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Syn-eruptive/inter-eruptive relations in the syn-rift deposits of the Precuyano Cycle, Sierra de Chacaico, Neuquén Basin, Argentina

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ABSTRACT

The syn-rift volcanic successions of the Upper Triassic–Lower Jurassic Precuyano Cycle (i.e. the Lapa Formation) from the Sierra de Chacaico in the Neuquén Basin, Argentina, were studied in order to address the distinctive characteristics of accumulation during syn-eruptive and inter-eruptive periods in a depocentre associated with active volcanism and extensional tectonics. In particular, the syn-rift fill in this area comprises a wide range of compositions, as well as of transport and depositional processes. Lava flows coexist with pyroclastic and epiclastic deposits in the same accumulation space. In order to analyse the complexities inherent in a volcanic environment subjected to extension, five different accumulation units were identified in the area: Lava Flow/Shallow Intrusion Units, Pyroclastic Units, Volcaniclastic Alluvial Units, Polymictic Alluvial Units, and Lacustrine Units. The analysis of each of these units and of the relationship between them provided meaningful insights into the evolution of the syn-rift sedimentary environments and the identification of different stages of effusive activity, explosive activity and relative quiescence, determining syn-eruptive and inter-eruptive rock units. The relationship between these units was examined, and two accumulation stages were defined. The underfilled stage originates when the material supplied to the depocentre during the eruptive events is not enough to level the existent topography, allowing the development of high-gradient alluvial systems during the next inter-eruptive period. The overfilled stage occurs when extensive pyroclastic density current deposits choke the accumulation space during syn-eruptive periods, causing low-gradient sedimentary systems to develop during the subsequent inter-eruptive periods.

1. Introduction

The characteristic physiography inherent to a rift landscape promotes the development of a wide diversity of accumulation systems (Gawthorpe and Leeder, 2000). Structure is dominated by normal faulting, allowing the existence of relatively small depocentres, highly compartmentalised and with abrupt changes in slope steepness during most of its history (Schlische, 1992; Morley, 1999; Morley et al., 1999). This situation produces a multiplicity of coexisting processes in the same accumulation space, generating numerous variations in the sedimentary systems inside the depocentres (Howell and Flint, 1996; Young et al., 2003; Jackson et al., 2005). The profuse volcanic activity commonly associated with the development of extensional environments (e.g. Ziegler and Cloething, 2004; Aguirre-Díaz et al., 2008) leaves a strong imprint on the sedimentary systems. Such interactions can be observed in the rock record of the syn-rift megasequence with a variable pattern in keeping with the alternation of periods of active or inactive volcanism. The existence of such different periods has been addressed as a major control over the sedimentary sequences that compose other basin types (e.g. Smith, 1987, 1991). Thus, identifying the variations in the volcanic expression offers predictive insights into the stratigraphic analysis of this kind of extensional environment.

The Neuquén Basin is located in the Andean margin between 32° and 40° S latitude (Fig. 1). It initiated in the Upper Triassic under an extensional tectonic regime (Vergani et al., 1995; Legarreta and Uliana, 1996; Franzese and Spalletti, 2001; Howell et al., 2005). The oldest units of syn-rift deposition are generically grouped under the denomination of Precuyano Cycle (Gulisano et al., 1984). The Precuyano record is the result of the interaction of complex processes in a scenario in which the effect of volcanism overlapped with extensional faulting (Franzese and Spalletti, 2001; Franzese et al., 2006, 2007). Purely epiclastic sedimentary processes (sensu Cas and Wright, 1987) and those derived from the volcanic activity converge on a unique sedimentary environment. The purpose of this contribution is to identify and understand the interrelationship between the sedimentary and volcanic processes occurring in the extensional setting of the Precuyano Cycle. Therefore, the focus is on the

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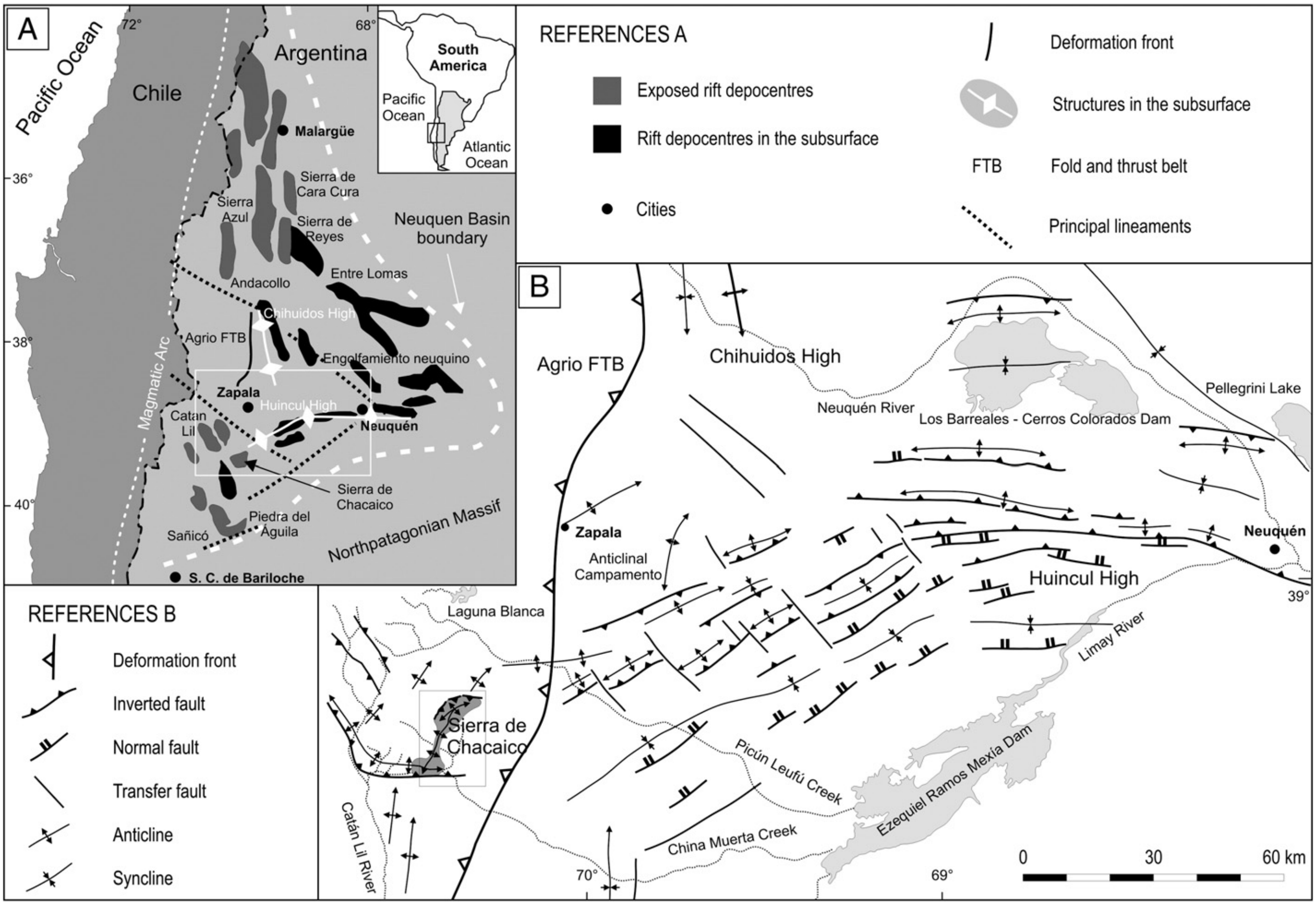

Fig. 1. Location maps. (A) Distribution of rift depocentres in the Neuquén Basin, Argentina. The white rectangle shows the areal extent of B. Modified from Franzese and Spalletti (2001). (B) Map of the major structures in the Sierra de Chacaico area and their continuation into the Huincul High in the subsurface. Location of the Sierra de Chacaico area is highlighted with a black rectangle. Structures from the Huincul High are according to Vergani (2005).

identification of the syn-eruptive or inter-eruptive character of the different units (Smith, 1991).

2. Geological setting

The Sierra de Chacaico is situated in the southern part of the Neuquén Basin (Figs. 1 and 2), where a complete succession of the earliest syn-rift sequences of the Precuyano Cycle is preserved directly overlying the basement (Fig. 3A and B). Igneous-metamorphic rocks form a basement constituted by low grade Siluro-Devonian schists and phyllites (Piedra Santa Formation) intruded by late Palaeozoic granitoids (Chachil Plutonic Complex) (Franzese, 1995). The Precuyano Cycle deposits in the area are known as the Lapa Formation (Leanza, 1990) and are mainly composed by lava flows, pyroclastic successions and siliciclastic continental sedimentary rocks. In minor proportion, carbonate rocks also occur. Overlying the volcanic syn-rift megasequence, the epiclastic and mainly marine sequences of the Cuyano Cycle (Gulisano, 1981) are well developed (Fig. 2). In the area, two Cuyano Cycle units can be recognised: the Sierra de Chacaico Formation (Volkheimer, 1973), comprising littoral to neritic sandstones and mudstones; and the Los Molles Formation (Weaver, 1931), composed of deep-marine dark shales and minor sandstones. On the basis of palaeofloristic records, the Precuyano syn-rift deposits date from the Upper Triassic to Lower Jurassic (Leanza, 1990; Spalletti et al., 1991, 2010). The age of the Cuyano units has been determined by their ammonite biozonation (Volkheimer, 1973; Leanza and Blasco, 1990): Lower Pliensbachian for the Sierra de Chacaico Formation and Toarcian to Middle Bajocian for the Los Molles Formation. The ages of neither the Cuyano Cycle nor the Precuyano Cycle have been determined by radiometric methods in this site. However, the few available radiometric data for the Precuyano Cycle in other depocentres is compatible with the age suggested by the macroflora fossil content: U–Pb method on single zircon crystals from wells in the

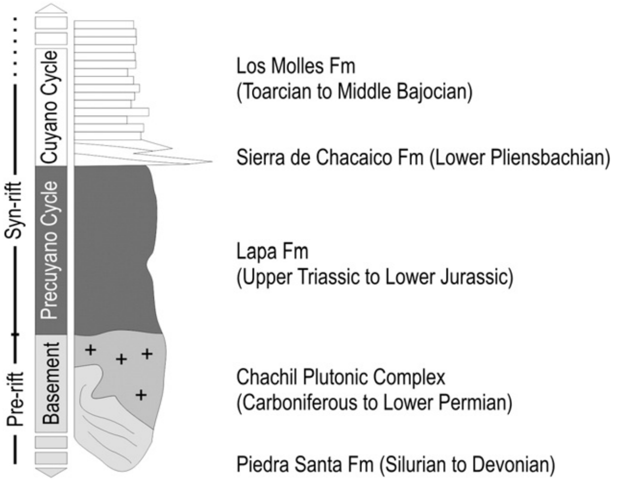

Fig. 2. Schematic stratigraphic column representing the different units present at the Sierra de Chacaico.

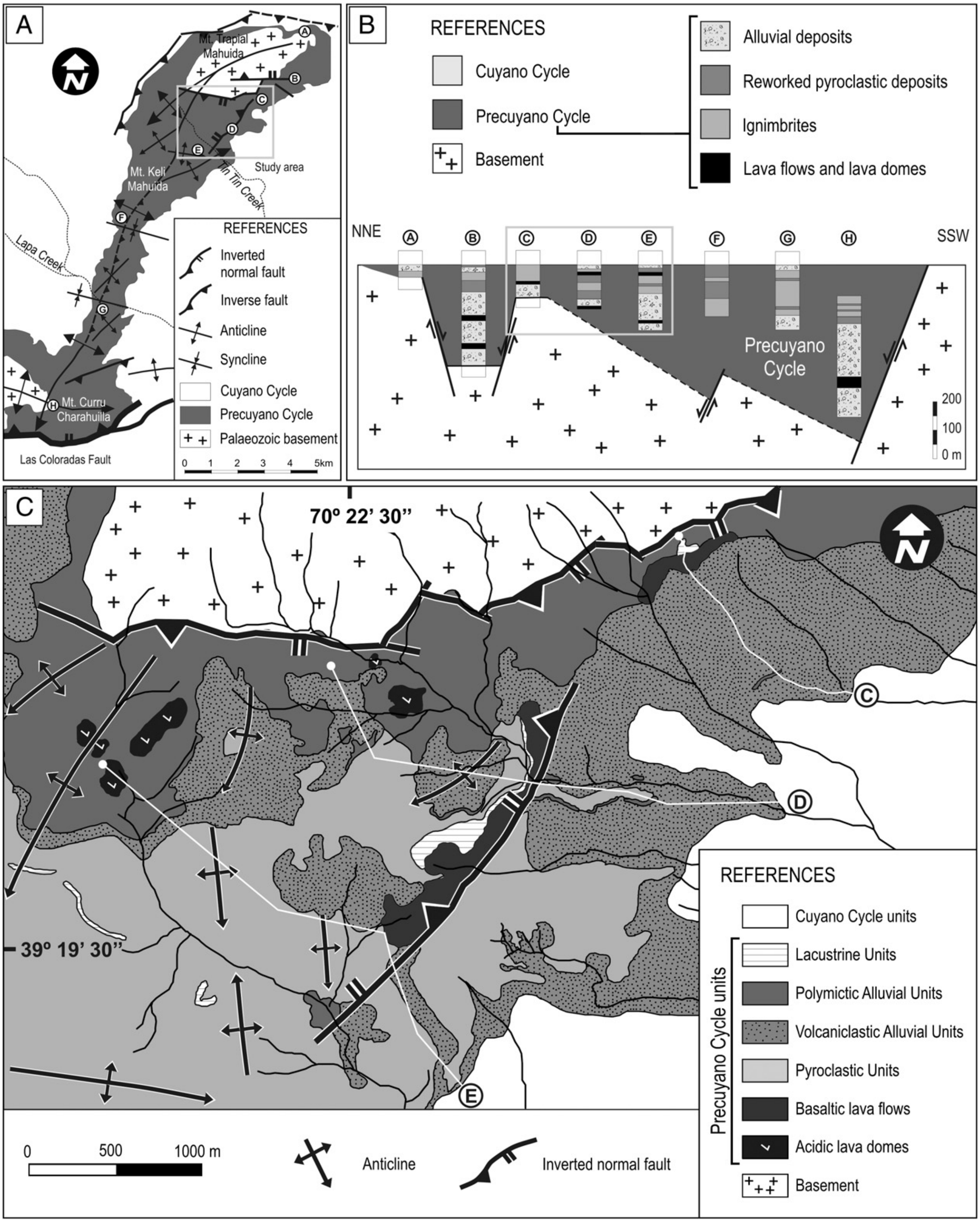

Fig. 3. Geological maps of the study area and location of logged sections. (A) Geological map of the Sierra de Chacaico depocentre and location of logged sections A–H. (B) Correlation panel of the logged sections A–H, showing the overall half-graben geometry of the depocentre. Modified from Franzese et al. (2007). (C) Detailed map of the northern Sierra de Chacaico area. Location of the logged sections C, D and E indicated with white lines. The top of the basalt flow represents a key surface that allows for correlations between the three sections and between the deposits exposed on the footwall and hangingwall of the fault. See Methodology section for further explanation.

Huincul High area (Schiuma and Llambías, 2008) shows Norian/Rhaetian (203.75 ± 0.26 Ma in Anticlinal Campamento area; Fig. 1B) and Sinemurian ages (199.0 ± 1.5 Ma in Cerro Guanaco area; Fig. 1B). In the Piedra del Águila depocentre (Fig. 1A) tuffs from the Sinemurian were dated by U–Pb SHRIMP method (191.7 ± 2.8 Ma; Spalletti et al., 2010).

The Sierra de Chacaico is a range of hills defined by a complex anticline structure of NNE–SSW orientation and west vergence generated by the propagation of an east-dipping reverse fault (Franzese et al., 2007; Fig. 3A), related to the evolution of the Andean margin during the Late Cretaceous and the Neogene (Howell et al., 2005). Its present configuration is the result of the interaction between the extensional structures inherited from the rifting stage and the superposed Pre-Andean (N–S) and Andean (E–W) compressive events. The Sierra de Chacaico depocentre corresponds to an exposed portion of the Huincul High (Franzese et al., 2007), which is constituted by a system of subparallel faults and folds of E–W to NE–SW orientation (Orchuela et al., 1981; Vergani, 2005; Fig. 1A). The Huincul High is the most prominent inversion feature of the southern Neuquén Basin. It consists of a series of syn-rift depocentres inverted along their most active boundary faults (Vergani, 2005).

The Sierra de Chacaico anticline has a gentler eastern flank dipping 10° to 15° to the east and a more inclined western one dipping 40° to 50° to the west. The western flank can reach a subvertical configuration in some places, closely associated to a blind inverse fault developed at the core of the Sierra de Chacaico anticline that breaches its crest in some locations. The anticline axis is curved to the east at its northern end and to the west at its southern end (Fig. 3A). The Sierra de Chacaico is abruptly disrupted at both ends by inverted faults of E–W orientation (Figs. 1B and 3A). Towards its northern end the basement is uplifted over the Cuyano Cycle deposits while towards its southern end (Las Coloradas Fault; Fig. 3A) the Precuyano Cycle sequence is uplifted over Cretaceous deposits, implying a displacement in the order of the thousand of metres (Franzese et al., 2007). Although the Sierra de Chacaico shows a definite NNE–SSW orientation, the existence of fold structures transverse and oblique to the range axis and subparallel to the E–W bounding faults to the north and south is conspicuous. These structures are of great magnitude and involve the uplift of either syn-rift or pre-rift elements, comprising the highest areas observed in the range. The Mount Trapial Mahuida is located to the north of the study area and consists in a faulted basement block tilted to the southeast. This block constitutes the core of an anticline structure developed in the overlying Precuyano Cycle deposits (Fig. 3A and C). Towards the middle part of the range a similar NE–SW oriented structure defines the Mount Keli Mahuida (Fig. 3A). At the southern end of the range a dome-shaped structure, the Mount Curru Charahuilla, is outlined by the intersection of the Sierra de Chacaico anticline and an E–W anticline subparallel to the Las Coloradas Fault (Figs. 1B and 3A).

The syn-rift stratigraphic framework of the whole Sierra de Chacaico depocentre was originally described by Franzese et al. (2007). The Precuyano Cycle deposits evolved in a continental environment controlled by E–W and NE–SW oriented structures during the Upper Triassic to Lower Jurassic. The maximum thickness is recorded to the south, next to the Las Coloradas Fault, which acted as the most active border structure of the Sierra de Chacaico depocentre during the deposition of the Precuyano Cycle (Fig. 3B). In this contribution we analyse the effect of volcanic activity over the sedimentary systems which developed during the rifting stage. Case studies for different types of interactions between them were specially chosen from the outcrops on the northern portion of the eastern limb of the Sierra de Chacaico anticline structure, immediately to the south of the Mount Trapial Mahuida, where the syn-rift sequences are better exposed (Fig. 3C).

3. Methodology

The study of the syn-rift succession was carried out through detailed geological mapping and measuring of stratigraphic and sedimentary logs. Several lithofacies and lithofacies associations were determined. For the purposes of this contribution, the use of the term 'volcaniclastic' is restricted to the composition of the fragments that make up a certain deposit, in keeping with its original definition (Fisher, 1961). The compositional characteristics of volcanic and pyroclastic rocks were studied through the analysis of thin sections. Petrographic analyses of the diverse clastic rocks determined the nature of their provenance and their relationship with the volcanic facies. Discrete depositional units, which will be referred to as 'accumulation units', were defined based on the identification of distinct bounding surfaces, in conjunction with the lithofacies associations that compose those units.

Depositional systems in volcanic environments tend to reflect the variations in frequency and intensity of the volcanic activity (Runkel, 1990; Waresback and Turbeville, 1990). The great volume of material released during a volcanic eruption has a clear effect on the sedimentary systems (Cole and Ridgway, 1993). To distinguish the inter-eruptive from the syn-eruptive characteristics of the sedimentary units, the analysis of the volcaniclastic deposits focused on three concepts: a) composition (Smith, 1988; Cole and Ridgway, 1993; Haughton, 1993; Riggs et al., 1997), b) mechanisms of transport and deposition (Brantley and Waitt, 1988; Walton and Palmer, 1988; Bahk and Chough, 1996), and c) aggradational versus degradational behaviour of the accumulation units (Smith, 1987; Bahk and Chough, 1996; Riggs et al., 1997). It is important to highlight that these three concepts were applied to volcanic successions with a wide areal distribution, situated in non-compartmentalised basins (i.e., a foreland basin; Smith, 1987, 1991). In contrast, in the Precuyano Cycle of the Chacaico area the volcanic activity took place entirely in deep, narrow extensional depocentres (15–20 km) (Franzese et al., 2007). Therefore, the previous models cannot be applied unless they are adapted to the specific geological setting of the study area.

The study area and the location of three sections logged through the exposed stratigraphy of the Precuyano Cycle are shown in the map in Fig. 3C. Two of these sections (D and E) cross the trace of an inverted fault which was an active extensional structure during part of the deposition of the syn-rift. The top of a basalt flow unit (Fig. 3C) constitutes a key surface for determining the fault displacement and the stratigraphic correlation between both the three different logs and the deposits at either side of the fault (i.e. hangingwall and footwall). The inversion of this fault generated a displacement of approximately 10 m for the log D area and of 15–20 m for the log E area. Corrections for the mentioned displacement were taken into account in the graphic representation of the three sections shown in Fig. 9.

4. Accumulation units of the Precuyano syn-rift successions

The combination of the typical factors that are involved in the evolution of an extensional depocentre and the complexity of a volcanic setting is responsible for the occurrence of a wide variety of lithologies in the successions considered herein. The interpretation of both clastic and coherent volcanic rocks requires a broader understanding of the relationship between non-volcanic and volcanic processes. In order to better constrain the interaction between syn-eruptive and inter-eruptive deposits in such a heterogeneous scenario, the different relations between the accumulation units will be investigated. Five kinds of accumulation units are distinguished in the syn-rift sequences analysed herein: Lava Flow/Shallow Intrusion Units, Pyroclastic Units, Volcaniclastic Alluvial Units, Polymictic Alluvial Units, and Lacustrine Units.

4.1. Lava Flow/Shallow Intrusion Units

These comprise all the rock bodies integrated by effusive or intrusive volcanic bodies (Fig. 4), whose composition ranges from basaltic to rhyolitic. Among them, lava flows, shallow intrusions, and lava domes are the most common ones. These units have no definite position in the syn-rift megasequence and do not occupy significant volumes in the stratigraphy of the Sierra de Chacaico (Fig. 3).

Basaltic flows are rock bodies of tabular geometry with variable thickness, spanning from 3 to 20 m, and they can be composed of a unique effusive event or include several overlapping flows. Their emplacement over an irregular topography can cause locally different, complex configurations. They are generally composed of aphyric lavas which grade into porphyric textures, showing also pervasive

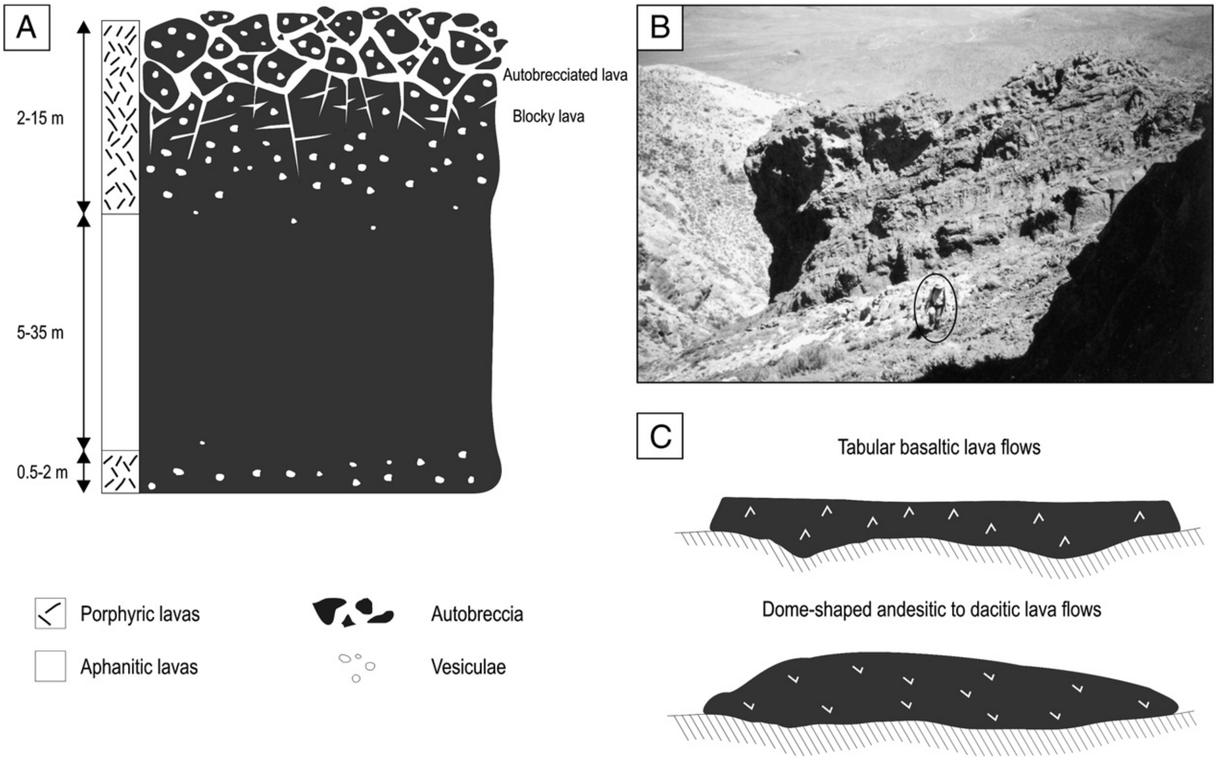

Fig. 4. Lava Flow/Shallow Intrusion Units. (A) Schematic log of a typical lava flow. (B) Photograph of a basaltic lava flow succession. Circle indicates person for scale. (C) Simplified cross-sections of lava rock bodies showing their characteristic geometry.

vesiculation. The development of significant blocky structures by auto-brecciation towards the border is another outstanding feature. The basaltic intrusions are normally related to flows of the same composition that appear in the same stratigraphic level, being mainly concordant with the surrounding country rocks.

Andesitic to rhyolitic bodies — which have porphyric textures with phenocrysts of plagioclase, K-feldspar and quartz — exhibit massive coherent structures or, to a lesser extent, auto-brecciated structures with variable degrees of alteration. The geometries observed have conspicuously convex tops, while the bases are relatively planar. The effusive rock bodies were defined as lava domes, and the intrusives as cryptodomes (McPhie et al., 1993).

4.2. Pyroclastic Units

They are present along the whole Precuyano Cycle stratigraphic record in the Sierra de Chacaico (Fig. 3B) and are mainly represented by ignimbrites (sensu Branney and Kokelaar, 2002) constituting thick homogeneous successions of pumiceous lapilli-tuffs (Fig. 5A). They are characterised by the presence of a lithofacies consisting in matrix-supported lapilli-tuffs with pumice fragments of 3 to 5 cm generally lacking grain fabrics. Occasionally, lithoclasts of volcanic and sedimentary origin also occur. These lithofacies are composed of massive or, less frequently, diffusely-stratified homogeneous successions, which on occasion also display gas escape structures. It is common to find plant debris that appears as non-carbonised pieces of trunks and stems. In thin section the pumices show different grades of porosity and magmatic crystal fragments of quartz, K-feldspar and biotite denoting a rhyolitic composition (D'Elia and Franzese, 2005). They are exposed either as small bodies with a restricted surface expression and a thickness of less than 10 m, or as tabular bodies of great lateral extent ranging from hundreds of metres to tens of kilometres and thicknesses of up to 120 m (Fig. 5B). The thinner units are characterised by their whitish or greenish colour, caused by argillic alteration in the diagenetic stages (McPhie et al., 1993; Gifkins et al., 2005). In the case of thicker units, silicification is common along the matrix, preserving or completely obliterating the primary depositional fabrics. When these are preserved, the particles are non-deformed and recrystallised to fine aggregates of cryptocrystalline silica with floating contacts. This process was interpreted as being caused by vapour-phase alteration (sensu Cas and Wright, 1987; Streck and Grunder, 1995) and/or deuteric alteration in the syn-volcanic stages (D'Elia and Franzese, 2005) (Fig. 5C). The thickest and most extensive pyroclastic deposits in the study area occur in the medial section of the Precuyano Cycle (Fig. 3B and C).

These units are deposited from pyroclastic density currents with fluid escape-dominated flow-boundary zones (Branney and Kokelaar, 2002). In both cases, the morphology of the pumice lapillus and the presence of recrystallised ashes imply temperatures below glass-transition during deposition (McArthur et al., 1998). Shards are incipiently to partially welded (Smith, 1960), reaching welded grades II to III (Quane and Russell, 2005). The ignimbrites are thus interpreted as being originally unconsolidated deposits made of loose non-welded particles.

The units of pyroclastic accumulation constitute the record of explosive volcanic activity during the evolution of the Precuyano Cycle. Because of the sudden, short term nature of volcanic eruptions, their magnitude is commonly reflected in the volume of their deposits. Thus, the thickest and most extensive ignimbrites in the study area represent the instant shedding of immense amounts of pyroclastic material to the depocentres. By contrast, the thinner units are the product of small-scale events.

4.3. Volcaniclastic Alluvial Units

These units are composed of volcaniclastic material reworked by epiclastic processes (Cas and Wright, 1987). They form widespread continuous sequences along the Sierra de Chacaico, specially

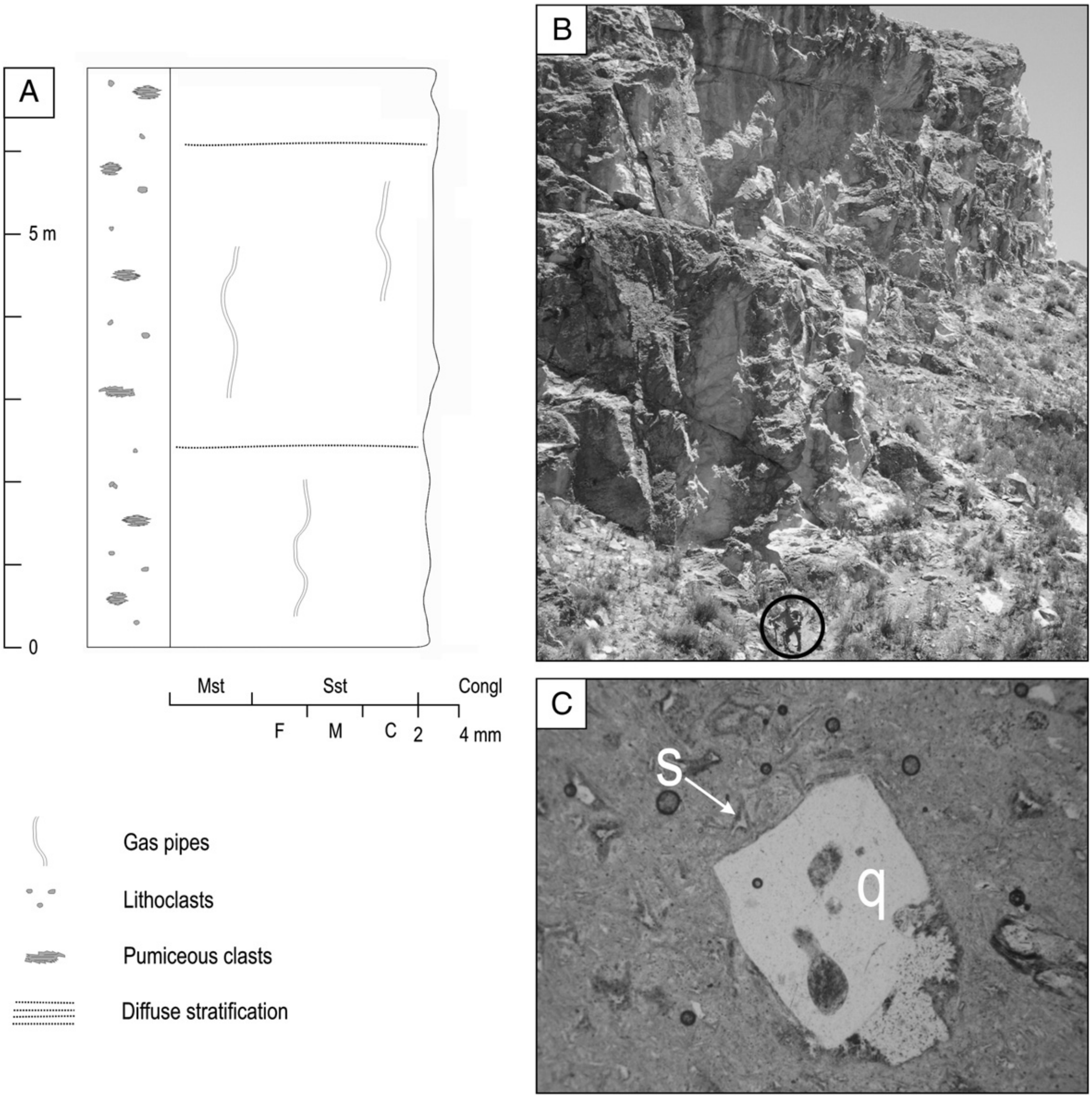

Fig. 5. Pyroclastic Units. (A) Sedimentary log representative of the pyroclastic density current deposits. (B) Outcrop-scale photograph of a massive to grossly stratified pyroclastic density current deposit. Circle indicates person for scale. (C) Thin-section photograph showing typical vapour-phase crystallisation texture for the pyroclastic units. Quartz crystal fragment is 2.7 mm in length. Mst: mudstones; Sst: sandstones; Congl: conglomerates; F: fine; M: medium; C: coarse; q: quartz crystal fragment; s: cuspate shards recrystallised to cryptocrystalline silica.

developed towards the medial to upper sections of the Precuyano Cycle, where they reach thicknesses of up to 40 m (Fig. 3). Among their constituents there is an abundance of glassy material such as pumices and variably altered shards. Quartz and feldspar crystal fragments and volcanic lithoclasts are also present. The successions are predominantly integrated by fine-grained, moderate- to well-sorted greenish tuffaceous sandstones. They occur in tabular beds which are massive or diffusely stratified, with a thickness that varies from 10 to 50 cm. In a more restricted way, lensoidal bodies with concave bases and planar tops are also found (Fig. 6). These lenses are composed of moderate- to well-sorted grain-supported fine conglomerates with abundant lithoclasts and planar to trough cross-stratified sandstones.

The absence of tractional structures or diffusive stratification with gradational contacts suggests that tabular bodies result from the rapid, progressive aggradation of hyperconcentrated sheet flows (Smith, 1986), which represents the main transport and deposition process involved within these units. Less frequently, on the basis of the occurrence of lensoidal bodies with planar to trough cross-stratified sandstones, channel fill deposits attributed to bedload transport from stream flows may be interpreted (Miall, 2006).

The deposits accumulated in these units suggest rapid aggradation during periods when the landscape was choked with debris. The predominance of hyperconcentrated sheet flow deposits with locally present channel bodies suggests deposition in an alluvial context (sensu Blair and McPherson, 1994). The provenance of this unit, which mainly comprises pyroclastic and effusive volcanic clasts, indicates high affinity with the volcanic landscape, as it is almost unrelated to the country rocks (i.e., Piedra Santa Formation and Chachil Plutonic Complex). The abundance of tuffaceous material clearly reveals a continuous delivery of pyroclasts, originated by the reworking and redeposition from primary pyroclastic units (i.e., ignimbrites) to the sedimentary system. The absence of major erosive surfaces and degradational cycles is consistent with a high aggradational rate. All of these characteristics are typical of syn-eruptive deposition (e.g., Smith, 1991).

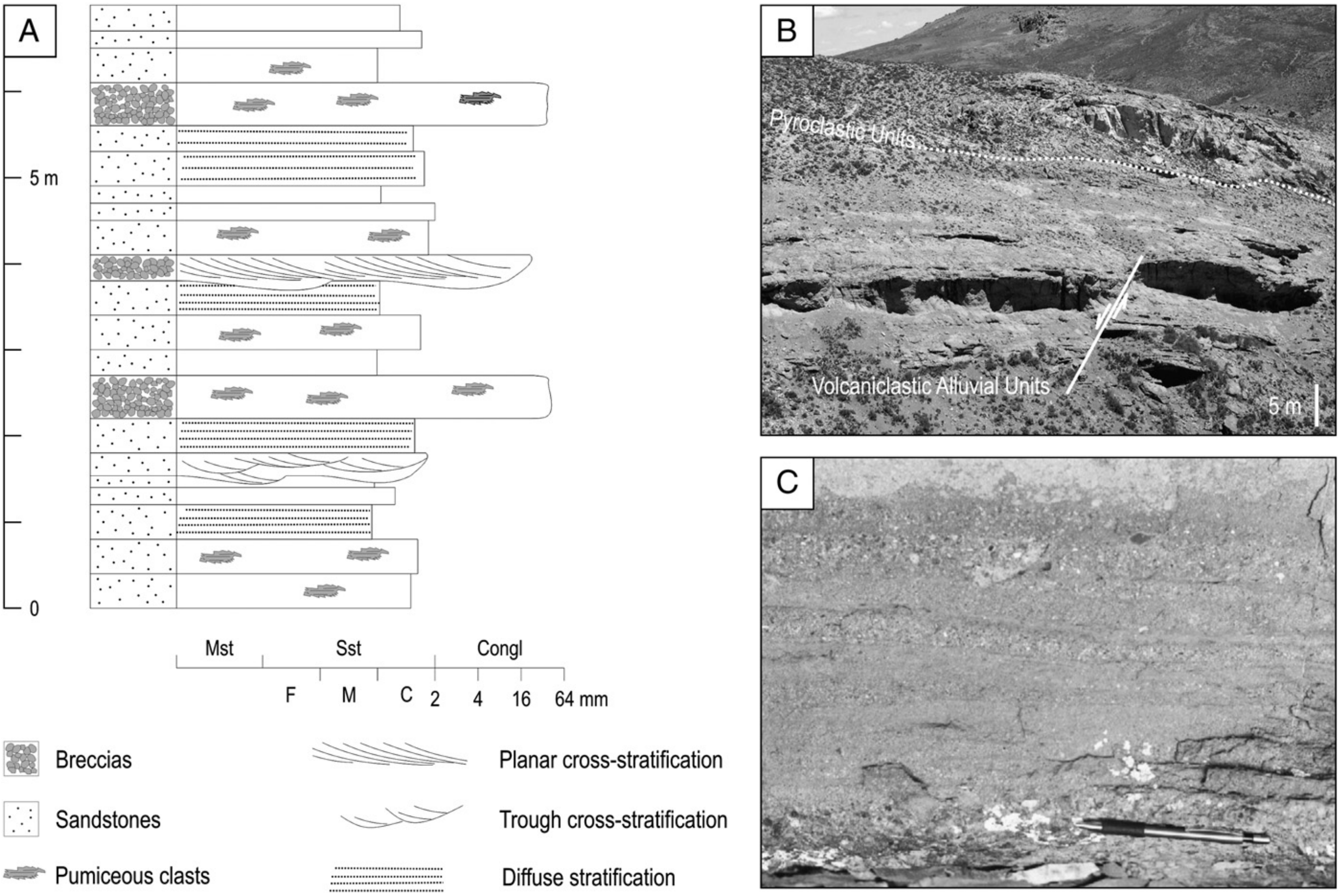

Fig. 6. Volcaniclastic Alluvial Units. (A) Sedimentary log showing the characteristic intercalation of hyperconcentrated-flow deposits and shallow conglomerate channels. (B) Volcaniclastic Alluvial Units affected by a syn-sedimentary fault and overlaid by deposits of pyroclastic density currents. (C) Photography of sandy hyperconcentrated-flow deposits typical of this unit. Mst: mudstones; Sst: sandstones; Congl: conglomerates; F: fine; M: medium; C: coarse.

4.4. Polymictic Alluvial Units

These units are formed by epiclastic deposits which fill incised depressions of up to 40 m in thickness and 500 m of lateral extent intercalating either with the Pyroclastic Units or the Volcaniclastic Alluvial Units (Figs. 3 and 7). The composition of the deposits is typically polymictic, with a predominance of volcanic, plutonic and metamorphic lithoclasts. In a smaller proportion, they contain quartz and feldspar crystal fragments and sedimentary lithoclasts.

Coarse-grained facies predominate, being almost completely made up of conglomerates. Two distinctive geometries are observed in the conglomerate bodies: lobate and lensoidal. Lobate bodies show planar bases and convex tops, whose internal lithofacies include either poorly sorted, matrix-supported fine to medium conglomerates or poorly sorted clast-supported fine to medium conglomerates with a polymodal matrix (Fig. 7A), in which pebbles oriented with their long axes parallel to stratification often occur. Lensoidal bodies show concave bases and planar tops, and are constituted by moderately sorted conglomerates with massive or diffuse horizontal stratification or, less frequently, planar cross-stratification. Occasionally, lithic sandstone and siltstone facies are intercalated with the conglomerates. The sandstone deposits show either tabular to slightly lensoidal bodies which are massive, inversely or else normally graded, or lensoidal bodies presenting ripples and planar cross-stratification. Siltstones appear as thin layers with horizontal lamination and desiccation cracks.

The absence of tractional structures in the conglomerates indicates that high density flow deposition is the most representative mechanism of accumulation in these units. The clast-supported conglomerates with polymodal matrix (Fig. 7B and C) correspond to hyperconcentrated-flow deposits (Smith, 1986; Smith and Lowe, 1991; Orton, 2002), whereas the matrix-supported conglomerates can be interpreted as non-cohesive debris-flow deposits (Shultz, 1984; Pierson et al., 1990). Massive sand lithofacies with normal or inverse grading (Fig. 7D) are deposited from high density sheet flows. To a lesser extent, gravelly and sandy lithofacies with tractional structures suggest that they originated as small isolated stream flow channels.

The association of these facies is indicative of alluvial processes (sensu Blair and McPherson, 1994) which developed as the passive infill of a steeply incised landscape generated by previous erosive events (Fig. 7E). The significant presence of basement-derived clasts (i.e., plutonic and metamorphic rocks) coincides with the compositions expected for deposits which originated during periods of reduced explosive volcanic activity (Smith, 1988; Cole and Ridgway, 1993; Haughton, 1993; Riggs et al., 1997). Therefore, the development of degradational surfaces which were subsequently filled by polymictic and ash-poor lithofacies suggests the inter-eruptive character of these units.

4.5. Lacustrine Units

They consist in successions of carbonate rocks intercalated with reworked volcaniclastic materials (Fig. 8A). Their thickness is considerably variable along the Sierra de Chacaico, from 15 to 30 m. They show a very restricted stratigraphic position in the Precuyano Cycle, almost invariably on top of the units of pyroclastic accumulation and below basaltic lava flows (Fig. 3B and C).

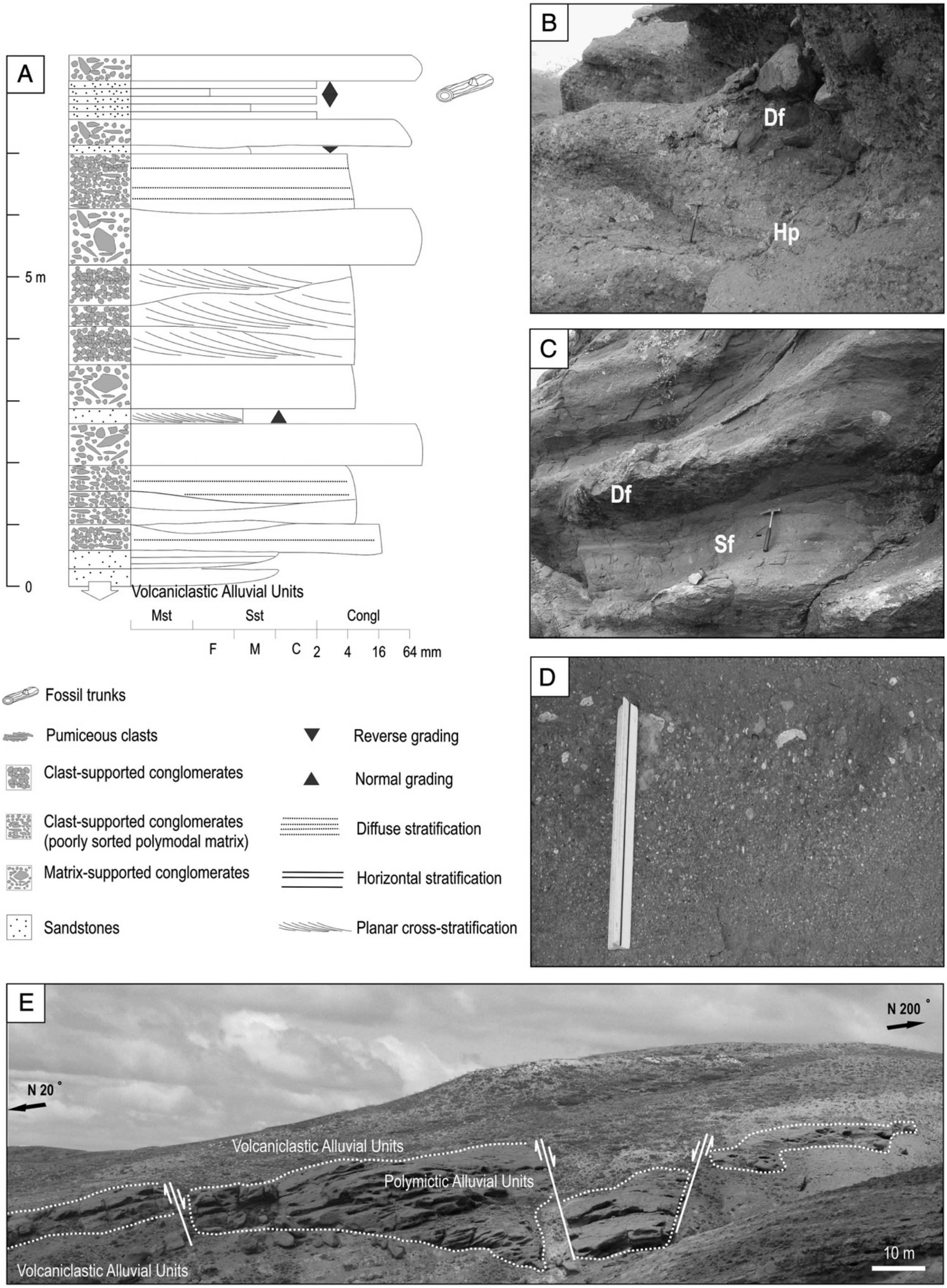

Fig. 7. Polymictic Alluvial Units. (A) Sedimentary log showing a succession of hyperconcentrated- and debris-flow deposits with minor intercalations of diluted flow deposits. (B) Hyperconcentrated-flow deposits (Hp) overlaid by debris-flow deposits (Df). Hammer for scale is 30 cm long. (C) Debris-flow deposits (Df) intercalated with sandy mass-flow deposits (Sf). Hammer for scale is 30 cm long. (D) Detail of a sandy mass-flow deposit (C) with typical inverse-graded stratification. Ruler for scale is 13 cm long. (E) Palaeovalley generated on the Volcaniclastic Alluvial Unit deposits with passive infill of the Polymictic Alluvial Units. Extensional faults affect both units. Mst: mudstones; Sst: sandstones; Congl: conglomerates; F: fine; M: medium; C: coarse.

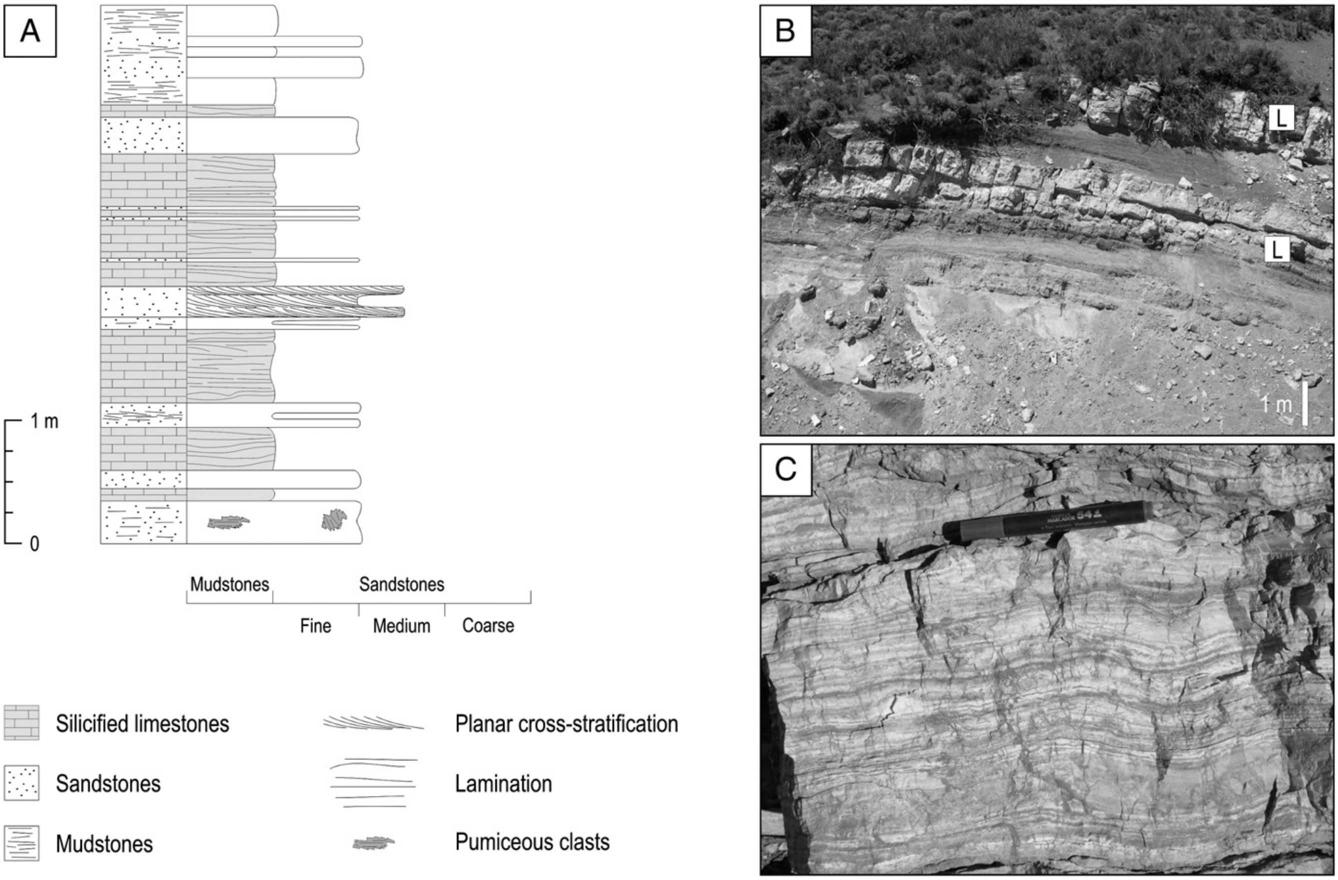

Fig. 8. Lacustrine Units. (A) Sedimentary log showing the intercalation between carbonate and volcaniclastic facies. (B) Tabular carbonate beds (marked with a letter 'L') intercalating with volcaniclastic mudstones and sandstones. (C) Wavy lamination typical of the carbonate beds.

The carbonate successions are characterised by a tabular geometry with planar bases and slightly wavy tops (Fig. 8B). They are composed of limestone or siliciclastic layers which range from 0.45 to 0.75 mm in thickness. Their most conspicuous structure is determined by an even planar or wavy lamination (Fig. 8C). Occasionally, they display dissolution structures and isolated flat clasts among their deposits (Muravchik and Franzese, 2005). The carbonate layers are formed by finely laminated mudstones with occasional peloids and massive wackestones with peloids of up to 0.3 mm in diameter, surrounded by finer particles. The development of siliceous bands originated by replacement processes in post-depositional stages is common. Siliciclastic layers are fine-to-medium sandstones composed of quartz and K-feldspar crystal fragments, volcanic lithoclasts and occasionally also by carbonate lithoclasts. Their grain size varies from 0.15 to 0.36 mm and can be cemented by silica, or less frequently, they have a carbonate matrix.

Reworked volcaniclastic deposits are integrated by fine-to-medium massive sandstones with cross-stratification and, to a lesser extent, siltstones and conglomerates (Fig. 8B). The geometry of the rock bodies is either tabular or lenticular with a concave erosive base. The clast composition of these deposits is characterised by pyroclastic (i.e., pumice vitroclasts and vitric shards) and effusive volcanic fragments (i.e., andesitic to dacitic lithoclasts) and K-feldspar crystal fragments.

Carbonate successions were formed in aqueous environments of relatively low energy and moderate clastic input, under conditions of $CaCO_3$ precipitation. Internal structures were interpreted as algal limestones (e.g. Riding, 2000; Dupraz et al., 2004) on the basis of microtextural and compositional analyses (Muravchik and Franzese, 2005). Reworked volcaniclastic deposits originated as a result of the reworking of primary pyroclastic and volcaniclastic material which could have been fed to the water bodies by alluvial or fluvial supplies associated to the evolution of the subaerial volcanic landscape. Therefore, the carbonate successions and reworked volcaniclastic deposits indicate the sporadic existence of shallow, low-energy water bodies interpreted as a lacustrine environment related to the subaerial input systems.

This kind of lacustrine system is common in different volcanic environments (e.g., Renaut and Owen, 1988; Schubel and Simonson, 1990; Tiercelin et al., 1993; Krainer and Spötl, 1998; Renaut et al., 1998; Renaut et al., 2002). The lack of any pyroclastic primary deposits in these successions, in addition to the presence of calcareous facies, implies the absence of a simultaneous explosive event. Hence, the Lacustrine Units clearly constitute a series of inter-eruptive deposits occurring during the evolution of the syn-rift volcanic environment.

5. Syn-eruptive/inter-eruptive process interaction

In the previous sections, the eruptive and syn-eruptive/inter-eruptive characteristics of the syn-rift units were described. In order to establish the main interactions between the accumulation processes, some types of key relationships among them will be considered. Two distinctive cases will be analysed in detail: 1) Polymictic Alluvial Units passively infilling incisions on Volcaniclastic Alluvial Units and the small volume Pyroclastic Units and 2) Lacustrine Units deposited on top of large Pyroclastic Units and covered by basaltic Lava Flow Units.

5.1. Case I: Polymictic Alluvial Units passively infilling incisions on Volcaniclastic Alluvial Units and the small volume Pyroclastic Units

The inter-eruptive Polymictic Alluvial Units overlie both syn-eruptive units, i.e., the Volcaniclastic Alluvial Units and the smallest and thinnest Pyroclastic Units. This kind of relationship can be found either at the lower or at the upper portions of the Precuyano Cycle (Fig. 9). The contact between inter-eruptive and syn-eruptive units is sharp, unconformable and developed over irregular topography. The inter-eruptive units are deposited in depressions with variable grades of incision on top of the syn-eruptive units (Figs. 7E and 9). When the syn-eruptive and the inter-eruptive alluvial units are in contact, they can be distinguished by their compositional features. The Volcaniclastic Alluvial Units originated fundamentally due to the remobilization of pyroclastic material, synchronous to the eruptive event. On the other hand, the accumulation of the Polymictic Alluvial Units, which are formed by lithoclasts derived from the igneous-metamorphic basement and volcanic rocks, suggests the continuous and generalised degradation of the rift landscape affecting both the basement fault blocks and the volcanic edifices.

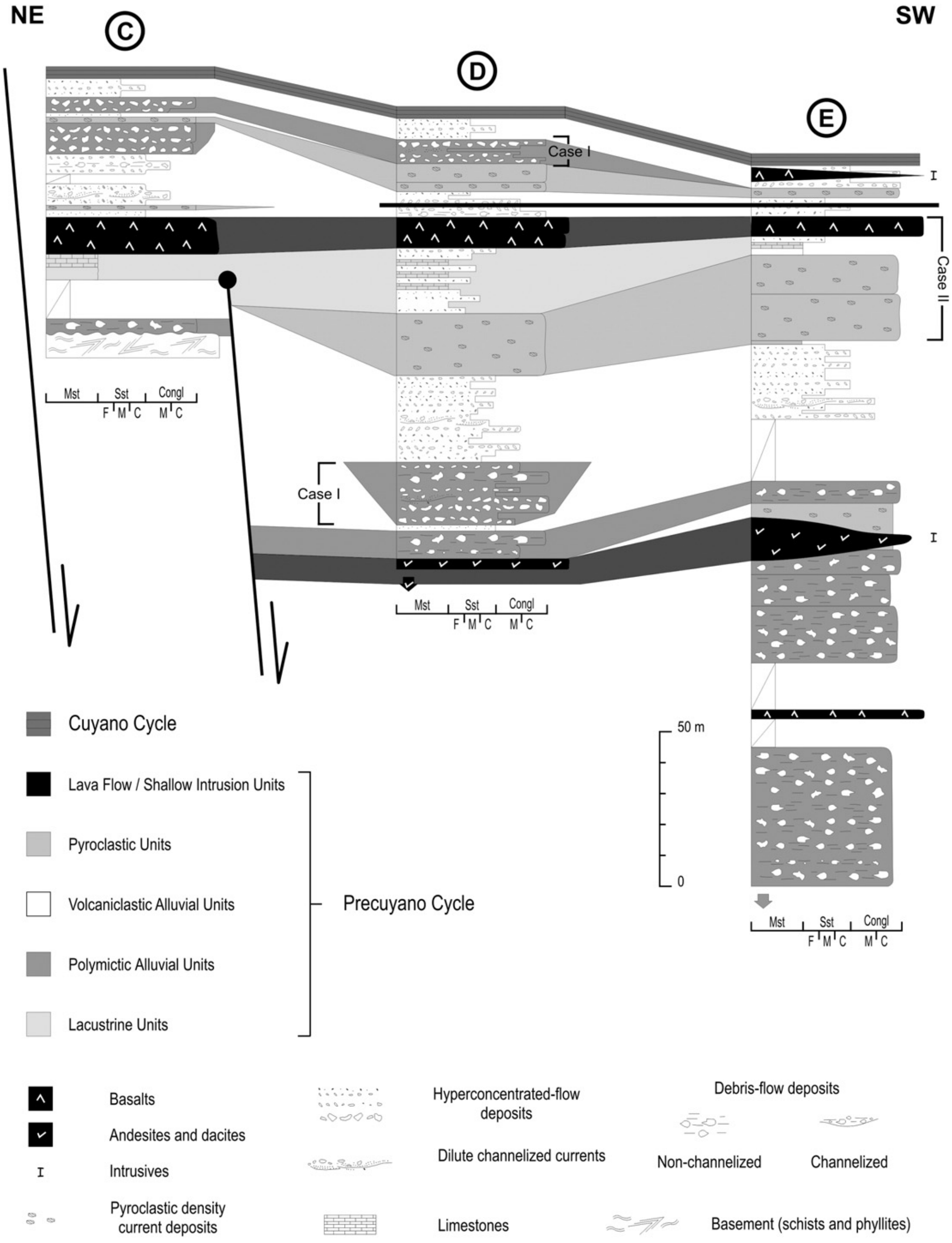

Fig. 9. Sedimentary logs of the Precuyano Cycle successions and their correlation; see Fig. 3C for location. Stratigraphic positions for Case I and Case II are indicated. The occurrence of Case I examples is always localised, while Case II has a wider distribution throughout the whole area. The black line on the upper half of logs D and E shows the relative position of the fault in Fig. 3C. The portion of section above that line in both logs corresponds to the footwall and the section below to the hangingwall. The top of the basalt flow represents a key surface that allows for the correlation between the three sections and between the deposits exposed on the footwall and hangingwall of the fault. Mst: mudstones; Sst: sandstones; Congl: conglomerates; F: fine; M: medium; C: coarse.

The inter-eruptive Polymictic Alluvial Units originated as passive infill which occurred after the degradational stage, indicating a hiatus in the pyroclastic supply rate. The development of a deeply incised topography is a feature typically occurring after the ending of an eruptive event (Smith, 1991). The great volume of material delivered during the eruptive periods modified the sedimentary systems, raising the local base level. The subsequent reestablishment of the original gradients causes the incision of deep, narrow valleys over the syn-eruptive units (Smith, 1987) and the deposition of inter-eruptive units in an alluvial context, which constitutes bypass zones for the sediment transported by stream flows (Blair and McPherson, 1994).

5.2. Case II: Lacustrine Units deposited on top of large Pyroclastic Units and covered by basaltic Lava Flow Units

The inter-eruptive Lacustrine Units are deposited on top of thick accumulations of ignimbrites found at the middle section of the Precuyano fill (Figs. 3C and 9). This stratigraphic interval is distinguished by the presence of large ignimbrite units which extend across the whole Sierra de Chacaico depocentre (Franzese et al., 2007; Figs. 3B, C and 9). The sudden accumulation of large amounts of material by the pyroclastic density currents implies the levelling of the pre-existent topography caused by the combination of volcanic edifices and the landscape created by the extensional structures. As a result, the accommodation space was choked and the topographic gradients lowered, generating appropriate conditions for the development of the shallow lacustrine units. Carbonate precipitation is incompatible with the existence of abundant debris in the system. Hence, calcareous beds are related to periods of low delivery of clasts and water with appropriate physicochemical conditions for the precipitation of carbonates. These lacustrine facies correspond to environments characterised by low energy, shallow water bodies, with good sunlight penetration and a constant oxygen supply (Wright and Burchette, 2002). On the other hand, periods of greater delivery of clastic material into the sedimentary systems are represented by the reworked volcaniclastic deposits. The coexistence of both types of deposits shows variations in the delivery of materials to a sedimentary system during inter-eruptive conditions. It is important to highlight that the Lacustrine Units are covered by basaltic lava flows spatially related to internal to the depocentre rift-faults (Figs. 3B, C and 9), indicating their contemporary nature with the precipitation of the carbonate beds. The occurrence of algal carbonates in alkaline lakes related to the extensional structures is a typical feature in rifts with active volcanism, where the associated basic volcanic flows provide a good medium for the silicification of carbonates (Renaut and Owen, 1988; Schubel and Simonson, 1990; Tiercelin et al., 1993; Krainer and Spötl, 1998; Renaut et al., 1998; Renaut et al., 2002).

5.3. Accumulation models for the syn-rift succession

The different types of relationships between syn-eruptive and inter-eruptive units established in this study depend on the distinct signature of the preceding syn-eruptive periods. Pyroclastic Units are much thicker and better distributed in Case II than in Case I, indicating eruptive events of a different magnitude and volume. Accordingly, the low-volume eruptive periods in Case I originated thin ignimbrites and syn-eruptive Volcaniclastic Alluvial Units which failed to fill the available accumulation space, occupying restricted areas along valleys

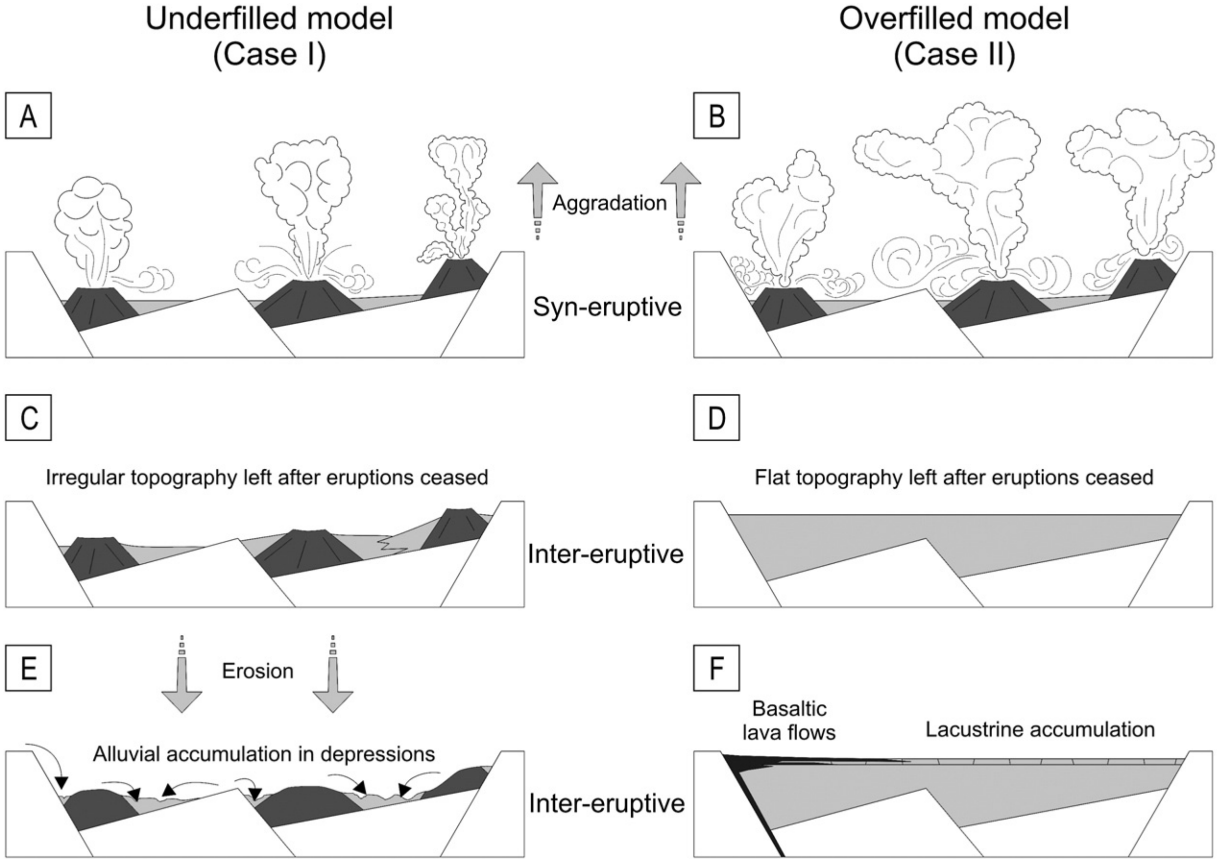

Fig. 10. Schematic evolutionary models for Case I and Case II. (A and B) Pyroclastic eruptions characterise syn-eruptive periods. The overall constant aggradation dominates the syn-eruptive stages. The magnitude of pyroclastic activity is greater in Case II (B) than in Case I (A). The volume of material shed is smaller in Case I (C) than in Case II (D). During the subsequent inter-eruptive periods, the sedimentary systems readjust to the newly created conditions. In Case I, the sedimentary systems respond to the elevation in base level by eroding the landscape and depositing the inter-eruptive sequence in the generated depressions (E). In Case II, the greater volume of material delivered by the previous eruptions drapes the original landscape, flattening the surface and choking the existent sedimentary systems (F).

and flanks of the previous positive features in the landscape (i.e., volcanic edifices and uplifted faulted blocks). The deposition of ignimbrites and Volcaniclastic Alluvial Units was enough to raise the local base levels of the sedimentary environment, but not enough to fill the whole depocentre. As a consequence, degradation events occurred and an irregular topography was developed on top of the previous syn-eruptive units. High-gradient Polymictic Alluvial Units were deposited in the incisions left. By contrast, extensive voluminous ignimbrites characterise the Pyroclastic Units in Case II. Large-volume explosive eruptions on the Sierra de Chacaico depocentre were interpreted as their main source (Franzese et al., 2007). Volcanic activity in extensional environments typically generates caldera-like settings where the deposition of large-volume ignimbrites is accommodated through rapid large-scale subsidence. This combination of magma chamber emptying and extensional faulting is not only observed in purely orthogonal depocentres but also in transtensional ones (Moore and Kokelaar, 1997, 1998; Aguirre-Díaz et al., 2008; Petrinovic et al., 2010). Although the stratigraphic analysis reveals a tectonic origin for the extensional faults in the depocentre (Franzese et al., 2007; Fig. 9), marked thickness changes in the large Pyroclastic Units are observed across the extensional faults, suggesting the superposition of a volcanotectonic subsidence component to the accommodation of such large ignimbrites (Muravchik et al., 2008). Therefore, the Lacustrine Units represent the readjustment of the hydrological system to the extensive low gradient area left on top of the ignimbrites and the modification of the drainage network, causing a dramatic depocentre-scale effect (Franzese et al., 2007).

As a result, two conceptual models of accumulation can be envisaged to describe the examples considered above (Fig. 10). Case I is an instance of an underfilled model where the amount of syn-eruptive volcaniclastic material created is relatively small. Inter-eruptive processes consist in extensive erosion as a consequence of the readjustment of the sedimentary systems to the new base levels and deposition. On the other hand, Case II is an example of an overfilled model in which the volume of syn-eruptive pyroclastic material was so large that it covered the whole area, completely choking the accumulation space of the depocentre and levelling the previous topography. Thus, an inter-eruptive lacustrine environment was originated due to the established low gradients.

It is important to note that cases like the ones described above are expected to happen several times during the lifespan of a volcanic rift. Their occurrence and frequency will depend on the volcanic activity rate, frequency and duration and its interaction with the evolving extensional structures. The duration of the initial volcanic rift for the whole Neuquén Basin is broadly constrained to the Upper Triassic–Lower Jurassic. However, little is known yet about its duration at a depocentre-scale level. Only few radiometric dates exist (e.g. Schiuma and Llambías, 2008; Spalletti et al., 2010) and the resolution of the fossil content is not enough to better constrain the duration of the accumulation processes occurring inside each depocentre (e.g. Spalletti et al., 1991, 2010). Furthermore, silicification and other typical diagenetic processes in volcanic settings commonly prevent any finding of palinomorphs in the Precuyano Cycle deposits (Muravchik and Franzese, 2005). Further work is needed on this matter in order to better compare the duration of the volcanic events and the different fault growth phases. What becomes clear from this particular study is that the effect of the volcanic activity must be taken into account in any extensional basin as its magnitude can be comparable to the most active tectonic structure and its stratigraphic expression is quite dramatic.

6. Conclusions

The volcanic syn-rift fill (i.e., the Precuyano Cycle) in the Sierra de Chacaico area, Neuquén Basin, Argentina, constitutes a complex arrangement of units of very diverse nature, accumulated in a geological setting where active volcanism and extensional tectonics occurred. Five units were identified: Lava Flow/Shallow Intrusion Units, Pyroclastic Units, Volcaniclastic Alluvial Units, Polymictic Alluvial Units and Lacustrine Units. The compositional characteristics of the Precuyano fill indicate a strong relationship with the volcanic environment. However, the genetic interpretation of the different accumulation units has made it possible to identify certain periods mainly dominated by sedimentary processes and other periods dominated by volcanic-related processes. Thus, the syn-eruptive units could be distinguished from the inter-eruptive units within the syn-rift succession.

Two conceptual models were defined for the interaction between syn-eruptive and inter-eruptive units: the 'underfilled model' and the 'overfilled model'. In the first model, the material supplied to the depocentre during the eruptive events is not enough to bury the topography completely, causing the development of high-gradient alluvial systems during the following inter-eruptive period. In the second model, large ignimbrites associated with volcanotectonic subsidence choked the accumulation space in the depocentre during large-volume eruptive events, originating low-gradient sedimentary systems during the subsequent inter-eruptive periods.

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References

Aguirre-Díaz, G.J., Labarthe-Hernández, G., Tristán-González, M., Nieto-Obregón, J., Gutiérrez-Palomares, I., 2008. The ignimbrite flare-up and graben caldera of the Sierra Madre Occidental, México. In: Gottsmann, J., Martí, J. (Eds.), Caldera Volcanism: Analysis, Modeling and Response. Elsevier, pp. 143–174.

Bahk, J.J., Chough, S.K., 1996. An interplay of syn- and inter-eruption depositional processes: the lower part of the Jangki Group (Miocene), SE Korea. Sedimentology 43, 421–438.

Blair, T.C., McPherson, J.G., 1994. Alluvial fans and their natural distinction from rivers based on morphology, hydraulic processes, sedimentary processes, and facies assemblages. J. Sediment. Res. 64, 450–489.

Branney, M.J., Kokelaar, B.P., 2002. Pyroclastic Density Currents and the Sedimentation of Ignimbrites. Geological Society, Memoir, 27. London, 144 pp.

Brantley, S.R., Waitt, R.B., 1988. Interrelations among pyroclastic surge, pyroclastic flow, and lahars in Smith Creek valley during first minutes of 18 May 1980 eruption of Mount St. Helens, USA. Bull. Volcanol. 50, 304–326.

Cas, R.A.F., Wright, J.W., 1987. Volcanic Successions: Modern and Ancient. Chapman and Hall, London. 528 pp.

Cole, R.B., Ridgway, K.D., 1993. The influence of volcanism on fluvial depositional systems in a Cenozoic strike-slip basin, Denali fault system, Yukon Territory, Canada. J. Sediment. Res. 63, 152–166.

D'Elia, L., Franzese, J.R., 2005. Caracterización litológica y estructural de ignimbritas precuyanas en la sierra de Chacaico, Neuquén, con énfasis en su potencial petrolero. VI Congreso de Exploración de Hidrocarburos, actas, trabajos técnicos, reservorios y desarrollo.

Dupraz, C., Visscher, P.T., Baumgartner, L.K., Reid, R.P., 2004. Microbe–mineral interactions: early carbonate precipitation in a hypersaline lake (Eleuthera Island, Bahamas). Sedimentology 51, 745–765.

Fisher, R.V., 1961. Proposed classification of volcaniclastic sediments and rocks. Geol. Soc. Am. Bull. 72, 1409–1414.

Franzese, J.R., 1995. El Complejo Piedra Santa (Neuquén, Argentina): parte de un cinturón metamórfico neopaleozoico del Gondwana suroccidental. Rev. Geol. Chile 22, 193–202.

Franzese, J.R., Spalletti, L.A., 2001. Late Triassic–early Jurassic continental extension in southwestern Gondwana: tectonic segmentation and pre-break-up rifting. J. S. Am. Earth Sci. 14, 257–270.

Franzese, J.R., Veiga, G.D., Schwarz, E., Gómez-Pérez, I., 2006. Tectonostratigraphic evolution of a Mesozoic graben border system: the Chachil depocentre, southern Neuquén Basin, Argentina. J. Geol. Soc. (Lond.) 163, 707–721.

Franzese, J.R., Veiga, G.D., Muravchik, M., Ancheta, D., D' Elia, L., 2007. Estratigrafía de 'sin-rift' (Triásico Superior-Jurásico Inferior) de la Cuenca Neuquina en la sierra de Chacaico, Neuquén, Argentina. Rev. Geol. Chile 34, 49–62.

Gawthorpe, R.L., Leeder, M.R., 2000. Tectono-sedimentary evolution of active extensional basins. Basin Res. 12, 195–218.

Gifkins, C., Herrmann, W., Large, R., 2005. Altered volcanic rocks. A Guide to Description and Interpretation. CODES — Centre for Ore Deposit Research, University of Tasmania. 286 pp.

Gulisano, C., 1981. El Ciclo Cuyano en el norte de Neuquén y sur de Mendoza. VIII Congreso Geológico Argentino, actas, vol. 3, pp. 579–592.

Gulisano, C.A., Gutiérrez Pleimling, A.R., Digregorio, R.E., 1984. Esquema estratigráfico de la secuencia jurásica del oeste de la provincia del Neuquén. IX Congreso Geológico Argentino, actas, vol. 1, pp. 236–259.

Haughton, P.D.W., 1993. Simultaneous dispersal of volcaniclastic and non-volcanic sediments in fluvial basins: examples from the Lower Old Red Sandstone, east-central Scotland. In: Marzo, M., Puigdefabregas, C. (Eds.), Alluvial Sedimentation. Spec. Pub. International Association of Sedimentologists, vol. 17. Blackwell, Oxford, pp. 451–471.

Howell, J.A., Flint, S.S., 1996. A model for high resolution sequence stratigraphy within extensional basins. In: Howell, J.A., Aitken, J.F. (Eds.), High Resolution Sequence Stratigraphy: Innovations and Applications. Spec. Pub. Geological Society, vol. 104. Blackwell, London, pp. 37–49.

Howell, J.A., Schwarz, E., Spalletti, L.A., Veiga, G.D., 2005. The Neuquén Basin: an overview. In: Veiga, G.D., Spalletti, L.A., Howell, J.A., Schwarz, E. (Eds.), The Neuquén Basin, Argentina: A Case Study in Sequence Stratigraphy and Basin Dynamics. Spec. Pub. Geological Society, vol. 252. Blackwell, London, pp. 1–14.

Jackson, C.A.L., Gawthorpe, R.L., Carr, I.D., Sharp, I.R., 2005. Normal faulting as a control on the stratigraphic development of shallow marine syn-rift sequences: the Nukhul and Lower Rudeis Formations, Hammam Faraun fault blocks, Suez Rift, Egypt. Sedimentology 52, 313–338.

Krainer, K., Spötl, C., 1998. Abiogenic silica layers within a fluvio-lacustrine succession, Bolzano Volcanic Complex, northern Italy: a Permian analogue for Magadi-type cherts? Sedimentology 45, 489–505.

Leanza, H.A., 1990. Estratigrafía del Paleozoico y Mesozoico anterior a los Movimientos Intermálmicos en la comarca del Cerro Chachil, provincia del Neuquén. Rev. Asoc. Geol. Argentina 45, 272–299.

Leanza, H.A., Blasco, G., 1990. Estratigrafía y ammonites pliensbachianos del área del Arroyo Ñireco, Neuquén, Argentina, con la descripción de Austromorphites gen. nov. Rev. Asoc. Geol. Argentina 45, 159–174.

Legarreta, L., Uliana, M.A., 1996. The Jurassic succession in west-central Argentina: stratal pattern, sequences and paleogeographic evolution. Palaeogeogr. Palaeoclimatol. Palaeoecol. 120, 303–330.

McArthur, A.M., Cas, R.A.F., Orton, G.J., 1998. Distribution and significance of crystalline, perlitic and vesicular textures in the Ordovician Garth Tuff (Wales). Bull. Volcanol. 60, 260–285.

McPhie, J., Doyle, M., Allen, R., 1993. Volcanic Textures: A Guide to the Interpretation of Textures in Volcanic Rocks. CODES — University of Tasmania. 198 pp.

Miall, A.D., 2006. The Geology of Fluvial Deposits: Sedimentary Facies, Basin Analysis, and Petroleum Geology. Springer. 582 pp.

Moore, I., Kokelaar, P., 1997. Tectonic influences in piecemeal caldera collapse at Glencoe Volcano, Scotland. J. Geol. Soc. (Lond.) 154, 765–768.

Moore, I., Kokelaar, P., 1998. Tectonically controlled piecemeal caldera collapse: a case study of Glencoe volcano, Scotland. Geol. Soc. Am. Bull. 110, 1448–1466.

Morley, C.K., 1999. Patterns of displacement along large normal faults: implication for basin evolution and fault propagation, based on examples from East Africa. AAPG Bull. 83, 613–634.

Morley, C.K., Ngenoh, D.K., Ego, J.K., 1999. Introduction to the East African Rift System. In: Morley, C.K. (Ed.), Geoscience of Rift Systems — Evolution of East Africa: AAPG Studies in Geology, 4, pp. 1–18.

Muravchik, M., Franzese, J.R., 2005. Carbonatos lacustres someros en las facies volcaniclásticas del Precuyano de la Sierra de Chacaico, Neuquén. XVI Congreso Geológico Argentino, actas, vol 3, pp. 111–116.

Muravchik, M., D'Elia, L., Bilmes, A., Franzese, J.R., 2008. Caracterización de los depocentros de rift (Ciclo Precuyano) aflorantes en el sector sudoccidental de la Cuenca Neuquina, Argentina. VII Congreso de Exploración y Desarrollo de Hidrocarburos, actas, pp. 457–470.

Orchuela, I.A., Ploszkiewicz, J.V., Viñes, R., 1981. Esquema estratigráfico de la secuencia jurásica del oeste de la provincia del Neuquén. VIII Congreso Geológico Argentino, actas, vol. 3, pp. 281–293.

Orton, G.J., 2002. Volcanic environments. In: Reading, H.G. (Ed.), Sedimentary Environments: Processes, Facies and Stratigraphy. Blackwell Science, Oxford, pp. 485–567.

Petrinovic, I.A., Martí, J., Aguirre-Díaz, G.J., Guzmán, S., Geyer, A., Salado Paz, N., 2010. The Cerro Aguas Calientes caldera, NW Argentina: an example of a tectonically controlled, polygenetic collapse caldera, and its regional significance. J. Volcanol. Geotherm. Res. 194, 15–26.

Pierson, T.C., Janda, R.J., Thouret, J.C., Borrero, C.A., 1990. Perturbation and melting of snow ice by the 13 November eruption of the Nevado Del Ruiz, Colombia, and consequent mobilization, flow and deposition of lahars. J. Volcanol. Geotherm. Res. 41, 17–66.

Quane, S.L., Russell, J.K., 2005. Ranking welding intensity in pyroclastic deposits. Bull. Volcanol. 67, 129–143.

Renaut, R.W., Owen, R.B., 1988. Opaline cherts associated with sublacustrine hydrothermal springs at Lake Bogoria, Kenya Rift valley. Geology 16, 699–702.

Renaut, R.W., Jones, B., Tiercelin, J.-J., 1998. Rapid in situ silicification of microbes at Loburu hot springs, Lake Bogoria, Kenya Rift Valley. Sedimentology 45, 1083–1103.

Renaut, R.W., Jones, B., Tiercelin, J.-J., Tarits, C., 2002. Sublacustrine precipitation of hydrothermal silica in rift lakes: evidence from Lake Baringo, Central Kenya Rift Valley. Sediment. Geol. 148, 235–257.

Riding, R., 2000. Microbial carbonates: the geological record of calcified bacterial-algal mats and biofilms. Sedimentology 47 (Suppl. 1), 179–214.

Riggs, N.R., Hurlbert, J.C., Schroeder, T.J., Ward, S.A., 1997. The interaction of volcanism and sedimentation in the proximal areas of a Mid-Tertiary volcanic dome field, Central Arizona, USA. J. Sediment. Res. 67, 142–153.

Runkel, A.C., 1990. Lateral and temporal changes in volcanogenic sedimentation; analysis of two Eocene sedimentary aprons, Big Bend region, Texas. J. Sediment. Petrol. 60, 747–760.

Schiuma, M., Llambías, E.J., 2008. New ages and chemical analysis on Lower Jurassic volcanism close to the Huincul High. Neuquén. Rev. Asoc. Geol. Argentina 63, 644–652.

Schlische, R.W., 1992. Structural and stratigraphic development of the Newark extensional basin, eastern North America: evidence for the growth of the basin and its bounding structures. Geol. Soc. Am. Bull. 104, 1246–1263.

Schubel, K.A., Simonson, B.M., 1990. Petrography and diagenesis of cherts from Lake Magadi, Kenya. J. Sediment. Petrol. 60, 761–766.

Shultz, A.W., 1984. Subaerial debris-flow deposition in the upper Paleozoic Cutler Formation, Western Colorado. J. Sediment. Petrol. 54, 759–772.

Smith, R.L., 1960. Zones and zonal variation in welded ash-flows. US Geol. Surv. Prof. Pap., 354-F, pp. 149–159.

Smith, G.A., 1986. Coarse-grained nonmarine volcaniclastic sediment — terminology and depositional process. Geol. Soc. Am. Bull. 97, 1–10.

Smith, G.A., 1987. The influence of explosive volcanism on fluvial sedimentation: the Deschutes Formation (Neogene) in Central Oregon. J. Sediment. Petrol. 57, 613–629.

Smith, G.A., 1988. Neogene synvolcanic and syntectonic sedimentation in central Washington. Geol. Soc. Am. Bull. 100, 1479–1492.

Smith, G.A., 1991. Facies sequences and geometries in continental volcaniclastic sediments. In: Fisher, R.V., Smith, G.A. (Eds.), Sedimentation in Volcanic Settings. Spec. Pub. SEPM (Society Economic Paleontologists and Mineralogists), vol. 45. SEPM, Tulsa, OK, pp. 109–121.

Smith, G.A., Lowe, D.R., 1991. Lahars: volcano-hydrologic events and deposition in the debris flow-hyperconcentrated flow continuum. In: Fisher, R.V., Smith, G.A. (Eds.), Sedimentation in Volcanic Settings. Spec. Pub. SEPM (Society Economic Paleontologists and Mineralogists), vol. 45. SEPM, Tulsa, OK, pp. 59–70.

Spalletti, L.A., Arrondo, O.G., Morel, E.M., Ganuza, D.G., 1991. Evidencias sobre la edad Triásica de la Formación Lapa en la región de Chacaico, Provincia del Neuquén. Rev. Asoc. Geol. Argentina, 46, pp. 167–172.

Spalletti, L.A., Franzese, J.R., Morel, E., D'Elia, L., Zúñiga, A., Fanning, C.M., 2010. Consideraciones acerca de la sedimentología, paleobotánica y geocronología de la Formación Piedra del Águila (Jurasico Inferior, Neuquén, Republica Argentina). Rev. Asoc. Geol. Argentina 66, 305–313.

Streck, M.J., Grunder, A.L., 1995. Crystallization and welding variations in a widespread ignimbrite sheet, the Rattlesnake Tuff, eastern Oregon, USA. Bull. Volcanol. 57, 151–169.

Tiercelin, J.J., Pflumio, C., Castrec, M., Boulègue, J., Gente, P., Rolet, J., Coussement, C., Stetter, K.O., Huber, R., Buku, S., Mifundi, W., 1993. Hydrotermal vents in Lake Tanganyka, East African Rift system. Geology 21, 499–502.

Vergani, G.D., 2005. Control estructural de la sedimentación jurásica (Grupo Cuyo) en la Dorsal de Huincul, Cuenca Neuquina, Argentina. Modelo de falla lístrica rampa-plano, invertida. Bol. Inf. Petrol. 1, 32–42.

Vergani, G.D., Tankard, A.J., Belotti, H.J., Weisink, H.J., 1995. Tectonic evolution and paleogeography of the Neuquén basin, Argentina. In: Tankard, A.J., Suárez, S.R., Welsink, H.J. (Eds.), Petroleum Basins of South America: Memoir Am. Assoc. Petrol. Geol., vol 62, pp. 382–402.

Volkheimer, W., 1973. Palinología estratigráfica del Jurásico de la Sierra de Chacai Co y adyacencias (cuenca Neuquina, Republica Argentina). 1-Estratigrafía de las formaciones Sierra Chacai Co (Pliensbachiano), de Los Molles (Toarciano, Aaleniano), Cura Niyeu (Bayociano) y Lajas (Caloviano inferior): Rev. Asoc. Geol. Argentina, 10, pp. 105–129.

Walton, A.W., Palmer, B.A., 1988. Lahar facies of the Mount Dutton Formation (Oligocene–Miocene) in the Mrysvale Volcanic Field, southwestern Utah. Geol. Soc. Am. Bull. 100, 1078–1091.

Waresback, D.R., Turbeville, B.N., 1990. Evolution of a Plio–Pleistocene volcanogenic-alluvial fan: the Puye Formation, Jemez Mountains, New Mexico. Geol. Soc. Am. Bull. 102, 283–314.

Weaver, C.E., 1931. Paleontology of the Jurassic and Cretaceous of West Central Argentina. Memoir of the University of Washington, 1, pp. 1–469.

Wright, V.P., Burchette, T.P., 2002. Shallow-water carbonate environments. In: Reading, H.G. (Ed.), Sedimentary Environments: Processes, Facies and Stratigraphy. Blackwell Science, pp. 325–394.

Young, M.J., Gawthorpe, R.L., Sharp, I.R., 2003. Normal fault growth and early syn-rift sedimentology and sequence stratigraphy: Thal Fault, Suez Rift, Egypt. Basin Res. 15, 479–502.

Ziegler, P.A., Cloething, S., 2004. Dynamic processes controlling evolution of rifted basins. Earth Sci. Rev. 64, 1–50.