Impact of volcanism on the sedimentary record of the Neuquén rift basin, Argentina: towards a cause and effect model

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ABSTRACT

The analysis of volcano-sedimentary infill in sedimentary basins constitutes a challenge for basin analysis and hydrocarbon exploration worldwide. In order to understand the contribution of volcanism to the sedimentary record in rift basins, we study the Jurassic effusive-explosive volcanic infill of an inverted extensional depocentre at the Neuquén Basin, Argentina. A cause and effect model that evaluates the relationship between volcanism and sedimentation was devised to develop a conceptual model for the tectono-stratigraphic evolution of this volcanic rift basin. We show how the variations in the volcanism, coupled with the activity of extensional faults, determined the types of volcanic edifices (i.e., composite volcanoes, graben-calderas, and lava fields). Volcanic edifices controlled the stacking patterns of the volcanic units as well as sedimentary systems. The landform of the volcanic edifices, as well as the styles and scales of the eruptions governed the sedimentary input to the basin, setting the main variables of the sedimentary systems, such as provenance, grain size, transport and deposition and geometry. As a result, the contrasting volcanioclastic input, from higher volcaniclastic input to lower volcanioclastic input, associated with different subsidence patterns, determined the high-resolution synrift infill patterns of the extensional depocentre. The cause and effect model presented in this study isolates the variables of the volcanic environments that control the sedimentary scenarios. We suggest that, by adjusting the first order input parameters of the model, these cause and effect scenarios could be adapted to similar rift basins, in order to establish predictive facies models with stratigraphic controls, and the impact of volcanism on their stratigraphic records.

INTRODUCTION

The development of volcanic activity synchronous with some of the evolutionary stages of rift basins (e.g., East African Rift, South Atlantic basins, Red Sea Basin, the Mesozoic Western Gondwana basins; Morley, 1999; Ziegler & Cloetingh, 2004; Chorowicz, 2005; Bosworth et al., 2005; Ramos, 2009; Ebinger & Scholz, 2012) and extensional intra-arc basins (e.g., Intra-arc Taupo Volcanic Zone; Wilson et al., 2009; Rowland et al., 2010; Downs et al., 2015) is a widely recognized phenomenon. However, most tectono-stratigraphic works on extensional basins that addressed high-resolution sedimentary models, were performed on successions with null concomitant volcanism (e.g., Leeder & Gawthorpe, 1987; Schlische, 1991, 1992; Leeder et al., 1996; Schlische & Anders, 1996; Ravns & Steel, 1998; Gawthorpe & Leeder, 2000). The mainstreams of research that took into account volcanic rift successes were focused on stratigraphic and chronostratigraphic schemes (e.g., Baker & Mitchell, 1976; Baker, 1986; Ebinger et al., 1989; Skilling, 1993; Moore & Kokelaar, 1997; D’Elia & Martí, 2013; Chambeafort et al., 2014; Downs et al., 2015) or the relationships between tectonic, magmatic and volcanic processes, such as the relation between tectonic structures and the magmatic system, the types and rate of subsidence (i.e., tectonic or volcano-tectonic subsidence), and what controls the development of different volcanic edifices (e.g., composite volcanoes and calderas) and their magmatic plumbing systems (e.g., Ebinger et al., 1989; Martí, 1991; Skilling, 1993; Moore & Kokelaar, 1997, 1998; Ebinger & Casey, 2001; Spinks et al., 2005; Wolfenden et al., 2005; Aguirre-Díaz et al., 2008; Ferguson et al., 2010; Rowland et al., 2010; Ebinger & Scholz, 2012;
Acocella, 2014). Together, these studies illustrate fundamental feedbacks between tectonic, magmatic and volcanic process in rift basins, and show how related basin subsidence affects sedimentary processes. However, they do not consider how the construction of volcanic edifices that form a continuum with sedimentary scenarios, as well as variations in the style, volume and frequency of volcanism, affect the high-resolution architecture of the rift basins. Although, the high potential for hydrocarbon exploration in volcanic and associated sedimentary rocks in marine and continental basin infills has recently been asserted (e.g., Hinterwimmer, 2002; Sruoga et al., 2004; Lenhardt & Götz, 2011; Caineng et al., 2013), and reservoir rocks in volcano-sedimentary successions have been reported in several sedimentary basins worldwide (Mathisen & McPherson, 1991; Pángaro et al., 2002; Sruoga et al., 2004; Feng, 2008; Legarreta et al., 2008; Pángaro et al., 2009), the difficulty in establishing predictable facies models (Németh & Martin, 2007) and the large variation in the petrophysical properties of volcanic and volcanlastic successions (Mathisen & McPherson, 1991; Sruoga et al., 2004) have contributed to the lack of information on the relationship between volcanism and sedimentation with regard to basin studies, in particular in extensional basins.

Volcanic activity has an effect of great magnitude on basins and sedimentary systems. In the long-term, as well as the short-term, volcanism affects the main variables of a sedimentary basin, which are taken into account in basin analysis, such as the uplift, subsidence and supply rate of sediments (Allen & Allen, 2013). The nature of volcanic edifices, whether as constructional features (e.g., composite volcanoes) or substrate collapse (e.g., caldera), affects and superimposes the tectonic relief (Thouret, 1999) and subsidence (Van Wyk de Vries & Merle, 1996; Moore & Kokelaar, 1997, 1998) within the sedimentary basins. In the short-term, the influence of volcanic activity on sedimentary basins is substantial due to the volume of the supplied material and its rate of supply, which is generally orders of magnitude bigger than those of non-volcanic sedimentary systems (Fisher & Smith, 1991; Mathisen & McPherson, 1991; Thouret, 1999; Manville et al., 2009). For instance, the average present-day discharge of the Brahmaputra River is \( 0.67 \, \text{km}^3 \, \text{year}^{-1} \) (Goodbred & Kuehl, 2000), whereas the 1991 eruption of Mount Pinatubo or the 2008 eruption of the Chaitén volcanoes delivered about \( 5-8 \, \text{km}^3 \) in a few days (cf. Scott et al., 1996a, b; Lara, 2009), causing the complete modification of the sedimentary environment (Hayes et al., 2002; Umazano et al., 2014). Volcanic products have a strong aggradational tendency (Smith, 1987; 1991; Haughton, 1993; Martina et al., 2006; Paredes et al., 2007), whether as positive topographic features (e.g., Palmer & Neall, 1991; Palmer et al., 1993; Karátson & Németh, 2001; Zanchetta et al., 2004) or filling pre-existing depressions (i.e., overfilled state; Busby & Bassett, 2007; Muravchik et al., 2011). During volcanic eruptions, the depositional landscape may be modified in a matter of only hours or days (e.g., Cas & Wright, 1987; Thouret, 1999; Davidson & de Silva, 2000; Németh & Martin, 2007). Such capacity to drastically modify the sedimentary conditions, as well as the basin configuration, leaves an unambiguous imprint in the stratigraphic record, which leads to the misunderstanding of the volcanic successions in the framework of basin analysis.

The present study includes a volcano-tectono-stratigraphic analysis of the Lower Jurassic exposures of the Sañicó half-graben in the Neuquén Basin, Argentina. It focuses on how the coupled activity of volcanism and extensional tectonics determined not only the 4D evolution of the rift depocentre, but also, on how the external controls interacted to set the high-resolution architecture of different syn-rift stages. The combination of uplift and tectonic deformation during Andean orogeny, as well as the Quaternary fluvial incision, facilitates exposure of the whole hanging-wall and footwall stratigraphy in the rift basin, both along- and across-strike, and the identification of the tectonic structures. Detailed geochemical, petrographic, petrologic data, as well as a tectono-stratigraphic model of this basin can be found in D’Elia et al. (2012a, b); D’Elia & Marti (2013); and D’Elia et al. (2015). Here, we integrate this dataset with new observations to perform the following comprehensive sequenced analysis: (i) analysis of genetically related lithofacies (grouped by unconformity) in order to determine the depositional

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Fig. 1. Location map showing the distribution of the surface and subsurface rift depocentres in the Neuquén Basin, Argentina (modified from Franzese & Spalletti, 2001). Location of the study area is highlighted with a rectangle.
Neogene (Uliana & Legarreta, 1993; Vergani 1995; Howell et al., 2005). The distribution of the basin fill can be divided into two distinctive regions: a western region, comprising the Andean Neuquén and Mendoza provinces, in which basin inversion caused the partial uplift and exposure of the basin infill (Fig. 1), and an eastern region, where most of the sedimentary record lies in the subsurface (e.g., Vergani et al., 1995; Howell et al., 2005). Surface and subsurface studies show that the rift segments are elongated troughs, 20–150 km long and 10–50 km wide, commonly composed of depocentres with half-graben geometries that display alternating polarity (Vergani et al., 1995; Cristallini et al., 2006). The initial half-graben depocentres were associated with profuse volcanic activity (Franzese & Spalletti, 2001; D’Elia et al., 2012a) that generated thick subaerial volcanic successions (Precuyano Cycle; Gulisano et al., 1984). The syn-rift contains a large volume of lava flows and pyroclastic deposits (D’Elia et al., 2012a), associated with volcaniclastic and epiclastic sedimentary environments (Franzese et al., 2006, 2007; Mur-avchik et al., 2011, 2014; D’Elia et al., 2012b). This rift phase was followed by a diachronic Upper Triassic–Lower Jurassic regional marine transgression (Guyano Cycle; Groeber, 1946) that flooded the Neuquén basin under the last syn-rift to post-rift stages (Vergani et al., 1995; D’Elia et al., 2015).

GEOLOGICAL SETTING

The Neuquén Basin is located on the eastern side of the Andean margin in central Argentina, and more restrictedly in Chile, between 32° and 40° S latitude (Fig. 1). The Neuquén Basin experienced a complex tectonic history that includes: (i) an initial extensional tectonic phase that developed in the palaeo-Pacific margin of Gondwana from the Late Triassic to the Early Jurassic; (ii) subduction-related thermal subsidence until the middle Cretaceous, in which punctuated episodes of localized inversion occurred; and (iii) a major basin inversion related to the Andean contractional tectonics, which occurred from the Late Cretaceous to the Neogene (Uliana & Legarreta, 1993; Vergani et al., 1995; Legarreta & Uliana, 1996; Franzese & Spalletti, 2001; Howell et al., 2005).

The pre-rift units in the study area (Fig. 2) are formed by igneous-metamorphic rocks, including the Cushamen Formation the Mamil Choique Formation of upper Palaeozoic age (Varela et al., 1991). The syn-rift megasequence (Precuyano Cycle; Gulisano et al., 1984) in the southern part of the Neuquén Basin is composed of three sequences (Fig. 2) that were accommodated in different extensional depocentres during the rifting evolution (Fig. 3; D’Elia et al., 2015). The first syn-rift sequence corresponds to a thin succession of fluvial siliciclastic deposits of Upper Triassic age (i.e., Paso Flores Formation; Morel & Ganuza, 2002), preserved in N-S-oriented depocentres (Figs 2 and 3). The second syn-rift sequence in the study area comprises a thick Lower Jurassic (i.e., Sinemurian age; Stipanicic et al., 1968) succession of lava flows and ignimbrites along with sedimentary deposits, grouped into the Sañicó Formation (Fig. 2; Stipanicic et al., 1968). This unit was accommodated in two NE-SW-oriented half-grabens, such as the Sañicó and the Piedra del Águila extensional depocentres (Fig. 3). The last syn-rift sequence, which is transitional with the post-rift phase of the basin, corresponds to the lower–upper Plio-Pleistocene marine succession (Damborenea & Mancenido, 1993) of the Piedra Pintada Formation (Stipanicic et al., 1968; Stipanicic, 1969). Marine deposits consist of a 250-m-thick succession of
massive to millimetre-scale laminated mudstones with ammonite and bivalve fossils, and plant remains. The boundary between the syn-rift and the transitional post-rift units is either a conformable surface or an angular unconformity, representing a short depositional hiatus (D’Elia et al., 2012b).

The Sañicó depocentre is a well-preserved uplifted rift depocentre of the Neuquén basin, where the complete volcanic syn-rift sequence can be analysed. During the Miocene, the Sañicó depocentre, as part of the North Patagonian Andes, was affected by contractual tectonics (Bilmes et al., 2013; Ramos et al., 2014). Even though it experienced partial inversion and uplifting, its original geometry can still be clearly recognized by stratigraphic correlation of the syn-rift units, revealing an overall half-graben geometry (Figs 3 and 4). The boundaries of the depocentre are presently exposed as NE-SW-trending basement-cored anticlines (Fig. 3c). The hanging-wall blocks are defined by mainly NE- and ENE-oriented extensional and partially inverted normal faults. These normal faults are spaced 0.1–3 km apart, ranging from 3 to 8 km in length, and show a predominant dip-slip sense of movement and a displacement ranging from tens to several hundred metres (Figs 3 and 4; D’Elia et al.,

Fig. 3. (a) Map of the major structures recognized at surface and subsurface of the southern part of the Neuquén rift basin. Location of the Sañicó depocentre is highlighted with a rectangle. Modified from Vergani et al. (1995), Vergani et al. (2005), D’Elia & Martí (2013) and D’Elia et al. (2015). (b) Geologic map and stratigraphy of the study area. (c) Cross-section of the Sañicó depocentre.
The syn-kinematic sequence of the Sañicó depocentre is the Sañicó Formation. It shows a large thickness change within the depocentre, with successions reaching a thickness of 1700 m thick at the NW margin of the depocentre, which contrasts with the 600- to 0-m-thick successions observed at its SE margin (Fig. 4d and e). Based on previous U–Pb SHRIMP geochronological data (Spalletti et al., 2010) and on the palaeontological analysis carried out with high-resolution ammonite biozonation in the lower marine deposits of the Piedra Pintada Formation (Damborenea & Mancenido, 1993), the Sañicó Formation is constrained between 191.7 ± 2.8 Ma and ~190.8 ± 1.0 Ma (International Chronostratigraphic Chart, 2015). Therefore, the syn-rift interval analysed is constrained from the middle to upper Sinemurian, with a maximum depositional lapse of approximately 4.5 Myr.

**METHODOLOGY AND TERMINOLOGY**

Detailed geological mapping, and sedimentary and stratigraphic logging were performed in order to determine the lateral and vertical variations of the syn-rift units of the Sañicó depocentre (Fig. 4). Seventeen log sections were logged at 1:100 scale (Fig. 4). To address a volcanotectono-stratigraphy analysis, the identification of unconformity-bounded assemblages of strata was performed, allowing the recognition of different relatively conformable successions of genetically related units deposited during distinct tectonic-volcanic events. Facies analysis of both volcanic and sedimentary units allowed the characterization of the main processes of transport and accumulation. Rock body geometry was assessed by analysing photomosaics and fence diagrams of the exposures to identify bounding surfaces and stratal patterns. Facies associations were determined and used to establish the key volcanic and sedimentary elements involved in the accumulation of the studied units and to characterize the accumulation environment. The relative abundance of lava, pyroclastic and sedimentary rocks and their minimum volumes were estimated by weighting the thickness variations deduced from the stratigraphic logs and their areal correlations. Provenance analysis of conglomerate was performed in the field by counting 200 clasts along a square matrix adjusted according to the grain size of the deposits at each counting site. In order to provide a detailed quantification of the compositional variations observed, sample stations were arranged following a vertical trend along logs in the sedimentary sectors. Sandstone
Facies were sampled and provenance analysis was determined by point counting under microscope.

In the present work, we use the term volcaniclastic as defined by White & Houghton (2006), to refer only to volcanic clasts directly related to volcanism, and not using it as a more general term applicable to all deposits containing clasts with a volcanic heritage (cf., Fisher, 1961). Thus, deposits of clasts resulting from weathering and erosion of previous volcanic rocks are named here epiclastic rocks/deposits. The term primary volcaniclastic rock (e.g., ignimbrite) is applied to every type of deposits resulting directly from a volcanic eruption (White & Houghton, 2006), which are described using the grain size classification introduced by Fisher & Schmincke (1984), such as ash, tuff, tuff breccia. The deposits originated by secondary surface processes of transport and deposition, with either volcaniclast or epiclast provenance, are described using grain size classification of classic siliciclastic sedimentology (i.e., conglomerate, sandstone, siltstone).

Facies analysis allowed determination of facies models corresponding to different types of volcanic edifices. We use the definition of Németh & Kereszturi (2015) for “monogenetic volcano” to refer to a volcanic edifice with a small cumulative volume that has been built up by one or many discontinuous, small eruptions occurring over a short timescale, whereas the term “polygenetic volcano” is applied to a volcanic edifice with a large cumulative volume that has been built up by many discontinuous, small or large eruptions occurred in a longer timescale (ka to Ma). In this sense, monogenetic or polygenetic successions were defined according to 3D volcanic facies associations (volume) and the evaluation of the stacking patterns, taking into account the boundary strata or unconformities surfaces (time).

SYN-RIFT SEQUENCE

Based on the intra-depocentre discontinuity surfaces and stacking patterns of the Sañicó syn-rift, this syn-kinematic sequence was separated into three sections, which in turn correspond to three accumulation stages: the lower, middle and upper stages (Fig. 5; D’Elia et al., 2012b; D’Elia & Martí, 2013). Volcanic rocks are volumetrically the most important units in the lower and middle stages, while they are less abundant in the upper stage of the syn-rift sequence (Fig. 4). Each stage is characterized by a particular volcanic environment, associated with contrasting sedimentary units.

Lower stage accumulation units

The lower stage comprises units accumulated during the earliest syn-rift phases (Fig. 4). During this stage, syn-rift deposits show a clear wedge shape, limited by faults, with a maximum thickness of up to 1100 m (Fig. 4). Lower stage accumulation units were mainly preserved in the hanging-wall blocks in a highly compartmentalized depocentre. Lower stage rocks are characterized by lava units, which form up to 61 % of the total volume of this phase (Fig. 4c), associated with volcaniclastic sediments and minor silicic pyroclastic deposits. All units are intruded by andesitic dykes, and silicic necks and cryptodomes (Fig. 4a). Although volcanic compositions vary from andesites to rhyodacites, andesitic lava successions constitute the dominant component.

Andesite lava units show particular thickness changes along and across the depocentre. Close to the depocentre boundary, at the footwall blocks, the volcanic products of this stage are characterized by andesitic lava flows up to 120 m thick, ranging from mainly sheet coherent andesitic lava flows to minor autobrecciated lavas (Fig. 6a and b). Dike swarms parallel to the border system faults occur, along with isolated plug- and dome-like intrusion bodies (Figs 4a and 6e) associated with penetrative hydrothermal alteration. At the hanging wall, transverse to the faulted margins of the depocentre, lava facies occur as mainly coherent lava flows with sheet geometries of tens of metres thick. Towards the interior of the depocentre, lava facies gradually change to lenticular or tabular lava flows with abrupt lateral lithofacies changes, characterized by autoclastic carapace breccia facies consisting of slabby or rubbly oxidized blocks with a sparse interstitial matrix (Fig. 6c and f). The proportion of autobreccias/coherent lava facies increases from the boundary (where vents are located, see D’Elia & Martí, 2013) towards the interior of
the depocentre, developing into block-lava flows (Fig. 6b). Pyroclastic density current (PDC) deposits and conglomerate and breccia sedimentary deposits occur as isolated bodies intercalated in lava successions (Figs 4 and 6d). PDC deposits appear either as thin decimetre-thick bodies or as large metre-thick lenticular bodies. They have an acid composition, a lapilli-tuff lithology with vitroclastic textures and a low grade of welding (Fig. 6d). Conglomerate and breccia sedimentary bodies, which show either tabular or lenticular geometries, prevail towards the interior of the depocentre and the top of the lower stage syn-rift succession (Fig. 4). Based on the analysis of the volcanic units, this stage was interpreted (Fig. 4a; D’Elia et al., 2012b; D’Elia & Martī, 2013) as originating from volcano composite edifices located at the boundaries of the depocentre (Fig. 5a). From the vents to the distal position, lava flow units cannot be traced along great distances and show angular discordance. Facies change, combined with the abrupt lateral variation in lava units towards distal zones—which may indicate channel-confined, low aspect ratio lavas typical of steep sides common in volcanic edifices—, records the occurrence of central/proximal volcanic cone units to middle/distal volcanic cone units (see Hackett & Houghton, 1989; Davidson & de Silva, 2000).

Two sedimentary facies associations characterize the lower stage accumulation units: on the one hand, tabular volcaniclastic megabreccias and conglomerates and, on the other, channelized volcaniclastic conglomerates and sandstones (Fig. 7). The tabular volcaniclastic megabreccias and conglomerates are composed of unsorted megabreccias and poorly sorted conglomerates, forming laterally extensive bodies that can be up to 3 km long, 3 km wide and 200 m thick (Figs 4, 7 and 8a). The megabreccias are clast- to matrix-supported massive deposits that compose successions up to 170 m thick. They are composed of angular to subangular andesitic clasts with sizes ranging from a few microns up to 20 m in length. The fabric of the
megabreccias varies from domains of jigsaw-fit texture to domains where the complete rotation and transport of clasts occurred (Fig. 9a and b). These characteristics, together with the composition of the clasts, suggest that the megabreccias derived from volcanic avalanche flows (Siebert, 1984; Glicken, 1991; Schneider & Fisher, 1998; Ui et al., 2000; Clavero et al., 2002; Zanchetta et al., 2004; Bernard et al., 2009), in which fragmentation and dispersion mechanisms were originated by high-speed granular mass movements (Coussot & Meunier, 1996) that behaved as dilatant fluids (Schneider & Fisher, 1998). Conglomerate facies are poorly sorted, medium- to coarse-grained, sandy matrix-supported with andesitic clasts (Fig. 8b, d and e). They generally develop as lobate or tabular bodies 2–5 m thick and 50–150 m long at distal positions on top of the megabreccia facies (Fig. 8b). Their massive nature and the complete lack of tractional structures are interpreted as the result of non-cohesive debris-flow deposition (Shultz, 1984; Pierson et al., 1990; Coussot & Meunier, 1996).

The channelized volcaniclastic conglomerate and sandstone facies association is constituted by horizontally stratified pebbly sandstones, massive to horizontally stratified conglomerates and, to a lesser extent, massive coarse-grained conglomerates and planar to trough cross-stratified sandstones (Figs 7, 8c, f and g). It occurs as large channels and gully-fill bodies 10–50 m thick and 100–300 m wide that eroded previous syn-rift deposits (Fig. 7). The horizontally stratified pebbly sandstones appear as moderately sorted tabular bodies 5–20 cm thick with sharp or transitional lower boundaries and common normal grading (Fig. 8g), and are interpreted as sandy hyperconcentrated-flow deposits (Smith, 1986; Smith & Lowe, 1991; Orton, 2002). The massive to horizontally stratified conglomerates are poorly sorted polymodal and clast-supported deposits, whose pebbles are aligned with their longest axes parallel to stratification (Fig. 8f). They occur as tabular or lenticular bodies decimetres to 1 m thick with transitional to sharp contacts. These features are indicative of gravelly hyperconcentrated-flow deposits (Smith, 1986; Smith & Lowe, 1991; Orton, 2002). The massive coarse-grained conglomerates are poorly sorted with a sandy matrix, occurring in tabular bodies up to 5 m thick, which is indicative of non-cohesive debris-flow deposition (Shultz, 1984; Pierson et al., 1990; Coussot & Meunier, 1996). The planar to trough cross-stratified sandstones occur as moderately well sorted, thin (1 m) and narrow (up to 10 m) bodies filling gullies eroded into the horizontally stratified pebbly sandstones (Fig. 8c). This relationship indicates overland floods associated with small shallow channels (see Blair, 2000). The channelized volcaniclastic conglomerates and sandstones show a conspicuous coarsening-upwards arrangement of facies from sandstones at the base towards conglomerates at the top. Among these deposits, the clast composition varies from andesitic lava clasts to polymictic clasts characterized by a mixture of provenances: andesitic lavas, pyroclastic materials and igneous-metamorphic clasts with an abundance that ranges from 5 to 30 % (Fig. 7).

The sedimentary facies associations that developed in the lower stage syn-rift are the result of alluvial systems (Blair & McPherson, 1994), reflecting different stages of degradation of volcanic edifices (Palmer & Neall, 1991). The tabular volcaniclastic megabreccia and conglomerate facies association indicates gravitational collapses in proximal settings of high-relief andesitic edifices. Absence of deep incisions between volcanic debris avalanche and debris-flow deposits, together with their monomictic nature, suggests that the conglomerates resulted from reworking and redeposition of the megabreccias (see Palmer et al., 1991; Bernard et al., 2009). The channelized volcaniclastic conglomerate and sandstone facies association corresponds to the deposition of high-density flows with more mixed sources, comprising heterogeneous syn-rift components as well as pre-rift lithologies. This observation indicates the establishment of longer periods of erosion and degradation that favoured more integrated drainages affecting both volcanic and structural highs (see Palmer & Neall, 1991; Zanchetta et al., 2004).

**Middle stage accumulation units**

In the middle stage, which is laterally continuous, a 400 m thick sequence of silicic PDC deposits occurs, constituting more than 85 % of the volume of the middle stage succession (Fig. 4c). The PDC deposits represent the emplacement of two large-scale ignimbrite units, of around 20 km long and hundreds meters thick, throughout the whole depocentre (Fig. 10a). The ignimbrite units were only identified inside the depocentre. They overlie the previous units throughout a sharp regional stratigraphic unconformity (Fig. 10b). Pyroclastic units are intercalated with volcaniclastic deposits and they are also intruded by domes associated with the internal faults of the depocentre (Fig. 4a, d and e).

The two rhyolitic/rhyodacite ignimbrites (Fig. 4e) are characterized by lapilli-tuff facies with massive or oriented fabrics, presenting moderate welding and particular post-depositional deuteric alteration (Fig. 10b). The two ignimbrite units are continuous along the interior of the depocentre and separated by thin tuffaceous volcaniclastic deposits (Fig. 4). These ignimbrites were only preserved inside the depocentre, showing facies and thickness variations. They are mostly developed in the interior zones of the depocentre and either gradually decrease in thickness, from hundreds of meters to tens of meters, or pinch out abruptly towards the depocentre margins, with important thickness changes related to extensional faults (Figs 4 and 10a). Intra-formational breccia facies occur in the hanging-wall blocks of the interior faults, at the base of the ignimbrite units. These facies were interpreted by D’Elia & Marti (2013) as co-ignimbrite lag deposits, deposits often form during phases of caldera-collapse (i.e., Lipman, 1976) when caldera faulting occurs to accommodate a loss
of mass (Figs 4 and 10d). The facies changes and intrusive acid domes (Fig. 10e) are related to the faults of the depocentre. This allows the definition of the location of another magma plumbing system, which is also located at the boundary of the depocentre (Fig. 4; see D’Elia & Martí, 2013). Therefore, ignimbrite units were associated
with a significant volcano-tectonic subsidence episode, in which they overfilled the depocentre in a very short-time, and are considered as representing a (half) graben-caldera stage (Fig. 5b; D’Elia & Martí, 2013).

The sedimentary units that developed during the middle stage correspond to amalgamated volcaniclastic tabular bodies 1–50 m thick and up to 300 m in lateral extent (Figs 4 and 11), which are intercalated between ignimbrite units (Figs 4, 11a and b). They are composed of horizontally stratified pebbly tuffaceous sandstones, massive tuffaceous sandstones and, to a lesser extent, massive pumiceous breccias (Fig. 11b, c and d). The horizontally stratified pebbly tuffaceous sandstones are moderately sorted and form tabular bodies 5–30 cm thick with sharp contacts. The massive tuffaceous sandstones, which in some cases include some pumice lapilli fragments, are moderately sorted and clast-supported, deposited in tabular bodies 10–30 cm thick (Fig. 11d). The massive pumiceous breccias are fine-grained, clast-supported with polymodal sorting. They occur as tabular bodies 5–30 cm thick that in some cases develop normal to inverse-normal grading (Fig. 11b). The compositional analysis of these facies indicates an exclusive pyroclastic provenance with minimum transport (Fig. 9d). The sedimentary textures and structures observed suggest deposition from sandy/gravelly sheet flows in hyperconcentrated flow conditions and subordinate debris flows (Smith, 1986; Smith & Lowe, 1991). Thus, these lithofacies suggest a close relationship between sediment gravity flow mechanisms of transport and deposition, and high rates of pyroclastic supply (Fisher & Smith, 1991; Smith & Lowe, 1991; Smith, 1991), which in conjunction with the absence of degradational cycles suggests a low-slope alluvial context in a high aggradational context with short depositional times (Smith, 1987; Smith, 1991; Fisher & Smith, 1991).

**Upper stage accumulation units**

In the upper stage, andesitic lava flow successions associated with coarse- to fine-grained epiclastic units and carbonate rocks occur. All these units are asymmetrically distributed within the depocentre (Fig. 4). Deposits of this phase are only preserved inside the depocentre. The volume of the volcanic products within the syn-rift sequence decreases to 55 % during this stage (Fig. 4c). The lower part of the upper stage syn-rift shows thickness changes across the interior faults and pinch out of the lava and sedimentary units. Towards the top, the lava and sedimentary units are laterally continuous, with subtle thickness changes across the interior faults. The andesite lava units occur as individual sheets that have been mapped along up to 7 km in length and are 5–30 m thick.

![Fig. 8.](image-url)
Intercalated with the lava flows, thin sedimentary units are recorded. Most of the andesite sheets consist of a simple flow in which the tops and bottoms of individual lavas are remarkably regular and sub-parallel over distances of 5–7 km (Fig. 12a, b and c). The frequent occurrence of conformable, bedded sedimentary rocks between flows that show conspicuous vein structures and filled vesicles at the base of the flows indicates that the lavas were dominantly sub-horizontal and developed close to the depositional time of the sedimentation (Fig. 12d). Although lateral terminations of individual flows are locally exposed, highly discordant contacts are rare. Therefore,
the upper stage volcanic units and sedimentary deposits were developed in a low gradient equilibrium (Fig. 5c; D’Elia et al., 2012b; D’Elia & Martí, 2013). All of the above-mentioned features indicate the occurrence of andesitic lava fields aggrading in a low-relief environment, formed by the coalescence of lava flows erupted from several centres or fissures in the extensional depocentre (see Petterson et al., 1992).

The sedimentary elements emplaced during the upper stage (Figs 4, 13 and 14a) consist of tabular and wedge-shaped bodies that are 50 m thick and up to 6 km long, grading from conglomerate-dominated facies in proximal areas to siltstones interbedded with limestones towards their distal reaches. The most proximal deposits to the depocentre margins display a distinctive vertical arrangement of the facies. At the base, they are characterized by poorly to moderately sorted, clast-supported fine to medium conglomerates forming tabular beds with irregular bases and a thickness of up to 1.5 m (Fig. 4). They are massive or stratified, either cross-stratified or horizontally stratified, with pebble long axes aligned parallel to the stratification. Moderately to well-sorted clast-supported sandstones appear intercalated as cross-stratified lenticular and tabular beds with concave or sharp flat erosive bases. Towards the middle part of the succession, deposits become dominated by moderately sorted clast-supported, fine to medium conglomerates organized in large-scale cross-beds, dipping 21° on average and grouped in 2- to 5-m-thick tabular packages (Figs 13 and 14b and c). At the top of the proximal succession, the facies consists of massive and horizontally stratified, fine to medium conglomerate tabular bodies 0.3–1 m thick. To a lesser degree, horizontally stratified–laminated sandstones are found intercalated (Fig. 13). The compositional analysis reveals a polymictic volcanic provenance of the epiclastic deposits, (i.e., intermediate to acidic lavas and pyroclastic materials) with a low proportion of igneous-metamorphic clasts (Fig. 9e). The facies described above grade distally into stratified or massive fine-grained sandstones and reddish horizontally laminated siltstone beds 1–3 cm thick (Fig. 14h and i), interbedded with highly silicified 5- to 20-cm-thick limestone beds. There is a very low preservation of primary sedimentary features in the carbonate facies. However, microbial lamination can be detected in some cases (Figs 9f and 14j).

The lithologies described and their particular stacking pattern are consistent with those observed in coarse-grained delta systems (e.g., Postma, 1983; McPherson et al., 1987; Nemec, 1990; Backert et al., 2010). The basal
part of the succession is thus interpreted to correspond to the toeset, with transitional characteristics between the coarser-grained foreset facies to the fine-grained prodelta facies. The absence of tractional structures in the conglomerate facies suggests their deposition from sediment gravity flow processes, whereas the stratified sandstone facies indicate underflow deposition caused mainly by low-density turbidity processes (e.g., Reading & Collinson, 2002; Blair & McPherson, 2008; Backert et al., 2010). The large-scale cross-bedded conglomerate packages occurring in the middle section represent different foreset progradation cycles, deposited by sediment gravity flows (Postma, 1983; Nemec, 1990; Backert et al., 2010). The massive and horizontally stratified conglomerates at

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Fig. 11. Middle stage sedimentary units. (a) Outcrop-scale photograph of the syn-eruptive ash/pumiceous-rich volcanioclastic sandstone and breccia deposits (I, intracaldera ignimbrite units; SED, syn-eruptive deposits). (b) Sedimentary logs showing the syn-eruptive ash/pumiceous-rich volcanioclastic sandstone and breccia deposits (see Figs 4 and 10 for the location of the sedimentary sections and the detailed correlation panel showing the relationships of the upper stage units). (c) Photograph of massive pumiceous breccias interbedded with massive to horizontally stratified pebbly tuffaceous sandstone, formed by hyperconcentrated flows. (d) Detail of massive pumiceous breccias with transitional contacts and normal grading.
the top are interpreted as gravelly hyperconcentrated flow deposits (Smith, 1986; Smith & Lowe, 1991) and the stratified and laminated sandstones as deposits from upper-flow-regime sheet floods (Blair & McPherson, 1994) or very shallow stream flows associated with small channels (Blair, 2000). Both facies constitute the topset of this coarse-grained delta system. The overall predominance of sheet floods and hyperconcentrated flow deposits in the topset is characteristic of alluvial dominated environments (sensu McPherson et al., 1987; Blair & McPherson, 1994).

The horizontally laminated siltstone facies represents deposition from suspension fallout or low-velocity flow and, together with the limestones, it constitutes the prodelta setting. The development of algal limestones requires aqueous environments of relatively low energy and moderate clastic input, under conditions of CaCO₃ precipitation (e.g., Riding, 2000; Tucker, 2001; Dupraz et al., 2004). Their presence indicates water depths within the photic zone range (~30 m) (e.g., Talbot & Allen, 2002), which is also compatible with the scale of the foreset cycles (up to 4 m thick), indicating the shoal-water profile (Postma, 1990) of this coarse-grained delta system.

### DISCUSSION

The analysis of the Sañicó half-graben infill succession carried out in this work, reveals how volcanism, in close relation with the tectonics, had different impacts on the stratigraphy and stacking patterns of that rift basin. In order to conceptualize and understand this volcano-sedimentary basin infill, we propose a cause and effect model (Fig. 15) in which the accurate evaluation of the volcanic activity (cause) makes it possible to understand the sedimentary systems that occurred (effect) in this rift basin. First, we will discuss the high-resolution facies models in the different contexts of the volcaniclastic input, taking into account the external controls on the infill, and then, we will discuss the cause and effect model and the implications for evaluating the impact of volcanism on the stratigraphic record of the rift basin.

### High-resolution facies model and external controls on the infill

According to the syn-rift sequence analysis carried out in this study, the lower and middle stages will be

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**Fig. 12.** Upper stage volcanic units. (a) Detailed correlation panel showing the relationships of the upper stage units. (b) Outcrop-scale photograph of the lacustrine deposits interbedded with lava flow units. (c) Outcrop-scale photograph of the sheet lava flows base, showing veins and filled vesicles formed by interaction between lava flows and wet sediment. (d) Detail of veins and filled vesicles shown in (c).
analysed within a high volcaniclastic input context, while the upper stage will be analysed within a lower volcaniclastic input context (Fig. 15). From the perspective of the basin analysis, we define the volcaniclastic input as the supply rate of volcaniclastic materials to the basin, which is governed by the complex...
interaction of several parameters, such as the landform of the volcanic edifices, the eruption styles, and scales and frequencies of the volcanic eruptions (effusive or explosive), for which it exists a fundamental link between frequency and scale of the eruptions (Parfitt & Wilson, 2008). It is important to remark that the style and scale of volcanic eruptions were obtained from volume estimates, dimensions and genetic analysis of the units (Fig. 4), whereas the chronologic framework was constrained from an allostratigraphic approach. Therefore, the analysis of genetic units and their boundary surfaces (discontinuities and surfaces) are assumed to have time-stratigraphic significance. From high resolution stratigraphy point of view, the volcanic and sedimentary processes involve 2–3 orders of temporal magnitude less than the error margin of the radiometric dating. For instance, caldera cycles for systems worldwide are around 4–20 kyr to 300–500 kyr (Costa, 2008), the constructional phases of a ring plain of composite volcanoes may take around 1 kyr (Palmer et al., 1993), and the eruptive frequencies of monogenetic volcanic fields are <1 kyr (Németh & Kereszturi, 2015), whereas
the average error margin of the U–Pb SHRIMP radiometric data for the syn-rift in the Neuquén basin is from 2.8–0.26 Ma, on average 1 Ma (e.g., Schiuma & Llambías, 2008; Spalletti et al., 2010; Leanza et al., 2013).

**High volcaniclastic input context**

The volcanic successions associated with the lower stage of the Sañicó depocentre suggest that they were related to composite volcanoes. This type of volcanic edifice implies strongly aggradational features that can reach high altitudes (Thouret, 1999; Davidson & de Silva, 2000; Németh & Martin, 2007), developing steep slope gradients. Their growth in height and areal development reflected the high rate of production of volcanic material. The supply of volcaniclastic material in this first stage was mainly provided by the emplacement of blocky lava flows and pyroclastic deposits, but also the erosion and degradation of the composite volcanoes, resulting in thick, extensive volcaniclastic aprons (e.g., Palmer & Neall, 1991; Palmer et al., 1991, 1993; Thouret, 1999; Orton, 2002; Németh & Martin, 2007). The landscape resulting from the growth of composite volcanoes typically has a high gradient, with different processes affecting the stability of the volcano slopes. This condition is made evident by the development of volcanic avalanche flow deposits in the lower stage (Fig. 15), in which the distribution of the sedimentary facies and sedimentary units was also controlled by the geometry of the depocentre. The volcanic debris avalanche deposits are preserved in the hanging-wall fault of the depocentre, where andesitic lava flows, intrusive domes and associated volcaniclastic deposits prevail at the base (Figs 4 and 7). The facies distribution suggests that the asymmetric shape of the volcanoes, caused by the tectonic structures and the polarity of the depocentre, controlled the occurrence and emplacement of the collapses. This situation agrees with analogue models and natural examples in which the close relationship between the structurally controlled asymmetry of the volcano and the position of the collapse can be observed (Van Wyk De Vries & Francis, 1997; le Corvec & Walter, 2009; Wooller et al., 2009). Subsequently, the short-lived resedimentation of the avalanche deposits originated debris flow deposits with andesitic provenance (see Bernard et al., 2009). Thus, the type of volcanism and depocentre position of the volcanic edifices controlled the main variables of the sedimentary environments. These variables include the distribution and dimension of the sedimentary environments, the high-gradient processes of transport and sedimentation, the coarse-grained size, and even the andesitic lithology of the sedimentary unit occurring in inter-eruptive stages (Fig. 15). Regarding the channelized volcaniclastic conglomerates and sandstone facies, large entrenchment channels associated with a passive infill suggest large degradational episodes of the volcanic relief (e.g., Palmer et al., 1993; Zanchetta et al., 2004). The predominantly andesitic composition suggests that flank lithology and local drainage networks controlled these units (Fig. 15). The drainage network was slightly integrated and dominated by the proximal conditions surrounding the volcanoes and, to a lesser extent, by epiclastic products originating from the erosion of the faulted pre-rift blocks. The vast dominance of andesitic lithoclasts among the deposits indicates that the degree of pre-rift exposure was very restricted. It is interpreted that this was not related to the small degree of uplift of faulted blocks, but to the aggrading nature of the composite volcanoes that grew over the pre-rift basement. The large amounts of sand-sized lava fragments originating from coherent or blocky lava flow units suggest that long-lived, inter-eruptive degradational processes took place (e.g., Brown & Bell, 2007). In this context, the volcanic landscape, both during eruptive and inter-eruptive episodes, was the main provider of volcaniclastic material to the sedimentary environment with a predominance of gravity flows as the main mechanisms of transport and deposition of the sediments. In this case, the inter-eruptive lapses controlled the degree of erosive relief of the sedimentary units, as well as their grain size (i.e., the longer the lapse, the smaller the grain size of the deposits; Fig. 15).

During the middle stage, the Sañicó depocentre evolved into a graben-collapse caldera scenario (D’Elia & Martí, 2013), produced by the emptying of a shallow magma chambers and the consequent collapse of the magma chamber roofs (e.g., Aguirre-Díaz et al., 2008). Collapse calderas provide the largest supply of volcaniclastic material in the shortest time (Lipman, 2000), saturating the capacity of the sedimentary agents to transport and redeposit the pyroclasts. In this particular case, the substantial synchronous subsidence undergone by the floor of the caldera trapped a big proportion of the supplied pyroclasts in the form of two main ignimbrites. In addition, the emplacement of these thick intra-caldera ignimbrites covered the previous topography and generated low-gradient environments (e.g., Németh & Martin, 2007; Manville et al., 2009). Overall, the volcanic activity during the formation of a caldera dominates the depositional environment, and the sedimentary units found within the caldera fill tend to constitute extremely thin and laterally restricted deposits (Fig. 15). Therefore, in this context, the large explosive eruption events triggered a phase of ash/pumiceous-rich volcaniclastic syn-eruptive sedimentation. The low-gradient relief resulting from the nearly instantaneous massive and widespread emplacement in the depocentre of a large volume of pyroclastic material (see Muravchik et al., 2011) caused low-slope conditions that favoured the formation of volcaniclastic hyperconcentrated flows after their deposition (Fig. 15). A short syn-eruptive lapse set a non-integrated drainage network that drove the thin, limited lateral distribution of the sedimentary units, which—combined with a high aggradational rate—prevented the occurrence of major erosive surfaces and degradation cycles (see Fisher & Smith, 1991; Fig. 15). A central point to the high-resolution stratigraphy of the middle stage is that, although the
volume of extra-caldera ignimbrites can also be significant (Cas & Wright, 1987), their preservation in the record of ancient extensional basins is interpreted to be relatively small, as the areas external to the depocentre constitute the footwalls of the border fault systems and, as such, are subjected to uplift and erosion or even further tectonics (e.g., Marti, 1991). This observation is substantial when comparing the example studied here with younger and better preserved examples (e.g., Taupo Volcanic Zone; Rowland & Sibson, 2001; Spinks et al., 2005; Gravley et al., 2007; Wilson et al., 2009; Rowland et al., 2010; Allan et al., 2012; Chambeafort et al., 2014; Downs et al., 2015).

During periods of high volcanioclastic input context (i.e., the lower and middle stages), a polygenetic, comosite volcano and graben-caldera were formed in association with either extensional tectonic subsidence or volcanotectonic (caldera collapse) subsidence, respectively (Marti, 1991; Moore & Kokelaar, 1997, 1998; Fig. 15). The interpretation of the boundary surfaces between different volcanic and sedimentary units marks diverse orders of depositional hiatus, evidencing the complex superposition in space and time of these units. Differences in eruptive style, frequency, and volume of the eruptions from composite volcanoes and graben-calderas, determined different kind of “effects” on the sedimentary scenarios, in particular related to the grain sizes of the material supplied and their mechanisms of transport and deposition, and the sizes of the sedimentary units (Fig. 15). Thus, the high volume of pyroclastic materials mainly provided coarse silt to fine gravel particle sizes (Vessell & Davies, 1981; Smith, 1991; Németh, 2010), and autoclastic lavas feed boulder and gravel size particles (see Hackett & Houghton, 1989; McPhie et al., 1993;
Brown & Bell, 2007), whereas the steep topography resulting from high aggradational volcanic edifices and/or the large volume of volcaniclastic material supplied to the depocentre led to mechanisms of transport and deposition dominated by gravity flow processes (Fig. 15). Regarding the scale of the sedimentary units, making a comparison between lower and upper middle units, the genetic interpretation of their boundary surface indicates that they have a positive correlation with the scale of the volume of the volcaniclastic input and a negative correlation with the lapse between the eruptions (Fig. 15).

**Lower volcaniclastic input context**

During the upper stage the input of volcanism to the sedimentation in the Sánicó depocentre decreased significantly. The most important change, with regards to the previous stages was the decrease or absence of eruptriverelated volcaniclastic deposits, and the development of large-extended, coherent, tabular lava flows that blanket the depocentre in low relief conditions (evidenced by lava units with remarkably regular and sub-parallel contacts over long distances and lack of avalanches deposits). These lava flows were emplaced from different vents, thus reflecting more the existence of a monogenetic volcanic field than that of a composite volcano. As a consequence, there was a low volcaniclastic input to the depocentre. This is important to remark because the total eruptive volume of a whole volcanic field may be comparable with the total volume of eruptive products of a polygenetic composite volcano (Németh, 2010), although the impact of the volcaniclastic supply to the sedimentary environment is low, resulting in low potential of preservation in the sedimentary record (White, 1991). Monogenetic volcanic fields are composed of individual, short-lived volcanoes that are commonly small in eruptive volume (see Walker, 2000; Németh & Martin, 2007; Cabrera & Caffé, 2009; Németh, 2010; Nishikia et al., 2011). The higher eruption frequency during this volcanic scenario could have been buffered in the record by the low volume of these eruptions and the change in vent locations over time, forming the typical dispersed patterns of volcanoes characteristic of volcanic fields (Németh & Kereszturi, 2015). For this reason, the boundary surfaces between lava field products and stabilized delta-lacustrine environments, mark longer lapses than in higher volcanic input conditions. The paucity in which the lavas were spilt inside the depocentre allowed the drainage system to accommodate to the new topographic conditions over longer periods of time, enabling a better integrated drainage system to evolve in the area.

The “effect” was a significant reduction in the influence of volcanism as an allocyclic control over the sedimentary systems, causing the high facies polarity—which is uncommon in volcano-dominated sedimentary environments (Németh & Martin, 2007)—, the polymictic provenance of the fan–delta facies, and the grain size (from gravel to siltstone), which were driven by weathering/erosion cycles of previous rocks. The widespread lava flow emplacement inside of the depocentre originated a new base level and low gradient conditions (adjusted to the landform of the lava field) and the relief was set by the tectonic processes. Therefore, the nature of the transport and depositional processes of the sedimentary environment were not different to those developed in non-volcanic rift depocentres (cf. Gawthorpe & Leeder, 2000; Fig. 15). In this syn-rift stage the type and the evolution of this volcanic environment reduced the impact of volcanism on the sedimentary record with respect to other variables, such as the climate, tectonics or bedrock lithology (see Reading & Level, 2002). This is evident in the development of limestones and stromatolitic facies in such starved depocentre conditions (e.g., Riding, 2000; Dupraz et al., 2004).

**Towards a cause and effect model to evaluate impact of volcanism on the sedimentary record**

In recent decades, most of the studies addressing volcanic influence over sedimentary environments have focused on non-compartmentalized basins with a large areal distribution (e.g., foreland basin or linked rift basins; e.g., Smith, 1987; Smith 1991; Haughton, 1993; Martina et al., 2006; Paredes et al., 2007) or non-restricted volcanic aprons (e.g., Walton & Palmer, 1988; Palmer & Neall, 1991; Palmer et al., 1993; Karátson & Németh, 2001; Zanchetta et al., 2004). Such studies have documented the controls of volcanic activity on sedimentation in either proximal areas or proximal to distal areas, based on provenance (Smith, 1988; Cole & Ridgway, 1993; Haughton, 1993; Riggs et al., 1997), mechanisms of transport and deposition (Brantley & Waits, 1988; Walton & Palmer, 1988; Bahk & Chough, 1996), and aggradational vs. degradational behaviour of the sedimentary units (Smith, 1987; Bahk & Chough, 1996; Riggs et al., 1997). As a result of such significant works, several models have been proposed to understand the mechanism of transport and deposition, aggradational vs. degradational behaviour, as well as the distribution and size of the volcano-related sedimentary environments. These models have been devised for several types of volcanoes and volcanic settings, as well as for several types of basins. However, these models may seem disconnected from each other, leading to a misinterpretation from the standpoint of basin analysis. The cause and effect model that we propose for the Sánicó basin, represents a “dynamic” scheme to explain the influence of the volcanic activity (cause) on the sedimentary regime of the basin (effect), for a specific accommodation space (i.e., tectonic or volcano-tectonic—caldera collapse—subsidence; Fig. 15). This evolution is similar to that observed in other extensional basins (Sierra Madre (Mexico), Aguirre-Díaz et al., 2008; Pyrenees (Spain), Marti, 1991; Glencoe (Scotland), Moore & Kokelaar, 1998; Taupo Volcanic Zone; (New Zeland), Spinks et al., 2005; Chambefort et al., 2014; Downs

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et al., 2015). In fact, many of the fundamental relationships established in this work, such as (i) coeval faulting and volcanism, (ii) monogenetic and polygenetic volcanoes associated with regional tectonic structures, have been found in other rift systems (e.g. Southern Red Sea, Main Ethiopian Rift, Iceland; see Ebinger et al., 1989; Gudmundsson, 2000; Acocella et al., 2002; Acocella, 2007; Spinks et al., 2005; Abebe et al., 2007; Ebinger & Casey, 2001; Wollenden et al., 2004, 2005; Rowland et al., 2010; Ebinger & Scholz, 2012). Nevertheless, it is not the aim of this work to propose a universal high resolution facies model for rift basins worldwide. Despite the similarities we may find, each case may have particular aspects that may imply important differences in the dynamics of each basin. The approach followed in this study may applied to other cases in order to facilitate obtaining a cause–effect model that could help to quantify the influence of volcanism on the sedimentary record of the basin. Essentially, the model presented in this study identifies the variables that control the influence of volcanic and tectonic activity on the sedimentary scenarios and the resulting stratigraphic record of a rift depocentre. Thus, adjusting the first order input parameters of the model this can be adapted to other similar rift basins, in order to establish predictive models on the impact of volcanism on their stratigraphic records.

**CONCLUSIONS**

Even though most rift basins may be associated with volcanism at some point of their evolution, stratigraphic analysis and high-resolution stratigraphy models do not always include volcanism as a major control over the sedimentary system. In such cases, the theoretical knowledge of the basin-fill architecture is mainly based on their 3D structural configuration, evolution of their drainage system, climate changes and variations of the base level or sea/lake level. Comparing with previous studies on volcanic rift basins where the focus is made on more specific aspects, the present work offers a multidisciplinary approach provides a holistic view of the interplay of tectonics, volcanism and sedimentation in the evolution of the Sañicó rift basin. We have considered volcanic and sedimentary units as a part of the continuum that took place in a particular space (i.e., accommodation space originated by tectonic or volcanotectonic subsidence). Also, we have recognized depocentre-scale unconformities that group packages of volcanic and sedimentary units genetically associated with the different tectonic and volcanic events. Finally, we have established high-resolution facies models with accurate identification of the stratigraphic controls. The volcaniclastic input conditions, from lower input to higher volcaniclastic input, was determined by the complex interaction of several parameters of the volcanic scenario, such as the landform of the volcanic edifices, as well as the eruption styles, scales and frequencies of the volcanic eruptions, which, in turn, set the parameters that control the internal dynamics of sedimentary environments. In order to obtain a high-resolution stratigraphic model capable of evaluating the tectono-stratigraphic evolution of the volcanic infill, we have proposed a cause and effect model assessing the relationship between volcanism and sedimentation, which can be easily generalized for other similar basins, in order to devise predictive models applied to the exploration and development of natural resources.

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**REFERENCES**

Abbe, B., Acocella, V., Korme, T. & Ayalew, D. (2007) Quaternary faulting and volcanism in the Main Ethiopian Rift. *J. Afr. Earth Sci.*, 48, 115–124.

Acocella, V. (2007) Understanding caldera structure and development: an overview of analogue models compared to natural calderas. *Earth Sci. Rev.*, 85, 125–160.

Acocella, V. (2014) Structural control on magmatism along divergent and convergent plate boundaries: overview, model, problems. *Earth Sci. Rev.*, 136, 226–288.

Acocella, V., Korme, T., Salvini, F. & Funiciello, R. (2002) Elliptic calderas in the Ethiopian Rift: control of pre-existing structures. *J. Volcanol. Geoth. Res.*, 119, 189–203.

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

Allan, A.S.R., Wilson, C.J.N., Millet, M.-A. & Wysoczanski, R.J. (2012) The invisible hand: tectonic triggering and modulation of a ryholitic supereruption. *Geology*, 40, 563–566.

Allen, P.A. & Allen, J.R. (2013) Basin Analysis. Principles and Application to Petroleum Play Assessment, 1019 pp. Wiley-Blackwell, Chichester.

Backert, N., Ford, M. & Malaret, F. (2010) Architecture and sedimentology of the Kerinitis Gilbert-type fan delta, Corinth Rift, Greece. *Sedimentology*, 57, 543–586.
Baker, B.H. (1986) Tectonics and volcanism of the southern Kenya Rift Valley and its influence on rift sedimentation. In: *Sedimentation in the African Rifts* (Ed. by Frostick L.E., Renault R.W., Reid I. & Tiercelin J.J.) Geol. Soc. Spec. Publ., 25, 45–57.

Baker, B.H. & Mitchell, J.G. (2000) Sedimentology and progressive tectonic relationships with the Late Triassic–Early Jurassic evolution of the Andean margin. *J. S. Am. Earth Sci.*, 157, 42–64.

Baker, B.H. & Muravchik, M., Franzese, J.R., Vega, G.D. & Herández, M. (2013) Miocene block uplift and basin formation in the Patagonian foreland: The Gastre Basin, Argentina. *Tectonophysics*, 601, 98–111.

Baker, B.H. & Mitchell, J.G. (2008) Synrift geometry of the Neuquén Basin in the northeastern Neuquén Province, Argentina. In: *Evolution of the Andean Margin: A Tectonic and Magmatic View From the Andes to the Neuquén Basin (35°–39°S lat)* (Ed. by Kay S.M. & Ramos V.A.) *Spec. Pap. Geol. Soc. Am.*, 407, 147–161.

Baker, B.H. & Mitchell, J.G. (2012) Continental rift basins: an impact of volcanism on the record of a rift basin of the Parinacota debris avalanche, northern Chile. *Bull. Volcanol.*, 64, 40–54.

Baker, B.H. & 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.

Baker, B.H. & Mitchell, J.G. (2009) Volcano spreading and fault interaction influenced by rift zone intrusions: Insights from analogue experiments analyzed with digital image correlation technique. *J. Volcanol. Geoth. Res.*, 183, 170–182.

Baker, B.H. & Murphy, M., Urrutia-Fucugauchi, J., Sibuet, J.M. & Bell, B.R. (2012) Debris flow deposits within the Patagonian foreland: The vial fan, Death Valley, California. *J. Geol. Soc. London*, 169, 467–484.

Baker, B.H. & Mitchell, J.G. (2001) Continental break-up in the southeastern margin of the Neuquén Basin. *Spec. Pap. Geol. Soc. Am.*, 313, 233–262.

Baker, B.H. & Mitchell, J.G. (1993) Piedra Pintada. In: *Léxico Estratigráfico de la Argentina, Volumen IX, Jurásico: 313* (Ed. by Riccardi A.C. & Damborenea S.E.) Asociación Geológica Argentina, Serie “B” (Didáctica y Complementaria), 21, 313–316.

Baker, B.H. & Mitchell, J.G. (2007) Debris flow deposits within the Palaeogene lava fields of NW Scotland: evidence for mass wasting of the volcanic landscape during emplacement of the Ardnamurchan Central Complex. *Bull. Volcanol.*, 69, 847–864.

Baker, B.H. & Mitchell, J.G. (2000) Continental rift basins: an impact of volcanism on the record of a rift basin of the Parinacota debris avalanche, northern Chile. *Bull. Volcanol.*, 64, 40–54.

Baker, B.H. & Mitchell, J.G. (2001) Continental break-up in the southeastern margin of the Neuquén Basin. *Spec. Pap. Geol. Soc. Am.*, 313, 233–262.

Baker, B.H. & Mitchell, J.G. (2009) Volcano spreading and fault interaction influenced by rift zone intrusions: Insights from analogue experiments analyzed with digital image correlation technique. *J. Volcanol. Geoth. Res.*, 183, 170–182.

Baker, B.H. & Mitchell, J.G. (2008) Synrift geometry of the Neuquén Basin in the northeastern Neuquén Province, Argentina. In: *Evolution of the Andean Margin: A Tectonic and Magmatic View From the Andes to the Neuquén Basin (35°–39°S lat)* (Ed. by Kay S.M. & Ramos V.A.) *Spec. Pap. Geol. Soc. Am.*, 407, 147–161.

Baker, B.H. & Mitchell, J.G. (2012) Continental rift basins: an impact of volcanism on the record of a rift basin of the Parinacota debris avalanche, northern Chile. *Bull. Volcanol.*, 64, 40–54.

Baker, B.H. & Mitchell, J.G. (2009) Volcano spreading and fault interaction influenced by rift zone intrusions: Insights from analogue experiments analyzed with digital image correlation technique. *J. Volcanol. Geoth. Res.*, 183, 170–182.

Baker, B.H. & Mitchell, J.G. (2008) Synrift geometry of the Neuquén Basin in the northeastern Neuquén Province, Argentina. In: *Evolution of the Andean Margin: A Tectonic and Magmatic View From the Andes to the Neuquén Basin (35°–39°S lat)* (Ed. by Kay S.M. & Ramos V.A.) *Spec. Pap. Geol. Soc. Am.*, 407, 147–161.

Baker, B.H. & Mitchell, J.G. (2012) Continental rift basins: an impact of volcanism on the record of a rift basin of the Parinacota debris avalanche, northern Chile. *Bull. Volcanol.*, 64, 40–54.

Baker, B.H. & Mitchell, J.G. (2009) Volcano spreading and fault interaction influenced by rift zone intrusions: Insights from analogue experiments analyzed with digital image correlation technique. *J. Volcanol. Geoth. Res.*, 183, 170–182.

Baker, B.H. & Mitchell, J.G. (2008) Synrift geometry of the Neuquén Basin in the northeastern Neuquén Province, Argentina. In: *Evolution of the Andean Margin: A Tectonic and Magmatic View From the Andes to the Neuquén Basin (35°–39°S lat)* (Ed. by Kay S.M. & Ramos V.A.) *Spec. Pap. Geol. Soc. Am.*, 407, 147–161.

Baker, B.H. & Mitchell, J.G. (2007) Debris flow deposits within the Palaeogene lava fields of NW Scotland: evidence for mass wasting of the volcanic landscape during emplacement of the Ardnamurchan Central Complex. *Bull. Volcanol.*, 69, 847–864.

Baker, B.H. & Mitchell, J.G. (2000) Continental rift basins: an impact of volcanism on the record of a rift basin of the Parinacota debris avalanche, northern Chile. *Bull. Volcanol.*, 64, 40–54.

Baker, B.H. & Mitchell, J.G. (2009) Volcano spreading and fault interaction influenced by rift zone intrusions: Insights from analogue experiments analyzed with digital image correlation technique. *J. Volcanol. Geoth. Res.*, 183, 170–182.

Baker, B.H. & Mitchell, J.G. (2008) Synrift geometry of the Neuquén Basin in the northeastern Neuquén Province, Argentina. In: *Evolution of the Andean Margin: A Tectonic and Magmatic View From the Andes to the Neuquén Basin (35°–39°S lat)* (Ed. by Kay S.M. & Ramos V.A.) *Spec. Pap. Geol. Soc. Am.*, 407, 147–161.

Baker, B.H. & Mitchell, J.G. (2012) Continental rift basins: an impact of volcanism on the record of a rift basin of the Parinacota debris avalanche, northern Chile. *Bull. Volcanol.*, 64, 40–54.

Baker, B.H. & Mitchell, J.G. (2009) Volcano spreading and fault interaction influenced by rift zone intrusions: Insights from analogue experiments analyzed with digital image correlation technique. *J. Volcanol. Geoth. Res.*, 183, 170–182.

Baker, B.H. & Mitchell, J.G. (2008) Synrift geometry of the Neuquén Basin in the northeastern Neuquén Province, Argentina. In: *Evolution of the Andean Margin: A Tectonic and Magmatic View From the Andes to the Neuquén Basin (35°–39°S lat)* (Ed. by Kay S.M. & Ramos V.A.) *Spec. Pap. Geol. Soc. Am.*, 407, 147–161.
Recent Advances (Ed. by C. Busby & A. Azor), pp. 185–208. Wiley-Blackwell, Oxford.

EBINGER, C.J., DEINO, A.L., DRAKE, R.E. & TESHA, A.L. (1989) Chronology of volcanism and rift basin propagation: Rungrue volcanic Province, East Africa. J. Geophys. Res., 94, 15785–15803.

FENG, Z. (2008) Volcanic rocks as prolific gas reservoir: a case study from the Qingshan field in the Songliao Basin, NE China. Mar. Petrol. Geol., 25, 416–432.

FERGUSSION, D.J., BARNE, T.D., D.M., OPPENHEIMER, C., YIRGU, G., LAW, E., KIDANE, T., CARN, S. & HAMLING, I. (2010) Recent rift-related volcanism in Afar, Ethiopia. Earth Planet. Sci. Lett., 292, 409–418.

FISHER, R.V. (1961) Proposed classification of volcaniclastic sediments and rocks. Geol. Soc. Am. Bull., 72, 1395–1408.

FISHER, R.V. & SCHINCKE, H.–U. (1984) Pyroclastic Rocks, 474 pp. Springer, Heidelberg.

FISHER, R.V. & SMITH, G.A. (1991) Sedimentation in Volcanic Settings. Special Publication 45. Society of Economic Paleontologists and Mineralogists, Tulsa, 257 pp.

FRANZESE, J.R., VEIGA, G.D., SCHWARZ, E. & GÓMEZ-PÉREZ, J. (2006) Tectonostratigraphic evolution of a Mesozoic graben border system: the Chachil depocentre, southern Neuquén Basin, Argentina. J. Geol. Soc., 163, 707–721.

FRANZESE, J.R., VEIGA, G.D., MURAVICH, M., ANCHETA, D. & D'ELIA, L. (2007) Estratigrafía de ‘sin-rift’ (Triásico Superior-Jurásico Inferior) de la Cuenca Neuquén en la sierra de Chacai, Neuquén, Argentina. Rev. Geol. Chil. 34, 49–62.

GAUTHORPE, R.L. & LEEDER, M.R. (2000) Tectono-sedimentary evolution of active extensional basins. Basin Res., 12, 195–218.

GLICKEN, H.X. (1991) Sedimentary architecture of large volcanic–debris avalanches. In: Sedimentation in Volcanic Settings (Ed. by Fisher R.V. & Smith G.A.) Spec. Publ. SEPM, 45, 99–111.

GOODBRED, S.L.J. & KUHEL, S.A. (2000) Enormous Ganges-Brahmaputra sediment discharge during strengthened early Holocene monsoon. Geology, 28, 1083–1086.

GRAVELY, D.M., WILSON, C.J.N., LEONARD, G.S. & COLE, J.W. (2007) Double trouble: paired ignimbrite eruptions and colateral subsidence in the Taupo Volcanic Zone, New Zealand. Geol. Soc. Am. Bull., 119, 18–30.

GRÖBER, P. (1946) Observaciones geológicas a lo largo del meridiano 70, Huja Chos Malal. Revista de la Asociación Geológica Argentina, 1, 177–208.

GUMUNDSSON, A. (2000) Dynamics of volcanic systems in Iceland: example of Tectonism and Volcanism at Juxtaposed Hot Spot and Mid-Ocean Ridge Systems. Earth Planet. Sci., 28, 107–140.

GULISANO, C.A., GUTIÉRREZ-PLEIMLING, A.R. & DIGREGORIO, R.E. (1984) Esquema estratigráfico de la secuencia jurásica del oeste de la provincia del Neuquén. In: IX Congreso Geológico Argentino, Actas I, 236–259.

HACKETT, W.R. & HOUGHTON, B.F. (1989) A facies model for a Quaternary andesitic composite volcano: Ruapehu, New Zealand. Bull. Volcanol., 51, 51–68.

HAUGHTON, P.D.W. (1993) Simultaneous dispersal of volcaniclastic and non-volcanic sediments in fluvial basins: examples from the Lower Old Red Sandstone, eastcentral Scotland. In: Alluvial Sedimentation (Ed. by Marzo M. & Puigdefabregas C.) Spec. Publ. Int. Assoc. Sedimentol., 17, 451–471.

HAYES, S.K., MONTGOMERY, D.R. & NEWHALL, C.G. (2002) Fluvial sediment transport and deposition following the 1991 eruption of Mount Pinatubo. Geomorphology, 45, 211–224.

HINTERWIMMER, G. (2002) Los reservorios de la Serie Tobía. In: Rocos Reservorio de las Cuencas Productivas de la Argentina (Ed. by M. Schiuma, G. Hinterwimmer & G. Vergani). pp. 27–47. Instituto Argentino de Petróleo y Gas, Buenos Aires.

HOWELL, J.A., SCHWARZ, E., SPALLETI, L.A. & VEIGA, G.D. (2005) The Neuquén Basin: an overview. In: The Neuquén Basin, Argentina: A Case Study in Sequence Stratigraphy and Basin Dynamics (Ed. by Veiga G.D., Spalletti L.A., Howell J.A. & Schwarz E.). Spec. Publ. Geol. Soc. London, 252, 1–14.

KARATSON, D. & NEMETH, K. (2001) Lithofacies associations of an emerging volcaniclastic apron in a Miocene volcanic complex: an example from the Börzsöny Mountains, Hungary. Int. J. Earth Sci., 90, 776–794.

LARA, L.E. (2009) The 2008 eruption of the Chaitén Volcano, Chile: a preliminary report. Andean Geol., 36, 125–129.

LEANZA, H.A., MAZZINI, A., CORFU, F., LLAMBIAS, E.J., SVENSEN, H., PLASKE, S. & GALLAND, O. (2013) The Chachil Limestone (Pliensbachian earliest Toarcian) Neuquén Basin, Argentina: U-Pb age calibration and its significance on the Early Jurassic evolution of southwestern Gondwana. J. S. Am. Earth Sci., 42, 171–185.

LEEDER, M.R. & GAWTHORPE, R.L. (1987) Sedimentary models for extensional tilt-block/half-graben basins. In: Continental Extensional Tectonics (Ed. by Coward M.P., Dewey J.F. & Hancock P.L.) Spec. Publ. Geol. Soc. London, 28, 139–152.

LEEDER, M.R., MACK, G.H. & SALYARD, S.L. (1996) Axial-transverse fluvial interactions in half-graben: Plio-Pleistocene Palomas Basin, southern Rio Grande Rift, New Mexico. USA Basin Res., 12, 225–241.

LEGARRETA, L. & ULIANA, M.A. (1996) The Jurassic succession in west-central Argentina: stratigraphic pattern, sequences and paleo-geographic evolution. Palaeogeogr. Palaeoclimatol. Palaeoecol., 120, 303–330.

LEGARRETA, L., VILLA, H.J., CRUZ, C.E., LAFITTE, G.A. & VARADE, R. (2008) Revisión integrada de los sistemas generadores, estilos de migración-entrampamiento y volumetría de hidrocarburos en los distintos productivos de la Cuenca Neuquina. In: Sistemas Petroleros de las Cuencas Andinas (Ed. by C.E. Cruz, J.F. Rodríguez, J.J. Hechem & J.H. Villar), pp. 79–108. Instituto Argentino del Petróleo y del Gas, Buenos Aires.

LENHARDT, N. & GÖTZ, A. (2011) Volcanic settings and their reservoir potential: an outcrop analog study on the Miocene Tepoztlán Formation, Central Mexico. J. Volcanol. Geoth. Res., 204, 66–75.

LIPMAN, P.W. (1976) Caldera-collapse breccias in the western San Juan Mountains, Colorado. Geol. Soc. Am. Bull., 87, 1397–1410.

LIPMAN, P.W. (2000) Calderas. In: Encyclopedia of Volcanoes (Ed. by H. Sigurdsson, B. Houghton, S.R. McNutt, H. Rymer & J. Stix), pp. 643–662. Academic Press, San Diego, CA.

MAVILLE, A. V., NEMETH, K. & KANO, C. (2009) Source to sink: a review of three decades of progress in the understanding of volcaniclastic processes, deposits, and hazards. Sed. Geol., 220, 136–161.

MARTI, J. (1991) Caldera-like structures related to Permo-Carboniferous volcanism of the Catalan Pyrenees (NE Spain). J. Volcanol. Geoth. Res., 45, 173–186.
MCPHIE, J., DOYLE, M. & ALLEN, R. (1993) Volcaniclastic deposits: Implications for hydrocarbon exploration. In: Sedimentation in Volcanic Settings (Ed. by Fisher R.V. & Smith G.A.) Spec. Publ. Soc. Econ. Paleontol. Mineral., 45, 27–36.

McPherson, J.G., Shanmugam, G. & Morea, R.J. (1987) Fan deltas and braid deltas: varieties of coarse-grained deltas. Bull. Geol. Soc. Am., 99, 331–340.

McPhee, J., Doyle, M. & Allen, R. (1993) Volcaniclastic Textures: A Guide to the Interpretation of Textures in Volcanic Rocks. CODES — University of Tasmania, Hobart.

Moore, I. & Kokelaar, P. (1997) Tectonic influences in piece-meal caldera collapse at Glencoe Volcano, Scotland. J. Geol. Soc. London, 154, 765–768.

Moore, I. & Kokelaar, P. (1998) Tectonically controlled piece-meal caldera collapse: a case study of Glencoe volcano, Scotland. Geol. Soc. Am. Bull., 110, 1448–1466.

Morel, E.M. & Gananza, D.G. (2002) Paso Flores. In: Léxico Estratigráfico de la Argentina, Volumen VIII, Triásico: 208 (Ed. by Stipanicic P.N. & Marsiscano C.A.) Asociación Geológica Argentina, Serie B (Didáctica y Complementaria), 26, 208–209.

Morley, C.K. (1999) Geosciences of Rift Systems—Evolution of East Africa. AAPG Studies in Geology Volume, 44.

Muraschkik, M., D’Elia, L., Billes, A. & Franzese, J.R. (2011) Syn-eruptive/inter-eruptive relations in the syn-rupt deposits of the Precordylo Cycle, Sierra de Chacai, Neuquén Basin, Argentina. Sed. Geol., 238, 132–144.

Muraschkik, M., Billes, A., D’Elia, L. & Franzese, J.R. (2014) Alluvial fan deposition along a rift depocentre border from the Neuquén Basin, Argentina. Sed. Geol., 301, 70–89.

Némec, W. (1990) Aspects of sediment movement on steep delta slopes. In: Coarse-Grained Deltas (Ed. by Colella A. & Prior D.B.) Spec. Publ. Int. Ass. Sedimentol., 10, 29–73.

Németh, K. (2010) Monogenetic volcanic fields: origin, sedimentary record, and relationship with polygenetic volcanism. Geol. Soc. Am. Spec. Pap., 470, 43–66.

Németh, K. & Kereszturi, G. (2013) Monogenetic volcanism: personal views and discussion. Int. J. Earth Sci., 104, 2131–2146.

Németh, K. & Martin, M. (2007) Practical Volcanology. Lecture Notes for Understanding Volcanic Rocks From Field-Based Studies. Geological Institute of Hungary, Occasional Papers, 27, Budapest.

Nishikia, K., Takahashi, K., Matsumotoa, A. & Miyake, Y. (2011) Quaternary volcanism and tectonic history of the Suwa-Yatsugatake Volcanic Province, Central Japan. J. Volcanol. Geoth. Res., 203, 158–167.

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

Palmer, B.A. & Neall, V.E. (1991) Contrasting lithofacies architecture in ring-plain deposits related to edifice construction and destruction, the Quaternary Stratford and Opuhake Formations, Egmont Volcano, New Zealand. Sed. Geol., 74, 71–88.

Palmer, B.A., Alloway, B.V. & Neall, V.E. (1991) Volcanic-debris-avalanche deposits in New Zealand—lithofacies organization in unconfined, wet-avalanche flows. In: Sedimentation in Volcanic Settings (Ed. by Fisher R.V. & Smith G.A.) Spec. Publ. Soc. Econ. Paleontol. Mineral., 45, 89–98.

Palmer, B.A., Purves, A.M. & Donohue, S.L. (1993) Controls on accumulation of a volcaniclastic fan, Ruapehu composite volcano, New Zealand. Bull. Volcanol., 55, 176–189.

Pangaro, F., Corriera, R., Carbone, O. & Hinterwimmer, G. (2002) Los reservorios del Precioylo. In: Rocas Reservorio de las Cuencas Productivas Argentinuas (Ed. by M. Schiuma, G. Hinterwimmer & G.D. Vergani), pp. 229–234. Instituto Argentino del Petróleo y del Gas, Buenos Aires.

Pangaro, F., Pereira, D.M. & Micucci, E. (2009) El sinrift de la dorsal de Huincul, Cuenca Neuquina: evolución y control sobre la estratigrafía y estructura del área. Revista de la Asociación Geológica Argentina, 65, 265–277.

Paredes, J.M., Fox, N., Colombo, F.N., Nillini, A., Allard, J.O. & Marquillas, R.A. (2007) Volcanic and climatic controls on fluvial style in a high-energy system: the Lower Cretaceous Matasiete Formation, Golfo San Jorge basin, Argentina. Sed. Geol., 202, 96–123.

Parfitt, L. & Wilson, L. (2008) Fundamentals of Physical Volcanology. Blackwell Scientific Publications, Oxford.

Pettersen, M.G., Breddige-Stephens, B., Millward, D. & Johnson, E.F. (1992) A pre-caldera plateau-andesite field in the Borrowdale Volcanic Group of the English Lake District. J. Geol. Soc. London, 149, 809–906.

Pierson, T.C., Janda, R.J., Thouret, J.C. & Borrello, C.A. (1990) Perturbation and melting of snow ice by the 11 November eruption of the Nevada Del Ruzo, Colombia, and consequent mobilization, flow and disposition of lahars. J. Volcanol. Geoth. Res., 41, 17–66.

Postma, G. (1983) Water escape structures in the context of a depositional model of a mass flow dominated conglomeratic fan-delta (Abrojion Formation, Pliocene, Almeria Basin, SE Spain). Sedimentology, 30, 91–103.

Postma, G. (1990) Depositional architecture and facies of river and fan deltas: a synthesis. In: Coarse-Grained Deltas (Ed. by Colella A. & Prior D.B.) I.A.S. Spec. Publ., 10, 13–27.

Ramos, V.A. (2009) Anatomy and global context of the Andes: main geologic features and the Andean orogen cycle. In: Backbone of the Americas: Shallow Subduction, Plateau Uplift, and Ridge and Terrane Collision (Ed. by Kay S.M., Ramos V.A. & Dickinson W.R.) Geol. Soc. Am. Mem., 204, 31–65.

Ramos, M.E., Folguera, A., Fennell, L., Giménez, M., Litvak, V.D., Dzierma, Y. & Ramos, V.A. (2014) Tectonic evolution of the North Patagonian Andes from field and gravity data (39°40’S). J. S. Am. Earth Sci., 51, 59–75.

Raynias, R. & Steil, R.J. (1998) Architecture of Marine Rift-Basin Successions. AAPG Bull., 82, 110–146.

Reading, H.G. & Collinson, J.D. (2002) Clastic coasts. In: Sedimentary Environments: Processes, Facies and Stratigraphy (Ed. by H.H. Reading), pp. 154–231. Blackwell Science, Oxford.

Reading, H.G. & Level, B.K. (2002) Control on the sedimentary rock record. In: Sedimentary Environments: Processes, Facies and Stratigraphy (Ed. by R.G. Reading), pp. 5–36. Blackwell Science, Oxford.

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

Rowland, J.V. & Sissons, R.H. (2001) Extensional fault kinematics within the Taupo Volcanic Zone, New Zealand: soft-linked segmentation of a continental rift system. NZ J. Geol. Geophys., 44, 271–283.

Rowland, J.V., Wilson, C.J.N. & Gravely, D.M. (2010) Spatial and temporal variations in magma-assisted rising, Taupo Volcanic Zone, New Zealand. J. Volcanol. Geoth. Res., 190, 89–108.

Schuma, M. & Llambias, E.J. (2008) New ages and chemical analysis on Lower Jurassic volcanism close to the Huincul High, Neuquén. Revista de la Asociación Geológica Argentina, 63, 644–652.

Schultheis, R.W. (1991) Half-graben basin filling models: new constraints on continental extensional basin development. Basin Res., 3, 123–141.

Schultheis, 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.

Schultheis, R.W. & Anders, M.H. (1996) Stratigraphic effects and tectonic implications of the growth of normal faults and extensional basins. Geol. Soc. Am. Spec. Pap., 303, 183–203.

Schneider, J. & Fisher, R.V. (1998) Transport and emplacement mechanisms of large volcanic debris avalanches: evidence from the northwest sector of Cantal volcano (France). J. Volcanol. Geoth. Res., 83, 141–165.

Scott, K.M., Janda, R.J., de la Cruz, E.G., Garnette, E., Eto, I., Isada, M., Sexton, M. & Hadley, K.C. (1996a) Channel and sedimentation responses to large volumes of 1991 volcanic deposits on the east flank of Mount Pinatubo. In: Fire and Mud, Eruptions and Lahars of Mount Pinatubo, Philippines (Ed. by C.G. Newhall & R.S. Punongbayan), pp. 971–988. PHIVOLCS Press, Quezon City, and University of Washington Press, Seattle.

Scott, W.E., Hoblit, R.P., Torres, R.C., Self, S., Martínez, M.M.L. & Nillos, T. (1996b) Pyroclastic flows of the June 15, 1991, clastic eruption of Mount Pinatubo. In: Fire and Mud, Eruptions and Lahars of Mount Pinatubo, Philippines (Ed. by C.G. Newhall & R.S. Punongbayan), pp. 545–570. PHIVOLCS Press, Quezon City, and University of Washington Press, Seattle.

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

Siebert, L. (1984) Large volcanic debris avalanches: characteristics of source areas, deposits, and associated eruptions. J. Volcanol. Geoth. Res., 22, 162–197.

Skilling, I.P. (1993) Incremental caldera collapse of Suswa volcano, Gregory Rift Valley, Kenya. J. Geol. Soc. London, 150, 885–896.

Smith, G.A. (1991) Facies sequences and geometries in continental volcanioclastic sediments. In: Sedimentation in Volcanic Settings (Ed. by Fisher R.V. & Smith G.A.) Spec. Publ. Soc. Econ. Paleontol. Mineral., 45, 109–121.

Smith, G.A. (1986) Coarse-grained nonmarine volcanioclastic 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. & Lowe, D.R. (1991) Lahars: Volcano-hydrologic events and deposition in the debris flow-hyperconcentrated flow continuum. In: Sedimentation in Volcanic Settings (Ed. by Fisher R.V. & Smith G.A.) Spec. Publ. Soc. Econ. Paleontol. Mineral., 45, 59–70.

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 (Jurásico Inferior, Neuquén, República Argentina). Revista de la Asociación Geológica Argentina, 66, 305–313.

Spinks, K.D., Acocella, V., Cole, J.W. & Bassett, K.N. (2005) Structural control of volcanism and caldera development in the transtensional Taupo Volcanic Zone, New Zealand. J. Volcanol. Geoth. Res., 134, 7–22.

Sruoga, P., Rubinstein, N. & Hinterwimmer, G. (2004) Porosity and permeability in volcanic rocks: a case study on the Serie Tobbífera, South Patagonia, Argentina. J. Volcanol. Geoth. Res., 132, 31–43.

Sruoga, P. & Rubinstein, N. (2007) Processes controlling porosity and permeability in volcanic reservoirs from the Austral and Neuquén basins. Argentina. AAPG Bull., 91, 115–129.

Stipanicic, P.N. (1969) El avance de los conocimientos del Jurásico argentino a partir del esquema de Groeber. Revista de la Asociación Geológica Argentina, 24, 367–388.

Stipanicic, P.N., Rodrigo, F., Bañes, O.L. & Martínez, C.G. (1968) Las formaciones presenonianas en el denominado Macizo Nordpatagónico y regiones adyacentes. Revista de la Asociación Geológica Argentina, 23, 67–98.

Taft, M.R. & Allen, P.A. (2002) Lakes. In: Sedimentary Environments: Processes, Facies and Stratigraphy (Ed. by H.G. Reading), pp. 83–124. Blackwell Science, Oxford.

Thouret, J.-C. (1999) Volcanic geomorphology—an overview. Earth Sci. Rev., 47, 95–131.

Tucker, M.E. (2001) Sedimentary Petrology, An Introduction to the Origin of Sedimentary Rocks. 3rd edn. Blackwell Scientific Publications, Oxford.

Ui, T., Takarada, S. & Yoshimoto, M. (2000) Debris avalanches. In: Encyclopedia of Volcanoes (Ed. by H. Sigurdsson, B. Houghton, S.R. McNutt, H. Rymer & J. Stix), pp. 617–626. Academic Press, San Diego, CA.

Ulana, M. & Legarrafla, L. (1993) Hydrocarbons habitat in a Triassic-to-Cretaceous sub-Andean setting: Neuquén Basin, Argentina. J. Petr. Geol., 16, 397–420.

Umazano, A.M., Melchor, R.N., Bedatou, E., Bellosi, E.S. & Kraus, J.J.M. (2014) Fluvial response to sudden input of pyroclastic sediments during the 2008–2009 eruption of the Chaitén Volcano (Chile): the role of logjams. J. S. Am. Earth Sci., 54, 140–157.

Van Wyk de Vries, B. & Francis, P.W. (1997) Catastrophic collapse at stratovolcanoes induced by gradual volcanic spreading. Nature, 387, 387–390.

Van Wyk de Vries, B. & Merle, O. (1996) The effect of volcanic constructs on rift fault patterns. Geology, 24, 643–646.

Varela, R., Dalla Salda, L., Cingolani, C. & Gómez, V. (1991) Estructura, petrología y geocronología del basamento de la región del Río Limay del Río Negro y Neuquén, Argentina. Rev. Geol. Chile, 18, 147–161.

Vergani, G.D. (2005) Control estructural de la sedimentación jurásica (Grupo Cuyo) en la Dorsal de Huincul, Cuenca.
Neuquina, Argentina, Modelo de falla lístrica rampaplano, 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: *Petroleum Basins of South America* (Ed. by Tankard A.J., Suárez S.R. & Welsink L.H.) *Mem. Am. Assoc. Pet. Geol.*, 62, 383–402.

VESSELL, R.D. & DAVIES, D.K. (1981) Nonmarine sedimentation in an active fore arc basin. In: *Nonmarine Depositional Environments: Models for Exploration* (Ed. by Ethridge F.G. & Flores R.M.) Spec. Publ. Soc. Econ. Paleontol. Mineral., 31, 34–45.

WALKER, G.P.L. (2000) Basaltic volcanoes and volcanic systems. In: *Encyclopedia of Volcanoes* (Ed. by H. Sigurdsson, B. Houghton, S.R. McNutt, H. Rymer & J. Stix), pp. 283–290. Academic Press, San Diego, CA.

WHITE, J.D.L. (1991) The depositional record of small, monogenetic volcanoes within terrestrial basins. In: *Sedimentation in Volcanic Settings* (Ed. by Fisher R.V. & Smith G.A.) Spec. Publ. Soc. Econ. Paleontol. Mineral., 45, 155–171.

WHITE, J.D.L. & HOUGHTON, B.F. (2006) Primary volcanioclastic rocks. *Geology*, 34, 677–680.

WILSON, C.J.N., GRAVLEY, D.M., LEONARD, G.S. & ROWLAND, J.V. (2009) Volcanism in the central Taupo Volcanic Zone, New Zealand: Tempo, styles, and controls. In: *Studies in Volcanology: The Legacy of George Walker* (Ed. by T. Thor-darson, S. Self, G. Larsen, S.K. Rowland & Á. Höskuldsson), pp. 225–247. Geological Society of London, London.

WOLFENDEN, E., YIRGU, G., EBINGER, C., DEINO, A. & AYALEW, D. (2004) Evolution of the northern Main Ethiopian Rift: Birth of a triple-junction. *Earth Planet. Sci. Lett.*, 24, 213–228.

WOLFENDEN, E., EBINGER, C., DEINO, A. & AYALEW, D. (2005) Evolution of a volcanic rifted margin: Southern Red Sea, Ethiopia. *GSA Bull.*, 117, 846–864.

WOOLLER, L., van Wyck De Vries, B., CECCHI, E. & Rymer, H. (2009) Analogue models of the effect of long-term basement fault movement on volcanic edifices. *Bull. Volcanol.*, 71, 1111–1131.

ZANCHETTA, G., SULPICO, R. & di VITO, M.A. (2004) The role of volcanic activity and climate in alluvial fan growth at volcanic areas: an example from southern Campania (Italy). *Sed. Geol.*, 168, 249–280.

ZIEGLER, P.A. & CLOETINGH, S. (2004) Dynamic processes controlling evolution of rifted basins. *Earth Sci. Rev.*, 64, 1–50.