Remarks on the Tithonian–Berriasian ammonite biostratigraphy of west central Argentina

Alberto C. RICCARDI [1]

Abstract. Status and correlation of Andean ammonite biozones are reviewed. Available calpionellid, nannofossil, and radiolarian data, as well as radioisotopic ages, are also considered, especially when directly related to ammonite zones. There is no attempt to deal with the definition of the Jurassic–Cretaceous limit. Correlation of the *V. mendozanum* Zone with the *Semiforme* Zone is ratified, but it is open to question if its lower part should be correlated with the upper part of the *Darwini* Zone. The *Pseudolissoceras zitteli* Zone is characterized by an assemblage also recorded from Mexico, Cuba and the Betic Ranges of Spain, indicative of the *Semiforme–Fallauxi* standard zones. The *Aulacosphinctes proximus* Zone, which is correlated with the *Ponti* Standard Zone, appears to be closely related to the overlying *Windhauseniceras internispinosum* Zone, although its biostratigraphic status needs to be reconsidered. On the basis of ammonites, radiolarians and calpionellids the *Windhauseniceras internispinosum* Assemblage Zone is approximately equivalent to the *Suarites bituberculatum* Zone of Mexico, the *Paralytohoplites caribbeanus* Zone of Cuba and the *Simplisphinctes/Microcanthum* Zone of the Standard Zonation. The *C. alternans* Zone could be correlated with the uppermost *Microcanthum* and "*Durangites*" zones, although in west central Argentina it could be mostly restricted to levels equivalent to the "*Durangites* Zone". The *Substeueroceras koeneni* Zone ranges into the *Occitanica* Zone, *Subalpina* and *Privasensis* subzones, the *A. noduliferum* Zone could be equivalent to the *Dalmasi* Subzone, *Occitanica* Zone, to lower part of the *Boissieri* Zone, and the *S. damesi* Zone could range through the upper part of the *Boissieri* Zone to the lower part of the *Pertransiens* Zone. Division of the *Substeueroceras koeneni* Zone and a precise correlation between the Andean ammonite zones and the international standard require new systematic and stratigraphic studies.

INTRODUCTION

In the last decades correlation of the Tithonian-Berriasian ammonite biostratigraphy of west central Argentina, as summarized in several papers published in Argentina (*cf.* Riccardi *et al.*, 2011; Vennari *et al.*, 2013), has not undergone major changes. Meanwhile, and as it will be discussed below, studies originated in other regions have modified it in different ways.

These circumstances prompted this study, and an attempt to analyze all available information on the status and correlation of the Andean biozones with the international standard,

in order to evaluate their reliability and, if necessary, to suggest changes and/or specific new studies.

Ammonite biostratigraphy discussed below applies to the sedimentary succession exposed in the Neuquén Basin of west central Argentina. This basin covers more than 160,000 km^2 and contains a thick Mesozoic sedimentary sequence characterized by Upper Triassic–Oxfordian, Tithonian–Barremian and Maastrichtian marine strata. The Tithonian–Berriasian is represented by time-transgressive lithofacies within a series of, at least, seven sequences that show progradation of continental and littoral facies over more distal facies. Boundaries between these depositional sequences

[1] Museo de La Plata, Paseo del Bosque s/n, 1900 La Plata, Argentina; e-mail: riccardi@fcnym.unlp.edu.ar.

represent stratigraphic discontinuities (*cf.* Gulisano *et al.*, 1984; Mitchum, Uliana, 1985; Riccardi, 1988; Legarreta, Gulisano, 1989; Legarreta, Uliana, 1991, 1996; Leanza *et al.*, 2011), and faunal diversity and correlation potential increase away from those boundaries.

The present remarks are focused on the ammonite faunas and biostratigraphy, although related information on other macro- and microfossils, and on geochronological data, is also considered. Correlations are therefore referred to ammonite zonal (Standard and local) schemes, whose correlation is the primary goal of this paper. There is no attempt to deal here with the precise definition of the Jurassic-Cretaceous limit, and therefore the use of terms such as "Tithonian", "Berriasian", "Upper/Late Jurassic" and "Lower/Early Cretaceous" have been kept to a minimum and is usually adopted when quoting other sources. It is considered that once biostratigraphic correlations are well established definition of Stage and System boundaries will follow by convention.

In relation to the ammonites zones of the international standard (see Fig. 1) it should be noticed that Wimbledon *et al.* (2013, p. 451; *cf.* also Bulot *et al.*, 2014) have proposed to abandon the "*Durangites* Zone" of the topmost Tithonian because of the possibility that this genus may be endemic to the Mexican-Cuban region. Moreover, they have proposed to use the "*Protocanthodiscus andreaei* Zone", as a local index for the Mediterranean area.

ANDEAN TITHONIAN-BERRIASIAN AMMONITE BIOZONES

VIRGATOSPHINCTES MENDOZANUS ZONE [≈ UPPERMOST *DARWINI*?–*SEMIFORME* STANDARD ZONES] (Fig. 1)
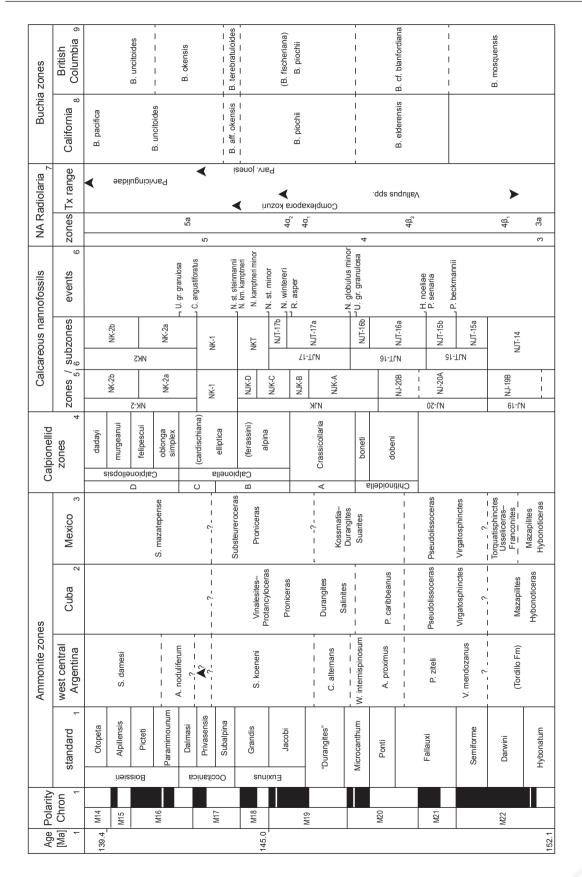
In the Neuquén Basin the first ammonite assemblages overlying the continental beds of the Tordillo Formation are typically represented in the lower beds of the Vaca Muerta Formation and were included in the *Virgatosphinctes mendozanus* (Assemblage) Zone (Burckhardt, 1900; *cf.* Leanza, 1980; Riccardi, 1984). This zone was usually considered (or its lower part or in full) as an approximate equivalent to the *Darwini* Zone (upper part) of the Lower Tithonian (Zeiss, 1968, 1977; Wiedmann, 1980a, b; Leanza, 1980, 1981; Riccardi, 1984). According to Zeiss (1968; Leanza, 1980) the *V. mendozanus* Zone could be equivalent to the *Palatinus* Subzone, uppermost *Darwini* Zone, of the German Franconia region, because of the similarities between the ammonites figured by Indans (1954) (fossils collected by C. Burckhardt and coming from two localities, *i.e.* Bardas Blancas

and Casa Pincheira, in southern Mendoza province) and the Franconian Sublithacoceratini. Leanza (1980, 1981) accepted this correlation, adding that the *V. mendozanus* Zone also includes the genus *Pseudinvoluticeras* Spath, 1925 "that in Somaliland, Madagascar and Mexico" is referred to the Lower Tithonian. The *V. mendozanus* Zone was also extended to the *Semiforme* Zone (*cf.* Enay, 1964; Callomon, 1992; Riccardi 2008a, b; Riccardi *et al.*, 2011) because of the co-occurrence of *Virgatosphinctes* spp. and *Pseudolissoceras* Spath.

In the last ten years some authors (Parent, Capello, 1999; Parent, 2003; Parent *et al.*, 2006, 2011a, b, 2013a; Parent, Cocca, 2007; Zeiss, Leanza, 2010) have separated the ammonites traditionally ascribed to the Early Tithonian *V. mendozanus* Zone into two different assemblages, whereas some (see Parent *et al.*, 2011a, b) have proposed that the lower assemblage could be Late Kimmeridgian. Ammonites included in the *V. mendozanus* Zone had, in fact, already been referred to two different Early Tithonian assemblages by Wiedmann (1968, 1980a, b), who characterized the lower one by the presence of "*Torquatisphinctes*" (or by "*Virgatosphinctes pseudolictor*") and the upper by "*Virgatosphinctes mendozanus*" (or by *V. andesensis* and *V. choicensis*). Zeiss and Leanza (2010) also divided, without much elaboration, the *V. mendozanus* Zone into a lower part with "*Lithacoceras*" *malarguense* (Spath) and an upper, with *Choicensisphinctes choicensis* (Burckhardt), which were referred respectively to the *Hybonotum* and *Darwini* zones. In addition they considered the *V. mendozanus* Zone as an equivalent to the *Mazapilites* beds of Mexico. Some of the authors mentioned above (see Parent *et al.*, 2011a, b) based the age proposed for the lower assemblage, underlying a redefined *V. mendozanus* Zone, in the supposed presence (see Parent, Capello, 1999; Parent, 2003) of representatives of *Virgalithacoceras* Olóriz, *i.e. V.* cf. *acricostatum* Ohmert et Zeiss/*V. malarguense* (Spath)/*V. picunleufuense* Parent *et al.*, later transferred, first (Parent, 2003) to *Euvirgalithacoceras* Zeiss *et al.* and later still (see Parent *et al.*, 2006, 2011a, b, 2013a, b) to "*Lithacoceras*" or *Lithacoceras* Hyatt. Inclusion in *Euvirgalithacoceras* was accepted by Salazar Soto (2012), who reported the species *E. malarguense* (Spath) from the Baños del Flaco Formation, in the Chilean Rio Maitenes section, together with representatives of *Virgatosphinctes*, *Choicensisphinctes* Leanza and *Pseudolissoceras*. This assemblage was referred to the lower Middle Tithonian (see below).

The presence of *Euvirgalithacoceras* in the Neuquén Basin, on the basis of "*Subplanites malarguensis* Spath", has been discounted by Riccardi (2008b, p. 636–637). It should also be mentioned that the supposed close similarity (Parent *et al.*, 2011a, p. 62) between "*Lithacoceras pinculeufuense*" and "*Perisphinctes (Lithacoceras) albulus*" (Quenstedt, 1887, pl. 25: 8; Berckhemer, Hölder, 1959, p. 55, pl. 9: 48;

Fig. 1. Chart showing the tentative correlation of the ammonite zones of west central Argentina with the International Standard, and the Mexican and Cuban ammonite successions, Numerical Ages, Polarity Chrons, Calpionellid Zones/Subzones, Calcareous Nannofossil Zones/Subzones and selected events, North American Radiolarian Zones and selected taxa ranges, and *Buchia* Zones for California and British Columbia are based on information compiled and modified from: (1) Ogg *et al.* (2012a, b); (2) Pszczółkowski and Myczyński (2010); (3) Imlay (1980), Villaseñor *et al.* (2012); (4) Lakova and Petrova, 2013; (5) Bralower *et al.* (1989); (6) Casellato (2010), Channell *et al.* (2010), Grabowski (2011); (7) Pessagno *et al.* (2009); (8) Jeletzky (1984); (9) Jeletzky (1984)

pl. 10: 51) – a species that is considered to belong in the *Hybonotum, Semiforme* (to *Ponti*) zones of the Lower–Middle Tithonian (*cf.* Berckhemer, Hölder, 1959, p. 16, 114; Enay, 1964; Zeiss, 1968; Ziegler, 1977; Mesezhnikov, 1988) – is hindered by the lack of a proper systematic study of its geographical range based on well preserved material (*cf.* Parent, 2003; Parent *et al.*, 2011a, b). It should be noted however, that ribbing at various growth stages appears to differ in the two species, and that in Europe *Lithacoceras* has been recorded from the *Hybonotum* to *Fallauxi* zones (*cf.* Enay, Geyssant, 1975; Olóriz, 1978; Geyssant, 1997),

Most Andean *Virgatosphinctes*, including *V. andesensis* (Douvillé) and *V. mendozanus* (Burckhardt), have recently been referred (Salazar Soto, 2012) to *Virgatosphinctes scythicus* (Vischniakoff, 1882), and to the lower Middle Tithonian. Assignment of the Andean Virgatosphinctinae to this species from the Tithonian of South Franconia and Volgian of central Poland, first proposed (partly) by Burckhardt (1903) was correctly discussed and discounted a long time ago (*cf.* Douvillé, 1910, p. 7; Leanza, 1980, p. 13), a conclusion that is upheld here although, as discussed below, nothing militates against an early Middle Tithonian age for the Andean material. It should also be mentioned that *Ammonites scythicus* is included in the genus *Zaraiskites* Semenov (*cf.* Kutek, Zeiss, 1974, 1994; Mesezhnikov, 1988; Mitta *et al.*, 1999), and that the Subzone of *Z. scythicus* has been correlated with the *Simplisphinctes* Subzone, lower part of the *Microcanthum* Zone, of the Upper Tithonian (*cf.* Zeiss, 2001).

Information on stratigraphy and ammonites provided by different authors (see, Gerth, 1925; Krantz, 1926, 1928; Weaver, 1931; Leanza, Hugo, 1978; Leanza, 1980; Parent *et al.*, 2006; Parent, Cocca, 2007; Parent *et al.*, 2011a, b, 2013a, b; Vennari, 2013) and information available to the present author, from more than 20 sections over a distance of five hundred kilometres in the eastern foothills of the Andes, between Rio Diamante (Mendoza province) and Catan Lil (Neuquén province), shows that *Pseudinvoluticeras*, *Choicensispinctes* and *Virgatosphinctes* range through the *V. mendozanus* Zone (and equivalents). In some cases they have been recorded in the lower levels together with doubtful representatives of "*Torquatisphinctes* Spath" and "*Lithacoceras*", whereas higher up they occur in levels where *Pseudolissoceras zitteli* (Burckhardt), *Pseudovolanoceras aesinense krantzense* (Cantu Chapa), *Pseudohimalayites steinmanni* (Haupt), and *Schaireria neoburgensis* (Oppel) also occur. Presence of these taxa provides a reliable relative date, as all them, usually ascribed to the Andean *Pseudolissoceras zitteli* Zone, are indicative of the *Semiforme* Zone.

A possible older age for representatives of the same genera found in levels below the *P. zitteli* Zone rests mainly on their lower stratigraphic occurrence.

Thus far, the ammonite fauna in the lower part of the *V. mendozanus* Zone has not provided representatives diagnostic enough to support correlation with the *Hybonotum* Zone and/or the *Darwini* Zone, as proposed by some authors (see above and below). In addition, systematic studies on the fauna, which in most cases, with the exception of Vennari's work (2013), are not based on collections from carefully sampled sections distributed along the whole outcrop of the basal Tithonian exposed in the Neuquén basin, do not contribute to the solution of the problem. This is clearly evident from the conflicting conclusions on the systematics and the age of this fauna, as in the works of Parent *et al.* (*cf.* 2006, 2011a, b), Salazar Soto (2012), and Vennari (2013).

Representative faunal elements of the *Virgatosphinctes mendozanus* Zone have been described from Antarctica (Tavera Jerez, 1970; Thomson, 1979, 1983; Howlett, 1989; Whitham, Doyle, 1989; Kiessling *et al.*, 1999), but in most cases material is poorly preserved and its distribution is patchy. Kiessling *et al.* (1999), who also provided biostratigraphic data from co-occurring radiolarians, recorded the *Virgatosphinctes mendozanus* Zone above levels corresponding to the *Hybonotum* and *Darwini* zones, and although the presence of the *Pseudolissoceras zitteli* and *Aulacosphinctes proximus* zones in the overlying beds was not documented, the *Virgatosphinctes* fauna was considered to represent the Middle Tithonian and earliest Late Tithonian.

Virgatosphinctes species have sometimes been considered to be restricted to the Middle–Late Tithonian of the Indian region, whereas the Andean and Mexican representatives were assigned to the Early Tithonian and regarded as probably an endemic root-stock of the genus characterized by a different ribbing style (*cf.* Enay, 1972; Enay, Geyssant, 1997; Enay, Cariou, 1997; Cecca, 1999).

Enay (1972) first stated that *Virgatosphinctes* characterized levels equivalent to the Middle Tithonian and was restricted to the Indian region. This was accepted by Callomon (1992), and Krishna *et al.* (1982) proposed a similar age for their *Hildoglochiceras–Virgatosphinctes* fauna in Spiti. Later Pathak and Krishna (1993), Krishna *et al.* (1994, 1996, 2000), Shome and Bardhan (2009) concluded that in the Spiti and Kachchh regions *Virgatosphinctes* occurs in levels corresponding to the *Microcanthum* Zone. Subsequently it was considered (Jain, Rahulgarg, 2012) that the levels with *Virgatosphinctes* in the Jaisalmer Basin (Rajasthan) represent the interval between the *Fallauxi* and *Durangites* spp. zones.

Virgatosphinctes was also recorded from the Sembar Formation of Pakistan (Fatmi, Zeiss, 1994), below and above levels with *Substeueroceras koeneni*, associated in both cases with *Aulacosphinctoides*, and in the upper level also with *Pseudinvoluticeras*. The whole fauna was considered to range from the *Microcanthum* (*Simplisphinctes/*

Transitorius) Zone to the *Jacobi* (*Jacobi/Grandis)* Zone, and correlated with the Andean *Alternans* and *Koeneni* zones.

Howarth and Morris (1998; *cf.* also Howarth, 1998) mentioned the presence of *Virgatosphinctes* – associated to *Choicensisphinctes* – in the Upper Tithonian "*Durangites* Zone" of Yemen and concluded that the genus ranges throughout the Tithonian. Later however, in describing the ammonoid biostratigraphy in eastern Himalayan Tibet, Yin and Enay (2004) considered the "*Virgatosphinctes–Aulacosphinctoides*" assemblage as a possible equivalent to, or older than, the *Semiforme/Fallauxi* zones, although *Virgatosphinctes*, *i.e. V. denseplicatus* (Waagen) was still recorded from higher levels, up to the "*Haplophylloceras pingue*" assemblage which was considered to be "early Late Tithonian".

Finally, in describing a large fauna from Nepal Enay (2009, p. 50) considered that his "*Virgatosphinctes* et *Aulacosphinctoides*" assemblage could not be dated with enough precision and concluded that the age of *Virgatosphinctes* in most areas is debatable but could be referred to the *Darwini* and lower part of the *Semiforme* Zone, mentioning that the probable presence in Nepal of a species close to S*emiformiceras semiforme*, if not coming from the levels with *Malagasites*, supports reference of the "*Aulacosphinctoides* and *Virgatosphinctes*" assemblage to the *Semiforme* Zone. Other material previously included in *Virgatosphinctes* by Uhlig (1910), Fatmi (1972), Pathak and Krishna (1993), Olóriz and Tintori (1990) has been referred to the new genus *Malagasites* – including *Virgatosphinctes denseplicatus* and *V. frequens* (Oppel). Material from Antarctica was also referred to *Malagasites*, specimens which had previously been assigned to *Virgatosphinctes*. The *Malagasites* fauna was considered equivalent to the *Semiforme* to *Ponti* zones.

In Mexico and Cuba (see Fig. 1) ammonites referred to *Virgatosphinctes* occur in and above levels with *Mazapilites* Burckhardt and were recorded in association with *Pseudolissoceras* and *Pseudinvoluticeras* (*cf.* Imlay, 1939, 1942, 1980; Verma, Westermann, 1973; Myczyński, 1989; Pszczółkowski, Myczyński, 2010). In Mexico *Virgatosphinctes* is associated, immediately above levels with *Schaireria neoburgensis*, with *Pseudovolanoceras aesinensis* (Meneghini), *P. aesinensis chignahuapensis* (Cantu Chapa), *Simocosmoceras pszczolkowskii apulcoensis* Villaseñor et Olóriz, and *Pseudohimalayites steinmanni*, an assemblage that was considered equivalent to the (upper *Albertinum/ Darwini-*) *Semiforme/Verruciferum* (lowermost *Richteri*) Zone (Olóriz *et al.*, 1999; Villaseñor *et al.*, 2003, 2011, 2012), whereas in Cuba this range is extended up to the upper *Fallauxi* Zone (*cf.* Pszczółkowski, Myczyński, 2010). *Virgatosphinctes* has even been mentioned (*cf.* Imlay, 1939) in association with *Substeueroceras* Spath and *Parodontoceras* Spath, from Cañadón Alamo, Sierra Jimulco, Coahuila, Mexico. The levels with *Mazapilites* were referred to the

"middle–upper *Hybonotum* Zone to lower *Albertinum/Darwini* Zone" (*cf.* Olóriz *et al.*, 1999), although from the works mentioned above (*cf.* Imlay, 1939, 1980) the genus appears to be also present in beds equivalent to the *Semiforme* Zone.

With regard to *Torquatisphinctes*, supposedly present in the lower part of the *V. mendozanus* Zone, the genus has been recorded from the *Hybonotum* to *Semiforme* zones of Europe (*cf.* Enay, Geyssant, 1975; Olóriz, 1978; Geyssant, 1997). In Mexico Villaseñor *et al.* (2000; see also Villaseñor *et al.*, 2012) recognized a "*Parastreblites-Torquatisphinctes*" or "*Torquatisphinctes*" Assemblage and considered it as equivalent to the *Palatinus* Zone (= upper part of the *Darwini* Zone), but also mentioned (Villaseñor *et al.*, 2000) that "the assemblage contains *Parastreblites* and *Pseudolissoceras* typical of the *Albertinum/Darwini* (to lowermost *Semiforme/Verruciferum*) Zone", on top of which is the "*Andiceras–Kossmatia* Assemblage" – which characterizes the "Virgatosphinctinae beds" of Verma and Westermann (1973) – of the *Semiforme* Zone.

More recently Enay (2009) mentioned *Torquatisphinctes* in Nepal, from the lower part of his beds with *Paraboliceras* Uhlig and lower part of the beds with *Kossmatia* Uhlig, assigned respectively to the Upper Kimmeridgian and Lower Tithonian, but he stressed (p. 112) the difficulties surrounding the definition of this genus, because the type species is based on a poorly preserved specimen.

An additional item to be considered here is the possible synchronicity throughout the Neuquén basin of the oldest ammonite levels represented in the *V. mendozanus* Zone. Different authors have considered that the oldest marine Tithonian rests conformably (Gerth, 1925; Leanza *et al.*, 1978, 2011; Leanza, 1981; Gulisano *et al.*, 1984; Naipauer *et al.*, 2014), or unconformably (*cf.* Weaver, 1931; Groeber *in* Groeber *et al.*, 1953), on top of the underlying continental beds of the Tordillo Formation, and is represented by an isochronous level, that according to Mutti *et al.* (1994) corresponds to the beginning of a catastrophic marine flooding when "the Neuquén Basin acted as the Messinian Mediterranean Sea". Most probably "a major inundation episode occurred in the Tithonian" and "during the early stages of this transgression, water remained shallow and slightly hypersaline, and an area in the order of tens of thousands of square kilometers was covered by a thin stromatolite zone" in the basin interior", and "as the transgression advanced conditions allowed the appearance of a well diversified fauna, the depositional site became strongly differentiated and a wide basinal area was developed" (Legarreta, Uliana, 1991, p. 434; see also Legarreta, Uliana, 1996). Within this context there was an important areal expansion of marine sedimentation with dominance of black organic-rich pelitic facies and poor development of sandy littoral sediments. In this regard it should be no-

ticed that the *V. mendozanus* Zone (and equivalents), as identified in different studies (Gerth, 1925; Weaver, 1931; Leanza, Hugo, 1978; Leanza, 1981; Parent *et al.*, 2011a, b, 2013a, b; Kietzmann, 2011) and on information from more than 20 sections, available to the author, between Rio Diamante (Mendoza province) and Catan Lil (Neuquén province), is represented, above the continental Tordillo Formation, with thicknesses ranging between 0,50 m and *c.* 30 m (and possibly up to 117 m, *cf.* Leanza, 1981). Therefore, it is probable the existence towards the basin margin of a diachronous relationship of the basal Ttithonian ammonite levels with variations in their distribution and stratigraphic arrangement, with due consideration to geometry of depositional sequences.

Based on the above considerations it is possible to ratify the correlation of the *V. mendozanum* Zone with the (lower part of the) *Semiforme* Zone (see Fig. 1), but it is open to question whether, as accepted thus far, its lower part should be correlated with the upper part of the *Darwini* Zone. The *V. mendozanus* Zone could be correlated with the *Mazapilites* beds of Mexico, as suggested by Zeiss and Leanza (2010), and that genus in Mexico also ranges from the *Hybonotum* to the *Semiforme* zones (see above), but most probably correlation should be restricted, at most, to the upper part of the Mexican beds. If so the *Virgatosphinctes mendozanum* Zone could well be correlated totally with the *Semiforme* Zone. Besides a stratigraphically conformable relationship with the *P. zitteli* Zone, thus far there is no other evidence in central west Argentina to clarify the exact age of the ammonite bearing levels of the lowermost Tithonian. In any circumstance it is still necessary to study possible variations in the age of this fauna throughout the basin. It is worth mentioning that according to Burckhardt (1930, p. 113, table 11), who had a first hand knowledge of the stratigraphy and ammonites of both regions, the levels with *Mazapilites* most probably have no faunal equivalents in west central Argentina and could be represented by the uppermost part of the continental beds of the Tordillo Formation.

Here it should be noted that U-Pb detrital zircon ages in the continental formation, that underlies the marine beds with ammonites (here included in the *Virgatosphinctes mendozanus* Zone), show a range between 153 Ma (Naipauer *et al.*, 2012) and 145.2–142.2 Ma (Naipauer *et al.*, 2014), in the last case with a statistical estimation of *c.* 144 Ma for the maximum age of deposition (Naipauer *et al.*, 2014).

The age obtained for the Tordillo Formation is younger than the 152.06 Ma proposed in GTS 2012 (*cf.* Ogg *et al.*, 2012a) for the base of the *Hybonotum* Zone, and even of the *Semiforme* Zone (150.41 Ma), mostly projected from M-sequence calibrations. In any case correlation of the *Virgatosphinctes mendozanus* Zone with the (uppermost *Darwini*-)*Semiforme* Zone, implies that the Tordillo Formation could

be extended into the basal Tithonian by at least 2 myr, or even more, considering that uncertainties of the extrapolated boundary ages are estimated as ±1 myr and that, depending on the method applied, results could differ by 2 myr (Ogg *et al.*, 2012a). In any circumstance these data are in agreement with a younger age for the *V. mendozanus* Zone and could indicate that the Tordillo Formation corresponds, at least in its upper part, to most or all of the *Hybonotum* + *Darwini* zones (see below).

PSEUDOLISSOCERAS ZITTELI ZONE (≈ *SEMIFORME*–LOWER *FALLAUXI* STANDARD ZONES) (Fig. 1)

The *P. zitteli* Zone has been correlated with the *Semiforme* and (lower) *Fallauxi* zones (Zeiss, 1977; Olóriz, 1978; Cecca, Enay, 1991; Zeiss, Leanza, 2008) and the index species recorded from Mexico (*cf.* Imlay, 1942; Cantu Chapa, 1968; Verma, Westermann, 1973; Callomon, 1992), Cuba (*cf.* Imlay, 1942; Myczyński, 1989; Pszczółkowski, Myczyński, 2010) and the Betic Ranges of Spain (Olóriz, 1978, p. 34; 1981, p. 37). Closely related species characterize the *Hybonotum* and/or *Semiforme* zones of France (Cecca, Enay, 1991; Geyssant, 1997), Franconia (*cf.* Enay, Geyssant, 1975), and the Russian Far East (Sey, Kalacheva 1996, 1997).

In west central Argentina, *Pseudolissoceras zitteli* has been recorded (Krantz, 1926, 1928) in association with *Pseudovolanoceras aesinense krantzense* (Cantu Chapa, 1990; *cf.* Santantonio, 1986; Cecca, 2002; Villaseñor *et al.*, 2011) and *Pseudhimalayites steinmanni* from Bardas Blancas, and together with *Schairieria neoburgensis* (="*Aspidoceras* aff. *cyclotum*" in Krantz, 1928, p. 10, pl. 1: 1; see Cecca, 1985, p. 199) from Rodeo Viejo, Mendoza province. Moreover, Leanza and Olóriz (1987) recorded *Simocosmoceras adversum andinum* Leanza et Olóriz associated with *P. steinmanni* in the upper part of the *P. zitteli* Zone. Both species are present in the *Semiforme* Zone of the Betic Ranges of Spain (*cf.* Olóriz, 1978), although both genera have been considered (Schweigert, 1997) to belong to a dimorphic pair, present from the Late Oxfordian onwards.

A similar assemblage has been recorded from the Betic Ranges (*cf.* Enay, Geyssant, 1975; Olóriz, 1978; Cecca, 1985), Cuba (*cf.* Myczyński, 1989, 1990; Pszczółkowski, Myczyński, 2010) and Mexico (*cf.* Villaseñor *et al.*, 2003, 2011, 2012).

Schairieria neoburgensis ranges from the *Hybonotum* Zone to the *Verruciferum* (= *Semiforme*) Zone, with its acme in the *Hybonotum* and *Darwini* zones, in the Betic Ranges (*cf.* Enay, Geyssant, 1975; Olóriz, 1978; Cecca, 1985), but in Morocco it ranges from the *Fallauxi* to the lowermost part of the *Microcanthum* Zone (Benzaggagh, Atrops, 1997).

In Mexico the species occurs in beds that are considered equivalent to the lower part of the *Darwini* Zone and has also been recorded above a *Torquatisphinctes* assemblage, which is referred to the upper part of the *Darwini* Zone. Thus the *S. neoburgensis* assemblage from Mexico, which is overlain by an assemblage with *Pseudolissoceras*, *Pseudohimalayites*, *Simocosmoceras* and *Pseudovolanoceras*, was referred to the lowermost part of the *Semiforme* Zone by Villaseñor *et al.* (2012).

All evidence indicates that *S. neoburgensis* is quite rare in the Neuquen Basin, and that could be considered as a weak representation of peak occurrences elsewhere (*cf.* Hoedemaeker, 1987, p. 27) or, in the absence of equivalent levels, as a record beyond its acme in the *Hybonotum–Darwini* zones, *i.e.* representing the *Semiforme* Zone.

It should also be mentioned that in the uppermost *Semiforme* Zone, *Pseudovolanoceras aesinense krantzense* has been considered (Schweigert *et al.*, 2002) to represent a phyletic link between *P. aesinense* (Meneghini) from the lower part of the *Semiforme* Zone and *P. schwertschlageri* (Schneid) from the *Fallauxi* Zone.

In Cuba the *P. zitteli* assemblage is associated with *Virgatosphinctes*, and on the basis of its position, "slightly above the *Mazapilites* Zone" and below levels with representatives of *Virgatosphinctes* and *Pseudinvoluticeras* which are followed by *Paralythohoplites caribbeanus* (Imlay), it has been considered (*cf.* Myczyński, 1989; Pszczółkowski, Myczyński, 2010) to be equivalent to the *Darwini*, *Semiforme* and *Fallauxi* zones.

It is relevant that Lescano and Kietzmann (2010), and Kietzmann *et al.* (2011b) recorded the FO of *Polycostella beckmannii* Thierstein, that defines Nannofossil Subzone NJT-15b (= magnetozone M21, *Fallauxi* Zone; *cf.* Channell *et al.*, 2010; Grabowski, 2011), in the middle part of the *P. zitteli* Zone exposed in Tres Esquinas, and in the Rahue and Loncoche creek sections of southern Mendoza. This suggests that the upper part of the *P. zitteli* Zone could reach levels younger than those of the *Richteri* Standard Subzone. Additionally, in Cuba the calpionellid *Chitinoidella boneti*, indicating basal Upper Tithonian, has been recorded (*cf.* Pszczółkowski, Myczyński, 2010) from levels of the upper part of the *P. caribbeanus* Zone. This supports the correlation (Zeiss, Leanza, 2008; see below) of the *P. caribbeanus* Zone with the *W. internispinosum* Zone and with the *Simplisphinctes* Subzone, of the *Microcanthum* Zone (see below) and of the underlying fauna with the *Fallauxi* Zone (see above). Moreover, the presence of *Saccocoma* facies in the *Pseudolissoceras–Virgatosphinctes* levels of Cuba (*cf.* Pszczółkowski, Myczyński, 2010; Lopez Martinez *et al.*, 2013a) and in the *P. zitteli* Zone of Argentina (Kietzmann, Palma, 2009) lends further support to the equivalence of the Argentinean, Cuban (and Mexican) ammonite faunas.

The apparent lack of a clear distinction between the *Virgatosphinctes mendozanus* and *Pseudolissoceras zitteli* zones, both related to a progressive development of a high-stand sequence, and the closer relationship of the overlying *Aulacosphinctes proximus* and *Windhauseniceras internispinosum* zones (see below), taken together with the correlations here proposed suggest that there is not a clearly defined Andean Middle Tithonian ammonite fauna. On that basis it appears advisable to adopt a bipartite division of the Andean Tithonian, as done elsewhere (*cf.* Tavera Benítez, 1985).

AULCOSPHINCTES PROXIMUS ZONE (≈ UPPERMOST *FALLAUXI* AND *PONTI* STANDARD ZONES) (Fig. 1)

As pointed out by Leanza (1980, 1981), this zone (introduced by Burckhardt, 1900, 1903) is one of the most poorly defined in the Andean Tithonian because it is based on few genera (and species), *i.e. Aulacosphinctes* Uhlig, *Pseudhimalayites* Spath, *Aspidoceras* Zittel, and it is not always clearly identifiable. Although it is usually mentioned in biostratigraphic studies and summaries for the Andean region (*cf.* Leanza 1980, 1981; Riccardi, 1984, 2008a, b; Zeiss, Leanza, 2010; Riccardi *et al.*, 2011), it has not been considered in most Tithonian-Berriasian global biostratigraphic reviews and studies on Mediterranean ammonites (*cf.* Enay, 1972; Wiedmann, 1968, 1980a; Zeiss, 1977; Olóriz, 1978). Inclusion of the index species in *Torquatisphinctes* (see Parent, 2003) or in *Catutosphinctes* Leanza et Zeiss (see Parent *et al.*, 2011b) was correctly disregarded by Salazar Soto (2012).

The species and/or zone have been recognized in the Russian Far East where it has been correlated with the *Ponti* Zone (Sey, Kalacheva, 1996), and in the eastern Himalayan Tibet in an assemblage that has been tentatively correlated with the *Ponti/Fallauxi* zones (Yin, Enay, 2004, p. 682). Moreover, in the *Aulacosphinctes proximus* Zone material has also been recorded (Zeiss, Leanza, 2010) that is closely related to *Corongoceras praecursor* Zeiss, a species previously described (Zeiss, 2001) from the lowermost Upper Tithonian *Simplisphinctes* Zone of Ernstbrunn, Austria.

As some of the genera mentioned above are also present in the underlying, and especially in the overlying zones, and as Mediterranean representatives of *Aulacosphinctes*, even if typical of the *Ponti* Zone, are present in the uppermost *Fallauxi* and *Microcanthum* zones (*cf.* Enay, Geyssant, 1975; Olóriz, 1978, 1981; Tavera Benítez, 1985; Geyssant, 1997), the extent of the *A. proximus* Zone has been defined between the last appearance of *Pseudolissoceras zitteli* and the first of *Windhauseniceras internispinosum* (*cf.* Leanza, 1980, 1981), and which is usually correlated with the (upper

part of the *Fallauxi* and) *Ponti* Zone(s) (Zeiss, 1983; Zeiss, Leanza, 2008, 2010; Riccardi *et al.*, 2011).

The presence of *Aulacosphinctes*, however, heralds the blooming of the Himalayitinae in the *Microcanthum* Zone (*cf.* Tavera Benítez, 1985, p. 332). The *Aulacosphinctes proximus* assemblage therefore is probably more closely related to the overlying *Windhauseniceras internispinosum* Zone, although its biostratigraphic status needs to be reconsidered, especially considering that *Aulacosphinctes proximus* has been recorded from levels with *Windhauseniceras internispinosum* in the Río Maitenes section of the Baños del Flaco Formation, Chile (*cf.* Salazar Soto, 2012).

WINDHAUSENICERAS INTERNISPINOSUM ZONE (≈ *SIMPLISPHINCTES* SUBZONE, *MICROCANTHUM* STANDARD ZONE) (Fig. 1)

Correlation of the Andean *Windhauseniceras internispinosum* Assemblage Zone with the *Simplisphinctes/Microcanthum* Zone of the Standard Zonation, originally proposed by A.F. Leanza (1945) and accepted by Zeiss (1983, 1984), was later ratified (*cf.* Tavera Benítez, 1985; Zeiss, Leanza, 2008, 2010; see also Riccardi *et al.*, 2011) on the basis of the presence of the genus *Simplisphinctes* Tavera (with representatives very similar to those recorded in Cuba and southern Spain and North Africa) and "early species" of *Corongoceras*: this is accepted here. Thus, within this zone occur *Corongoceras lotenoense* Spath and *C. mendozanum* (Behrendsen), species that have also been recorded (Tavera Benítez, 1985; but see below) from the *Simplisphinctes* Zone of the Betic Ranges in Spain, and that in the Andes appear to range into the *C. alternans* Zone (*cf.* Salazar Soto, 2012).

Representatives of the radiolarians *Vallupus hopsoni* Pessagno and Blome and other radiolarians, recorded from the levels of the *W. internispinosum* Zone in Mallin Quemado and Portada Covunco, Neuquén province, characterize (*cf.* Pujana, 1989, 1991, 1995, 1996; *cf.* also Zeiss, 2001; Zeiss, Leanza, 2008; Pessagno *et al.*, 1994; 2009) the upper part of Subzone 4 beta$_2$ – whose upper limit is in the lower part of the Upper Tithonian. This has been used to support the correlation (see Fig. 1) of the *W. internispinosum* Zone with the *Suarites bituberculatum* Zone and part of Imlay's (1980) *Kossmatia–Durangites* assemblage of North America (Pujana, 1991; Pessagno *et al.*, 2009, p. 233). In fact Cantu Chapa (1968) had previously correlated the *Suarites bituberculatum* of Mexico and the Andean (*W. internispinosum* and) *Corongoceras alternans* zones on the basis of the presence in both areas of representatives of *Wichmanniceras* Leanza and *Corongoceras* (*cf.* also Olóriz, Tavera, 1989; Callomon, 1992; López Caballero *et al.*, 2007).

The calpionellid *Chitinoidella* Trejo was recorded for the first time in the Tithonian of Rio Seco del Altar, Sierra de la Cara Cura, Neuquén Basin, by Fernández Carmona and Riccardi (1998). The taxa recorded came from a level with ammonites indicating the lower boundary of the *W. internispinosum* Zone and include *Chitinoidella boneti* Doben, *C.* cf. *pinarensis* (Furrazola-Bermúdez et Kreisel), and *Chitinoidella* spp.

According to Adatte *et al.* (1996; *cf.* also Benzaggagh, Atrops, 1995, 1997) the *Chitinoidella* Zone, including the Subzone of *C. dobeni*, below and the Subzone of *C. boneti*, above, ranges from the upper part of the *Fallauxi* to the lower part of the *Microcanthum* zones, whereas *Crassicollaria* Remane ranges from the upper part of the *Microcanthum* Zone to approximately the boundary between the *Durangites* and *Jacobi* zones. Thus, the *Chitinoidella boneti* Subzone is at the base of the *Microcanthum* Zone and the chitinoidellids of the upper part of *Fallauxi* to *Ponti* zones are restricted to the presence of *Ch. dobeni*. Recent studies (*cf.* Benzaggagh *et al.*, 2010, 2012; Pszczółkowski, Myczyński, 2010; Lakova, Petrova, 2013) have corroborated that the FAD of *Chitinoidella boneti* coincides with the base of the *Simplisphinctes* ammonite Subzone of the *Microcanthum* Zone.

Thus, direct evidence provided by the *Chitinoidella boneti* Subzone of the Standard *Chtinoidella* Zone for correlation "from Morocco to Turkey along the northern Mediterranean arch of the Tethys and also traceable to Cuba and Mexico and with corresponding ammonites to […] the Antarctic Peninsula, India and Japan" (Zeiss, 2001; Zeiss, Leanza, 2008, p. 240) is extended to the Andes of South America.

This conclusion does not conflict with calcareous nannoconid evidence provided by Scasso and Concheyro (1999, p. 294, fig. 2, table 1) on the presence of *Polycostella beckmannii* Thierstein, in the *W. internispinosum* Zone, whose FO is well below its first recorded presence at the base of their ZAPB section. As mentioned above, Lescano and Kietzmann (2010), and Kietzmann *et al.* (2011b) recorded the FO of *P. beckmannii* Thierstein within the *P. zitteli* Zone exposed in the Tres Esquinas, and the Rahue and Loncoche creek sections of southern Mendoza, and the presence of *P. senaria* Thierstein, whose FO is in the *Fallauxi* Zone (*cf.* Casellato, 2010; Channell *et al.*, 2010), within the *W. internispinosum* Zone.

Finally it should be mentioned that radiolarians present in Subzone 4 Beta$_2$, have been used (see Pessagno *et al.*, 2009, p. 223, 232–233) to correlate levels of the La Desirade Igneous Complex (Lesser Antilles) with beds exposed at San Pedro del Gallo, Canyon San Matias, and Taman, Mexico, characterized by the presence of *Salinites grossicostatum* and/or *Suarites bituberculatum* and, as mentioned above, with the *W. internispinosum* Zone of west central Argentina. As will be discussed below the La Desirade Igneous Complex was dated at 143.734 ±0.060 Ma (*cf.* Pessagno *et al.*, 2009).

CORONGOCERAS ALTERNANS ZONE (≈ *MICROCANTHUM* TO "*DURANGITES*" ZONES) (Fig. 1)

The *Corongoceras alternans* Zone, introduced by Gerth (1925) is characterized by supposed representatives of *Micracanthoceras* Spath, *Corongoceras* Spath, *Berriasella* Uhlig and *Chigaroceras* Howarth (*cf.* Leanza, 1980, 1981, 1996a; Riccardi, 2008a, b; Riccardi *et al.*, 2011).

It should be mentioned that the index species, *i.e.* "*Berriasella alternans* Gerth" (1925, p. 89, pl. 6: 3, 3a), included in *Corongoceras* Spath by A.F. Leanza (1945, p. 47), has been designated as the type species of *Steueria* Parent *et al.* (2011b, p. 65–67). Although discussion of this issue is beyond the scope of this paper it should be noted that the large variation in evolution and ornament of the type species of *Steueria* has been mostly based in an extended list of synonymzed Andean species and poorly preserved material (Parent *et al.*, 2011b, 2013a), whilst variation in *Corongoceras* morphology has been based in *C. mendozanum* (Behrendsen, 1891–1892) and no new evidence is provided on *C. lotenoense* (Haupt, 1908), the type species of *Corongoceras*. Inclusion of *C. alternans* in *Corongoceras* has been discussed and upheld by Salazar Soto (2012, p. 100–101).

Leaving aside the proposed transference of *Hoplites vetustus* Steuer (1897, p. 85, pl. 16: 4–10) from *Micracanthoceras* to *Blanfordiceras* Cossmann (*cf.* Parent *et al.*, 2011b, 2013a; but rejected by Salazar Soto, 2012), other species of *Micracanthoceras* from the *C. alternans* Zone of west central Argentina were described and figured by A.F. Leanza (1945; see also Jeletzky, 1984, p. 203).

In the Mediterranean *Corongoceras* and *Micracanthoceras* range through the *Simplisphinctes* and *Microcanthum* (*Durangites*) zones, a range that is not affected by the possible restriction of *Corongoceras* to the Andean, Mexican and Caribbean region and the transference to *Micracanthoceras* of most of the European material previously included in *Corongoceras* (*cf.* Bulot *et al.*, 2014), whereas *Berriasella* is present from the *Microcanthum–Jacobi* up to the *Boissieri* zones (*cf.* Tavera Benítez, 1985; Geyssant, 1997). *Corongoceras* has also been recorded in the Upper Tithonian of the Himalayas, Madagascar and Antarctica (*cf.* Collignon, 1960; Thomson, 1979; Matsumoto, Sakai, 1983; Enay, 2009).

Chigaroceras is a genus originally recorded from Iraq, in association with *Proniceras* cf. *jimulcense* Imlay, from a level ascribed to the "Zone of *Durangites*" (Howarth, 1992), that falls in the *Crassicollaria* Zone (equivalent to the upper part of the *Microcanthum* Zone and lowermost part of the *Andreaei* Zone) and has FAD of *N. steinmannii minor* (within the "*Jacobi* Zone") 5 m above (W.A.P. Wimbledon, pers. comm.). Thus far, presence of *Chigaroceras* in the Andean region has been mostly based (*cf.* Leanza, 1996a) on one specimen described and figured as "*Berriasella*" *gerthi*

Krantz (1928, p. 22, pl. 1: 8a, b), coming from levels with *Parodontoceras calistoides*, *i.e.* the *Substeueroceras koeneni* Zone of Bardas Blancas, Mendoza province (*cf.* Krantz, 1928, p. 47), and another specimen figured by A.F. Leanza (1945, pl. 11: 3, 4) from the *Corongoceras alternans* Zone of Mallín Redondo, Mendoza province. These specimens appear to differ from the type material from Iraq (*cf.* Howarth, 1992) in being less involute and by lacking umbilical and lateral tubercles. Other Andean specimens assigned to this species are poorly preserved (Salazar Soto, 2012, figs. 4.67.a–f) or more evolute throughout (Parent *et al.*, 2011b, fig. 26A; 2013a, fig. 21A).

Material assigned to *Chigaroceras* has also been figured (Kalacheva, Sey, in Kolpenskaya *et al.*, 2000, pl. 8: 3, 4) from beds in the North Caucasus correlated with the lower *Boissieri* Zone, although the figured specimens appear to be too evolute when compared with the material from Iraq.

The *Corongoceras alternans* Zone has been recorded (Enay *et al.*, 1996) in the Chicama Basin of northern Peru, where Andean species of *Corongoceras*, *Micracanthoceras* and *Chigaroceras* are associated with *Moravisphinctes* sp. and *Zittelia* sp., two genera known from the *Microcanthum* Zone of the Betic Ranges, Spain (*cf.* Tavera Benítez, 1985), but the material has not been figured.

The *C. alternans* Zone has been correlated with the *Microcanthum* and *Durangites* zones (*cf.* Zeiss, 1977; Tavera Benítez, 1985; Riccardi *et al.*, 2011), although in west central Argentina its equivalence could be mostly restricted to levels in the "*Durangites* Zone" (*cf.* Leanza, 1996a).

SUBSTEUEROCERAS KOENENI (≈ UPPERMOST "*DURANGITES*" TO *OCCITANICA*), *ARGENTINICERAS NODULIFERUM* (≈ UPPERMOST *OCCITANICA* TO LOWER *BOISSIERI*), AND *SPITICERAS DAMESI* (≈ UPPER *BOISSIERI* ? TO *PERTRANSIENS*) ZONES (Fig. 1)

The *Substeueroceras koeneni* Zone was introduced by Gerth (1921, 1925) and referred to the "Infravalanginian" (= Berriasian). This was accepted by Weaver (1931), although Burckhardt (1910, 1912, 1930) referred it to Kilian's "Berriasién inferieur" (= *Grandis* Zone; *cf.* Hoedemaeker, 1982, p. 20), *i.e.* below Kilian's "Infravalanginian" or Berriasian, which was restricted to the *Boissieri* Zone. In the *Substeueroceras koeneni* Zone have been included, besides *Substeueroceras* and *Parodontoceras* (which have been considered synonyms by Verma, Westermannn, 1973, and Salazar Soto, 2012), several species referred to the genera *Himalayites* Diener, *Aulacosphinctes* Uhlig, *Berriasella* Uhlig, and *Spiticeras* Uhlig, although inclusion of Andean species in *Berriasella* has been questioned (*cf.* Hoedemaeker,

1987; Arkadiev, Bogdanova, 2012), and a modern revision is needed.

The fauna overlying the beds with *Substeueroceras koeneni* (Steuer) is characterized by the presence of ammonites mostly referred (Steuer, 1897; Gerth, 1925; Krantz, 1928; Burckhardt, 1930; Weaver, 1931) to different species of *Spiticeras* and *Thurmanniceras* Cossmann, which were included in several zones ascribed to the "Infravalanginian" (= Berriasian) and lower part of the Valanginian. Later A.F. Leanza (1945) differentiated these assemblages as a "Zone of *Argentiniceras noduliferum*" between a *S. koeneni* Zone, below, and a "Zone of *Spiticeras damesi* (Steuer) and *Cyaniceras transgrediens* (Steuer)", above. But he did not discuss evidence supporting the distinction of the intermediate zone. Excepting the fact that, in describing the two sections on which his study was based, he mentioned at one site (Arroyo del Yeso, Mendoza province) one level with *Argentiniceras* Spath intercalated between levels with ammonites that he included in the *Substeueroceras koeneni* and *Spiticeras damesi* zones. Here it should be noted that species of *Argentiniceras*, *Spiticeras* and tuberculated neocomitids were recorded together by Steuer (1897) and Gerth (1925), and that although the *Spiticeras damesi* Zone was referred by Gerth (1925) to the Valanginian, Burckhardt (1912, 1930) assigned the whole assemblage, *i.e.* including the species now included in *Argentiniceras*, to the *Boissieri* Zone. The assemblage with *Argentiniceras* also includes (Steuer, 1897) ?*Protacanthodiscus quadripartitus* (Steuer, 1897), a species that also appears to be present (*cf.* A.F. Leanza, 1945) in the *Substeueroceras koeneni* Zone.

The *Substeueroceras koeneni* (or *Parodontoceras callistoides*) Zone was considered to be Tithonian by A.F. Leanza (1946, 1947, p. 837) because it included *Aspidoceras* Zittel and *Micracanthoceras* Spath in the same levels. He also mentioned that this zone contains some representatives of *Spiticeras* (*i.e. S. acutum* Gerth and *S. hauthali* Gerth) that "constitute a special group" (in fact possible representatives of *Proniceras* Burckhardt) and included all other species of the genus in the *Spiticeras damesi* Zone. This last zone was correlated with the *Boissieri* Zone of Europe, "the horizons which contain *Substeueroceras* in the Argentine and Mexico [...] can be correlated, because of their stratigraphic position, with a level between the *transitorius* zone and that of the *boissieri*" (A.F. Leanza, 1947, p. 840). Later, the *S. koeneni* Zone was referred to the uppermost Tithonian (*cf.* Leanza, Hugo, 1978; Riccardi, 1984; Riccardi *et al.*, 1990), or considered equivalent to the *Jacobi* Zone by Wiedmann (1968, 1980a, b; see also Enay, 1964; Zeiss, 1977; Leanza, 1981), or to the *Durangites* to lower *Occitanica* zones, probably up to the *Privasensis* Subzone (Leanza, 1996a, b; Riccardi *et al.*, 2000, 2011; Riccardi, 2008a, b; Zeiss, Leanza, 2010.

According to Wiedmann (1980a, b), the *Substeueroceras koeneni* Zone would be equivalent to the *Jacobi* Zone, whereas the *Argentiniceras noduliferum* and the *Spiticeras damesi* zones would be equivalent to the *Occitanica* Zone and the *Boissieri* Zone.

In fact, the *Substeueroceras koeneni* Zone includes taxa which could be referred to both the "*Durangites*" and *Jacobi* (to *Occitanica*) zones. "*Reineckeia*" *striolata* Steuer (1897) has been included (*cf.* Krantz, 1926, 1928; Tavera Benítez, 1985) in *Paraulacosphinctes* Schindewolf, a genus recorded (*cf.* Tavera Benítez, 1985) from the *Transitorius* and *Durangites* zones of the Betic Ranges. This species could also be included in *Substeueroceras*, as done by Salazar Soto (2012), but transference to *Choicensisphinctes* Leanza (*cf.* Parent *et al.*, 2011b, 2013a) is questionable. *Himalayites* is known from the same zones up to lowermost *Occitanica* Zone, *Berriasella* ranges from the "*Durangites*" to the *Boissieri* zones, although it is frequent in the *Jacobi–Occitanica* zones, and *Malbosiceras* Grigorieva from the *Jacobi* to the *Occitanica* Zone (*cf.* Le Hegarat, 1973; Tavera Benítez, 1985).

Meanwhile, in Mexico Verma and Westermann (1973) recorded *S. koeneni* associated with representatives of *Kossmatia* and *Berriasella* in their *Substeueroceras–Berriasella* Zone, which they correlated with the *Chaperi/Transitorius* zones of Europe. This assemblage is equivalent to the "*Substeueroceras–Proniceras Zone*" recognized by Imlay (1980) in the uppermost Tithonian of North America. In Mexico this assemblage, besides *Substeueroceras*, *Parodontoceras*, includes representatives of *Durangites* Burckhardt, *Protacanthodiscus* Spath and *Protancyloceras* Spath, although *Proniceras* Burckhardt appears to be missing in Sierra de Catorce, San Luis Potosí (*cf.* Burckhardt, 1930; Imlay, 1939, 1980; Cantu Chapa, 1968, 1980, 1984, 1989; Verma, Westermann, 1973). This fauna is overlain by Berriasian representatives of *Subthurmannia*, *Spiticeras* and *Berriasella*. Here it should be noted that a correct assessment of the Tithonian–Berriasian macro- and microfossil distribution in Mexico could be hindered due to frequent facies changes and gaps (*cf.* Olóriz, Tavera, 1989), in some cases probably related to tectono-sedimentary conditions and sea-level changes of global significance (*cf.* Eguiluz de Antuñano *et al.*, 2012).

Although the stratigraphic occurrence (Burckhardt, 1930) of *Proniceras* below *Kossmatia* in San Pedro del Gallo and Sierra Zuloaga was disregarded (on different grounds) by Imlay (1939, p. 23), *Substeueroceras* has been recorded in levels above *Proniceras* at Sierra Ramirez (*cf.* Burckhardt, 1930, p. 57, fig. 18c), Sierra de Jimulco, Coahuila, and Cañadon del Toboso, Zacatecas (Imlay, 1939, p. 9). This occurrence is in agreement with data from Mazatepec provided by Cantu Chapa (1968) and Pessagno *et al.* (2009), where *Substeueroceras* occurs with and above *Proniceras* and *Protacanthodiscus*, although occurrence of *Proniceras* –

stratigraphically below and above *Parodontoceras* and *Substeueroceras* – has been mentioned by Cantu Chapa (1980, 1982, 1989) in the subsurface of northeastern Mexico. In California, *Proniceras* was recorded (Imlay, Jones, 1970) in association with *Protacanthodiscus* and *Neocosmoceras* Blanchet.

Here it must be remarked that in Europe *Proniceras* ranges through the "*Durangites* Zone", has its acme in the *Jacobi* Subzone and reaches the *Grandis* Subzone (*cf.* Le Hegarat, 1973; Cecca, 1985; Hoedemaker, 1987; Olóriz, Tavera, 1989), *Protacanthodiscus* reaches the *Jacobi* Subzone (*cf.* Tavera Benítez, 1985; Olóriz, Tavera, 1989; Wimbledon *et al.*, 2013) and *Protancyloceras* is a genus that ranges throughout the Berriasian and reaches the Lower Valanginian *Pertransiens* Zone (*cf.* Vašíček, Hoedemaeker, 2003).

Zeiss (1984, p. 252; see also 1983, 1986) referred the *Substeueroceras* from Mexico and Argentina to the *Euxinus* and *Occitanica* zones, due to the fact that in Mexico Cantu Chapa (1968) had recorded calpionellids (assigned to the Berriasian) in levels with *Substeueroceras*. He also correlated the *Argentiniceras noduliferum* and *Spiticeras damesi* zones with the ?lower (*Paramimounum* Subzone) and middle (*Picteti* Subzone) part of the Upper Berriasian *Boissieri* Zone (see also Tavera Benítez, 1985; Hoedemaeker, 1990; Howarth, 1992) on the basis of the presence of a calpionellid assemblage (≈ Zone D) recorded by Cantu Chapa (1968). This was in a presumed equivalent level in Mexico (*Subthurmannia mazatepense* Zone), although calpionellid biostratigraphy there has been the subject of disagreement (see below). Correlation of the uppermost *Spiticeras damesi* Zone with the *Boissieri* Zone (*Picteti* Subzone) was indicated by Leanza and Wiedmann (1989; *cf.* Leanza, 1996b).

Equivalence of the *Substeueroceras koeneni* Zone with the *Euxinus* (and *Occitanica*) Zones was accepted by Tavera Benítez (1985), Callomon (1992) and Olóriz *et al.* (1999). Olóriz *et al.* (1999) and Adatte *et al.* (1994, 1996) discussed the relationship between calpionellids and ammonites across the Jurassic-Cretaceous boundary in different localities of Mexico (Sierra Catorce, Sierra Jabalí). They agreed that levels with *Substeueroceras*, even if present in the Tithonian calpionellid Zone A, range into zones B and C and therefore could be correlated with the *Jacobi* and *Occitanica* (*Subalpina* Subzone) zones. At San Pedro de Gallo, calpionellids taken to represent Zone C were found associated with *Substeueroceras*, *Spiticeras* and *Jabronella* Nikolov, and these were thus correlated with the upper part of the *Occitanica* Zone (*Privasensis* and *Dalmasi* subzones) (Adatte *et al.*, 1994, 1996) (but see discussion below on discrepancies with radiolarian biostratigraphy, as summarized by Pessagno *et al.*, 2009). Moreover, in Puerto Piñones, above calpionellids of Zone B with *Substeueroceras*, and Zone C with *Berria-*

sella and *Kossmatia* (correlated with the *Jacobi* and *Occitanica* zones), the same authors recorded calpionellids of *Calpionellopsis simplex* – D1 Zone, associated with *Spiticeras* and *Neocosmoceras*, which were thus correlated to the *Paramimounum* Subzone of the *Boissieri* Zone (see Fig. 1).

A rather similar situation occurs in Cuba, where despite the fact that taxa also have long ranges and that precise establishment of the ammonite succession is made difficult by incomplete exposures, presence of faults, and the condensed nature of the sequence (*cf.* Myczyński, 1989; Pszczółkowski, Myczyński, 2010), *Parodontoceras* has been recorded from levels with *Salinites* and with *Vinalesites* Thieuloy and *Protancyloceras* (*cf.* Imlay, 1942; Myczyński, 1989; Pszczółkowski, Myczyński, 2010), and where calpionellids (*cf.* López Martínez *et al.*, 2013b) and calcareous nannofossils (*cf.* Pszczółkowski *et al.*, 2005) indicate that this ammonite fauna could range into the Berriasian, up to the *Subalpina* Subzone (*Occitanica* Zone) (see below).

These conclusions appear to be consistent with information from other regions. Thus, Howarth (1998; *cf.* also Howarth, Morris, 1998) has also recorded a fauna including representatives of *Substeueroceras*, *Argentiniceras*, *Malbosiceras*, *Neocosmoceras* and *Spiticeras* from Yemen and referred the source levels to the *Durangites–Occitanica* zones, and Krishna (1991) reported the presence of *Argentiniceras* from the lower part of the "Upper Tithonian to Valanginian" Umia Member of Kachchh, India, and referred it to the Berriasian. *Substeueroceras* was also reported from the uppermost part of the *Durangites* Zone of the Betic Ranges, Spain (Tavera Benítez, 1985) and from the Berriasian of the Russian Far East (Sey, Kalacheva, 1999b, 2001). Presence of *Substeueroceras* in the (lower) *Durangites*–(upper) *Microcanthum* zones at Chia Gara (Howarth, 1992) has, however, been discounted by Leanza (1996a), who referred that material to *Kossmatia*, and most of the other records are based on poorly preserved material. The specimens from Yemen figured by Howarth (1998) are distorted (pl. 19: 5) or appear to be too evolute (pl. 20: 3, 6), and only one (pl. 20: 5) could be included in *Substeueroceras*. The specimens figured from Spain (Tavera Benítez, 1985, pl. 33: 1–2; Olóriz, Tavera, 1989, fig. 2.1), from levels ascribed to the *Durangites* Zone or lower part of the *Jacobi* Zone, are also too evolute throughout and with coarser and less flexuous ribbing. Presence of *Substeueroceras* in the *Jacobi* and *Grandis* zones of the Mediterranean area, on the basis of *Pseudoargentiniceras beneckei* (Roman, Mazenot), see Mazenot (1939, pl. 32: 11–14), Le Hegarat (1973, p. 51: 2), Hoedemaeker (1982, pl. 1: 3), and *P. flandrini* Le Hegarat (1973, pl. 26: 7–10; pl. 51: 3; pl. 52: 2), was proposed by Hoedemaeker (1979, 1982), but both species appear to differ in ribbing and evolution of the outer whorls, and inclusion in *Substeuer-*

oceras was rejected by Jeletzky (1984, p. 179–180). Material from the Lower Berriasian of the Russian Far East referred to *Substeueroceras* by Sey and Kalacheva (1999b, 2001) appears by its ribbing to be closer to *Parodontoceras*.

As indicated above for the basal Tithonian, modern systematic studies on the Upper Tithonian–Berriasian and lowermost Valanginian ammonites of central western Argentina, based on collections coming from carefully sampled sections distributed along the entire exposed marine successions, are wanting. Therefore the existing changes in the lateral and vertical distribution of the ammonites that justify the biozones have not been studied in detail. Some biostratigraphic information (Gerth, 1925; Weaver, 1931; A.F. Leanza, 1945; Leanza, Hugo, 1978; Kietzmann *et al.*, 2011b) and identifications made by the present author in more than 20 sections between Rio Diamante (Mendoza province) and Picún Leufú (Neuquén province), indicate that the *Substeueroceras koeneni* Zone varies in thickness between 13 m and 425 m. Moreover, identifications have been used to build a sequence-stratigraphic framework (*cf.* Gulisano *et al.*, 1984; Legarreta, Uliana, 1991, 1996) consisting of a series of depositional units bounded by stratigraphic discontinuities. This situation has a direct effect in changes in faunal diversity as shown for the whole Jurassic of the Andean region (Riccardi, 1991, 2008a, b), and it determines the correlation potential of the recorded faunas as this is best achieved on those intervals deposited when sea-level was high (*cf.* Hoedemaeker, 1987).Within this scheme, the *Substeueroceras koeneni* Zone is within a highstand sequence and its boundary with the *Argentiniceras noduliferum* Zone corresponds to a lowstand period, when there was reduction of the basinal area through progradational sedimentation, resulting in a widespread discontinuity. Therefore, ammonites typical of the base of the *A. noduliferum* Zone are not always present, and the *S. koeneni* Zone is overlain by the upper part of that zone and the *Spiticeras damesi* Zone, which correspond to a new highstand sequence.

As mentioned above, correlation of the Andean ammonite faunas with the European Standard zonation is hindered by the lack of modern studies on most of the Andean Tithonian-Berriasian ammonite faunas. Nevertheless, Salazar Soto (2012) on the basis of material, mostly from the Lo Valdes Formation, Chile, has recognized the presence of some diagnostic Tethyan species of *Berriasella* and *Groebericeras* Leanza and has used them to divide the *S. koeneni* Zone in two subzones, which were correlated with the Lower and Upper Berriasian, although most of the identified species range through both subzones and some even reach the overlying Lower Valanginian "*Thurmaniceras thurmanni/ Argentiniceras fasciculatum* Zone". This study has highlighted, once again, the need to undertake a modern study of

the uppermost Tithonian to Lower Valanginian Neocomitids from west central Argentina.

Studies on other South American faunas included in the *Substeueroceras koeneni* Zone have not contributed to the improvement of the systematic and biostratigraphic knowledge of this fauna. Representatives of the *S. koeneni* Zone were recognized in northern (Steinmann, 1881; Welter, 1913; Geyer, 1983; Enay *et al.*, 1996) and central Peru (Rivera, 1951; but see Wiedmann, 1980a) and Colombia (*cf.* Bürgl, 1957; Geyer, 1973; Haas, 1960), but, in general preservation and stratigraphic information, they are rather poor. In most cases, the biostratigraphic scheme of west central Argentina has been followed, although in some cases ammonites of the *S. koeneni* Zone have been correlated with the *Jacobi* Zone (*cf.* Geyer, 1983), and in others (*cf.* Enay *et al.*, 1996) they were mentioned above ammonites indicative of the *Corongoceras alternans* Zone, which was correlated with the *Microcanthum* Zone.

The ammonite fauna included in the *S. koeneni* Zone appears to be transitional to that represented in the underlying *Corongoceras alternans* Zone, whereas upwards there exists a more defined change with regard to the overlying *Argentiniceras noduliferum* and *Spiticeras damesi* zones. In those, besides endemic *Frenguelliceras* and *Cuyaniceras*, there are usually representatives of *Neocosmoceras*, *Malbosiceras*, *Spiticeras*, *Groebericeras*, *Subthurmannia* Spath and "*Thurmanniceras*". This situation appears to be similar to that exposed through the *Durangites*, *Jacobi* and *Occitanica–Boissieri* zones (*cf.* Le Hegarat, 1973; Wiedmann, 1975; Hoedemaeker, 1979, 1982, 1987; Kvantaliani, 1999; Aguado *et al.*, 2000; Kolpenskaya *et al.*, 2000; Arkadiev, Bogdanova, 2012).

Groebericeras is a genus that, as first defined from the Mallin Redondo section of southern Mendoza province, occurs in the *Argentiniceras noduliferum* Zone (*cf.* A.F. Leanza, 1945). In the Mediterranean region, it is represented by *G. rocardi* (Pomel), a species considered (Howarth, 1992) to be a synonym of the Andean *G. bifrons* Leanza, which also occurs in the *Paramimounum*, *Picteti* and base of the *Alpillensis* subzones of south-east Spain (Hoedemaeker, 1982; Aguado *et al.*, 2000), and the *Paramimounum* (Sub)zone of Iraq (Howarth, 1992). The genus was doubtfully recorded from California in association with *Buchia piochii* (Imlay, Jones, 1970; an identification rejected by Jeletzky, 1984, p. 191; but see Zakharov, 2015) and appears to be present in Canada and Mexico, where it has been recorded (Cantu Chapa, 1968) in association with *Subthurmannia mazatepense* Cantu Chapa and *Spiticeras* sp., probably from levels with calpionellids of the *Elliptica* Subzone (≈ *Occitanica* Zone, *Subalpina* Subzone) in Mazatepec, Puebla (*cf.* López *et al.*, 2013a; see Fig. 1 and below), and with other species

of *Spiticeras* in the *Buchia uncitoides* Zone (see below) from Vancouver island (Jeletzky, 1965, 1984).

Neocosmoceras, on the other hand, ranges from the *Subalpina* Subzone of the *Occitanica* Zone to the *Paramimounum-Picteti* subzones of the *Boissieri* Zone. Therefore, it appears that the *Argentiniceras noduliferum* Zone should be correlated with the ?upper part of the *Occitanica* and lower part of the *Boissieri* Zone. Here it should be noted that *Argentiniceras* cf. *noduliferum* and *Fauriella* n. sp. aff. *gallica* beds, exposed in the Taseko Lakes, Canada (see below under Nannofossils), were correlated with the lower part of the *Occitanica* Zone by Jeletzky (1984, p. 210).

The presence of a number of species usually referred to *Thurmanniceras* suggests (*cf.* Leanza, 1996b) that the *Spiticeras damesi* Zone should be correlated with the (upper part of) *Paramimounum* and *Picteti*, *Alpillensis* and *Otopeta* subzones, *Boissieri* (and perhaps *Pertransiens*) zones (*cf.* Company, 1987; Hoedemaeker, 1987; Kvantaliani, 1999; Wippich, 2003; Arkadiev, Bogdanova, 2012), although Andean species included in *Thurmanniceras* have been considered to belong in a different endemic lineage (Company, 1987), and are in need of a modern revision (*cf.* Company, 1987; Rawson, 2007; Reboulet *et al.*, 2014). Moreover, the possible presence of representatives of the *Thurmanniceras pertransiens* Zone (*cf.* A.F. Leanza, 1945, p. 62–63; but see Company, 1987, p. 120) could extend the range of the *S. damesi* Zone into the Valanginian, unless they are included in the overlying "*Neocomites wichmanni* Zone" (*cf.* Hoedemaeker, 1987, p. 42).

All these considerations suggest (see Fig. 1) that the *Substeueroceras koeneni* Zone could range into the *Occitanica* Zone and that the *Argentiniceras noduliferum* plus *Spiticeras damesi* (totally or in part) zones could be equivalent to the (? upper part of the *Occitanica* and) *Boissieri* Zone(s) and could reach as high as the *Pertransiens* Zone. The division of the *Substeueroceras koeneni* Zone and a precise correlation between the Andean ammonite zones and the Mediterranean Standard require new systematic and biostratigraphic studies.

In this context it becomes important, as indicated above and discussed below, to evaluate biostratigraphic evidence provided by microfossils, *i.e.* calpionellids, nannoconids, and radiolarians, especially when associated to ammonites.

MICROFOSSIL EVIDENCE

CALPIONELLIDS

Calpionellids are widespread in Tethys and are also present in west central Argentina (Fernández Carmona, Riccardi, 1998, 1999; Kietzmann *et al.*, 2011a). When studied in

the last area they will probably contribute to improve the correlation of the Andean and Tehyan regions (*cf.* Michalík, Reháková, 2011; Wimbledon *et al.*, 2011).

Since calpionellid biostratigraphy was used to extend upwards the range of the *Substeueroceras koeneni* fauna in Mexico, the subject has been the focus of controversy (*cf.* Cantu Chapa, 1989; 1996; Stinnesbeck *et al.*, 1993; Olóriz, Tavera, 1989; Pessagno *et al.*, 2009). Disagreement was founded on the presence/absence of specific calpionellids, ammonites and radiolarians (see below) in the same levels and the supposed ages indicated by these.

Here it must be remarked that Tithonian–Lower Berriasian calpionellid stratigraphy is based on relative abundance and morphological changes (*cf.* Barthel *et al.*, 1966). Thus *Calpionella alpina* ranges through the whole *Crassicollaria* Zone and the boundary between the *Crassicollaria* and the *Calpionella* zones is mostly placed at a level where small orbicular *C. alpina* becomes dominant, where *Crassicollaria parvula* persists together with *Tintinopsella carpathica*, but all other *Crassicollaria* dwindle or disappear. Calpionellid biostratigraphy also extends to the *Occitanica*, *Boissieri* zones (*cf.* Tavera *et al.*, 1994; Olóriz *et al.*, 1995; Reháková, Michalik, 1997; Enay *et al.*, 1998; Benzaggagh *et al.*, 2010, 2012; Krische *et al.*, 2013; Abdesselam-Mahdaoui *et al.*, 2011; Lakova, Petrova, 2013; López-Martínez *et al.*, 2013a, b; Platonov *et al.*, 2014). Thus, the bloom of small globular *Calpionella alpina* and the decline of species of *Crassicollaria*, at the beginning of the *Alpina* Subzone of the *Calpionella* Zone has become a preferred alternative in identifying the base of the *Grandis* Zone (Wimbledon *et al.*, 2011).

West Central Argentina

The study of Fernández Carmona and Riccardi (1998), mentioned above, ratified the conclusions of Zeiss and Leanza (2008) on the equivalence (see Fig. 1) of the *Windhauseniceras internispinosum* Zone with the *Paralytohoplites caribbeanus* Zone of Cuba, which in its upper part is also characterized by the presence of *Chitinoidella boneti* (*cf.* Pszczółkowski, Myczyński, 2010; López-Martínez *et al.*, 2013b).

Presence at Chacay Melehue of *Calpionella alpina* (small form) together with large forms of *Tintinopsella carpathica* (Murgeanu et Filipescu), abundant *Nannoconus* spp., calcareous dinoflagellate cysts (*Cadosina fusca* Wanner, *Colomisphaera* Nowak) (*cf.* Fernández Carmona, Riccardi, 1999) in the middle intervals with ammonites of the *Substeueroceras koeneni–Argentiniceras noduliferum* zones confirms for Argentina the extension of the *Substeueroceras koeneni* Zone into the Berriasian.

Mexico

It has already been mentioned that in Sierra Jabali and Puerto Piñones, Mexico, calpionellids of zones A and B were recorded from levels with *Substeueroceras*, and these have been correlated to the *Jacobi* and lower part of the *Occitanica* (*Subalpina* Subzone) zones (see Fig. 1). Moreover, in a large number of oil-wells (over a distance of 1300 km on the eastern Gulf Plain of Mexico) (Cantu Chapa, 1989, figs 1, 2) the calpionellids *Calpionella alpina*, *C. elliptica* (Cadisch) (*Jacobi–Occitanica* zones) and the nannoconids *Nannoconus globulus* Brönnimann, *N. colomi* (de Lapparent), *N. bermudezi* Brönnimann, *N. steinmannii* and *N. kamptneri* Brönnimann (the first with its FAD in the latest Tithonian and the others in the Berriasian–Valanginian; *cf.* Bralower *et al.*, 1989; Casellato, 2010) occur in and above levels with ammonites of the genera *Kossmatia*, *Durangites*, *Substeueroceras* and *Parodontoceras*.

Ammonites such as *Substeueroceras*, *Parodontoceras* and *Protacanthodiscus* have been recorded (Cantu Chapa, 1968; *cf.* Pessagno *et al.*, 2009, text-fig. 36a; see also Stinnesbeck *et al.*, 1993) in the upper 48 m of the Pimienta Formation in the Mazatepec region, and *Calpionella alpina* Subzone (*Calpionella* Zone) calpionellids, with the acme of small forms in another locality in the same region, near the top of the formation (*cf.* López Martínez *et al.*, 2013a, fig. 7). According to Pessagno *et al.* (2009, p. 218), ammonites recorded in the upper part of the Pimienta Formation are correlative with the upper part of the *Substeueroceras–Proniceras* Assemblage and the uppermost Tithonian radiolarian Subzone 4 alfa$_2$ (although identifiable radiolarians apparently were not recovered from this section and interval, *cf.* Pessagno *et al.*, 2009, p. 215, 218). From the same locality and levels in the Pimienta Formation, Pessagno *et al.* (2009) mentioned the calpionellids *Calpionella alpina*, *Tintinopsella* spp. as well as *Nannoconus steinmannii* Kamptner, which are also present in the overlying Lower Tamaulipas Formation (= Chapulhuacán Limestone) (Pessagno *et al.*, 2009, p. 218; see also Stinnesbeck *et al.*, 1993), where in *c.* 15 m calpionellids of the *Alpina*, *Ferasini* and *Elliptica* subzones were recorded (*cf.* López-Martínez *et al.*, 2013a), and where ammonites of the *Subthurmannia mazatepense* Zone appear to occur *c.* 9 m above the contact with the Pimienta Formation (*cf.* Cantu Chapa, 1968, fig. 2), *i.e.* within levels (?) assigned to the calpionellid *Elliptica* Subzone (*cf.* López Martínez *et al.*, 2013a, fig. 7) (see Fig. 1). This is consistent with the fact that FAD of *N. steinmannii minor* and of *N. steinmannii steinmannii* are, respectively in the *Jacobi* and *Occitanica* zones (*cf.* Casellato, 2010; Wimbledon *et al.*, 2013).

Cuba

A somewhat similar situation apparently occurs in western Cuba (López-Martínez *et al.*, 2013b) where calpionellids of the *Crassicollaria* Zone, and the *Alpina*, *Ferasini* and *Elliptica* subzones (*Microcanthum* Zone to *Subalpina* Subzone, *Occitanica* Zone) of the *Calpionella* Zone, and, above, the lower part of the *Calpionellopsis* Zone (≈ *Paramimounum* Zone) were recovered from the El Americano Member, Guasasa Formation, of the Rancho San Vicente section. There the El Americano Member is 27.5 m thick and, the *Alpina* Subzone starts at Bed RSV-23, and the *Elliptica* Subzone at Bed RSV-52, about 6–8 and 18–20 m, respectively, above the contact between the El Americano and San Vicente Members (López-Martínez *et al.*, 2013b, p. 206, fig. 9). The El Americano Member exposed at the nearby Valle de Ancon section (*cf.* Myczyński, 1989; Pszczółkowski, Myczyński, 2010) is *c.* 24 m thick, the lower *c.* 9 m with a *Pseudolissoceras–Virgatosphinctes* assemblage, whereas in the upper *c.* 15 m, there are *c.* 12.5 m with ammonites of the "*Durangites–Salinites–Proniceras*" Zone. This overlain by *c.* 3 m with representatives of *Vinalesites* and *Protancyloceras*, which range into the Tumbadero Member of the Guasasa Formation. If both sections are stratigraphically similar – although the Valle de Ancon section appears to be more condensed – the lower ammonite assemblage would be equivalent to the calpionellid *C. boneti* and *Crassicollaria* zones/subzones, the "*Durangites–Salinites–Proniceras*" Zone to the *Alpina* (to *Ferasini*) subzones, whereas the *Vinalesites-Protancyloceras* levels would be equivalent at least to the lower part of the *Elliptica* Subzone. This assumption is in part supported by the presence in the uppermost part of the El Americano Member, at Sierra del Infierno (see Pszczółkowski *et al.*, 2005, fig. 3, table 3; Pszczółkowski, Myczyński, 2010, fig. 4), of *Nannoconus kamptneri kamptneri* and *N. k. minor*, indicative of the nannoconid Zone NK-1 (uppermost *Grandis* Subzone, *Euxinus* Zone to *Privasensis* Subzone, *Occitanica* Zone), immediately below levels with *Protancyloceras* ex. gr. *hondense* (Imlay) and *Vinalesites* sp., which are within the *Calpionella alpina* Subzone.

NANNOFOSSILS

Nannofossil stratigraphy is an important tool for correlation of the Tithonian–Berriasian (*cf.* Bralower *et al.*, 1989). One problem, however, is that in active-margin sedimentary environments the calcareous nannofossil component is usually extremely impoverished as a result of the large clastic

input, and, further, deep burial and high thermal gradients also have lead to the early recrystallization of much carbonate (Bralower, 1990). Moreover, stratigraphic discontinuity of marker species ranges and large gaps between samples has been mentioned as a difficulty in pinning down events with any great certainty (Bralower, 1990), although nowadays there has been an important improvement with new data from the Mediterranean, Crimea, Tunisia and Iraq (W.A.P. Wimbledon, pers. comm.).

The study of Bralower *et al.* (1989) established a zonation (see Fig. 1) based in six European land sections with ammonite-bearing levels, and two Deep Sea Drilling Project Sites (3901C and 534A), where for each species there was established a "Reliability Index (RI)" of stratigraphic significance. Although ammonites were not necessarily linked directly to nannofossils and assumptions about correlation were founded on common magnetozones. This study was extended to some surface sections in Northern California (Bralower, 1990) which are important for the ammonite stratigraphy of Mexico and west central Argentina (see below). Subsequently Casellato (2010) has published an updated nannofossil biostratigraphy for the Upper Callovian–Berriasian of the Mediterranean region based on an extensive study of Southern Alps successions (see Fig. 1).

West Central Argentina

Thus far there are few published studies on the Upper Jurassic–Lower Cretaceous nannofossils of Argentina. Two of them have already been mentioned above in relation to the *Pseudolissoceras zitteli* and *Windhauseniceras internispinosum* zones, and a few others will be mentioned below, although some (*cf.* Ballent *et al.*, 2004, 2011) do not provide information detailed enough relative to their significance for correlation of ammonite biozones.

A study by Bown and Concheyro (2004) on the Lower Cretaceous calcareous nannofossils from the Neuquén Basin was focused on Lower Valanginian–Lower Hauterivian levels, and although it was mentioned that Tithonian levels of the Vaca Muerta Formation "yielded low-diversity assemblages dominated by watznauerid coccoliths that are not age diagnostic", confirming "previous observations from this interval" as reported by Scasso and Concheyro (1999), no new information was added for the Tithonian–Berriasian. Some data, however, provided by Bown and Concheyro (2004) indicate that the oldest nannoconids recorded, *i.e. Eiffelithus primus* (Perch-Nielsen) and *E. windii* Applegate et Bergen, from levels probably equivalent to the lower part of the *Neocomites wichmanni* Zone, in the Pampa Tril section, Vaca Muerta Formation, have a close proximity of their LO and FO, respectively. On this basis, it was remarked that both

bioevents correspond to the upper Lower Valanginian *Campylotoxus* Zone. This would support a possible extension of the underlying *Spiticeras damesi* Zone into the Lower Valanginian *Pertransiens* Zone. No relevant information in relation to Tithonian and Berriasian ammonite biozones was added in a subsequent nannoconid study (Lescano, Concheyro, 2014) on eleven Berriasian–Hauterivian sections of the Neuquén Basin. Only one of those sections, *i.e.* Lonco Vaca, includes Tithonian strata and the recorded nannoconids from this section, as well as those from the Berriasian of the Quebrada Maravilla section are indicative of the *Jacobi* Zone, but ammonites were not mentioned from the same levels.

An attempt (Vennari *et al.*, 2013) to correlate nannofossil and ammonite stratigraphy has focused in one stratigraphic section, Las Loicas, in southern Mendoza, but nannofossil evidence[s] is too patchy and data provided on ammonite systematics and biostratigraphy are not detailed enough. As nannoconiids there could provide additional constraints on the age of recorded ammonite zones, it is worth to analyzing that evidence in some detail.

According to Vennari *et al.* (2013), calcareous nannofossils present in the same levels characterized by ammonites of the *Substeueroceras koeneni* Zone belong to nannofossil zones NJK-A, NJK-B, NJK-C and lower part of NJK-D (see Fig. 1).

The lowest nannofossil record (samples 3850 and 3851, from the initial 2 m of the studied section at Las Loicas) is within the *S. koeneni* Zone, which was defined by the presence of *Substeueroceras ellipsostomum* (Steuer) and *S. striolatissimum* (Steuer), and this corresponds to Subzone NJK-A (*H. noeliae* Zone, with a range equivalent to the uppermost *Ponti–Microcanthum–Durangites* zones; *cf.* Bralower *et al.*, 1989; Cassellato, 2010), but no new elements besides those in the previous work by Kietzmann *et al.* (2011b) were added for its definition in this section.

Zone NJK-B (=*Umbria granulosa granulosa* Zone; considered equivalent to the middle part of the *Durangites* Zone; Bralower *et al.*, 1989; FAD of *Umbria granulosa glanulosa* is in M20n in Europe, *i.e.* lower *Crassicollaria*, equivalent to the upper part of ammonite *Microcanthum* Zone, Casellato, 2010; Wimbledon *et al.*, 2013) was based on the FO of *Umbria granulosa granulosa* from a level *c.* 15 m above the base of the section (sample 3853) where no ammonites were recorded, but the first occurrence of this species could be lower, as sampling in the lower levels are too sparse, especially considering the species' patchy record in the studied samples (*cf.* Vennari *et al.*, 2013, fig. 3 and table 1). Presence of *Rhagodiscus asper* (Stradner) *c.* 26 m above the base of the section (sample 3864), 1–2 m above a level with *Parodontoceras callistoides*, *"Spiticeras"* acutum and *Berriasella* sp., was proposed as a second marker

for the upper part of Zone NJK-B, but this species has its FAD in the middle of M19n, and is a proxy for the base of the *C. alpina* Subzone (*cf.* Wimbledon *et al.*, 2013), had its first recorded occurrence in the Las Loicas section (sample 3864) immediately above the middle part of the defined Zone NJK-B.

The Zone NJK-C (*N. laffittei* Subzone, supposed equivalent to the upper part of *Durangites* and lower part of *Jacobi* zones, Bralower *et al.*, 1989), was referred to the Late Tithonian and defined by the FO of *N. wintereri* in sample 3872, *c.* 33 m above the base of the section, although this species has its FAD in the middle part of 19n, within the *Jacobi* Subzone (*cf.* Bralower *et al.*, 1989; Casellato, 2010; Wimbledon *et al.*, 2013) and shows a very sparse record in the Las Loicas section (see Vennari *et al.*, 2013, table 1). So, it is open to question if its FAD is represented at the level of sample 3872.

The Zone NJK-D (supposed equivalent to upper part of *Jacobi* and lower part of *Grandis* subzone; Bralower *et al.*, 1989) was defined by the FO of *Nannoconus kamptneri minor* Bralower in sample 3874 (immediately above sample 3872, in a 2–3 m thick interval where *Substeueroceras* sp., *Blanfordiceras* sp. and *Berriasella* aff. *gerthi* Krantz were recorded), a species with its FAD within the *Jacobi* and *Calpionella alpina* subzones (Bralower *et al.*, 1989; Casellato, 2010; Wimbledon *et al.*, 2013), and with a very sparse record in the Las Loicas section (*cf.* Vennari *et al.*, 2013). In the definition of Zone NJK-D the presence of *Polycostella senaria* Thierstein and *N. wintereri* Bralower are also mentioned. The first species has its FAD in the *Fallauxi* Zone and the last in the *Jacobi* Zone (*cf.* Bralower *et al.*, 1989; Wimbledon *et al.*, 2013). The base of the *Argenticeras noduliferum* Zone was marked by the first occurrence of *A.* cf. *fasciculatum* (Steuer) – 3–4 m above the base of NJK-D, although *A. noduliferum* was recorded *c.* 13 m above that base. As the top of Zone NJK-D was not defined, part of the section assigned to Zone NJK-D (below levels with *A. noduliferum*) could, in fact, belong in Zone NK-1 (equivalent to *Grandis–Privasensis* subzones). All taxa mentioned for the definition of Zone NJK-D were not recorded higher up, in levels where *A. noduliferum* is present.

Depending on where the lower boundary of the *A. noduliferum* Zone is placed, nannoconid evidence could suggest (see Fig. 1) that *S. koeneni* ranges into the *Occitanica* Zone (*Subalpina* and *Privasensis* subzones), and the *A. noduliferum* Zone could be equivalent to the uppermost *Dalmasi* Subzone, *Occitanica* Zone, to the lower part of the *Boissieri* Zone, and that *S. damesi* Zone could range through the upper part of the *Boissieri* Zone and perhaps up to the lower part of the *Pertransiens* Zone. In this context, the 'absolute' age of 139.58 Ma provided by Vennari *et al.* (2013) could correspond (see below) to the upper part of the *Boissieri* Zone.

California

As mentioned above, Bralower's (1990) study on the nannofossils from sections in California has some relevance for the ammonite stratigraphy of Mexico and west central Argentina.

Bralower's (1990) study on the Great Valley Sequence (GVS) of northern California was directed towards dating with nannofossils the *Buchia* zones (see Fig. 1) recognized by Jones *et al.* (1969), previously dated on the basis of ammonites (Imlay, Jones, 1970). As remarked by all those authors, one important aspect of the GVS is that fossil faunas contain Tethyan and Boreal components, as Berriasian–Valanginian *Buchia* species related to those present in British Columbia (see Fig. 1) and the Arctic region are associated with ammonites that are also present in Mexico and Argentina.

Of special interest are the *Buchia* aff. *okensis* and the *B. uncitoides* zones that were first referred (Jones *et al.*, 1969; Imlay, Jones, 1970) to the Tithonian and Berriasian respectively. The *B.* aff. *okensis* Zone was referred to the Late Tithonian because of the presence of *Substeueroceras*, *Parodontoceras*, *Blanfordiceras*, and *Proniceras*, although species of *Spiticeras* were also recorded from the same levels (*cf.* Imlay, Jones, 1970, p. B6–B7). Both *Buchia* species occur also in the Taseko Lakes of western Canada (see Fig. 1), where equivalents of the Californian *Buchia* aff. *okensis* Zone (= *B. terebratuloides* Zone, *sensu* Jeletzky, 1984) are associated to *Parodontoceras reedi* (Anderson) and ?*Substeueroceras* sp. indet., and of "*B. uncitoides* Zone" (lower part ≈ *B. okensis* s.s. Zone, *sensu* Jeletzky, 1984) occur together with *Argenticeras* cf. *noduliferum* (Steuer) and *Fauriella* n. sp. aff. *gallica* (Mazenot) (*cf.* Jeletzky, 1984).

Especially important in this context are nannofossils collected in the Grindstone Creek (Glenn County) and McCarty Creek (Tehama County), California.

In the Grindstone Creek section the recorded lowest level with nannofossils (Sample 665.0; Bralower, 1990, fig. 6) is within the *B. uncitoides* Zone and was assigned to the *Nannoconnus steinmannii steinmannii* (FAD at base of NK-1) Zone (≈ middle of CM 17, Occitanica Zone; Casellato, 2010; Ogg *et al.*, 2012b). This level has been recorded as being 54.5 m below the top of the *B. uncitoides* Zone (*cf.* Pessagno *et al.*, 2009, text-fig. 42, and p. 227) and *c.* 95 m above a level (Loc. M 2599, Jones *et al.*, 1969, fig. 4; Imlay, Jones, 1970, table 2) with *Parodontoceras reedi* (Anderson). This last level is within a *c.* 60 m interval from where no radiolarians have been recorded, limited by levels with radiolarians referred by Pessagno, below (Sample 94-8) to the Tithonian and above (Sample 94-20A) to the Berriasian (Pessagno *et al.*, 2009, p. 226–227, text-figs. 42, 43; see below), so that it

cannot be determined whether this interval "is assignable to the upper Tithonian or to the lower Berriasian (or both)" (Pessagno *et al.*, 2009, p. 227) (see below under Radiolarians).

In the McCarty Creek section (lower part) nannofossils were recorded (Bralower, 1990, fig. 8) from the *Buchia* aff. *okensis* and *B. uncitoides* zones, and were referred to the nannofossil *Cretarhabdus angustiforatus* (NK-2) Zone (although the species FAD in Crimea appears to be in *Jacobi* to *Grandis* subzones; W.A.P. Wimbledon, pers. comm). All ammonites recorded from the McCarty Creek came from the *B. uncitoides* (Loc. 29505, M 4066, CAS 28667), *B. pacifica* (UC-A-2925) or *B. keyserlingi* (1095, CAS 144, CAS 33502, M1580) zones (Imlay, Jones, 1970, table 2) and were included in species of *Spiticeras*, *Thurmanniceras*, *Neocosmoceras* and *Kilianella*, and dated as Berriasian, although those with *B. pacifica* and *B. keyserlingi* were later dated as Early Valanginian (*cf.* Zakharov, 2004; Rogov *et al.*, 2011). Pessagno *et al.* (2009, p. 227) correctly pointed out that assigment at McCarty Creek of the *B.* aff. *okensis* Zone to nannofossil Zone NK-2 is not consistent with the assignment of the base of the *B. uncitoides* Zone at the Grindstone Creek section to nannofossil Zone NK-1. Here it should be noted that according to Bralower (1990, p. 114, 117) at McCarty Creek distribution of nannofossils is too patchy, that only a few events can be detected with a fair amount of certainty, and that is difficult to demarcate zones. In fact, there is a strong discrepancy in the thickness given for both the *B.* aff. *okensis* Zone and the *B. uncitoides* Zone between Jones *et al.* (1969) and Bralower (1990) for this section.

The *B.* aff. *okensis* and *Buchia uncitoides* zones have been considered (Zakharov, 1987, 2004) as equivalent to part of the Ryazanian (≈ Upper Berriasian) *B. okensis* Zone in the Russian Boreal region, and the range of *B. okensis* and *B. uncitoides* in California has been correlated with the *Occitanica* and *Boissieri* zones (*cf.* Sey, Kalacheva, 1999a; Rogov *et al.*, 2011; Arkadiev, Bogdanova, 2012). Possible presence of *Spiticeras*, *Groebericeras* and *Parodontoceras* in the upper part of the *Buchia piochii* Zone at Grindstone creek (Zakharov, 2015) suggests a Berriasian age for the basal levels of that section. Moreover, on the basis of Californian and Canadian records the *Substeueroceras koeneni* Zone has been correlated (Sey, Kalacheva, 1993) with the *B. piochii*, *B. fisheriana* and *B. terebratuloides* zones and with the *Jacobi* and *Occitanica* zones, the *Argentiniceras moduliferum* Zone with the *B. okensis* and lower part of the *Boissieri* Zone and the *Spiticeras damesi* Zone with the *B. uncitoides* and upper part of the *Boissieri* Zone.

These conclusions are in agreement with Bralower's (1990) correlation of the *N. steinmannii steinmannii* Zone (or NK1) (*Occitanica* Zone) with the lower part of the *Buchia uncitoides* Zone, whilst the upper part of *B. uncitoides*

and the *B. pacifica* zones are correlated with the Zone NK-2 (uppermost *Occitanica* to *Otopeta* ammonite zones). Reference of the *Buchia* aff. *okensis* Zone to the Upper Tithonian (see Jones *et al.*, 1969) can be discounted if the *Substeueroceras* Zone in the same sections is (partially or totally) Berriasian (though *N. steinmannii steinmannii* and *N. kamptneri kamptneri* occur in the Jacobi/Grandis Zone of Crimea; W.A.P. Wimbledon, pers. comm.).

Disparity in age based on ammonites and nannofossils for the *B.* aff. *okensis* Zone was attributed by Bralower (1990) to a possible extension of nannofossils lower than the first occurrence or, conversely, to the possibility that the indirect correlation provided by ammonites was incorrect. Alternatively it seems that the age of nannofossils in this locality determines the age of *Parodontoceras* and *Substeueroceras*, although the occurrence of these genera in other areas (Mexico, Peru, and Argentina) could start earlier, as mentioned above.

RADIOLARIANS

Pessagno *et al.* (2009) have suggested that radiolarians offer the best means of correlation with ammonite biozones among the planktonic microfossils and have tried to use them to correlate the Jurassic-Cretaceous boundary in North America and the Caribbean, and to delineate relationships with other regions, including west central Argentina and Antarctica.

But, even if detailed radiolarian zonations have been developed for different regions the calibration to standard geological stages and to the reference ammonite zone "has been challenging and controversial" (Ogg *et al.*, 2012a, p. 751), since local macrofossil standards have been used for calibration in different regions (*e.g.* Europe, Japan, North and South America and Antarctica). As an analysis of this issue is beyond the scope of this paper, remarks included below are restricted to conflicting evidence that bears on ammonite biostratigraphy.

West Central Argentina

As mentioned above, radiolarians have been used to correlate the *W. internispinosum* Zone with the *Suarites bituberculatum* Zone and part of Imlay's (1980) *Kossmatia–Durangites* assemblage of Mexico (Pessagno *et al.*, 2009, p. 233).

Radiolarians from west central Argentina were studied by Pujana (Pujana, 1989, 1991, 1995, 1996; *in*: Ballent *et al.*, 2011, and in Vennari *et al.*, 2014).

Pujana (1989, 1991) first recorded two different assemblages (A and B) from the *Windhauseniceras internispinosum and* the *Substeueroceras koeneni* and *Argentiniceras noduliferum* zones exposed in Mallin Quemado, Neuquén

province. Both assemblages were characterized by species of *Parvicingula* Pessagno, *Pantanellium* Pessagno, *Archeo-dictyomitra* Pessagno, and *Gorgansium* Pessagno and Blome, which differed by, the additional presence in assemblage "A" of *Vallupus hopsoni* Pessagno and Blome, *V. japonicus* Kawata and *Protovallupus* cf. *excellens* Yang and Pessagno, and by a slightly lower diversity recorded in assemblage "B". Assemblage "A" was based in material from 3 different levels (MQ 51-1, 37-2 and 40-2) (*cf.* Pujana, 1991, fig. 2) from the lower part of the Vaca Muerta Formation, immediately above "*Pseudolissoceras* sp." and distributed in *c.* 60 m of sediments, where in the middle part was recorded a level with "*Corongoceras lotenoense*". Assemblage "B" was from 4 different levels (MQ 57-2, 59-2, 66-2, 34-1), *c.* 500 m higher, distributed in *c.* 120 m of sediments, with two samples (MQ 57-2, 59-2) coming from levels immediately above a level with "*Substeueroceras exstans*" and immediately below levels with "*Neocosmoceras ? egregium*" and "*Himalayites* sp.", and the other two samples from levels *c.* 80 m higher and *c.* 200 m below levels with "*Cuyaniceras* sp.", "*Spiticeras fraternum*" and "*Hemispiticeras* cf. *steinmanni*".

Presence of *V. hopsoni*, a primary marker of the North American Zone 4, Subzone Beta (*cf.* Pujana, 1991) suggested correlation of Assemblage "A" with the upper part of North American Subzone 4 beta. Therefore, the *Windhauseniceras internispinosum* Zone was correlated with Imlay's (1980) North American *Kossmatia–Durangites* Assemblage or with the lower part of the *Substeueroceras–Proniceras* Assemblage.

Subsequently, Pujana (1995, 1996) described new material and discussed radiolarian occurrences in three different sections: Mallin Quemado, Portada Covunco and Bardas Blancas. He recognized a "*Vallupus hopsoni* event" from the "lower part of the *Pseudolissoceras zitteli* Zone to at least upper part of *Aulacosphinctes proximus* Zone" and a "*V. japonicus* event" from the upper part of the *Windahuseniceras internispinosum* Zone and *Corongoceras alternans* Zone. The two species *V. hopsoni* and *V. japonicus* were recorded associated, although morphological differences were mentioned throughout their range.

Pessagno *et al.* (2009, p. 232–233) mentioned *V. nodosus* in an assemblage characterizing the *W. internispinosum* Zone, and, as that species in Mexico occurs near the top of radiolarian Subzone 4 beta$_2$ (see Fig. 1) and the boundary between this subzone and Subzone 4 alpha$_1$, this corresponds to the boundary between Imlay's (1980) *Kossmatia–Durangites* assemblage and *Substeueroceras-Proniceras* assemblage (= *Substeueroceras-Berriasella* complex of Jeletzky, 1984). Its presence at Mallin Quemado was used by Pessagno *et al.* (2009, p. 232–233) to corroborate the correlation of the *Windhauseniceras internispinosum* Zone with the Mexican *Suarites bituberculatum* Zone of Cantu Chapa

(1971) and the uppermost part of Imlay's (1980) *Kossmatia–Durangites* assemblage (*cf.* Pujana, 1989, 1991, 1995, 1996; *cf.* also Zeiss, 2001; Zeiss, Leanza, 2008; Pessagno *et al.*, 1994; 2009).

More recently, Pujana (in Ballent *et al.*, 2011) listed radiolarians that in the Mallin Quemado and Portada Covunco region, Neuquén province (see above), are present through: 1) the *Virgatosphinctes mendozanus* and *Corongoceras alternans* zones – labelled as "Association J3-A", and 2) the *Substeueroceras koeneni* to *Neocomites wichmanni* zones – labelled as "Association J3-B" –, but no additional information on their significance for correlation of the ammonite zones was provided. A similar listing of genera was given by Pujana (in Vennari *et al.*, 2014) for the *Virgatosphinctes mendozanus* and *Substeueroceras koeneni* zones of the Vega de Escalone section, northern Neuquén Province, but again without enough detail on their significance for correlation of ammonite biozones. It is worth mentioning, however, a statement indicating that the radiolarian assemblage recorded in the *Argentiniceras noduliferum* Zone did not show significant differences from the two lower ones, except that it is less diverse and abundant.

From what has been published, it seems, therefore, that radiolarians identified thus far in west central Argentina have some significance for ammonite biostratigraphy only in that they support correlation of the *Windhauseniceras internispinosum* Zone with the *Suarites bituberculatum* Zone of Mexico, and radiolarians for the *Substeueroceras koeneni* Zone are still unstudied, as reported by Pessagno *et al.* (2009, p. 232).

Mexico

Pessagno *et al.* (2009), however, mostly on the basis of information from Mexico, have discussed several correlation problems in relation to levels equivalent to the *Substeueroceras koeneni* Zone. Analysis was mainly focused on ammonites, calpionellids, nannofossils and the bivalve *Buchia*, but especially on what they mentioned as conflicting evidences in North America between ammonite and calpionellid biotratigraphic and chronostratigraphic data.

Radiolarian relative-age data appear to agree with ammonite biostratigraphy below and above the *Substeueroceras koeneni* Zone and its equivalents. A main concern here is, therefore, the apparent conflict between radiolarian ages provided by Pessagno *et al.* (2009), not only with calpionellid data, but also with possible ammonite evidence (see above) supporting an extension of Mexican equivalents of the *Substeueroceras koeneni* Zone into the Berriasian.

Pessagno *et al.* (2009) discussed in some detail the Tithonian–Berriasian stratigraphy of several regions of Mexico, especially those of San Pedro del Gallo (Durango),

Mazapil (Zacatecas), Taman-Tamazunchale (San Luis Potosi) and Mazatepec (Puebla), and their correlation with California, the Lesser Antilles and west central Argentina. In all these areas their evidence supported a Late Tithonian age for the *Substeueroceras* beds on the basis of radiolarians assigned to subzones 4 alfa$_1$ and 4 alfa$_2$.

In the San Pedro del Gallo area, some discrepancies, mainly between radiolarian and calpionellid stratigraphy, could be due to the fact that calpionellid information from some localities was based in an unpublished report on the calpionellids by J. Remane (in Pessagno *et al.*, 2009, p. 261), where it is stated that calpionellids "are mostly rare and often not very well preserved" and that "new thin sections are being made in order to have more material for a precise age assignment". Discrepancies could also be due to the existence of geological structures that make it difficult, in the absence of diagnostic fossils, to date rocks with similar lithologies (*cf.* Burckhardt, 1910). Discrepancies can be extended to the thicknesses reported for some units. Thus, for instance, the uppermost part of the "Capas de San Pedro" (or Puerto del Cielo Shale Member) is 200 m thick according to Burckhardt (1910) and 20–45 m thick *fide* Pessagno *et al.* (2009, p. 200). The main discrepancies, however, relate to the dating of Burckhardt's boundary beds between the Jurassic and Cretaceous ("*capas limítrofes entre el Jurásico y el Cretácico*") (= Cerro Panteón Member, in Pessagno *et al.*, 2009) in two localities, *i.e.* Voodoo Hill and La Peña.

In the Voodoo Hill section, samples SPG 92-24 and SPG 92-27 did not come, as indicated (*cf.* Pessagno *et al.*, 2009, text-fig. 13), from the Cerro Panteon Member, but from the San Pedro del Gallo Chert Member (*cf.* Pessagno *et al.*, 2009, text-fig. 15). The top of this last unit is recorded at the level of Sample SPG 94-48 (*cf.* Pessagno *et al.*, 2009, text-figs. 15 and p. 203), so that the Cerro Panteon Member could be represented in the overlying *c.* 50 m, at the top of which are levels (Samples SPG 92-54 and 92-57) with *Calpionella alpina*. It should be noted that in this area overlying the Cerro Panteón Member (in apparent conformity) is the Chapulhuacán Limestone, and it contains ammonites, and these are similar to some recorded from Argentina (Malargue 1 and 3, Loncoche 3, Cieneguita 5, and Rodeo Viejo 5 units, in Steuer,1897), indicating the (*Occitanica–*) *Boissieri* Zone(s) (*cf.* Burckhardt, 1910, 1912, 1930).

A clear discrepancy occurs in the La Peña section (10 km north of San Pedro del Gallo), where 50–60 m above the base Pessagno *et al.* (2009, text-fig. 20) recorded *Substeueroceras* and *Durangites*, and 30 m higher (text-figs 19, 21; sample SPG 96-9AB) radiolarians of the 4 alpha$_1$ and 4 alpha$_2$ zones (see Fig. 1), assigned to the Upper Tithonian. These data differ from those reported by Adatte *et al.* (1996), who in the lower 10 m of the same section recorded species of *Substeueroceras*, *Spiticeras*, *Jabronella* and *Shaireria*

with calpionellids of Zone C (*Occitanica* Zone, *Privasensis* and *Dalmasi* subzones). It should be mentioned that radiolarians were apparently not recorded in the upper *c.* 20 m of this formation (Pessagno *et al.*, 2009, text-fig. 19, 21, samples SPG 10 to 12A-B), which are overlain by the Chapulhuacán Limestone, a unit characterized by ammonites indicating the (*Occitanica–*) *Boissieri* Zone(s) (*cf.* Burckhardt, 1910, 1930).

In Canyon San Matias, Pessagno *et al.* (2009, p. 209) recorded *Parodontoceras* aff. *callistoides* and *Durangites* sp. 76 m above the base of La Caja Formation, and *Substeueroceras* sp. at 78.2 m above the base (samples SM94-62 and SM94-60; *cf.* Pessagno *et al.*, 2009, p. 209, text-fig. 26B). Radiolarians from the same interval belong to the upper part of Subzone 4 alpha$_2$ (assigned to the uppermost Tithonian; see Fig. 1). A possible Lower Berriasian ammonite, identified as "cf. *Protothurmannia* sp.", was recorded from a level 4.72 m below the contact with the Chapulhuacán Limestone "and 81.08 m above the base of the La Caja Formation". Radiolarians from the same horizon (Sample SM96-64) indicate Subzone 4 alpha$_2$, and a specimen of "cf. *Substeueroceras* sp." was recovered "from float in the creek bed approximately 99 m above the base of the La Caja Formation" (Pessagno *et al.*, 2009, p. 209). On this evidence, it was "suggested that the Tithonian-Berriasian boundary may occur at approximately 81 m above the base of the La Caja Formation and 4.72 m below the contact with the Chapulhuacán Limestone" (Pessagno *et al.*, 2009, p. 210). If so, a stratigraphic discontinuity could be present and radiolarian Zone 4 alpha$_2$ and *Substeueroceras* could range into the Berriasian, although Pessagno *et al.* (2009, p. 210) indicated that additional samples from the upper part of this section were needed to derive definite results.

Significance of radiolarians for the stratigraphy of the Pimienta Formation exposed in Mazatepec was discussed above in relation to calpionellids. It was noted that although Pessagno *et al.* (2009, p. 218) correlated the ammonites recorded in the upper part of the Pimienta Formation with the upper part of Imlay's (1980) *Substeueroceras–Proniceras* Assemblage and the uppermost Tithonian radiolarian Subzone 4 alfa$_2$ (see Fig. 1), radiolarians were apparently not recovered from this section and interval (*cf.* Pessagno *et al.*, 2009, p. 215, 218). Moreover, from the same locality and levels of the Pimienta Formation, Pessagno *et al.* (2009) mentioned the calpionellids *C. alpina* and *Tintinopsella* spp. as well as the calcareous nannofossil *Nannoconus steinmannii* Kamptner, which are also present in the overlying *Subthurmannia mazatepense* Zone, referred to the Berriasian (Pessagno *et al.*, 2009, p. 218). As mentioned above, the FAD of *N. steinmannii minor* is in the *Jacobi* Zone (Wimbledon *et al.*, 2013) and the FAD of *N. steinmannii steinmannii* is in the *Occitanica* Zone (Casellato, 2010) (see Fig. 1).

California

Radiolarians, *i.e. Complexapora kozuri* Hull and *Parvicingula jonesi* Pessagno, were used by Pessagno *et al.* (2009) to refer the *Buchia* aff. *okensis* at Grindstone Creek to the Upper Tithonian radiolarian Subzone 4 alpha $_2$. *Parvicingula jonesi*, however, was mentioned (Pessagno *et al.*, 2009, p. 227) as ranging from the Upper Tithonian to the Berriasian. *C. kozuri* instead ranges through the Upper Tithonian zones 4 beta$_2$, 4 alpha$_1$ and 4 alpha$_2$. In the Grindstone Creek section this species was recorded from level GR 94-8 (Pessagno *et al.*, 2009, text-figs 42, 43), *c.* 20–25 m below levels with *Parodontoceras*, and 60 m below the next record of (Berriasian) radiolarians, where also *B. uncitoides* and *Spiticeras*, are present. Therefore, "as a 60 m interval in which no Radiolaria were recovered separates the highest Subzone 4 alpha$_2$ sample from the base of the overlying *Buchia uncitoides* Zone […] and radiolarian Subzone 5A (lower Berriasian) […] it cannot be determined whether this part of the *B.* aff. *okensis* Zone is assignable to the upper Tithonian or to the lower Berriasian (or both)" (Pessagno *et al.*, 2009, p. 227). This interval includes the only level with *Parodontoceras reedi* (Anderson) recorded in this section (Jones *et al.*, 1969, fig. 4; Imlay, Jones, 1970, table 2, pl. 11: 2–5). Here it should also be taken into account that radiolarian biostratigraphic investigation in the *Buchia* zones of Grindstone and McCarty creeks apparently relied on macrofossil stratigraphy to establish the age of radiolarian zones (*cf.* Bralower, 1990, p. 118), and that the original work on radiolarian biostratigraphy of the California Coast Ranges was first developed (*cf.* Pessagno, 1977) utilizing the *Buchia* zonal framework of Jones *et al.* (1969).

Cuba

Finally, it is worth mentioning that radiolarian taxa identified in the El Americano Member in the Sierra del Infierno section, Sierra de los Organos, Cuba (Pszczółkowski *et al.*, 2005), differ from those of North America recorded by Pessagno *et al.* (2009), and the only taxon in common [for both areas] appears to be *Ristola altissima altissima* (Rüst) of the radiolarian Late Tithonian to Berriasian Subzone 4α$_2$; which in Cuba was recorded (Pszczółkowski *et al.*, 2005), from levels with *Crassicollaria intermedia* (Durand-Delga) and *Nannoconus wintereri* (FAD in the *Jacobi* Subzone), *c.* 1 m, 2 m, and 3 m below levels, respectively, with *Nannoconus kamptneri kamptneri* (NK-1 Zone, ≈ *Subalpina* and *Privasensis* subzones, *Occitanica* Zone), *Protancyloceras* ex. gr. *hondense*, and *Vinalesites* sp.

GEOCHRONOLOGY

Discrepancies between radio-isotopic dates using U-Pb methods, especially with reference to GTS 2012, could be partly due to technical differences (*cf.* Ogg *et al.*, 2012a). Thus, most U-Pb ages, including nearly all those used in GTS 2004 and by Palfy *et al.* (2000), utilized multi-grain analysis without treatment of annealing followed by chemical abrasion, so that ages obtained with earlier methods should be viewed as minimum ages, prone to slight (*c.* +1–2 Ma) adjustment (Palfy, 2008; Ogg *et al.*, 2012a, p. 763). It has also been indicated that ^{40}Ar/^{39}Ar results provide ages that are ≥1% younger than those of U-Pb ages from the same samples (Palfy, 2008).

Thus, most age estimates for the Late Jurassic do not meet the GTS 2012 standards, and secondary guides, as those based on dates obtained by earlier methods, are contradictory in some intervals, so that the Late Jurassic has been considered the poorest epoch with regard to the availability of calibration points (Palfy, 2008; Ogg *et al.*, 2012a).

Most ages adopted in GTS 2012 are based in the M-sequence age model, which has been used to calibrate Tethyan Tithonian and Berriasian ammonite zones. Calcareous nannofossils allow direct correlation with the historic Berriasian type section (above the *T. subalpina* Subzone), with onshore sections and DSDP sites drilled between known magnetic anomalies. Nevertheless, it has been pointed out that "some ambiguity remains in accurately anchoring the M-sequence, due to the scarcity of high quality Late Jurassic and earliest Cretaceous radioisotopic dates" (Palfy, 2008).

Thus, according to Ogg *et al.* (2012a) (see Fig. 1) the base of the Tithonian is tied to the base of magnetozone M22An with a corresponding M-sequence age of 152.1 ±0.9 Ma (Ogg *et al.*, 2012a, p. 776), and the base of the Berriasian using the base of Chron 18r has an age of 145.0 ±0.8 Ma from the M-sequence model, which is consistent with a recalibrated ^{40}Ar/^{39}Ar date of 145.5 ±0.8 Ma from reversed-polarity sills intruding Early Berriasian sediments on the Shatsky Rise of the Pacific (Mahoney *et al.*, 2005; Ogg *et al.*, 2012b). Although the base of the *C. alpina* subzone as a contender definition for the base of the Berrisian Stage falls in the middle of M19n, and the base of the *Jacobi* Subzone would be base of M19n (W.A.P. Wimbledon, pers. comm.; *cf.* Pruner *et al.*, 2010; Michalík, Reháková, 2011; Wimbledon *et al.*, 2013). The age assigned to the base of the Valanginian is 139.4 ±0.7 corresponding to the lower part of Chron M14r3 (Ogg *et al.*, 2012b).

Of main concern here are those ages obtained from levels which can be correlated with ammonite zones. The few ages

within this category are: 1) a 137.1 +1.6/–0.6 Ma U-Pb age obtained (Bralower *et al.*, 1990), for two tuffs levels in the Grindstone Creek section in the Sacramento Valley; 2) a 137.9 ±0.9 Ma U-Pb SHRIMP age obtained (Vennari *et al.* 2013), for a level immediately above a level with *Argentiniceras noduliferum*, Neuquén Basin; 3) a ^{40}Ar–^{39}Ar age of 144.6 ±0.8 Ma obtained (Mahoney *et al.*, 2005) for basalt sills on Shatsky Rise (Hole 1213B) injected into sediments with calcareous nannofossils of Zone NK-1 (*N. steinmannii steinmannii*) – equivalent to the *Occitanica* Zone (Casellato, 2010; Grabowski, 2011; Ogg *et al.*, 2012b); 4) a U-Pb age of 143.734 ±0.060 Ma obtained (*cf.* Pessagno *et al.*, 2009) in levels of La Desirade Igneous Complex (Lesser Antilles) with radiolarians of Subzone 4 Beta$_2$ correlatable with ammonite beds of the *Suarites bituberculatum* Zone of Mexico and the *W. internispinosum* Zone of west central Argentina; 5) several U-Pb ages (ranging between 153 Ma and 142.2 Ma) obtained in the Neuquén Basin (Naipauer *et al.*, 2012, 2014) from the Tordillo Formation, directly underlying the *Virgatosphinctes mendozanus* Zone.

These ages show an apparent discrepancy with those of GTS 2012, in which the base of the Tithonian is dated at 152.1 ±0.9 Ma, the base of the *Jacobi* Zone (Jurassic-Cretaceous boundary) at 145.0 ±0.8 Ma and the base of the Valanginian at 139.4 ±0.7.

With regard to the 137.1 +1.6/–0.6 Ma U-Pb age obtained by Bralower *et al.*, 1990) in the Grindstone section, there is an unsolved discrepancy in the absolute ages defined for nannofossil zones in relation to the base of the *Jacobi* Zone.

Thus, Bralower *et al.* (1990) obtained an age of 137.1 +1.6/–0.6 Ma for the lower part of the *C. angustiforatum* (NK-2) Nannofossil Zone (*Assipetra cretacea* Subzone, which is correlated with the magnetozones M16 and M16n, *Dalmasi* Subzone, upper part of the *Occitanica* Zone to middle part of the *Picteti* Subzone, *Boissieri* Zone, or on the basis of a revision of nannofossil ranges with CM16-CM15 magnetochrons, uppermost *Occitanica* to *Otopeta* zones, see Palfy *et al.*, 2000). This age was obtained from two volcanic horizons that were 65 m apart at Grindstone Creek, the lower one in the upper *B. uncitoides* Zone and the upper in the *B. pacifica* Zone, although Ogg *et al.* (2012b, p. 822) mentioned values "older than ~138 Ma" for the same sequence and area. Here it is worth mentioning that sensitive high-resolution ion microprobe age determinations on detrital zircon grains collected from 100 km along strike in the purported Tithonian strata of the Great Valley Group (GVG) (Surpless *et al.*, 2006) resulted in ages ranging between 143.6 ±2.1 and 140 ±2.7 for samples from the Grindstone Creek area and 140.1 ±1.9 for the nearby Stony Creek area.

It is possible that the age obtained by Bralower *et al.* (1990) includes some uncertainty, due to the fact that it was obtained from tuff levels which were 65 m apart, although it

was considered by Palfy *et al.* (2000) as a precise and well documented U-Pb zircon age. In fact, the 137.1 ±1.6/–0.6 Ma age is in agreement with the a 137.9 ±0.9 Ma U-Pb SHRIMP age obtained (Vennari *et al.* 2013), for a level immediately above the occurrence of *Argentiniceras noduliferum* in the Neuquén Basin, Argentina, which could be equivalent to the *Spiticeras damesi* Zone and to the upper part of the *Boissieri* Zone (see above). In any circumstance, these values are compatible, if methodological uncertainties are considered, with those of Surpless *et al.* (2006), and all them support an age younger than Tithonian for the GVG and the fossiliferous levels at Grindstone Creek and McCarty Creek.

Bralower's results, however, contrast with those of Mahoney *et al.* (2005), of a ^{40}Ar–^{39}Ar age of 144.6 ±0.8 Ma from levels with calcareous nannofossils of Zone NK-1 (*N. steinmannii steinmannii*) – correlative with the *Occitanica* Zone (*cf.* Casellato, 2010; Grabowski, 2011; Ogg *et al.*, 2012b) – and radiolarians of the *Pseudodictyomitra carpatica* Zone – equivalent (*cf.* Matsuoka, Yang, 2000) to the uppermost Tithonian–lowermost Valanginian interval.

Even if nannofossil Subzone NK-2a is younger than Zone NK-1, the difference in their absolute ages determined respectively by Bralower *et al.* (1989) and Mahoney *et al.* (2005) imply a difference between them and the ammonite zones with which they are correlated of *c.* 5 Ma. This is a value that does not fit with the usually accepted duration of Jurassic and Cretaceous nannofossil and ammonite zones and lies well outside the 2 myr range mentioned by Ogg *et al.* (2012a) as the usual difference between dates obtained from older and newer geochronological methods.

With regard to the U-Pb age of 143.734 ±0.060 Ma obtained (*cf.* Pessagno *et al.*, 2009) in levels of the La Desirade Igneous Complex, that contain radiolarians of Subzone 4 Beta$_2$ correlatable with ammonite beds of the *Suarites bituberculatum* Zone of Mexico and the *W. internispinosum* Zone of west central Argentina, it disagrees with an age of 145.0 ±0,8 Ma for the base of the *Jacobi* Zone (Jurassic-Cretaceous boundary) as proposed in the GTS 2012. This discrepancy is within the 2 myr range mentioned by Ogg *et al.* (2012a) for technical differences in geochronological methods, but it could also be that accuracy of the age obtained for the La Desirade Igneous Complex is not directly applicable to the ammonite levels of Mexico and Argentina.

Finally, in the Neuquén Basin the discrepancy between the U-Pb ages obtained (Naipauer *et al.*, 2012, 2014) with a statistical estimation at *c.* 144 Ma for the maximum depositional age for the Tordillo Formation, which directly underlies the *Virgatosphinctes mendozanus* Zone, with regard to the GTS 2012 value of 152.1 ±0.9 Ma for the base of the Tithonian, could be related to technical uncertainties and to the age assigned to the *Virgatosphinctes mendozanus* Zone.

As mentioned above, U-Pb detrital zircon ages obtained from the continental formation, that underlies the ammonite-bearing marine beds here included in the *Virgatosphinctes mendozanus* Zone, show a range between 153 Ma (Naipauer *et al.*, 2012) and 145.2–142.2 Ma (Naipauer *et al.*, 2014). These ages are similar to those obtained (Oliveros *et al.*, 2012) for the Lagunillas Formation of northern Chile, an equivalent of the Tordillo Formation, where the U-Pb of detrital zircons gave values in the range of 144.6 ±3.5 to 151.7 ±2.8 Ma, on which was inferred a maximum depositional age of 150.8 ±4.0 Ma.

The age obtained for the Tordillo Formation is younger than the 152.06 Ma proposed (*cf.* Ogg *et al.*, 2012a) for the base of the *Hybonotum* Zone, and even of the *Semiforme* Zone (150.41 Ma), projected from the M-sequence calibrations. In any case, correlation of the *Virgatosphinctes mendozanus* Zone with the (uppermost *Darwini*–) *Semiforme* Zone implies that the Tordillo Formation could be extended by at least 2 myr into the basal Tithonian, or even more, considering that uncertainties of the extrapolated boundary ages are estimated as ±1 myr, and that, depending of the method applied, results could differ in a range of 2 myr (*cf.* Ogg *et al.*, 2012a). In any circumstance these data are in agreement with a younger age for the *V. mendozanus* Zone and could indicate that the Tordillo Formation corresponds, at least in its upper part, to most or all of the Lower Tithonian. It is significant in this respect that the *Hybonotum* Zone, recorded from Cuba, Mexico and Antarctica, below levels with *Virgatosphinctes*, has not been documented in the Andes of west central Argentina, where it could be represented by the continental strata included in the Tordillo Formation, as already suggested by Burckhardt (1930).

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