



Taphonomy and depositional environment of a Lower Cretaceous monospecific dinosaur bone assemblage (Puesto Quiroga Member, Lohan Cura Formation), Neuquén Province, Argentina

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ABSTRACT

The Puesto Díaz Quarry (Lohan Cura Formation, Lower Cretaceous of Neuquén Basin, Argentina) consists of a monospecific dinosaur bone assemblage that includes 126 specimens from, at least, three individuals of the rebbachisaurid sauropod *Comahuesaurus windhausenii*. The bonebed was originated as a debris flow of an ephemeral-river bed, in distal areas of low relief. Bones are disarticulated, three-dimensionally distributed through the host facies, showing a normal grading arrangement, which can be correlated with the size, shape and hydraulic behavior inferred for each specimen. Taphonomic evidence suggests that the bones did not experience a prolonged transport, and that these were quickly buried by the debris flow event. The fact that there are more than one individual of the same species suggests a mass mortality by a catastrophic event. Scattered skeletal elements would indicate that the corpses must have been subaerially exposed, long enough to allow disarticulation by scavenging, decay, and defleshing.

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1. Introduction

The Lower Cretaceous continental deposits of the Neuquén Basin have yielded relatively few dinosaur bones. Most fossils have been recovered from La Amarga Formation (Bonaparte, 1986, 1996b; Chiappe, 1988; Salgado and Bonaparte, 1991; Salgado et al., 2006; Apesteguía, 2007), whose age has been estimated by Leanza (2003) as Barremian-early Aptian.

The Lohan Cura Formation, of presumed Aptian-Albian age, was formally established by Leanza and Hugo (1995) and consists of a sequence of red beds, 177 m thick, bounded by the Pichinequenian and the Patagonidican unconformities (Leanza, 2009). According to these workers, the Lohan Cura Formation can be divided into two members, in ascending order, Puesto Quiroga and Cullín Grande (Leanza and Hugo, 1997). This last unit has yielded diverse vertebrate fossils, mainly represented by the sauropods *Agustina ligabuei* (Bonaparte, 1999) and *Ligabuesaurus leanzai* (Bonaparte

et al., 2006), as well as fish, chelonian, crocodilian and theropod dinosaur remains (Martinelli et al., 2007).

The fossiliferous locality in the lower section of the Lohan Cura Formation, referred to as Puesto Díaz Quarry, is situated approximately 48 km to east of Catar Lal town (Fig. 1), on northern slope of Cerro Aguada del León, south central Neuquén Province, Argentina ($39^{\circ} 34' 54.3'' S$; $70^{\circ} 5' 18.8'' W$). The sauropod assemblage from the Puesto Díaz Quarry is dominated by postcranial remains of, at least, three individuals of the rebbachisaurid sauropod *Comahuesaurus windhausenii* Carballido et al. (2012). This bone bed constitutes the first record of fossils remains from the Puesto Quiroga Member (Salgado et al., 2004).

Here, we present a study on the taphonomy and depositional environment of this locality, and discuss some of the previous interpretations on the paleoenvironment of the Puesto Quiroga Member of the Lohan Cura Formation.

2. Methods

A trench approximately 32 m long, 2.5 m wide, and up to 2.00 m deep was excavated in order to expose the bone bed. Approximately 150 m³ of sediment were removed from the quarry during

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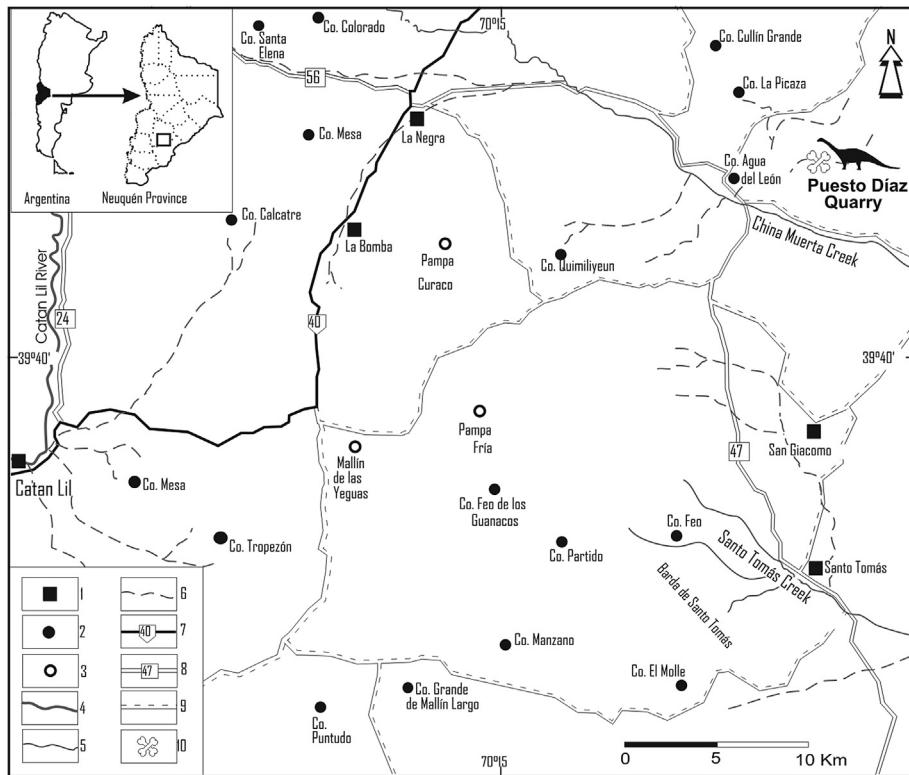


Fig. 1. Location map. References: 1 = village, 2 = hill, 3 = geographical spot, 4 = river, 5 = creek, 6 = ephemeral creek, 7 = national route, 8 = provincial route, 9 = trail, 10 = saurropod quarry.

four weeks of excavation conducted in December, 2002 and May, 2004.

The quarry map was compiled using a meter grid linked to the lower contact plane of the bed, and orientations of elongate skeletal elements were measured using a Brunton compass. The position of the bones respect to the base of the bed was measured using a tape.

Stratigraphic sections were measured and described during the field work. Surficial characteristics of the bones were studied both in the quarry and in the laboratory after preparation. The rock-color codes employed in the lithological description correspond to the "Rock-color Chart Committee" (1991) published by the Geological Society of America.

Finally, the grain-size analysis of the sediments was made following the conventional method of screening, in the petrological laboratory of the Mining Bureau of the Neuquén Province (Argentina).

3. Geologic setting

The Lohan Cura Formation represents a continental phase of sedimentation, following the last Mesozoic Pacific transgression of the Neuquén Basin. This phase was characterized by the emplacement of extensive alluvial plains, developed in a back-arc basin controlled by thermal subsidence during the Aptian and Albian times (Andreis, 2001). This unit was deposited close to the southern margin of the basin, occupying the area of the named Picún Leufú Sub-basin (Hogg, 1993; Leanza and Hugo, 2011). Toward the northern area of the Neuquén Basin (main depocenter), The Lohan Cura Formation can be correlated with the muddy lacustrine and saline lake deposits of the Rayoso Formation (Leanza and Hugo, 1999; Leanza, 2003; Zavala et al., 2006, Fig. 2). In this last case, arid conditions were inferred for its depositional environment (Vallati, 2006; Zavala et al., 2006).

Leanza and Hugo (1995, 1997) subdivided the Lohan Cura Formation into two members: in ascending order, Puesto Quiroga and Cullín Grande. According to these workers, the Puesto Quiroga Member consists of an 85 m thick succession of red color, medium to fine-grained sandstone and mudstone, with intercalated thin gray siltstone levels. In the lower part of the section, small conglomerate lenses and paleochannels are present. Previous studies have correlated this lower member with the Bajada Colorada Formation (Leanza and Leanza, 1979; Rolleri et al., 1984), with the uppermost part of the Rayoso Group, or with the lower units of the Neuquén Group (Foucault et al., 1987). All these correlations have been made mainly on lithological bases, although lacking of detailed sedimentologic, paleoenvironmental and/or regional correlation studies. However, according to the recent regional lithostratigraphic scheme proposed by Leanza (2003), the Puesto Quiroga Member is correlated with the Rincón and Quili Malal members (lower section of the Rayoso Formation), and ascribed to the upper Aptian (Fig. 2). This last scheme has been elaborated on the basis of paleogeographic, paleoenvironmental, and microfossil data (Leanza, 2003).

The overlying Cullín Grande Member is a 95 m thick package of red-beds consisting of interbedded, coarse-grained sandstone, and thin mudstones. Traditionally, these deposits have been correlated with the Candeleros Formation (Cenomanian) of the Neuquén Group (Leanza and Leanza, 1979; Rolleri et al., 1984). However, Leanza (2003) correlated the Cullín Grande Member with the Pichi Neuquén and Cañadón de la Zorra members (Albian, upper section of the Rayoso Formation).

In the Puesto Díaz fossiliferous site, the Puesto Quiroga Member is 69 m thick, while the bone assemblage is situated approximately 55 m from the base (Fig. 3). In this area, the Puesto Quiroga Member is conformed in more than 90% of the total thick by dark red, massive to laminated mudstones, with thin intercalations of

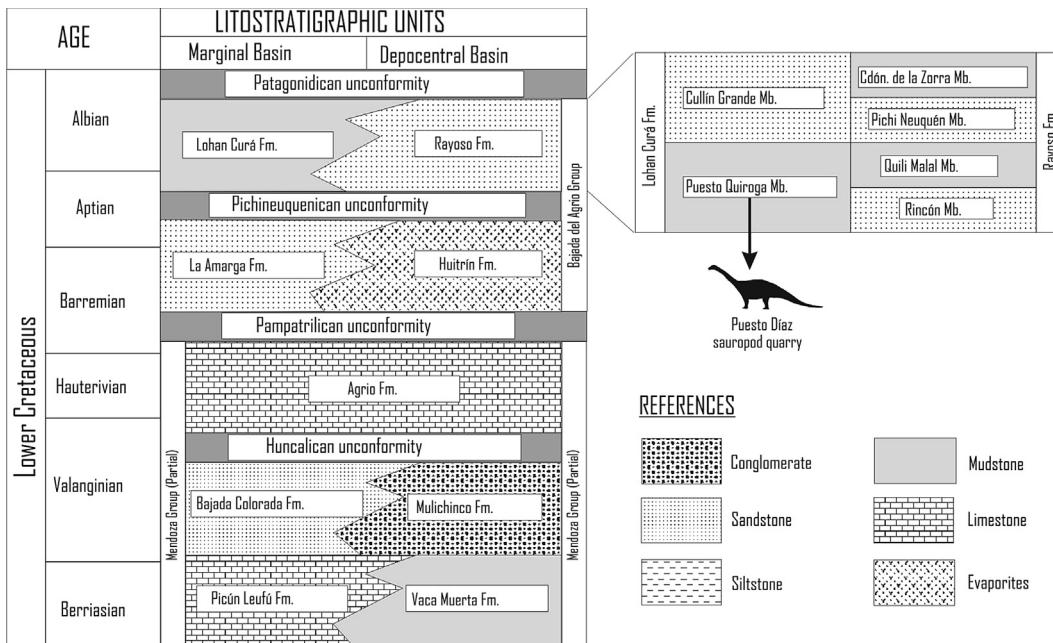


Fig. 2. Stratigraphy scheme of Lower Cretaceous strata of Neuquén Basin.

greenish-gray, massive, fine-grained, quartzitic sandstones, and scarce tuffaceous levels (Fig. 3). Discontinuous, poorly preserved caliche horizons and faint root traces occur frequently within the muddy beds.

Large scale sandstone bodies are scarce, being represented by isolated, ribbon-like, channelized forms with an average thick of 1 m, reaching exceptionally a maximum thickness of 2 m. The apparent lateral extension of these bodies in cross-section rarely exceeds 11 m (Fig. 4). These deposits are conformed by yellowish gray, medium to coarse-grained quartzitic sandstones. Their basal contact is clearly erosive, and is commonly accompanied by abundant pelitic intraclasts and small fine-grained conglomeratic lens. Internally, these bodies contain an association of sedimentary structures conformed by planar cross-stratification, trough cross-stratification, low angle cross-stratification and horizontal stratification, indicating a dominant tractive transport mechanism during sedimentation. The architectural elements recognized in these deposits (*sensu* Miall, 1996) are conformed by sandy bedforms and reduced-size lateral accretion macroforms, suggesting the developed of small-size, sinuous channels (Shepard, 1987; Miall, 1992, 1996).

The presence of a dominant muddy succession with scarce, small, and isolated channel bodies, allows inferring the existence of a distal, poorly developed fluvial drainage network. In this sense, the occurrence of sinuous, single-storey channel-bodies is consistent with the development of an ephemeral fluvial distributary system in medial to distal alluvial fans, where the decrease in slope enables the generation of less confined and more sinuosity water courses (Allen et al., 1983; Nichols and Fisher, 2007). Sporadic unconfined flood deposits are represented by the occasional occurrence of the thin tabular, fine-grained sandy bodies (Tunbridge, 1981; Collinson, 1986; Bridge and Demico, 2008). The abundance of caliche in paleosoils, as observed in this succession, is indicative of marked alternance of wet and dry seasonal periods, under a prevailing warm to hot semiarid climatic condition (Leeder, 1975; Watts, 1980; Esteban and Klappa, 1983; Jerzykiewicz and Sweet, 1987; Smith, 1990). Thin ash-fall levels can be attributed to the distal source of pyroclastic deposits.

This scenario is consistent with the occurrence of terminal fans or endorheic basin deposits developed under arid conditions (Parkash et al., 1983; Kelly and Olsen, 1993; Nichols, 2007; Nichols and Fisher, 2007), with the episodic source of pyroclastic material proceeding from a distant magmatic arc. The recent paleogeographic reconstruction elaborated by Leanza and Hugo (2011) and Tunik et al. (2010) for the Lower Cretaceous of the Neuquén Basin, are coincident with the proposed scheme in this work.

4. Sedimentology of the Puesto Díaz quarry

The Puesto Díaz Quarry (39°34'54.3" S, 70°05'18.8" W) is located on the south flank of an unnamed canyon emplaced close to Cerro Aguada del León, La Picasa area (Fig. 1). In this point, the Puesto Quiroga Member outcrop is 2.80 m thick, being covered by a fine bed of modern eolian and alluvial deposits. Along the outcrop the bonebed is well exposed, forming a single channelized body 32.0 m width and 1.80 m thick, bounded by an erosive, concave up base, which cut into underlying mudstones.

This fossiliferous bed is overlain in sharp contact by 0.30 m of pedoturbated moderate pink mudstone (5R7/4), characterized by the presence of caliche and root traces. Finally, the succession is covered by thin (less than 0.70 m thick) channel-form, trough cross-bedded sandstone, indicating a unidirectional current trending toward N–NE (Fig. 3).

The bone bed facies that constituted the major channelized form consists of poorly sorted, fining-upward deposits, showing a continuous change of the grain size and the lacking of clear internal limits. The dominant lithology along the bonebed is represented by massive muddy sandstones, of moderate orange pink color (10R7/4). These deposits are unconsolidated, texturally immature, offering a cohesive aspect due to the presence of a high content of clay (montmorillonite). The psammitic fraction is composed by quartz and lithic grains of volcanic origin, showing a wide range of grain-size.

The base of this succession (the first 30 cm) contains isolated extraformational pebbles and cobbles of quartz, granitic and volcanic composition, ranging between 2 and 12 cm in long axis. These

REFERENCES

	Conglomerate		Mudstone
	Sandstone		Limestone
	Siltstone		Evaporites

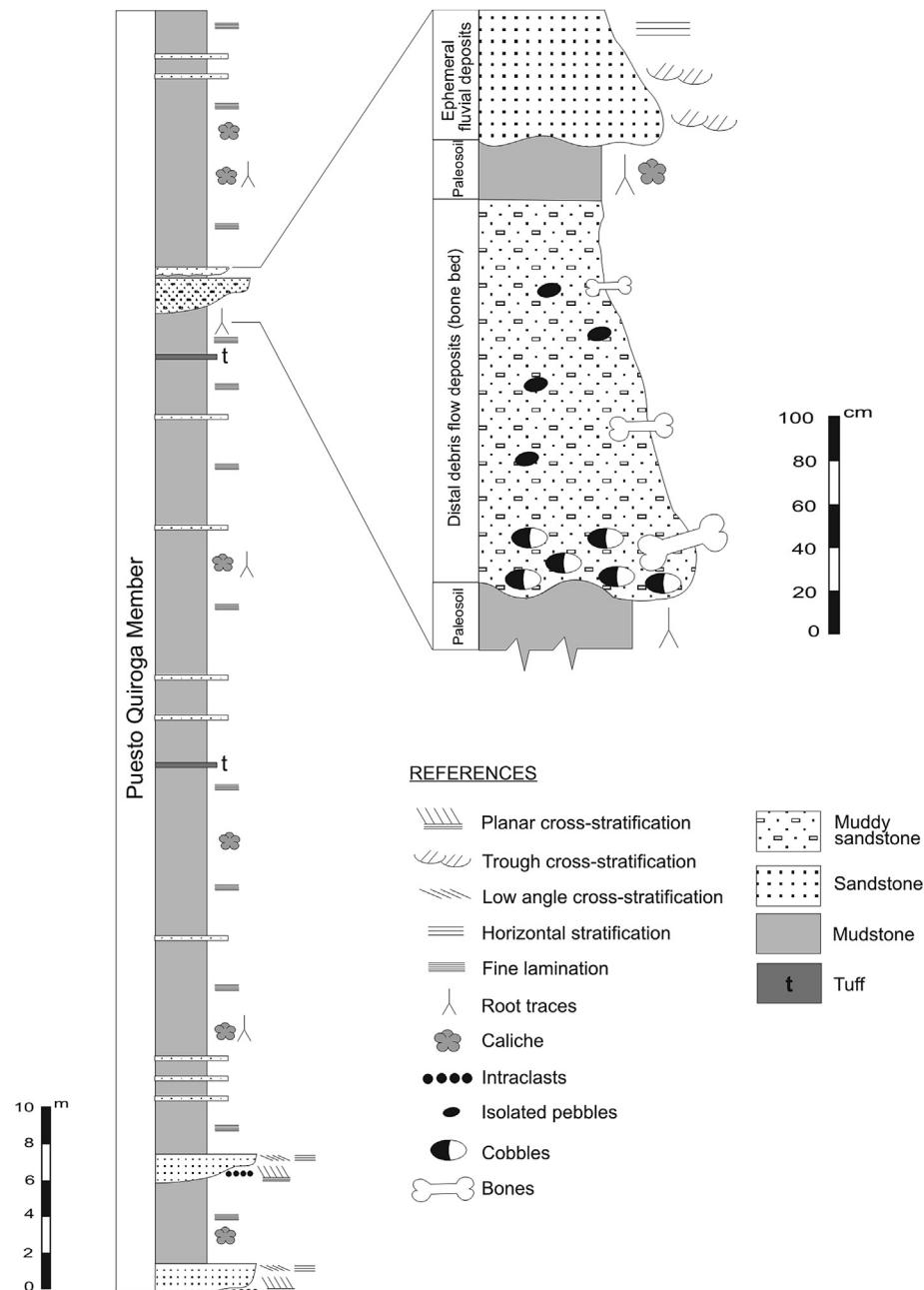


Fig. 3. Lithologic profile of the Puesto Díaz quarry.



Fig. 4. Characteristic paleochannel body of the Lohan Cura Formation. References: CH = channel body; FF = floodplain fines.

clasts are well-rounded, embedded within the muddy sandstone matrix and showing a chaotic distribution. The presence and the size clast decrease upward, being only represented by scarce fine to medium-size pebbles.

These bone bed facies exhibit strong differences with the others channel-fill deposits described previously for the Puesto Quiroga Member (see geological context). Bone bed channel facies contains a high proportion of fine-grained sediments, mainly composed of a mixture of fine-grained sandstone, silt and mudstone (Fig. 5). The lack of stratification is interpreted as a primary depositional feature, because there is no indication of pedogenic modification and/or other bioturbation processes. On the other hand, this normally-graded bed is interstratified with other deposits that exhibit pervasive stratification or pedogenic alteration (cf. Rogers, 2005; Eberth et al., 2006).

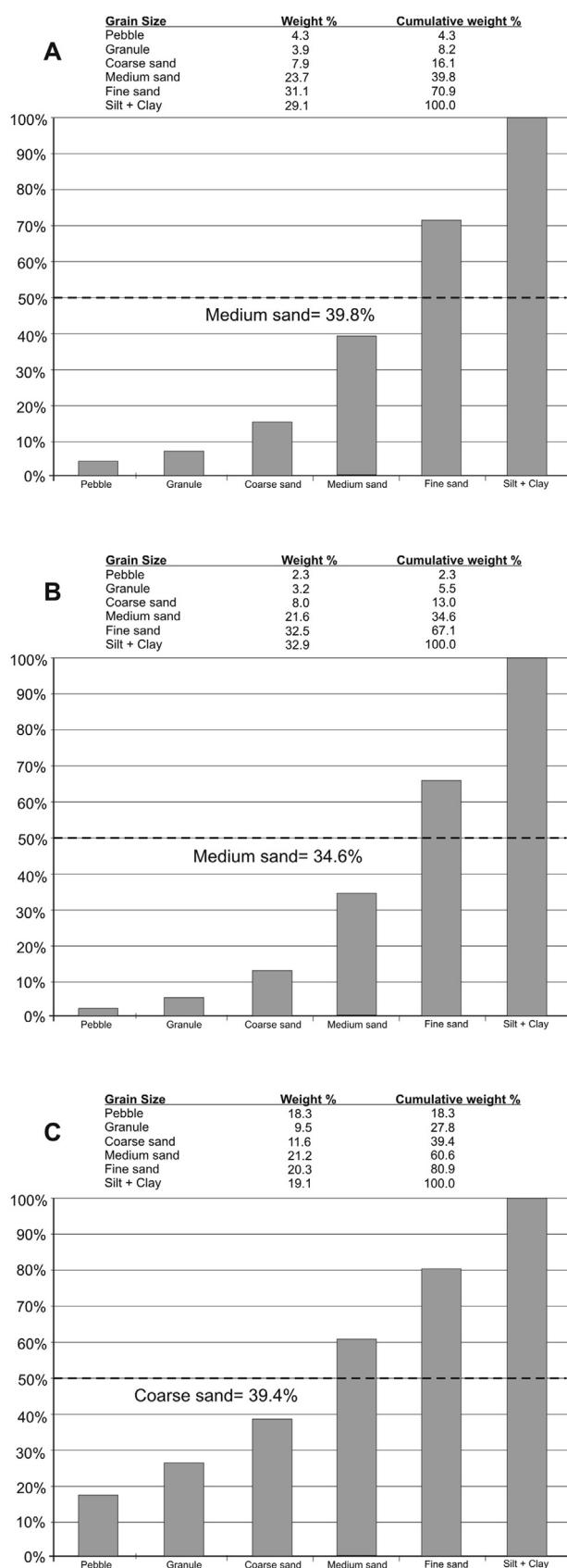


Fig. 5. Sediment grain size analysis of matrix from Puesto Díaz quarry. (A) Sample taken from top of the bonebed. (B) Sample taken from middle part of the bonebed. (C) Sample taken from bottom of the bonebed.

5. Taphonomic features

The bone bed consists of a three-dimensional accumulation of disarticulated bones that extends along 32 m of outcrop and over a thickness of up to 1.85 m (Fig. 6). The bones show an up section decrease in size; with different orientations according to their size and shape.

During the field works, 126 identifiable elements, teeth and postcranial bones, and 33 unidentified fragments were recovered from the quarry. Ribs, limb bones, pelvic bones, and caudal vertebrae are the most abundant components of the assemblage. Large bones (femora, fibulae, humeri, ischia and pubes) are present within these basal deposits (Fig. 6).

The material collected belongs to multiple subadult to adult individuals of a single sauropod species: *Comahuesaurus windhausenii* Carballido et al., 2012 (Salgado et al., 2004; Carballido et al., 2012). The developmental stage of the specimens was based on their size, comparable to other subadult to adult rebbachisaurid specimens (Calvo and Salgado, 1995; Cerda, personal communication), and by the fact that all the axial elements preserved showed fused neurocentral sutures, which is typical in subadult to adult reptiles.

A minimum of three individuals of *Comahuesaurus windhausenii* are represented by the presence of three right femora. With the exception of a couple of isolated carcharodontosaurid theropod teeth, no other taxon has been found at the quarry.

Generally, the bones show a clear superficial alteration that affects the outermost layer of the bone tissue, which tends to disintegrate in small grains. This is the reason because of which certain taphonomical traits, such as marks of scavenging, are not preserved (Fig. 7). Likely, the weathering that affects the outer layer of the bone tissue is the result of hypergenesis during the stage of epidiagenesis of the sedimentary sequence. However, on the best-preserved pieces, no significant damage can be observed. The bones usually show light abrasion and moderate rounding as the more conspicuous features, characteristics that can be originated by attrition during the transport through a flow stream (Behrensmeyer, 1975). The thinnest elements, such as ribs, can show preburial breakage or fractures, unlike the larger or compact bones, which are mostly undamaged. These fractures may be due to multiple factors, such as trampling action or chewing by predators (Voorhies, 1969; Hill, 1979; Bown and Kraus, 1981). In this sense, and according to Holz and Barberena (1994), bone breakage by transport is only admissible under the action of long and intense streams.

The low degree of abrasion coupled with the fact that bone surfaces are only moderately rounded, indicates that the bones at Puesto Díaz have not experienced too much transport. The predominant presence of elements such as ribs, vertebrae, sacrum, limb bones and phalanges, suggests a low dispersion of material, supporting the idea that the bones were locally derived from a surrounding place. Therefore, we infer that the breakage of some bones may have been produced by trampling and/or scavengers action.

Trend data collected from long bone orientations measured in plan-view indicate that the large elements (such as limb and pelvic bones), situated in the coarse-grained basal deposits, are oriented sub-parallel to the trend of the paleochannel (NNE-SSW) and to the paleoflows of the overlying deposits. Small concentrations of clasts are deposited on the up-stream face of big bones. Contrarily, the small pieces of bones (such as rib fragments, vertebrae, haemal arches, neural spines, and other small-unidentified bones) are distributed in higher levels of the quarry without any preferential orientation.

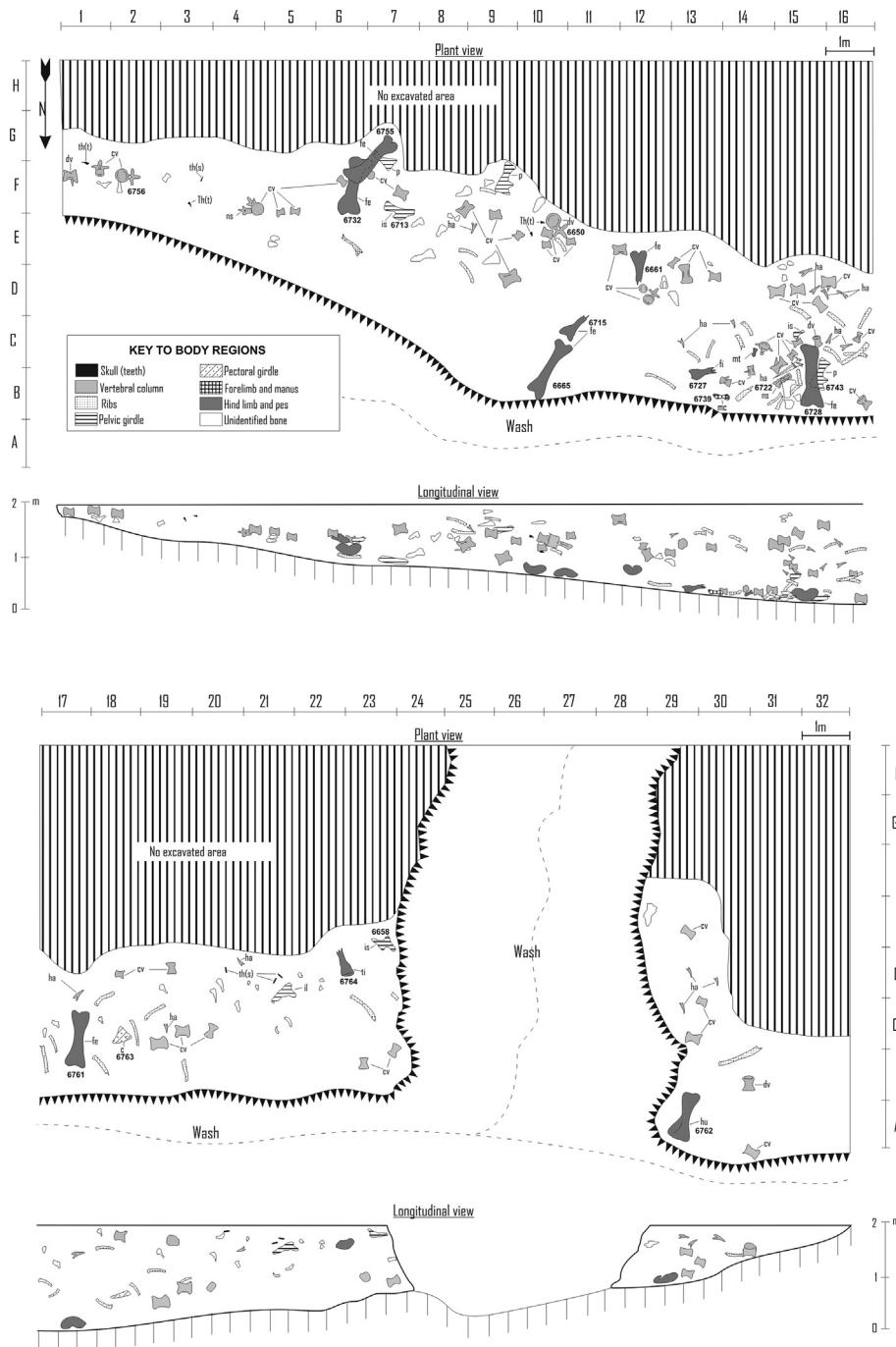


Fig. 6. Puesto Díaz quarry map. References: c = coracoid, cv = caudal vertebrae, dv = dorsal vertebrae, fe = femur, fi = fibula, ha = haemal arch, hu = humerus, il = ilium, is = ischium, mc = metacarpals, mt = metatarsals, ns = neural spine, p = pubis, ti = tibia, th(s) = sauropod tooth, th(t) = theropod tooth. Collection numbers in bold.

6. Depositional interpretation

The presence of poorly organized, unstratified, unsorted, matrix-supported polymictic clasts in a sandy to silty mud-rich matrix, suggests fine-grained cohesive debris flow origin for this bone-bearing deposit (Polansky, 1966; Smith, 1986; Pierson and Costa, 1987; Fastovsky et al., 1995; Rogers, 2005; Eberth et al., 2006).

The architecture and sedimentological features of the bone bed at Puesto Diaz are consistent with the emplacement of a distal debris flow deposited in areas of low relief, that allowed the

formation of wide, partially channelized lobes of sediment (Polansky, 1966).

Apparently, two sources occurred in these deposits: one source supplied unconsolidated detrital material, which constitutes the main part of the debris flow; the other provided well-rounded fluvial pebbles of igneous and volcanic rocks, which were incorporated during the advance and confinement of the debris flow on a dry bed of an ephemeral river (cf. Polansky, 1966).

The support of large clasts and bones in debris flows is a function of the strength and cohesion of the matrix, buoyancy and disperse pressure (Hampton, 1979; Smith, 1986). In debris flows,

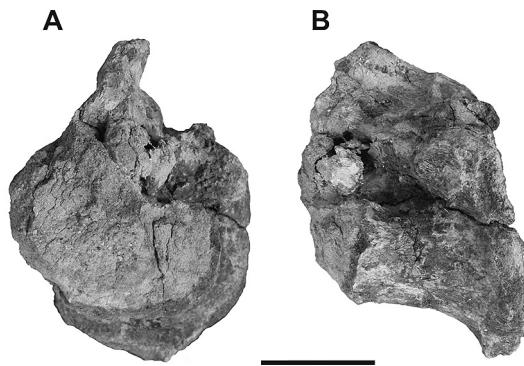


Fig. 7. Anterior dorsal centrum showing superficial alteration. Scale bar: 10 cm.

the transport of clasts occurs under turbulent conditions, but their deposition takes place under a laminar flow regime (Polansky, 1966; Fastovsky et al., 1995). In this manner, bones and large clasts can be incorporated in first instance to the flow, and then transported by traction, buoyancy or a combination of both; exhibiting differences in clast distribution, orientation and size (Polansky, 1966; Fastovsky et al., 1995).

The normal grading in clay-rich debris flows is attributed to differential gravitational settling of clasts within the flow (e.g. Fischer and Schminke, 1984), which is favored with the distance from the source area concomitant with a decrease in mean and maximum size of the clasts (Pierson, 1982; Shultz, 1984; Smith, 1986). However, Vallance and Scott (1997) established a new model of sedimentation in debris-flow deposits rich in large clasts, where the mechanism of deposition is accretionary rather than *in mass*. In the debris-flow wave model of Vallance and Scott (1997), the flow scours and assimilates coarse material in its path. Thus, longitudinal size sorting occurred along flow axis, with large clast in front and smaller clasts behind. During the sedimentation, the coarse-grained debris is deposited in first instance at the front, and then is overlain by finer sediments sourced from the debris flow site of origin (Vallance and Scott, 1997; Eberth et al., 2006).

As seen above, in Puesto Díaz Quarry, big bones and pebbles are highly concentrated in the base, while in the major part of the sequence the pebbles are isolated and scattered into a clay-rich matrix. The pronounced switch of the grain-size and concentration of pebbles and big bones, on the one hand, and the remarkable difference of thickness between the thin basal, coarse-grained deposits, and the overlain fine-grained deposit (thickness ratio 1/6), on the other hand, are compatible with the model of Vallance and Scott (1997). In fact, this marked clast-size, upward decreasing, can be better explained as accretionary deposits, because in a differential gravitational settling of clasts a more gradual normal grading is expected.

Following the accretionary mode of deposition, it is possible that the debris flow did not have had energy enough to transport long distances big clasts and bones, which finally were laid as "lag deposits" on the channel bed. In this regard, the concentration of pebbles on the up-stream face of bones suggests that big bones operated as obstacles, trapping some pebbles transported by traction. The orientation of the long (a) axes of the big bones parallel to the flow is attributed to a preferential orientation of lesser resistance to the shear stress effects (Walker, 1975; Lawson, 1979; Houmark-Nielsen, 1983). In the case of the clasts, small bones, and bone fragments contained into the muddy upper part of the sequence, the buoyancy probably had a dominant role in the manner of their transport of the minor size pieces. The inclusion of isolated bones in a muddy matrix with no preferential orientation supports this last hypothesis.

Modern subaerial debris flows occur in a wide variety of settings (Leeder, 1999; Eberth et al., 2006), which frequently result from slope slipping and remobilization of poorly consolidated sediment substrates. According to Eberth et al. (2006), debris flows can be triggered by exceptional rainfall, seismic activity, volcanism, or by changes in surface and substrate cohesiveness due to modification of ground water flow patterns, plant denudation, or climate change.

Sedimentological features of the Puesto Díaz deposits as massive bedding, poor sorting, graded distribution of the coarse component, and absence of current-flow sedimentary structures, are considered by some workers and in modern environment, as typical features of debris and mudflow deposits in alluvial fans and alluvial environments, mainly in areas of pronounced relief or where the slope stability is affected due to heavy rainfall (e.g., Leeder, 1982; Eberth et al., 2006).

We did not find evidences of contemporaneous tectonism or volcanic activity that can be correlated with this debris flow event, for what we speculate that a strong rainfall could be responsible of the debris flow. The semiarid conditions that affected the basin during this time, and a source area rich in pelitic sediment inferred by the high content of clay in Puesto Díaz deposits, may have contributed to source-slope instability during exceptional rain falls (cf. Fastovsky et al., 1995; Rogers, 2005; Eberth et al., 2006).

7. Discussion

Mass accumulation suggests either mass death, or accumulation of individual carcasses over time (Sander, 1992). In Puesto Diaz assemblage the sedimentological evidences indicate that the bones were likely accumulated by a single and rapid episode of sedimentation, due to a sudden mud-rich debris flow originated up-dip of a site of bone concentration. In this sense, the fact that the bones correspond very probably to several individuals of a single species (*Comahuesaurus windhausenii*) suggests a mass mortality, followed by transport and deposition.

Unlike other cases where a single catastrophic event is proposed as cause both of demise and burial, the record of disarticulated bones in Puesto Diaz suggests that the corpses remained exposed during a time long enough to allow decay and defleshing. Accordingly, the presence of isolated theropod teeth can be interpreted as shed by scavengers (e.g. Buffetaut and Suteethorn, 1989; Sander, 1992). Possibly, during this stage, the action of scavengers provoked the breakage of some bones. The fact that the major group of broken bones is represented by ribs could be due to scavenging, because in actual examples, the rib breakage occurs when medium and big scavengers try of removing and eat the viscera.

Sedimentological and taphonomical evidence suggests that the disarticulated bones were concentrated over a short distance by a debris flow wave event, which distributed them over a thickness of 1.80 m. The predominance of limb and axial bones may be explained by a gradual selection of the bones, similarly to the experimental data provided by Voorhies (1969). In this regard, the horizontal and vertical bone arrangement observed in Puesto Diaz may be related to the mode of transport and the hydraulic behavior of each bone.

Many modern monospecific skeletal assemblages result from drought-induced mortalities as consequence of the varying susceptibility of different species to adverse conditions (Conybeare and Haynes, 1984; Rogers, 1990; Schwartz and Gillette, 1994; Falcon-Lang, 2003).

8. Conclusions

The Puesto Díaz Quarry constitutes an exceptional three-dimensional, monospecific bone assemblage for the Lower

Cretaceous of Neuquén Basin, Argentina. At the moment, 126 specimens of at least three individuals belonging to the rebbachisaurid sauropod dinosaur *Comahuesaurus windhausenii* have been recovered from this site.

Its sedimentologic setting shows that this bone bed was formed and preserved in a debris flow deposit event, which operated under an accretionary mechanism of deposition. Close examination of this deposit suggests that, in this site, debris flow was partially channeled along a dry course of an ephemeral river developed in low relief distal areas.

Taphonomic evidence indicates that debris flow did not kill these dinosaurs; contrarily, disarticulated bones, three-dimensional distribution, and pre-burial bone features, suggest a *postmortem* transport by debris flow. Bone distribution and their spatial arrangement are in relation with their size, form and hydraulic behavior.

The fact that there are more than one individual of the same species indicates a mass mortality by a catastrophic event, perhaps induced by environmentally stressed conditions (e.g., drought). Scattered skeletal elements indicate that the corpses must have been enough time of subaerial exposition as for render possible the bone disarticulation by a combined effect of scavenging, decay, and defleshing.

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