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A NEW UPPER CRETACEOUS TITANOSAUR FOSSIL ASSEMBLAGE IN THE NORTHERN PATAGONIA (RIO NEGRO, ARGENTINA). PRELIMINARY PALEONTOLOGICAL ANALYSIS AND EXPERIMENTAL GEOPHYSICAL APPLICATIONS

Abstract - A new titanosaur fossil assemblage has been discovered by researchers of the Italian museum network Pangea in collaboration with the Museo Patagonico de Ciencia Naturales of General Roca (Rio Negro, Argentina). This fossiliferous deposit is included in the continental sediments of the Anacleto Formation (late Santonian-early Campanian), outcropping in the northern sector of the of El Cuy valley.
Preliminary studies on the 3D digital models of five significant fossil remains allowed us to preliminarily attribute them to the genus *Laplatasaurus* Huene (1929). Taphonomic, sedimentological and paleontological analyses indicate a fluvial-lacustrine depositional environment. The well preserved bones, their concentration at the base of the fossiliferous layer, the presence of sub-adult and adult individuals allow us to hypothesize a gregarious behavior. The cause of death can be attributed to a sudden flooding of the basin that buried a whole herd of titanosaurs.
During the paleontological digging fields (2008-2010) new not invasive methods of geophysical survey (geoelectric and passive seismic techniques) have been tested to find fossil vertebrate remains within sedimentary bodies without any direct contact with the specimens (remote sensing). The results of these applications have been of some interest and, if integrated with paleontological excavation activities, can become strategic to the selection of fossiliferous areas.

Key words - Dinosaurs, Cretaceous, Patagonia, geophysic applications.

Riassunto - *Un nuovo giacimento a titanosauri nella Patagonia settentrionale (Rio Negro, Argentina). Analisi paleontologica preliminare e applicazioni di geofisica sperimentale.* Un nuovo giacimento a titanosauri è stato scoperto da ricercatori della rete museale italiana Pangea in collaborazione con il Museo Patagonico di Scienze Naturali di General Roca (Rio Negro, Argentina). Il deposito fossilifero è incluso nei sedimenti continentali della Formazione Anacleto (Santoniano superiore-Campaniano inferiore), che affiorano nel settore settentrionale della valle di El Cuy.
Gli studi preliminari condotti su modelli digitali in 3D di cinque dei reperti recuperati consentono di attribuirli, in via preliminare, al genere *Laplatasaurus* Huene (1929). Analisi tafonomiche, sedimentologiche e paleontologiche indicano un ambiente di deposizione di tipo fluvio-lacustre.
La buona conservazione dei reperti, la loro concentrazione alla base del livello fossilifero, la presenza di individui adulti e subadulti consentono di ipotizzare un modo di vita gregario per questo tipo di dinosauri. Le cause della morte possono essere ricondotte ad un improvviso allagamento del bacino che avrebbe sepolto un intero branco di titanosauri.
Sono state condotte, in via del tutto sperimentale, delle applicazioni geofisiche (geoelettrica e sismica passiva) nell'area fossilifera, per individuare vertebrati fossili all'interno dei corpi sedimentari, senza contatto diretto con i reperti (remote sensing). I risultati di queste applicazioni sono stati di un certo interesse e, se integrati con le attività di scavo paleontologico, possono diventare strategici per la selezione delle aree fossilifere.

Parole chiave - Dinosauri, Cretaceo, Patagonia, applicazioni geofisiche.

Introduction

Dinosaur remains are spread in all the continents from the North of Alaska to the Antarctic Peninsula. Argentina in general and Patagonia in particular are areas of world-wide paleontological importance for the great amount of findings and for their temporal range almost continue since the upper Triassic (Noric) to the end of Cretaceous (Maastrichtian).
Among the dinosaur paleontological heritage of Argentina, Titanosauria (Sauropoda) represent one of the most meaningful and best represented groups. Titanosaurs, in fact, although diffused in many continental areas (North America, Europe, Africa, Madagascar, India), in South America present the most complete record (Powell, 2003). Since the first studies of Huene (1929) to the present (Juarez Valieri *et al.*, 2011), a rich paleontological literature allows to trace a much articulated picture of their radiation, even if the incompleteness of many specimens and, in several cases, the not well dated historical fossil deposits, leave still open questions involving systematics, phylogeny and paloebiogeography.
In these last decades, with the aim to valorize this rich paleontological heritage, field researches and museum projects have been started. In Patagonia, among the main activities in this field, are the Paleontological Museum «E. Feruglio» in Trelew (Chubut) and some meaningful local museums realized as a result of some spectacular findings (the *Argentinosaurus* in Plaza Huincul, the *Giganotosaurus* in the «Museo del Chocon», etc.). However, although the immense Patagonian territory is one of the most famous for the density of the fossiliferous outcrops and quality of the

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findings, the projects on the geoconservation, protection and valorization of this huge heritage are very few and many meaningful fossiliferous areas are at risk of a fast endangerment.

Beginning since 2005, the Natural History Museum of the Pisa University as scientific advisor of the Pangea museums network (whose other members are the Museum of Rovereto (TN), the Geopaleontological Museum of Lerici (SP), the Fossils and Ambers Museum of San Valentino (PE) and the regional Museum of Natural Sciences of Turin) started a project for the valorization of the paleontological heritage in the Rio Negro province (northern Patagonia, Argentina) as a tool for cultural promotion, technological application and socio-economic development in the area (Landini & Rissicini, 2008; Finotti & Landini, 2009).

The project, besides the field research, the scientific study and the valorization of the paleontological resources, has among its main objectives the testing of new not invasive geophysical technologies for the location of vertebrate fossiliferous outcrops and the use of 3D models for conservation, cataloguing and duplication of the specimens.

Since 2005, the Pangea network in collaboration with the MACN of Buenos Aires, the Patagonian Association for Natural Sciences of General Roca (Rio Negro) and, since 2008, the newly born Museo Patagonico de Ciencias Naturales of General Roca, has organized a series of field researches in the Rio Negro province with the aim to locate new dinosaur fossiliferous outcrops and to test for the first time some geophysical methodologies. Such researches have been focused on the area of Passo Cordoba (Rio Negro), where the upper Cretaceous continental sediments of Bajo de la Carpa and Anacleto Formations outcrop with a wide continuity.

These first investigations (2005-06) allowed to locate several sites with dinosaur skeletal remains and/or eggs, even if the majority of them turned out to be not particularly meaningful because their way of exposure and incompleteness. On the contrary, the site located in the northern part of the El Cuy valley, in the «Campo Verdecchia», resulted to be the most interesting due to the high concentration of bony remains on the surface, even if mostly fragmentary, and for the giacitural mode of the fossiliferous layers suitable for the geophysical tests (Finotti & Landini, 2009).

The digging fields of the following years (2008-10), resulted in the discovery of an important fossiliferous site in a upper level of the Anacleto Formation (Rio Colorado, Subgroup Neuquen Group), containing almost exclusively titanosaur remains in primary position (Finotti & Landini, 2009; Finotti *et al.*, 2010).

Geological-stratigraphic framework

In the area of General Roca, and particularly in the El Cuy valley, continental deposits of upper Cretaceous outcrop with a remarkable continuity. Such deposits (Fig. 1) from a stratigraphic point of view have been referred to the Neuquen (Cenomanian-Albian) and Malargue (Campanian-Maastrichtian) groups (Hugo & Leanza, 2001). The Neuquen group (Leanza *et al.*, 2004) is divided in three subgroups: Rio Limay (Cenomanian-lower Turonian), Rio Neuquen (lower Turonian-Santonian) and Rio Colorado (lower Santonian-Campanian). The Neuquen group is stratigraphically overlapped by the Malargue group, whose lowermost part is represented by the Allen Formation, through an erosive unconformity.

All the investigated sites in which dinosaurs bony remains have been found during the surveys organized by Pangea (2005-2010) belong to deposits of the Rio Colorado subgroup (Neuquen group), and precisely to the Bajo de la Carpa (Santonian) and Anacleto (Santonian-Campanian) Formations.

The Bajo de la Carpa Formation consists of medium-large grained and well cemented quartz sandstones, outcropping for a thickness of 90-105 meters in various colors from pink-grayish to purple-reddish, whose alternation results in an evident horizontal striping. The thick benches represent continental sediments with cross stratification interrupted by the frequent presence of quartz geodes filled by calcite crystals. In the upper part of the Formation are exposed some layers interpreted as paleo-soils, which are evidence of periods of marked stability of the zone with interruption of the sedimentation. The Anacleto Formation develops in transition with the Bajo de la Carpa Formation for a thickness ranging between 10 and 60 meters. As the preceding one, it is formed by continental sediments: dark purple-reddish in color alternated to white-pinkish sandstones and claystones and concretional limestone (Fig. 2). This alternation of layers with different chromatic shadings gives to the deposit a typical striped aspect.

In both Formations abundant fossil remains have been found: silicized trunks even of large dimensions, a well represented flora of ferns (Bajo de la Carpa) and numerous vertebrates remains among which snakes, chelonids, crocodiles, birds and saurischian dinosaurs (Hugo & Leanza, 2001).

The transition with the Allen Formation of the Malargue Group is represented by a clean erosive unconformity.

Paleontological analysis

Since 2005, the researchers of the Pangea network performed a series of investigations in different localities of the Rio Negro area, where continental sediments of upper Cretaceous (Bajo de la Carpa and Anacleto Formations) outcrop. In particular a wide area of great paleontological interest has been localized in the northern part of El Cuy valley, near Passo Cordoba. Inside this area, the first survey (2005) resulted in the discovery of numerous dinosaur bony fragments on the surface, some of which of a juvenile titanosaur. Later on, a strong concentration of titanosaur bones in primary position has been localized along the flanks of a hill where the sediments of the Anacleto Formation are well exposed. Weathering has greatly damaged these bony remains, compromising the possibility to study their morphology and structure. The fossiliferous forehead

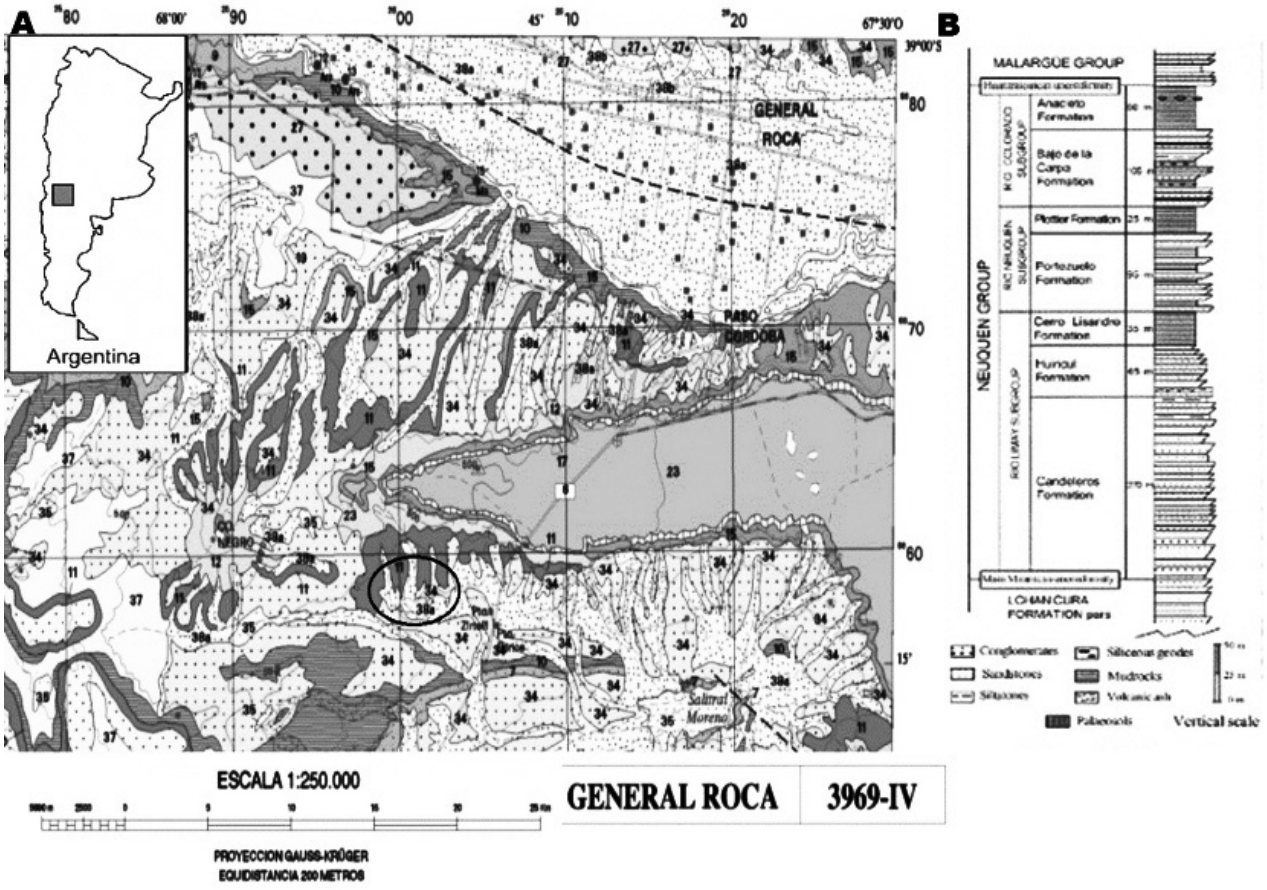

Fig. 1 - A: localization (circle) and geologic details of the Northern El Cuy valley (modified from Hugo & Leanza, 2001); B: stratigraphic column of the Neuquén Group (modified from Leanza *et al.* 2004).

extends along a line distance of approximately 200 m (Fig. 3) and is associated to a 1.5-2 m thick layer of gray/green sandstones.

In order to establish the importance of the fossil deposit, the way of fossilization and the state of preservation of the remains, four digging tests have been realized in different positions along the fossiliferous forehead, (individuated by the acronyms L, L1, G, G1, Fig. 3). Even if these digging activities are still in progress, all the four sites have already supplied titanosaur bones in good state of preservation and with a fair anatomical connection. The remains extracted till now have been deposited in the Museo Patagonico de Ciencias Naturales in General Roca and are presently under restoration. The most meaningful specimens among the ones already restored have been photographed with a metric Zscan camera for three-dimensional (3D) modeling. This technique has been recently applied, for the first time in the archaeological field, by researchers of the Pangea network (Museum of Rovereto) to the 3D modeling of the digging sites and of the bony remains there found.

The technique is based on a series of partially overlapping pictures, generally three for each subject, taken using a high resolution digital camera running on a calibrated guide. Each series of three images is analyzed by a specific software that generates a numerical distribution as a three-dimensional cloud of points. Depending on the precision required, by modifying the density of the points in the cloud it is possible to obtain data with a resolution of 10-20 μ. The cloud of numerical data is then transformed in a three-dimensional surface identically reproducing the original subject, even under the chromatic aspect.

This technique, associated to the possibility to georeference all the surfaces, allows to realize a complete 3D digital model of the remains by approaching the surfaces obtained by all the three-image series available.

As a first test, five 3D models have been realized, chosen among the digitalized specimens most meaningful under a diagnostic point of view. Such remains come from two of the four digging test areas (site G and site L). In particular from site L are: an anterior caudal vertebra, a left third metacarpal, a right fibula

Fig. 2 - Anacleto Formation: alternation of layers with different chromatic sandstones. The fossiliferous deposit is located at the base of this sequence.

and a right tibia. Even if the digging activities are not yet finished and only a part of the remains has been recovered, taphonomic analysis, sedimentological evidences and well preserved articulated skeleton remains allow the tentative attribution of these specimens to the same individual. From site G comes a right cubitus. The vertebral body is well preserved (Fig. 4). It is slightly dorsoventrally flattened and strongly procelic (character present in many specialized titanosaurs). The transversal processes and the neural spine are almost completely missing. The anterior articular surface is nearly circular and weakly inclined, while the caudal one is strongly convex, irregular in shape and a little higher than wide. The length-height ratio of the centrum and its being strongly procelic suggest that it is a proximal caudal vertebra (they become less procelic in tail direction), compatible with those attributed to genus *Laplatasaurus*.

The metacarpal is complete, rather compact and lengthened in shape, with wide and flat extremities and the diaphysis narrower latero-medially than antero-posteriorly (Fig. 4). The proximal extremity is triangular in shape: the medium side is convex, the latero-posterior one is weakly concave and the anterior one is straight. The distal extremity is trapezoidal in shape: the longer side being convex and the opposite one, turned towards the inside of the hand, strongly concave. Based on the morphology of the two extremities and of the diaphysis, this bony remain can be identified as the III°SX metacarpal.

The right tibia is elongated with wide epiphyses. The body of the diaphysis is strongly flattened in shape. The lateral surface is slightly concave, while the medial one is flat in the center and distally convex (Fig. 4).

The proximal epiphysis, excluding the cnemial crest, is globally elliptic in shape and vaguely rhomboidal, especially in the lateral half. The cnemial crest is anteriorly and laterally developed and forms and almost right angle with the anterior side of the proximal surface, as in many titanosaurs. It is almost triangular in shape, much lengthened till the half of the entire bone length. This morphology is also found in other remains referred to *Laplatasaurus*.

The right fibula is relatively thin and strongly sigmoidal in shape in lateral view (Fig. 4). Along the diaphysis, at approximately one third of the entire bone length is a lateral tuberosity, high and wide, almost oval in shape. In the distal part, an area of muscular insertion is clearly visible, it is drop-shaped with the vertex in distal direction. The epiphyses are wide and robust in anteroposterior direction. The distal one is irregular in shape with a vaguely trapezoidal profile.

The ulna is long, unlike in many titanosaurs. The diaphysis is triangular in cross section with concave sides in correspondence with the proximal extremity, till approximately one third of the total length. Where the superficies straighten, the posterior and lateral sides distally join to form a wide convex surface which determines the profile of the distal epiphysis. The anteromedial side of the diaphysis in its central part is flat

Fig. 3 - The 200 m extension of the fossiliferous forehead and the four sites excavated (G; G1; L; L1).

and for a great part of its length is furrowed by a low crest. The proximal extremity, three-rayed as in all the sauropods, is partially damaged. The distal epiphysis, whose surface is uniformly flat, has semicircular profile with a notch on the anteromedial side.

The characters of the body of the anterior caudal vertebra, the morphology of the proximal epiphyses of the tibia and above all the structure of III metacarpal, highly diagnostic in the titanosaurs, allow to refer these remains to *Laplatasaurus araukanicus* Huene,1929.

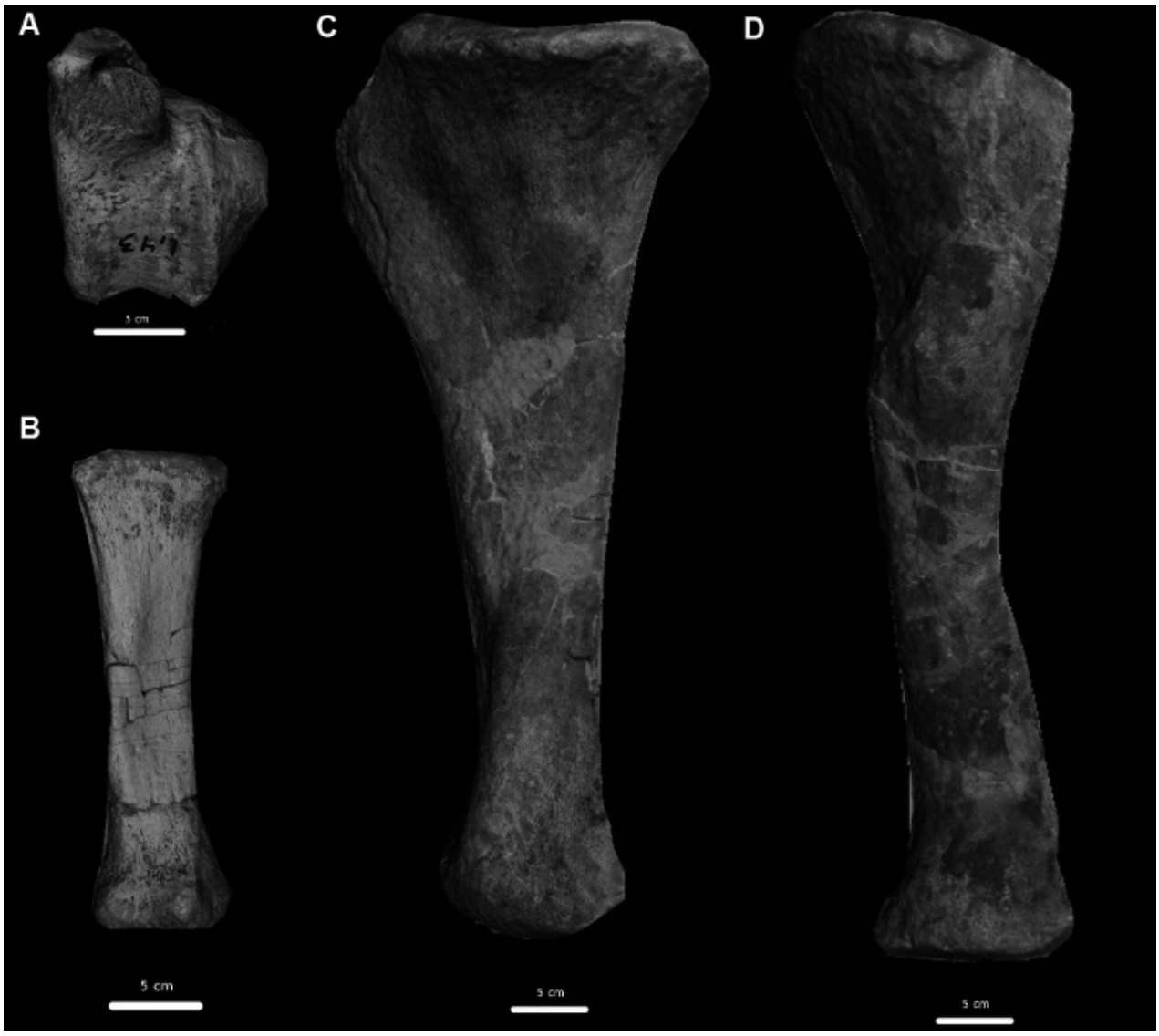

Fig. 4 - Digital models of the specimens studied: A: Anterior caudal vertebra; B: left third metacarpal; C: right tibia; and D: right fibula from the site L. These specimens have been photographed with a metric Z Scan camera for 3D modeling.

(Bonaparte & Gasparini, 1978; Wilson & Upchurch, 2003; Powell, 2003). In the same way, as regards the right cubitus from site G, even if lacking nearly the whole proximal part, its morphostructural characters are compatible with those of genus *Laplatasaurus* Huene,1929.
The detailed systematic study will be realized when the digging will be completed and the huge amount of specimens restored.

Geophysical analysis

During the paleontological digging fields (2008-2010) new not invasive methods of geophysical survey have been tested by the researchers of the Pangea network, these methods are low cost and suitable for the location of vertebrate remains in the uppermost underground (Landini & Rissicini, 2008; Finotti & Landini, 2009).
The peculiar geological, geomorphologic and environmental characteristics of the studied area reduced the choice of the geophysical methods available by focusing on geoelectrics (e.g. electrical tomography), which provides meaningful measures in case of both very high and extremely low values of resistivity, and seismics (e.g. passive seismics). The geoelectrical methods, whose effectiveness was methodologically sure, have been joined by a new passive seismics procedure for the preliminary survey of the uppermost underground by using a new generation digital tromograph (Tromino, Micromed). Preliminary methods as georadar have been avoided in this first phase of the survey because their penetration capability is strongly depending on the conductivity value of the sediments investigated.
The objective was twofold: 1) to individuate the small scale subsuperficial heterogeneities by volumetrically mapping limited portions (10 m × 10 m) of the area, in order to establish the position of levels with different compactness; and 2) to collect from great depths meaningful stratigraphic data by simply acting on the frequency of sampling and the measurement time of the surrounding noise.
In the area of paleontological investigation (Campo Verdecchia), sites suitable for the geophysical tests have been individuated both along the digging forehead and in the near adjacencies. In particular site S, located at a short distance south-east of the fossiliferous deposit, for the depositional mode and exposure of the layers and for the few vegetation present, has been used as test area for the geoelectric prospectings and for the passive seismic acquisitions.
The geoelectric survey was articulated in a series of parallel spreadings in EW direction, with interelectrodic step of 0.3 m (for a total length of 14.1 m) and interdistance among the spreads of 0.5 m (Fig. 5).
The field measures have shown values of «appearing resistivity» markedly low, due to the fine webbing of the sediment which resulted to be very rich in mineral salts. The reversal of the sections in «appearing resistivity» and their successive treatment according to a pseudo 3D model (Fig. 5) allowed the reconstruction of the investigated volume (maximum survey depth 1.2 m) and distinguished portions of greater compactness from those constituted entirely by fine and completely melted sediments. The control by mechanical survey confirmed the reliability of the result.
The passive seismics surveying was performed in parallel with the geoelectric one and in some points the two are completely overlapped (see Fig. 5 outline 1) in order to facilitate the comparison of seismic and electrical data. Thirty-four measures of passive seismics at 512 Hz were collected in correspondence to the nodes of a grind composed by three lines (2 m interdistant) with 11 nodes each (1 m step).
All the data relative to the geophysical prospectings are available on the web site (http://www.museocivico.rovereto.tn.it).

Discussion

Titanosauria is the most widespread clade of sauropod dinosaurs. Relatively to the Cretaceous period, they have been recorded in all the continental landmasses excepted Antarctica (Weishampel *et al.*, 1990; Hunt *et al.*, 1994; Wilson & Upchurch, 2003).
However, despite their wide distribution, their origins, biodiversity and biogeographical interrelationships are poorly known (Salgado *et al.*, 1997; Upchurch, 1998; Wilson & Sereno, 1998; Sanz *et al.*, 1999; Curry Rogers & Forster, 2001; Wilson, 2002, Wilson & Upchurch, 2003). An important topic in the systematics of this group is the validity of genus *Laplatasaurus*.
Huene (1929) based the description of the new genus and new species *Laplatasaurus araukanicus* on some specimens from Cinco Saltos (Rio Negro, Argentina), previously attributed by Lydekker (1893) to *Titanosaurus*, and from other minor localities (rancho Avila, Rio Neuquen, 2 km north of the railway bridge, close to General Roca). No holotype was specified by this author. Bonaparte & Gasparini (1978) specified as lectotype for this species a right tibia and fibula (MLP26-306) kept in the La Plata Museum of the same individual, from Cinco Saltos (Rio Negro). Powell (1986), after comparison between *Titanosaurus indicus* Lydekker 1877 and *L. araukanicus* recognized a generic synonymy and proposed the combination *Titanosaurus araukanicus*. Bonaparte (1996) in a new annotated list of Cretaceous tetrapods of Argentina accepts the latter interpretation. However Powell (2003), in the revision of the South American titanosauroid dinosaurs assigned to *T. araukanicus* only the specimens discovered from Cinco Saltos and Lago Pellegrini, found in the lower part of the Allen Formation. According to Powell (2003) the specimens from other geographic localities and belonging to different stratigraphic levels described by previous authors, should be attributed to *Titanosaurus* sp.
Finally, in their revision on genus *Titanosaurus*, Wilson & Uppchurch (2003) suggest that *Laplatasaurus* Huene (1929) should be retained for the lectotype MLP 26-306 (right tibia and fibula) described by Bonaparte & Gasparini (1978).
The discussion above demonstrates that any decision about the validity of the genus *Laplatasaurus* remains

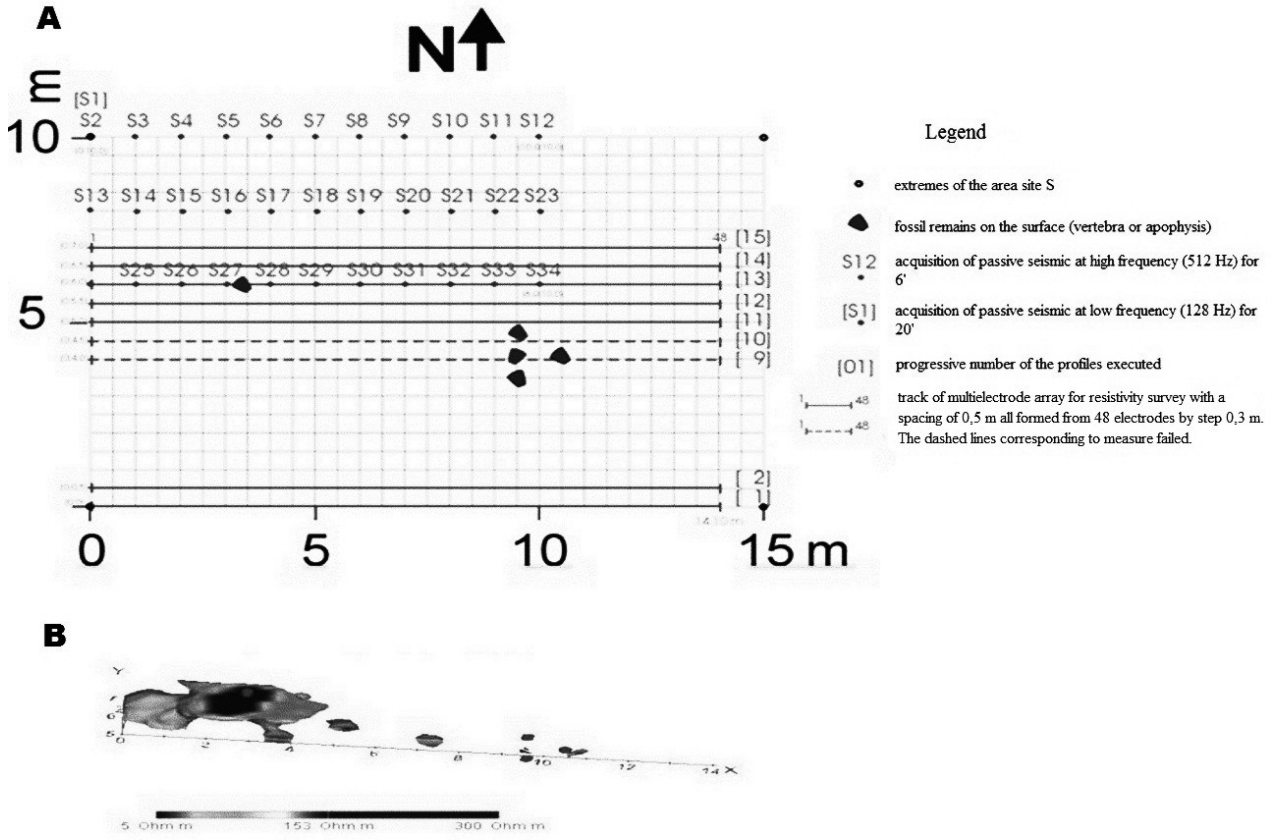

Fig. 5 - A: geoelectric survey: mapping of electric resistivity (see legend); B: 3D reconstruction of the electrical resistivity in the S site. The volume of the subsoil is characterized by values higher than 50 Ohm m.

confuse and controversial. In addition we can observe that in many paleontological sites, the absence of detailed field records and of stratigraphic excavations, combined with the poor preservation of the bones, does not allow the certain attribution of the fossil remains to the same individual and/or to the same species.

In this preliminary paper, we agree with the Wilson & Upchurch (2003) considerations.

Our recent discovery of articulated skeletons with well preserved bones, in the Santonian sediments of the Anacleto Formation (Rio Negro, Argentina) may thus provide a significant contribution to the resolution of this systematic, tassononic and phylogenetic controversial.

The excavations, still in progress, have been conducted stratigraphically (layer by layer) to define the mode of deposition and the stratigraphic relationships. As previously reported, the Anacleto Formation ranges between 60 and 90 meters of thickness and consists mainly of claystones and mudstones of fluvial origin, purple and dark red in color with thin grey/green layers of mudstone and siltstone in between (Hugo & Leanza, 2001).

The fossil bone assemblages are recovered in a grey-green layer, 1.5-2 meter thick. In particular these remains are strongly concentrated along a continuous linear extension of about 200 m in length.

All the articulated skeletons recognized are located at the base of the grey/green layer and show a similar stratigraphic relation. We believe, on the base of our preliminary field observations, that these skeleton remains can be referred to the same taxon. The study of the digital models of five fossil bony remains, collected in two of the four sites investigated (L and G), as previously discussed, are compatible with *Laplatasaurus araukanicus*.

The sedimentological analysis of the fossiliferous gray/green level, the discovery, in the same deposits, of isolate dermal plates of freshwater turtles, allow us to hypothesize a fluvial-lacustrine environment.

The presence of several well-preserved dinosaurs skeletal remains at the base of this stratigraphic level, belonging to *L. araukanicus*, allow us to hypothesize a catastrophic event as cause of their death: a sudden flooding of the basin that could have buried an entire herd of *Laplatasaurs*.

Bonaparte (1996) reports in the Lech Formation (Maastrichtian) of Salta (Argentina) an association of five

individuals, including adult and juveniles. This fossil assemblage has been interpreted as the result of gregarious habits. Our discovery, in the Santonian deposits of the El Cuy Valley, of several adult and subadult skeletal remains attributed to *L. araukanicus*, confirms a gregarious behavior for this sauropod group.

The geophysical applications tested in the fossiliferous area provided interesting results (Finotti & Landini 2009; Finotti *et al.*, 2010). Both the data collected at great depth and the superficial ones show good lateral continuity of discontinuities and present a clear coincidence with the stratigraphic succession outcropping in this area. As regards the paleontological survey, it is more interesting to focus on the first 2.5 meters below ground level. Within this sedimentary body the seismic method used is able to highlight an alternation of a «slow layer» (like the one on the surface) with others of greater consistency, usually represented by compact sandstone. The paleontological excavations confirmed the geophysical data. In fact at about 1.0 m below the ground level is located the fossiliferous bonebed, indicated in the reverse section by a broken line.

Conclusions

The discovery of a relevant titanosaurid fossil assemblage with well preserved articulated skeletons could contribute to solve the controversial systematic and taxonomic problems about genus *Laplatasaurus*. The excavation, still in progress, realized with stratigraphic modalities could allow us to define the genesis of this paleontological assemblage and to clarify the cause of the death of this titanosaurid herd. The preliminary data about the presence of individual of different age (adults and subadults) confirm the gregarious behavior hypothesized by Bonaparte (1996) in other titanosaurid groups.

The use of geophisical technologies, such as geoelectrics and passive seismic, to detect fossil vertebrate remains in a sedimentary body without any physical contact with the object (remote sensing), in the excavations conducted in the El Cuy Valley (Rio Negro, Argentina), was of some interest. These methods even when used in a situation apparently not proper, demonstrated to be able to detect even small vertical and lateral discontinuities such as those determined by paleontological remains. Therefore, if properly integrated with other survey techniques, they can be strategic to select the areas of excavation.

The calibration of a low cost technique of 3D digital modeling of the fossil remains by using a Zscan camera resulted to be very useful.

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