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High-precision U–Pb geochronology and a new chronostratigraphy for the Cañadón Asfalto Basin, Chubut, central Patagonia: Implications for terrestrial faunal and floral evolution in Jurassic

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ABSTRACT

The fluvial, lacustrine and tuffaceous sedimentary succession of the Cañadón Asfalto continental basin exposed in the Argentinean Chubut Province of central Patagonia preserves an extraordinary record of Jurassic fauna and flora that marks key events in the evolution of Dinosauria, early mammals and major South American plant groups. However, basin-wide correlation of the fossiliferous units is complicated by fault displacements, unconformities and repetitive lithofacies. New U–Pb analyses of zircon (CA-TIMS method) from five primary tuff beds interstratified with the lacustrine strata establish a new chronostratigraphic framework for the sedimentary and volcanic units of Cañadón Asfalto Basin, constraining ca. 33 m.y. of depositional history and biotic evolution that spans nearly all three epochs of the Jurassic. Five major vertebrate- and plant-rich stratigraphic intervals have been identified, and are being actively investigated, that range in age from Pliensbachian to Kimmeridgian (or younger). Our combined biostratigraphic and high-precision geochronologic results indicate that the major faunal turnover of the sauropodomorph dinosaurs which led to the rise of the eusauropods took place in the Early Jurassic, earlier than previously recognized. Similarly, the first successful radiation of the ornithischian dinosaurs (heterodontosaurids), as well as the evolutionary diversifications of the araucarian conifers and the osmundaceous ferns, all occurred before the end of the Early Jurassic. The diverse palynofloral assemblage of the Cañadón Calcáreo Formation that was once considered to be early Cretaceous in age, is now entirely constrained to the Late Jurassic.

1. Introduction

Mesozoic non-marine sedimentary deposits have been known from the middle Chubut River valley region (Fig. 1) of the extra-Andean central Patagonia in Argentina since the early twentieth century (Piatnitzky, 1936; Feruglio, 1949; Frenguelli, 1949). These deposits that once filled the Cañadón Asfalto continental basin were originally included in the so-called "Estratos con *Estheria*" and were assigned Rhaetic (late Triassic) to Cretaceous ages (Piatnitzky, 1936). The ensuing decades witnessed a multitude of stratigraphic nomenclatures which, despite attempts to adhere to a stratigraphic code, resulted in many inconsistencies and misinterpretations. Age constraints were initially provided by macrofossils, such as freshwater invertebrates and fishes, dinosaurs and plants (e.g., Frenguelli, 1949; Bonaparte, 1979), and later by palynomorph, charophyte and ostracod microfossils (Tasch and Volkheimer, 1970; Musacchio et al., 1990; Volkheimer et al., 2009). More recently, sequence-stratigraphic (Fígari and Courtade, 1993) and radioisotopic dating (Cabaleri et al., 2010a) methods have been employed, although with mixed results, to better calibrate the stratigraphic record. Difficulties in stratigraphic correlation generally arise from the repetitive and/or laterally variable lithofacies associated with non-marine rocks and the inability to trace strata over long distances.

The remarkable record of fossil fauna and flora preserved in the sedimentary rocks of the Cañadón Asfalto Basin is essential to reconstructing the evolution of Mesozoic life. Once put in a proper temporal framework, the fossil record can be used to test biostratigraphic correlations, to decipher the phylogenetic relationships among taxa, and to better understand the dominant patterns of biotic evolution. However, establishing the necessary temporal framework relies on robust and adequately precise geochronologic data independent of the fossil record. The abundance of primary volcanic ash (tuff) beds interstratified with the fossiliferous

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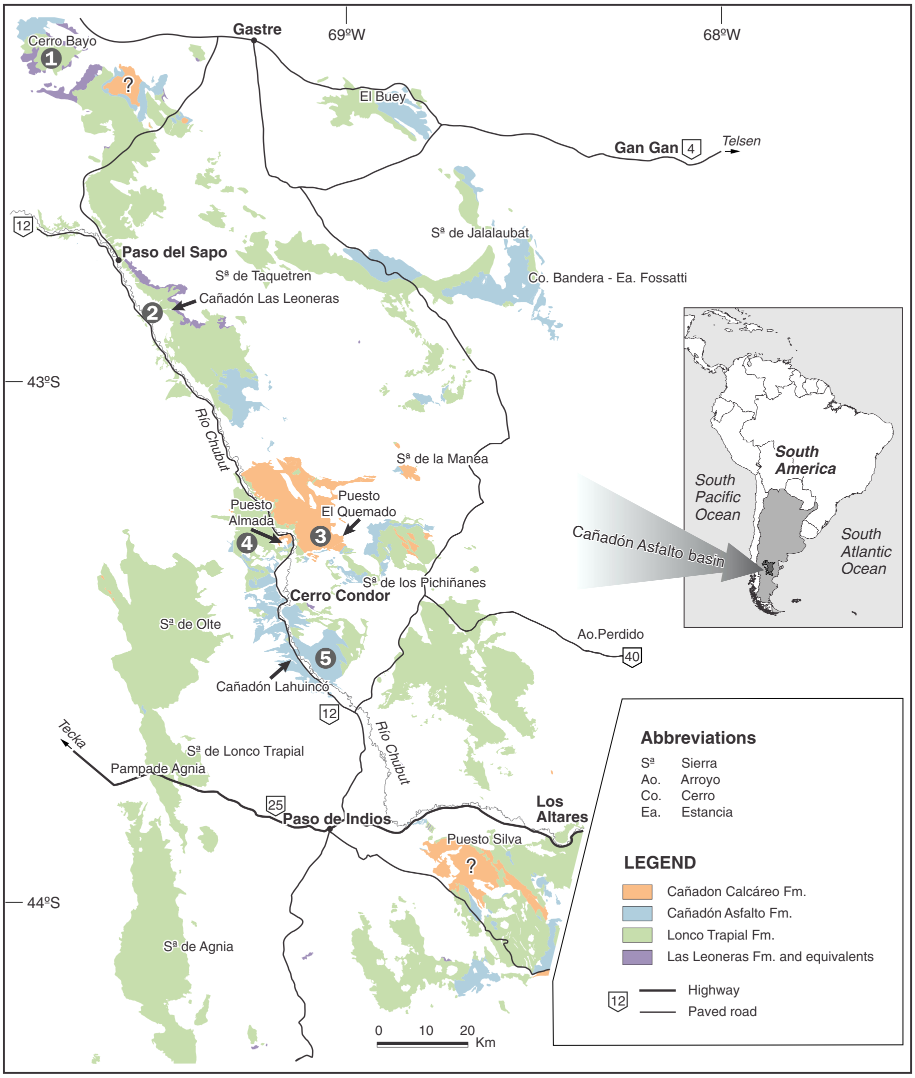

Fig. 1. Location map and distribution of Jurassic outcrops in the Chubut River valley area, Argentina (modified from Figari, 2005). 1 = Cerro Bayo area; 2 = Las Leoneras area; 3 = Estancia El Torito in the Puesto Almada area; 4 = Puesto el Quemado area; and 5 = Cerro Cóndor area. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

lacustrine strata of the Cañadón Asfalto Basin presents a unique opportunity for combining high-precision radioisotopic dating with detailed litho- and bio-stratigrapies. This is a significant step towards resolution of the outstanding problems involved in the regional stratigraphic correlations, identification of the fossil-bearing horizons and their unequivocal correlation to the marine-based geologic time scale.

Here we present the first results of our integrated stratigraphic, paleontological and U–Pb geochronological investigations on the Jurassic successions of the Cañadón Asfalto Basin exposed along the Chubut River valley. A revised chronostratigraphy for the corresponding lithologic units is proposed and new age constraints are provided for a number of the important fossil intervals. The implications of the new results for the Jurassic evolution of the relevant faunal and floral groups are discussed.

2. Regional geology and stratigraphy

The most extensive exposures of Jurassic terrestrial rocks in South America are found throughout the central Patagonian Chubut Province of Argentina (Fig. 1). These fluvial, volcanic, volcaniclastic and lacustrine deposits are part of the Somuncurá-Cañadón Asfalto rift basin (Stipanicic and Methol, 1980; Cortiñas, 1996) that extends between the latitudes of 40°30′ and 44°30′ South, and the longitudes of 66°00′ and 70°30′ West (present-day coordinates). The present study is focused on the southern and southwestern outcrops of the basin, generally referred to as the Cañadón Asfalto Basin (Silva Nieto et al., 2002), which are exposed chiefly in a northwest-trending belt along the Chubut River valley between Paso Berwyn and Cerro Bayo (Fig. 1).

The tectonosedimentary evolution of the Cañadón Asfalto Basin has been the subject of numerous studies (e.g., Fígari and Courtade, 1993; Figari et al., 1996; Silva Nieto et al., 2007 and references therein). It is commonly described in terms of a pull-apart basin based on structural and depositional features such as deep lacustrine lithofacies, basaltic intercalations, evaporite horizons and synsedimentary deformation. In addition, three depocenters have been envisaged within the basin, namely Cerro Cóndor, Cañadón Calcáreo and Fossati, which served as micro-basins in response to the driving tectonosedimentary processes (Silva Nieto et al., 2007).

The Jurassic rocks of the Chubut River valley are subdivided into several widely accepted lithostratigraphic units, although differences exist among workers on regional correlations and lower order subdivisions. The sequence starts with the Las Leoneras Formation (and its unnamed correlatives) of presumed Early Jurassic age, which is a relatively thin unit of fluvial channel sandstones, flood-plain mudstones and lacustrine tuff/agglomerate, deposited over the Paleozoic crystalline basement (Nakayama, 1973; Pol et al., 2011a). The overlying Lonco Trapial Formation is composed of poorly stratified agglomerates, volcanic breccias, subvolcanic andesite and basaltic lava, with closely associated volcaniclastic conglomerates, sandstones and lahar deposits, and with significant lateral lithofacies variations. Its conglomeratic facies and its volcanic-dominated facies have been give alternative names (e.g., Taquetrén Formation, Cerro Carnerero Formation and Cañadón Puelman beds), collectively grouped under the so-called Lonco Trapial Group (e.g., Nullo and Proserpio, 1975; Musacchio, 1995). The cumulative thickness of the Lonco Trapial Formation is estimated to be 500–800 m and its age is thought to be Middle to Late Jurassic (176–146 Ma) based on K–Ar geochronology (Nullo, 1983; Pankhurst et al., 1998).

Jurassic deposition continued on top of, and locally in transition with, the Lonco Trapial Formation with the intercalated lacustrine, fluvio-deltaic, calcareous and tuffaceous rocks of the Cañadón Asfalto Formation (Stipanicic et al., 1968). Some workers have subdivided the formation into a lower lacustrine/tuffaceous (Las Chacritas) member and an upper siliciclastic fluvial (Puesto Almada) member (Cabaleri et al., 2010a). In the Cerro Cóndor area (Fig. 1), the Lonco Trapial–Cañadón Asfalto transition is marked by several distinct basalt flows interlayered with fossiliferous lacustrine strata. The Cañadón Asfalto Formation has been traditionally considered Middle to Late Jurassic (Callovian–Oxfordian) in age mainly based on its record of freshwater invertebrates (Tasch and Volkheimer, 1970) and plants (Frenguelli, 1949). Salani (2007) reported a whole-rock K–Ar date of 170.9 ± 4.4 Ma (Aalenian–Bajocian) from the basal Cañadón Asfalto Formation (no supporting analytical data provided), which is comparable to that obtained by Stipanicic and Bonetti (1970) from an intercalated basalt. Significantly younger radioisotopic dates of 161 ± 3 Ma, based on LA-ICPMS U–Pb analyses of tuffaceous zircon (Cabaleri et al., 2010b; Gallego et al., 2011; no supporting analytical data provided), and 147.1 ± 3.3 Ma, based on biotite K–Ar analysis of a dacitic tuff (Cabaleri et al., 2010a) from what has been described as the upper Puesto Almada Member, greatly expanded the age range of the formation to the Jurassic–Cretaceous boundary. However, a significant portion of the fluvial strata commonly assigned to the latter member arguably belongs to the overlying Cañadón Calcáreo Formation (e.g., Fígari and Courtade, 1993), raising questions about the above age interpretations.

The sequence of fluvial to lacustrine sandstones, conglomerates, laminated shales and tuff that overlies the Cañadón Asfalto (and older) strata with an unconformity is known as the Cañadón Calcáreo Formation (Proserpio, 1987). It is distinguished from the underlying Cañadón Asfalto Formation by its near total absence of calcareous rocks and its moderate deformation (Volkheimer et al., 2009). The age of Cañadón Calcáreo Formation has been estimated to be Late Jurassic on the basis of its vertebrate fossils (see Rauhut et al., 2005), and Early Cretaceous on the basis of its palynofloral and invertebrate contents (Volkheimer et al., 2009; Gallego et al., 2011).

The Jurassic formations of the Cañadón Asfalto Basin are overlain by a thick sequence of intercalated fluvial-channel, flood plain and tuffaceous deposits knows as the Chubut Group, via a regional angular unconformity. In the Chubut River valley area, the group is considered to range in age from Early to Late Cretaceous (Barremian to Campanian) based on its invertebrate and palynofloral biostratigraphy (Codignotto et al., 1978).

3. U–Pb geochronology

3.1. Methods and results

Thirty-four single zircons from six tuff samples were analyzed by the U–Pb IDTIMS method. Samples were collected from primary tuff beds interstratified with the predominantly lacustrine strata of the Las Leoneras, Cañadón Asfalto and Cañadón Calcáreo Formations of the Jurassic Cañadón Asfalto Basin[1] (Fig. 1). Sample locations are listed in the Supplementary Table S1 available from the journal website. Rock samples were processed by standard crushing and pulverization methods and zircon separation from heavy mineral concentrates was achieved by step-wise magnetic and high-density liquid separation techniques, followed by hand-selection under a binocular microscope. Single zircon grains were dissolved in concentrated HF inside high-pressure hydrothermal vessels; dissolved uranium and lead were separated using ion-exchange chemical procedures and their isotopic compositions were measured on the VG Sector 54 multi-collector thermal ionization mass spectrometer at the Massachusetts Institute of Technology.

All zircon grains were pre-treated by the chemical abrasion or CA-TIMS technique of Mattinson (2005) in order to mitigate the effects of radiation-induced Pb loss resulting in anomalously young measured dates, and were spiked with the EARTHTIME ET535 mixed ^{205}Pb–^{233}U–^{235}U tracer solution prior to dissolution. Details of the U–Pb analytical procedures, data reduction, date and error calculation, and age interpretation are similar to those described in Ramezani et al. (2011).

Complete U–Pb analytical data appear in Supplementary Table S2, available from the journal website. Calculated dates and their 95% confidence level uncertainties are summarized in Table 1and illustrated on the standard concordia plots in Fig. 2. Uncertainties in U–Pb dates are reported as ± X/Y/Z Ma, where X is the exclusively internal (analytical) uncertainty, Y incorporates the U–Pb tracer calibration (external) error and Z includes the latter in addition to the U decay constant (external) errors of Jaffey et al. (1971). The geologic time scale follows that of Gradstein et al. (2012).

3.1.1. Las Leoneras Formation

A sample of welded ash tuff (LL041012-2) with brick-red weathering was collected from the Las Leoneras Formation in its type locality (Cañadón Las Leoneras, Fig. 1), about 40 m below the basal agglomerates of the overlying Lonco Trapial Formation (see Pol et al., 2011a). Five single zircon analyses from this sample define a statistically coherent cluster with a weighted mean ^{206}Pb/^{238}U date of 188.946 ± 0.096/0.13/0.24 Ma (Fig. 2A) and a mean square of weighted deviates (MSWD) of 1.1 (see Table 1 for error notation). This date serves as the best estimate for the (maximum) depositional age of the tuff bed within the upper Las Leoneras Fm. and places a maximum limit on the age of the Lonco Trapial Fm. (Fig. 3).

3.1.2. Cañadón Asfalto Formation

Three intercalated tuff samples were collected from various stratigraphic levels of the Cañadón Asfalto Formation for U–Pb geochronology. Sample Nestor-1 is from a distinct, 10 cm-thick tuff bed in the stratigraphic interval between the two lower basalt flows of the lower Cañadón Asfalto Formation (transition with the underlying Lonco Trapial Formation) at the Cañadón Lahuincó locality in the Cerro Cóndor area (Fig. 1). It is located approximately 10 m above the lacustrine beds that host the Frenguelli fossil site (see Escapa et al., 2008c). A coherent cluster of four zircon analyses from this sample yielded a weighted mean ^{206}Pb/^{238}U date of 178.766 ± 0.092/0.13/0.23 Ma (MSWD = 0.88; Fig. 2B), which is interpreted as the (maximum) age of deposition of the lower Cañadón Asfalto Formation. This date also places a minimum limit on the age of the Lonco Trapial Formation (Fig. 3).

A fine-grained tuffaceous bed (110210-4) sampled ~40 m above the base of the Cañadón Asfalto Formation at the Cerro Bayo Chico locality (Fig. 1) produced zircon ^{206}Pb/^{238}U dates, all but one of which were in the 285.84 Ma to 282.77 Ma (Early Permian) range. A single analysis with a ^{206}Pb/^{238}U date of 177.37 ± 0.12 Ma provides a provisional maximum age estimate for the deposition of the tuff bed,

[1] Geographic coordinates of the sample locations are available from the corresponding author upon request.

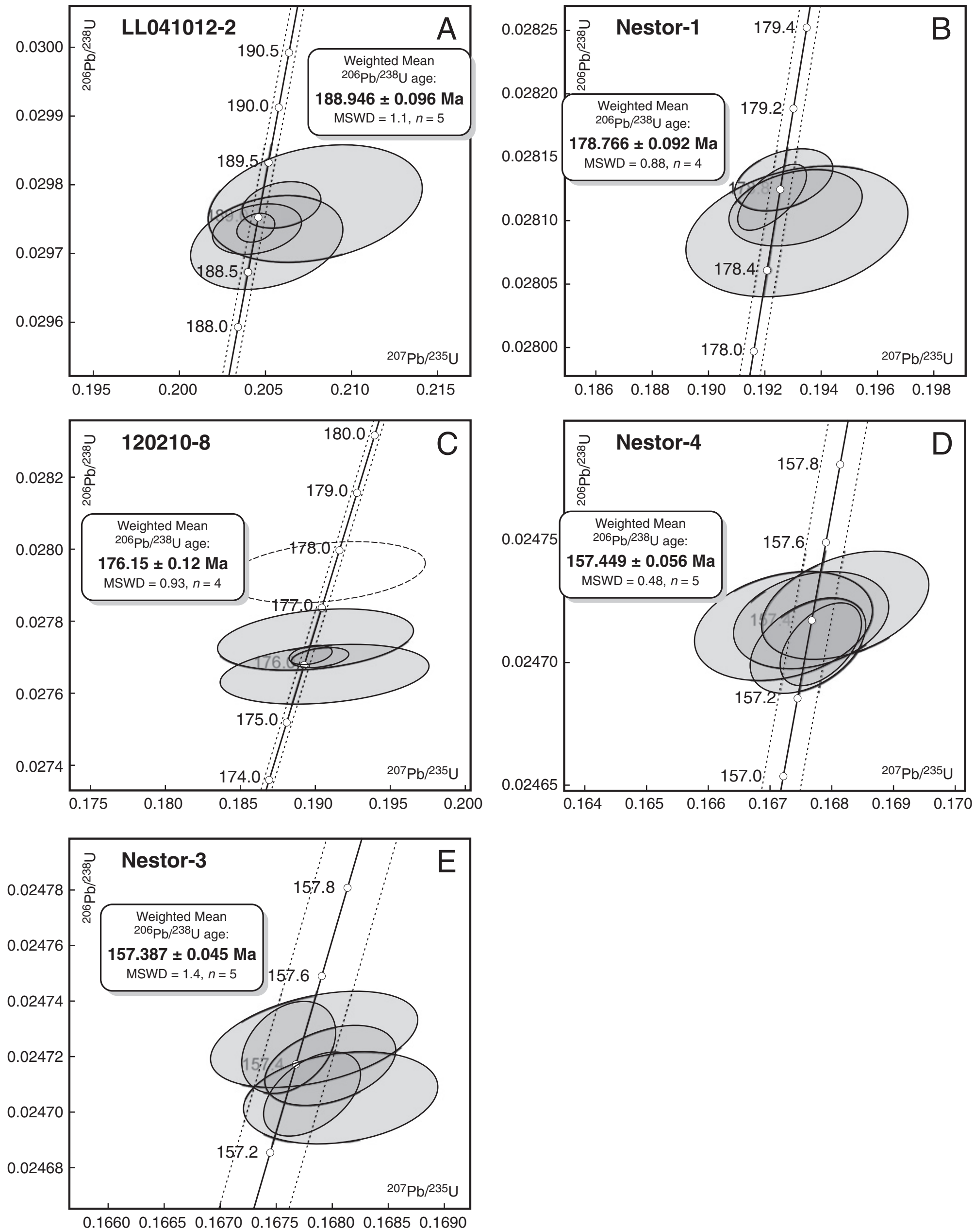

Fig. 2. A–E. U–Pb concordia plots for dated volcanic ash beds from the Cañadón Asfalto Basin, Argentina. Error ellipses represent 2σ internal uncertainties; shaded ellipses mark analyses used for age calculation. Dashed lines parallel to the solid concordia curve represent 95% confidence envelope associated with uncertainties in the uranium decay constants (Jaffey et al., 1971). See Supplementary Table S2, available from the journal website for U–Pb data and Table 1 for calculated ages and details of error reporting. MSWD = mean square of weighted deviates; n = number of analyses used in age calculation.

whereas the Early Permian analyses probably represent detrital and/or xenocrystic material from the crystalline basement (Mamil Choike Formation, Fig. 3) incorporated in the tuffaceous bed.

A second, coarse-grained, ash tuff (120210-8) from Cerro Bayo Chico was collected from ca.100 m above the previous sample. Four out of five zircon analyses from this sample form a coherent cluster with a weighted mean $^{206}Pb/^{238}U$ date of 176.15 ± 0.12/0.15/0.24 Ma (MSWD = 0.93; Fig. 2C). This date represents the (maximum) depositional age for the Cañadón Asfalto Formation below its lowermost carbonate horizon and is consistent with the single analyses from the underlying tuff bed described above. The fifth analysis was slightly older (177.62 ± 0.53 Ma) and may reflect incorporation of slightly older zircon, perhaps from an older eruption.

3.1.3. Cañadón Calcáreo Formation

Tuff samples from the Cañadón Calcáreo Formation were collected from its type locality at Puesto el Quemado, and from 10 km to the west at Puesto Almada locality, west of the Chubut River (Fig. 1). At the former locality, an ~50 cm-thick tuff layer interbedded with a massive sandstone bed directly overlying the lower, thin-bedded, lacustrine section of the Cañadón Calcáreo Formation was sampled (Nestor-4). Five zircon analyses yield a weighted mean $^{206}Pb/^{238}U$ date of 157.449 ± 0.056/0.090/0.19 Ma (MSWD = 0.48; Fig. 2D). The sample from Puesto Almada (Nestor-3) is a crystal tuff with visible biotite collected from immediately above the lower lacustrine section of the Cañadón Calcáreo Formation containing abundant fish fossils (the Almada fish fauna: López-Arbarello et al., 2008). A coherent

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Table 1
Summary of calculated U–Pb dates and their uncertainties.

Sample	Formation	Location	$^{206}Pb/^{238}U$ date (Ma)	Error (2σ)			MSWD	*n*
				X	Y	Z		
Nestor-3	Cañadón Calcáreo	3	157.387	0.045	0.082	0.19	1.4	5
Nestor-4	Cañadón Calcáreo	4	157.449	0.056	0.090	0.19	0.48	5
120210-8	Cañadón Asfalto	1	176.15	0.12	0.15	0.24	0.93	4
110210-4	Cañadón Asfalto	1	≤177.4	–	–	–	–	1
Nestor-1	Cañadón Asfalto	5	178.766	0.092	0.13	0.23	0.88	4
LL041012-2	Las Leoneras	2	188.946	0.096	0.13	0.24	1.1	5

Note:
Locations as shown in Fig. 1.
X—internal (analytical) uncertainty in the absence of all external or systematic errors; Y—incorporates the U–Pb tracer calibration error; Z—includes X and Y, as well as the uranium decay constant errors.
MSWD—mean square of weighted deviates.
n—number of analyses included in the calculated date.

cluster of five zircon analyses from Nestor-3 gives a weighted mean $^{206}Pb/^{238}U$ date of 157.387 ± 0.045/0.082/0.19 Ma (MSWD = 1.4; Fig. 2E) that is indistinguishable within uncertainty from that of the Puesto el Quemado sample. Both dates constrain the (maximum) depositional age of the Cañadón Calcáreo Formation at the top of its lower lacustrine section (Fig. 3).

4. Discussion

4.1. Geological implications

The geochronologic results presented here provide new insights into the depositional history of the Jurassic Cañadón Asfalto Basin in central Patagonia by placing reliable temporal constraints on its sedimentary and volcanic rock units. Accordingly, the unconformable deposition of the fluvial and lacustrine strata of the Las Leoneras Formation over the basement igneous and metamorphic rocks (Mamil Choike Formation) started in Early Jurassic, most probably in the latest Sinemurian.

The age of the volcanic, volcaniclastic and coarse epiclastic rocks of the Lonco Trapial Formation is now bracketed between 188.95 Ma and 178.77 Ma, entirely within the Early Jurassic (Pliensbachian–Toarcian). This is significantly older than the Middle to Late Jurassic ages previously assigned to this unit. The Lonco Trapial Formation and its correlative volcanic units comprise the Chon Aike large igneous province (LIP) of east-central Patagonia and the Antarctic Peninsula (Pankhurst et al., 1998). Although the exact age and duration of magmatism throughout the Chon Aike province are not well constrained, our new geochronology indicates possible contemporaneity between the latter and the voluminous

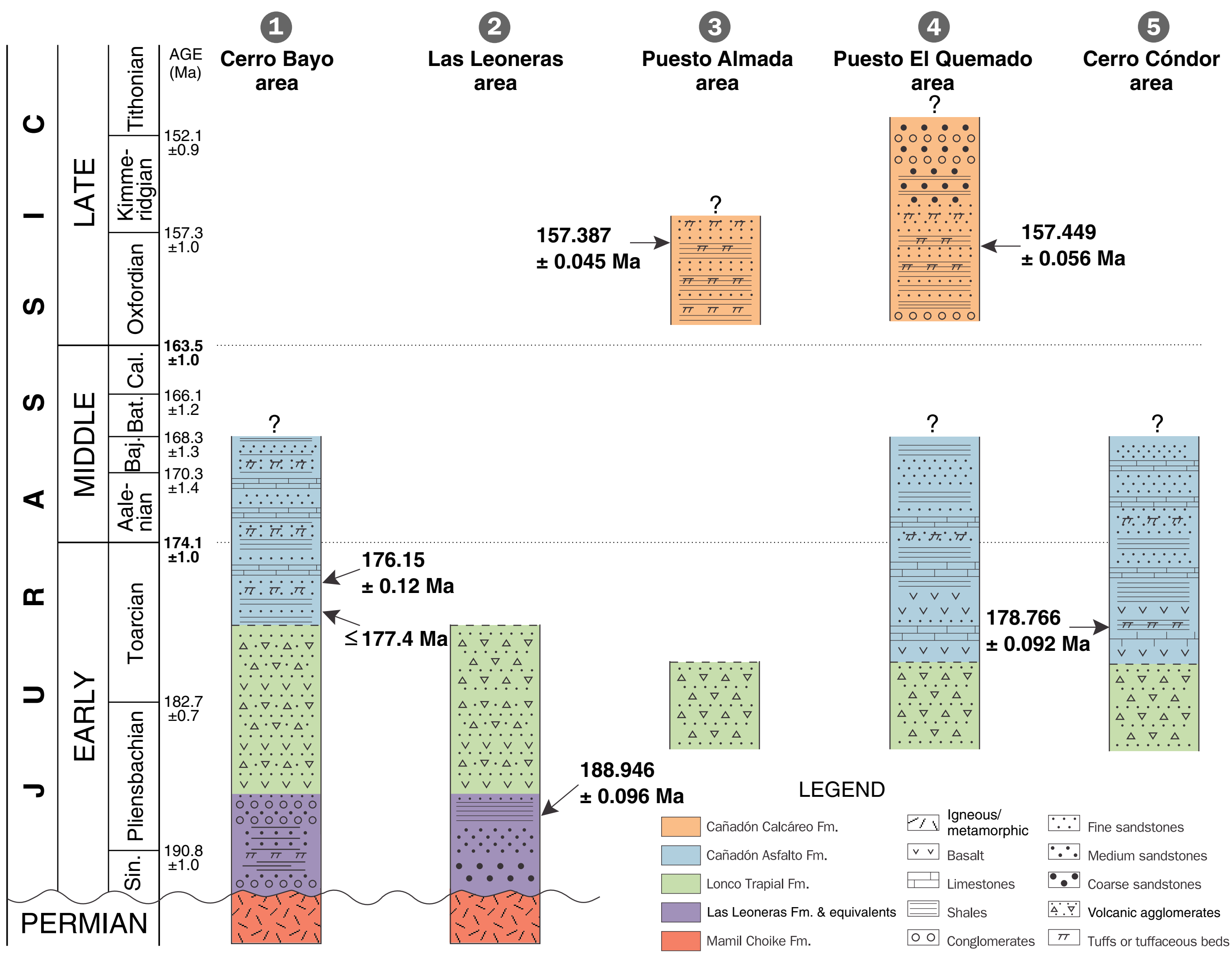

Fig. 3. Chronostratigraphic framework for the Jurassic rocks of the Cañadón Asfalto Basin based on the new geochronologic results (thicknesses not to scale). Section locations as in Fig. 1. Jurassic timescale based on GTS 2012 (Gradstein et al., 2012).

basaltic magmatism of Early Jurassic age in South Africa and West Antarctica that comprise the Gondwanan Karoo-Ferrar LIP (e.g., Encarnación et al., 1996). Recent U–Pb zircon ages from the widely distributed mafic sills (183.0 ± 0.5 Ma to 182.3 ± 0.6 Ma) as well as mineral $^{40}Ar/^{39}Ar$ geochronology on the continental flood basalts (182.3 ± 1.6 to 181.0 ± 2.0 Ma) emplaced throughout the Karoo Basin of South Africa have revealed a narrow age range, in the order of 800 ky or shorter, for the main pulse of LIP magmatism (Jourdan et al., 2007; Svensen et al., 2012). The abrupt LIP magmatism has been proposed as the cause of prominent paleoenvironmental perturbations and biotic changes that occurred in the early Toarcian (see 4.2.1).

After the Lonco Trapial volcano-tectonic episode, the fluvial–lacustrine system resumed throughout the Cañadón Asfalto Basin at ca. 179 Ma (early-mid Toarcian) with the deposition of the Cañadón Asfalto Formation, which most probably continued into the early Middle Jurassic (Aalenian or Bajocian). At present, the exact age of the upper Cañadón Asfalto Formation is poorly constrained. A post-Aalenian tectonic event resulted in an angular unconformity and down-cutting into the Cañadón Asfalto strata, which locally reached the Lonco Trapial stratigraphic levels (e.g., in the Puesto Almada area). The deposition of the predominantly fluvial and lacustrine Cañadón Calcáreo Formation on top of the latter unconformity started prior to ca. 158 Ma, probably in the Oxfordian, and continued during Late Jurassic time. Although no direct age constraints presently exists for the upper Cañadón Calcáreo Formation, its fossil content (see 4.2.6) makes its extension beyond the Late Jurassic (i.e., Kimmeridgian or Tithonian) unlikely.

4.2. Paleontological implications

The new chronostratigraphic framework for the Jurassic Cañadón Asfalto Basin in central Patagonia places more precise and reliable temporal constraints on its rich record of fauna and flora. The latter includes a remarkable variety of basal sauropodomorph, eusauropod, theropod and basal ornithischian dinosaurs, taxa representing the earliest mammals discovered in South America, and a diverse flora dominated by conifers, ferns, cycadophytes and palynoflora. Freshwater fish and conchostracans are abundant in some faunal assemblages, as well. Our results indicate that fossil flora and fauna are distributed in five major stratigraphic intervals ranging in age from Early Jurassic (Pliensbachian) to middle Late Jurassic (Oxfordian–Kimmeridgian?), as described below. Enhanced temporal resolution of these assemblages provides invaluable information as to the timeframes of biotic divergence and the placement of phylogenetic nodes, and thus a better understanding of the patterns of biotic evolution in the Jurassic.

4.2.1. Early Jurassic faunal assemblages

The oldest fauna discovered from the Cañadón Asfalto Basin is a basal sauropodomorph (*Leonerasaurus taquetrensis*) described by Pol et al. (2011a) from the Upper Member of the Las Leoneras Formation (Figs. 1 and 3), below the Lonco Trapial volcanic rocks. Our U–Pb date of 188.946 ± 0.096 Ma (Section 3.1.1) from a tuff bed less than 10 m below this fossil horizon constrains its age to early Pliensbachian. Two other basal sauropodomorphs have recently been described from the Early Jurassic of Northwest Argentina (Martínez, 2009; Apaldetti et al., 2011). Together, the Argentine record points to the basal sauropodomorphs of South America as long-lived lineages that originated during the Late Triassic (Norian) radiation, survived the subsequent end-Triassic faunal extinction, and went on to dominate the Early Jurassic Dinosauria.

The next stratigraphically higher fauna occurs in the lower strata of the Cañadón Asfalto Formation and thus postdates the Lonco Trapial volcanism. These assemblages correspond to both the northern and southern outcrops of the formation and include both dinosaurs and mammals, locally accompanied by plant fossils. In the south, remains of a new eusauropod taxon have been recovered from the Cañadón Bagual locality (Fig. 1; Pol et al., 2009) in the lacustrine strata underlying the uppermost basalt of the Cañadón Asfalto Formation. The new U–Pb date of ca. 178.766 ± 0.092 Ma from the same stratigraphic level in the adjacent Cañadón Lahuincó section (Section 3.1.2) places the above-mentioned taxon in the middle-late Toarcian, providing the first unequivocal record of Eusauropoda from the Early Jurassic. This implies that the evolutionary radiation of large-bodied eusauropods at the demise of basal sauropodomorphs took place by the end of the Early Jurassic, rather than the Middle Jurassic as recently suggested by Mannion et al. (2010).

A mid-late Early Jurassic age for the sauropodomorph faunal turnover and its spatial and temporal relation to the Lonco Trapial (Chon Aike LIP) volcanism allow its possible driving mechanisms to be explored from a global perspective. The early Toarcian paleoenvironmental proxy records worldwide indicate severe perturbations in the atmospheric carbon dioxide content accompanied by ocean anoxic conditions and mass extinctions among marine fauna (e.g., Mazzini et al., 2010; Guex et al., 2012). These have been tied to the large-scale release of greenhouse gases from the organic-rich sediments to the atmosphere due to contact metamorphism by mafic intrusions associated with the Karoo-Ferrar LIP (e.g., McElwain et al., 2005; Svensen et al., 2007; Mazzini et al., 2010). Considering the possible contemporaneity of the Chon Aike magmatism (Section 4.1), the same processes might have been responsible for the Early Jurassic terrestrial biotic events recorded in the Cañadón Asfalto Basin.

At a second southern locality (Queso Rallado; Fig. 1), strata belonging to the lowermost Cañadón Asfalto Formation (or beds transitional with the underlying Lonco Trapial Formation) have yielded a diverse assemblage of microvertebrates, including the basal ornithischian dinosaur *Manidens condoriensis* (Pol et al., 2011b). The latter is considered the closest relative of the heterodontosaurids from the Early Jurassic of South Africa (e.g., Sereno, 2012). Based on the dental apomorphies of *Manidens* and South African heterodontosaurids, the series of cladogenetic events that mark the first successful radiation of the ornithischian dinosaurs is now entirely restricted to the Early Jurassic, given the new age bracket for the *Manidens*.

Other microvertebrates recovered from Queso Rallado are the oldest South American mammals: the australophenidan *Asfaltomylos* and *Henosferus* (Rauhut et al., 2002; Martin and Rauhut, 2005; Rougier et al., 2007b), as well as the triconodontid *Argentoconodon* (Rougier et al., 2007a; Gaetano and Rougier, 2011). The middle-late Toarcian age of the associated strata renders these mammals the oldest representatives of their clades, predating their closest relatives by 10 to 30 m.y. Accordingly, the characteristic and derived traits of these taxa, such as the tribosphenic dentition of australophenidans or the putative gliding adaptations in triconodontid lineages, must have appeared earlier than previously recognized.

Ongoing investigations on the lower Cañadón Asfalto Formation continue to produce faunal remains, including the most recent discovery of material from a new basal eusauropod (personal observation by D.P.) from the Cerro Bayo Chico locality in the northern part of the study area (Figs. 1 and 3). The bone bed is stratigraphically bound to the top by a tuff bed dated at ca. 176.15 ± 0.12 Ma and to the bottom by another tuff determined to be equal to or younger than 177.4 Ma (see Section 3.1.2), placing tight limits on its age (late Toarcian). The latter discovery indicates that certain fossil-producing intervals may be widely distributed throughout the Cañadón Asfalto Basin.

4.2.2. Early Jurassic plant assemblages

Fossil floras have been recovered from the basal strata of the Lonco Trapial Formation at the Cañadón del Zaino locality, Taquetrén Hill (Fig. 1; Bonetti, 1963; Escapa et al., 2008b), and from an unnamed unit (equivalent of the Las Leoneras Formation) underlying the Lonco Trapial Formation in the Cerro Bayo area of the northern Cañadón Asfalto Basin. Our new geochronology confirms the overall Early Jurassic age estimate for the above flora (Escapa et al., 2008a,b;

Escapa and Cúneo, 2012) and, more specifically, restricts them to the Pliensbachian.

The sub-Lonco Trapial flora are dominated by conifers, ferns, caytonials, cycadophytes and sphenophytes, and are biostratigraphically characterized by the *Goeppertella–Dictyophyllum–Sagenopteris* association, which is also reported from other Early Jurassic assemblages in Argentina (e.g., Spalletti et al., 2007). Among conifers, *Austrohamia minuta* (Escapa et al., 2008a) is recognized as the oldest Cupressaceae (Rothwell et al., 2012) based on its now confirmed Early Jurassic age. From a phylogenetic point of view this conifer belongs to a basal clade in the family Cupressaceae, which consists of the extant genera *Taiwania* and *Cunninghamia* and several other fossil taxa and is distinctly Pangeic (Mao et al., 2012). The presence of osmundaceous ferns in this assemblage is of particular interest. Some of the taxa from this group display the coeval occurrence of the two main morphologies of the family by as early as Early Jurassic, which is significantly older than previously recognized.

Two fossil plant occurrences have been identified from the lower strata of the Cañadón Asfalto Formation in the southern outcrops of the basin (Cerro Cóndor area; Fig. 1); one from the Frenguelli site (Escapa et al., 2008c) and another from the Cañadón Bagual locality (RC and IE, in prep.). Their associated floral assemblages are different in composition from those of the Pliensbachian discussed above and the new geochronology indicates that they are distinguishably younger (middle-late Toarcian) as well. Fossil plants at these localities are dominated by conifer remains of at least two different families—Araucariaceae and Cupressaceae. The araucarian conifers here are among the oldest of the family, which place their initial diversification before the end of the Toarcian. The Cupressaceae, on the other hand, is represented by leafy shoots, seeds and pollen cones, which have been preliminarily assigned to the *Elatides* (Escapa, 2009), a genus classically known from the Middle Jurassic of Yorkshire (Harris, 1979), and also included in the basal clade of the Cupressaceae (Escapa et al., 2008a).

4.2.3. Middle Jurassic faunal assemblages

The middle to upper sections of the Cañadón Asfalto Formation, the interval that overlies its uppermost basalt flow in the Cerro Cóndor area (Fig. 1), can now be considered essentially early Middle Jurassic in age (Aalenian to probably Bajocian) based on the new geochronologic results. However, the presently available data do not preclude a latest Toarcian age for the strata closest to the basalt horizons. Recorded in this interval are a host of historic as well as newly discovered dinosaur fauna represented by eusauropods and theropods (Bonaparte, 1979; Bonaparte and Lange-Badre, 1986; Rauhut, 2005; Pol and Rauhut, 2012). An early Middle Jurassic age for eusauropods such as *Patagosaurus* and *Volkheimeria* implies that the middle-late Toarcian diversification of the basal eusauropods (see 4.2.1) gave rise to lineages that proceeded into the Middle Jurassic without significant changes. This provides further evidence that the major faunal replacement of the sauropodomorph dinosaurs in Patagonia occurred in the late Early Jurassic, rather than the Middle Jurassic.

The most important theropods associated with the middle/upper Cañadón Asfalto Formation are *Piatnitzkysaurus*, *Condorraptor*, and *Eoabelisaurus* (Bonaparte, 1979; Rauhut, 2005; Pol and Rauhut, 2012), which occur in the Cerro Cóndor area (Fig. 1). The ages of these taxa are key to understanding the major diversification of the Tetanurae and the Ceratosauria, the two main clades of the modern theropods (Carrano et al., 2012; Pol and Rauhut, 2012), which is now constrained essentially to the Toarcian–Aalenian boundary interval. In particular, *Eoabelisaurus* is deeply nested within the Ceratosauria as the most basal member of the derived clade Abelisauridae, implying that the initial diversification of this family started in excess of 40 m.y. earlier than previously thought (Pol and Rauhut, 2012).

4.2.4. Middle Jurassic plant assemblages

The macrofloral record of the middle/upper Cañadón Asfalto Formation is represented by permineralized wood and compression–impression plant remains from multiple localities in the southernmost outcrops of the basin (Pomelo, A-12 and El Alambre). Based on preliminary results, the associated flora is dominated by abundant conifer wood and a diverse suite of cutinized plant components involving conifers, seed ferns and cycads (personal observations by RC and IE).

A diverse palynofloral assemblage has also been identified from this stratigraphic interval, which is dominated by the cheirolepidiaceous *Classopollis* pollen along with that of other conifers of the families Araucariaceae and Podocarpaceae (Volkheimer et al., 2008; Olivera et al., 2012). Pteridosperms, ferns, lycopods and bryophytes are present in minor proportions. The assemblage has been thought to be of Late Bajocian to Early Kimmeridgian age by correlation with similar palynofloras from the Jurassic Neuquén basin in northwestern Patagonia (Volkheimer et al., 2008). However, our new geochronology suggests an Aalenian to possibly Bajocian age for the assemblage, which makes it more compatible with the early Middle Jurassic Araucariacean pollen phase (*Callialasporites turbatus* Zone) of eastern Australia (Grant-Mackie et al., 2000, p. 339).

4.2.5. Late Jurassic faunal assemblages

The Jurassic succession of the Cañadón Asfalto Basin comes to completion with the deposition of the conspicuously fossiliferous Cañadón Calcáreo Formation. The middle lacustrine section of the formation is host to the neosauropod dinosaur *Tehuelchesaurus benitezii* recovered from the Estancia Fernández locality (Fig. 1; Rich et al., 1999; Carballido et al., 2011). *Tehuelchesaurus* belongs to the large clade of macronarian sauropods and its appearance in the fossil record is closely related to the emergence of the clade titanosauriforms (Carballido et al., 2011). Based on the new geochronology, the Late Jurassic marks the earliest record of radiation of the latter clade in South America.

Our geochronologic results provide a direct, age-based correlation between the Cañadón Calcáreo sections at Puesto El Quemado and the Puesto Almada localities (ca. 10 km apart), despite significant dissimilarities in thickness and lithology. Accordingly, the classical freshwater fish record at Puesto Almada (the Almada fauna *sensu* López-Arbarello et al., 2008) occurs in the same lacustrine interval of the Cañadón Calcáreo Formation, approximately 50 m below a tuff bed with a U–Pb age of 157.387 ± 0.045 Ma, and is thus Oxfordian in age. The fauna includes the coccolepid "*Coccolepis*" *groeberi* and the teleosts "*Tharrias*" *feruglioi* and *Luisiella inexcutata*. These constitute one of the few Jurassic freshwater fish assemblages of Gondwana with close affiliation to the Talbragar beds from the Late Jurassic of Australia (López-Arbarello et al., 2008).

The fluvial conglomerates and coarse sandstones of the upper Cañadón Calcáreo Formation incorporate another dinosaur- and plant-bearing interval which, by stratigraphic correlation, occurs approximately 100 m above the tuff bed at Puesto El Quemado with a U–Pb age of 157.449 ± 0.056 Ma (see 3.1.3). This constrains the age of the fossil interval essentially to the Kimmeridgian, although an early Tithonian age cannot be ruled out based on the available geochronologic data. Among the most notable fauna from this interval is *Brachytrachelopan mesai* (Rauhut et al., 2005), a dinosaur that represents the earliest record of dicraeosaurid sauropods in South America. Dicraeosaurids are a typical Gondwanan clade that additionally occur in the Late Jurassic of Tanzania and Early Cretaceous of northern Patagonia. Brachiosaurid remains are also found in this interval, suggesting a rapid and global distribution for the group (Rauhut, 2006).

4.2.6. Late Jurassic plant assemblages

Fossil plants are present in the same two dinosaur- (and fish-) bearing stratigraphic intervals of the Cañadón Calcáreo Formation described above. A well-preserved compression–impression and permineralized fossil flora represented by conifer seed cones, seedlings and wood (Rich et al., 1999; Escapa, 2009) in association with abundant conchostracan fauna (Gallego et al., 2011) has been identified from the middle lacustrine section at the Estancia Fernández and Estancia Vilán localities (Fig. 1). The permineralized flora is dominated by conifers of the families

Araucariaceae and Cheirolepidiaceae, with minor cycad and fern components. Among conifers, the anatomically preserved *Araucaria* seed cones (Escapa, 2009) represent the second species with this type of preservation from the Mesozoic of South America, whereas the coexisting *Pararaucaria delfueyoi* seed cones are considered the first anatomically preserved seed cone of the extinct conifer family Cheirolepidiaceae (Escapa et al., 2012, 2013). It is notable that the same *Araucaria*/*Pararaucaria* association has been observed in the classical paleoforests of the Middle Jurassic La Matilde Formation from the Santa Cruz Province (Argentina) and, more recently, in the Jurassic (Callovian) Trowbridge Formation of Oregon (western U.S.) (Stockey et al., 2012). These occurrences highlight the spatial and temporal distributions of the Araucariaceae/Cheirolepidiaceae forests during the Jurassic.

A diverse palynoflora has been described from the middle lacustrine section of the Cañadón Calcáreo Formation at Puesto El Quemado that includes more than 130 species (51 new in Argentina) of gymnospermous pollen and spores of bryophytes, lycophytes and ferns (Volkheimer et al., 2009; Zavattieri et al., 2010). Although the assemblage was considered to be Early Cretaceous in age (Volkheimer et al., 2009), further analyses and new collections (Zavattieri et al., 2010 and in prep.) suggest an older, Late Jurassic (late Oxfordian to early Tithonian) age. Some of the evidence in support of the older palynofloral age are the first appearance of the *Balmeiopsis* genus (Late Jurassic), the absence of unequivocal Early Cretaceous forms such as *Cycluphaera psilata* or *Coptospora* sp., and the first appearance of characteristic late Jurassic forms from eastern Australia such as *Aequitriradites acusus* and *Retitriletes watherooensis*. The latter forms precede the late Tithonian to early Valanginian *Cicatricosisporites australiensis* Zone (Sajjadi and Playford, 2002). The Late Jurassic palynofloral age is supported by the new U–Pb geochronologic results from the Cañadón Calcáreo Formation (see 3.1.3).

Work in progress on the plant fossils of the upper fluvial section of the Cañadón Calcáreo Formation has identified permineralized araucarian seed cones and conifer wood (personal observation by RC and IE) suggesting the continued presence of coniferous forests throughout the Cañadón Asfalto basin during the Late Jurassic.

5. Concluding remarks

High-precision geochronology based on five lacustrine tuff beds analyzed by the U–Pb CA-TIMS method establishes a new chronostratigraphy for the fossil-rich Jurassic formations of the Cañadón Asfalto Basin in the Chubut Province of Argentina. The results indicate a Sinemurian to Pliensbachian age for the Las Leoneras Formation and its equivalents, a Pliensbachian to Toarcian age for the Lonco Trapial Formation, a mid-late Toarcian to Aalenian (–Bajocian?) age for the Cañadón Asfalto Formation, and an Oxfordian to Kimmeridgian (–Tithonian?) age for the Cañadón Calcáreo Formation.

Combined with ongoing biostratigraphic investigations, the new geochronology resolves the temporal ranges of several major, fossil-rich, stratigraphic intervals that preserve a remarkable record of Jurassic vertebrate fauna and flora. The new age-calibrated fossil record allows correlation to the global time scale and highlights a number of key events in the biotic evolution that occurred in the Early Jurassic, significantly earlier in geologic time than previously recognized. These include the major faunal turnover of the sauropodomorph dinosaurs, the first successful radiation of the ornithischian dinosaurs, and the diversification of the araucarian and cupressaceous conifers and the osmundaceous ferns. The Cañadón Asfalto Formation palynofloras seem to be confined to the late Toarcian–Bajocian period, whereas the Cañadón Calcáreo Formation and its diverse palynofloral record are now entirely restricted to the Late Jurassic.

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Appendix A. Supplementary data

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