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Finding of two new radiolarian associations calibrated with ammonoids in the Vaca Muerta Formation (Late Jurassic–Early Cretaceous), Neuquén Basin, Argentina

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ABSTRACT

An association of ammonoids and radiolarians retrieved from a sedimentary section of the Vaca Muerta Formation at Vega de Escalone, Neuquén Basin, Argentina, was analized under a strict stratigraphic control. Nine ammonoid assemblage biozones were identified, indicating an age span from Early Tithonian to Late Berriasian/earlymost Valanginian for the Vaca Muerta Formation at the studied section. In connection to the ammonoid record, two radiolarian faunas were identified and named J3A1 and J3B1. Fauna J3A1, corresponding to the *Virgatosphinctes andesensis* Biozone, is dominated by nasellarian genera and represents the first Lower Tithonian radiolarian fauna described from the Neuquén Basin. Fauna J3B1, linked to the interval assigned to the *Substeueroceras koeneni* Biozone (Late Tithonian–Early Berriasian), yields abundant representatives of the Pantanellid Family. The presence of *Complexapora kozuri* (Kiessling and Zeiss) and *Loopus primitivus* (Matsuoka and Yao), two important radiolarian primary markers of the Late Jurassic in North America, supports a Late Tithonian age for at least part of the *S. koeneni* Biozone in the studied area. Nor certain Berriasian radiolarian faunas nor elements of the Vallupinae Family were identified so far at the Vega de Escalone section.

1. Introduction

The Jurassic–Cretaceous transition is recorded in Argentina in the marine rocks of the Vaca Muerta Formation, whose deposition was related to a sudden and widespread marine transgression that started in the late Lower Tithonian in the Neuquén Basin (Legarreta and Uliana, 1991). This basin (Fig. 1) is widely known for its nearly uninterrupted sedimentary infill from Late Triassic to Cenozoic times, its large extended outcrops and by the fine quality of its fossil record. All these features have made the Neuquén Basin the source of a great variety of both geological and paleontological studies in former times. Nevertheless, much remains to be described and interpreted to improve our knowledge of this western Gondwana basin.

The radiolaria have proven to be one of the most abundant zooplankton groups in Late Jurassic–Early Cretaceous rocks (Pessagno, 1976, 1977a, b; Pessagno et al., 1984, 1987, 1993; Baumgartner et al., 1995) with important biostratigraphic and taxonomic implications. Representatives of this time interval are well known worldwide but in the Neuquén Basin they were only studied by one of us in a number of articles (Pujana, 1988, 1989, 1991, 1995, 1996a, 1996b, 2000). In this contribution, we present two new radiolarian faunas, one of Early Tithonian (Fauna J3A1), and the other of Late Tithonian to Early Berriasian age (Fauna J3B1). Both are recorded in northern Neuquén province, Argentina and in connection with an accurate ammonoid based biostratigraphic control.

Figured ammonoid specimens are stored at the Paleontological Collection of the University of Buenos Aires, Argentina under numbers CPBA 21240.5, 21560-21563; 21566-21571, and fertile radiolarian slides containing the illustrated specimens are held at the Micropaleontological Collection of the University of Buenos

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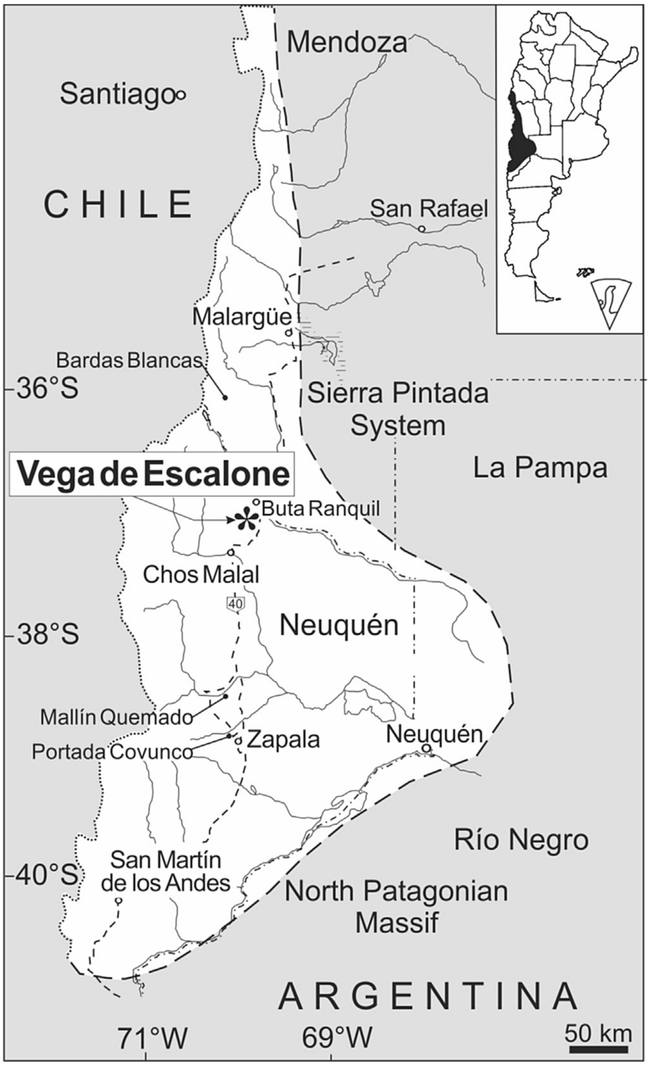

Fig. 1. Neuquén Basin geographic situation in Argentina with indication of the study area.

Aires, Argentina under numbers LM-FCEN N° 3670–3671.

2. Geological setting

2.1. Regional setting

The Neuquén Basin (Fig. 1) is a retroarc basin formed on a convergent continental margin (Legarreta and Uliana, 1996) at the foothill of the Andes. It extends over Chile and west-central Argentina between 33° and 39° southern latitude. During Mesozoic times the basin was limited eastward by the Sierra Pintada System, southeastward by the Patagonian Massif and to the west by a discontinuous active volcanic arc which allowed its communication with the Pacific Ocean (Howell et al., 2005).

The Lower Tithonian–Upper Berriasian marine rocks of the Vaca Muerta Formation (Weaver, 1931; emend. Leanza, 1972) are the result of a sudden marine transgression that, in the studied area (Fig. 2A and B), flooded the earlier continental siliciclastic sediments of the Tordillo Formation. Both lithostratigraphic units integrate the base of the Mendoza Group (Groeber, 1946; emend. Stipanicic et al., 1968).

The Vaca Muerta Formation is characterized by the rhythmic alternation of bituminous dark shales, marls and calcareous beds deposited over an homoclinal carbonate-siliciclastic ramp system dominated by external ramp facies during the Tithonian (Spalletti et al., 2000; Scasso et al., 2002; Kietzmann et al., 2008; Kietzmann and Palma, 2009), which leaded to a more inclined or a distally steepened ramp during the Berriasian (Mitchum and Uliana, 1985; Kietzmann et al., 2008). The prevailing oxygen deficient bottom conditions allowed the excellent preservation of both micro and macrofauna among which ammonoid shells are the most abundantly represented. These environmental conditions also promoted the formation of extended organic-rich facies that turned the Vaca Muerta Formation as the most important hydrocarbon source of the Neuquén Basin (Mitchum and Uliana, 1985; Vergani et al., 2011).

2.2. Fossil locality

The Vega de Escalone section (37° 11′ S; 69° 48′ W) is easily accessible. It is located in the Pampa Tril area (Fig. 2A), 72 km north of Chos Malal City. It can be reached through the intersection of the national road N° 40 with a narrow gravel road situated some kilometers north of the Chihuido del Tril (a Cenozoic basaltic neck). The gravel pathway heads to a small farm inside a marsh (*vega* in Spanish), situated over the eastward boundary of the Yesera del Tromen evaporites. The contact of the Vaca Muerta Formation with the Tordillo Formation can be reached after a 1.5 km walk either through the gravel road or through an old seismic line parallel to it. The analyzed section lies over the eastern flank of the most conspicuous structure in the region, the Yesera del Tromen Anticline (Herrero Ducloux, 1946). Nearby Vaca Muerta Formation outcrops and faunal content have been also studied by Leanza and Hugo (1977), Gulisano and Gutiérrez Pleimling (1994), Spalleti et al. (1999) and Parent et al. (2015).

2.3. Description of the section

In Vega de Escalone the Vaca Muerta Formation is 482 m thick (Fig. 3). The unit starts with thinly laminated microbialite layers and continues upwards with an abundant intercalation of mudstones, wackestones and marls forming massive, laminated and nodular beds. Calcareous nodules up to 1.5 m in diameter are common in the first part of the section, a feature which has also been observed in other areas of the basin (Damborenea and Leanza, 2016). Some tuff layers, siltstones and calcareous sandstones had also been recorded scattered over the column, as well as ferruginous surfaces and thin fibrous calcite layers. The later usually occur parallel to the stratification and are more frequent near the top of the section. These fibrous calcite layers have been formerly observed in many others localities (*e.g.* Leanza, 1973, Leanza et al., 2001), and frequently yield ammonoid and bivalve imprints (*e.g.* Damborenea and Leanza, 2016). Their formation has been recently associated with fluid overpressure episodes during hydrocarbon generation (Rodrigues et al., 2009). The top of the Vaca Muerta Formation in this locality is transitional with the coarser and shallower deposits of the Valanginian Mulichinco Formation.

Ammonoid shells are by far the most abundant fossil invertebrates through all the section, recorded both as three-dimensional internal molds holding neomorfic shell remains, or as detailed imprints. Small gastropods (*e.g. Protohemichenopus*), oysters, epibisated and shallow burrower bivalves are also found (*e.g. Liostrea*, *Huncalotis*, and "*Lucina*"). Vertebrates are usually represented by small disarticulated fish scales and bones; however a Late Tithonian to Early Berriasian crocodile skull from this locality has been recently described (Herrera, 2012; Herrera and Vennari, 2014).

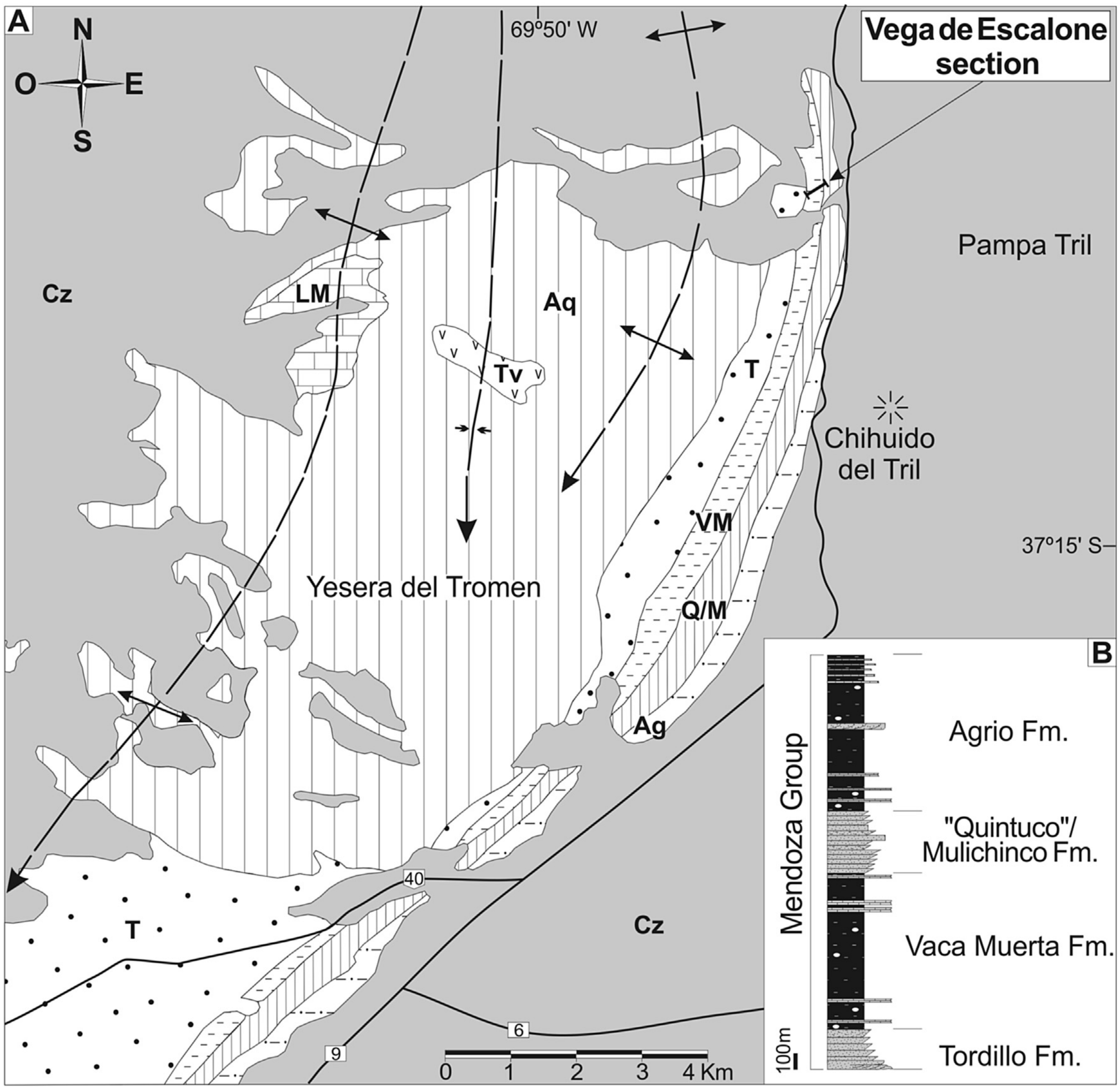

Fig. 2. A. Geological map of the study area (modified from Gulisano and Gutiérrez Pleimling, 1994). LM: La Manga Formation (Lower Oxfordian); Aq: Auquilco Formation (Upper Oxfordian); T: Tordillo Formation (Kimmeridgian); VM: Vaca Muerta Formation (Tithonian–Lower Valanginian); Q/M: "Quintuco"/Mulichinco Formation (Lower Valanginian); Ag: Agrio Formation (Upper Valanginian–Hauterivian); Tv: Tertiary volcanics; Cz: Cenozoic cover. **B**. Lithostratigraphy of the Mendoza Group in Central-northern Neuquén (modified from Leanza et al., 2001).

3. Material and methods

Ammonoid specimens were analyzed bed by bed in Vega de Escalone section. Shells were prepared at the laboratory with the assistance of pneumatic tools and a diluted solution of hydrochloric acid (HCL) before their taxonomic identification.

To separate and study the radiolarian skeletons, several disaggregation techniques were applied according to the nature of the matrix and the replacement of the original opal. A summary of these techniques, including the use of dilute and concentrated acids, is described in Pessagno (1977a). Particularly useful for our material was the use of diluted hydrofluoric acid technique as described in Pessagno and Newport (1972).

4. Results and discussion

4.1. Ammonoid biostratigraphy

A twofold division of the Tithonian is adopted here, making it easier the comparision between Standard ammonoid and radiolarian biozonation schemes and following Riccardi (2015) suggestions.

Nine ammonoid assemblage biozones have been identified in Vega de Escalone section (Figs. 4, 5 and 8) from a total of thirty-two ammonoid fertile beds (Fig. 3). Those biozones are consistent with the traditional Andean biostratigraphic scheme of Leanza, (1980, 1981a, b) and Riccardi (1984, 1988), and its recent modifications introduced by both authors, mainly involving the late Early and Late Tithonian interval (Zeiss and Leanza, 2008; Riccardi et al., 2011; Riccardi, 2015). Lowermost Tithonian biozonation follows the proposal of Vennari (2016), where the new name *Virgatosphinctes andesensis* Assemblage Biozone is recommended to be used instead of *V. mendozanus* Assemblage Biozone, since the former is the valid name of the index species by priority of publication. Also, the *V. andesensis* Biozone was tentatively subdivided into two interval subzones, of which the uppermost, the *Indansites malarguensis* Interval Subzone is well represented at the studied section.

Lower Cretaceous ammonoid biozones and their correlation

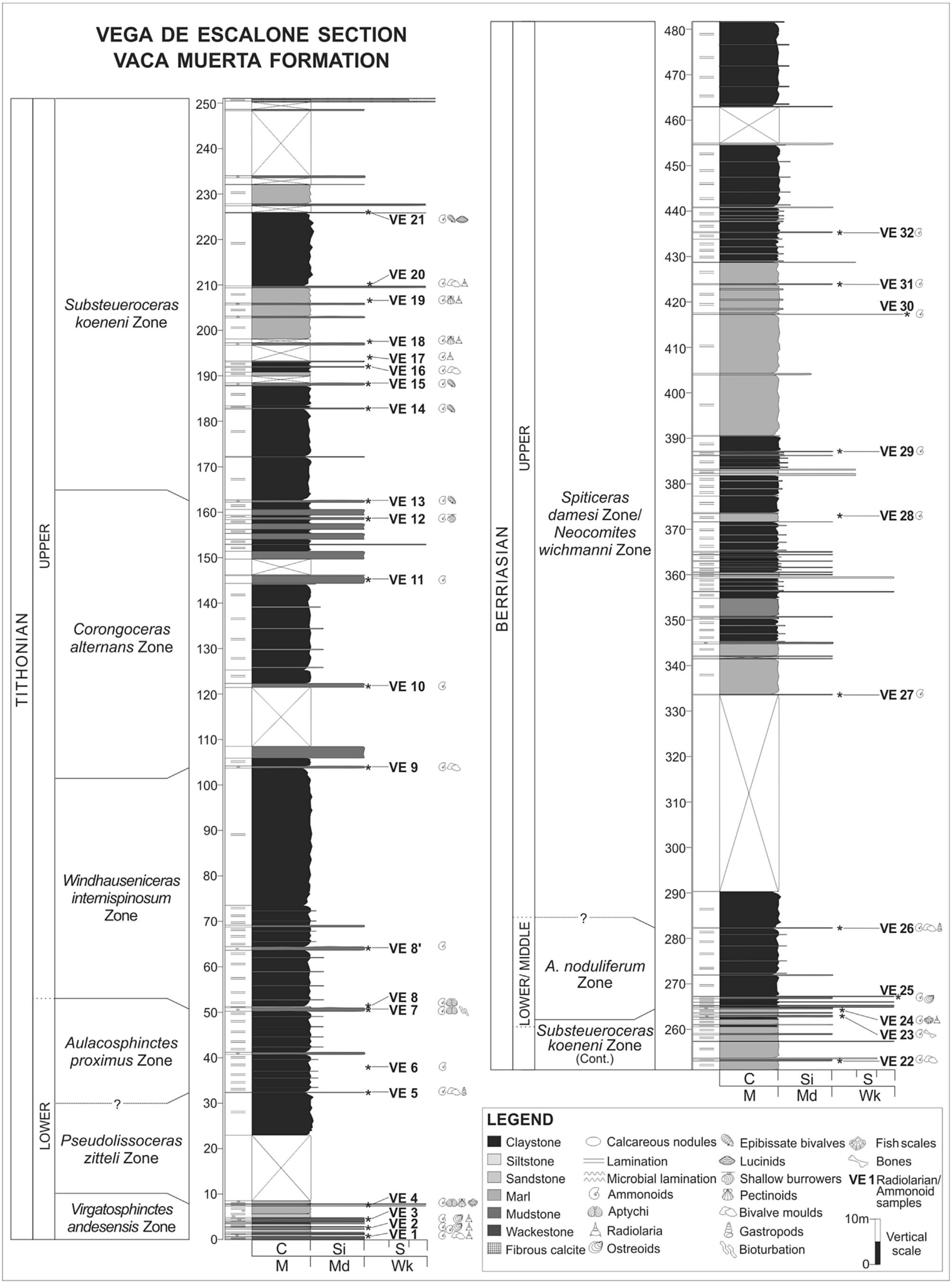

Fig. 3. Vega de Escalone stratigraphic section (Vaca Muerta Formation) depicting the ammonoid zonation and stratigraphic position of radiolarian fertile samples.

with the Tethys region were based on those presented by Aguirre-Urreta et al. (2007) and Reboulet et al. (2014).

The faunal composition of each ammonoid biozone and their correlation with the current Mediterranean Standard biozonation (Hardenbol et al., 1998; Reboulet et al., 2014) is presented below:

Ammonoid beds VE 1–VE 3: *Virgatosphinctes andesensis* Assemblage Biozone (Vennari, 2016). Lower Tithonian, Upper Darwini to Lower Semiforme Zones. It includes abundant and well preserved specimens of *Indansites malarguensis* (Spath,) (Fig. 4.1), less numerous representatives of *Virgatosphinctes andesensis* (Douvillé, 1910) and *Choicensisphinctes choicensis* (Burckhardt, 1903), and only one specimen assigned to *Pseudovolanoceras* cf. *P. aesinense kranzense* (Cantú-Chapa, 1990). This species, a simoceratid usually ascribed to the younger *Pseudolissoceras zitelli* Biozone, is poorly represented in the Neuquén Basin and can be correlated with the Semiforme standard Zone (Villaseñor et al., 2011). Two morphotypes temporally ascribed to the tethyan genera "*Subplanitoides* sp." and "*Torquatisphinctes* sp." have also been recognized. Dominance of representatives of Subfamilies Virgatosphinctinae and Lithacoceratinae at this association is in agreement with previous records of this stratigaphic interval in other areas of the basin (Leanza, 1980; Vennari and Aguirre-Urreta, 2014; Vennari, 2016) and enables recognizing an *Indansites malarguensis* Interval Subzone (Vennari, 2016) in this section.

Ammonoid bed VE 4: *Pseudolissoceras zitteli* Assemblage Biozone. Lower Tithonian, Upper Semiforme to Lower Fallauxi Zones. Mainly represented by abundant and well preserved specimens of *Pseudolissoceras zitteli* (Burckhardt, 1903) (Fig. 4.2), *Cieneguiticeras perlaevis* (Steuer, 1897) and some *Lamellaptychus* remains usually related to haploceratid ammonoids (Trauth, 1938; Engeser and Keupp, 2002).

Ammonoid beds VE 5–VE 6: *Aulacosphinctes proximus* Assemblage Biozone. Lower Tithonian, Upper Fallauxi to Ponti Zones. Represented by poorly preserved *Aulacosphinctes proximus*?

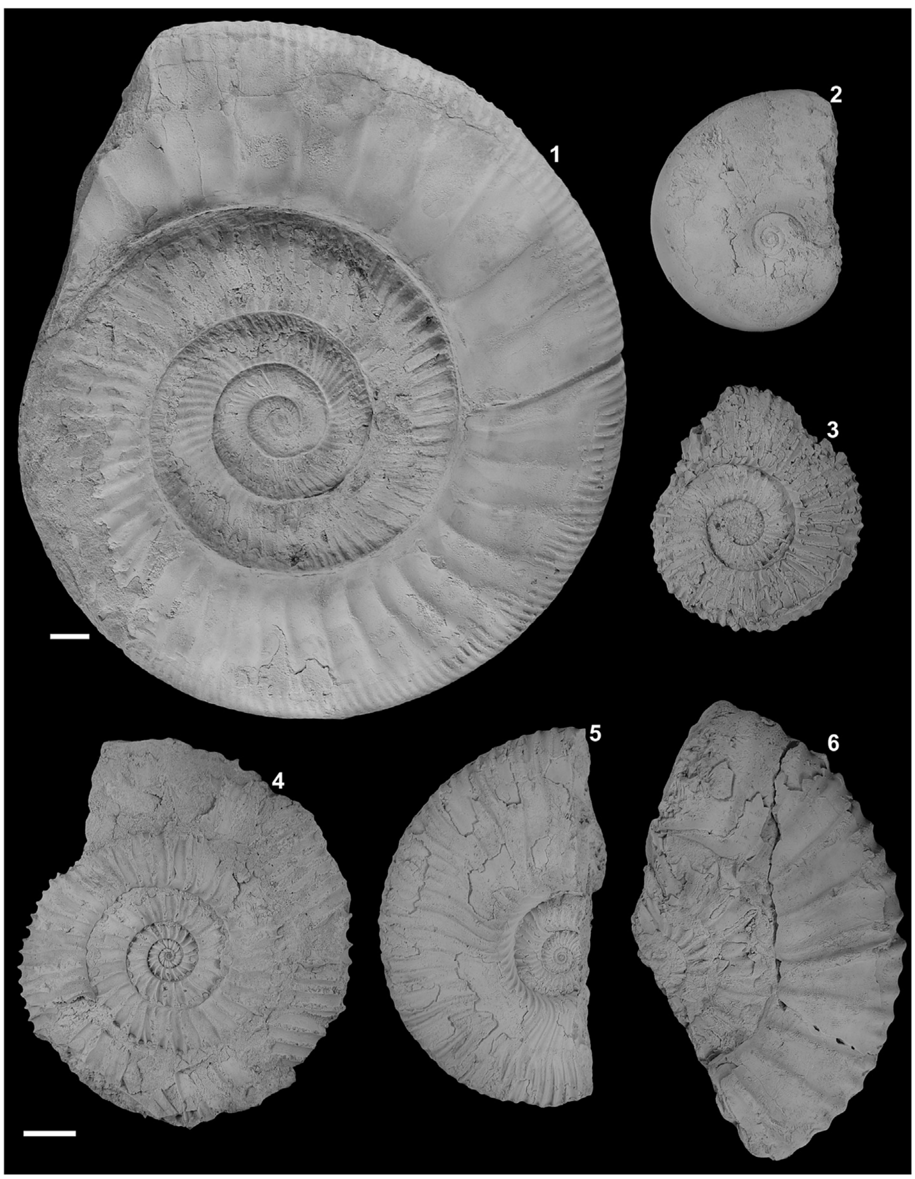

Fig. 4. Ammonoids from Vega de Escalone section: **1**, CPBA 21240.5, *Indansites malarguensis* (Spath,); **2**, CPBA 21560, *Pseudolissoceras zitteli* (Burckhardt, 1903); **3**, CPBA 21562, *Micracanthoceras lamberti* Leanza, 1945; **4**, CPBA 21561, "*Subdichotomoceras*" *araucanense* Leanza, 1980; **5**, CPBA 21568, *Parodontoceras calistoides* (Behrendsen, 1922); **6**, CPBA 21563, *Corongoceras* sp. cf. *C. mendozanum* (Behrendsen, 1922). All specimens covered with ammonium chloride. All Fig. 1X except **1** at 3/4X. Graphic scale = 1 cm.

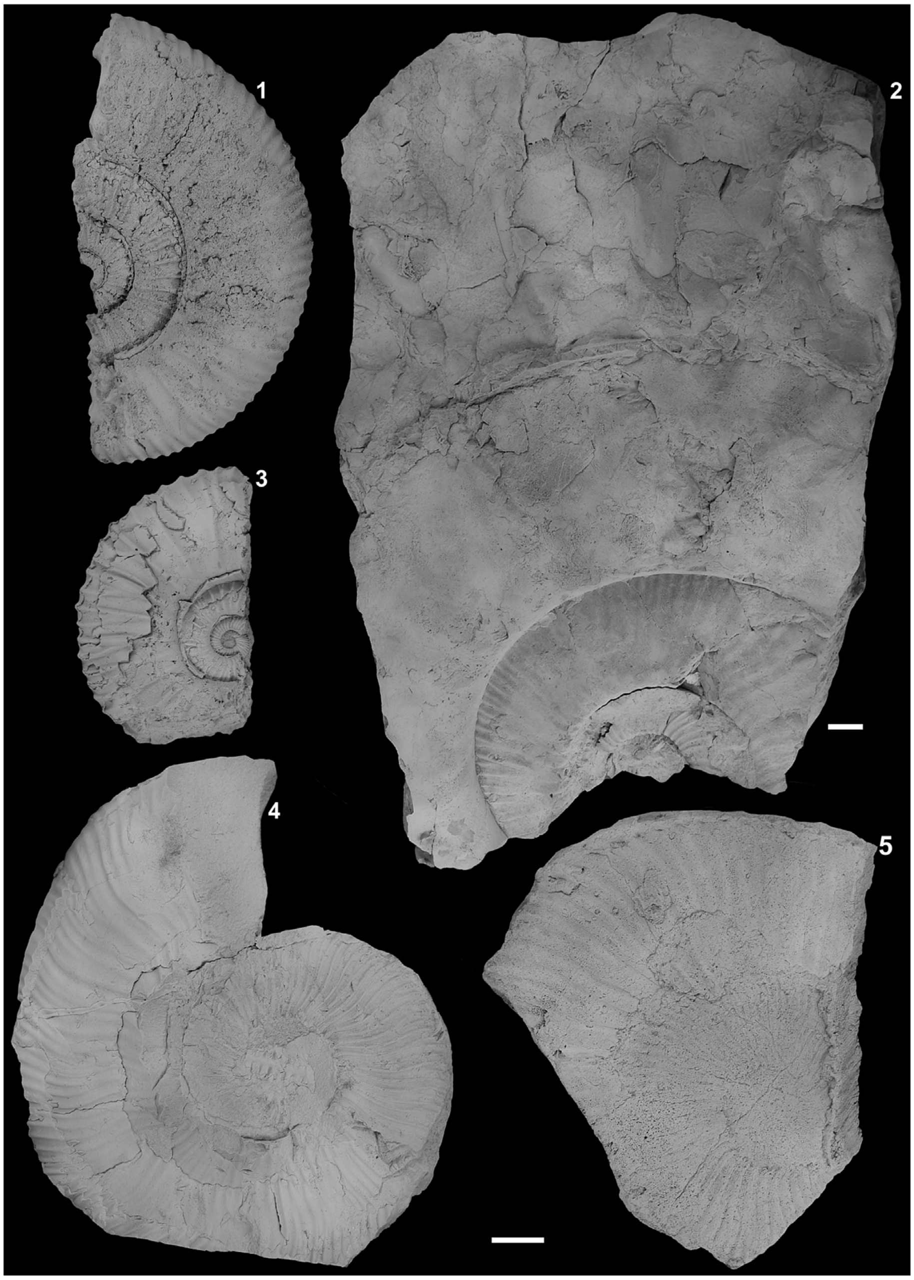

Fig. 5. Ammonoids from Vega de Escalone section: **1**, CPBA 21566, *Aulacosphinctes*? *azulensis* Leanza, 1945; **2**, CPBA 21569, *Argentiniceras* sp.; **3**, CPBA 21567, *Chigaroceras* sp.; **4**, CPBA 21570, "*Thurmanniceras*" *discoidale* (Gerth, 1925); **5**, CPBA 21571, *Cuyaniceras transgrediens* (Steuer, 1897). All specimens covered with ammonium chloride. All Fig. 1X except **2** at 2/3X. Graphic scale = 1 cm.

(Steuer, 1897) remains.

Ammonoid beds VE 7–VE 8': *Windhauseniceras internispinosum* Assemblage Biozone. Upper Tithonian, Lower Microcanthum Zone. Yields representatives of *Windhauseniceras internispinosum*? (Krantz, 1926), *Aspidoceras euomphalum* Steuer, 1897, "*Subdichotomoceras*" *araucanense* Leanza, 1980 (Fig. 4.4), *Corongoceras lotenoense* Spath, 1925 and some aptychi of *Lamellaptychus* and *Laevaptychus* type; the later usually ascribed to aspidoceratids (Trauth, 1931; Cloos, 1961).

Ammonoid beds VE 9–VE 12: *Corongoceras alternans* Assemblage Biozone. Upper Tithonian, Upper Microcanthum to Lower "Durangites" Zone. Includes representatives of *Micracanthoceras lamberti* Leanza, 1945 (Fig. 4.3), *Aulacosphinctes mangaensis*? (Steuer, 1897), *Corongoceras* sp. cf. *C. mendozanum* (Behrendsen, 1922) (Fig. 4.6) and some specimens of "*Berriasella*" *australis* Leanza, 1945. A single specimen assigned to *Parodontoceras calistoides* (Behrendsen, 1922) was recorded on the topmost fossiliferous bed of this association along with representatives of *M. lamberti* and *A. mangaensis*?

Ammonoid beds VE 13–VE 23: *Substeueroceras koeneni* Assemblage Biozone. Uppermost Tithonian to Lower Berriasian, "Durangites" to Jacobi Zones. Includes abundant representatives of *P. calistoides* (Fig. 4.5). In addition were identified some specimens of *Aulacosphinctes*? *azulensis* Leanza, 1945 (Fig. 5.1), *Corongoceras*? sp., *C.*? *steinmanni* Krantz, 1926, *Micracanthoceras*? *spinulosum* Gerth, 1925, *Micracanthoceras*? aff. *M.*? *spinulosum*, *M.*? sp. cf. *M. koellikeri* (Steuer, 1897 non Oppel), *M. vetustum* (Steuer, 1897), *Aspidoceras rogoznicense* (Zeuschner, 1846), *Chigaroceras* sp.

(Fig. 5.3), *Substeueroceras koeneni*? (Steuer, 1897), *S. extans* Leanza, 1945, *S. striolatissimum* (Steuer, 1897), and a single litoceratid fragment, a group traditionally interpreted as offshore dwellers (Kennedy and Cobban, 1976). Upper age limit indicated for this biozone is in accordance to the recently proved co-occurrence of representatives of this biozone with *Nannoconus kamptneri minor*, as a marker for the base of the Berriasian, in Las Loicas section, Mendoza (see Vennari et al., 2014).

Ammonoid bed VE 24: *Argentiniceras noduliferum* Assemblage Biozone. Lower Berrisian, Jacobi to Occitanica Zones. Represented by few specimens of *Argentiniceras* sp. (Fig. 5.2).

Ammonoid beds VE 25?, VE 26–VE 32: *Spiticeras damesi* to *Neocomites wichmanni* Assemblage Biozone. Upper Berriasian to lowermost Valanginian. Boissieri to Pertransiens Zone. It only includes shell imprints on fibrous calcite layers or on calcareous siltstones. Nonetheless, some specimens of *Cuyaniceras transgrediens* (Steuer, 1897) (Fig. 5.5), *Cuyaniceras* sp., "*Thurmanniceras*" *discoidale* (Gerth, 1925) (Fig. 5.4) and indeterminate neocomitids were recorded to the top of the interval. Lack of identification of index species of the *Neocomites wichmanni* Biozone prevented separating this biozone from the previous one.

4.2. Radiolarian taxonomy and biostratigraphy

The micropaleontologic analysis is based on a total of thirty-two samples taken consecutively along the section. Of these, the most abundant and well preserved material recovered from two main intervals with ammonoids is described below. The poor preservation of the fauna impedes conducting a statistical analysis of abundance and to assess the relative taxonomic composition of the fauna. However, many forms are described for first time in the Neuquén Basin as also is the radiolarian association from the *V. andesensis* Biozone.

A total of seven fertile samples (Fig. 3) allow discriminating two faunas of radiolarians (Figs. 6–8). The first one, Fauna J3A1 (Fig. 6), is recognized from three samples obtained from beds VE 1, VE 2 and VE 3, included in the *V. andesensis* Biozone (Lower Tithonian). Fauna J3A1 is dominated by nasellarians, among which *Parvicingula*, *Archaeodyctiomitra* and *Xitus* are the most abundant forms. Among the members of the Pantanellidae Family, only *Pantanellium* aff. *P. ranchitoensis* is abundant. This J3A1 Fauna constitutes the first fauna of radiolarians thoroughly described from levels of the *Virgatosphinctes andesensis* Biozone in the Neuquén Basin. It corresponds to the lower part of J3A radiolarian association from late Early Tithonian to middle Late Tithonian age identified in the basin by Pujana (2000, in Ballent et al., 2011). In particular, the sample from bed VE 2 can be as old as Zone 4, base of Subzone $4\beta_2$ of Pessagno et al. (2009) due to the presence of *Complexapora kozuri* (Figs. 6.10, 8–9).

The second fauna of radiolarians, named J3B1 (Fig. 7), is determined from four fertile samples recovered from beds VE 17, 18, 19 and 20, corresponding to levels assigned to the *Substeueroceras koeneni* Biozone (uppermost Tithonian to Lower Berriasian). In particular, the sample obtained from bed VE 19 allows to assign a Late Tithonian age to the fauna, based on the presence of *C. kozuri* (Fig. 7.15) and *Loopus primitivus* (Fig. 7.6) primary markers for Zone 4 Subzone $4\alpha_2$ of Pessagno et al. (2009). Fauna J3B1, which is assigned to the lowest part of J3B radiolarian association from Late Tithonian to Early Valanginian age (Pujana, 2000), has a strong representation of the Pantanellidae Family with genera *Gorgansium* and *Pantanellium*. Also recognized are *Napora*, *Podobursa*, *Acanthocircus*, *Pseudocyrtis*, *Neoparonaella* and *Xitus*. It is remarkable the absence on these levels of members of *Parvicingula* as well as any species of the Vallupinae Subfamily.

Between faunas J3A1 and J3B1 there is a 154 m thick interval barren of any radiolarians. Some local environmental factors may have inhibited radiolarian preservation in the middle portion of Vega de Escalone section. However, this upper Lower to middle Upper Tithonian interval has provided a rich radiolarian fauna in several other Vaca Muerta sections both in Neuquén, (*i.e.* Mallín Quemado, Portada Covunco) and Mendoza, (*i.e.* Bardas Blancas) (Pujana, 1991, 1995, 1996a,b). Those faunas held elements of the Subfamily Vallupinae which allow recognizing two conspicuous evolutive events named "*Vallupus hopsoni* Event" and "*Vallupus japonicus* Event". The older "*Vallupus hopsoni*" event is characterized by the presence of specimens with multiple cortical collars and indentations. These forms always have a cylindrical to conical cortical collar that expands continuously towards an aperture with irregular borders. The occurrence of that event is on the lower part of the *Pseudolissoceras zitelli* Biozone to at least the upper part of the *Aulacosphinctes proximus* Biozone (middle to upper Lower Tithonian). The younger "*Vallupus japonicus*" event is also defined by an abundance of forms with multiple and indented cortical collars with a distinctive bell-like shape, and also includes some *Vallupus hopsoni* specimens. This event occurs in coincidence with the upper part of the *Windhauseniceras internispinosum* Biozone and in the *Corongoceras alternans* Biozone (lower to middle Upper Tithonian).

Finally, the fauna observed in a single sample obtained from bed VE 24, included in the *Argentiniceras noduliferum* Biozone (Lower Berriasian), do not present significant differences in its composition with the J3B1 fauna, despite its higher stratigraphic position. However poor preservation as well as relatively less diversity and abundance hinder its significance.

4.3. Radiolarian taxonomy

The classification of De Wever et al. (2001) is followed up to the Order level, Families are alphabetically ordered. Biostratigraphic ranges of genera and species follow the biostratigraphic scheme proposed by Pessagno et al. (2009). (Fig. 9).

Class ACTINOPODA
Subclass, 1858 Subclass RADIOLARIA (Müller, 1858)
Superorder POLYCYSTIDA Ehrenberg, 1838, emend. Riedel, 1967
Order SPUMELLARIINA Ehrenberg, 1875, emend. De Wever et al., 2001
Family PANTANELLIIDAE Pessagno, 1977a
Type genus: Pantanellium Pessagno, 1977a; sensu Pessagno and Blome, 1980.
Range: Late Triassic (Carnian) to Early Cretaceous (Aptian/Albian).
Occurrence: Worldwide.
Subfamily PANTANELLIINAE Pessagno, 1977a; sensu Pessagno and Blome, 1980

Type genus: Pantanellium Pessagno, 1977a; sensu Pessagno and Blome, 1980.
Range and occurrence: Same as for family.
Genus ***Gorgansium*** Pessagno and Blome, 1980

Type species: Gorgansium silviesense Pessagno and Blome, 1980.
Range and occurrence: Late Triassic (Norian) to Early Cretaceous (Berriasian). Same as for the family.
Gorgansium sp. A (Fig. 7.8)

Remarks: This form is characterized by well-developed nodes and slender polar spines similar to the form under *Pantanellium* sp. A (see Fig. 7.4). The remainder basal spine, wider and longer is deviated from the polar axis by approximately 30°.

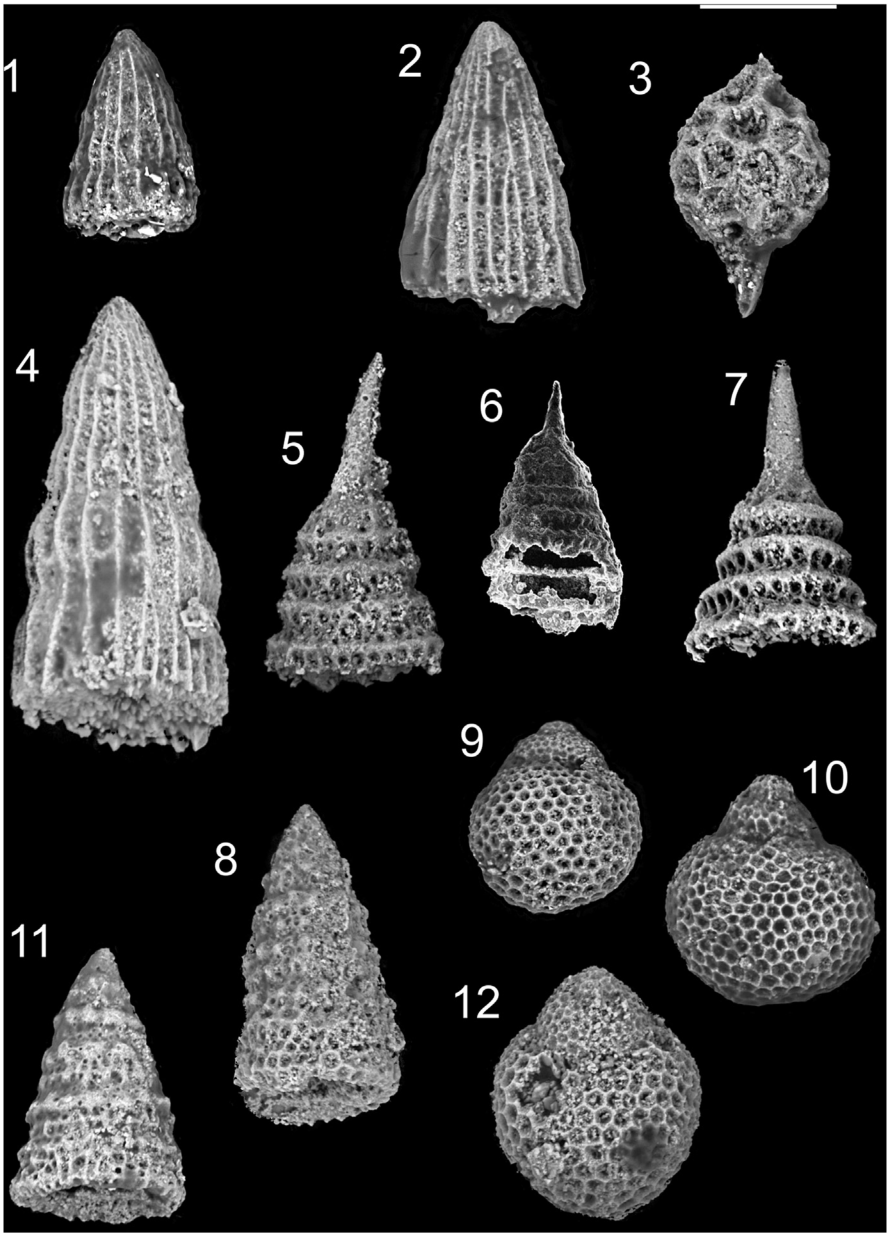

Fig. 6. Upper Jurassic Nassellaria and Spumellaria from Vega de Escalone section. All figures are scanning electron micrographs of radiolarians from Sample VE 2, Fauna J3A1 (*Virgatosphinctes andesensis* Biozone): **1–2**, *Archaeodyctiomitra* sp. cf. *A. vulgaris* Pessagno, Scale = 50 μm and 40 μm; **3**, *Pantanellium ranchitoense* Pessagno and Blome, Scale = 46.15 μm; **4**, *Archaeodyctiomitra sixy* Yang; Scale = 40 μm; **5**, *Praeparvicingula vacaensis* Pujana, Scale = 40 μm; **6**, *Praeparvicingula* sp. A, Scale = 40 μm; **7**, *Praeparvicingula vacaensis* Pujana, Scale = 40 μm; **8**, *Xitus* sp. A, Scale = 40 μm; **9**, *Complexapora* sp. A, Scale = 40 μm; **10**, *Complexapora kozuri,* Hull, Scale = 40 μm; **11**, *Xitus* (?) sp. A, Scale = 50 μm; **12**, *Complexapora* sp. B, Scale = 40 μm. Graphic scale (upper right) = number of microns cited for each figure.

Range and occurrence: Vaca Muerta Formation, Neuquén Basin, Vega de Escalone, Argentina. Sample VE 19; Fauna J3B1; *Substeueroceras koeneni* Biozone. Rare.

Genus ***Pantanellium*** Pessagno, 1977a, sensu Pessagno and Blome, 1980

Type species: Pantanellium riedeli Pessagno, 1977a.
Range and occurrence: Same as for family.
Pantanellium meraceibaense Pessagno and MacLeod, (1987) (Fig. 7.9)

1987 *Pantanellium meraceibaense* Pessagno and Macleod, p. 22, pl. 5, Figs. 5–6, 18–19; pl. 7, Fig. 4.
1991 *Pantanellium* sp. aff. *P. meraceibaense* Pessagno and Macleod; Pujana, p. 399, pl. 1, Figs. 6–7.
1993 *Pantanellium meraceibaense* Pessagno and Macleod; Pessagno et al. p. 130, pl. 4, Fig. 17.
1993 *Pantanellium meraceibaense* Pessagno and Macleod; Yang, p. 15, pl. 2, Figs. 6 and 22.
2013 *Pantanellium meraceibaense* Pessagno and Macleod; Staerker et al. p. 115, pl. 3, fig. b.

Range and occurrence: Superzone 1, Zone 11 to Zone 4, Subzone 4β; Lower Oxfordian to Lower Berriasian. Taman Formation, East-central Mexico; Argolis Peninsula, Greece; Stanley Mountain, California; strata overlying the Josephine Ophiolite, Klamath Mountains; northwestern California and southwestern Oregon; Mazapil,

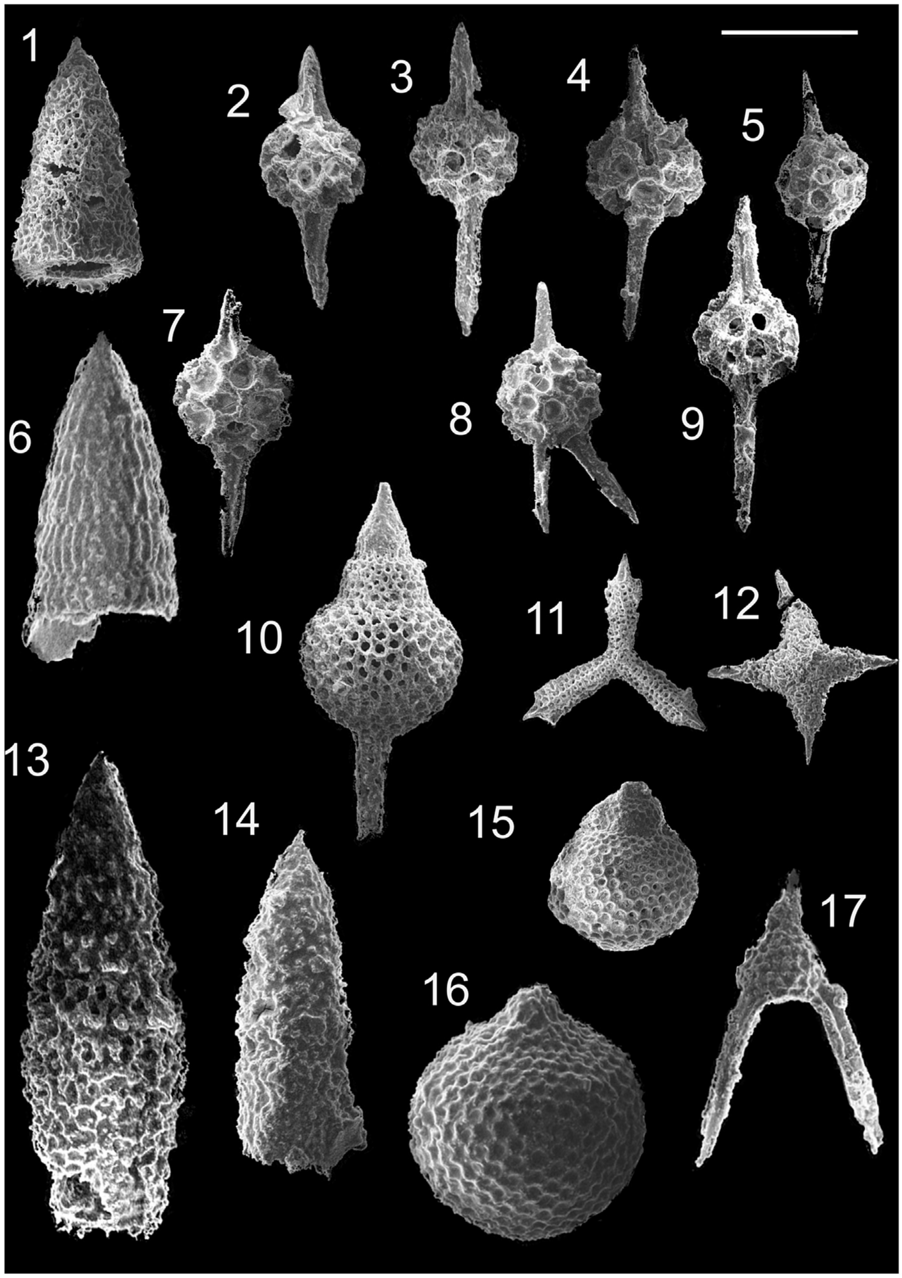

Fig. 7. Upper Jurassic Nassellaria and Spumellaria from Vega de Escalone section. All figures are scanning electron micrographs of radiolarians from Sample VE 19, Fauna J3B1 (*Substeueroceras koeneni* Biozone): **1**, *Xitus antiquus* Hull, Scale = 66.66 μm; **2**, *Pantanellium neuquensis* Pujana, Scale = 60 μm; **3**, *Pantanellium quintachillaensis* Pessagno and MacLeod, Scale = 60 μm; **4**, *Pantanellium* sp. A, Scale = 60 μm; **5**, *Pantanellium* sp. aff. *P. riedeli* Pessagno, Scale = 60 μm; **6**, *Loopus primitivus* Matsuoka and Yao, Scale = 40 μm; **7**, *Pantanellium quintachillaensis* Pessagno and MacLeod; **8**, *Gorgansium* sp. A, Scale = 60 μm; **9**, *Pantanellium meraceibaensis* Pessagno and Blome, Scale = 66.66 μm; **10**, *Podobursa* sp. A, Scale = 60 μm; **11**, *Neoparonaella delicata* Yang, Scale = 71.42 μm, **12**, *Crucella* sp. cf. *C. mexicana* Yang, Scale = 156.25 μm; **13**–**14**, *Pseudoeucyrtis* (?) sp., Scale = 40 μm, 66.6 μm; **15**, *Complexapora kozuri*, Scale = 50 μm; **16**, *Gongylothorax* sp. A, Scale = 40 μm; **17**, *Napora pacifica,* Kiessling, Scale = 60 μm. Graphic scale (upper right) = number of microns cited for each figure.

Sierra de Santa Rosa, Mexico; Haynesville Formation, North Louisiana Salt Province, Gulf of Mexico; Vaca Muerta Formation, Neuquén Basin, Mallín Quemado and Vega de Escalone, Argentina. Sample VE 19; Fauna J3B1; *Substeueroceras koeneni* Biozone.

Pantanellium neuquensis Pujana, (1991) (Fig. 7.2)
1991 *Pantanellium neuquensis* Pujana, p. 399, pl. 1, Figs. 3 and 6.

Range and occurrence: Vaca Muerta Formation, Neuquén Basin, Mallín Quemado (*Windhauseniceras internispinosum* Biozone) and Vega de Escalone, Argentina. Sample VE 19; Fauna J3B1; *Substeueroceras koeneni* Biozone.

Pantanellium quintachillaense Pessagno and MacLeod (1987) (Figs. 7.3 and 7.7)

1987 *Pantanellium quintachillaense* Pessagno and Macleod, p. 23, pl. 4, Figs. 14 and 23.
1999 *Pantanellium quintachillaense* Pessagno and Macleod; Kiessling, p. 22, pl. 4, Figs. 6 and 12.

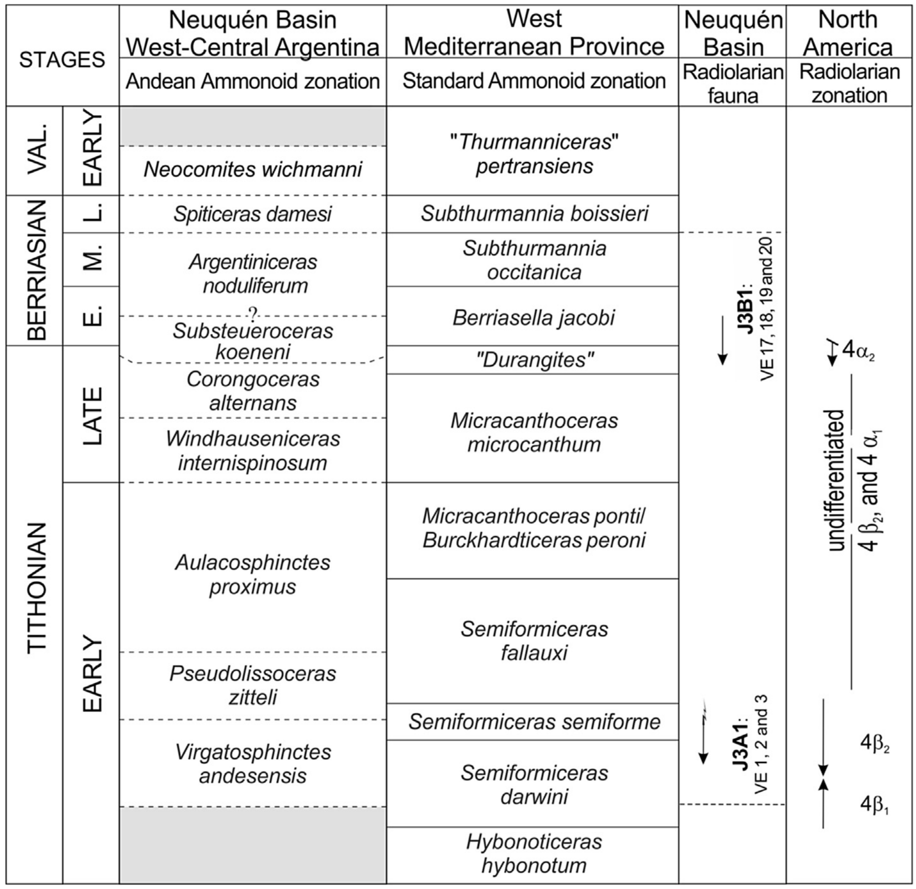

Fig. 8. Correlation of Andean, Standard ammonoid biozones and radiolarian faunas described in this study according to North American Radiolarian Zonation. Ammonoid zonation modified after Aguirre-Urreta et al. (2007), Vennari et al. (2014), Vennari (2016) and Reboulet et al. (2014). Radiolarian zonation modified after Pessagno et al. (2009).

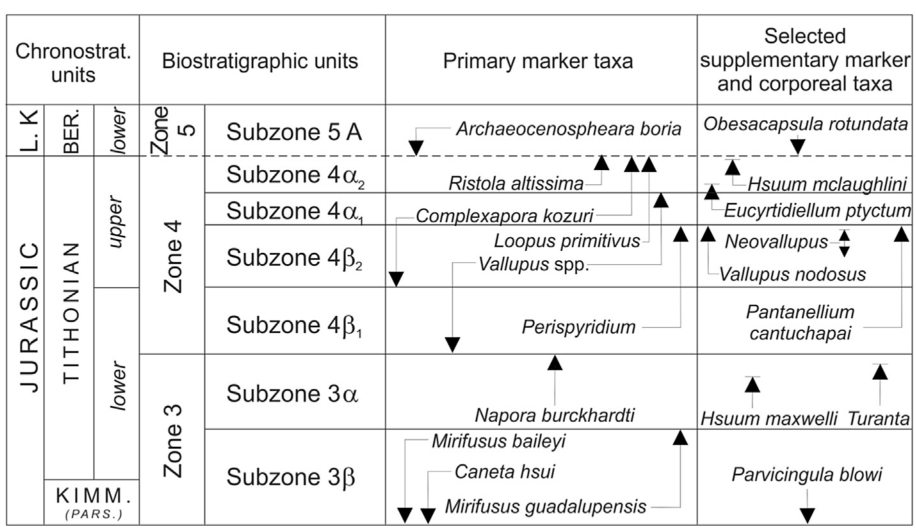

Fig. 9. Late Jurassic to Early Cretaceous radiolarian zonation from Pessagno et al. (2009).

2013 *Pantanellium quintachillaense* Pessagno and Macleod; Staerker et al. p. 115, pl. 3, fig. b.

Range and occurrence: Zone 2, Subzone 2β to Zone 4, Subzone 4α; Oxfordian to Late Tithonian. Taman Formation, east-central Mexico; Ameghino Formation, Antarctic Peninsula; Haynesville Formation, North Louisiana Salt Province, Gulf of Mexico; and herein, Vaca Muerta Formation, Neuquén Basin, Vega de Escalone. Sample VE 19; Fauna J3B1; *Substeueroceras koeneni* Biozone.

Pantanellium ranchitoense Pessagno and Macleod (1987) (Fig. 6.3)

1987 *Pantanellium ranchitoense* Pessagno and Macleod, p. 23, pl. 1, Figs. 1 and 25; pl. 5, Figs. 4, 8, 22; pl. 7, Fig. 6.
1991 *Pantanellium* sp. aff. *P. ranchitoense* Pessagno and Macleod; Pujana, p. 400, pl. 1, Fig. 10.
1993 *Pantanellium ranchitoense* Pessagno and Macleod; Yang, p. 16, pl. 1, Fig. 6; pl. 2, Fig. 3.
1999 *Pantanellium ranchitoense* Pessagno and Macleod; Kiessling, pl. 4, Fig. 10.
2013 *Pantanellium ranchitoense* Pessagno and Macleod; Staerker et al. p. 115, pl. 3, fig. b.

Range and occurrence: Zone 5; Callovian to Lower Berriasian. Taman Formation, east-central Mexico; Titoniano Bianco, Southern Alps, Italy; Ameghino Formation, Antarctic Peninsula; Haynesville Formation, North Louisiana Salt Province, Gulf of Mexico; Vaca Muerta Formation, Neuquén Basin, Vega de Escalone, Argentina. Sample VE 2, Fauna J3A1; *Virgatosphinctes andesensis* Biozone.

Pantanellium sp. aff. ***P. riedeli*** Pessagno, 1977b (Fig. 7.5)

1977b ***Pantanellium riedeli*** Pessagno, p. 78, pl. 6, Figs. 5–11.

Remarks: This specimen differs from *Pantanellium riedeli* Pessagno by possessing less massive primary spines and a less nodose cortical shell.

Range and occurrence: Vaca Muerta Formation, Neuquén Basin, Vega de Escalone, Argentina. Sample VE 19; Fauna J3B1; *Substeueroceras koeneni* Biozone.

Pantanellium sp. A (Fig. 7.4)

Remarks: This species is characterized by large pores on a slightly wider cortical shell and very long and slender polar spines. There is no similarity with to any published *Pantanellium* species.
Range and occurrence: Vaca Muerta Formation, Neuquén Basin, Vega de Escalone, Argentina. Sample VE 19; Fauna J3B1; *Substeueroceras koeneni* Biozone.

Family **PATULIBRACCHIINAE** Pessagno, 1971; emend. De Wever et al., 2001

Type genus: Patulibracchium Pessagno, 1971
Range and occurrence: Late Paleozoic to Late Cretaceous. Worldwide.
Genus ***Crucella*** Pessagno, 1971; emend. Baumgartner, 1980

Type species: Crucella messinae Pessagno, 1971.
Range and occurrence: Late Triassic (Rhaetian) to Late Cretaceous. Worldwide.
Crucella sp. cf. ***C. mexicana*** Yang, 1993 (Fig. 7.12)

1993 *Crucella mexicana* Yang, pl. 40, Figs. 10–11, 14, 16; pl. 5, Figs. 10 and 21.

Remarks: This form is related to *Crucella mexicana* Yang, differing by having the arm ends gradually tapering into a spine.

Range and occurrence: Vaca Muerta Formation, Neuquén Basin, Vega de Escalone, Argentina. Sample VE 19; Fauna J3B1; *Substeueroceras koeneni* Biozone.

Family TRITRABIDAE Baumgartner, 1980

Genus ***Neoparonaella*** Yang, 1993

Type species: Neoparonaella delicata Yang, 1993

Remarks: Kiessling (1999) noticed that the internal structure of arms is consistent with the Tritrabidae rather than the Hagiastridae.
Range: Kimmeridgian to Late Tithonian.

Neoparonaella delicata Yang, 1993 (Fig. 7.11)

1993 *Neoparonaella delicata* Yang, p. 30, pl. 3, Figs. 1, 5–6, 9–10, 17, 22: pl. 7, Fig. 12.
1996 *Neoparonaella delicata* Yang; Kiessling and Scasso, pl. 2, Fig. 2.
1997 *Neoparonaella delicata* Yang; Hull p. 43, pl. 15, Figs. 2 and 18.

Range and occurrence: Late Kimmeridgian to Late Tithonian. Ameghino Formation, Antarctica; Taman Formation, east-central Mexico; volcano-pelagic strata at Stanley Mountain, California, United States; Dachhornstein Formation, Germany; Rosso di Aptici Formation, Italy. Vaca Muerta Formation, Neuquén Basin, Vega de Escalone, Argentina. Sample VE 19; Fauna J3B1; *Substeueroceras koeneni* Biozone.

Order NASSELLARIINA Ehrenberg, 1875

Family ARCHAEODICTYOMITRIDAE, Pessagno, 1976; emend. Pessagno, 1977b
Type genus: Archaeodictyomitra Pessagno, 1976; emend. Pessagno, 1977b.

Range and occurrence: Jurassic to Late Cretaceous (Maastrichtian). Worldwide.

Genus ***Archaeodictyomitra*** Pessagno, 1976; emend. Pessagno, 1977b; Yang, 1993

Type species: Archaeodictyomitra squinaboli Pessagno, 1976.
Range and occurrence: Middle Jurassic (Bajocian) to Late Cretaceous (Campanian). Worldwide.
Archaeodictyomitra sixi Yang, 1993 (Fig. 6.4)

1993 *Archaeodictyomitra sixi* Yang, p. 112–113, pl. 19, Figs. 3 and 19; pl. 20, Figs. 9–10, 19.
1997 *Archaeodictyomitra sixi* Yang; Hull, p. 79, pl. 32, Figs. 9, 22–23.
1999 *Archaeodictyomitra* (?) *sixi* Yang; Kiessling, p. 45, pl. 9, Fig. 10.

Remarks: This form was ascribed by Kiessling (1999) to *Archaeodictyomitra* (?) *sixi*, because of the presence of primary pores and smooth constrictions on the distal postabdominal chambers, similar to *Thanarla* Pessagno, 1977a. The definition of Yang (1993) is followed here.

Range and occurrence: Zone 2, Subzone 2α to Zone 4, Subzone 4α; early Late Kimmeridgian to Late Tithonian. Upper and lower members of the Taman Formation, east-central Mexico; Volcano-pelagic strata overlying the Coast Range ophiolite, Stanley Mountain California; Japan; Antarctic Peninsula; Vaca Muerta Formation, Neuquén Basin, Vega de Escalone, Argentina. Sample VE 2, Fauna J3A1; *Virgatosphinctes andesensis* Biozone.

Archaeodictyomitra sp. cf. ***A. vulgaris*** Pessagno, 1977b (Figs. 6.1–6.2)

1977 b *Archaeodictyomitra vulgaris* Pessagno, 1977b; Pessagno, p. 44, pl. 6, Fig. 15.

Remarks: This specimen differs from *Archaeodictyomitra vulgaris* Pessagno (Pessagno, 1977b) by possessing a shorter and broader test with more prominent irregular bladed costae. The outline exhibits smooth constrictions on the postabdominal chambers.

Range and occurrence: Vaca Muerta Formation, Neuquén Basin, Vega de Escalone, Argentina. Sample VE 2, Fauna J3A1; *Virgatosphinctes andesensis* Biozone.

Family PARVICINGULIDAE Pessagno, 1977a; emend. Pessagno and Whalen, 1982

Type genus: Parvicingula Pessagno, 1977a.
Range and occurrence: Early Jurassic (Toarcian) to Early Cretaceous (Aptian). Worldwide.

Genus ***Praeparvicingula*** Pessagno et al., 1993

Type species: Parvicingula profunda Pessagno and Whalen, 1982.
Range and occurrence: Same as for the family.
Praeparvicingula vacaensis Pujana, 1989 (Figs. 6.5 and 6.7)

1989 *Parvicingula vacaensis* Pujana, p. 1046–1048, pl. 1, Fig. 1.
1995 *Praeparvicingula vacaensis* Pujana, Kiessling, p. 346, pl. 40, fig, 19.

Range and occurrence: Limanangcong Formation, Philippines (Tithonian); Vaca Muerta Formation, Neuquén Basin, Mallín Quemado (*Windhauseniceras internispinosum* Biozone) and Vega de Escalone, Argentina. Sample VE 2, Fauna J3A1; *Virgatosphinctes andesensis* Biozone.

Praeparvicingula sp. A (Fig. 6.6)

Range and occurrence: Vaca Muerta Formation, Neuquén Basin, Vega de Escalone, Argentina. Sample VE 2, Fauna J3A1; *Virgatosphinctes andesensis* Biozone.

Family PSEUDODICTYOMITRIDAE Pessagno, 1977b

Type genus: Pseudodictyomitra Pessagno, 1977b.
Range and occurrence: Middle Jurassic (Bathonian–Callovian) to Late Cretaceous (Middle Turonian). Worldwide.
Genus ***Loopus*** Yang, 1993

Type species: Pseudodictyomitra primitiva Matsuoka and Yao, 1985
Loopus primitivus (Matsuoka and Yao, 1985); emend. Yang, 1993 (Fig. 7.6)

1985 *Pseudodictyomitra primitiva* Matsuoka and Yao, p. 131, pl. 1, Figs. 1–6; pl. 3, Figs. 1–4.
1993 *Loopus primitivus* (Matsuoka and Yao); Yang, p. 125, pl. 23, Figs. 5–6, 13, 21.
1999 *Loopus primitivus* (Matsuoka and Yao); Kiessling, p. 54, pl. 12, Fig. 15.

Range and occurrence: Zone 2, Subzone 2α 1 to Zone 4, Subzone 4β; early Late Kimmeridgian to early Late to Late Tithonian. Upper and lower members of the Taman Formation, east-central Mexico; Japan; Stanley Mountain, southern California Coast Range; Greece; Carpathians; Mazapil, Sierra de Santa Rosa, Zacatecas, Mexico; Ameghino Formation, Antarctic Peninsula; and herein, Vaca Muerta Formation, Neuquén Basin. Sample VE 19, Fauna J3B1; *Substeueroceras koeneni* Biozone.

Family SYRINGOCAPSIDAE Foreman, 1973; emend. Hull, 1997

Type genus: Syringocapsa Neviani, 1900.
Range and occurrence: Triassic to Cretaceous. Worldwide.
Genus ***Podobursa*** Wisniowski, 1889; emend. Foreman, 1973

Type species: Podobursa dunikowski, Wisnioski, 1889.
Range and occurrence: Triassic to Cretaceous. Worldwide.
Podobursa sp. A (Fig. 7.10)

Remarks: This form is characterized by a well-defined conical cephalous covered by micro-granular silica, and a conical thorax with regularly distributed small pores. Spherical post abdominal chamber, formed by a meshwork of medium size hexagonal regularly distributed pores; without circumferential spines. Tubular extension slender and composed of linearly arranged polygonal pore frames.

Range and occurrence: Vaca Muerta Formation, Neuquén Basin. Sample VE 19; Fauna J3B1; *Substeueroceras koeneni* Biozone.

Family SETHOCAPSIDAE Haeckel, 1881

Type genus: Sethocapsa Haeckel, 1881.

Remarks: The proposed restrictions by Dumitrica (1995) of the Sethocapsidae to dicyrtid forms with the last segment inflated are followed herein. See Hull (1997) for a comprehensive discussion of this family.

Range and occurrence: Middle Jurassic to Recent. Worldwide.

Genus ***Gongylothorax*** Foreman, 1968; emend. Dumitrica, 1970

Type species: Dicolocapsa verbeeki Tan, 1927.

Range and occurrence: Middle Jurassic (Bajocian) to Late Cretaceous (Campanian). Worldwide.

Gongylothorax sp. A (Fig. 7.16)

1970 *Gongylothorax favosus* Dumitrica, p. 56, pl. 1, figs. l a–c, 2.

Range and occurrence: Vaca Muerta Formation, Neuquén Basin. Sample VE 19; Fauna J3B1; *Substeueroceras koeneni* Biozone.

Family ULTRANAPORIDAE Pessagno, 1977b

Type genus: Napora Pessagno, 1977a = *Ultranapora* Pessagno, 1977b.
Range and occurrence: Middle Triassic to Late Cretaceous. Worldwide.
Genus ***Napora*** Pessagno, 1977a

Type species: *Napora bukryi* Pessagno, 1977a.
Range and occurrence: Early Jurassic (Sinemurian) to Late Cretaceous. Worldwide.
Napora pacifica Kiessling, 1999 (Fig. 7.17)

1997 *Napora pacifica* Kiessling; Hull, p. 120, pl. 46, Figs. 5–6, 17.
1999 *Napora pacifica* Kiessling, p.70, pl. 14, Figs. 1 and 6.

Remarks: Napora pacifica Kiessling is characterized by straight longer feet and a short apical horn.

Range and occurrence: Zone 3, Subzone 3α to Zone 4, Subzone 4β; early Late to Late Tithonian. Stanley Mountain, California; Antarctic Peninsula; Vaca Muerta Formation, Neuquén Basin, Vega de Escalone, Argentina. Sample VE 19; Fauna J3B1; *Substeueroceras koeneni* Biozone.

Family XITIDAE Pessagno, 1977b

Type genus: Xitus Pessagno, 1977b.
Range and occurrence: Kimmeridgian to Maastrichtian. Worldwide.
Genus ***Xitus*** Pessagno, 1977b

Type species: Xitus plenus Pessagno, 1977b.
Range and occurrence: Same as for family.
Xitus antiquus Hull, 1997 (Fig. 7.1)

1997 *Xitus antiquus* Hull, p. 136, pl. 47, Figs. 3, 9, 13, 18.

Remarks: Xitus antiquus Hull, is characterized by an extremely irregular arrangement of tubercles and rays on the outside of the skeleton.

Range and occurrence: Zone 4, Subzone 4β; early Late to Late Tithonian, insofar as known. Volcanopelagic strata, Stanley Mountain, California; Vaca Muerta Formation, Neuquén Basin, Vega de Escalone. Sample VE 19; Fauna J3B1; *Substeueroceras koeneni* Biozone.

Xitus sp. A (Fig. 6.8)

Remarks: This form possesses an elongate, slightly spindle-shaped test. Outer layer with numerous well-developed pointed tubercles. However, preservation is not good enough to assign it to species level.

Range and occurrence: Vaca Muerta Formation, Neuquén Basin, Vega de Escalone, Argentina. Sample VE 2, Fauna J3A1; *Virgatosphinctes andesensis* Biozone.

Xitus (?) sp. A (Fig. 6.11)

Remarks: This form is questionably assigned to *Xitus* owing to the vanishing of the nodose outer layer on distal segments.

Range and occurrence: Vaca Muerta Formation, Neuquén Basin, Vega de Escalone, Argentina. Sample VE 2, Fauna J3A1; *Virgatosphinctes andesensis* Biozone.

Family WILLIRIEDELLIDAE Dumitrica, 1970

Type genus: *Williriedellum Dumitrica*, 1970

Remarks: According to Hull (1997), it includes cryptothoracic tricyrtid or tetracyrtid Nassellaria; test open or closed, with or without sutural pore. Several forms assigned to this family are only slightly cryptothoracic in nature.
Range and occurrence: Middle Jurassic to Cretaceous. Worldwide.

Genus ***Complexapora*** Kiessling and Zeiss, 1992

Type species: Complexapora tirolica Kiessling and Zeiss, 1992.

Remarks: Complexapora Kiessling and Zeiss, 1992 includes cryptothoracic, three-chambered nassellarians which possess an inflated terminal chamber that is closed, and have a well-developed, complex sutural pore at the lumbar stricture.
Range and occurrence: Late Jurassic. Worldwide.

Complexapora kozuri Hull, 1997 (Figs. 7.15 and 6.10)

1997 ***Complexapora kozuri*** Hull, p. 124, pl. 37, Figs. 11, 14, 17.

Remarks: This form is assigned to *Complexapora kozuri* Hull, 1997 as was described by Hull (1997). The presence of this radiolarian is an important primary marker in Late Jurassic successions as defined on Pessagno's zonation (Pessagno et al., 2009).
Range and occurrence: Jurassic, insofar as is known. First occurrence defines the base of Zone 4, Subzones 4β2 and final occurrence defines the top of Subzone 4α2. Early to Late Tithonian. Volcanopelagic strata overlying the Coast Range ophiolite, Stanley Mountain, California. Mazapil, Sierra de Santa Rosa, Zacatecas, Mexico. Vaca Muerta Formation, Neuquén Basin, Vega de Escalone, Argentina. Sample VE 2, Fauna J3A1; *Virgatosphinctes andesensis* Biozone; and Sample VE 19; Fauna J3B1; *Substeueroceras koeneni* Biozone.

***Complexapora* sp. A** (Fig. 6.9)

Remarks: Short torax, rare.

Range and occurrence: Vaca Muerta Formation, Neuquén Basin, Vega de Escalone, Argentina. Sample VE 2, Fauna J3A1; *Virgatosphinctes andesensis* Biozone.

***Complexapora* sp. B** (Fig. 6.12)

Remarks: Abdominal chamber with larger pores and pointy shape towards the end.
Range and occurrence: Vaca Muerta Formation, Neuquén Basin, Vega de Escalone, Argentina. Sample VE 2, Fauna J3A1; *Virgatosphinctes andesensis* Biozone.

FAMILY EUCYRTIDIIDAE Ehrenberg, 1847

Type genus: *Eucyrtidium* Ehrenberg, 1847

Range and occurrence: Triassic to Recent. Worldwide.

Genus ***Pseudoeucyrtis*** (?) (Figs. 7.13–7.14)

Remarks: This form possesses a relatively broad test without the characteristic spindle-shape and irregular pore structure. Poor preservation hinders most of the pore structure and a more assertive assignation.

Range and occurrence: Vaca Muerta Formation, Neuquén Basin, Vega de Escalone. Sample VE 19; Fauna J3B1; *Substeueroceras koeneni* Biozone.

5. Conclusions

The Vega de Escalone section holds 482 m of exposures of the Vaca Muerta Formation. Bed by bed ammonoid analysis resulted in the identification of nine Late Jurassic to Early Cretaceous ammonoid assemblage biozones, spanning from Early Tithonian to Late

Berriasian/earlymost Valanginian times.

Linked to the ammonoid record, two radiolarian faunas were identified, J3A1 and J3B1 based on seven fertile samples. On one hand, fauna J3A1, recovered from three samples obtained from the base of the section, is dominated by nasellarian genera and represents the first thoroughly described record of radiolarians from the Early Tithonian *Virgatosphinctes andesensis* Biozone in the Neuquén Basin. While on the other hand, Fauna J3B1, based on four samples coming from the *Substeueroceras koeneni* Biozone interval, showed a remarkable abundance of representatives of the Pantanellidae Family. Identification at the J3B1 Fauna of *Complexapora kozuri* and *Loopus primitivus*, important primary markers of Late Jurassic according to Pessagno et al. (2009), supports a Late Tithonian age for at least part of the *S. koeneni* Biozone in the studied area, although still no Berriasian radiolarians have been identified on this section to verify its upper age limit. No representatives of the Vallupinae Subfamily were identified on neither of the described radiolarian faunas, and the stratigraphic interval where they have been previously described in other localities of the Neuquén Basin was unfortunately barren of any radiolarians in Vega de Escalone.

Lastly, an additional sample VE 25, obtained from a bed bearing representatives of the Early Berriasian *Argentiniceras noduliferum* Assemblage Biozone, yielded a poorly preserved radiolarian fauna of relatively low abundance and diversity, which did not exhibit any significant compositional signature with respect to the previously described faunas.

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