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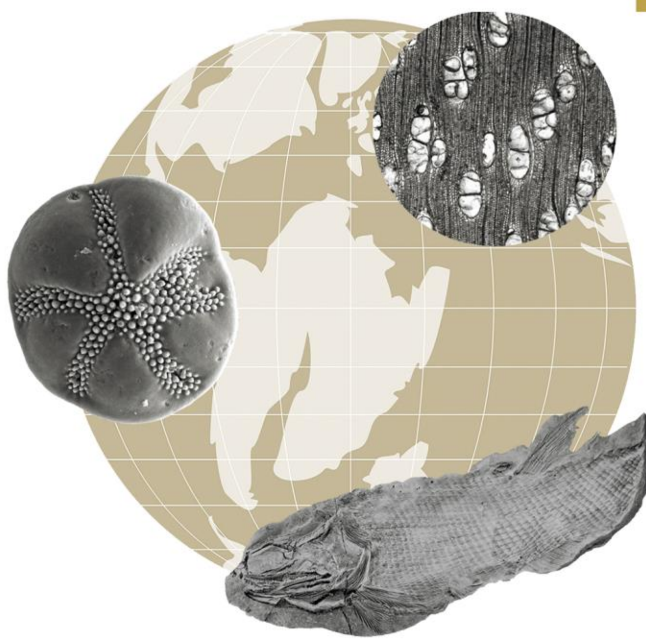

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The pollen record of Zoko Andi 1 archaeological site: contributions for understanding late Holocene paleoenvironments of the southwestern Pampa and northeastern Patagonia (Argentina)

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Short Description: Late Holocene fossil pollen record from Zoko Andi 1 site reconstructs vegetation dynamics and palaeoenvironmental change at multiple spatial scales.

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Abstract. Paleoenvironmental proxies have enabled the reconstruction of late Holocene paleoclimatic and paleoenvironmental conditions in the lower basin of the Colorado River (LBCR), within the eastern Pampa–Patagonia transition (Argentina). However, these reconstructions require refinement and testing through new data. Fossil pollen evidence for the last ca. 1500 cal BP was obtained from the Zoko Andi 1 archaeological site, located in the Espinal phytogeographic province within this transitional region. This study aims to present and analyze the pollen record from the site in order to reconstruct local vegetation dynamics and palaeoenvironmental conditions during the late Holocene, and to contribute to the existing knowledge derived from other proxies in the LBCR. Based on the geomorphological characteristics of the sequence, two archaeological components are distinguished: a lower component (ca. 1350 — 1200 cal BP) associated with an abandoned meander environment, and an upper component (since ca. 700 cal BP) related to aeolian deposition. The pollen assemblages indicate that the lower component was dominated by hydrophytic communities associated with wetland conditions under a semiarid climate. After ca. 700 cal BP, halophytic and subsequently psammophytic communities expanded in association with increasing aeolian activity and dune development, suggesting a progressive trend toward greater aridity, particularly during the last ca. 400 cal BP. This decrease in moisture availability during the final late Holocene has also been documented in nearby regions. Results provide new palaeoenvironmental information and contribute to the reconstruction of late Holocene environmental dynamics and climatic variability in the LBCR and adjacent regions of southwestern Pampas and northeastern Patagonia.

Keywords. Eastern Pampa-Patagonia transition. late Holocene. Pollen. Espinal phytogeographic unit. Palaeoenvironmental reconstruction. Archaeological site.

Resumen. El registro polínico del sitio arqueológico Zoko Andi 1: contribuciones para la comprensión de los paleoambientes del Holoceno tardío del suroeste Pampeano y noreste de Patagonia (Argentina). Los proxies paleoambientales han permitido reconstruir las condiciones paleoclimáticas y paleoambientales del Holoceno tardío en la cuenca inferior del río Colorado (LBCR), dentro de la transición oriental Pampa–Patagonia (Argentina). Sin embargo, estas reconstrucciones requieren ser refinadas y evaluadas mediante nuevos datos. Se obtuvo evidencia de polen fósil para los últimos ca. 1500 años cal AP en el sitio arqueológico Zoko Andi 1, localizado en la provincia fitogeográfica del Espinal dentro de esta región transicional. Este estudio tiene como objetivo presentar y analizar el registro polínico del sitio con el fin de reconstruir la dinámica de la vegetación local y las condiciones paleoambientales durante el Holoceno tardío, así como contribuir al conocimiento existente derivado de otros proxies en la LBCR. Sobre la base de las características geomorfológicas de la secuencia, se distinguen dos componentes arqueológicos: un componente inferior (ca. 1350 — 1200 años cal AP) asociado con un ambiente de meandro abandonado, y un componente superior (desde ca. 700 años cal AP) relacionado con depositación eólica. Las asociaciones polínicas indican que el componente inferior estuvo dominado por comunidades hidrófitas asociadas con condiciones de humedad bajo un clima semiárido. Después de ca. 700 años cal AP, comunidades halófitas y posteriormente psamófitas se expandieron en asociación con un incremento de la actividad eólica y el desarrollo de dunas, sugiriendo una tendencia progresiva hacia una mayor aridez, particularmente durante los últimos ca. 400 años cal AP. Esta disminución en la disponibilidad de humedad durante la parte final del Holoceno tardío también ha sido documentada en regiones cercanas. Los resultados aportan nueva información paleoambiental y

contribuyen a la reconstrucción de la dinámica ambiental y la variabilidad climática del Holoceno tardío en la LBCR y regiones adyacentes del sudoeste pampeano y noreste de Patagonia.

Palabras clave. Transición oriental Pampa-Patagonia. Holoceno tardío. Polen. Unidad fitogeográfica del Espinal. Reconstrucción paleoambiental. Sitio arqueológico.

Introduction

Palynological analyses of stratified sequences from natural deposits associated with human occupation in Argentina (32°–52° S) have become an important source of information on Holocene vegetation and environmental dynamics, particularly in areas where other depositional archives (e.g., peat bogs and lakes) are scarce (Prieto et al., 2018). Pollen assemblages generally reflect regional vegetation patterns (Fontana, 2005); however, multidisciplinary integration and the comparison of independent proxies are essential for testing palaeoecological hypotheses and achieving robust environmental interpretations (Bennett & Willis, 2001; Birks & Birks, 2006; Mancini et al., 2018). Paleoenvironmental studies from the Eastern Pampa–Patagonia transition, currently characterized by xerophytic woodlands associated with grass steppes and shrublands, indicate that semiarid to subhumid conditions prevailed during the last ca. 1500 cal BP, followed by a decrease in moisture availability over the last ca. 500 cal BP (Martínez et al., 2021; Zucol et al., 2022). Along a north-south transect, this pattern has been documented in Pampa grasslands (Grill, 1995, 1997; Borromei, 1995, 1998; Quattrocchio et al., 1998, 2008; Prieto, 2000; Grill et al., 2010; Tonello & Prieto, 2010), Espinal Province (Fernández, 2012), Monte-Espinal transition (Schäbitz, 1994, 1999, 2003), and Monte phytogeographic unit (Schäbitz, 1999; Marcos et al., 2012, 2014) (Fig. 1). Despite these regional consistencies, local reconstructions show significant variability related to edaphic characteristics and site-specific factors such as water availability. In this context, pollen studies based on stratigraphic sequences from the Espinal phytogeographic province remain scarce and need to be expanded in order to improve paleoenvironmental understanding at this spatial scale, particularly in the lower basin of the Colorado River (LBCR).

Paleoenvironmental research in the LBCR is currently developing along several lines of investigation, although pollen analysis remains relatively scarce. Previous studies based on fossil pollen from the archaeological sites Loma Ruiz 1 and El Tigre (located in the central and southeastern sectors of the basin, respectively; Fig. 1) allowed Fernández (2012) to infer the development of local halophytic to psammophytic communities under semiarid to arid conditions during the late Holocene. Additional contributions from geology, geomorphology, and geoarchaeology (Martínez & Martínez, 2011, 2017; Martínez et al., 2014), as well as from microvertebrate (Stoessel et al., 2008; Alcaráz, 2015, 2017), anthracological (Martínez et al., 2021), and phytolith studies (Zucol et al., 2022), have provided further insights into the environmental history of the LBCR. For the late Holocene, geomorphological studies indicate phases of intense morphogenesis, followed by periods of landscape stability and soil formation, and subsequently renewed erosional activity (Martínez & Martínez, 2011, 2017; Martínez et al., 2014, 2024). Results from anthracological and microvertebrate analyses reveal an ecotonal setting between the Monte and Espinal provinces, with shrub communities developing between ca. 1500 and 1300 cal BP under arid to semiarid conditions. Subsequently, warmer and more humid conditions were inferred after ca. 1300 cal BP (Stoessel et al., 2008; Alcaráz, 2015, 2017; Martínez et al., 2021). Phytolith assemblages from El Tigre site indicate the persistence of halophytic steppes until ca. 300 cal BP, followed by lower temperatures and fluctuations in humidity during the last three centuries (Zucol et al., 2022).

Despite these efforts, environmental conditions directly associated with human occupations in the LBCR remain poorly understood. The Zoko Andi 1 site constitutes a key archaeological site to address these issues. Its location on an active dune adjacent to the Colorado River, together with its characterization as a multi-purpose base camp (Martínez et al., 2014), provides an exceptional opportunity to link local vegetation dynamics with human activities in an ecotonal setting between the Espinal and Monte provinces. The aim of this study is to present and analyze the pollen record from the Zoko Andi 1 sedimentary sequence in order to reconstruct local vegetation dynamics and palaeoenvironmental conditions during the late Holocene, and to contribute to the state of the art regarding on past climates and landscapes derived from other proxies in the area. Taphonomic implications are also addressed through integration with geomorphological, zooarchaeological, and anthracological evidence. Finally, the results are compared with palaeoenvironmental records from northeastern Patagonia and the southwestern Pampas.

FIGURE 1

Study area

Climate. The area between the Colorado and Negro River basins (north of 40° S), also referred to as the Eastern Pampa–Patagonia transition (Martínez, 2017), is mainly influenced by the semi-permanent Subtropical Atlantic Anticyclone, which supplies moisture from the east (Prohaska, 1976). The LBCR (39° S, 63° W; Fig. 1) is located within the South American Arid Diagonal (Abraham de Vázquez et al., 2000). The regional climate is semiarid, and the area is intersected by the 466 mm isohyet (Burgos & Vidal, 1951; González Uriarte et al., 1987), with a marked seasonal precipitation regime. Precipitation is mainly concentrated during summer, when the southern westerlies weaken and humid air masses transported by easterly and northeasterly winds penetrate inland (Schäbitz, 2003). In contrast, during winter, the strengthening of the westerlies and the predominance of cold, dry air masses result in reduced precipitation and a pronounced moisture deficit. This marked seasonality is further reinforced by high summer evapotranspiration rates, which enhance aridity throughout most of the year (Schäbitz, 2003; Garreaud et al., 2013). Mean monthly temperatures range from 22.2 °C in January (summer) to 7.5 °C in July (winter), and decrease from north to south due to the moderating influence of the Atlantic Ocean (Prohaska, 1976; Garreaud et al., 2013).

Geologic and geomorphologic settings. The Colorado River flows from the Andes to the Atlantic Ocean. Within this alluvial landscape, a series of flat geomorphic surfaces developed at different elevations. The relief is stepped, with maximum elevations reaching 60 m a.s.l., decreasing from west to east (González Uriarte, 1984). These surfaces are mainly developed on sandstones of the Río Negro Formation (late Miocene–late Pliocene; Andreis, 1965). They have been partially incised by the Colorado and Negro rivers, forming a system of valleys and palaeovalleys (González Uriarte, 1984). The alluvial plain has a gentle slope and is characterized by abundant active channels, palaeochannels, abandoned meanders, levees, and saltpans. The paleovalleys are filled with fluvial sediments derived from the alluvial plain, including sandy-gravelly and floodplain facies such as bar deposits, abandoned meanders, shallow lakes, and levees (Martínez & Martínez, 2011, 2017). On the alluvial plain, the ancient delta of the Colorado River extends for approximately 110 km in a NW–SE direction (Cappannini & Lores, 1966). Aeolian deposits formed during different denudational phases mantle the older geomorphic surfaces, as well as fluvial and marine deposits. These consist of shallow sand sheets with small, isolated dunes. Most archaeological sites are associated with this aeolian sedimentary context and date to the mid-late Holocene (ca. 7200 — 230 cal BP) (Martínez, 2017; Martínez et al., 2024).

Vegetation. The LBCR belongs to the Chacoan Domain of the Neotropical Region (Cabrera, 1971). The Espinal phytogeographic province, where the Calden District is represented toward its southeastern extreme, extends in an irregular arc surrounding the Pampa grasslands. Xerophytic woodland constitutes the dominant vegetation type. This vegetation community is dominated by species of the genus *Neltuma* (= *Prosopis* in the broad traditional sense; Hughes et al., 2022), particularly *Neltuma caldenia*, accompanied by other tree species such as *Neltuma nigra* and *Neltuma flexuosa*, as well as *Geoffroea decorticans*, *Jodina rhombifolia*, *Schinus fasciculatus*, and *Ximenia americana*. Shrub communities include *Atamisquea emarginata*, *Neltuma alpataco*, *Senna aphylla*, *Prosopidastrum globosum*, *Larrea divaricata*, *Lycium chilense*, *Ephedra triandra*, *Ephedra ochreata*, *Baccharis artemisoides*, and *Baccharis ulicina*. The herbaceous layer is represented by species such as *Trichloris crinita*, *Elionurus muticus*, *Schizachyrium consanguineum*, *Setaria mendocina*, *Setaria globulifera*, *Jarava ichu* (= *Stipa gynerioides*), *Nassella tenuissima* (= *Stipa tenuissima*), *Nassella tenuis* (= *Stipa tenuis*), *Poa lanuginosa*, and *Poa ligularis* (Cabrera, 1971; Cialdella, et al., 2013; Oyarzabal et al., 2018). In addition, local vegetation units include edaphic communities developed on sandy soils (psammophytic vegetation), dominated by *Nassella tenuis*, *Nassella longiglumis* (= *Stipa clarazii*), *Piptochaetium napostaense*, *Sporobolus rigens*, and *Panicum urvilleanum* (Cabrera, 1971; Cialdella, et al., 2013). Halophytic vegetation is characterized by *Heterostachys ritteriana*, *Heterostachys olivascens*, and *Allenrolfea patagonica* (Cabrera, 1971; Fernández & Grill, 2016), whereas hydrophytic communities are mainly represented by taxa such as *Scirpus* sp., *Eleocharis macrostachya*, and *Hydrocotyle bonaeriensis* (Fernández & Grill, 2016). To the north, the LBCR borders the Pampa grasslands (Fig. 1), where grasses such as *Piptochaetium*, accompanied by herbs and shrubs including *Baccharis* (Cabrera, 1976; Soriano, 1991). The Pampa grasslands exhibit marked heterogeneity related to edaphic conditions (Cabrera, 1971; Oyarzabal et al., 2018). South of this unit, a broad ecotone develops between the dry Pampa and the xerophytic woodland of the Espinal under semiarid and relatively cooler climatic conditions (Prieto et al., 2004). Further south, the LBCR transitions into the Monte phytogeographic province (Fig. 1), where vegetation is dominated by xerophytic, psammophytic, and halophytic shrublands forming an ecotonal landscape (Cabrera, 1971). This vegetation is characterized by species such as *Larrea divaricata*, *Larrea cuneifolia*, and *Montea aphylla* (Roig et al., 2009; Oyarzabal et al., 2018). Climatic variability, together with edaphic and topographic conditions, controls vegetation distribution along environmental gradients (Morello, 1958; Cabrera, 1971, 1976; Soriano et al., 1983; León et al., 1998). Relationships between modern vegetation, pollen assemblages, and climatic conditions have been investigated across different phytogeographic units between 38° and 40° S, including the Pampa grasslands (Fontana, 2003, 2005; Tonello & Prieto, 2008), the Espinal (Paez et al., 2001; Fernández, 2012; Fernández & Grill, 2016), and the Monte provinces (Morello, 1958; Paez et al., 2001; Schäbitz, 2003; Marcos & Mancini, 2012a, 2012b).

Previous research: geoarchaeology and hunter-gatherer organization at the site

The Zoko Andi 1 site (39°28′10.3″ S, 63°05′58.3″ W; Fig. 1) is located on a sand dune along the southern margin of the present Colorado River, at the outer erosional bend of a meander, approximately 80 km upstream from the low-sinuosity, multichannel distributary system of the delta that drains into the Atlantic Ocean (Spalletti & Isla, 2003). The fluvial system is meandering and actively erodes older fluvial and aeolian deposits that overlie the alluvial plain (Martínez et al., 2014). According to Martínez and Martínez (2017), the sequence comprises two archaeological components (Fig. 2) associated with the late Holocene. Stratigraphic and sedimentological analyses conducted by Martínez et al. (2014) identified six allostratigraphic units (U6, U5, U4, U3, U2b, U2a, and U1; Fig. 2.1). The basal units (U6 and U5) are of fluvial origin and correspond to an abandoned meander (oxbow lake) sequence, represented by clay and silt deposits (Martínez et al., 2014; Martínez & Martínez, 2017). The unconformity between U5 and U4 marks the end of fluvio-lacustrine sedimentation and the onset of aeolian deposition. Overlying these basal deposits, aeolian sediments (U4, U3, and U2b), characterized by high sand content, accumulated during a phase of rapid sedimentation, culminating in the development of a buried soil (U2a; Fig. 2.1). Periods of landscape stability and pedogenesis favored the formation of the buried 2ACb horizon. Subsequently, a new unconformity is recorded, above which the sediments of unit U1 were deposited (Fig. 2). In summary, the stratigraphic framework, together with radiocarbon dating (Table 1), indicates two distinct phases of human occupation at the site: the lower component (U6–U5), dated between 1527 ± 34 ^{14}C yr BP (1363 cal BP) and 1330 ± 50 ^{14}C yr BP (1212 cal BP), and the upper component (U4–U1), dated from 818 ± 25 ^{14}C yr BP (702 cal BP) onwards (Table 1; Martínez & Martínez, 2017; Martínez et al., 2021).

Regarding hunter-gatherer organization, subsistence strategies at the site during the late Holocene included the exploitation of both large vertebrates (e.g., guanaco, deer, and rhea) and small fauna (e.g., rodents, armadillos, and birds) (Martínez et al., 2014, 2025; Alcaráz, 2017; Stoessel & Martínez, 2022). Lithic assemblages indicate a predominance of locally available raw materials (silica, basalt/andesite, and chalcedony), although non-local resources such as translucent chalcedony were also utilized (Martínez et al., 2014; Santos Valero, 2021). Pottery was recorded in both archaeological components (Borges Vaz, 2019), whereas the bioarchaeological record is restricted to the interval between ca. 1500 and 1300 cal BP, when secondary burials were documented (Martínez & Flensborg, 2020). Charcoal remains recovered from the lower component constitute direct evidence of the use of fire by these societies (Martínez et al., 2021). Altogether, these data support the interpretation of the site as a multi-purpose base camp repeatedly occupied through time, with spatial differentiation between domestic activities in riverside sectors and mixed domestic–funerary contexts in the upper dune areas (Martínez et al., 2014, 2025; Martínez & Flensborg, 2020).

FIGURE 2

TABLE 1

Methods

The samples for pollen analysis (Fig. 2a) were taken from the grid 6 (C6), located on the southern wall of the excavation (Fig.1). Thirty-three samples were analyzed from a sediment sequence of 1.93 m depth (Supplementary Online Information). Samples had an average thickness of 5 cm and were collected following sedimentological criteria to ensure representation of the different sedimentary units (Fig. 2). The samples weighed between 12 and 22 grams, with the exception of the basal sample that weighed 30 grams due to its sediment component (clay). The samples were sieved through 120 µm mesh screens and treated by the standard procedures proposed by Faegri and Iversen (1989): KOH 10 % to remove clays and humid acids, HCl 10 % to remove carbonates, $ZnCl_2$ (δ = 2 g/ml) to separate the mineral fraction by flotation, HF to remove silicates, and finally, acetolysis to remove the organic matter. A minimum of 300 pollen grains was counted per sample, as this is generally considered adequate when pollen-type diversity is not high (Birks and Gordon, 1985; Odgaard, 2007). In samples with low pollen concentration or high pollen-type diversity, counting was continued beyond 300 grains to ensure adequate representation of the pollen assemblage. Pollen sums ranged from 300 to 1220 grains per sample. The pollen samples were plotted using the TILIA program (Grimm, 2004). Each taxon was expressed as a percentage of the total pollen sum. *Nothofagus* and *Podocarpus* were not included in the pollen sum because they represent extra-regional taxa. The same criterion was applied to *Pinus* due to the fact that this taxon is related to anthropic changes. The samples were grouped by Cluster Analysis, applying square root transformation with Edwards's dissimilarity coefficient and Cavalli-Sforza's chord distance to distinguish pollen zones, considering taxa that reach percentages of 2% of the sum of terrestrial pollen using the TILIA program (Grimm, 2004). Photographs were taken of the main pollen types. The radiocarbon dates were calibrated using the software CALIB 8.2 (Stuiver et al., 2021) with the Southern Hemisphere calibration curve (SHCal20) (Hogg et al., 2020). The calibrated dates presented in Table 1 represents the mean age of each date from all the runs.

Results

The pollen spectrum is described according to the six allostratigraphic units defined by Martínez et al. (2014) (Fig. 3). The CONISS analysis grouped the pollen samples from U4–U3 and U5–U6 according to the similarity of their pollen assemblages. Nevertheless, the pollen results are described according to the allostratigraphic units in order to preserve their stratigraphic context. The main pollen types can be observed in Figure 4.

Lower component:

Unit 6 (between ca. 1350—1200 cal BP). This unit is characterized by the highest values of Asteraceae subf. Asteroideae (75 to 90%). Amaranthaceae subf. Chenopodioideae and Poaceae present values that reach 10%. Malvaceae and Geraniaceae around 1.5%. Apiaceae and Cyperaceae around 5% and lower values of Monocotiledoneae, Caryophyllaceae, Asteraceae subf. Cichorioideae. *Ephedra* shows values of 5%. *Podocarpus* (extra-regional) is present with values lower than 2%.

Unit 5. This unit is represented by a sample with 90% of Asteraceae subf. Asteroideae, 10% of Poaceae and Amaranthaceae subf. Chenopodioideae, < 5% of Malvaceae, Asteraceae subf. Cichorioideae and *Ephedra*.

Upper component:

Unit 4 (ca. 700 cal BP). This unit is characterized by the highest values of Amaranthaceae subf. Chenopodioideae (30 to 60%) and Asteraceae subf. Asteroideae (30% to 60%). Other important taxa are Poaceae (5 to 10%), Malvaceae and Geraniaceae < 5% and the rest of herbs with values lower than 1%. *Ephedra* 3% and low representation of other shrubs.

Unit 3. This unit is represented by Asteraceae subf. Asteroideae (40% to 60%), Amaranthaceae subf. Chenopodioideae (30 to 50%), Poaceae (10%), Malvaceae, Geraniaceae and Brassicaceae, Asteraceae subf. Cichorioideae < 2%. *Geoffroea decorticans* with < 2%. *Ephedra* < 5% and *Lycium* < 2%.

Unit 2 (ca. 630—400 cal BP). The subunit 2b is represented by Asteraceae subf. Asteroideae (40 to 50%), Amaranthaceae subf. Chenopodioideae (20 to 30%), Poaceae

(20%). Geraniaceae < 5% and other pollen types with values < 1%. *Ephedra* reaches 20%. Other shrubs < 1%. The subunit 2a presents Asteraceae subf. Asteroideae (35%), Amaranthaceae subf. Chenopodioideae (15 to 25%), Poaceae (10%), Malvaecae (5%), Geraniaceae (5%) and Brassicaceae (15%). Some herbs present values < 1%. *Ephedra* reaches 30%. Other shrubs < 1%.

Unit 1. This zone is characterized by Asteraceae subf. Asteroideae (5% to 30%), Poaceae (10 to 35%), Amaranthaceae subf. Chenopodioideae (until 15%), Malvaceae and Geraniaceae (< 10%) and Brassicaceae (10 to 45%). *Plantago* and other herbs < 5%. *Ephedra* (< 2 to 30%). This unit shows the highest values of excluded pollen types; *Pinus* and *Nothofagus*.

FIGURE 3

FIGURE 4

Discussion

Integration of pollen evidence into the current knowledge of the Zoko Andi 1 site.

The palaeoenvironmental interpretation (Fig. 5) is based on the integration of temporal frameworks defined by sedimentary units, radiocarbon dates, and pollen assemblages (Table 1; Figs. 2 and 3). However, it is important to consider that pollination types, as well as differences in pollen production, flowering, and dispersal, influence the representativeness of pollen taxa in the fossil record (Prentice, 1988). Studies on the relationship between modern pollen and vegetation, such as those conducted by Fernández (2012) and Fernández and Grill (2016), have highlighted the implications of these factors for palaeoenvironmental reconstructions, particularly in terms of the differential representation of plant communities and the relative contribution of local versus regional vegetation signals.

The lower component (ca. 1350—1200 cal BP), comprising units U6 and U5 (Fig. 3), corresponds to an abandoned meander (Martínez et al., 2014; Martínez & Martínez, 2017). It is characterized by a pollen assemblage with high values of Asteraceae subf. Asteroideae, together with hygrophilous taxa such as Cyperaceae (e.g., *Scirpus* sp. and *Eleocharis macrostachya*) and *Hydrocotyle*-type pollen, indicating the development of hydrophytic communities under local wetland conditions associated with the abandoned meander. These taxa are typical of palustrine or marginal environments, although some (e.g., *Hydrocotyle*) may also occur in moist interdunal settings. This evidence suggests the establishment of a locally humid environment controlled by geomorphological conditions, while the presence of *Ephedra* indicates semiarid regional conditions. The occurrence of microvertebrates such as *Microcavia australis*, *Calomys* sp., and *Dolichotis patagonum* further supports the presence of open shrub-steppe environments under arid to semiarid conditions during this interval (Stoessel et al., 2008; Alcaráz, 2015, 2017). Anthracological analyses from the lower component identified taxa such as *Neltuma caldenia*, *Neltuma* sp., *Senna* sp. (Fabaceae), *Jodina rhombifolia* (Santalaceae), *Condalia* sp. (Rhamnaceae), and *Larrea* sp. (Zygophyllaceae). These results indicate the development of an ecotonal landscape between the Monte and Espinal provinces under arid to semiarid conditions. A xerophytic open woodland dominated by *N. caldenia* and shrub communities dominated by *Larrea* spp. were inferred from the charcoal record (Martínez et al., 2021).
Following the model proposed by Fernández and Grill (2016) for the LBCR, the low representation of xerophytic taxa in the pollen assemblages may be explained by their

limited pollen production and entomophilous pollination, which reduces their visibility in the pollen record despite their presence in the local vegetation.

Following the main unconformity, the upper component corresponds to the onset of aeolian deposition, which culminates in the development of a palaeosol (Martínez et al., 2014). This component includes units U4 (ca. 700 cal BP) and U3, representing a phase of rapid aeolian sedimentation. The pollen assemblages are characterized by high values of Amaranthaceae subf. Chenopodioideae, accompanied by Asteraceae subf. Asteroideae and Poaceae, indicating the development of halophytic vegetation associated with sandy sediments (Figs. 2 and 3). The persistence of *Ephedra* further suggests continued semiarid regional conditions. The presence of taxa such as *Geoffroea decorticans* and *Lycium* (e.g., *L. chilense*), characteristic of the Espinal phytogeographic unit, also supports the interpretation of dry environmental conditions during this interval. The presence of fossil remains of *Ceratophrys* sp. associated with these units at Zoko Andi 1 may also be consistent with these environmental conditions. A study carried out by van der Kamp and Ortega-Andrade (2024), based on genetic and morphological data, indicates that *C. ornata* (a species that, given its distribution, is likely to be found at the site) is associated with more semi-arid environments characterized by higher and variable temperature seasonality. Although its ecological significance should be interpreted with caution given its broad environmental tolerance as a grassland-associated amphibian (Nicoli, 2019).

In units U2a and U2b (ca. 600—400 cal BP), the pollen record reflects a transition from halophytic to psammophytic communities, as indicated by the decrease in Amaranthaceae subf. Chenopodioideae and the increase in psammophilous taxa such as Malvaceae, Geraniaceae, and Brassicaceae, which are associated with sandy substrates. The development of a palaeosol (U2a) indicates a phase of environmental stability. Furthermore, increased values of *Ephedra* suggest a trend toward more arid conditions and enhanced landscape stability, which would have favored the expansion of regional vegetation components. Following the second unconformity, a psammophytic community associated with dune environments is inferred for unit U1 (last ca. 400 cal BP), based on a pollen assemblage dominated by Asteraceae subf. Asteroideae, Amaranthaceae subf. Chenopodioideae, Poaceae, Geraniaceae, Malvaceae, and Brassicaceae. The Poaceae component includes taxa commonly associated with sandy edaphic communities, such as *Nassella tenuis*, *Nassella longiglumis*, and *Sporobolus rigens*. This assemblage, together with the presence of Brassicaceae and *Plantago*, suggests disturbed environments likely related to active sand mobilization. Although *Ephedra* remains present, its relative decrease compared to the underlying palaeosol indicates a shift in vegetation dynamics under increasingly arid conditions. The occurrence of *Pinus* pollen may reflect anthropogenic influence; however, given its bisaccate morphology and high dispersal capacity, long-distance transport cannot be ruled out, as is also the case for *Nothofagus*, a genus typical of the subantarctic forests.

Geoarchaeological studies indicate the occurrence of intense geomorphic processes that persisted until the development of an extensive buried soil in the LBCR (including inland areas, the ancient delta, and the Atlantic coast), dated between ca. 1000 and 400 cal BP (Martínez et al., 2019). The pedogenetic development of this soil reflects a phase of landscape stability (Martínez & Martínez, 2017). The pollen record from Zoko Andi 1 reflects local environmental conditions throughout the temporal blocks, showing a transition from hydrophytic to halophytic and subsequently psammophytic communities, largely controlled by local edaphic factors. Following this pedogenetic phase, renewed erosion and landscape reactivation led to the truncation and burial of the soil, generating unconformities over which a shallow aeolian mantle was deposited (Martínez & Martínez, 2017). For this later period, the reconstructed vegetation is associated with dune environments and reflects disturbed conditions linked to active sand mobilization.

FIGURE 5

Taphonomic considerations: natural and anthropogenic factors. The basal fluvio-lacustrine units of the lower component (U6–U5), associated with an abandoned meander system, likely acted as efficient pollen traps, favoring the accumulation of predominantly local pollen. Such depositional environments typically promote the incorporation of pollen derived from nearby wetland vegetation, together with a secondary input from the broader catchment. Accordingly, the pollen assemblages from this component primarily reflect local vegetation, as indicated by the presence of hydrophilous taxa such as Cyperaceae. The absence of xerophytic taxa such as *Prosopis*-type, *Condalia*, and *Larrea* in the pollen assemblages is likely related to their entomophilous pollination and relatively low pollen production, which reduces their preservation and representation in the pollen record. These characteristics often result in the underrepresentation of such taxa in pollen records, even when they are locally present in the vegetation (Fernández & Grill, 2016), particularly when the pollen assemblage reflects local environmental conditions. In contrast, anthracological assemblages may represent vegetation from a broader area, as fuelwood could have been collected from different sectors of the surrounding landscape but nearby the site (Martínez et al., 2021). Therefore, charcoal taxa such as *Prosopis*/*Neltuma*, *Condalia*, and *Larrea* likely reflect woody vegetation growing in the regional ecotonal landscape between the Monte and Espinal provinces. The integration of pollen and anthracological evidence suggests that Zoko Andi 1 was located within a heterogeneous landscape: while the pollen assemblages mainly record local wetland vegetation associated with the abandoned meander, the charcoal record indicates the presence of xerophytic woody communities typical of the Monte–Espinal ecotone in the surrounding area (Martínez et al., 2021). In addition to the pollination characteristics of these taxa, the selective gathering of woody resources, related to their combustion properties and other cultural factors, should also be considered. Moreover, the presence of charcoal remains in U6 (Martínez et al., 2021) suggests the occurrence of burning events that may have affected pollen preservation. High temperatures associated with fire can destroy pollen grains, particularly those with thinner exines, such as Cyperaceae, potentially biasing the assemblage toward more resistant taxa (e.g., Asteraceae subf. Asteroideae) (Marcos et al., 2019, 2020). The dominance of Asteraceae subf. Asteroideae in the lower component likely results from a combination of factors, including high pollen productivity, efficient wind dispersal, and ecological affinity with open and semiarid environments. In addition, local disturbances related to fire events and human occupation may have promoted the expansion of these taxa, while the abandoned meander depositional setting may have enhanced the accumulation of airborne pollen derived from the surrounding steppe vegetation.

In contrast, the overlying aeolian units of the upper component (U4–U1) are primarily influenced by wind transport and may incorporate a greater proportion of regionally derived pollen. Aeolian sedimentation may also involve the reworking of previously deposited material, potentially mixing pollen from different sources.

Furthermore, the relatively dry and oxidizing conditions associated with well-drained sandy sediments, together with neutral to alkaline pH values as reported by Martínez et al. (2014), are unfavorable for pollen preservation and promote corrosion and differential preservation, which are typical of sandy depositional environments (Marcos et al., 2019, 2020). The pollen assemblages reflect a combination of local vegetation associated with specific depositional environments and regional pollen rain transported by wind, as exemplified by *Ephedra*. As in many pollen records from semiarid environments of southern South America, the representation of taxa is influenced by differences in pollen production, dispersal capacity, and preservation. Woody taxa such as *Lycium* and *Geoffroea decorticans* may be underrepresented due to their relatively low pollen production and frequent insect pollination. In contrast, anemophilous taxa such as Poaceae, Asteraceae subf. Asteroideae, and Amaranthaceae subf. Chenopodioideae tend to be overrepresented because of their high pollen productivity and efficient wind dispersal. Consequently, pollen assemblages often emphasize the herbaceous component of vegetation, even when woody species are locally significant. In this context, the palaeoenvironmental inferences derived from Zoko Andi 1 indicate that xerophytic woodland is not clearly represented in the pollen record; instead, the reconstructed vegetation primarily reflects local environmental variability. Furthermore, the presence of archaeological materials throughout the sequence indicates repeated human occupation of the site. Human activities may have modified the local vegetation, promoting disturbance-tolerant taxa such as Brassicaceae, which are commonly associated with open and disturbed environments. In fossil pollen records, this taxon is often linked to disturbed settings, whether of natural or anthropogenic origin (Prieto, 2000; Grill et al., 2010). The occurrence of arboreal taxa such as *Nothofagus* and

Podocarpus is interpreted as the result of long-distance transport from the Andean region, a pattern commonly observed in pollen records from northern Patagonia and the Pampas. Similarly, *Pinus* pollen may reflect either long-distance transport or local disturbance. Overall, the pollen record from Zoko Andi 1 likely integrates both local vegetation signals and regional pollen rain, with the relative contribution of each component varying according to the depositional environment represented by each stratigraphic unit.

A synthesis of palaeoenvironmental reconstructions from the LBCR. The Zoko Andi 1 record can be contextualized within the palaeoenvironmental framework of the LBCR, allowing comparison with other sequences from the basin. The El Tigre site, located in the ancient delta of the Colorado River (Fig. 1), presents a palaeoenvironmental history characterized by halophytic steppe vegetation and vegetated dune environments, indicating semiarid conditions between ca. 1500 and 700 cal BP (Fernández, 2012). Phytolith studies from this site suggest temperate climatic conditions and a phase of increased water availability, during which halophytic steppe vegetation persisted between ca. 1500 and 300 cal BP. Microvertebrate evidence supports this interpretation, as the presence of *Holochilus vulpinus* and *Cavia aperea* indicates relatively moist and warm conditions between ca. 900 and 400 cal BP (Stoessel et al., 2008; Alcaráz, 2015, 2017). After ca. 500–400 cal BP, pollen records from El Tigre indicate the development of halophytic grasslands with xerophytic shrubs under semiarid conditions. From ca. 300 cal BP onwards, ruderal communities and psammophytic grasslands associated with scattered xerophytic shrubs were reconstructed, suggesting increasing environmental disturbance and more arid climatic conditions (Fernández, 2012). The Loma Ruiz 1 site, located inland to the north of the basin (Fig. 1), exhibits a different local vegetation structure under broadly similar regional climatic conditions. Pollen assemblages from this site indicate the presence of psammophytic grasslands with scattered xerophytic shrubs, reflecting a semiarid regional climate during the last ca. 1800 cal BP. These plant communities suggest the persistence of dry sandy environments controlled by local edaphic conditions and aeolian processes, comparable to the psammophytic communities reconstructed in the upper part of the Zoko Andi 1 sequence.

When these records are considered together, several areal patterns become evident. Pollen data from Zoko Andi 1 and Loma Ruiz 1 indicate that semiarid to dry conditions prevailed in the LBCR at least between ca. 1800 and 1200 cal BP, with local environmental variability largely controlled by geomorphological settings and water availability. Multiple proxies further suggest that, across inland sites (Loma Ruiz 1 and Zoko Andi 1) as well as the ancient delta (El Tigre), a relatively synchronous pedogenic phase occurred between ca. 1000 and 400 cal BP, indicating landscape stability under relatively warmer and more humid conditions. A trend toward increasing aridity after ca. 400 cal BP is supported by several proxies across most of the analyzed sites. At both Zoko Andi 1 and El Tigre, high values of Brassicaceae pollen are interpreted as indicators of arid conditions and environmental disturbance associated with low moisture availability. Species within this family are efficient colonizers of disturbed environments and commonly expand under conditions of climatic stress, particularly increasing aridity and landscape instability (Bazzaz, 1998). Additional evidence from phytolith studies indicates that during the last ca. 300 cal BP, environmental conditions were characterized by lower temperatures and fluctuations in humidity, supporting the interpretation of increased climatic variability during the final late Holocene (Zucol et al., 2022). Overall, the integration of palaeoenvironmental records from Zoko Andi 1, El Tigre, and Loma Ruiz indicates that vegetation dynamics in the LBCR during the last ca. 1500 cal BP were primarily controlled by local edaphic conditions and water availability, within a persistent semiarid climatic framework. Despite local variability, the records consistently suggest a trend toward increasing aridity during the last ca. 400 years.

Zoko Andi 1 in a regional palaeoenvironmental context. Palaeoenvironmental reconstructions from northeastern Patagonia and the southwestern Pampas provide a broader regional framework for interpreting the environmental history recorded at Zoko Andi 1, located within the Espinal phytogeographic province at the transition between the Monte and the Pampa grasslands.

Pollen records from Salina Anzoátegui and Salina Piedra (Fig. 1), situated within the Monte–Espinal transition, indicate that semiarid climatic conditions broadly similar to modern ones prevailed during the last ca. 1500 cal BP (Schäbitz, 1994). Additional records from the Monte region, including Salinas Gualicho 1 and 2 and Salina Inglés (Fig. 1), also suggest arid to semiarid conditions throughout the late Holocene (Schäbitz, 1999). These environmental conditions have been linked to variations in the position and intensity of the southern westerly wind belt in northeastern Patagonia (Schäbitz & Liebricht, 1998). When the southern westerlies shift southward, humid air masses from the Atlantic can penetrate inland, increasing precipitation. According to Schäbitz (2003), mean precipitation values ranged between 320 and 380 mm during the last ca. 1500 cal BP (Fig. 5). Further south of the Colorado River basin, within the Monte phytogeographic province, pollen assemblages from the Bajo de la Quinta site (Fig. 1) indicate the development of xerophytic steppe vegetation with

Monte–Espinal elements, suggesting semiarid conditions since ca. 3000 cal BP (Marcos et al., 2012, 2014). However, an arid pulse was recorded around ca. 1000 cal BP, intensifying between 600 and 500 cal BP (Marcos et al., 2014; Fig. 5).

To the north of the Espinal, within the Pampa grasslands, pollen records from Río Sauce Grande and Arroyo Napostá Grande (Fig. 1) indicate the presence of halophytic steppes and psammophytic herbaceous communities during the late Holocene. These vegetation types are associated with aeolian environments under semiarid conditions (Borromei, 1995, 1998; Grill, 1995, 1997; Quattrocchio et al., 1998). Alluvial pollen records from other sites in the southern Pampa grasslands reflect marked climatic variability, characterized by alternating episodes of aridity and relatively wetter and warmer conditions (Quattrocchio et al., 2008). Additional palaeoclimatic reconstructions based on precipitation data from the Arroyo Sauce Chico sequence indicate that between ca. 1500 and 500 cal BP, precipitation values were higher than present (by approximately 100 mm), suggesting subhumid to dry conditions. These conditions shifted toward semiarid conditions during the last ca. 500 years, when precipitation decreased as the southern westerly wind belt moved southward, producing climatic conditions broadly comparable to those observed today (Tonello & Prieto, 2010; Fig. 5).

The palaeoenvironmental changes inferred from these regional records provide a framework for interpreting the environmental evolution of the LBCR. Quantitative palaeoprecipitation reconstructions for the Pampa grasslands (Tonello & Prieto, 2010) and the Monte region (Schäbitz, 2003) indicate that semiarid conditions prevailed during the last ca. 1500 cal BP, albeit with fluctuations in moisture availability. Within this regional context, vegetation changes were primarily controlled by local edaphic conditions and water availability, superimposed on a semiarid climatic framework with a trend toward increasing aridity during the last centuries. In particular, the aridization process recorded around ca. 400 cal BP at Zoko Andi 1 is consistent with regional climatic changes documented in both northeastern Patagonia and the southwestern Pampas. Likewise, the increase in aridity during the last four centuries, associated with decreasing precipitation particularly in the southwestern Pampas, is reflected in pollen records by the predominance of ruderal taxa and indicators of anthropogenic disturbance in natural vegetation (Prieto, 2000; Grill et al., 2010; Fig. 5).

Conclusions

The present study provides new information on past local plant communities within the Espinal phytogeographic unit, although the representation of regional vegetation in the pollen record remains limited, as previously suggested by Fernández and Grill (2016). Taphonomic analyses of fossil pollen assemblages are still scarce in this region. Although the pollen grains analyzed in this study show generally good preservation, future research should include more detailed analyses of pollen deterioration types. Such analyses have been carried out in other regions of Argentina, including Patagonia (Marcos et al., 2019, 2020) and the Pampas (Prieto et al., 2004), as well as qualitative assessments in modern sediments from the LBCR, where chemical oxidation has been identified as a major cause of pollen deterioration (Fernández & Grill, 2016).

The palaeoenvironmental reconstruction based on the pollen record from the Zoko Andi 1 site indicates the development of distinct local vegetation communities throughout the sequence. Hydrophytic communities were present during the lower component (ca. 1350–1200 cal BP), reflecting local conditions associated with water availability under arid to semiarid climatic conditions. Subsequently, during the upper component (since ca. 700 cal BP), halophytic and later psammophytic communities developed in association with dune environments, indicating increasing aeolian activity. These changes suggest a progressive trend toward more arid conditions, particularly after ca. 400 cal BP. Overall, the environmental reconstruction points to increasing aridity toward the upper part of the sequence.

The integration of these results with other palaeoenvironmental proxies from the LBCR supports a transition from semiarid conditions, with vegetation dynamics mainly controlled by local edaphic conditions and fluctuations in moisture availability between ca. 1350 and 400 cal BP, to more arid conditions and increased aeolian activity after ca. 400 cal BP. Similar palaeoenvironmental trends have been documented in northeastern Patagonia and the Pampa grasslands, where palaeoprecipitation reconstructions indicate subhumid to dry conditions before ca. 500 cal BP, followed by a progressive decrease in moisture availability during the final late Holocene.

The palaeoenvironmental interpretations derived from the Zoko Andi 1 site represent an important contribution to the study of the Eastern Pampa–Patagonia transition, a region where palaeoenvironmental records remain relatively scarce. The results are framed within a broader regional context and reinforce previous palaeoenvironmental reconstructions proposed for the LBCR and adjacent areas. The environmental scenarios inferred from this study contribute to the reconstruction of late Holocene landscapes and, together with other proxies, provide a useful framework for understanding past environmental variability in the region. In this sense, while pollen analyses show some limitations in detecting xerophytic taxa, anthracological evidence helps to overcome this limitation. In other words, although the pollen record primarily reflects natural environmental changes driven by climatic variability and geomorphological processes, other proxies suggest that human activities may have locally influenced vegetation composition during the late Holocene.

Moreover, the location of the Zoko Andi 1 site within the Espinal phytogeographic province, at the transition between the Monte and the Pampa grasslands, likely contributes to the heterogeneous pollen signal observed in the record. This ecotonal position makes the site particularly valuable for understanding the interaction between local environmental dynamics and broader regional climatic trends during the late Holocene.

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Figure captions

Figure 1. A, location of the study area; B-C, the photos show the square 6 (C6) where analyzed pollen samples were taken; D, eastern Pampa-Patagonia transition (Argentina), phytogeographic units (Pampa, Espinal and Monte), the Zoko Andi 1 site and location of sites mentioned in the text: the El Tigre and Loma Ruiz 1 sites (Fernández, 2012); Bajo de la Quinta site (Marcos et al., 2012, 2014); Salina Piedra and Anzoátegui (Schäbitz, 1994, 2003); Salina Inglés and Gualicho 1 and 2 (Schäbitz, 1999); Río Sauce Grande and Arroyo Napostá Grande (Borromei, 1995; 1998; Grill, 1995, 1997; Quattrocchio et al., 1998, 2008; Grill et al., 2010;); Arroyo Sauce Chico (Tonello & Prieto, 2010).

Figure 2. A, stratigraphic sequence and location of pollen samples and radiocarbon dates; B, allostratigraphic units and their sedimentological components. Modified from Martínez et al. (2021).

Figure 3. Pollen diagram in percentage and total pollen concentration of Zoko Andi 1 site. The asterisks (*) indicate the location of each radiocarbon dates: *[1] 380 ± 43 ^{14}C yr

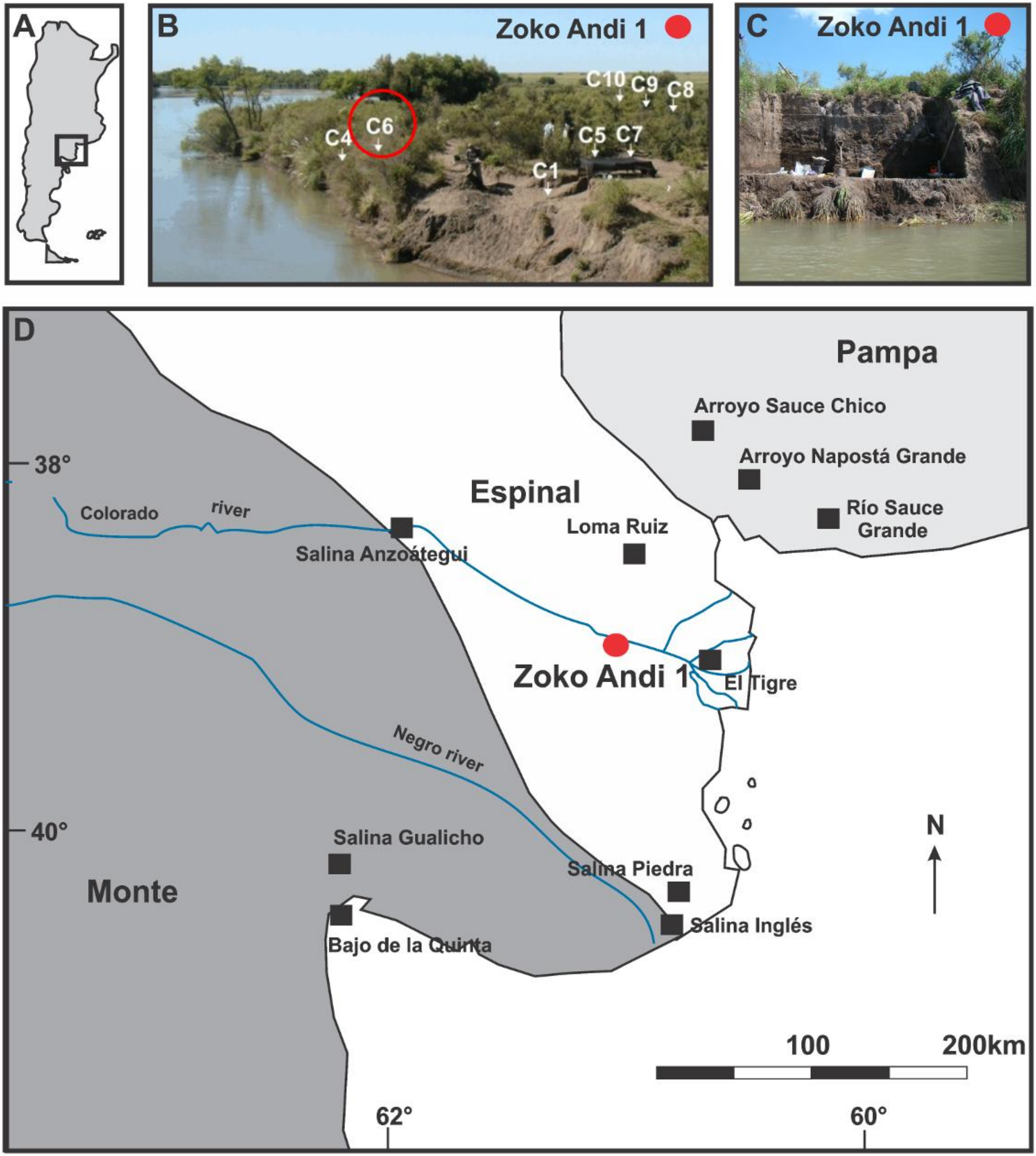
BP (397 cal BP); *[2] 726 ± 57 ^{14}C yr BP (633 cal BP); *[3] 793 ± 39 ^{14}C yr BP (688 cal BP); *[4] 818 ± 25 ^{14}C yr BP (702 cal BP); *[5] 1330 ±50 ^{14}C yr BP (1212 cal BP); *[6] 1508 ± 44 ^{14}C yr BP (1352 cal BP); *[7] 1526 ± 34 ^{14}C yr BP (1362 cal BP); *[8] 1527 ± 34 ^{14}C yr BP (1363 cal BP).

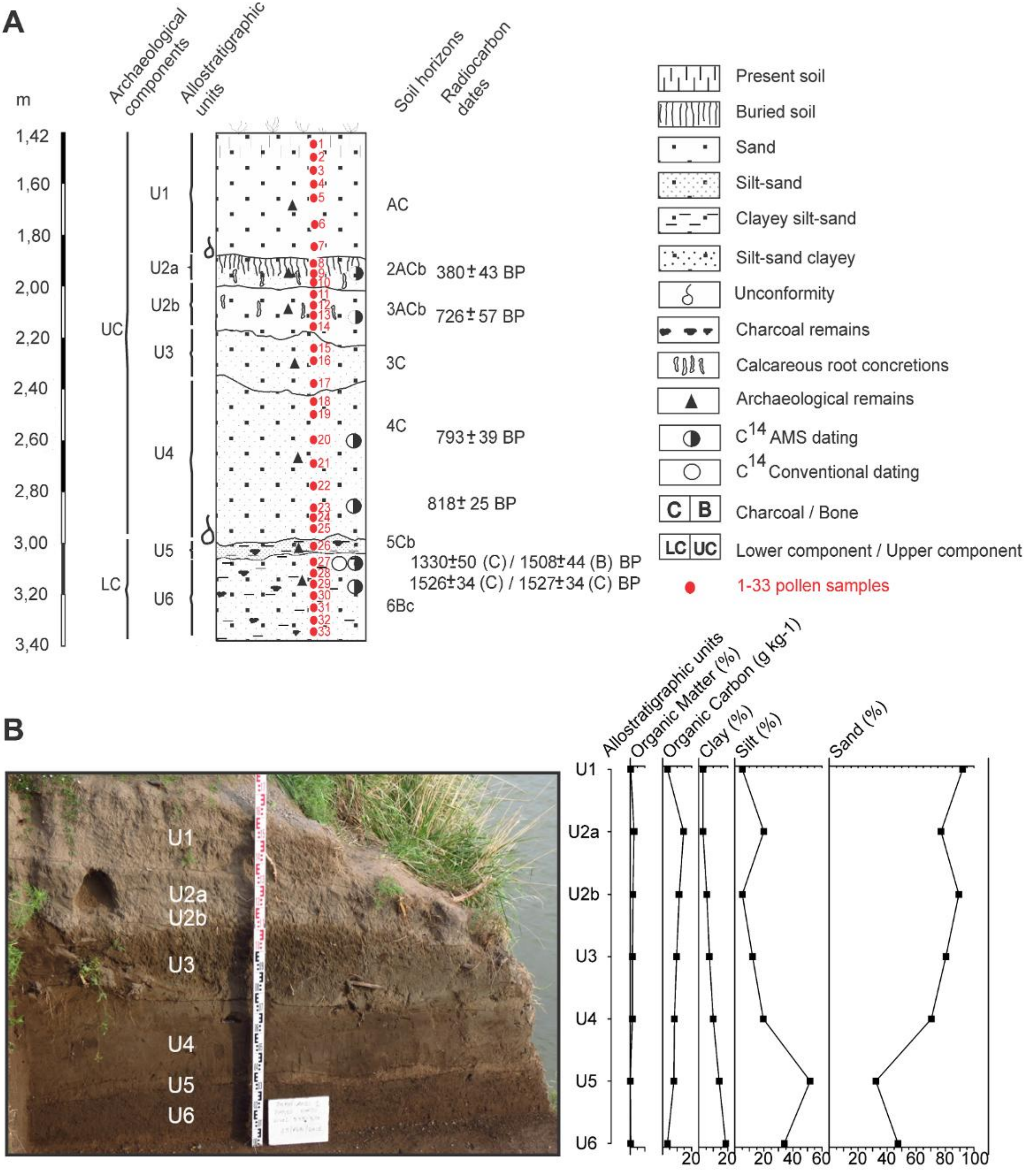
Figure 4. Microphotographs of the main pollen types. A, Poaceae; B, Amaranthaceae subf. Chenopodioideae; C, Malvaceae; D, Geraniaceae; E, Brassicaceae; F, *Plantago*; G, Asteraceae subf. Asteroideae; H, Cyperaceae; I, Rosaceae; J, Asteraceae subf. Cichorioideae; K, *Geoffroea decorticans*; L, *Ephedra*.

Figure 5. Integration of palaeoenvironmental reconstructions: In the middle, lower Colorado River basin: Zoko Andi 1 (pollen analysis-present paper); geomorphology (Martínez & Martínez, 2011, 2017; Martínez et al., 2014; Martínez, 2017); anthrachology –black circles correspond to charcoals- (Martínez et al., 2021); microvertebrates (Stoessel et al., 2008; Alcaráz, 2015, 2017); palaeoenvironmental reconstruction based on pollen and phytolith assemblages from El Tigre and Loma Ruiz 1 sites (Fernández, 2012; Zucol et al., 2022). Palaeoenvironmental reconstruction (Borromei, 1995, 1998; Grill, 1995, 1997; Quattrocchio et al., 1988, 2008; Grill, et al., 2010; Prieto, 2000; Tonello & Prieto, 2010) and quantitative reconstruction of Holocene precipitation changes (Tonello & Prieto, 2010) for the SW Pampa grasslands. Palaeoenvironmental reconstruction (Schäbitz 1994, 1999; Marcos et al., 2012, 2014) and quantitative reconstruction of Holocene precipitation (Schäbitz, 2003) for the NE Patagonia (Espinal and Monte).

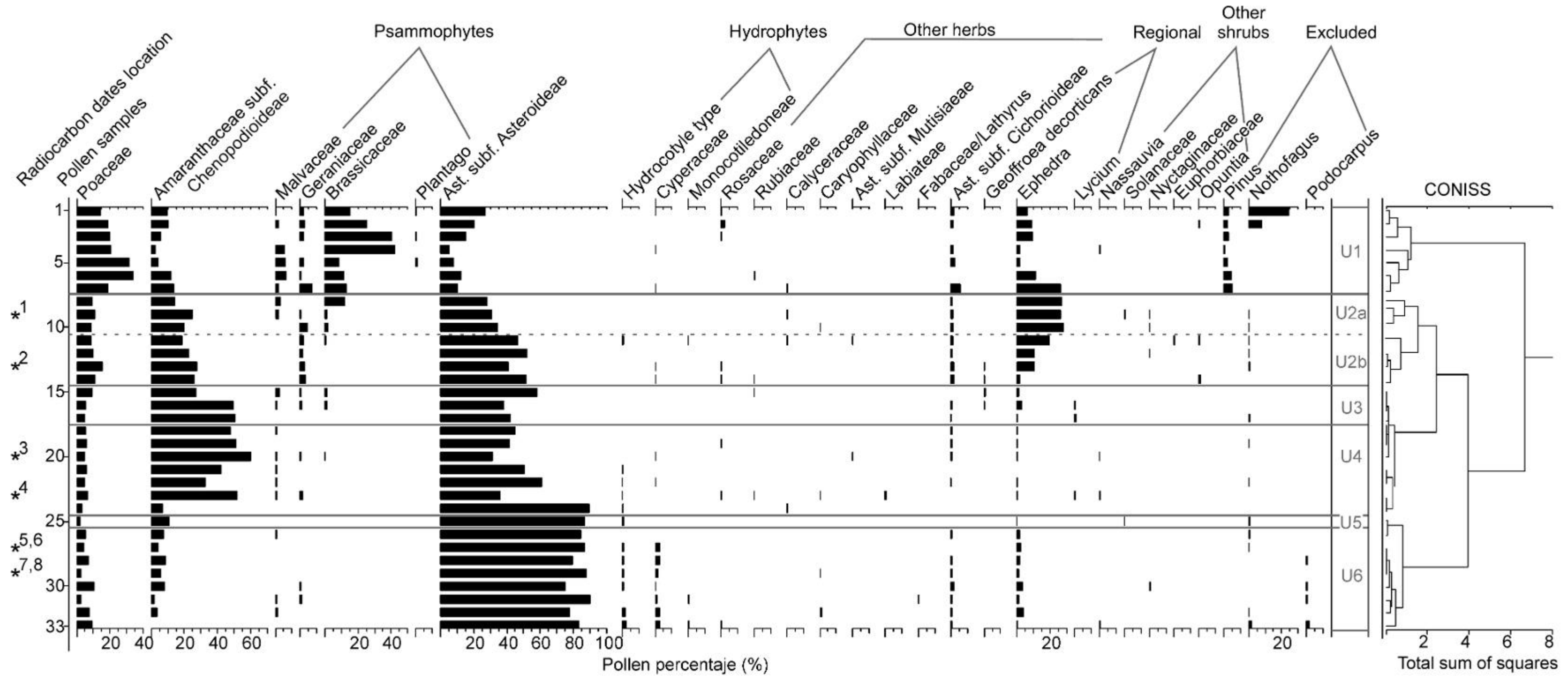
Table 1. Radiocarbon dates from Zoko Andi 1 site.

Lab. Code	Material	^{14}C years BP	Median probability (cal BP)	2 σ range	Allostratigraphic units	References
AA92657	bone (*L. guanicoe*)	380 ± 43	397	314-492	U2a	Martínez et al., 2014
AA92656	bone (*L. guanicoe*)	726 ± 57	633	552-686	U2b	Martínez et al., 2014
AA94088	bone (*L. guanicoe*)	793 ± 39	688	646-736	U4	Martínez et al., 2014
AA107622	bone (*Ceratophrys* sp.)	818 ± 25	702	669-730	U4	Martínez, 2017
LP-2526	charcoal	1330 ±50	1212	1175-1293	U6	Martínez et al., 2014
AA94087	bone (*L. guanicoe*)	1508 ± 44	1352	1287-1427	U6	Martínez et al., 2014
AA94085	charcoal	1526 ± 34	1362	1303-1426	U6	Martínez et al., 2014
AA94086	charcoal	1527 ± 34	1363	1304-1450	U6	Martínez et al., 2014

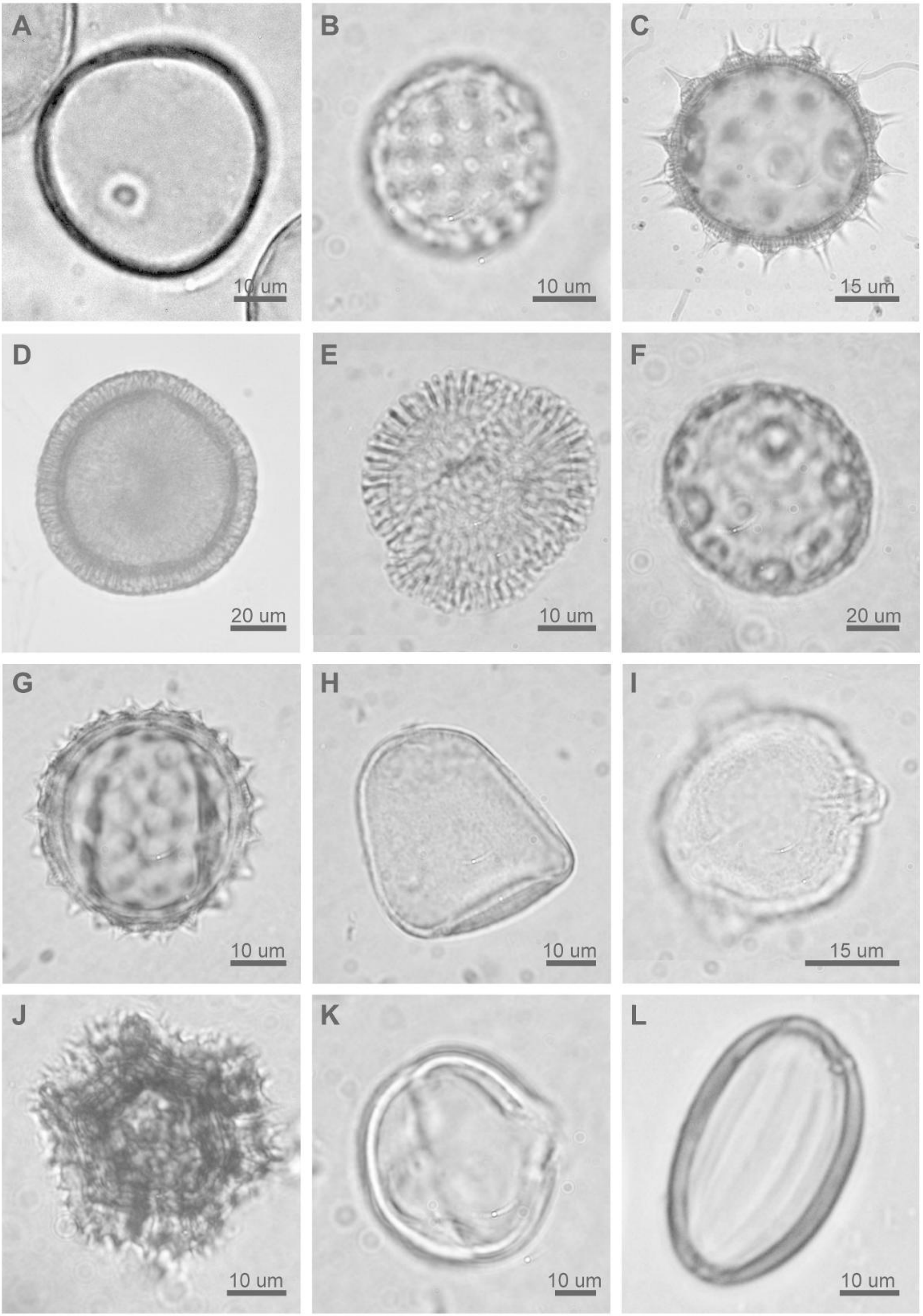

A
B
Zoko Andi 1
C10
C9
C8
C6
C4
C5
C7
C1
C
Zoko Andi 1
D
Pampa
Arroyo Sauce Chico
Arroyo Napostá Grande
Río Sauce Grande
38°
Espinal
Colorado
river
Loma Ruiz
Salina Anzoátegui
Zoko Andi 1
El Tigre
Negro river
N
40°
Salina Gualicho
Salina Piedra
Monte
Salina Inglés
Bajo de la Quinta
100
200km
62°
60°



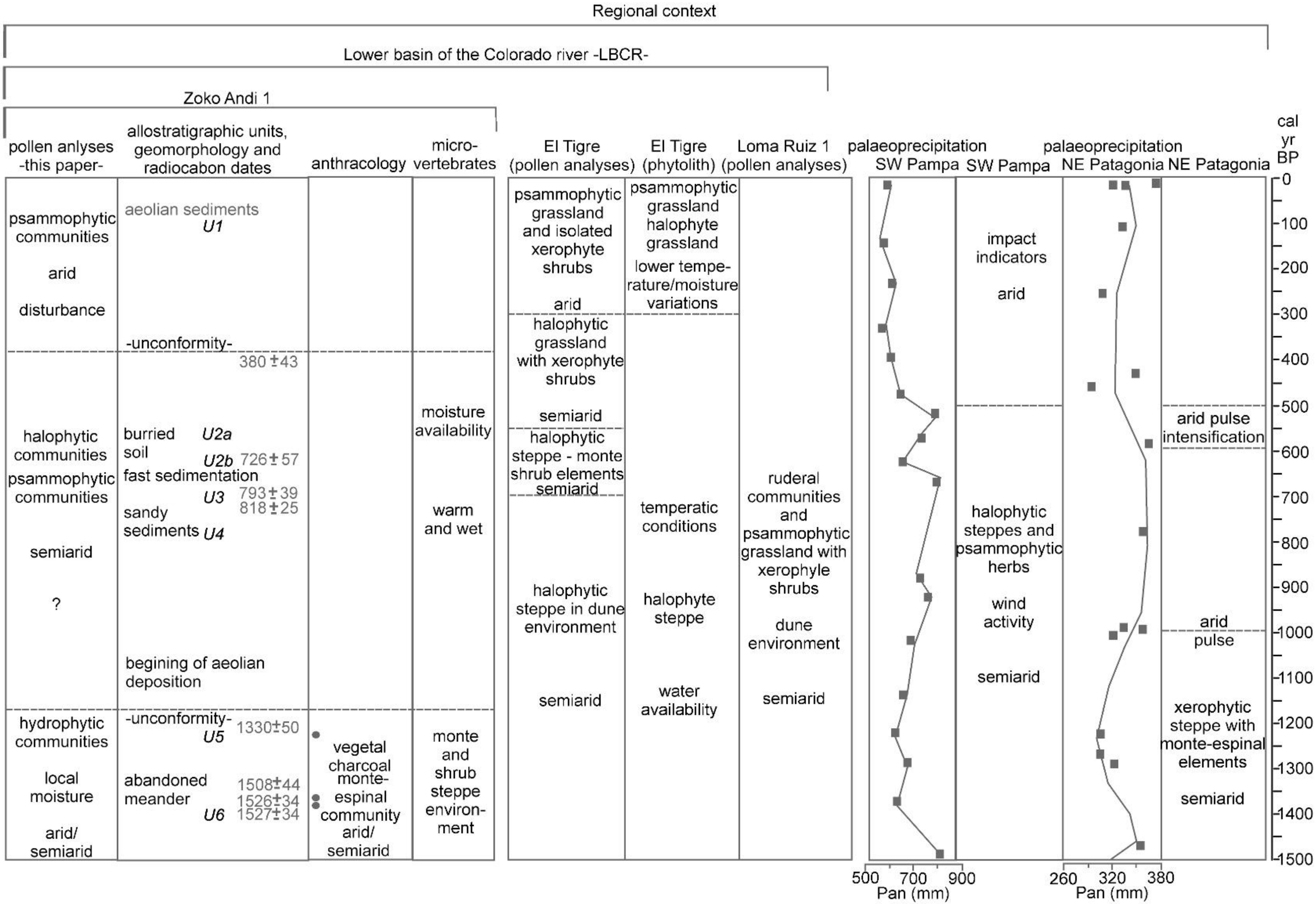
A
m
Archaeological components
Allostratigraphic units
Soil horizons
Radiocarbon dates
1,42
1,60
1,80
2,00
2,20
2,40
2,60
2,80
3,00
3,20
3,40
UC
LC
U1
U2a
U2b
U3
U4
U5
U6
AC
2ACb
3ACb
3C
4C
5Cb
6Bc
380 ± 43 BP
726 ± 57 BP
793 ± 39 BP
818 ± 25 BP
1330±50 (C) / 1508±44 (B) BP
1526±34 (C) / 1527±34 (C) BP
Present soil
Buried soil
Sand
Silt-sand
Clayey silt-sand
Silt-sand clayey
Unconformity
Charcoal remains
Calcareous root concretions
Archaeological remains
C14 AMS dating
C14 Conventional dating
C B
Charcoal / Bone
LC UC
Lower component / Upper component
1-33 pollen samples
B
U1
U2a
U2b
U3
U4
U5
U6
Allostratigraphic units
Organic Matter (%)
Organic Carbon (g kg-1)
Clay (%)
Silt (%)
Sand (%)
20
20
20 40 60
20 40 60 80 100



Psammophytes
Hydrophytes
Other herbs
Regional
Other shrubs
Excluded
Radiocarbon dates location
Pollen samples
Poaceae
Amaranthaceae subf. Chenopodioideae
Malvaceae
Geraniaceae
Brassicaceae
Plantago
Ast. subf. Asteroideae
Hydrocotyle type
Cyperaceae
Monocotiledoneae
Rosaceae
Rubiaceae
Calyceraceae
Caryophyllaceae
Ast. subf. Mutisiaeae
Labiateae
Fabaceae/Lathyrus
Ast. subf. Cichorioideae
Geoffroea decorticans
Ephedra
Lycium
Nassauvia
Solanaceae
Nyctaginaceae
Euphorbiaceae
Opuntia
Pinus
Nothofagus
Podocarpus
CONISS
U1
U2a
U2b
U3
U4
U5
U6
Pollen percentaje (%)
Total sum of squares



A
10 um
B
10 um
C
15 um
D
20 um
E
10 um
F
20 um
G
10 um
H
10 um
I
15 um
J
10 um
K
10 um
L
10 um



Regional context
Lower basin of the Colorado river -LBCR-
Zoko Andi 1
pollen anlyses -this paper-
allostratigraphic units, geomorphology and radiocabon dates
anthracology
micro-vertebrates
El Tigre (pollen analyses)
El Tigre (phytolith)
Loma Ruiz 1 (pollen analyses)
palaeoprecipitation SW Pampa
SW Pampa
palaeoprecipitation NE Patagonia
NE Patagonia
cal yr BP
psammophytic communities
arid
disturbance
aeolian sediments
U1
-unconformity-
380 ± 43
halophytic communities
psammophytic communities
semiarid
?
burried soil
U2a
U2b
726 ± 57
fast sedimentation
U3
793 ± 39
818 ± 25
sandy sediments
U4
begining of aeolian deposition
hydrophytic communities
local moisture
arid/ semiarid
-unconformity-
1330±50
U5
abandoned meander
1508±44
1526±34
1527±34
U6
vegetal charcoal
monte-espinal community
arid/ semiarid
moisture availability
warm and wet
monte and shrub steppe environ-ment
psammophytic grassland and isolated xerophyte shrubs
arid
halophytic grassland with xerophyte shrubs
semiarid
halophytic steppe - monte shrub elements
semiarid
halophytic steppe in dune environment
semiarid
psammophytic grassland
halophyte grassland
lower tempe-rature/moisture variations
temperatic conditions
halophyte steppe
water availability
ruderal communities and psammophytic grassland with xerophyle shrubs
dune environment
semiarid
impact indicators
arid
halophytic steppes and psammophytic herbs
wind activity
semiarid
arid pulse intensification
arid pulse
xerophytic steppe with monte-espinal elements
semiarid
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
500
700
900
Pan (mm)
260
320
380
Pan (mm)

Table 1. Radiocarbon dates from Zoko Andi 1 site.

Lab. Code	Material	^{14}C years BP	cal BP	2 σ range	Allostratigraphic units	References
AA92657	bone (*L. guanicoe*)	380 ± 43	397	314-492	U2a	Martínez et al., 2014
AA92656	bone (*L. guanicoe*)	726 ± 57	633	552-686	U2b	Martínez et al., 2014
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