Pumice clasts in cross stratified basalt-dominated sandstones and conglomerates. Characteristics and depositional significance: Huarenchenque Fm (Neuquén, Argentina)

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ABSTRACT

The Huarenchenque Fm is a Pleistocene clastic sedimentary unit that crops out in the SW of the province of Neuquén, Argentina. This unit is made up of cross stratified basalt-dominated sandstones and conglomerates with pumice clasts accumulated in a fluvial context. The roundness of these pumice clasts, the numerous fragments of volcanic glass (shards) and their association with polymodal basalt-rich clasts in cross-bedded conglomerates strongly suggest that these clasts were transported together during hydraulic flow. Pumice clasts are usually buoyant in cold water whenever their density is lower than 1g/cm^3. However, since their density exceeds that of water during sediment transport, they form part of the sedimentary record. An artificial channel (ASSUT-1 flume, University of Barcelona) was employed to yield fresh insight into the behavior of these clasts mixed with sands during transport and accumulation processes. The hydraulic equivalence of both materials was calculated by evaluating the density of the pumice clasts and that of the quartz sands. The pumice clasts sank as a result of the interaction of pumice-rich pyroclastic flows with a moving mass of shallow water. However, they retained their buoyancy after recovery

from the sedimentary record (field outcrop). The sinking process is therefore rapid and reversible.

Key words: pumice clasts in polygenic conglomerate, sinking of pumice, pumice water saturation, Neuquén Basin, Argentina.

1. Introduction

The non-marine Huarenchenque Fm is characterized by cross-bedded and clast-supported polygenic and polymodal unsorted conglomerates displaying rounded, subrounded, subangular basalt, and rounded pumice clasts (Groeber, 1956; Holmberg, 1973; Zanettini et al., 2010). The conglomerates have an unsorted sandy matrix with small lenses of clasts. Some levels of fine to very coarse-grained conglomeratic sandstones are interfingered. Several pyroclastic deposits are intercalated with conglomerate and sandstone levels locally (Stura and Mazzoni, 1994). A number of lenticular to tabular levels of basalt-rich sandstones (blue sands) display pumice-rich laminae (white-gray sands) made up of pumice granules and shards. The Huarenchenque Fm that fills former fluvial paleovalley varies considerably in thickness, attaining 80 – 100 m towards Loncopué, whereas to the SE of the Neuquén province the values attain 30 – 40 m. In conglomerates, a mixture of basalt and pumice clasts is uncommon given their differences in density. Despite the occurrence of pumice clasts in non-marine deposits in the fossil record, there are many data on their sinking process in marine environments (Manville et al., 2002; Jutzeler et al., 2017). Several volcanic rock fragments are incorporated as clasts into different fluvial contexts (Cole, 1991; Paredes et al., 2015; D' Elia et al., 2016) as a result of reworking processes produced by hydraulic flows on previously accumulated volcanic materials (Smith, 1987; Cole and Ridgway, 1993; Paredes et al., 2007; Sohn et al., 2013). However, these reworking processes rarely develop during mixing of low and high-density clasts in a context of active fluvial systems. Such is the case of the Huarenchenque Fm which displays large and small pumice fragments acting as clasts (D >1 g/cm^3) coevally with pyroclastic deposits that prevent them from being reworked. Our study seeks to gain a better understanding of the sedimentological significance of pumice clasts that are mixed with basalt clasts in a non-marine sedimentary record (Huarenchenque Fm). We provide abundant evidence in support of the coeval transport of pumice and basalt clasts in an active fluvial system.

2. Geological setting of the Huarenchenque Formation

The studied area (Fig. 1) is located at Alto del Copahue-Pino Hachado in the province of Neuquén near the Argentine-Chilean border. Geologically, it straddles the boundary between the Loncopué Trough and the Northern Precordillera of Neuquén (Ramos et al., 2011). The Loncopué Trough is a Pliocene-Quaternary basin mainly filled with large effusive basalt-rich flows from monogenetic volcanic vents. The morphology of basin floor is constituted by an irregular topography developed on thick Mesozoic sedimentary deposits. The Northern Precordillera of Neuquén, which was produced by a tectonic inversion of Triassic - Jurassic halfgrabens, displays thick Jurassic and Cretaceous deposits crossed by Cretaceous to Palaeogene volcanic and subvolcanic intrusive bodies (D'Elia et al., 2016). The Huarenchenque Fm is situated in a tectonic transitional area in the Neuquén basin. The northern sector underwent a continuous compressive episode that gave rise to a mountain range, attaining a height of 4000 m locally. The southern sector is characterized by alternating compressive-extensive episodes that resulted in heights not exceeding 3000 m (Folguera and García-Morabito, 2006). The area have a continuous volcanic activity from the Miocene. The Huarenchenque Fm, which was formed along the Pleistocene and Holocene, is the most recent volcano sedimentary lithostratigraphic unit in Neuquén (Lambert, 1956; Leanza et al., 2001; Zanettini et al., 2010). This unit crops out along the western and southern (austral) banks of the Agrio River between latitude 38° and 38° 30´ S and longitude 70° 20´ and 70° 30´ W and to the west of the Haichal and Liu Cullín creeks (Fig. 1).

3. Materials

The Huarenchenque Fm, which is made up of basalt-dominated conglomerates and sandstones containing pumice clasts, displays different facies characterized by their composition and by their internal primary sedimentary structures. The basalt-rich deposits form the irregular basement on which the sandstones, conglomerates and pyroclastic rocks were laid down.

3.1. Facies associations

The clastic materials were studied applying the paleohydraulics for the analysis of cross laminations or cross stratifications. It should be pointed out that the

Pumice is made up of highly vesicular silicic to mafic glass foam that is usually buoyant in water (Fisher and Schmincke, 1984). With a density lower than that of water, Pumice is a product of silicic explosive eruptions (pyroclastic eruptions or domes). Its behavior in volcanic and sedimentary processes is well documented (Cas and Wright, 1987; Branney and Kokelaar 2002; Allen et al., 2008). To study the sedimentary characteristics of the Huarenchenque Fm, their lithofacies were classified in accordance with the system of Miall, (1977, 1978) and Rust (1978), which have subsequently been refined by other authors for fluvial and alluvial-related deposits in volcanic settings (Smith, 1986, 1987; Waresback and Turbeville, 1990; Zanchetta et al., 2004). In order to define depositional settings, these facies were grouped into two different associations: fluvial and pyroclastic.

3.1.1. Fluvial facies association

Two types of facies, volcaniclastic pebbly and sandy, are closely related in the fluvial facies association. The conglomerates are moderately sorted and clast-supported. The clasts are subangular to rounded, and vary in size between granule and cobble with a predominance of medium to coarse pebbles. Outsize clasts (up to 50 cm) are common in some beds. The matrix is moderately sorted volcaniclastic sand with grains varying in size from fine to coarse. Pebble composition is dominated by basalt lithoclasts accompanied by (well rounded) pumice fragments, and less commonly by muddy intraclasts derived from reworking of the fluvial floodplain and/or bar tops. Conglomerate beds are stacked or occur as single rock bodies and display both sheet and lenticular geometries with basal sharp contacts. These deposits are characterized by internal sedimentary structures such as planar and low angle stratification (Gh, Gl) and trough cross-bedding (Gt). The cross-bedded conglomerates occur as laterally continuous deposits of three-dimensional gravel dunes (sets Gt) and as infill of isolated scours or pools. These deposits show a basal, concave upward surface and a progressive downturn in the dip of the foresets in a downstream direction (Gp, Fig. 5). Internally, some conglomerate beds display normal grading. Larger clasts (>10 cm) are usually imbricated with their longest axes perpendicular to flow direction. However, in some instances, the scarcity of elongated clasts prevents a reliable assessment of clast imbrication. Elongated clasts are oriented subhorizontally in some places. Conglomerate beds consist of moderately to poorly sorted, massive or crudely bedded, poorly imbricated, clast-supported gravels with matrix rich in coarse sand and granules (Gm). These beds are 0.3 to 0.5 m thick and vary considerably in terms of geometry, ranging from laterally continuous beds to single scour fills.

The Huarenchenque Fm sandstones display a gradual variation in clast content between sandstones and pebbly-rich sandstones. The lithofacies display different modes of stratification (parallel laminations, low-angle and high-angle cross-stratification). Bed thickness varies between 0.10 m and 1.50 m, on average are around 0.30 m. In many instances, these beds are continuous layers, scour and fill structures being rare. The sandy portion is made up of volcaniclastics moderately sorted including subrounded to rounded basalt and/or coarse pumice grains. The pebbles of the gravelly sandstones as well as those of the thin gravel lineations are mainly rounded basalts. The composition of sandstones is not uniform. Some beds (Sl facies code) are made up of basalt grains (blue sandstones) whereas others are rich in pumice clasts. An alternation of basalt-rich and pumice-rich laminae in the foresets of cross-bedded sandstones is also common.

3.1. *2. Pyroclastic facies association*

Pyroclastic deposits are whitish to pale pink in color (Figs. 2, 3 and 4). They consist of lapilli tuff beds in a vitric ash matrix. Lithofacies LT(1) is largely made up of well sorted angular to subrounded pumice lapilli and coarse vitric ash. The deposits are massive (sometimes with faint lamination), vary in thickness from 0.10 m to 0.40 m, and are usually intercalated in the volcaniclastic-rich fluvial succession. Lithofacies LT(2) is composed of subangular to subrounded, matrix to clast supported, pumice lapilli with scarce basalt blocks in a vitric ash matrix. The main unwelded deposit of the volcanic facies is 400 m long and about 10 m thick. Its basal section displays very poorly sorted dark gray massive volcaniclastic pebbly sandstones with outsized and very angular basalt boulders from the cliffs and screes bounding the paleovalley. The middle section consists of light colored massive pumice lapilli with isolated angular volcanic blocks. Towards the base are “pockets” and “lineations” of subrounded and rounded basalt pebbles from previously deposited fluvial gravels. The lower surface of this unit is sharp and irregular owing to scour and loading. The upper section lies on a marked non-erosional surface. It is composed of pink pumice lapilli with crude lamination and displays a reverse grading of pumice from middle to top. Lithofacies LT(3) consists of a single 0.8 to 1 m thick lithosome characterized by a bipartite alternation of light gray ash tuffs and lapilli tuffs that are almost entirely made up of juvenile components. The deposits are parallel-laminated and laterally continuous. Individual laminae are in the order of millimeters to a few centimeters. This unit shows a faded cross-bedding towards its basal part where its tangential geometry is displayed (Fig.6).

3.2. Pumice in the sedimentary record

Pumice, which has been studied for several decades, has a low density, which contributes to its marked buoyancy in water (Fisher and Schmincke, 1984; Witham and Sparks, 1986; Cas and Wright, 1987; White et al., 1997; Branney and Kokelaar, 2002; Jokiel and Cox, 2003; Pattan et al., 2008). Large pumice fragments have been known to drift over long distances across the oceans (Richards, 1958; Coombs and Landis, 1966; Frick and Kent, 1984; Larsen et al., 2001; Risso et al., 2002; Bryan et al., 2004, 2012). However, small pumice fragments that are waterlogged (Manville et al., 2002; Dufek et al., 2007; Vella and Huppert, 2007; Allen et al., 2008; Patel et al., 2013) have a much higher density. Consequently, the pumice sinks resulting in its addition to sedimentation (Houghton and Wilson, 1989; Cashman and Fiske, 1991; Manville et al., 1998; Riggs et al., 2001; Allen and Freundt, 2006; Fauria et al., 2017; Jutzeler et al., 2017). This accumulation is mainly produced by high-density currents (Sohn et al., 1999; Fülöp, 2001; Kataoka and Nakajo, 2002) or by hydraulic currents (White et al., 2001; Manville et al., 2002; Fülöp, 2004; Kataoka, 2005). Thus, pumice is incorporated into the sedimentary record as bedload clasts in the main bedforms generated by hydraulic variations.

4. Experimental Methods

3.3.1. Volume of vesicles in Pumice

The experiments were carried out with pumice from a quarry under exploitation. Various samples from the Canary Islands (quarry of Cantos Blancos del Sur SL, Tenerife) were examined to better understand the volume of vesicles and their network in pumice. The dry and saturated weights of each sample were evaluated on the assumption that the proportion of (cold or lukewarm) water that could penetrate the dry pumice clasts during the experiments is not significant. The volume of each pumice sample was then calculated. A mechanical device was employed to sink the pumice in a beaker filled with water. The errors in the detailed measurement of the free water surface level in the beaker were attributed to the surface tension of the water, which produced a meniscus. To minimize errors, a pipette was used to transfer water to the beaker until the maximum level was reached and the first overflow was produced. The volume of displaced water was controlled by means of high precision scales.

For each sample, the volume and weight in dry conditions were determined and compared with the weight of the sample whose vesicles were filled with water. The volume of pulverized pumice (1 g) was calculated. Only when all these values were obtained was it possible to determine the ratio of the vesicles and their network of in the pumice, attaining values of about 80% and 90%, respectively (Table I). These findings are consistent with the results of other authors (e.g., Klug et al., 2002).

3.3.2. Hydraulic equivalences of pumice clasts and sediment grain-sizes

A sound understanding of the hydraulic equivalences between the pumice clasts and the sand is necessary to obtain the adequate pumice size to simulate the sedimentary deposit in the laboratory. Using Stokes' law to describe the depositional characteristics, it can be shown that the ratio of falling particle sizes depends on the effective densities of the particles. The value of the quartz density used in the flume experiment was 2.65 g/cm^3 and sand grains were medium sized (0.25 to 0.5 mm). Water filled pumice samples of the Huarenchenque Fm had densities ranging between 1.56 g/cm^3 and 1.43 g/cm^3. The calculation of equivalent diameters of quartz and pumice using different equations (Rubey ,1933; Tourtelot, 1968; Jutzeler et al., 2015) yields a pumice diameter 6 to 10 times greater than those of quartz grains (about 3 to 5 mm). After the pumice clasts (and/or shards) sink in an active fluvial environment they are mixed with the clastic sediments carried by the turbulent currents and are incorporated into the sedimentary record as part of the cross bedding or cross lamination.

3.4. Experimentation

A series of experiments with a mixture of sands and pumice clasts was undertaken in order to elucidate the behavior of pumice and other clasts of different densities.

3.4.1. Sedimentary experiments

The experiments were carried out at the Assut-1 flume in the SIMGEO laboratory of the Faculty of Earth Sciences at the University of Barcelona to study a number of tractive primary sedimentary structures. These bedforms were produced by the transport of a mixture of quartz sands and pumice clasts. The pumice clasts sank rapidly in a beaker of water at room temperature following exposure to steam.

3.4.2. Flume characteristics

The Assut 1 flume consists of a watertight channel of 15.20 m useful length, 37 cm in width and 40 cm in depth (Fig. 7). The lateral walls consist of reinforced glass panels that allow the experiments to be visible without distortion. The metallic floor is mechanized to eliminate any irregularities that could increase the flume drag. The system is supported by a rigid structure that allows neither flexures nor significant torsion. An elevation device enables the simulation of variable gradients. The elevation is produced by hydraulic cylinders that act upon the channel structure that pivots on a large hinge. The channel has two sluices: one for the entry (apical area) and another for the evacuation (distal area) of water flow. The effective depth of flow is controlled by the position of the sluices that are driven by electrical mechanisms. Water, which circulates in a closed circuit from the apical to the distal ends of the channel, proceeds from a water storage tank equipped with a pump that drives the flow round the circuit and then into a tank for sediment decantation, whence it is driven by means of another pump to the initial water storage tanks.

3.4.3. Experimental procedures

The first experiment was carried out in a flume (Assut-1) placed in the building of the Faculty of Earth Sciences of the Barcelona University (Fig. 9A) with pumice samples from the Canary Islands and from Huarenchenque and la Rinconada (locality close to Huarenchenque Fm outcrops). Pumice samples from Iceland and Turkey were also used for comparison. A volume of about 10 liters (l) of pumice fragments with a grain-size between 3 and 5 mm was used. A volume of about 60 l of quartz sand with a median grain size (0.5 – 0.25 mm) was also employed. In one experiment, the channel system was inclined, attaining a height of 155 cm, equivalent to a general dip of 0.3º and maintained in the same position throughout the process. The distal sluice had an angle of 60º that controlled a hydraulic jump generated at 6.5 m from the end of the channel. The water supply was fixed at 10,000 liters/hour (l/h), which corresponded to velocities of about 1.26 to 1.34 meters/second (m/s) at point 1 (Fig. 8). The linear water velocities are measured by means of MiniAir 20 current meter (provided by Schiltknecht, a Swiss Company) at the points indicated in figure 8. After the hydraulic jump (a) between the points 1 and 2, the velocity fell to about 0.38 to 0.42 m/s in points 3 and 4 respectively, whereas downstream the velocities ranged from 0.31 to 0.09 m/s (6, 7 in Fig. 8), which facilitated the generation of different types of tractive primary sedimentary structures. Once the flume was stabilized, half of the sand (30 l) was added, contributing to the generation of bedforms downstream of the hydraulic jump. By contrast, at the other end of these sandy deposits, the velocities ranged from 0.09 to 0.15 m/s, resulting in the accumulation of very fine to fine-grained sands. Thereafter, pumice samples were incorporated into the sediment and the experiment continued until stabilization was achieved. Thus, the bedforms were stabilized as a function of the grain-size of the clastic sediments and of the water depth and flow velocity. Subsequently, the other half of the sand (30 l) was added and the experiment continued for a further 30 minutes, resulting in an accumulation of a pumice-dominated bed. This was then reworked and the pumice clasts were carried away together with the sand, generating different cross laminations with pumice clasts mixed with sandy sediments (B to F in Fig. 9). In another experiment, the position of the terminal sluice from 60º to 45º was changed. Thereafter, the initial sedimentary accumulation underwent erosion and all the sandy materials mixed with small pumice clasts were transported to the end of the flume. The accumulated materials show sand-dominated and pumice-dominated intercalations in tabular deposits. The pumice-rich layers are not planar but have a gentle lenticular morphology (Fig. 9 B). The mixed megaripples of medium sand and pumice are prominent (Figs. 9 C, D, E and F), displaying characteristics similar to those studied at the outcrops of Huarenchenque Fm.

4. Results of pumice clasts

It is common knowledge that pumice is generated at high temperatures in domes and in pyroclastic flows (Fisher and Schmincke, 1984; Jokiel and Cox, 2003). In our study, the theoretical high temperatures of the pumice-dominated pyroclastic flow placements were simulated to determine their values. However, the increase in temperature in the oven (600ºC - 750ºC) led to the melting of the Huarenchenque Fm pumice samples, which resulted in the irreversible closure of the vesicles. Heating pumice samples at variable temperatures (300ºC – 600ºC) produces their partial melting. Once the hot samples were placed in water, a number of micro fractures appeared and water penetrated the pumice, causing the samples to sink. Consequently, pumice buoyancy was lost.

By contrast, in the case of the Huarenchenque Fm samples, the buoyancy of the interstratified pumice was not affected. This strongly suggests that the temperature range of the pumice-rich pyroclastic flows were equal to or lower than 300ºC, when these reached the Agrio River. These values are consistent with those obtained by other authors (Banks and Hoblitt, 1981; Cas and Wright, 1987). At the end of the experiments and after a short drying period, buoyancy was restored in the pumice that did not undergo any significant change such as cementation or fracturing. Pumice buoyancy was recovered when sampling in the field outcrop. It strongly suggests that the pumice internal structure remained intact when the pumice-rich flow reached fresh shallow waters.

4.1. Sinking processes of pumice

The presence of pumice clasts in a number of conglomeratic successions (Fig. 10 B, D) affords strong evidence that they sank and transported together with clastic sediments. Thus, in a non-marine context as is the case of the Huarenchenque Fm, the increase in density of pumice clasts probably occurs during sediment transport by hydraulic flows. Our study of the internal structure of pumice and their mixing with other clasts in the sedimentary record provides fresh insights into pumice behavior. Despite the existence of isolated vesicles that contribute to pumice buoyancy, electronic microscopy (DADES DEL MICROSCOPI) reveals that the vesicles are interconnected by tiny ducts (Fig. 10 E, F) that facilitate sinking. Buoyancy is normally attributed to the high vesicularity of pumice. If the vesicles are isolated (very low permeability) they cannot retain enough water and the density remains below 1 g/cm^3. By contrast, and in several cases during pumice generation, some of the remnant gas may be trapped in bubbles (Fauria et al., 2017) and buoyancy is maintained. However if the vesicles are interconnected (high permeability) the air or gas can be displaced by water, resulting in density values >1 g/cm^3. The surface tension of water also prevents air or gas from leaving the ducts. In our experiments, the best results of sinking processes were obtained from the interaction of steam with the pumice clasts when these were placed in water.

5. Geochemical and mineralogical data

Pumice samples of different origin and composition were obtained for comparison from the Canary Islands (Spain), Snaefellsnes and Askjia (Iceland), Erciyes Dagi (Turkey) and from La Rinconada in the Neuquén basin (Argentina). The chemical analyses of this pumice reveal a wide compositional range (Tabl. II).The samples from the Canary Islands (La Granadilla area, Tenerife) are phonolites whereas those from Iceland are mainly trachytes and dacites. The pumice samples from Turkey are rhyolites and the ones from Huarenchenque (FHCH) and La Rinconada are dacites with the exception of samples 8, 9 and 10 (FHCH), which are andesites. Despite their compositional diversity, no significant differences were observed in their sinking processes.

The geochemical characteristics of all the samples were studied by means of bulk-rock X-ray fluorescence for major elements. To this end, an energy dispersive X-ray fluorescence spectrometer (S2 Ranger, Bruker/AXS GmbH, Germany) equipped with a Pd target X-ray tube was used. The sample was homogenized and crushed in an agate mortar until a grain size not exceeding 125 microns was attained. Material for analysis was prepared to obtain pressed powder pellets in accordance with the procedures detailed in Marguí et al., (2009). Four scan runs for each sample were obtained at 10, 20, 40 and 50 kV. The recorded EDXRF spectra were evaluated to determine their elemental composition using the empirical calibration model consisting of twenty certified reference materials. The results were processed by the software package (DADES DEL SOFTWARE) linked to the instrumentation. Ten major elements (Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K and P), which were converted into oxides, were analyzed. Total iron was expressed as Fe_2O_3. Analytical precision exceeded ±2.5% (relative) for all major elements. The results were plotted in a total alkali-silica diagram for chemical classification (Le Maitre et al., 2002) of volcanic rocks (Fig. 11). According to these authors, each analysis was recalculated to 100% on an H_2O and CO_2 free basis (Table II). Samples of pumice from the Huarenchenque Fm are clearly plotted in the subalkaline field and are mainly classified as dacites, and a few, as andesites. All of the pumice samples show a significantly lower alkali content when compared with the main evolutionary trend of the rocks from the Copahue-Caviahue volcanic complex and other volcanic centers of the region (Kay et al., 2006) and most of them have a high silica content (63-70%). By contrast, a basaltic pebble from the same formation plots as a trachybasalt on the alkaline/subalkaline border. This rock, although slightly differentiated, has a similar composition to that of the olivine basalts of back-arc from the Loncopué trough (Varekamp *et al.,* 2006) in the Caviahue zone. The mineralogical study was carried out by means of X-ray diffraction (XRD) analysis following the powder diffraction methodology for bulk composition and oriented aggregates deposited onto a glass slide for identification of clay minerals. XRD spectra were obtained in a Bruker diffractometer (D2 Phaser model) equipped with a Cu target tube and a Linxeye detector. The Huarenchenque samples are mainly amorphous, with low crystallinity, showing small peaks that allow the identification of at least five mineral phases (smectite, K-feldspar, amphibole, pyroxene and quartz). The identification of the precise mineral species is currently not possible owing to the low intensity of the identifiable peaks.

6. Discussion

The most striking finding of this work is that pumice clasts mixed with sands give rise to diverse types of cross bedding and cross laminations. It is noteworthy that basalt clasts and sands are mixed with some pumice clasts. This seems a paradox given that large pumice clasts are usually buoyant in cold water for long periods (Manville et al., 1998; Witham and Sparks, 1986) and sink with difficulty. Several studies (Richards, 1958; Jokiel and Cox, 2003; Frick and Kent, 1984; Mandeville et al., 1996; Pattan et al., 2008; Risso et al., 2002; Coombs and Landis, 1966) have documented transport of floating pumices over oceanic distances. Although pumice clasts are usually buoyant in cold water, experiments carried out with boiling water and steam resulted in a rapid sinking of pumice due to the displacement of internal air and other gases by steam with the consequent absorption of water.

A simple experiment (Bargalló et al., 2013) demonstrates how the air in the vesicles is displaced by steam whenever the pumice fragments are in contact with boiling water. When the pumice is placed in cold or lukewarm water, the temperature drops below the boiling point, resulting in rapid condensation. Consequently, the resulting vacuum sucks the water into the vesicles, giving rise to pumice saturation (waterlogging). All the pumice samples have an interconnected vesicularity and their exposure to steam is the main reason for their immediate sinking. One reason for the increase in density of these pumice clasts could be that the steam penetrates their vesicles and cools. Large amounts of steam were generated as the hot pyroclastic density current reached the shallow waters of the Agrio fluvial system. In theory, some pumice samples could be filled with different mineralogical assemblages, considerably increasing their density, which would facilitate recycling and incorporation into the transported sediments. This, however, is not the case of the pumice clasts of the Huarenchenque Fm given the lack of evidence.

In the Neuquén Basin, the basalts of different origin (González and Vergara, 1962; Pesce, 1989) accumulated 45 My (Folguera and Ramos, 2000). It is noteworthy that the largest volumes of basalts are not older than the Pliocene (Ramos et al., 2011). The basalt clasts display different morphologies from subangular to well and very well rounded, which suggests that their transport was produced by rolling and impact processes. Some subrounded basalt clasts such as second-generation clasts indicate that the previously accumulated fluvial clastic materials were reworked. The well rounded pumice clasts also suggest that they had undergone repetitive impacts (erosion) during transport. Trituration generated numerous fragments (shards) of pumice (Pattan et al., 2008) that were incorporated into the unsorted sandy matrix. Thus, the pumice clasts increased in density and were transported as bedload by large discharges. It should be noted that locally the rounded pumice and basalt clasts are of similar size because the fragile clasts (pumice) were easily eroded during transport. Large number of fragments were incorporated into the cross bedding of the blue sands as a result of the generation of different bedforms (hydraulic dunes, megaripples).The vesicles of pumice have a network of tiny ducts that allow the air-steam-water interchange. The experiments carried out in the flume (Assut-1) provide ample evidence that the pumice and sands accumulated together. If water had not penetrated the vesicles, buoyancy would have remained intact and the pumice would not have been incorporated into the fossil record generating primary sedimentary structures. The most reasonable explanation for the immediate sinking of pumice clasts was the steam produced by the hot pyroclastic flow as it came into contact with shallow fresh water. In marine environments, submarine turbidity currents are generated when the subaerial pyroclastic density current reaches water at the shoreline (Jutzeler el al., 2017). In the conglomerate deposits, the mixing of pumice and basalt clasts suggests that these clastic materials were transported together. In contrast, the sandstone deposits display marked variations in grain-size. Thus, white (pumice-rich) sandstones are coarser than blue (basalt-rich) sandstones because of the hydraulic equivalence phenomenon. The cross bedded sandstones and conglomeratic sandstones show foresets in the blue sands and in the pumice-dominated materials owing to hydrodynamic variations during their transport. The coarse materials were poorly-sorted compared with the sandy ones, suggesting that the rapid discharges and short flow duration prevented sorting of the clasts despite their density contrast. The mixing of similar-size high-density and low-density large clasts in the poorly sorted and cross stratified conglomerates was brought about by the activity of supercritical flows and not by high-density (hyper concentrated) flows. Thus, the behaviour of these high-density flows do not allow the good development of cross-bedding. The large cross bedding was due to the accretion in the frontal area of the diagonal or transversal fluvial bars in a braided context and not generated by migration of megaripples or hydraulic dunes. By contrast, the sandstones and micro conglomeratic sandstones display textural variations because of the differentiation of clasts produced during transport by subcritical hydraulic flows. It should be noted that the marked large incision in the cross bedded conglomerates is asymmetrical (Fig. 5). Initially, a major incision was generated by a heavy discharge. Thereafter, a local cementation or hardening (approximately 10 cm thick) of the scar surface probably occurred as a result of the accumulation of volcanic ash. This contributed to the preservation of the scar geometry after a subsequent discharge. The dip of prominent foresets to the SE could have been produced by a subtle variation in flow direction or by a marked increase in flow velocity. This event was probably without significance and the scar geometry would have been maintained since the basal scar was modified by a high velocity flow. But if the original geometry had been protected by the hardening of the scar surface, the subsequent discharge would have led to a downturn in the dip of the conglomeratic foresets to the SE. This was due to a combination of high-energy events of gravel transport. The sedimentary context was probably made up of longitudinal and transversal bars that were generated in a gravel-dominated sedimentary environment (braided) that underwent high discharges due to extensive snowmelt or ENSO "El Niño Southern Oscillation" (Markgraf, 2001) episodes. Although it is not possible to rule out some episodes of the ENSO such as the origin of large discharges which could have affected the generation of the Huarenchenque Fm, no clear evidence for this was found. Thus, these high magnitude discharges were therefore caused by extensive meltwater as a result of the rapid Andean Last Glacial Maximum deglaciation (Hulton et al., 2002; McCulloch et al., 2000). Other possibility for the generation of sudden and large discharges could be related to the eating of the volcanic edifice covered by thick snow accumulations, when the magma reaches the surface resulting in a strong snowmelt. The fluvial lithofacies described are typical of stream flow deposits and are the result of rapid accumulation under fast-moving, sediment-laden turbulent flows in gravelly braided streams with laterally unstable channels. Ample evidence for this is provided by the scoured basal contacts, imbricated clasts, clast-supported texture, and the absence of intervening fine-grained deposits (Miall, 1977, 1978; Rust, 1978). Conglomerates, gravelly sandstones and sandstones are interpreted as bedload deposits. Horizontally laminated and low-angle inclined beds and reverse-oriented cross-stratified sets indicate high energy supercritical flash flows. Trough and laterally continuous bedsets of conglomerates were generated by frontal accretion of longitudinal bars, whereas sandstone trough cross-bedded sets were deposited by waning flows as a result of downstream migration of 3D dunes on bar tops and along their margins or in secondary channels of the braided fluvial system. Cross-bedded lenticular conglomerate lithosomes Gt(2) with a marked decrease in the dip of foresets downstream (Fig. 5) are interpreted as the infill of isolated pools by frontal and/or oblique bar progradation (Khadkikar, 1999). Moreover, the crudely stratified conglomerates (Gm) were deposited by rapid suspension fallout with some traction on the bed owing to turbulent hyperconcentrated flood flows (Smith, 1986; Sohn et al., 1999).

The LT(1) facies is a pyroclastic fall deposit accumulated rapidly. The facies LT(2) rapidly accumulated due to pyroclastic density currents without tractional grain segregation (Branney and Kokelaar, 2002). Variable grading patterns of lapilli clasts strongly suggest a progressive aggradation because of turbulent pyroclastic density currents in association with the waxing and waning of volcanic eruptions (Sohn et al., 2013). The pyroclastic couplets of facies LT(3) were produced by the passage of single density stratified surges such as those recorded in modern eruptions (Fisher, 1990; Edmonds et al., 2005; Vazquez and Ort, 2006). In such a context, the ash and lapilli tuff cross-stratified set represents the downstream migration of surge-induced “progressive” sand waves or dunes (Schmincke et al., 1973; Cole, 1991; Gençalioğlu-Kuşcu et al., 2007).

Chemical analyses of the clasts of pumice from the Huarenchenque Fm are not consistent with the trend of the main volcanic rocks (Fig. 11) of the Copahue-Caviahue volcanic complex (Kay et al., 2006; Ramos and Kay, 2006; Varekamp et al., 2006; Petrinovic et al., 2014). Thus, it is highly unlikely that these materials originated in the Copahue volcanic area. The volcanic flows which carried the pumice clasts to the former course of the Agrio river could not have spread over so many kilometers from the volcanic vent. Consequently, the primary origin of these volcanic materials must be traced to the areas surrounding the outcrops of the Huarenchenque Fm. Thus, the volcanic vent was probably located in the nearby uplift of Copahue-Pino Hachado. Rahue and Butahuo volcanoes are only about 30 km to the west and the latest eruptions have been dated at only 1 Ma (Tunstall and Folguera, 2005; Folguera and García-Morabito, 2006).

7. Concluding remarks

In theory, pumice clasts are buoyant if their vesicles are isolated. However, if the vesicles are interconnected by tiny ducts, their buoyancy remains intact since cold water does not penetrate the vesicles. But water is able to penetrate pumice without difficulty under certain conditions. The sinking capacity of pumice clasts was borne out by experiments in which pumice was exposed to a column of steam. Samples from Iceland, Turkey and Argentina also underwent experiments in a steam column. The behavior of these samples matched that of the specimens from the Canary Islands. These samples sank rapidly when placed in a beaker filled with water at room temperature. Although sinking capacity does not depend on the chemical and mineralogical composition of the pumice, it does depend on the number of vesicles and on their fabric characterized by vesicle micro-connections. The vesicular interconnectivity may attain high values. As the hot pyroclastic flow comes into contact with water a large amount of steam is produced. The shallow water and the large surface area, facilitated the generation of great amount of steam. The pumice clasts that increase in density sink rapidly and are incorporated into the geological record. This may account for the outcrops of the Huarenchenque Fm where the pumice clasts are mixed with basalt clasts in the conglomerates and with basalt grains in the sandstones. Since the area offers very little evidence of a main fluvial valley or palaeovalley in the proximity of the present Agrio River, we may assume that this river followed the same course from the Pliocene to the

Present. A large discharge is essential for the transport of the basalt-dominated clastic sediments. The contact of the pyroclastic flow with the snowy areas at high altitudes near the Pino Hachado Caldera probably resulted in high magnitude discharges. Such discharges attain velocities that carry vast amounts of high-density clasts without sorting during transport. These discharges are able to rework temporary dams in fluvial valleys that are obstructed by pyroclastic or other deposits carrying many outsized clasts of local origin. In the flume experiment, the behavior of the flow resulted in an accumulation of cross bedded sediments (mixture of sand and pumice) has a pattern similar to that of the facies displayed in the Huarenchenque Fm outcrops. The sedimentary accumulation after the experiment shows a number of small units limited by scars. The lower unit is characterized by large scale and low angle cross bedding overlain by a central unit constituted by cross-laminated sands. The upper unit is made up of sandstones with plane beds. The lower unit consists of sands deposited by critical flow (upper flow regime) whereas the central unit corresponds to ripple progradation. The upper unit was also deposited by critical flow (upper flow regime). The outcrop of the Huarenchenque Fm exhibits a similar vertical trend. The lower unit (layer), which displays large scale and low angle cross bedding, was brought about by heavy discharges under critical conditions. The central unit resulted from the accumulation of basalt-dominated sandy and clastic materials from hydraulic dunes/bars, giving rise to transverse fill cross bedding under subcritical conditions. The upper unit was produced by a large discharge that led to the generation of plane beds and other associated bedforms. This suggests that the sedimentary accumulation was episodic and that the variations in water velocity were brought about by significant changes in discharge and in the snowmelt due to subsequent eruptions of the Pino Hachado caldera.

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FIGURE CAPTIONS

Fig. 1. Location of Huarenchenque in the Neuquén basin (upper left) in Argentina (upper right). The box indicates the area under study. The main outcrops are along the Agrio river banks.

Fig. 2. Outcrop at 38º 18’ 22.5” S and 070º 36’ 09.9” W, near Huarenchenque where the basalt-rich scree deposits predate the first volcanic materials (facies LT (1), LT(2)). The pumice clasts are the white ones. The position of samples FHCH 0- 8 is displayed. Overlying these materials are (shaded) fluvial deposits (facies Gt). The basalt clasts (rounded) and fragments (angular) are the black ones. The upper part is made up of basalt-rich scree accumulations. The legend for the clasts and fragments is the same in all the figures.

Fig. 3. Outcrop at 38º 18’ 52.4” S and 070º 35’ 39.3” W near Huarenchenque. The fluvial deposits are interfingered with volcanic materials.

Fig. 4. Outcrop at S 38º 19’ 15.4” S and W 070º 35’ 10.9” near Huarenchenque, where the fluvial deposits predate the volcanic materials that are overlain by other fluvial deposits. The intercalation of a massive conglomerate level (Gm) is noteworthy. The position of the sample FHCH 10 is displayed.

Fig. 5. Outcrop of the Huarenchenque Fm at S 38º 31’ 17.0” S and 070º 24’ 28.7” W and the distribution of the main cross stratified deposits. Flow is from right to left. The main facies are depicted by their specific codes.

Fig. 6. Detailed aspects of the outcrop displayed in Figure 5. (A) Lower unit of Sl. (B) Close up of the low angle and large scale cross bedding with imbricated clasts. (C) Pumice-rich layer (small, rounded, light colored clasts) over cross-bedded blue sands. (D) Trough cross bedding caused by progradation of hydraulic dunes. Close up of St (facies) in figure 5B. (E) The pumice-rich

lineation (light colored shards) denotes asymptotic cross bedding. (F) Blue sands facies intercalated with prominent pumice-rich laminations.

Fig. 7. Conceptual arrangement of the Assut-1 flume. Floodgate dip variations during the experiment. (A) The upper position of the terminal floodgate (angle k) controls the position of the hydraulic jump (a) and the position (xa-xb) of the deposit of sediments that display diverse bedforms (a-b). (B) The lower position of the terminal floodgate (angle k’) results in the reworking and progradation of previously accumulated sediments. Note the shift of the sedimentary deposits towards the flume exit and also the reduction of the distance from the position (xa’ and xb’) of the deposits towards the end of the flume.

Fig. 8. Punctual variations of flow velocity that affect the sedimentary accumulation in the Assut-1 flume during the initial experiment (Fig. 8). Average velocities in meters per second (m/s) at the numbered points: (1).- 1.30 m/s; (2).- 0.53 m/s; (3).- 0.42 m/s; (4).- 0.38 m/s; (5).- 0.43 m/s; (6).- 0.31 m/s; (7).- 0.09 m/s; (8).- 0.15 m/s.

Fig. 9. (A) Assut-1 flume in the SIMGEO laboratory; (B) Lenticular accumulation of pumice at the toe of the foresets of the main sedimentary form. Flow towards the observer. The flume is 37 cm in width; (C) Progradation of the bedform towards the right. The internal structure of the bedform is displayed by the interfingering of pumice-rich and sand-rich laminae. Scale in centimeters; (D) Cross-bedding generation as a result of the addition of sand when the bedform progrades to the left. Scale in centimeters; (E) New progradation to the left and

superimposition of the bedforms. Scale in centimeters; (F) Two superimposed cross bedded deposits accumulate at the end of the experiment. The internal structure of both deposits is magnified by alternation of sand-rich and pumice-rich foresets prograding to the left. The pumice clasts are therefore transported together with the siliceous sands. Scale in centimeters.

Fig. 10. (A) Rounded composite cobble of the conglomerate deposits of the Huarenchenque Fm. A mixture of pumice clasts (1) and basalt clasts (2) are shown. (B) Well rounded basalt clasts (dark) displayed together with pumice clasts (light). Pencil tip for scale. (C) Pumice clasts from the Snaefellsnes volcano (Iceland) treated with steam are displayed at the bottom of a beaker filled with lukewarm water. Coin (24 mm across) for scale. (D) Basalt-dominated conglomerates with poor sorting. Note the subrounded basal clasts mixed with rounded ones. Pencil is 15 cm in length. (E and F) Electron microscope images of pumice clasts from the Canary Islands. (E) Original image. (F) Vesicle interconnections (Red highlights). The small size of the vesicle interconnections is noteworthy. The scale is the same in both images.

Fig. 11. Plot of the volcanic clasts included in the Huarenchenque and Rinconada (FR) Formations on the TAS diagram (Le Maitre et al., 2002). Filled circles: pumice; rhombus: basaltic clast. Crosses: pumice analyses from other compositions used as comparison in this work. SN: Snaesfellnes, Iceland; ER: Erciyes Dagi, Turkey; AS: Askjia, Iceland; AR: Arico, Canary Islands (Alonso et al., 1988). Open symbols show the scattering of Plio-Quaternary volcanic rocks

from the Copahue-Caviahue volcanic complex (Varekamp et al., 2006). Triangles: Copahue; squares: Caviahue.

Table I. Characteristics of some pumice samples from the Canary Islands used in the flume experiments.

Table II. Major-element compositions of volcanic rocks studied in this work. Samples labeled FHCH- (except FHCH-9b) are pumice pebbles from the Huarenchenque Formation. Sample FHCH-9b is a basalt pebble from the same conglomerate as the pumice FHCH-9. FR is pumice from the Rinconada Formation. SN, ER, AS, and AR are pumice from other localities and compositions. SN: trachytic pumice from Snaesfellnes, Iceland; ER: rhyolitic pumice from Erciyes Dagi, Turkey; AS: dacitic pumice from Askjia, Iceland; AR: phonolitic pumice from Arico, Canary Islands (Alonso et al., 1988). Following Le Maitre el al. (2002) each analysis was recalculated to 100% on an H_2O and CO_2 free basis.