs were processed using Global Mapper software, while aerial imagery was obtained from the World Imagery plug-in in ArcGIS Online.

Field evaluation

The field campaign aimed to (1) confirm the geomorphological features recognized through remote sensing, (2) characterize the morphological elements, (3) describe the sedimentological characteristics, and (4) collect samples from the Quaternary deposits for future laboratory analysis. Sedimentological descriptions were made on outcrops by the road and in trenches. During the field campaigns, which were conducted in September 2018 and January 2020, we visited alluvial fans, dunes, and alluvial terraces along the São Francisco River.

Optically stimulated luminescence (OSL)

The Optically Stimulated Luminescence (OSL) dating technique estimates the burial age of quartz grains by measuring the equivalent-dose and environmental-dose rates, covering a range from 10 years to 200 ka (Rhodes, 2011). A sample of sands from the fan was dated using the single-aliquot regenerative dose (SAR) protocol (Murray and Wintle, 2003). The sample, collected from an 50-cm-deep trench, was processed at the Luminescence and

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Gamma Spectrometry Laboratory (LEGaL) at the University of São Paulo.

Standard procedures were followed to prepare quartz sand grains (Wintle, 1997), including wet-sieving to isolate the 180–250 μm fraction, chemical treatments (to remove organic matter, carbonates, heavy minerals, and feldspar), followed by etching with hydrofluoric acid to eliminate remnant feldspar and contribution alpha particles. Purity was confirmed through infrared (IR) stimulation.

Aliquots of 100–200 quartz grains were mounted on aluminum discs and measured on a Risø TL/OSL DA-20 using the SAR protocol (Murray and Wintle, 2003). The OSL signal was calculated by integrating the initial 0.8 seconds of light emission and subtracting the last 10 seconds as background. Only aliquots meeting quality criteria were used in equivalent dose (De) calculations. The Central Age Model (Galbraith et al., 1999) was used to calculate the age, employing the LDAC program (Liang and Forman, 2019). The Central Age Model was used because of the absence of evidence indicating partial bleaching in the studied sample.

The dose rate was estimated through radionuclide determination by Gamma spectrometry, with U, Th, and K concentrations converted to dose rates using Guérin et al. (2011) factors. Water saturation was determined and adjusted by ± 10% for past uncertainty. The cosmic dose rate was calculated using the LDAC program as described by Liang and Forman (2019), taking into account both the geographic coordinates and the sample collection depth.

Results

Distributary river system

We identified three coalescing alluvial fans associated with the Xique-Xique eolian system along the southern part of the left bank of São Francisco River: the Olhos d'Água, Passagem, and Banguê fans (Fig. 3). Alluvial fans within the middle reaches of the São Francisco River show a typical distributary drainage pattern with concave longitudinal and transversal sections (Fig. 4), which is typical of this depositional system. Because the three fans have topographic gradients of less than 0.007 m/m, they are classified as river-dominated fans (Assine, 2008).

The Olhos d'Água fluvial fan is named after the nearby village. It is confined on its right margin by the Serra do Estreito (Fig. 5D) and on its left margin by the Passagem Fan. It has an elongated and asymmetrical shape, approximately 30 km in length between its apex and toe, 9 km wide, an area of 280 km^2, and a topographic gradient of 0.0016 m/m. At least seven distinct depositional lobes were identified on the Olhos d'Água Fan.

The Passagem Fan is limited to the east by eolian sand deposits, which are approximately 20 m higher than the fan surface, thereby acting as a topographic barrier. Its morphology is similar to that of the Olhos d'Água Fan—asymmetrical, with dimensions reaching tens of kilometers (~24 km long, ~7.6 km wide, and an area of ~185 km^2). This fan has a topographic gradient of 0.0017 m/m and shows multiple depositional lobes.

The smallest fluvial fan in the area is the Banguê Fan, with a length of ~4 km between apex and toe, a width of ~3.6 km, and an area of ~8.5 km^2. It differs from the other fans in morphology, exhibiting an almost circular shape, similar to the Taquari Fan in Pantanal (Assine et al., 2015). The Banguê Fan also has a higher topographic gradient (0.0056 m/m). It is possible to identify five depositional lobes, all of which are abandoned today. Through morphostratigraphical correlations it is also possible to observe the evolution of these lobes and identify the last nodal point of avulsion (Fig. 6). The only age obtained in this study was for the Banguê Fan, indicating deposition during the Late Holocene (4.49 ± 0.55 ka). The sample was collected at a depth of 50 cm, from a section of well-sorted, fine- to medium-grained, quartzose brown sand, with rounded and spherical grains. In the dated sample, quartz grains with high sensitivity to luminescence were predominant, exhibiting dose-response curves that can be well defined by a single exponential saturation function. Thirty-four aliquots were measured, yielding an equivalent dose of 1.19 ± 0.11 Gy and a total dose rate of 0.27 ± 0.02 Gy/ka.

Although the fans are located within the São Francisco River alluvial plain, they end before reaching the São Francisco River. Thus, the fans had no connection with the river, which did not act as the collecting system for the channels that formed the fans.

The fan-forming channels have their origins in Serra do Estreito, an important Proterozoic quartzite ridge that served as a topographic barrier to the formation of the Xique-Xique eolian system (Fig. 5; Mescolotti et al., 2021). The ancient paleochannel that originally formed the fans (today an ephemeral river known as "Gado Bravo") collected water primarily from Serra do Estreito, but also from the Xique-Xique eolian system, before flowing parallel to the ridge (N–S) to the south. Although this drainage is ephemeral today, it formed an approximately 100-m river valley between the western ridge and the advancing eastern dunes. The river valley that formed the Olhos d'Água fan widens to approximately 800 meters, about 1 km upstream from where the river spreads out to form the fan. Although the rivers that formed the fans are ephemeral today, the interfan regions are low-lying and receive seasonal river flow during the wet season, creating small wetlands confined by sand deposits from the paleofans

Geomorphological relations and sedimentology of the alluvial fans

The coalescent alluvial fans advance over the surface of the oldest terraces of the São Francisco River (Mescolotti et al., 2021). Textural differences observed in DEMs between the alluvial fans and the degradational surface of the São Francisco River alluvial plain were essential in recognizing the morphology of the alluvial fans for the first time. The degradational surface exhibits low-amplitude vertical variation, rough patterns, and several coalescing ephemeral circular and semi-circular lakes. The alluvial fans exhibit smoother patterns and a gentle radial slope towards the São Francisco River.

Additionally, although the rivers that feed the alluvial fans of the middle reaches of the São Francisco River originate in Serra do Estreito, the difference in slope between the southwest portion of the Xique-Xique eolian fields and the alluvial plain of the São Francisco River is around 80 m, which caused the flow to be unconfined; thus, the channels created exhibit a radial pattern, which is typical of this system. Channels originating from Serra do Estreito generally create erosive valleys on the eolian field due to the preferential directions of dune features, such as deflation basins (Fig. 7A), and may discordantly cut the eolian features.

No sedimentological distinctions were observed along a transvers section of the alluvial fans. The surface of the alluvial

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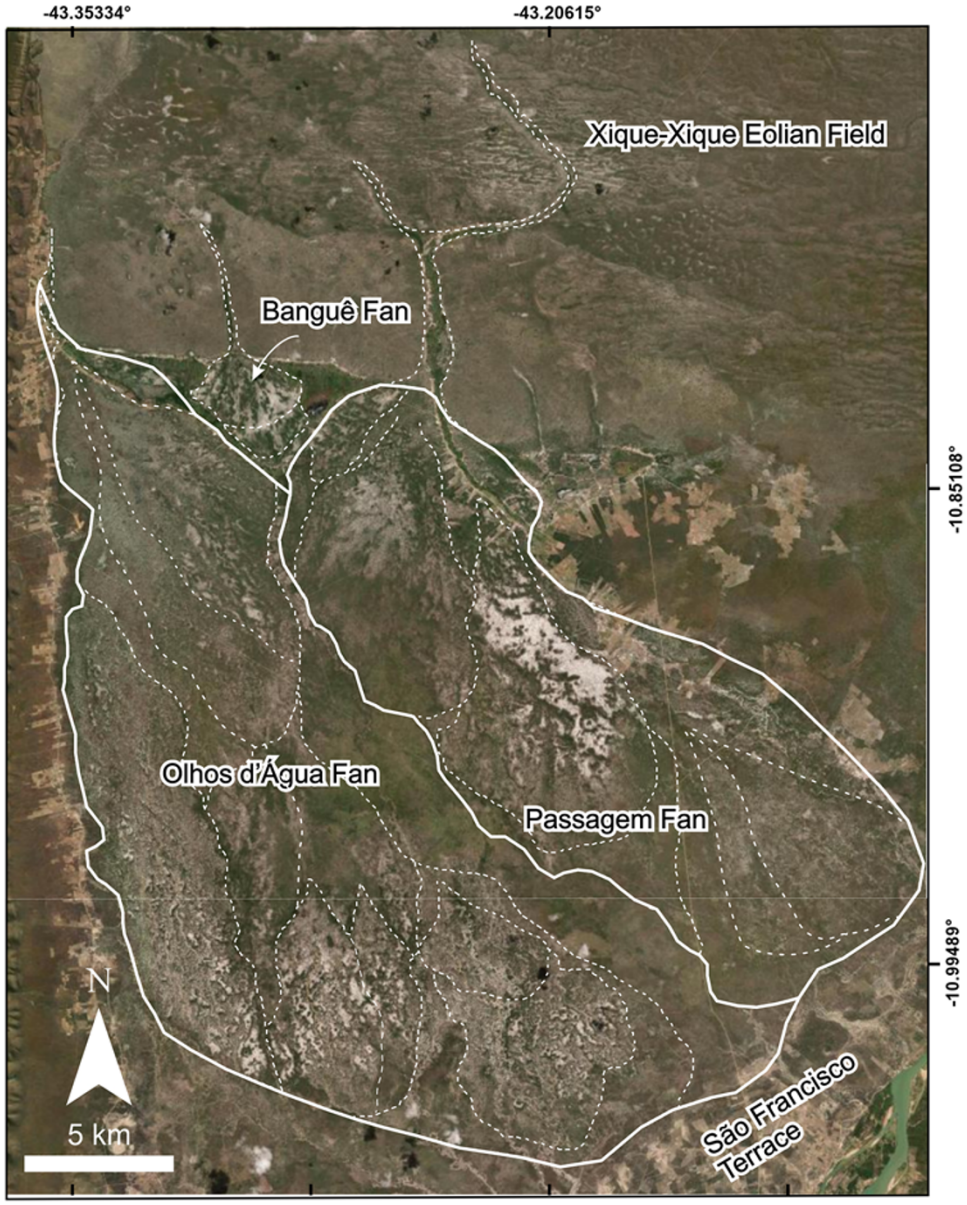

Figure 3. Delimitation of alluvial fans (solid white lines) and depositional paleolobes (dashed white lines).

fan consists of white, well-sorted, quartz-rich sands extending to a depth of approximately 20 cm (Fig. 5F). Below this depth, the fan deposits comprise very well-sorted, fine- to medium-grained sand, with rounded and spherical grains. These deposits differ significantly from the alluvial sediments of the older terraces of the São Francisco River, which are composed of poorly sorted, mottled fine-grained sands mixed with silt and clay. Additionally, clast-supported gravels with a sandy matrix and coarse-grained sands with scattered pebbles are commonly found in the terraces of the São Francisco River.

Degradation of the alluvial fans

The alluvial fans in the middle reaches of the São Francisco River are currently undergoing degradation. Surface degradation is irregular, with greater dissection in the distal part of the Olhos d'Água and Passagem fans. The erosion process results mainly from rainwater runoff and ephemeral channels that form an incipient tributary network responsible for draining water to the floodplains of the São Francisco and Grande rivers (Fig. 7), the main tributary of the São Francisco River in the area. The channels of the alluvial fans currently function as erosive agents, carving through the fans and forming terraces. This process is most evident in the Banguê Fan (Fig. 6) and the proximal Passagem Fan. This overlapping drainage network is formed by intermittent streams whose erosional base levels correspond to the current river channel.

During field work, it was noted that the reworking of the sands on the surface of the alluvial fans by the wind forms proto-dunes. Presently, the study region exhibits high wind speeds with great potential for wind power generation. The degradation and reworking of the surface of the Xique-Xique fans leads to obliteration of both the feeder channels and distributary channels features; consequently, it can be difficult to recognize fluvial morphologies.

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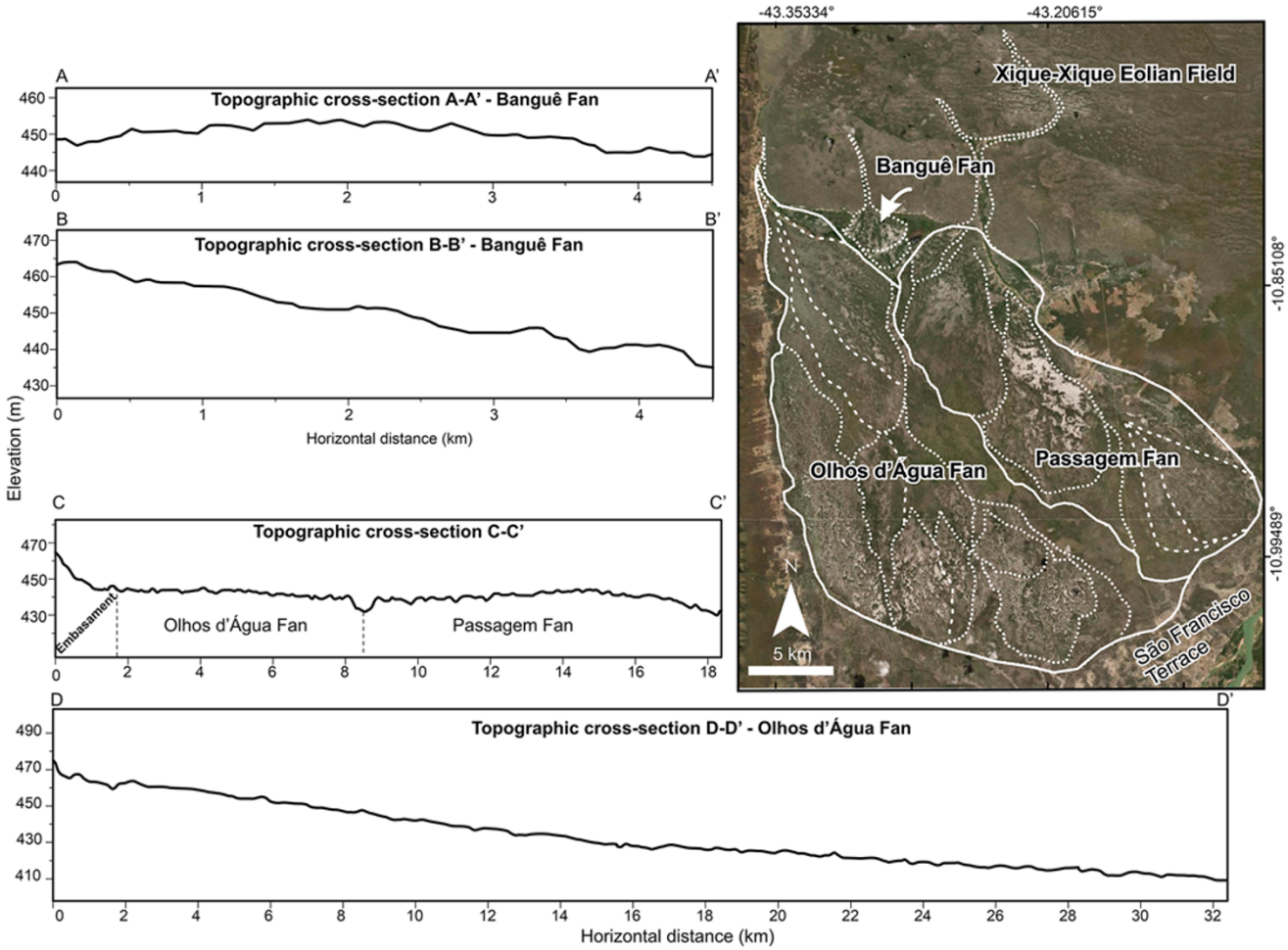

Figure 4. Longitudinal and transversal cross-sections of the alluvial fans.

Discussion

Fan chronology

The only absolute age of about 4.5 ka (lab code: L1291) obtained for alluvial fans (the Banguê Fan) gives us an idea of the period of formation of the coalescing alluvial fans in Xique-Xique; however, a more robust geochronology is needed to better understand the dynamics of this system. From geomorphologic considerations, we observed that the age obtained is from the last depositional lobe of the Banguê Fan (i.e., from the system most proximal to the dunes).

Because the eolian and fluvial systems related to the fans have different ages (Mescolotti et al., 2021, 2023), their overlapping relationships help to establish a relative chronology of the alluvial fans. The fans are superimposed on alluvial deposits of the São Francisco dated at about 88 ka, which provides their maximum age. Furthermore, the feeder channels of the alluvial fans overlie the eolian deposits, suggesting that they are either later than, or partially related to, these deposits. While the eolian deposits have been dated from about 250 ka to about 1 ka, the majority of ages indicate heightened eolian activity between 16 ka and 5 ka (Mescolotti et al., 2023). Among the eolian morphologies affected by these drainages are the compound parabolic dunes, which were deposited between about 14 ka and 5 ka. From interpretations of aerial images, feeder channels were not covered by the dunes in the eolian field, indicating that the alluvial fan system was probably active until after 5 ka. This interpretation is consistent with the only absolute age we obtained (ca. 4.5 ka).

Geomorphological evolution

Fluvial fans are systems that typically exhibit high sediment supply, and their evolution occurs through the construction and abandonment of depositional lobes (Assine, 2008). The sedimentologic characteristics of fluvial fans are very similar to those observed in the Xique-Xique eolian deposits (Mescolotti et al., 2021). The dominance of very well-sorted, fine-grained sands is precisely due to relationships with the eolian field. It is clear that the channels forming the fans are incising and eroding the eolian system, forming an entrenched valley. This eroded eolian material served as the sediment source for the fluvial fans. The sediments from the source area are very well sorted and there are no lateral variations between the heads and bases of the fans. Such sedimentary characteristics, widely observed in the Xique-Xique fluvial fans, are composed of very well-sorted, fine-grained sands and distinguishes these fans from the arid and semi-arid alluvial fans of South America, which are almost always formed of poorly sorted coarse-grained sediments (Mather and Harthey, 2005; Sancho et al., 2008; Hedrick et al., 2013). This stands in contrast to the majority of alluvial fans worldwide, which often exhibit mixed sediment sources.

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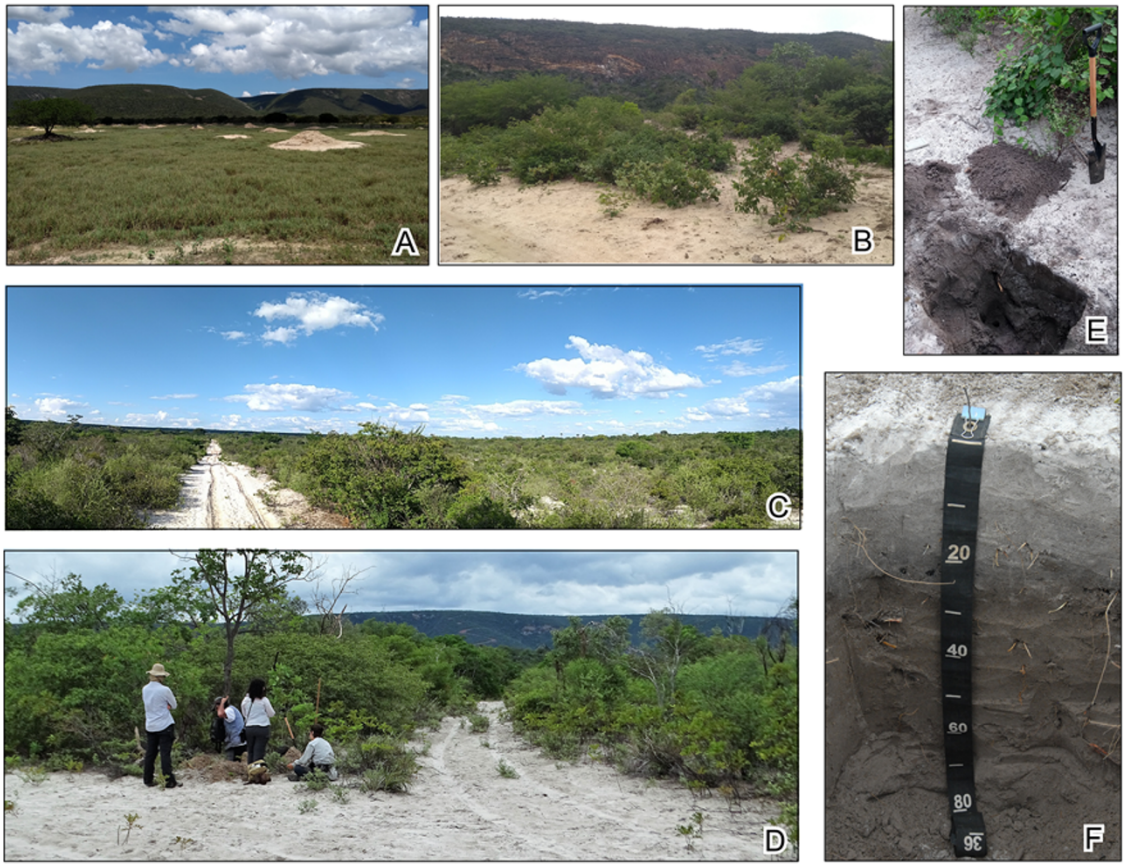

Figure 5. (A) Surface of the São Francisco River terrace in the foreground, and the Serra do Estreito in the background. (B) Detail of the eolian deposits near Serra do Estreito. (C) Surface of the Banguê Fan and, in the background, the Xique-Xique eolian field (north view). (D) West view over the Olhos d'Água Fan, with the Serra do Estreito in the background. (E) Excavation site at Olhos d'Água Fan, highlighting the dark-colored subsurface sand in contrast to the white sand in the upper 20 cm. (F) Section where the sand sample was collected in the Banguê Fan for dating.

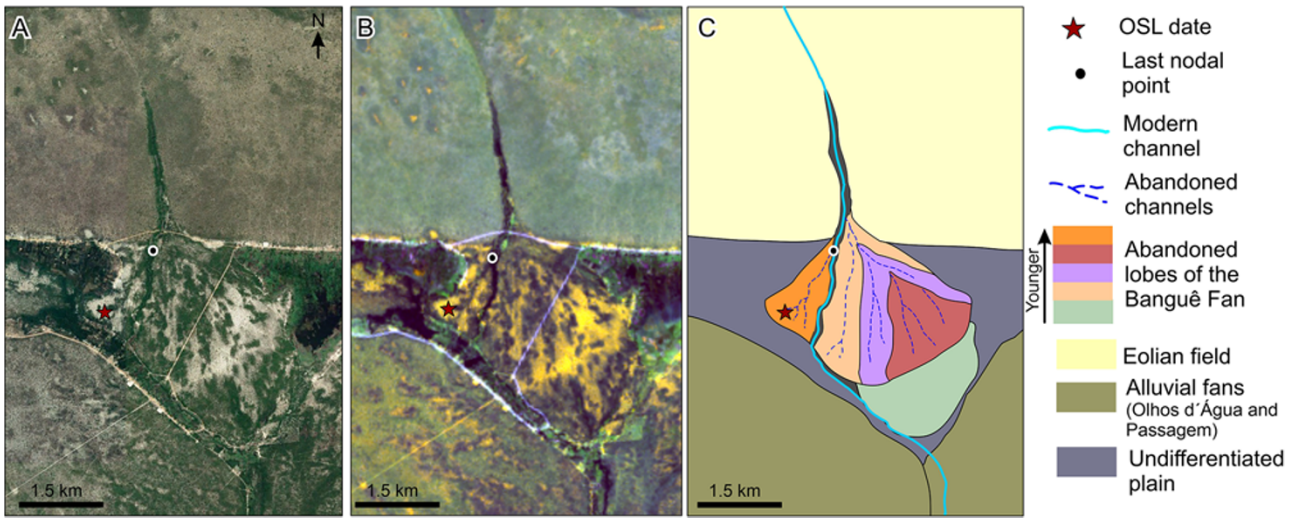

Figure 6. Banguê Fan, with details for the collection point of the OSL sample, for the modern channel incision and for the nodal point of the last avulsion. (A, B) Processed Landsat images. (C) Schematic model of the evolution of the Banguê Fan lobes.

The significant eolian sediment supply was likely facilitated by sparse vegetation over the eolian deposits. Today, the eolian field exhibits typical caatinga vegetation (cacti, shrubs, thorny trees, and bromeliads). However, according to Mescolotti et al. (2023), the Xique-Xique dunes were active until the Middle Holocene, meaning they probably did not have significant vegetation cover before 5 ka.

The eolian deposits of Xique-Xique were not only important as a sediment source for the fans but also in the genesis of the fluvial fans. The eolian deposits are thicker near the

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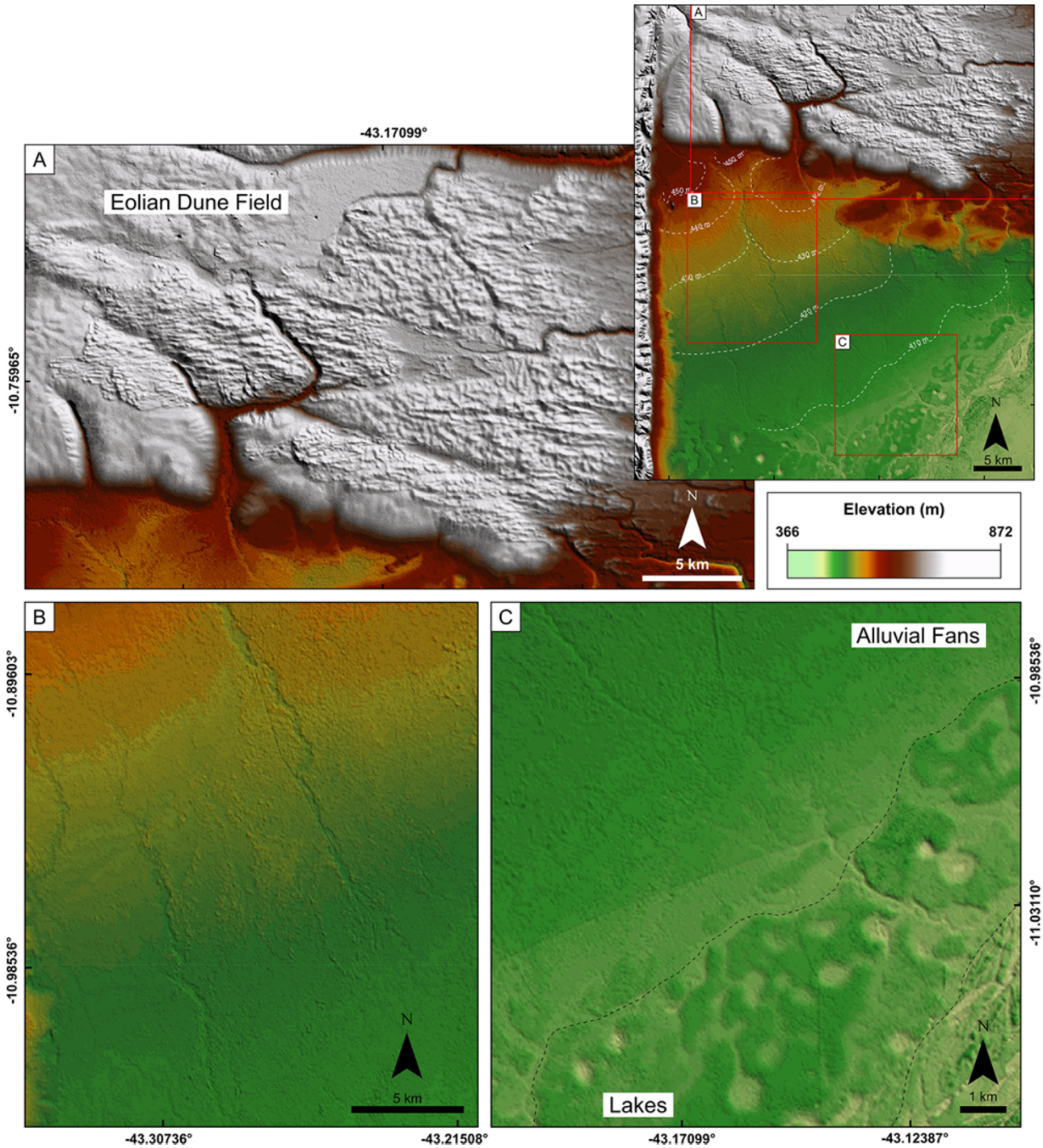

Figure 7. (A) Detail of the drainages following dune deflation basins and cutting across the eolian morphologies. (B) Detail of the tributary drainages superimposed on the Olhos d'Água and Passagem fans, today degrading the surface. (C) Detail of the textural difference in the DEM of the alluvial fans (smooth texture) and the river terrace of the São Francisco River (rough texture, with recurrence of circular depressions).

Serra do Estreito (Barreto, 1996; Mescolotti et al., 2021), which served as a physical barrier for the accumulation of these deposits. Greater sediment thicknesses near the Serra resulted in a greater elevation difference between the eolian surface and the alluvial plain, causing the channels originating from the Serra do Estreito to spread out upon entering the wide surface of the alluvial plain. This distributary drainage also prevented the dunes from effectively reaching the Serra do Estreito, forming a valley between the Serra and the dune field. Waters from the Serra and partially from the dune field itself migrated southward because the eolian deposits prevented their westward migration. Thus, the origin and evolution of the fans studied herein are associated with the dynamics of adjacent fluvio-eolian systems.

The superimposition of erosive channels onto fans, including the feeder channels of fans, denotes a change in the equilibrium

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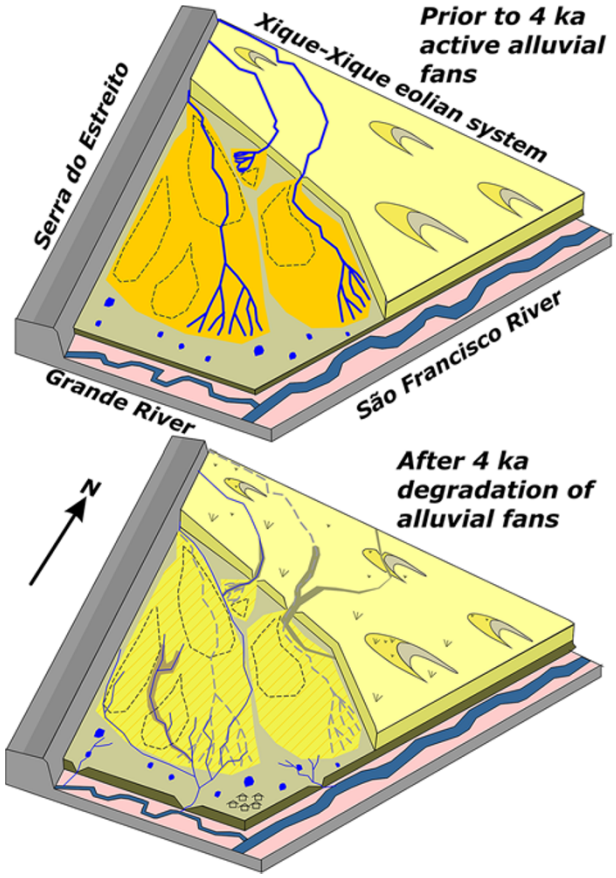

Figure 8. Schematic model of the Xique-Xique alluvial fans active before 4 ka and fossil alluvial fans after 4 ka, already undergoing degradation and a lowered base level.

profile in the region, probably corresponding to lowering of the base level of erosion. These feeder channels ceased to be a distributary fluvial system and have taken on the character of a tributary alluvial system, in which the Grande and São Francisco rivers function as trunk rivers (Miall, 1990; Fig. 8). The Xique-Xique alluvial fans are now fossilized systems.

With only one absolute age obtained (4.49 ± 0.55 ka), it is difficult to achieve greater precision regarding the time at which the channels feeding the fans changed from a distributary to a tributary pattern, and the time at which the fans began to undergo degradation. However, considering that the base level of erosion is the current channel of the São Francisco River, Mescolotti et al. (2021) proposed a phase of fluvial incision in the São Francisco River in the Late Holocene (5–2 ka).

The complex sedimentary system described herein, featuring coalescing fluvial fans with feeder channels eroding an eolian field and fan spreading on the plain of a main trunk river, is very similar to the Okavango alluvial fan in Botswana (Thomas and Shaw, 1991; McCarthy et al., 1997). However, the Okavango fan is situated in a tectonic graben that developed in the southwestern extension of the East African Rift system (McCarthy, 2013; Pastier et al., 2017). In contrast, while the Xique-Xique fans are influenced by waters from the Serra do Estreito, their formation is primarily governed by the dynamics of the sedimentary systems (aggradation and erosion; high sediment supply) rather than by tectonic controls, with climate playing a significant role.

Xique-Xique alluvial fans and climate

Alluvial fans are common geomorphological features in many arid and semi-arid regions and can provide a key record of tectonics and climate change (Bull, 1991). Several triggers, particularly related to tectonics and climate change, could have led to the formation of the Xique-Xique alluvial fans. However, the area was tectonically stable during this period of fluvial fan formation (Pleistocene/Holocene); consequently, the hypothesis of regional changes in hydrological conditions is the most likely explanation for the formation of this fluvial system.

The drainages that exist today over the fluvial fans are ephemeral and do not correspond to the fossil fluvial system. The fluvial fans were probably formed during periods of higher rainfall in the region. Although these fans are currently located in a semi-arid climate region, they likely reflect a period when the area experienced a more humid climate. However, without a robust geochronology of the fans, it is difficult to suggest when this wetter period occurred.

Based on proxies from nearby areas (Wang et al., 2004; Stríkis et al., 2015, 2018), the Xique-Xique region has experienced five periods of increased precipitation during the last 80 ka, the last of which occurred at the end of the Pleistocene (18–15 ka). These wet events are closely associated with Heinrich stadials, with pollen proxies suggesting the presence of southern montane forests in the region during these time intervals (Pinaya et al., 2019). Recent studies close to the area have linked soil formation under wet conditions to Heinrich stadials and the Younger Dryas period, with the last wet event being recorded in the Middle Holocene (Sousa et al., 2023).

The abundance of forest and cerrado/caatinga pollen in the study area (Oliveira et al., 1999) suggests wetter conditions in the Late Holocene, and the establishment of drier conditions after 4 ka. Considering that the depositional age obtained in our study refers to the last depositional lobe of the most proximal alluvial fan (i.e., before incision), the change from aggradational to degradational patterns in the Xique-Xique fluvial fan system probably occurred after about 4 ka. In other words, extinction of the alluvial fan system recognized here may reflect a change in the climatic conditions in the area after the Middle Holocene, as indicated by climate proxies reported in previous studies (Oliveira et al., 1999; Sousa et al., 2023).

Conclusions

The fluvial fans described in this study are significant geomorphological features within Brazil. Their formation is attributed to a combination of factors: (1) a significant sediment supply from both the dunes and the basement, coupled with relatively sparse vegetation cover; (2) the steep vertical gradient between the Xique-Xique eolian field and the fluvial terrace of the São Francisco River; (3) periods of increased water availability during their development; and (4) the Serra do Estreito, located on the western border, provides the main water source for formation of the fans. Despite advances in understanding the formation of these fans, additional dating is needed to better reconstruct the geochronological history of the Xique-Xique fluvial fans.

Geomorphologically, these fluvial fans are notable for being an authigenic system, primarily shaped by the dynamics of eolian and fluvial deposits in response to climate change. Notably, they differ from classical fan systems, because their main sediment source is eolian deposits.

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As fossilized systems now undergoing degradation, these fans preserve a sedimentary record of past environmental conditions, particularly periods of increased rainfall, the most recent of which occurred during the Middle Holocene. This period represents a key climatic transitional phase, where palynological data indicate the onset of long-term aridification in the region after 4 ka. Furthermore, the current superposition of São Francisco River tributary channels over the fans indicates a significant lowering of base level, consistent with Late Holocene incision of the São Francisco River (Mescolotti et al., 2021).

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