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# Earliest Permian brachiopod faunas of west-central Argentina: Defining the Pennsylvanian–Permian boundary in Gondwana

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ABSTRACT

Late Palaeozoic marine successions in the west-central Argentinian basins have one of the most complete stratigraphic records of the earliest Permian in Gondwana. Two brachiopod faunal assemblages characterize this interval: the *Tivertonia jachalensis–Streptorhynchus inaequiornatus* fauna, widely documented in the Río Blanco and western Paganzo basins; and the *Costatumulus amosi* fauna identified in the earliest Permian successions of the southern Calingasta–Uspallata Basin. This study reviews the composition and biostratigraphy of these two brachiopod faunas with special reference to their global significance for defining the Carboniferous–Permian boundary in Gondwana and deciphering the Early Permian climate change in western Gondwana.



## 1. Introduction

The Late Palaeozoic marine successions in the west-central Argentinian basins (Río Blanco, Calingasta–Uspallata and western Paganzo basins, Fig. 1A), have the most complete stratigraphic records of the earliest Permian in Gondwana. Two main brachiopod faunal assemblages characterize this interval of time: the *Tivertonia jachalensis–Streptorhynchus inaequiornatus* fauna (T–S fauna), widely documented in the Río Blanco and western Paganzo basins and the *Costatumulus amosi* fauna identified in the earliest Permian successions of southern Calingasta–Uspallata Basin (Fig. 1B).

The geological record of the Late Palaeozoic in the west-central of Argentina has been interpreted as a complex history of interaction among tectonism, sea-level changes and climatic conditions (Limarino et al., 2006). Also, several diachronous Palaeo-Pacific transgressive events affected the Precordilleran basins, from the Early Carboniferous to the Early Permian (Limarino et al., 2002, 2006). The brachiopod faunal assemblages herein studied are associated with the youngest of these transgressive events (Gzhelian–Sakmarian, Limarino et al., 2006), which represents the transition from glacial to postglacial conditions, with a later climatic amelioration.

This paper provides a detailed review of the composition and biostratigraphy of the *Tivertonia jachalensis–Streptorhynchus inaequiornatus* and *Costatumulus amosi* faunas with special reference to their global significance for defining the Carboniferous–Permian boundary in Gondwana and deciphering the Early Permian climate change in western Gondwana.

## 2. The *Tivertonia jachalensis–Streptorhynchus inaequiornatus* (T–S) fauna

The *Tivertonia jachalensis–Streptorhynchus inaequiornatus* (T–S) fauna is largely restricted to the Río Blanco Basin and to the western sector of the Paganzo Basin, where it appears associated with the latest Carboniferous–earliest Permian Palaeo-Pacific transgressive event (Cisterna et al., 2005). However, some of this fauna's diagnostic taxa have been recently noted from the Calingasta–Uspallata Basin (Taboada, 2006).

The T–S fauna is composed of a diversified marine invertebrate assemblage of brachiopods, bivalves, gastropods and ostracods, which were assigned to the *Tivertonia jachalensis–Streptorhynchus inaequiornatus* Zone (Sabattini et al., 1990). The Tupe Formation (Cuerda, 1965) at La Herradura Creek has been proposed as the stratotype for this biozone. The stratigraphic sections of the Río del Peñón Formation (Borrello, 1955; González and Bossi, 1986) and the Tupe Formation at La Delfina Creek, are the para-stratotypes. The *Tivertonia jachalensis–Streptorhynchus inaequiornatus* Zone originally named as *Lissochonetes jachalensis–Streptorhynchus inaequiornatus* Zone, was previously assigned to the Pennsylvanian (Sabattini et al., 1990). Because of the inclusion of the species *Lissochonetes jachalensis* Amos in the Permian genus *Tivertonia* Archbold, Archangelsky et al. (1996) suggested that this biozone was extended to the Permian. More recent works in the Río del Peñón Formation (Cisterna and Sabattini, 1998; Cisterna and Simanauskas, 2000; Cisterna et al., 2006b) and in the Tupe Formation at La Herradura Creek, La Delfina Creek and Mina

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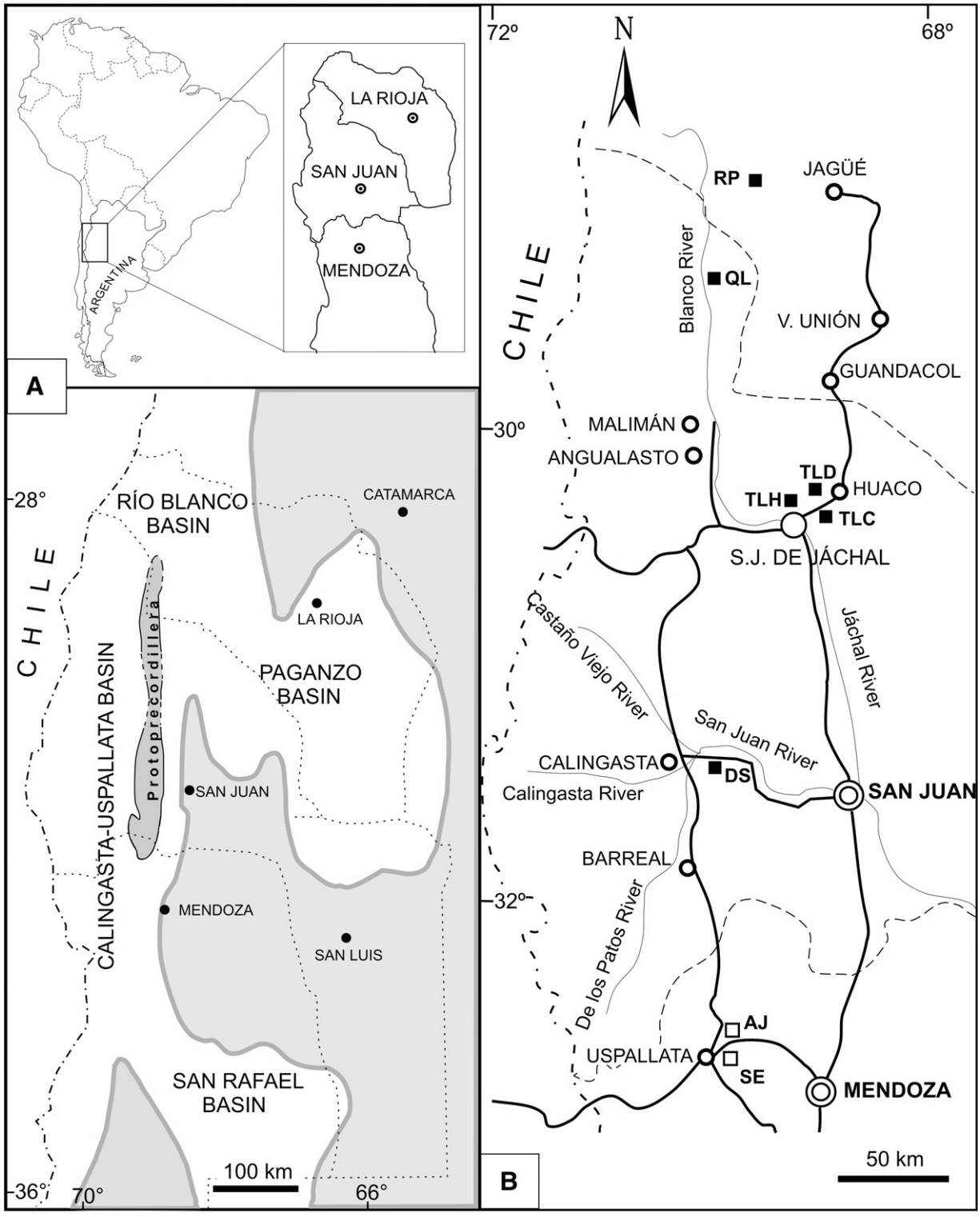



**Fig. 1.** A, Location maps showing the palaeogeography and geography of the Río Blanco, Calingasta–Uspallata and Paganzo basins in western Argentina. B, Generalized map showing the location of the key sections that contain the T–S and *Costatumulus* faunas. RP: Río del Peñón Formation; QL: Quebrada Larga Formation; TLH, Tupe Formation al La Herradura Creek; TLD: Tupe Formation al La Delfina creek; TLC: Tupe Formation at Mina La Ciénaga; DS: Del Salto Formation; AJ: Agua del Jagüel Formation; SE: Santa Elena Formation.

La Ciénaga (Archbold and Simanauskas, 2001; Cisterna et al., 2002; Sterren, 2004; Cisterna et al., 2005; Gutiérrez et al., 2005; Cisterna et al., 2006b; Desjardins et al., 2009), have confirmed the Early Permian age (Asselian) for this biostratigraphic unit.

The main brachiopods that characterize the T–S fauna (Fig. 2A–R) are *Tivertonia jachalensis* (Amos), *Kochiproductus riojanus* (Leanza), *Kochiproductus* sp., *Costatumulus* sp., *Coronalosia argentinensis* Archbold and Simanauskas, *Tupelosia paganzoensis* Archbold and Simanauskas, *Streptorhynchus inaequiornatus* Leanza, *Crurithyris*? sp., *Pericospira pericoensis* (Leanza), *Pericospira riojanensis* (Lech and Aceñolaza), *Septosyringothyris* aff. *jaguelensis* Lech and linguliforms (*Orbiculoidea* sp.). A recent review of the different key stratigraphic

sections where the T–S fauna has been recognized, has revealed some variations in the species composition of the fauna within the Argentine Precordillera, as well as its importance in the definition of the Carboniferous–Permian boundary in this part of Gondwana.

A review of the compositional variations and biostratigraphical aspects of the T–S fauna is herein considered. The key stratigraphic sections corresponding to the stratotype and para-stratotypes are also figured.

### 2.1. Western Paganzo Basin

The T–S fauna has been identified in the outcrops of the Tupe Formation located in western Paganzo Basin (La Herradura Creek, La Defina Creek and Mina La Ciénaga localities, on the west flank of Perico Hill in San Juan province, Fig. 1B). Although the Tupe Formation was mostly deposited in continental environments, in the west part of the basin it is punctuated by a marine interval that contains the T–S fauna. This marine event has been interpreted as the Panthalassan marine transgression that suggests an areally extensive breach of the local north-trending high called Proto-Precordillera (Amos and Rolleri, 1965; López Gamundí et al., 1994). In the Tupe Formation at La Herradura Creek, the stratotype of the *Tivertonia jachalensis–Streptorhynchus inaequiornatus* Zone, the marine horizons that contain the T–S fauna is located in the middle part of the section (Fig. 3). The fossil assemblage is dominated by the brachiopods *Tivertonia jachalensis*, *Kochiproductus* sp., *Costatumulus* sp., *Coronalosia argentinensis*, *Tupelosia paganzoensis*, *Streptorhynchus inaequiornatus*, *Crurithyris*? sp., *Pericospira pericoensis*, *Septosyringothyris* sp. *jaguelensis* and linguliforms (*Lingula* sp. and *Orbiculoidea* sp.). Taxonomy and biostratigraphy of the brachiopods from this assemblage have been widely studied by Archbold and Simanauskas (2001) and Cisterna et al. (2002). A recent study of the palynological data from this section (Vergel, 2008) supports the Early Permian age suggested by the T–S fauna.

Diagnostic brachiopods of the T–S fauna have been also identified in the marine interval of the Tupe Formation at the La Defina Creek (Cisterna et al., 2006a). The brachiopod assemblage recognized in the middle part of the section is composed of *Costatumulus* sp. and *Orbiculoidea* sp. as dominant species, accompanied by *Pericospira pericoensis*, *Kochiproductus* sp., *Streptorhynchus inaequiornatus*, *Septosyringothyris* sp. and scarce *Tivertonia jachalensis.* The faunal assemblage is compositionally comparable to the fauna described from the lowest horizon of the marine interval of the Tupe Formation at La Herradura Creek (Fig. 3), and it is the oldest part of the *Tivertonia jachalensis–Streptorhynchus inaequiornatus* Zone in the Paganzo Basin (Cisterna et al., 2006a). The T–S fauna in the Tupe Formation at La Delfina Creek is located above horizons that contain diagnostic latest Carboniferous megaflora and palynological records (NBG — *Nothorhacopteris–Botrychiopsis–Ginkgophyllum*- and Interval megafloristic zones; *Raistrickia densa–Convolutispora muriornata* Palynological Zone), described by Coturel and Gutiérrez (2005) and Gutiérrez et al. (2005).

### 2.2. Río Blanco Basin

The T–S fauna, well documented in the Río Blanco Basin, has also been identified in the Río del Peñón Formation (La Rioja Province) and in the Quebrada Larga Formation, San Juan Province (Fig. 1B). The T–S fauna from the middle part of the Río del Peñón Formation (Fig. 4) is composed of the brachiopods *Tivertonia jachalensis*, *Kochiproductus riojanus*, *Costatumulus* sp. B, *Streptorhynchus inaequiornatus*, *Pericospira riojanensis*, *Spiriferellina* sp. and linguliforms (*Orbiculoidea* sp.). However, my more recent field work has identified new taxa and recognition of a pattern of vertical faunal distribution within the marine interval that contains the T–S fauna. The lower part is dominated by *Pericospira riojanensis*, accompanied by *Kochiproductus riojanus*, *Costatumulus* sp. B, *Septosyringothyris* sp., *Spiriferellina* sp. and *Orbiculoidea* sp., but *Tivertonia jachalensis* and *Streptorhynchus inaequiornatus* that define the T–S fauna are very scarce. In the upper part of the fossiliferous interval, the faunal assemblage is composed of brachiopods and ostracods. The dominant brachiopod species are *T. jachalensis* and *S. inaequiornatus*, accompanied by *Kochiproductus*? sp., Productidae indet. (probably a new species awaiting detailed description) and very scarce linguliforms.

A faunal brachiopod assemblage that appears to be slightly younger than the T–S fauna has been also identified in the Río del Peñón Formation (Fig. 2S–X). This assemblage from the middle part of the section (Assemblage III of Cisterna and Simanauskas, 2000), is composed of the brachiopods *Neochonetes pegnonensis* Cisterna and Simanauskas, *Costatumulus* sp. C, *Rhynchopora* sp., *Septosyringothyris jaguelensis* and *Orbiculoidea* sp., accompanied by bivalves, gastropods, crinoids and ostracods. Taxonomy and faunal affinities of the brachiopods identified in this assemblage have been discussed by Cisterna and Simanauskas (2000) and Archbold et al. (2004).

In the Río del Peñón Formation, which can be considered one of the best sections for defining the Carboniferous–Permian boundary in the Río Blanco Basin, the T–S fauna is closely related to palaeofloral records. This fauna is stratigraphically bracketed between two palynological zones. The fauna is underlain by the latest Carboniferous NBG megaflora and DM (*Raistrickia densa–Convolutispora muriornata*) Palynological Zone (Fig. 4), described from the lower part of the section (Cisterna et al., 2006b; Gutiérrez and Limarino, 2006). Stratigraphically accompanying and also overlying the T–S fauna in the Río del Peñón Formation is the Early Permian (early Cisuralian) *Pakhapites fusus–Vittatina subsaccata* Palynological Zone (Gutiérrez and Limarino, 2006) (FS Zone in Fig. 3).

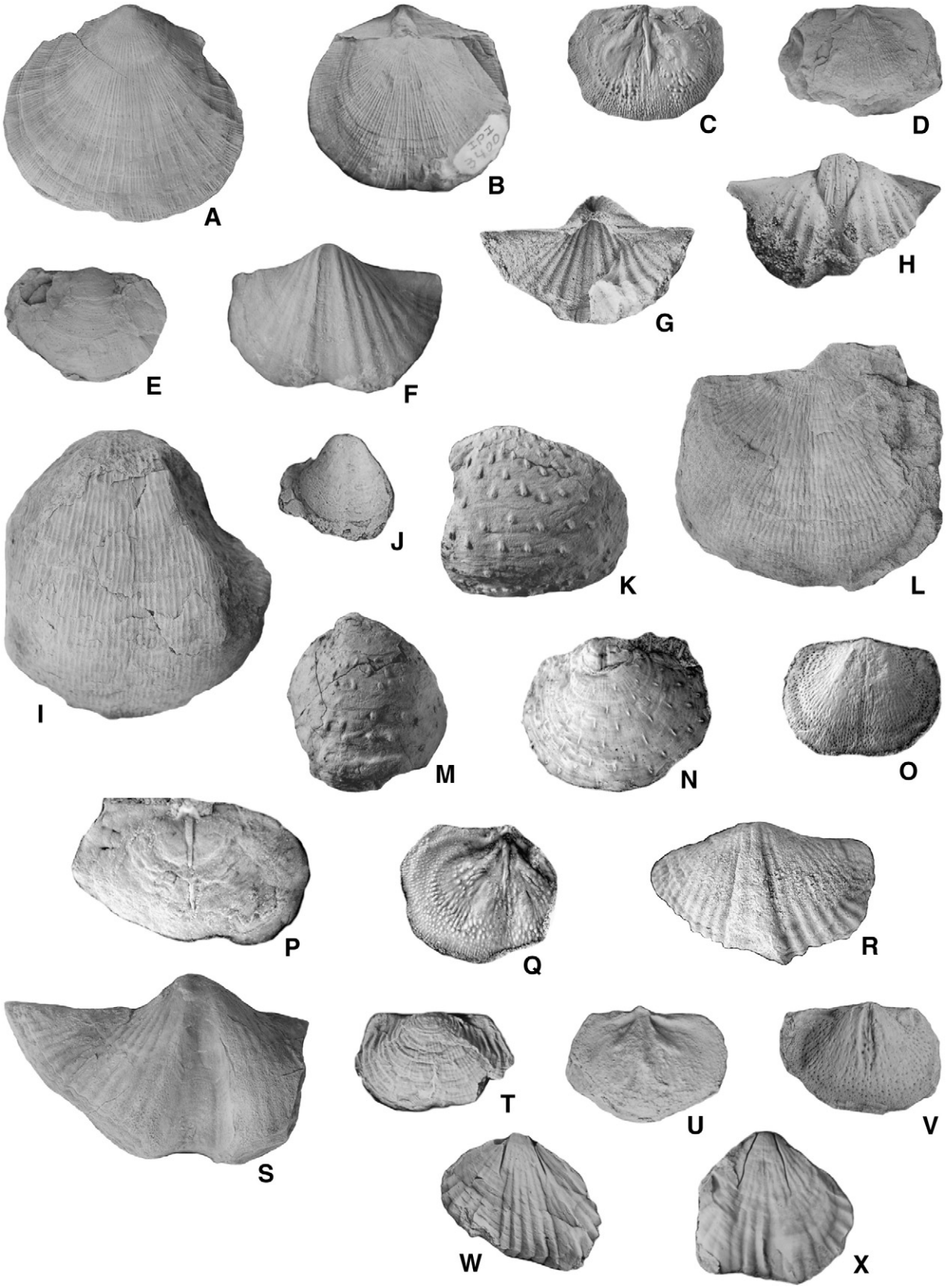
In the upper part of the Quebrada Larga Formation (Scalabrini Ortiz, 1972) in the type locality, two marine fossil assemblages that can be included in the T–S fauna have been described (Cisterna and Sterren, 2007). The lower one is dominated by brachiopods (*Septosyringothyris* aff. *jaguelensis* accompanied by *Tivertonia jachalensis*, *Orbiculoidea* sp., along with very scarce and fragmentary *Streptorhynchus inaequiornatus*), as well as gastropods and bivalves. The upper assemblage is composed of the brachiopods *Svalbardia* sp., *Coronalosia* sp., *Septosyringothyris* aff. *jaguelensis* and scarce gastropods. The occurrence of *Coronalosia* sp. and *Svalbardia* sp. (the latter is likely to represent two new species with Permian Gondwanan affinities) represents a clear compositional variation within the T–S fauna in this part of the basin. Because this fauna occurs above the bed carrying elements of the Pennsylvanian NBG megafloral assemblage, such as *Nothorhacopteris argentinica*, the type section of the Quebrada Larga Formation has been proposed as a key section the Carboniferous–Permian boundary (Cisterna and Sterren, 2007).

### 2.3. Calingasta–Uspallata Basin

Although the T–S fauna is mainly restricted to the Río Blanco and western Paganzo basins, the diagnostic species *Tivertonia jachalensis* has recently also been described by Taboada (2006), from the Del Salto Formation in the San Juan Province and from the Santa Elena Formation in Mendoza Province (Fig. 1B). In the upper horizons of the marine interval of the Del Salto Formation (Quartino et al., 1971), *Tivertonia jachalensis* occurs with *Septosyngothyris*, *Costatumulus* and *Etherilosia*? (Cisterna and Archbold, 2007). *Pericospira sanjuanesis* (Lech and Aceñolaza) and *Saltospirifer guevarii* (Cisterna and Archbold) have been also described from the lower part of this interval (Cisterna and Archbold, 2007). Occurrence of *Tivertonia jachalensis* in the Del Salto Formation would extend the palaeogeographical distribution of the T–S fauna to the Calingasta–Uspallata Basin. However, because this specie is in the Santa Elena Formation, where it occurs with the *Costatumulus amosi* fauna, a re-evaluation of the biostratigraphical relationship between both faunal assemblages is necessary.

### 3. The *Costatumulus amosi* fauna

The *Costatumulus* fauna is geographically restricted to the southernmost part of the Calingasta–Uspallata Basin, where it has been identified in the successions of the Agua del Jagüel and Santa Elena formations (Figs. 1B, 5, 7). The marine assemblages composed of brachiopods, bivalves and gastropods that typify this fauna have been assigned to the Early Permian (Asselian–Tastubian, Taboada, 2001)



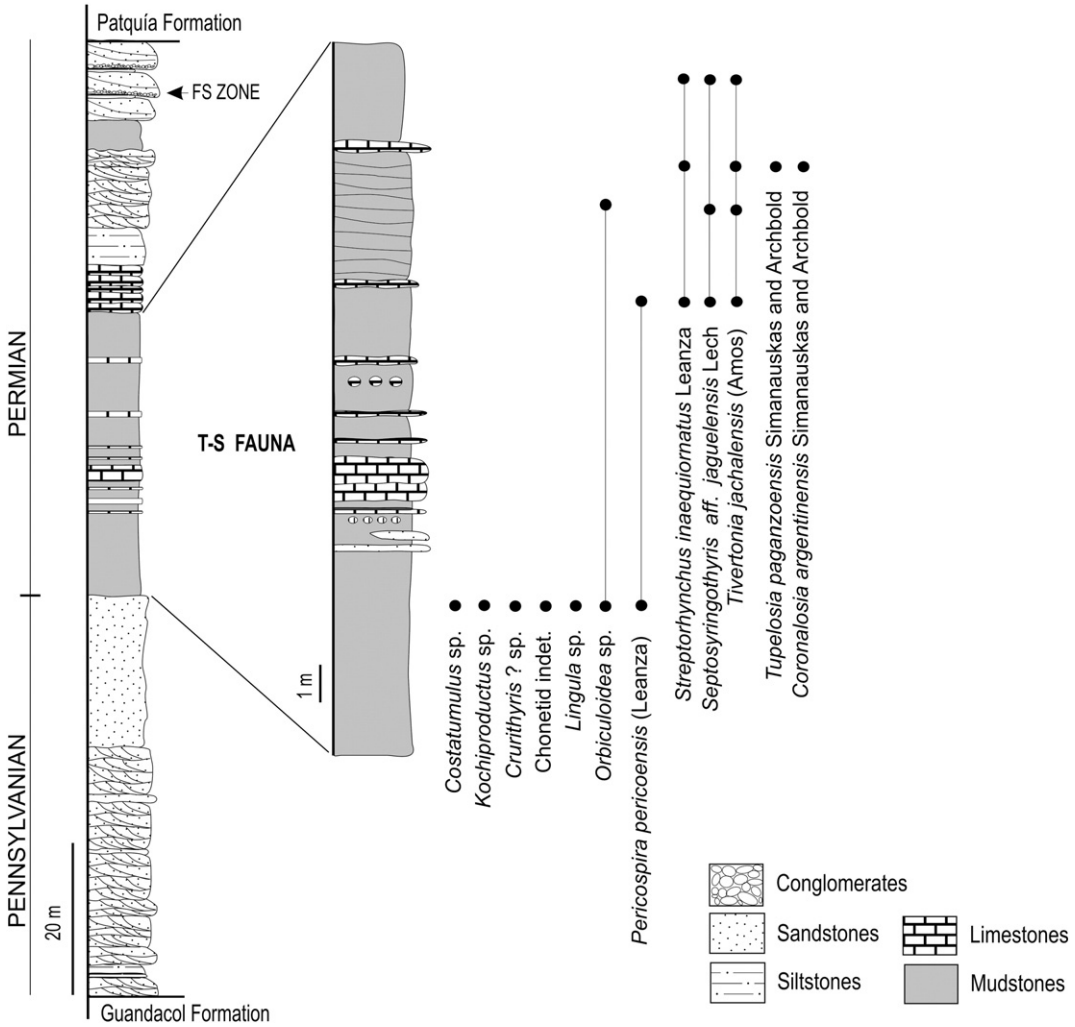



**Fig. 3.** Stratigraphical section of the Tupe Formation at La Herradura Creek showing the vertical distribution of the T–S fauna and microflora assemblage (FS Zone: *Pakhapites fusus–Vittatina subsaccata* Palynological Zone) (modified from Cisterna et al., 2005).

*Costatumulus amosi* Zone [= *Cancrinella* cf. *C. farleyensis* (Etheridge and Dun) of Amos, 1961]. The brachiopods that characterize this biozone are notably less diverse than those from the T–S fauna, whilst the bivalves and gastropods are more diverse.

The Agua del Jagüel Formation (Harrington, 1971) in its type locality (Agua del Jagüel Creek, Mendoza Province), appears to be one of the best sections to study the *Costatumulus* fauna. Compositional variations of the faunal assemblages from this succession (Fig. 5) are related to the latest Carboniferous–earliest Permian palaeoclimatic events, as evidenced in associated sedimentary features (Ciccioli et al., 2008). The Agua del Jagüel Formation is characterized by a deglaciation succession that is overlain by fluvial and shallow marine deposits. At its type locality, the Agua del Jagüel Formation is composed of three depositional successions (Henry et al., 2008). The first, characterizing the glacial and early postglacial phase, contains the diagnostic Pennsylvanian *Rhipidomella–Micraphelia* faunal assemblage (*Rhipidomella*? sp. and *Micraphelia indianae* Simanauskas and Cisterna), immediately above the diamictitic horizons in the lower part of the section (Martínez et al., 2001; Simanauskas and Cisterna, 2001) (Fig. 5). This *Rhipidomella–Micraphelia* fauna was previously identified from the El Paso Formation (Mésigos, 1953), located in the northernmost part of the Calingasta–Uspallata Basin, where it has been related to a deglaciation stage and has been dated as Pennsylvanian age by associated palynological data (Vergel et al., 2008). This accepted, the *Rhipidomella–Micraphelia* fauna would mark the last pulse of the Pennsylvanian glaciation in the basin (Martínez et al., 1998; Simanauskas and Cisterna, 2001; Vergel et al., 2008). Radiometric K–Ar data from the pillow lavas located 150 m above the *Rhipidomella–Micraphelia* faunal assemblage suggest an age of 307 ± 5.2 Ma, or late Bashkirian–early Gzhelian (Lech, 2002).

**Fig. 2.** Diagnostic brachiopods of the T–S fauna and the youngest *Neochonetes–Rhynchopora* assemblage. A–B, *Streptorhynchus inaequiornatus* Leanza. A, articulate specimen, ventral view, IPI 3398, ×1; B, articulate specimen, dorsal view, IPI 3400, ×2. C–E, *Tivertonia jachalensis* (Amos). C, dorsal interior, DCG-MLP 354f, ×2; D, dorsal valve, IPI 2942, ×2; E, ventral valve, IPI 2941, ×2; F, *Pericospira pericoensis* (Leanza), ventral valve, IPI 2869, ×2; G–H, *Pericospira riojanensis* (Lech and Aceñolaza). G, external mould of articulate specimen, dorsal view, IPI 4516, ×1,2; H, internal mould of ventral valve, IPI 4515, ×1.2; I, L *Kochiproductus riojanus* (Leanza). I, ventral valve, IPI 3169b, ×1; L, dorsal valve, IPI 3169a, ×1; J, *Crurithyris?* sp., ventral valve, IPI 2895, ×3; K, *Coronalosia argentinensis* Archbold and Simanauskas, ventral valve, DCG-MLP 356b, ×2; 6, M, *Tupelosia paganzoensis* Archbold and Simanauskas, ventral valve, DCG-MLP 356e, ×1.8; N, P, *Coronalosia* sp. N, ventral valve, CEGH-UNC 22847, ×2.5; P, dorsal interior, CEGH-UNC 22848, ×2; O, Q, *Svalbardia*, sp. O, internal mould of ventral valve, CEGH-UNC 22853, ×2.5; Q, dorsal interior, CEGH-UNC 22855, ×3.5; R, *Septosyringothyris* sp. aff. *Septosyringothyris jaguelensis* Lech, internal mould of dorsal valve, CEGH-UNC 22862, ×1; S, *Septosyringothyris jaguelensis* Lech, ventral valve, IPI3066, ×1; T, *Costatumulus* sp. C, dorsal valve, IPI 3389, ×2; U–V, *Neochonetes pegnonensis* Cisterna and Simanauskas. U, dorsal valve, IPI 2969, ×2.5; V, internal mould of ventral valve, IPI 2960, ×2.5; W–X, *Rhynchopora* sp. W, internal mould of ventral valve, IPI 3364, ×1.5; X, internal mould of ventral valve, IP 3361, ×1.5. A–C, F, J, K, M, specimens from the Tupe Formation; D, E, G, H, I, L, S–X, specimens from the Río del Peñón Formation; N–R, specimens from the Quebrada Larga Formation. Repository: IPI, *Instituto de Paleontología, Fundación Miguel Lillo*; DCG-MLP, *Departamento Científico de Geología, Museo de La Plata*; CEGH-UNC, *Centro de Investigaciones Paleobiológicas (CIPAL), Facultad de Ciencias Exactas, Físicas y Naturales, Universidad Nacional de Córdoba*.

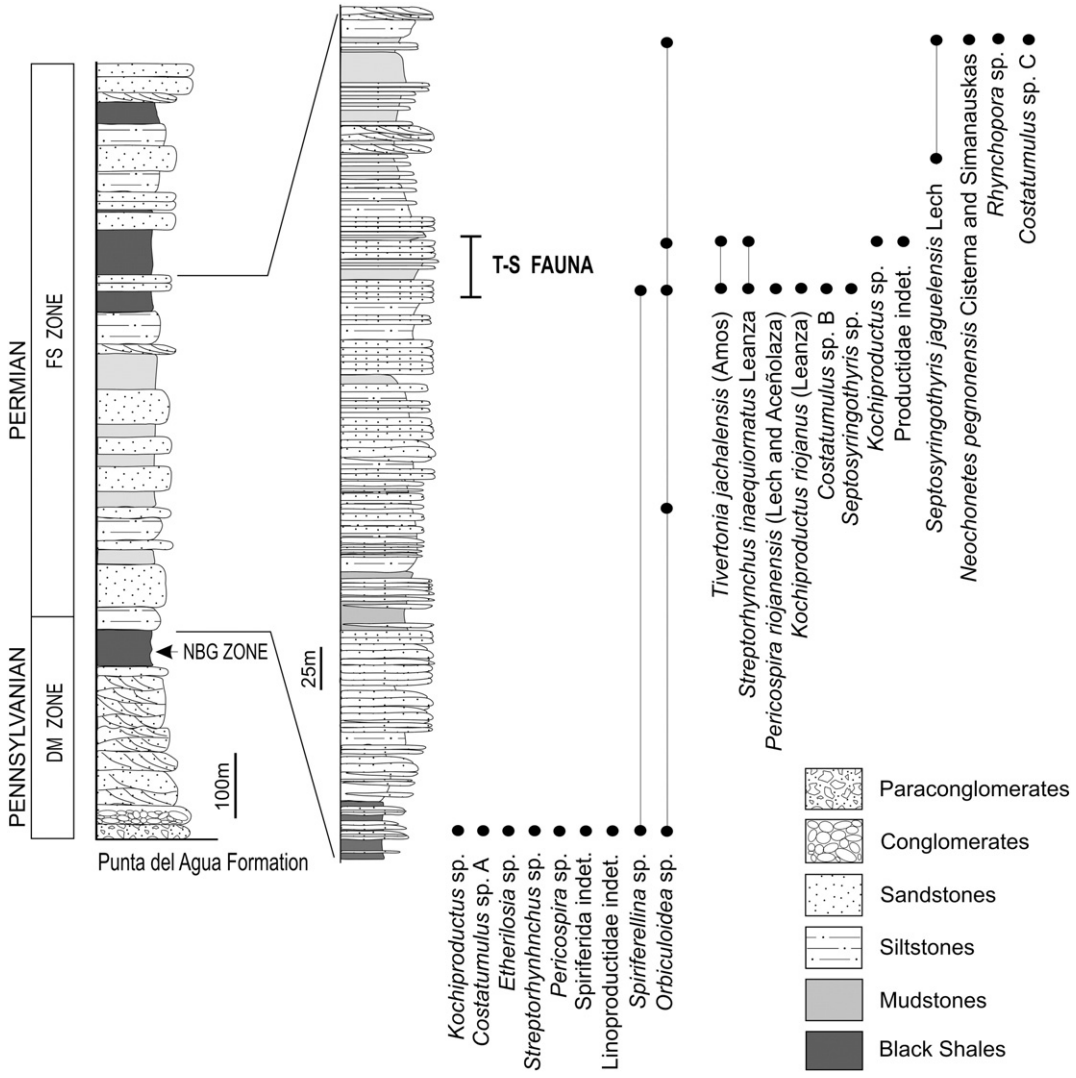



**Fig. 4.** Stratigraphical section of the Río del Peñón Formation (modified from Cisterna and Simanauskas, 2000) and vertical distribution of the brachiopod, mega and microflora assemblages. DM ZONE: *Raistrickia densa–Convolutispora muriornata* Palynological Zone, FS Zone: *Pakhapites fusus–Vittatina subsaccata* Palynological Zone, NBG ZONE: *Nothorhacopteris argentinica*, *Botrychiopsis weissiana*, *Ginkgophyllum diazii* Megafloristic Zone, TS ZONE: *Tivertonia jachalensis–Streptorhynchus inaequiornatus* Zone.

The upper part of the Agua del Jagüel Formation has shoreface sandstones and offshore shales, containing the lower Permian *Costatumulus* fauna (Fig. 5). Although previous work has suggested that the *Costatumulus* fauna occurs throughout the Agua del Jagüel Formation at its type locality (Taboada, 2001, 2006), recent work, including structural and palaeoenvironmental re-interpretations (Martínez et al., 2001; Ciccioli et al., 2008; Henry et al., 2008), confirms that the *Costatumulus* fauna is restricted to the upper part of the section.

The marine interval with the *Costatumulus* fauna at the type section of Agua del Jagüel Formation is dominated by species of *Costatumulus*, *Crurithyris* and *Orbiculoidea* in the lower horizons. The upper part has *Septosyringothyris jaguelenis*, *Tivertonia* sp. and *Orbiculoidea* (Fig. 5). From this upper horizon Lech (2002) has reported *Streptorhynchus inaequiornatus*, but so far this reported species has not been illustrated.

Taboada (1998, 2006) has described *Costatumulus amosi* Taboada, *Coolkilella keideli* Taboada and *Tivertonia leanzai* Taboada from the fossiliferous horizons below the diamictitic deposits at the type section of the Agua del Jagüel Formation (horizon 3 of Taboada, 1998), which have also recently provided palynological data that support the Early Permian age of the *Costatumulus* fauna (Césari et al., 2008). However, with recent reinterpretations of this sequence (Ciccioli et al., 2008; Henry et al., 2008), the lower diamicitites should be established as the base of the section. The fossiliferous levels located below them, which also contain diagnostic elements of the *Costatumulus* fauna, would be chronologically equivalent to those from the upper part of the section. The stratigraphic position of these levels has been explained as a result of faulting indicated by the repetition of a wedge of the upper part occurring in the basal part of the section (Martínez et al., 2001).

The *Costatumulus* fauna has also been identified in outcrops of the Santa Elena Formation (Yrigoyen, 1967), south of the Uspallata Creek on the west flank of the Uspallata Hill in Mendoza Province (Fig. 1B), which would correspond to the "Tramojo Serie" of Keidel (1939). Several fossiliferous horizons have been recognized from the alternating sandstone and mudstone facies that characterize this sequence (Archbold et al., 2006). Diagnostic elements of the *Costatumulus* fauna (Fig. 6) have been identified from the middle part of the section (horizons S2 of Archbold et al., 2006) in an interval dominated by the *Costatumulus*, *Crurithyris*, *Tivertonia* and *Orbiculoidea*, accompanied by *Septosyringothyris* sp. (Fig. 7). *Coolkilella keideli* Taboada has been also described in this assemblage (Taboada, 1998). From the marine interval of the lower part of this section, different brachiopod faunal assemblages have also been described: the lowest ("Lingulida horizon" of Archbold et al., 2006), characterized by the inarticulate brachiopods *Argentiella stappenbecki* Archbold, Cisterna and Sterren and *Orbiculoidea* sp. A. Above this (horizons S0–S1 of

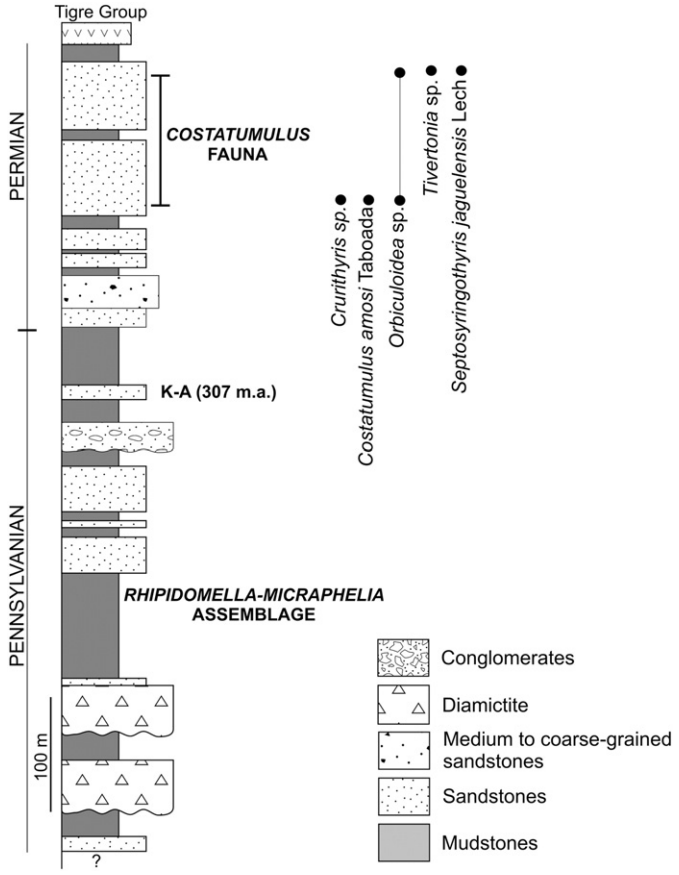



**Fig. 5.** Stratigraphical section of the Agua del Jagüel Formation (modified from Lech, 2002), showing the vertical distribution of the brachiopod assemblages (*Rhipidomella–Micraphelia* and *Costatumulus* fauna).

Archbold et al., 2006) is an assemblage characterized by species of Trigonotretinae ind. (probably a genus related to *Saltospirifer* Cisterna and Archbold), *Septosyringothyris* and *Orbiculoidea.* The fossil assemblages identified in this interval overlie a bed with a megaflora equivalent to the Pennsylvanian NBG assemblage (Fig. 7).

Recently, Taboada (2006) has discussed the chronologic relationship between the *Tivertonia jachalensis–Streptorhynchus inaequiornatus* and *Costatumulus amosi* faunas, suggesting that their stratigraphic relationships are obscured by structural problems. However, he indicated a superpositional stratigraphic relationship between these two faunas in the type section of the Agua del Jagüel Formation and proposed latest Asselian–Sakmarian? Age for the *Costatumulus amosi* Zone (Taboada, 2006, Fig. 2), younger than the T–S fauna. However, our review of the brachiopod assemblages from the Agua del Jagüel Formation clearly indicates that the T–S fauna does not appear below the *Costatumulus* fauna. Further, a number of genera that characterize the T–S fauna, i.e. *Tivertonia*, *Streptorhynchus*, *Septosyringothyris*, have also been identified in association with the *Costatumulus* fauna. Additionally, *Tivertonia jachalensis* identified from the Santa Elena Formation (Taboada, 2006), is the only common diagnostic species described. Therefore, there is insufficient evidence to consider the *Costatumulus* fauna to be younger than the T–S fauna. Instead, the T–S fauna appears to be chronologically equivalent to the *Costatumulus* fauna, but geographically mostly restricted to the Río Blanco and Paganzo basins.

## 4. Significance of the T–S and *Costatumulus* faunas for defining the Carboniferous–Permian boundary in Gondwana

Gondwana and peripheral Gondwanan regions are characterized by the absence of the faunal groups considered to be the principal tools for defining the Carboniferous–Permian (Gzhelian–Asselian) boundary in the northern hemisphere and correlation (i.e. conodonts, fusulinid foraminiferida and diagnostic species of ammonoids). In the last few years, studies that integrate marine faunas with palynological data of the Gondwanan basins have improved Early Permian biostratigraphic correlations across Gondwanan continents. Archbold (2001a) compiled and integrated data of marine faunas (fundamentally brachiopods and bivalves) and microflora from Early Permian (Asselian–Early Artinskian) Gondwanan successions (Australia, Afghanistan–Pakistan, Himalaya, China, Southeast Asia, India, Africa, Arabia, Antarctica and South America). Archbold's study has highlighted the importance of combining palynological and marine invertebrate data for defining and locating the Pennsylvanian–Permian boundary in Gondwana.

The west-central Argentinian basins appear to have the most complete Pennsylvanian–early Permian successions in Gondwanan. The early Permian marine faunas and palynological records from the Argentine Precordillera and eastern Australia have been discussed by Archbold et al. (2004). A number of correlations between marine faunal successions and megafloral and palynological records in different key sections within the Río Blanco (Río del Peñón Formation) and western Paganzo basins (Tupe Formation at La Herradura Creek, La Delfina Creek and Mina La Ciénaga localities), have been recently provided (Coturel and Gutiérrez, 2005; Gutiérrez et al., 2005; Cisterna et al., 2005, 2006a,b; Gutiérrez and Limarino, 2006). Occurrence of the T–S fauna in these key sections and its relationship with the records of mega and microflora, allows a biostratigraphic framework that integrates the latest Carboniferous assemblages NBG and Interval megafloral Zones and DM (*Raistrickia densa–Convolutispora muriornata*) Palynological Zone, in the lower part, and the earliest Permian assemblages [T–S invertebrate Zone and FS (*Pakhapites fusus–Vittatina subsaccata*) Palynological Zone] in the middle to upper part of each section studied (Cisterna et al., 2005). This scheme can also be applied to intra- and inter-basinal correlations, and is the basis of locating the Carboniferous–Permian boundary in the Argentine Precordillera.

The occurrence of diagnostic elements of the widely distributed T–S fauna and its biostratigraphical position in relation to the megaflora and palynological data, has important implications in for the definition of the Carboniferous–Permian boundary within the west-central Argentinian basins. The oldest occurrences of *Tivertonia jachalensis–Streptorhynchus inaequiornatus* fauna representing the earliest Permian (early–middle Asselian) marine horizons in Gondwana, are characterized by a brachiopod assemblage dominated by brachiopod genera, *Pericospira*, *Kochiproductus and Costatumulus*. The upper part of the *Tivertonia jachalensis–Streptorhynchus inaequiornatus* fauna, considered to be late Asselian in age, is dominated by the two diagnostic zonal species: *Tivertonia jachalensis* and *Streptorhynchus inaequiornatus*.

The significance of the *Costatumulus* fauna for defining the Carboniferous–Permian boundary in Gondwana is more easily seen in the Agua del Jagüel Formation, which is herein considered a key section in the Calingasta–Uspallata Basin (Fig. 5). At this section, the Agua del Jagüel Formation contains, in its lower part, Pennsylvanian glacial sediments (Martínez et al., 2001; Ciccioli et al., 2008), immediately overlain by the Late Pennsylvanian brachiopod assemblage *Rhipidomella–Micraphelia* (Simanauskas and Cisterna, 2001; Vergel et al., 2008). The upper part of the Agua del Jagüel Formation contains the *Costatumulus* fauna. Pillow lavas have been found from the middle part of the type section, stratigraphically located between the *Rhipidomella–Micraphelia* assemblage and the *Costatumulus* fauna (Fig. 5). Radiometric K–Ar data from these lavas suggest a late Bashkirian–early Gzhelian age (Lech, 2002). This quantitative age indicates that this section potentially can serve as a key section to define the Carboniferous–Permian boundary in Gondwana. We recognize, however, further palynological studies would be needed to refine and reinforce the Carboniferous–Permian boundary at this section.

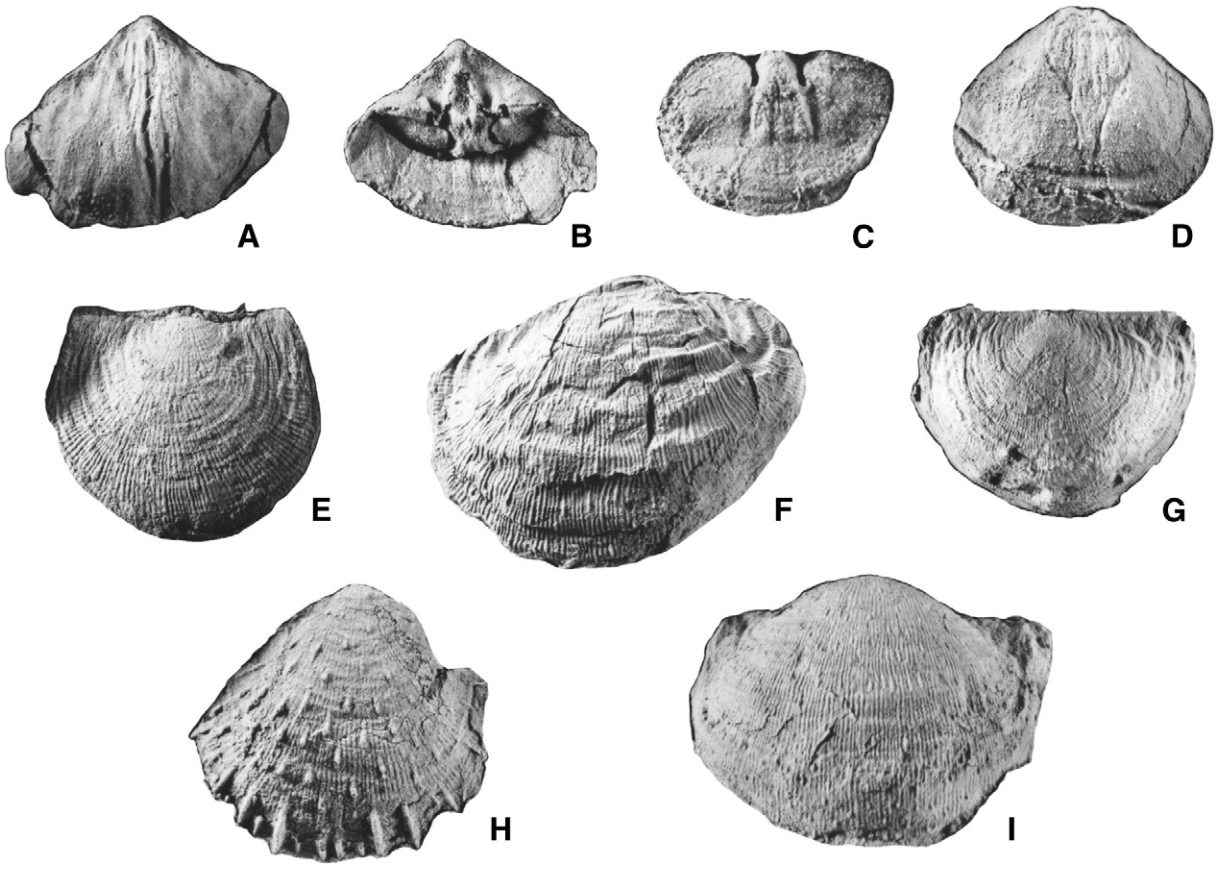



**Fig. 6.** Diagnostic brachiopods of the *Costatumulus* fauna. A–D, *Crurithyris* sp., A–B, ventral and dorsal view of the internal mould of ventral valve, IPI 4520, ×5; C, internal mould of dorsal valve, IPI 4518, ×2; D, internal mould of ventral valve, IPI 4517, ×4; E–I, *Costatumulus amosi* Taboada. E, dorsal valve, IPI 4522, ×2.2; F, internal mould of ventral valve, IPI 4526, ×1.5; G, dorsal valve, IPI 4524, ×1; H, incomplete ventral valve showing the detail of spines, IPI 4521, ×1.5; I, ventral valve, IPI 4525, ×1.5. Specimens figured from the Santa Elena Formation.

## 5. Global relationship and palaeoclimatic implications of the earliest Permian Precordilleran brachiopod faunas

Earliest Permian brachiopod faunas from the west-central Argentinian basins include mixtures of groups of genera whose palaeobiogeographic affinities have been previously discussed by Cisterna et al. (2006a,b). Some of the genera typifying Gondwana faunas include *Tivertonia* Archbold, *Coolkilella* Archbold, *Costatumulus* Watherhouse, *Coronalosia* Waterhouse and Gupta, and possibly *Etherilosia* Archbold, the latter having been documented from the lower faunal assemblage of the Río del Peñón Formation (Cisterna and Simanauskas, 2000; Archbold et al., 2004). *Tivertonia* is a typical Gondwanan Permian genus, whose species are mostly known from the Sakmarian of eastern Australia and Himalaya. *Coolkilella* and *Costatumulus* are typical genera of the Westralian Province of Australia that appear to indicate cold or cold temperate water temperatures (Archbold and Shi, 1995). *Coolkilella*, mainly reported from the upper Artinskian–lower Kungurian of Western Australia, has been considered a Westralian endemic genus by Archbold (2001b). *Costatumulus*, an Sterlitamakian–Artinskian Westralian genus, is also known from the Early Permian of India, as well as from the Austrazean faunas (Tasmania basin, Sydney basin, Bowen basin and New Zealand) faunas (Archbold, 2001a,b). Both *Coronalosia* (originally described from the early Permian (?Sakmarian) of India) and *Etherilosia* (a common Sakmarian–Artinskian genus of Western Australia) belong to the highly diversified strophalosiid brachiopods that underwent significant evolutionary expansion in areas of cold and temperate marine waters during the Permian (Waterhouse, 1967; Archbold and Simanauskas, 2001).

A second group of genera identified from the Argentine Precordillera appear to be endemic to this region during the Early Permian. It includes *Pericospira* Archbold and Cisterna, *Argentiella* Archbold, Cisterna and Sterren, and *Saltospirifer* Cisterna and Archbold. Also, several Permian Argentinian septosyringothyrid species (*Septosyringothyris jaguelensis* Lech, *Septosyringothyris* aff. *jaguelensis*, *Septosyringothyris globosa* Lech and, probably, *Septosyringothyris feruglioi* (Amos) and *Septosyringothyris* aff. *feruglioi*), possibly belong to a new endemic genus whose species occurrences are restricted to the late Palaeozoic Argentinian basins (Cisterna, 2010).

Some brachiopods, such as *Streptorhynchus* King, *Rhynchospora* King and *Svalbardia* Barchatova, also identified in the earliest Permian faunal assemblages from Argentine Precordillera, have been described as bipolar genera (Archbold and Shi, 1995; Archbold, 1998, 2001b). This phenomenon of bipolar distribution, also described by some as antitropicality (e.g., Shi and Grunt, 2000), is an interesting aspect of Permian global marine biogeography, and has been explained by trans-equatorial migrations between the Boreal and Gondwanan realms, through deeper water oceanic currents (Archbold, 1998). Shi and Grunt (2000), on the other hand, suggested several other possible mechanisms, including: south-to-north 'stepping-stone' migratory mechanism via island terranes scattered in the eastern Palaeotethys; a vicariance model; and a shelf, north-to-south migration model along the western coast of the Palaeotethys.

Of particular relevance is the presence in the T–S fauna of the Permian genus *Kochiproductus* that appears to indicate a warmer temperature and Tethyan influence. Although it is generally considered to be a "typical Boreal genus" widely distributed in the Permian Arctic successions (Tazawa, 2003), *Kochiproductus* is conspicuous in

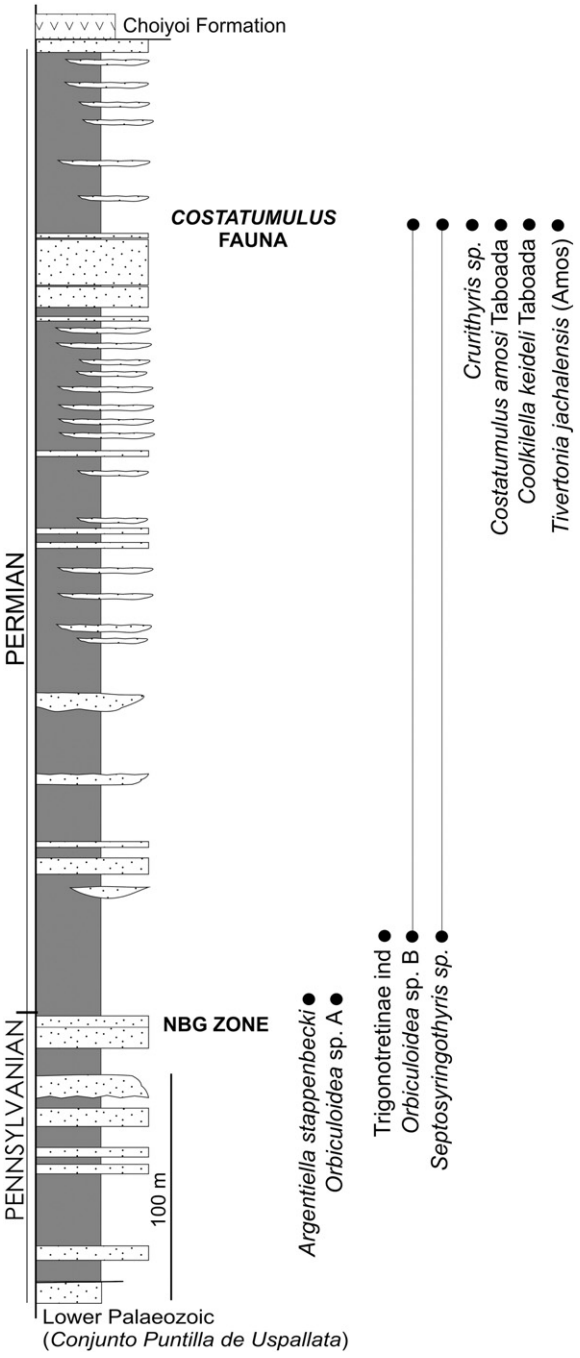



**Fig. 7.** Stratigraphical section of the Santa Elena Formation (modified from Archbold et al., 2006), showing the vertical distribution of the *Costatumulus* fauna and NBG Megafloristic Zone.

some Tethyan assemblages (i.e. Permian of West Texas and the Peruvian–Bolivian basins) and in mixed marine faunas with Boreal and Tethyan elements, such as in the Middle Permian of northeast Japan (Tazawa, 2003). *Kochiproductus* in the west-central Argentinian basins could have migrated from Bolivia and Chile during a time of warmer climate. The recent preliminary studies of faunal assemblages from Permian carbonate successions of northern Chile, which are dominated by *Kochiproductus* species (Cisterna and Niemeyer, 2008; 2010; Cisterna et al., 2009), indicate that this genus might be a key taxon for understanding the probable late Palaeozoic palaeobiogeographic links of this area with the Argentine Precordillera.

The development of the T–S and *Costatumulus* faunas is associated with an important climatic amelioration recorded in the west-central Argentinian basins. This association is also strongly reflected in the composition of the bivalves, whose diversity pattern shows an important increase, at familial and generic levels, at this interval of time (Sterren and Cisterna, in press). On a global scale, Gondwana's lithologic and palaeontological data suggest that for this interval of time (i.e., Asselian), a climatic amelioration occurred in most parts of Gondwana, accompanied by an increase in temperature compared to glacial times (Dickins, 1978, 1996). Palaeotemperature curves for the Western Australian Permian constructed on the basis of brachiopod diversity fluctuations (Archbold and Shi, 1995, 1996), also indicate a warming trend from cold to cold temperate conditions from late Asselian to early Sakmarian (*Lionia lyoni* and *Trigonotreta occidentalis* brachiopod zones; Archbold and Shi, 1995, Fig. 2).

In the west-central Argentinian basins the onset of the temperate conditions would have occurred near the end of the Pennsylvanian (Kasimovian–Gzhelian, López Gamundí et al., 1993). Sedimentological evidence, such as significant coal horizons found in the Río Blanco and Paganzo basins (López Gamundí et al., 1993), as well as palaeobiological records (e.g., occurrences of palaeoequatorial bivalve assemblages in the T–S fauna; Sterren, 2004), also indicate warmer conditions for the Pennsylvanian–Early Permian boundary interval. This interval was also marked by increased tectonic stability in west-central Argentina, as evidenced by active postorogenic sedimentation that followed the uplift of the Protoprecordillera orogen (Limarino et al., 2006). The warming is also reflected in the diversity of the marine faunal assemblages of the Precordilleran basins (Sterren and Cisterna, in press). Recent studies of diversification and faunal turnover of the Late Palaeozoic bivalve and brachiopod faunas from the Argentine Precordillera suggest that faunal diversity fluctuations are closely related to the inferred palaeoclimatic, palaeogeographic/palaeotectonic evolutionary trends of the southwestern Gondwana margin. A combination of local factors, such as the Palaeo-Pacific transgressive events that produced new accommodation space, climatic amelioration, volcanic activity and the influence of relatively warmer marine currents, have been suggested as responsible for the brachiopod and bivalve distribution patterns in the Latest Carboniferous–Early Permian interval (Sterren and Cisterna, in press). These factors would have caused an increase and diversification of the fauna, more so for bivalves than brachiopods. Recent brachiopod diversity studies by Sterren and Cisterna (in press) suggest that in the Early Permian the brachiopods show almost the same diversity as the Pennsylvanian at the familial level, although there is an increase of generic richness in the order Lingulida and a decrease in the order Spiriferida. In the Pennsylvanian, Productida was the most dominant group, followed by Lingulida, Spiriferida and Spiriferinida.

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