Chapter

Miocene Volcaniclastic Environments Developed in the Distal Sector of the Bermejo Basin, Argentina

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Abstract

During the Miocene, in the distal sectors of the Bermejo Basin, a complex relationship developed between a floodplain and contemporary volcanic activity. Seven stages of sedimentation are established to interpret this paleoenvironmental relationship. Stage I corresponds to the development of the floodplain previous to pyroclastic activity; in Stage II, pyroclastic activity is manifested by fall deposits and dry pyroclastic surges. A probable calm in the volcanic activity, associated with exceptional rains, generates laharic deposits (Stage III). Stage IV is dry pyroclastic surges that collapse the floodplain. Subsequently, the river system is reestablished (Stage V) under a regime of low to null volcanic activity. During Stages VI and VII, thick deposits of dry and wet pyroclastic surges, which have records of contemporary seismic activity. The presence of deformational structures within the pyroclastic deposits and lahars indicate that the volcanic centers were in distant areas. The volcanism that generated these deposits is probably associated with the migration to the east of the Miocene volcanic arc of the Cordillera de Los Andes or could be associate with the volcanism of the Sierra de Famatina.

Keywords: Miocene, pyroclastic rocks, floodplains, Bermejo basin

1. Introduction

The study area is located southwest of Campo de Talampaya, La Rioja Province, Argentina. In this sector, there is a topographic high called Alto de San Nicolás, in which the Grupo San Nicolás [1] emerges. The San Nicolás Group is made up of the Rio Mañero and Desencuentro Formations, both of continental origin (**Figure 1b** and **c**), which together have a thickness greater than 2000 meters [4]. The pyroclastic sediments in these units were dated by [5], in 15,0 ± 1,2 Ma and 7,54 ± 1,56 Ma placing this sequence in the middle-late Miocene.

The Desencuentro Formation was divided into four informal Members named D1, D2, D3 and D4 [1, 2, 4] based on their facies and paleoenvironmental evolution, emphasizing the description of clastic sediments. However [6, 7], the study and interpretation of the important pyroclastic deposits present within this Formation, calling it Member P. These authors point out that member P is interdigitated within members D2 and D3. Paleontological and paleoenvironmental papers indicate that

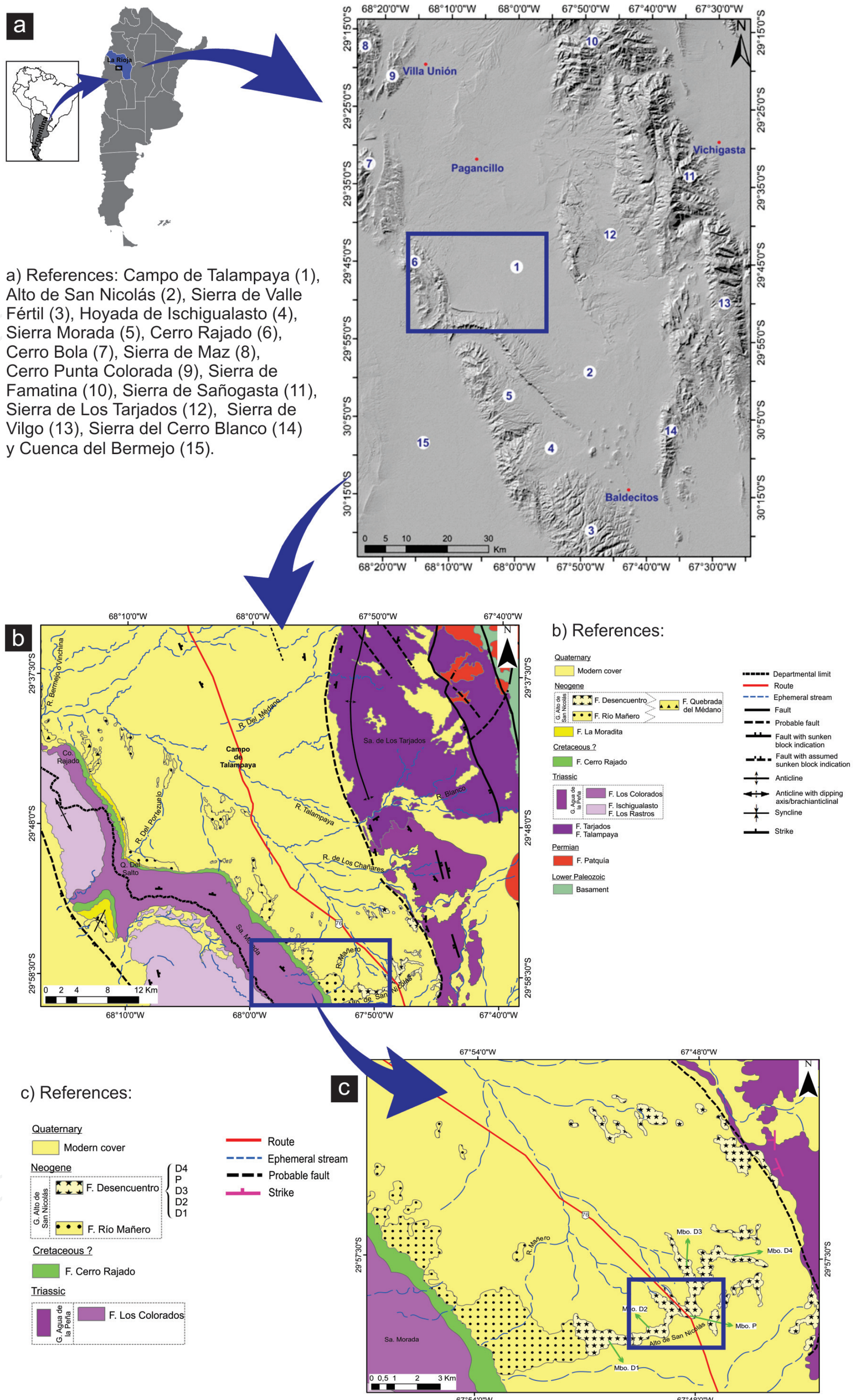

Figure 1.
(a) Topographic map and its environments with map of South America and Argentina; (b) Local geology of study area (modified of [2, 3]); (c) Detailed geological map of study area.

the prevailing climate for that period was warm, seasonal with torrential rains [1, 2, 8].

The objective of this contribution is to determine the prevailing paleoenvironmental conditions during the late Miocene and their evolution, through detailed sedimentological studies, in the middle section of the Desencuentro Formation in Campo de Talampaya, La Rioja Province, Argentina.

2. Geology and tectonic evolution

Since the beginning of the Andean Orogeny (Maastrichtian-Danian), the extensional basins of southwestern South America have changed their tectonic configuration. Most of them went from extensional to compressive regimes, and those near the elevated front became foreland basins (Austral Basin, Neuquina, Cuyana, and Bermejo Basin, etc.).

The Alto de San Nicolás Group deposits in what was the distal sector of the Bermejo basin correspond to this stage of sedimentation of a predominantly continental character [1, 4]. The basal section of the Alto de San Nicolás Group is conditioned by the elevation of the Cordillera Frontal and by the ascent and migration of the continuous and folded belt in the Precordillera. On the other hand, the upper section is associated with the elevation of the Sierras Pampeanas, more precisely with the Sierra de Velasco [1]. Finally, with the ascent between the end of the Miocene and the Pliocene of the Sierra de Valle Fértil, Sierra Morada and Sierra de Los Tarjados produces the disconnection of the most distal parts of the basin (Campo de Talampaya Basin) with the main depocenter of Bermejo [9].

Currently, in the central-western sector of Argentina (Pampean segment), the low inclination (5°-10°) with which the Nazca Plate subducts below the South American Plate conditions the tectonics of the sector [10, 11]. This Pampean segment is characterized by the development of foreland basins, which are fragmented by elevated basement blocks and originate intermountain depressions. Among the foreland intermontane basin that develops on the Pampean segment is the Campo de Talampaya which is related to the uplift of the Sierra de Los Tarjados [1].

In the southwestern sector of Campo de Talampaya (**Figure 1a,b** and **c**), there is a topographic high that extends in a NE–SW direction called Alto de San Nicolás (**Figure 1a,b** and **c**), which consists of a succession of continental Neogene (Alto de San Nicolás Group) age strata, 2320 m thick, which also exhibit a dip to the east that varies between 5° and 21° [1, 4]. In this sector, the Alto de San Nicolás Group (**Figure 1a,b** and **c**) comprises the Río Mañero and Desencuentro Formations. The base of this stratigraphic unit rests paraconformity or by angular unconformity upon Cerro Rajado Formation (Cretaceous?) depending on which is the sector of the Campo de Talampaya [4]. Discordant on the neogenic units are an alluvial fan, ephemeral fluvial systems, and eolian deposits of the Quaternary [12].

The Desencuentro Formation (upper Miocene) consists of a clastic sequence that overlaps the Río Mañero Formation through a transitional passage, which consists of sandstones, mudstones, few conglomerate lenses, and tuff levels deposited in a saline mud-flat environment which are finally covered by sand-flat/mudflat [1]. This unit was divided into four informal Members (D1, D2, D3, and D4) emphasizing the description of the widely developed clastic sediments [1, 2, 4], but not in the case of the rocks of volcanic origin, since these, they are only mentioned as participants in the sedimentary record. Subsequently, a new member (called P) is included for the Desencuentro Formation, depending on its pyroclastic/volcaniclastic character, leaving the stratigraphic column composed of D1, D2, P and D3, D4 [6]. The recognition of Member P indicates characteristic volcanic participation during the deposition of the Desencuentro Formation in the distal sector of the Bermejo Basin [7].

3. Methodology

Five field works were performed in the middle section of Alto de San Nicolás, where traditional field techniques were used: description of detailed stratigraphic profiles (lithology, grain size, contacts, geometry, color, and sedimentary structures/biogenic were the data taken) and measurement of strike and dip of strata with Brunton compass. Subsequently, the different lithofacies were classified and interpreted, which were grouped into associations of facies and architectural elements to interpret the depositional environments. In the case of clastic and volcaniclastic lithofacies, the associations will be interpreted as architectural elements, following what was stated by [13, 14]. Pyroclastic lithofacies, their genetic processes will be interpreted in a general way, following the methodology of [15] and other authors [16, 17].

The identified pyroclastic lithofacies were coded adapting the proposal of [15]. The capital letter is used for the grain size classes and the lower case for the sedimentary structures: (T) tuffs, (L) lapillita, (m) massive, (b) lamination, (db) diffuse lamination, (//b) parallel lamination, (xb) cross-lamination, (ob) sinusoidal ripple-drift lamination, (dob) diffuse sinusoidal ripple-drift lamination, (r) deformational structures, (ch) chute and pool, (esc) climbing structures, (acc) accretional lapilli. For the clastic and volcaniclastic lithofacies, they were coded by adapting the scheme of [13, 14]. Also, for these lithofacies the capital letter is used for the grain size classes and the lower case for the sedimentary structures and identification of volcaniclastic rocks: (F) claystone, (S) sandstone, (G) conglomerate; (m) massive, (pl) planar cross-lamination, (ps) planar cross-stratification (t) tangential cross-stratification, (h) parallel lamination, (v) volcaniclastic (s) matrix supported.

In this work, sedimentary rocks without the content of volcanic fragments will be called clastic rocks. Following the scheme [18], rocks or pyroclastic deposits will be called those that demonstrate a mode of fragmentation, transport and deposition [fall, surge or flow] directly related to volcanic activity. The term volcaniclastic will be used, following the criteria of [18], to refer to those deposits that have a connection with volcanism, but that result from the transport and deposition of exogenous cycle agents (mudflows, river currents, etc.), regardless of the fragmentation mechanism (during the eruption or if they are new particles formed by the weathering of older rocks). For this reason, for their classification, they will be considered as clastic rocks to which the qualifying noun volcaniclastic will be added.

For the granulometric classification of the sedimentary particles, the Udden-Wentworth classification and Phi scale were used and for the pyroclastic particles the modified proposal of [17] was used.

4. Sedimentological and paleoenvironmental analysis

A total of **23** facies were identified in the deposits of the middle section of the Desencuentro Formation in Alto de San Nicolás, which were grouped into three facies associations (pyroclastic facies) and six architectural elements (clastic and volcaniclastic facies). The nomenclature used in the identification of lithofacies is indicated in **Tables 1**–**4**, together with the sedimentary structures and other characteristics of each one; and the terminology applied for the associations of facies (DPS, WPS and PF) and architectural elements (FF, CH(FF), CR, CH and SG) is indicated in **Table 5**. The different interpretations that were inferred from the identified lithofacies, associations of facies and architectural elements are briefly described below:

The presence of sismites (fluid leaks, flaming structures, ball pillow, etc.) in the sediments originated by the humid pyroclastic surges, allows us to infer, following what was stated by [19] that the sedimentation area would be in a distal sector with respect to the eruptive center (**Figure 2k**).

Pyroclastic lithofacies			
Code	**Description**	**Interpretation**	
//bT1	Coarse tuffs, well-selected, grayish, in tabular bodies, with variable thickness (0,8 to 1,50 m), exhibiting wavy, net, and transitional boundaries. Internally they present parallel lamination, which is sometmes better denoted by observing layers that individually exhibit whitish pumice clasts or dark lithic clasts.	The development of sharp parallel lamination and good selection suggest that these deposits were formed from a high flow regime [15].	Dry pyroclastic surges
obT	Coarse tuffs, well-selected and grayish in bodies with irregular geometries, exhibiting wavy and net contacts, with thicknesses of approximately 10 to 50 cm. Internally, they present sinusoidal ripple-drift laminations (**Figure 2a**) and sometimes shows concretions, some pumiceous clasts and pipes (**Figure 2j**) that cut to the lamination.	The development of sinusoidal ripple-drift laminations and bodies with marked and erosive limits indicates a genesis associated with surges [20]. The different pipes that cross the base of this lithofacies indicate different forms of fluid expulsion. On the one hand, you can see "classic" vertical pipes that cut the pre-existing structure [15], implying a vertical rise of the fluids that have not encountered resistance to their passage, probably due to lack of cohesion in the pre-existing sediments, while there are pipes that modify the vertical layout, becoming horizontal and vertical again.	Dry pyroclastic surges
escTL	Coarse tuffs and coarse lapilli, grayish-white, which occur in irregular bodies, with wavy transitional limits and thicknesses of approximately 8 to 12 cm. Internally these tuffs present "scaling structures", marked by intercalations of thin to thick laminae (**Figure 2d**). In some sectors, these scaling structures consist of clast-support pumiceous sigmoid bodies.	The climbing structures observed originate from these types of pyroclastic surges that slide over topographic irregularities [21, 22]. When this lithofacies develops clast-support deposits, its origin within the surges is punctual and does not condition their dynamics. In this point space, a granular deposit is produced.	Dry pyroclastic surges
bL	Coarse and medium/coarse lapilli, grayish, which develop bodies of tabular to slightly irregular geometries, with thicknesses that vary between approximately 10 to 35 cm and planar and wavy transitional limits. Internally, this bodies have thin and thick, parallel or sinusoidal, clast-support, which show variations in the proportion of lapilli pumiceous (**Figure 2g**). The white laminae are characterized by having a greater amount of pumice than lithic clasts. In some sectors, weakly laminated whitish pumice lenses are found at the base of the bodies. Lenses sometimes have reverse or normal gradation.	The alternation of enriched or depleted levels in pumiceous clasts originates from successive surges with variations in the clast populations, from sustained currents over time [15]. The development of pumiceous lenses at the base of the bodies probably responds to punctual and local flow regime changes, which deposit the clasts of greater granulometry, the rest of the particles are carried as bed load by turbulence, generating, in this way, the lamination observed.	Dry pyroclastic surges
pmL	Medium and coarse lapilli, massive, moderately selected, clast-support, which occur in tabular bodies. These lapillitic bodies have thicknesses ranging from 4 to 15 cm and exhibit	They are interpreted as deposits originated from pyroclastic fall [15, 16]. The presence of units with contrasting granulometry (in this case, thick and fine lapilli) is related to non-sustained	Pyroclastic falls

Pyroclastic lithofacies			
Code	**Description**	**Interpretation**	
	planar, net, and transitional contacts. In some sectors, includes a set of strata made up of intercalations of medium and coarse lapilli that together present a growing grain arrangement (**Figure 2f**). Lapilli are white in color and arranged randomly, although few imbricated clasts can be observed.	eruptions that have several short-duration pulses or to partial collapses of the eruptive column [23]. At interruptive moments, rework may have occurred by tractive agents, which produced imbrication of clasts in certain sectors of the deposit.	
mT	Fine tuffs, massive, white that develop into mantiform bodies (**Figure 2i**). These tuff deposits have thicknesses ranging from 20 to 50 cm and have lateral extensions that can be followed for more than 80 m and planar net limits.	The development of massive, mantiform bodies that extend great distances are associated with deposits that correspond to pyroclastic fall (PF) [23].	Pyroclastic falls

Table 1.
Table of pyroclastic lithofacies and their codes adapting from the proposal by [15].

Pyroclastic lithofacies			
Code	**Description**	**Interpretation**	
rL dbTacc	Coarse tuffs (well-selected) and fine lapilli, grayish that develop irregular or tabular geometries, exhibiting wavy, net and transitional contacts, with thicknesses of approximately 0,4 to 1,20 m. Internment they present diffuse lamination (**Figure 2c**). The original lamination can be deduced by the presence of levels enriched in fine pumiceous lapilli and other levels enriched in lithics. This lamination is deformed by fluid leaks (**Figure 2h**), flame and load structures. Other deformational structures are sedimentary folds and convolute lamination. They also observed accretional lapilli (**Figure 2e**) and specks of oxides.	The presence of accretional lapilli would indicate the union of ash particles by condensation of water in humid eruptive clouds [16, 24–26]. In this pyroclastic currents, the vapor, by accompanying the sediment during its transport, is retained in the pores and, when it cools, it becomes water, which causes the sediment to be embedded in fluids, giving it plasticity and ease for the liquefaction. Deformational structures (convolute lamination, flame structures, etc.) are interpreted sismites [19, 27, 28]. Another genesis for these structures is associated with a rapid sedimentary loading of denser sediments [29].	Wet pyroclastic surges
dobT	Coarse tuffs, well-selected, grayish that develop irregular geometries with wavy and transitional contacts, and thicknesses of approximately 0,1 to 1,10 m. They present diffuse sinusoidal ripple-drift lamination, with a wide wavelength that in some sectors graded laterally to sheets with horizontal lamination. It also has rust specks of oxides, accretional lapilli, concretions, and few white pumiceous clasts. The concretions are subequant, with diameters ranging from 2 to 10 cm. The core of the anterior structures is formed by claystone intraclasts. In	The presence of thin bodies with transitional boundaries could represent rapidly stacked and partially amalgamated flow units [30]. The concretions are formed by precipitation or segregation of minerals around a core (in this case of claystone intraclasts). The claystones intraclasts located at the base of the bodies are consistent with the turbulent character of these pyroclastic currents, which would have eroded previous clastic sedimentary environments. The preservation of the primary lamination in concretions	Wet pyroclastic surges

Pyroclastic lithofacies			
Code	**Description**	**Interpretation**	
	addition, concretions can be aligned or located at the base of the bodies.	indicates that concretions are postdepositional [31].	
xbT	Coarse tuffs, well-selected, grayish, generating tabular bodies with a thickness of 0,4 m, with wavy net bases. Internally they develop tangential cross-lamination (**Figure 2l**), which varies vertically to parallel lamination. These deposits also exhibit specks of oxides, pipes of various sizes and concretions.	Tangential cross-lamination and parallel lamination are interpreted as the product of two or more pyroclastic surges pulses, with different speeds. The specks of oxides originate from the instantaneous oxidation of the pyroclasts during their transport/ deposition, generating instantaneous metasomatic oxidative processes [32].	Wet pyroclastic surges
//bT2	Coarse tuffs, well-selected, grayish, which develop bodies of tabular and irregular geometries, with thicknesses that vary between approximately 0,25 to 1 m and with wavy, net, and transitional contacts. They present thin and thick, parallel (**Figure 2b**) and deformational lamination, in addition to sinusoidal ripple-drift laminations of short wavelength in phase. These deposits also exhibit, ripples in phase, specks of oxides and concretions (**Figure 2k**).	Sinusoidal ripple-drift laminations of short wavelength are associated with these pyroclastic currents [20].	Wet pyroclastic surges
chT	Coarse tuffs, well-selected grayish, and with irregular bodies, which develop net and wavy contacts. Internally they present chute and pool structures (**Figure 2m**), denoted by intercalations of thin and thick sheets that present angularity.	Chute and pool are associated with wet pyroclastic surges [18], and also point out that they are indicators of high flow regimes [20].	Wet pyroclastic surges
mTacc	Coarse tuffs, grayish, in approximately tabular bodies, with a thickness of 40 to 60 cm and transitional and wavy contacts. Internally they are massive, exhibiting specks of oxides and accretion lapilli.	The development of massive bodies and the presence of accretional lapilli are associated with wet pyroclastic surges [32]. The presence of moisture in the cloud that accompanies these flows that counteracts the effects of elutriation due to fluid leaks [15].	Wet pyroclastic surges

Table 2.
Table of pyroclastic lithofacies and their codes adapting from the proposal by [15].

5. Sedimentary model

For the development of the paleoenvironmental model that involves the genesis of Member P and part of Members D2 and D3 [6, 7], the different sedimentation moments were divided into seven temporarily consecutive stages.

5.1 Stage I

The first sedimentation event is made up of fine clastic deposits, represented by the architectural elements FF, SG, CR and CH (FF) (**Figures 4** and **5**). The element FF represented by claystone, tabular bodies and of great extension, corresponds to wide flood plains. The interdigitation between FF and SG

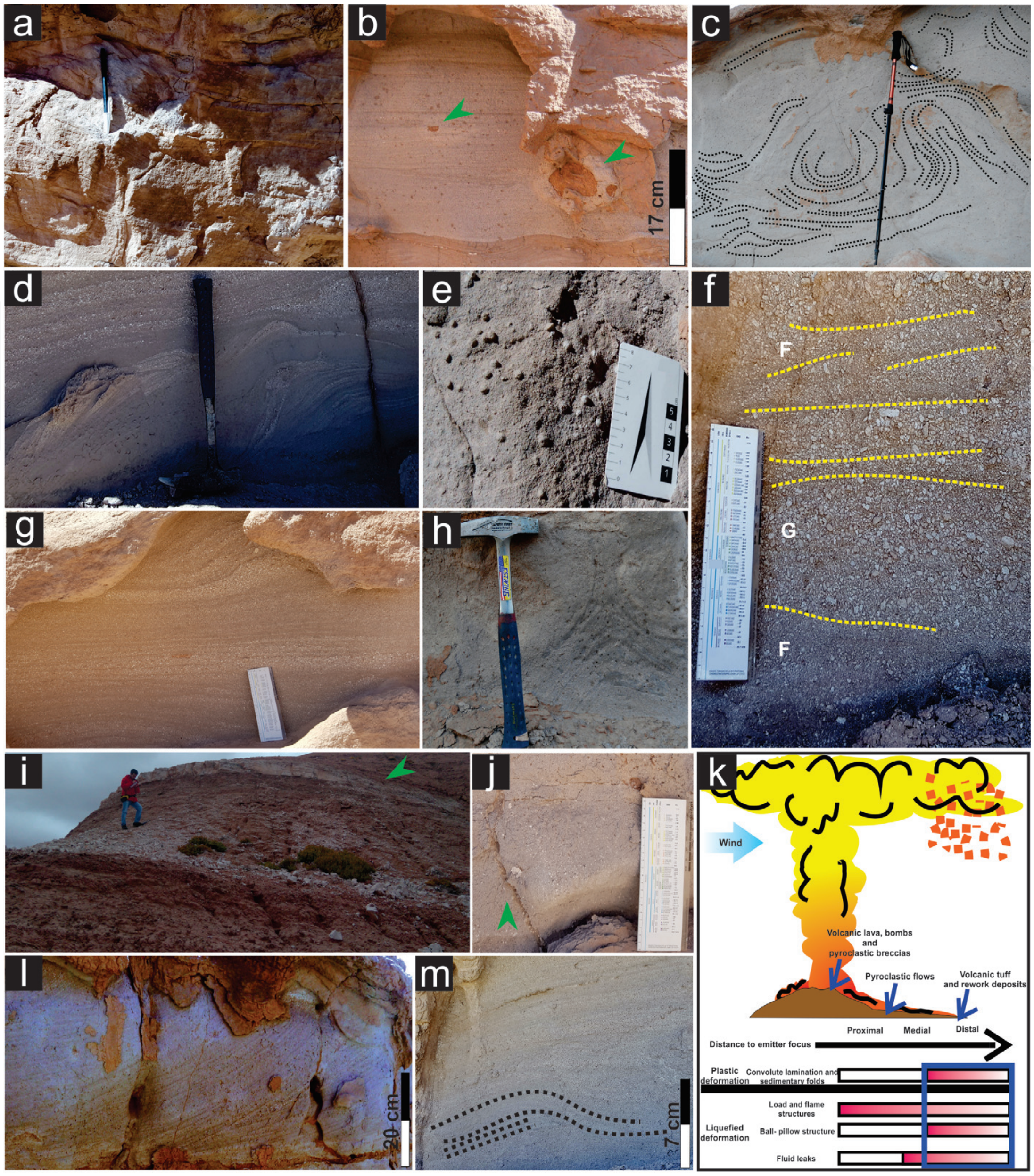

Figure 2.
(a) Bodies exhibiting internally ripple-drift laminations, the pen measures 15 cm; (b) level with internally parallel lamination and concretions (indicated by green arrows); c) level with diffuse sedimentary folds, the cane measures 1 m; d) level that presents scaling structures and where, in addition, the direction of flow is indicated; e) Accretional lapilli; f) outcrop showing intercalations of levels with medium (M) and coarse (G) lapilli; g) outcrop where intercalations of tabular to slightly irregular levels are observed, which internally present sheets with variations in the proportion of pumiceous clasts; h) fluid exhaust structure, the pickaxe measures 33 cm; i) outcrop where one level of fall are observed (indicated by green arrow); the person is 1.65 m tall; j) level that is crossed by a pipe that presents elutriation of fines and a vertical trajectory (indicated by green arrow); k) scheme where the structures found in the field are indicated with a table and from which the distance to the emitter focus can be inferred (modified from [19]); l) tabular body exhibiting internally tangential cross-lamination; m) level with parallel lamination structures and chute and pool.

indicates that these floodplains are intermittently invaded by hyperconcentrated flows, represented by approximately tabular bodies of great thickness (more than 1.5 m), probably amalgamated. The origin of these mass movements (sheet flood) would be associated with humid times, where the pluvial discharge peaks generate floods, which can transport considerable amounts of sand and pellets. These laminar processes [38] can sometimes generate deposits of more than 2 m thick [4]. In an arid climate or dry seasons, the plains would have dried out, generating levels with desiccation cracks observed in the Fm lithofacies.

Clastic lithofacies			
Code	**Description**	**Interpretation**	
Gm	Conglomerates, clast-support, reddish-brown in color, appear in irregular bodies with irregular net boundaries and thicknesses of approximately 5 to 7 cm. They are made up of claystone intraclasts, brown in color and which are also imbricated.	They are interpreted as lag [14]. These originate from high flow regimes, capable of transporting even cohesive fragments of the floodplain [33].	Lag
Sm	Fine and medium grayish sandstones, which occur in tabular bodies, with thicknesses that vary between 0.20 to 2 m and lateral extensions that exceed 20 meters (**Figure 3k**). These bodies exhibit net planar and deformational limits, although sometimes these can be transitional, in which case they form amalgamated bodies. This facies tends to have a massive structure, however, in some sections of these deposits, diffuse parallel lamination (**Figure 3c**) and incipient low angle cross-lamination can be observed. Likewise, small and isolated levels of whitish pumiceous paraconglomerates are observed. In addition, it presents clastic dikes, load structures and pinch and swell (**Figure 3l**), the latter denoted by reddish-brown claystone levels, immersed in a sandy matrix.	It is interpreted as deposits of gravitational flows [13] corresponding to hyperconcentrated flows. The massive structure is the result of the high concentration of particles and the rapid deposition, however, the presence of diffuse parallel lamination and incipient low-angle cross-lamination could be signaling the dilution of these flows and a change in dynamics in the transport of the sediment [34]. The presence of small and isolated levels of pumiceous paraconglomerates would indicate the remobilization of previous pyroclastic deposits.	Gravity flows
Spl	Fine and medium sandstones, reddish-brown in color, present in tabular bodies, with thicknesses ranging from 0.10 to 1 m and lateral extensions of approximately 1 to 5 m. These deposits exhibit wavy, net, and transitional contacts. Internally they develop planar cross-lamination (sometimes diffuse) (**Figure 3h**). In some sectors, this lithofacies has reddish-brown claystone intraclasts at the base.	They are interpreted as bottom charge deposits, the result of the migration of megawaves from straight ridges in a low flow regime [13, 14].	Bars
Sh	Fine and medium sandstones, well-selected and with parallel lamination (sometimes incipient), which occur in irregular to slightly tabular bodies, brown (**Figure 3e**). These bodies exhibit thicknesses that vary between 30 to 70 cm and net, irregular and planar limits. When the limits are transitional the bodies appear amalgamated.	This facies is interpreted as flat layer deposits with a high flow regime as a result of the decrease in water hair [13]. Upper regime plane lamination	Planar bed flow
Fm	Massive reddish-brown claystones that develop tabular bodies, with thicknesses ranging from 0.6 to 2 m and lateral extensions ranging from 8 to 25 m approximately (**Figure 3a**). The limits of these claystone deposits are net planar. Internally, this facies is massive, although in some sectors bioturbations can be observed, rhizolites, and	The massive claystone deposits (Fm) are generated by settling fine suspended sediments under conditions of very low energy [14].	Flood plains

Clastic lithofacies			
Code	**Description**	**Interpretation**	
	desiccation cracks (**Figure 3d**) that are mainly concentrated on the roof of the bodies.		
Fl	Parallel lamination claystone, of lighter reddish-brown colors, that form tabular bodies with thicknesses of 2 to 10 cm and lateral extensions ranging from 2 to 8 m (**Figure 3f**). In addition, they present net planar limits, although they can sometimes be deformational. Internally they present thin and thick, parallel and deformational laminaes. The deformational structures can have different scales; from small to large scale, the latter comes to separate sandstone bodies (lithofacies Sm). Raindrop marks, load structures (**Figure 3g**), and isolated whitish pumice clasts are observed in some sectors on the roof of these claystone bodies (**Figure 3c**). Occasionally the pumiceous clasts form very thin pumiceous sheets.	This lithofacies can be interpreted as deposits formed by decantation in shallow water bodies where the sediment has been transported by suspension [13].	Flood plains

Table 3.
Table of clastic lithofacies and their codes adapting from the proposal by [13, 14].

Volcaniclastic lithofacies			
Code	**Description**	**Interpretation**	
Gmsv	Volcaniclastic conglomerates with an abundant fine sandy matrix of light brown color, which develop tabular bodies, with thicknesses that vary between 40 and 80 cm (**Figure 3a** and **k**). These bodies have net and planar boundaries. Internally, in sectors, very diffuse thick lamination can be observed (**Figure 3b**). The few gravel clasts are white pumice, with diameters ranging from 0.5 to 3 cm, white, subangular to sub-rounded, and with semi-equant and tabular shapes. These clast swarms can exhibit diffuse reverse gradation (**Figure 3b**). This spatial arrangement of the pumice clasts could be interpreted as boundaries of bodies with similar textural characteristics that appear amalgamated. Sometimes the pumiceous clasts are arranged vertically. In some sectors, this facies limits inferiorly with the lithofacies Fm. In this limit, claystone intraclasts and flame structures can be observed.	The facial features described correspond to the deposits formed under conditions of hyperconcentrated flows, directly or indirectly related to contemporary volcanic activity. The presence of massive deposits with incipient lamination, with generally flat limits, moderate textural selection, vertical pumiceous clasts, and accumulation are common characteristics in laharic deposits [35]. The observed accumulations of pumiceous clasts mark the upper limits of these laharic events that form amalgamated bodies. The transitional and wavy contacts that are observed in some levels could respond to load structures, probably caused by the rapid deposition of one level on a less competent one that causes its deformation.	Lahars

Volcaniclastic lithofacies			
Code	**Description**	**Interpretation**	
Gtv	Volcaniclastic conglomerates polymictic, clast-support, which occur in tabular bodies, whitish brown and with thicknesses of approximately 25 to 40 cm, which exhibit planar net lower limits (**Figure 3i**). Internally they present tangential cross-stratification (sometimes deformed) represented by levels with varying proportions in pumiceous clasts and to a lesser extent by claystone clasts. In some sectors, these deposits have perforating bioturbations on the roof.	They are interpreted as product deposits from the migration of gravelly accretion bars downstream or longitudinal bars during periods of high discharge [14]. The presence of pumiceous clasts indicates the remobilization and/or reworking of pyroclastic deposits, and in the case of claystone clasts of the sediments of previous plains.	Bars
Shv	Fine to coarse volcaniclastic sandstones that occur in tabular to slightly irregular bodies, light brown in color, with thicknesses ranging from 10 to 15 cm and wavy planar or transitional net limits (**Figure 3i**). Internally they exhibit thin parallel lamination (diffuse), formed by whitish pumiceous clasts and some claystone intraclasts.	It is interpreted as bottom charge deposits, probably originated by currents with relatively low flow velocities [13, 36]. Parallel lamination of low flow regime can be interpreted as part of 2D megaondules (dunes with straight ridges), with a view perpendicular to the flow direction.	Sandwaves
Spsv	Coarse volcaniclastic sandstones, which appear in tabular bodies, light brown, which exhibit powers of approximately 15 to 20 cm and planar net limits. Internally they develop thick and fine planar cross-stratification (**Figure 3j**), represented by levels with varying proportions in pumiceous clasts and lithic clasts.	They are interpreted as deposits of low flow regime bedforms [14, 37] resulting from the migration of straight crested megaondules (2D) [13].	Sandwaves

Table 4.
Table of volcaniclastic lithofacies and their codes adapting from the proposal by [13, 14].

In some sectors, interacting with the flood plains, sandy channels develop, of little thickness (between 50 and 70 cm) and tabular to slightly lenticular geometries, interpreted as probable channel systems belonging to crevasses (corresponding to the architectural element CR), originated by erosion of the edges of the main channel during flood events. These channeled systems are sometimes laterally amalgamated, a circumstance that could indicate the topographic compensation of different episodes of flooding-breakdown of the sloping-crevasse formation. The channels are filled by deposits of sand bars (SB), originated from currents with low flow regimes. Interdigitated with FF and SB, sporadically, there are bodies with concave bases filled with fine material (silts and clays), interpreted as deposits of abandoned channels CH (FF). Based on the architecture, spatial relationships and interrelationship that the element FF, CR and CH(FF) present, considered as overbank deposits, it is possible to indirectly infer that the canal system that would have originated them would correspond to an anastomosed fluvial system [13].

5.2 Stage II

Gradually, this sedimentary system began to be influenced by the volcanism of the region (**Figure 5**). The record of this volcanic activity begins in the study area

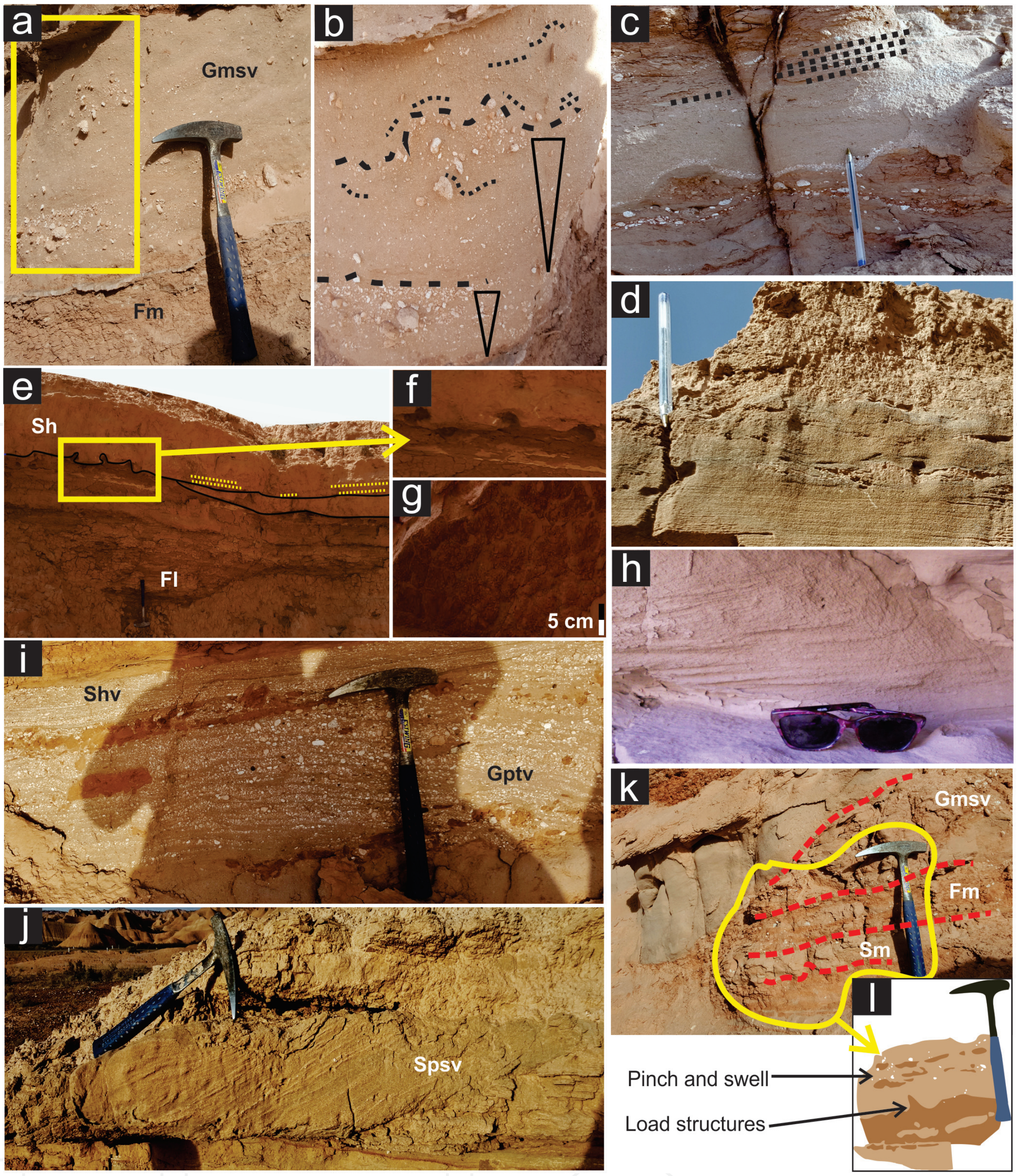

Figure 3.
(a) Outcrop where the lithofacies Fm and Gmsv are indicated; b) figure b corresponds to an enlargement of figure a, where lahars levels are observed with inverse gradation and also very diffuse lamination; c) outcrop where claystone levels are observed that internally present pumiceous clasts and, in addition, a level of fine sandstone that presents diffuse parallel lamination, the pen measures 14 cm; d) level featuring parallel lamination; e) outcrop where the Sh and FI facies are indicated; f) figure f corresponds to an enlargement of figure e, where the load structures are better observed (indicated with yellow arrows); g) desiccation crack structures; h) level internally featuring planar cross lamination, glasses are 13 cm wide; i) outcrop where the lithofacies Gptv and Shv are indicated. The Gtv lithofacies internally presents tangential cross-stratification, denoted by levels with varying proportions of pumiceous and claystone clasts; j) outcrop where the lithofacies Spsv is indicated, which internally presents planar cross-lamination; k) outcrop where the lithofacies Gmsv, Sm and Fm are indicated; l) scheme of figure k, where the load structures and pinch and swell are indicated.

with falling pyroclastic deposits (facies association PF). The facies association PF (**Figure 4**) is interpreted as a product of the gravitational fall of material from pyroclastic clouds, formed during high-energy explosive eruptions. The energy condition mentioned above would be indicated by the grain size (ash and lapilli) that the lithofacies mT and pmL present [17]. The contribution of pyroclastic material would have caused changes in the dynamics of the fluvial system, by observing a decrease in the size and frequency of crevasse systems. These changes

Facies associations and architectural elements

Code	Facies	Description	Interpretation
DPS	//bT1 obT escTL bL	Tuffs (coarse and fine) and lapillita (medium and coarse), grayish, in tabular and irregular bodies, which generally exhibit wavy, net and transitional. The presence of parallel lamination, sinusoidal ripple-drift lamination, scaling structures, etc. indicate that these pyroclastic surges are dry. This association is generated by turbulent flows with low concentrations of particles.	Dry pyroclastic surges
WPS	dbTacc rL dobT xbT //bT2 chT mTacc	Coarse tuffs, grayish, which occur in tabular and irregular bodies, with wavy, net and transitional contacts. Internally present tractive structures (tangential cross-lamination, chute and pool, etc.), deformational structures (convolute lamination, fluid leaks, flame structures, etc.). Sometimes they appear as massive deposits. This association is generated by turbulent and dilute flows. The presence of accretional lapilli, specks of oxides and other structures indicates generated by wet pyroclastic surges.	Wet pyroclastic surges
PF	mT pmL	Fine tuffs and lapillita (medium and coarse), grayish, in tabular bodies, with planar, net, and transitional contacts. They are characterized by being massive deposits and with a clast-support texture. This association is interpreted as deposits of pyroclastic falls from pyroclastic clouds where the sediments are transported by the turbulence and gases of the cloud at different distances. During this transport, the sediments fall in free fall, depending on their size.	Pyroclastic falls
FF	Fm Fl	Massive and/or laminated claystone, of a reddish-brown color, that occur in tabular bodies, which generally develop large extensions (∼25 m) and exhibit planar net limits, although sometimes they can be deformational. Internally, they present desiccation cracks, bioturbations, raindrop marks, load structures, and rhizolites, among others. This architectural element consists of plains (areas with very little slope), which intermittently flood and dry out [13].	Floodplain fines
CH(FF)	Fm Fl	Claystone units, reddish-brown in color, in canaliform bodies, which exhibit concave basal limits and are filled with laminated or massive-looking claystone material. This element represents abandoned channels [14].	Abandoned channels
CR	Sh Shv Sp	Clastic and volcaniclastic sandstones (fine to coarse), which present planar parallel and planar cross-lamination that develop lenticular to slightly tabular bodies, with net irregular contacts and sometimes planar. It is interpreted as deposits of crevasses splays (spill lobes), originated by the erosion of the edges of the main channel [13, 14].	Crevasses splays
CH SB	Sp Spv Shv	Set of fine to coarse clastic and volcaniclastic sandstones, exhibiting planar cross-lamination. These deposits develop in tabular bodies, which generally exhibit planar and sometimes irregular, net, and transitional contacts. Element SB1 represents background shapes, the result of the migration of crossbars (2D). When these facies present pumiceous clasts, it is assumed that the currents eroded and/or remobilized previous pyroclastic deposits.	Sand bars
CH GB	Gtv Gm	Coarse volcaniclastic sandstones and volcaniclastic and clastic clast-support conglomerates. They are presented in tabular bodies, with net planar contacts. Internally they develop lamination and tangential cross-stratification and present variable amounts of pumiceous and lithic clasts. This set of intrinsically related facies is interpreted as bar and	Grave bars

Facies associations and architectural elements			
Code	Facies	Description	Interpretation
		channel bottom deposits (lag). Both bottom structures originate from high flow regimes and normally form in the deepest areas of active channels [13, 33].	
SG	Sm Gmsv	Fine and medium sandstones and matrix-support conglomerates form tabular bodies, often amalgamated, which generally develop large extensions (∼20 m) and exhibit planar net contacts and/or transitional. These deposits are characterized by being massive, although in some sectors they can present diffuse parallel lamination and deformational structures (pinch and swell, clastic dikes, load-bearing structures, etc.). This set of characteristics are typical of the SG element [14]. The genesis of this element is related to hyperconcentrated flows. If the deposit has pumiceous clasts, these are considered lahars.	Lahars and hyperconcentrated flows

Table 5.
Table of facies associations (pyroclastic facies) and architectural elements (clastic and volcaniclastic facies).

could be associated with the migration of the river system and/or the loss of its identity, as it has to transport a greater sedimentary load (pyroclastic), under the same tectonic and climatic conditions. In this way, interdigitated volcaniclastic deposits (represented by crevasses) begin to appear in the sedimentary record with the facies association PF and the FF architectural element, the latter element sometimes carrying few pumiceous clasts.

Subsequently, a new volcanic episode represented by the lithofacies bL (association facies DPS) records the activity of dry pyroclastic surges on these plains. The association DPS is interleaved with the FF element. The variations in the content of pumiceous clasts that each of the sheets that make up these pyroclastic deposits (bL) present, allows us to infer that they would have originated from successive surges with oscillations in the populations of clasts, a product of currents fluctuating sustained over time [15].

The plains are areas that are characterized by developing gentle slopes, so a greater contribution of sediments, from pyroclastic falls and successively surges, has probably caused an even greater loss of slope of these plains, being the topographic features very scarce.

5.3 Stage III

In these plains sedimentary events occur (**Figure 5**) whose characteristics are high fluid discharge and high sedimentary load (SG architectural element), which can be interpreted as lahars and hyperconcentrated flows. The origin of both types of gravitational flows is associated with floods as a result of exceptional rains, which allow the generation of hyperconcentrated currents, which by remobilizing pyroclastic materials generate lahars. The deposits product of these processes of mass movements is characterized by being tabular, of great lateral extension (greater than 25 m) and being internally massive, although sometimes they can present tractive structures (for example, diffuse parallel lamination), which could be explained due to dilution of these flows due to loss of sedimentary head, which results in a different fluid/head ratio of the event.

Sometimes the interdigitation of the Gmsv and Sm lithofacies with the FF element generates bodies that present deformational basal contacts and structures

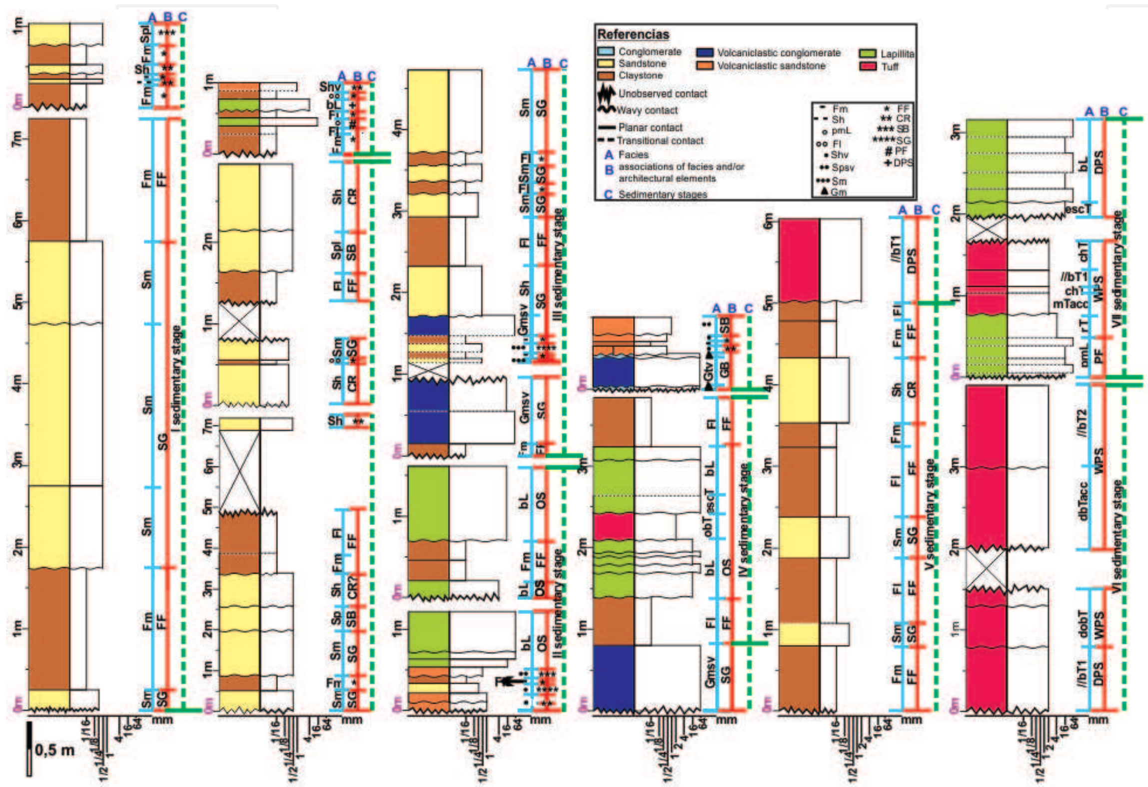

Figure 4.
Composite stratigraphic column and facies of the middle section of the Desencuentro formation. From left to right, the sections from the base to top are described. The lithofacies codes corresponds to ***Tables 1–4****; and the facies associations and architectural elements to* ***Table 5****.*

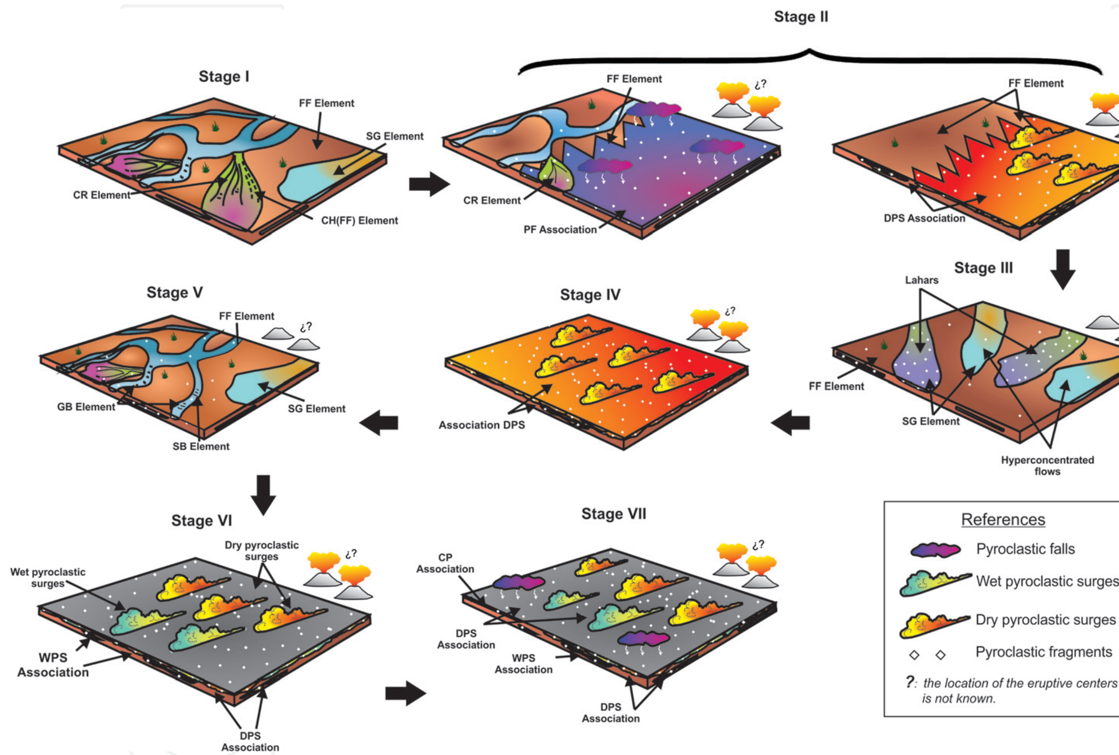

Figure 5.
Scheme unscaled outline showing the seven sedimentary stages and their evolution over time.

such as clastic dikes, pinch and swell, structures in flame, among others; which indicate that these sediments would have been embedded in fluids and that, due to differences in densities and pressures, the aforementioned structures are produced.

5.4 Stage IV

A new volcanic event, also represented by explosive eruptions, gives rise to dry pyroclastic surges (facies association DPS), which are deposited again on these plains (**Figure 5**). The pyroclastic deposits resulting from this eruptive moment, internally develop sharp tractive structures and high flow regime (e.g. parallel lamination, scaling structures, etc.), which correlate with dry pyroclastic surges, which probably respond to a rapid stacking and amalgamation of successive pyroclastic events. This is indicated by the transitional contacts between the different bodies.

5.5 Stage V

On top of this pyroclastic sedimentation, a new volcaniclastic sedimentation cycle begins that shows an interuptive period (**Figure 5**). This period of mixed sedimentation is represented by the architectural element FF that interdigitates with SB and SG vertically, which would indicate that the river system would be recovering its old position within the area. Fluvial deposits consist of conglomerate and coarse sandy lithofacies. The development of these deposits could correspond to new crevasses that, by vertical accretion, continue to generate the floodplain.

Later, massive, mantiform and sandy bodies are deposited, whose origin is related to hyperconcentrated flows caused by torrential rains.

5.6 Stage VI

In this sedimentary stage, the area is influenced by pyroclastic(s) event(s) which are registered as deposits of wet surges (facies association WPS) and dry (facies association DPS) that once again cover the extensive plains (**Figure 5**). The associations of WPS and DPS facies interdigitate with each other, and together present power of approximately 25 to 30 m, with a great absence of clastic sedimentation. In the deposits produced by wet pyroclastic surges, deformational structures develop (e.g. fluid leaks, sedimentary folds, convolute lamination, flame structures, etc.), observed in the dbTacc and rL lithofacies. The origin for these deformational structures is associated with seismic waves; gravity and inertia effects by pyroclastic flows and/or differential gas pressures [30]. Seismic waves can be attributed to contemporary volcanic activity, which causes unconsolidated and plastic sediments to deform and/or undergo liquefaction. However, a probable deformation generated by a rapid stacking of successive surges should not be ruled out.

The facies association DPS corresponds to dry pyroclastic surges, where no deformational structures have been observed, which implies a different behavior when passing seismic waves. This behavior would be related to the lack of interporal fluid in the sediments. In the sedimentary record, the dry and wet surge deposits are interdigitated, however, in the upper terms of the sequence, those of the DPS association prevail.

5.7 Stage VII

On the surge deposits (DPS and WPS indistinctly), tabular and low-power deposits (4 to 8 cm approximately) develop, interpreted as deposits of gravitational fall from pyroclastic clouds, which present levels with contrasting granulometry (CP association) (**Figures 4** and **5**). This type of deposition is related to non-sustained eruptions that have several pulses of short duration or to partial collapses of the eruptive column [23]. The last pulse of volcanic activity is recorded, in the study area, as a new wet surge event, followed by dry surges.

6. Conclusions

- These pyroclastics, clastic and volcaniclastic paleoenvironments in the section were developed in the most distal areas of the Bermejo Basin, and later were fragmented from the main part of the basin.

- The middle section of the Desencuentro Formation (Member P and part of Members D2 and D3) consists of clastic, volcaniclastic and pyroclastic sediments that generate a complex pattern of mixed paleoenvironmental evolution, which indicates interruptions in the volcanic activity of the Miocene arc in more distal areas of the Bermejo Basin.

- The detailed study of the sequences indicates the presence of an anastomosed river system (stage I), with the development of flood plains and mass removal events. This fluvial system, probably ephemeral with seasonal reactivations, develops in arid climatic conditions.

- The presence of fall deposits with dry pyroclastic waves in the floodplain (stage II) signals the beginning of the interaction of the river system with contemporary pyroclastic deposits. A probable lull in volcanic activity, coupled with exceptional rains (common in arid climates), generated lahars deposits (stage III). Stage IV represents a new hydromagmatic eruptive period, which consists of dry pyroclastic surges that cause the collapse of the river system. The river system begins to recover (stage V), with the development of SB and GB, as volcanic activity decreases. The presence of deposits associated with mass removal (SG element) confirms cycles in the climate. Later, thick deposits of wet and dry pyroclastic surges intercalated with fall deposits, indicate greater participation of pyroclastic sedimentation on fluvial sedimentation. However, the presence of levels of claystone intraclasts indicates that there were moments of development of plains with fine to very fine sedimentation of little importance, which was eroded by the pyroclastic surges (stages VI and VII).

- Sedimentation in the study area was not only controlled by the prevailing climatic conditions, but also by a rapid collapse of the river system due to the high load of pyroclastic sediments, which could not be transported to other areas, due to peneplanization generated by the volcanic deposits and the distal position within the Bermejo Basin.

- These paleogeographic conditions (peneplanization) prevailed in the formation of the posterior paleoenvironments (shallow lagoons with high evaporation and fluvial environments with very low energy and little channeling) described by [2] in member D4.

- The volcanic system contemporary to these sedimentation stages was not recognized, however, the general characteristics of the pyroclastic deposits described suggest that the volcanic events that generated the DPS, WPS and PF facies associations correspond to magmatic or hydromagmatic eruptions.

- The presence of sismites (fluid leaks, flaming structures, ball pillow, etc.) in the pyroclastic rocks allows us to infer that the sedimentation area would be in a distal for the eruptive(s) center(s).

- The volcanic focus (s) would be related to the Miocene volcanism that would have occurred at these latitudes. In the Miocene, the arc was migrating to eastern positions [39], we consider that these pyroclastic activities show the arc activity in the area; although it is not clear if these pyroclastic deposits are associated with the Miocene volcanism of Sierra de Famatina, to the east of the study area. The authors are currently conducting further studies to determine the origin of the volcanites.

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