

Lower Cretaceous (Berriasian–Aptian) biostratigraphy of the Neuquén Basin

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Abstract: The Berriasian–Aptian succession in the Neuquén Basin is mainly marine in the lower part and non-marine in the upper portion. A detailed ammonite zonation is presented for the Berriasian–?Early Barremian interval. While some ammonite taxa are endemic, others are widely distributed and there are several levels where correlation can be suggested with the ‘standard’ stages and zones of the Tethyan Mediterranean area. Several nannofossil bioevents are recognized, and these provide evidence for correlation with Tethyan areas. Correlations suggested by both groups are reasonably consistent. Berriasian–Aptian palynomorphs include both terrestrial and marine forms. Several terrestrial assemblages can be recognized, but the marine forms are mainly long-ranging taxa, especially in the Agrio Formation.

The infill of the Neuquén Basin comprises more than 6000 m of marine and continental sedimentary rocks ranging in age from Late Triassic to Palaeogene. The Lower Cretaceous succession is represented by the Mendoza (part) and Rayoso groups.

Sediments of Berriasian–?Early Barremian age are mostly marine and crop out extensively in the Neuquén and Mendoza provinces yielding rich marine faunas and floras. In Neuquén they form the upper part of the Vaca Muerta Formation, the Mulichinco Formation and the Agrio Formation of the Mendoza Group. Here ammonites are often abundant and well preserved. Further north, in southern and central Mendoza, the facies are generally calcareous (Chachao and Agrio formations) and ammonites are less common and often flattened. Conversely, nannofossils are more abundant in the more calcareous facies. Palynomorphs have been studied mainly in the Neuquén sections.

During most of the Barremian up to the Aptian, sedimentation in the basin was characterized by evaporites and red continental deposits of the Huitrín and Rayoso–Ranquiles formations (Rayoso Group) (Fig. 1). In these rocks, only palynomorphs have been recovered.

The research focused initially on establishing a detailed ammonite succession (see below), to

improve correlation of the marine beds both within the basin and with the succession in the Mediterranean area, where the standard stages were defined. Then the work expanded to embrace other biostratigraphically important and geographically widespread fossil groups in marine succession, of which nannofossils and palynomorphs (especially dinoflagellates) are potentially the most useful over the interval of time represented, when planktonic foraminifera were still rare. Many of the palynomorphs proved to be long-ranging forms of little value in long-distance correlation, but the nannofossils provided a valuable cross-check on the correlation indicated by the ammonites and thus on the application of the ‘standard’ stage names to the Neuquén Basin. This paper reviews and synthesizes the work completed to date, and also summarizes the palynology of the overlying non-marine beds of the Rayoso Group. Aguirre-Urreta and Rawson are responsible for the ammonite studies, Bown and Concheyro for the nannofossils, and Ottone for the palynomorphs.

Ammonite biostratigraphy

The main descriptions of the ammonites of the Vaca Muerta Formation (Tithonian–Lower

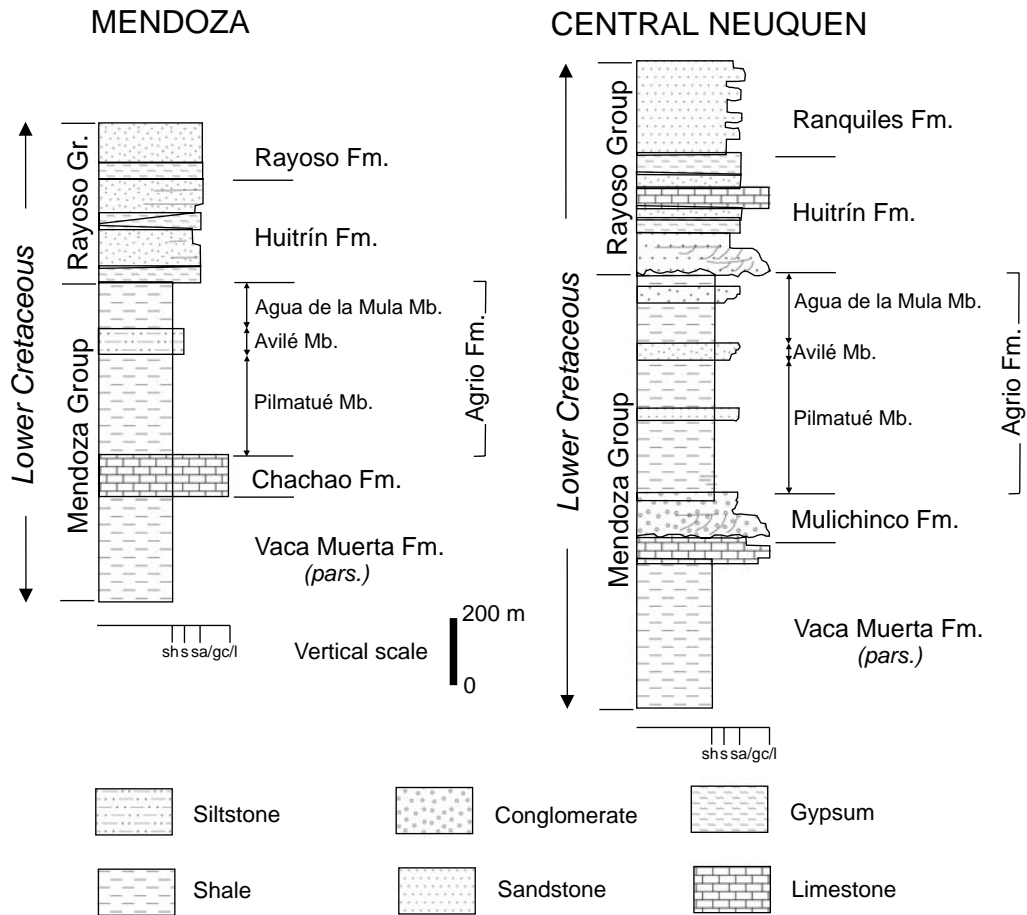


Fig. 1. Generalized stratigraphic columns of the Lower Cretaceous Mendoza and Rayoso groups in Mendoza and Central Neuquén.

Valanginian) are by Burckhardt (1903), Gerth (1925), Weaver (1931), Windhausen (1931), Leanza (1945) and Aguirre-Urreta & Alvarez (1999). Leanza (1945) concentrated on faunas from Mendoza and for the Berriasian–earliest Valanginian interval, and proposed three biozones, *Argentinceras noduliferum*, *Spiticeras damesi* and *Neocomites wichmanni*, all of which are still used. Leanza (1981a, b) and Riccardi (1984) listed the faunas of each biozone. With the exception of a study on *Groebericeras* (Aguirre-Urreta & Alvarez 1999) there has been little recent systematic work on the faunas of this age, but Riccardi (1988) and Aguirre-Urreta (1993) have both provided a general biostratigraphy with illustrations of the most characteristic ammonites. Conversely, over the last 12 years, the late Early Valanginian–latest

Hauterivian/Early Barremian faunas have been studied in detail, the authors spending several field seasons visiting numerous localities (Fig. 2) and collecting the rich ammonite faunas that occur in the top Vaca Muerta, Mulichinco and Agrio formations. This led to the publication of a much more detailed and accurate biostratigraphy than any previous one (Aguirre-Urreta & Rawson 1997).

In that paper we noted that many of the cited taxa were in need of systematic revision. Since then we have collected much additional material and have revised the systematics of some of the key genera (Aguirre-Urreta 1998; Aguirre-Urreta & Rawson 1999a–c, 2001, 2002, 2003). Others still await revision. Hence, although we still recognize the same general succession of faunas, the names of some of the index taxa



Fig. 2. Principal localities of the Neuquén Basin where recent studies on ammonites, palynomorphs and nannoplankton have been made.

have had to be changed, resulting in changes to some subzonal names (Fig. 3). We have also been able to define some of the zonal/subzonal boundaries with greater precision, and to establish the precise levels at which some of the less well-known forms occur (e.g. *Lissonia*, *Valanginites*, *Hoplitocrioceras*).

The zonal sequence that we now recognize is comparable in detail to zonations for both the 'standard' Mediterranean sequences and the Boreal ones of NW Europe. The Neuquén faunal succession is now known in more detail than that in any other South American or Gondwanan sequence of similar age, and thus serves as a model for comparison across the region. There are some ammonites in common with the Austral Basin of southern Patagonia (*Olcostephanus*, *Chacantuceras*, *Crioceratites*), while others (e.g. *Lissonia*) extend northwards from Neuquén to northern Chile, Peru and Colombia.

The zonation is shown in Figures 3 (partially), 8 and 9, and individual zones are discussed briefly below. Examples of each zonal/subzonal index fossil are illustrated in Figs 4–7. In general, the faunas in any one subzone are of low generic diversity, and diversity generally decreases upwards, so that most of the Hauterivian and ?Early Barremian assemblages are monogeneric. Zonal boundaries mark major faunal turnovers; some of the subzonal boundaries also do, while others reflect an evolutionary sequence within a particular taxonomic group.

The Jurassic–Cretaceous boundary in the Neuquén Basin has traditionally been marked on biostratigraphic grounds, as there is a complete lithological continuity within the black shales of the Vaca Muerta Formation across the passage from one system to another. The boundary has habitually been placed between the *Substeueroceras koeneni* Zone (Upper Tithonian)

AGE	Aguirre-Urreta & Rawson 1997		This paper	
	BIOZONE	SUB-BIOZONE	BIOZONE	SUB-BIOZONE
EARLY HAUTERIVIAN	<i>Weavericeras vacaensis</i>		<i>Weavericeras vacaensis</i>	
	<i>Hoplitocrioceras gentilii</i>	<i>Hop. gentilii</i>	<i>Hoplitocrioceras gentilii</i>	<i>Hop. gentilii</i>
		<i>Hop. sp. nov.</i>		<i>Hop. giovinei</i>
	<i>Holcoptychites neuquensis</i>	<i>Olcostephanus</i> (O.) <i>leanzai</i>	<i>Holcoptychites neuquensis</i>	<i>Olcostephanus</i> (O.) <i>laticosta</i>
		<i>Hol. compressum</i>		<i>Hol. agrioensis</i>
		<i>Hol. neuquensis</i>		<i>Hol. neuquensis</i>
EARLY VALANGINIAN	<i>Pseudofavrella angulatiformis</i>	<i>Neocomites</i> sp.	<i>Neocomites</i> sp.	
		' <i>Acanthodiscus</i> ' sp.	<i>Chacantuceras ornatum</i>	
		<i>Pseudofavrella angulatiformis</i>	<i>Pseudofavrella angulatiformis</i>	
EARLY VALAN.	<i>Olcostephanus</i> (<i>Olcostephanus</i>) <i>atherstoni</i>	<i>O.</i> (<i>Lemurostephanus</i>) sp.	<i>O.</i> (<i>Viluceras</i>) <i>permolestus</i>	
		<i>Karakaschiceras attenuatus</i>	<i>Karakaschiceras attenuatus</i>	
		<i>Olcostephanus</i> (O.) <i>atherstoni</i>	<i>Olcostephanus</i> (O.) <i>atherstoni</i>	
EARLY VALAN.	<i>Neocomites wichmanni</i>	<i>Lissonia riveroi</i>		
		<i>Neocomites wichmanni</i>		

Fig. 3. Early Valanginian–Early Hauterivian ammonite zones and subzones of the Neuquén Basin: comparison between the proposal of Aguirre-Urreta & Rawson (1997) and this paper.

and the *Argentiniceras noduliferum* Zone (Lower Berriasian). However, Riccardi *et al.* (2000) recently placed most of the *Substeuoceras koeneni* Zone in the Berriasian without explanation. Howarth (1992) in his study on the Tithonian and Berriasian ammonites from Iraq produced a correlation chart, including two different zonal schemes for South America. The traditional scheme was after Jeletzky (1984) while the other one was from Zeiss (1986), and in the latter the *Substeuoceras koeneni* Zone represents a large portion of the Berriasian. As further work is necessary to solve these problems, which are out of the scope of this paper, the traditional zonation is provisionally followed here.

The Argentiniceras noduliferum Assemblage Biozone (Leanza 1945)

The zone was proposed by Leanza (1945) for southern Mendoza and placed in the Lower Berriasian. This author studied the ammonites that were collected by Groeber in southern Mendoza, and there has been no further research on this fauna, except the study on *Groebericeras* by Aguirre-Urreta & Alvarez (1999). Species of *Argentiniceras* (Fig. 4c), *Berriasella*, '*Thurmanniceras*', *Frenguelliceras* and *Substeuoceras* are other components of this zone.

The Spiticeras damesi Assemblage Biozone (Gerth 1921)

This zone was proposed by Gerth (1921) who assigned it to the Valanginian. Later, Burckhardt (1930) transferred it to the Berriasian. Leanza (1945) studied the ammonites and placed the index species *S. damesi* (Fig. 4d) in the Upper Berriasian together with *Cuyaniceras transgrediens*. The diverse components of the fauna, including species of *Neocosmoceras*, *Neocomites* and '*Thurmanniceras*', await detailed sampling and a modern systematic revision.

The Neocomites wichmanni Assemblage Biozone (Leanza 1945)

Proposed for beds containing the index species (Fig. 4e, f) and '*Thurmannites pertransiens* Sayn'. Aguirre-Urreta & Rawson (1999a) figured some forms from this zone as '*Thurmanniceras*' but noted that the faunas needed thorough revision. At about the boundary between this and the overlying *Lissonia riveroi* Zone is a thin horizon with *Valanginites*

argentinicus Leanza & Wiedmann; a single *Olcostephanus* sp. is probably from the *Valanginites* bed and represents the earliest Argentine record of this genus (Aguirre-Urreta & Rawson 1999a).

The Lissonia riveroi Local Range Biozone (Aguirre-Urreta & Rawson 1999a)

The base of the zone is defined by the first appearance of the index species, which apparently evolved from late '*Thurmanniceras*' and co-occurs with *Acantholissonia gerthi* (Weaver) in the highest part of the Vaca Muerta Formation in Neuquén (Aguirre-Urreta & Rawson 1999a). *Lissonia riveroi* (Lisson) (Fig. 4a, b) is a widely distributed South American form, known from Chile, Peru and Colombia.

The Olcostephanus atherstoni Assemblage Biozone (Aguirre-Urreta & Rawson 1997)

Proposed as a new name for the former zone of *Olcostephanus curacoensis* (named by Leanza 1945) because the original index species is regarded as a junior subjective synonym of *O. atherstoni* (Sharpe). The base of the zone is defined by the first appearance of *Olcostephanus atherstoni* (Fig. 5a), which is often within the upper part of the Mulichinco Formation. This marks a major faunal turnover, from neocomitid to olcostephanid ammonites. The zone is developed mainly in the lower part of the Pilmatué Member of the Agrio Formation.

Three subzones are distinguished. At the base is the *O. (O.) atherstoni* Subzone (Aguirre-Urreta & Rawson 1997), which contains abundant examples of the index species, are both microconchs and large macroconchs up to 150 mm in diameter. The base of the overlying *Karakaschiceras attenuatus* Subzone (Aguirre-Urreta & Rawson 1997) is defined by the sudden appearance of abundant neocomitids (*Karakaschiceras* and *Neohoploceras*: Aguirre-Urreta 1998) (Fig. 5e). *Olcostephanus atherstoni* co-occurs in the lowest beds, then disappears.

A group of unusually evolute olcostephanids eventually replaced the neocomitids to characterize the *O. (Viluceras) permolestus* Subzone. First proposed as the *O. (Lemurostephanus)* sp. Zone by Aguirre-Urreta & Rawson (1995) to accommodate Leanza's (1958) '*Simbirskites*' fauna, it was renamed by Aguirre-Urreta & Rawson (1999c) following taxonomic revision of the characteristic fauna. The base of the subzone is defined by the first appearance of *Viluceras* (Fig. 5b). Evolute forms of *Olcostephanus*

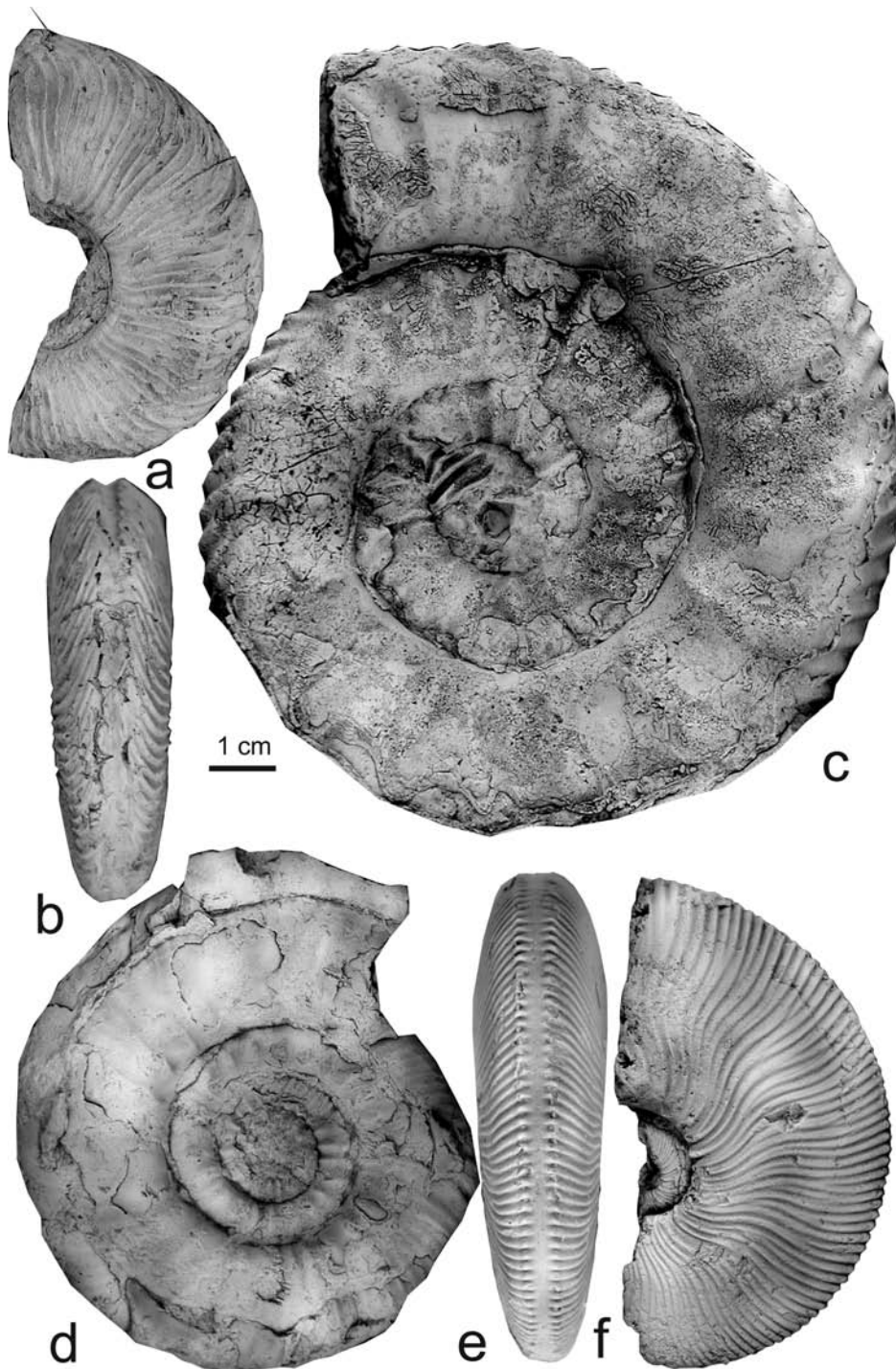


Fig. 4. Berriasian–Early Valanginian index ammonites from the Vaca Muerta Formation. (a) & (b) *Lissonia riveroi* (Lisson) (CPBA 17307). (c) *Argentiniceras noduliferum* (Steuer) (CPBA 17306). (d) *Spiticeras damesi* (Steuer) (CPBA 7606). (e) & (f) *Neocomites wichmanni* (DNGM 7260). CPBA, Repository of the University of Buenos Aires, Argentina. DNGM, Repository of the Geological Survey of Argentina.

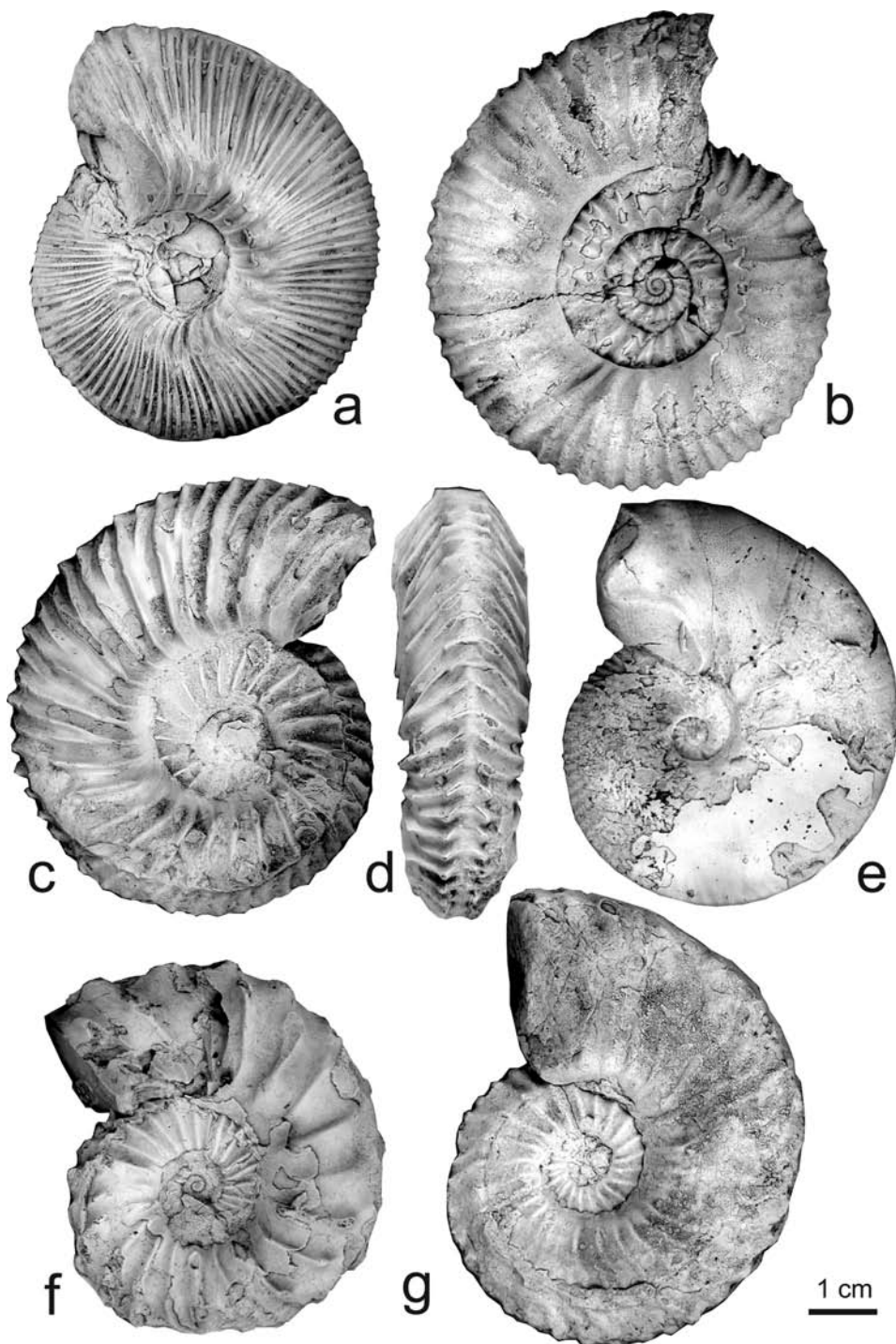


Fig. 5. Valanginian index ammonites from the Agrio Formation. (a) *Olcostephanus (Olcostephanus) atherstoni* (Sharpe) (CPBA 11481). (b) *Olcostephanus (Viluceras) permolestus* (Leanza) (CPBA 19149). (c) & (d) *Pseudofavrella angulatiformis* (Behreidsen) (CPBA 17308). (e) *Karakaschiceras attenuatus* (Behreidsen) (CPBA 17309). (f) *Chacantuceras ornatum* Aguirre-Urreta & Rawson (CPBA 18380). (g) *Neocomites* sp. (CPBA 17310).

sensu stricto form a minority element of the fauna (Aguirre-Urreta & Rawson 1999c, fig. 4a–d, g, h, k).

The Pseudofavrella angulatiformis
Assemblage Biozone (Aguirre-Urreta &
Rawson 1995)

The name was proposed as a replacement for the ‘*Lyticoceras pseudoregale* Zone’ of Gerth (1925). ‘*Lyticoceras pseudoregale*’ is poorly known and often misinterpreted, while *Pseudofavrella angulatiformis* (Fig. 5c, d) is a characteristic and distinctive component of the lower beds. The base of the zone marks another major faunal turnover, from olcostephanid to neocomitid ammonites, with slight overlap in the lowest bed at some localities. Neocomitids characterize the whole zone.

Three subzones were proposed by Aguirre-Urreta & Rawson (1997), those of *P. angulatiformis*, ‘*Acanthodiscus*’ sp. and ‘*Neocomites*’ sp. At the base, a *Pseudofavrella*–‘*Besaireceras*’ fauna characterizes the *P. angulatiformis* Subzone. The fauna is widely distributed, although often flattened in dark shales. But at Pichaihue (Fig. 2) it is beautifully preserved and bed-by-bed collecting has shown that *P. garatei* Leanza & Wiedmann is the first species to appear. A few metres higher it is largely replaced by *Pseudofavrella angulatiformis* (Behrendsen) and then ‘*Besaireceras*’ *australe* (Leanza & Wiedmann) appears a little higher. The fauna still awaits revision, but examples of all three species were described and figured by Leanza & Wiedmann (1980); their ‘*Acanthodiscus vacecki* (Neumayr & Uhlig)’ is an advanced growth stage of ‘*B. australe*’.

The ‘*Acanthodiscus*’ sp. Subzone is characterized by a very distinctive, strongly tuberculate neocomitid that we have since described as a new genus, *Chacantuceras*: as a result, the name of the subzone was changed to that of *Chacantuceras ornatum* (Fig. 5f) (Aguirre-Urreta & Rawson 1999b).

The fauna of the *Neocomites* sp. Subzone consists of involute, compressed neocomitids (Fig. 5g), some closely similar in lateral view to European forms of the *Neocomites* (*Teschennites*) *pachydicranus* group. The fauna awaits description: two specimens were figured by Aguirre-Urreta & Rawson (1997, fig. 7d–f) as *Neocomites* sp. nov.

In the highest part of the subzone and in the lowest part of the overlying *H. neuquensis* Subzone rare *Oosterella* occur (Aguirre-Urreta & Rawson 1996, 2003).

The Holcoptychites neuquensis Assemblage
Biozone (Gerth 1921, modified)

As originally defined (Gerth 1921, p. 143), the zone extended from immediately above the beds with *Neocomites* (the top of Gerth’s ‘*Acanthodiscus radiatus* Zone’) to immediately beneath the first appearance of *Crioceratites* (his ‘*Crioceras andinum* Zone’). It thus embraces several distinct faunal horizons through a considerable thickness of sediment. Aguirre-Urreta & Rawson (1997) restricted it to include only those beds characterized by *Holcoptychites*, plus a thin horizon immediately above that contains *Olcostephanus*. They recognized three subzones, of *H. neuquensis*, *H. compressum* and *Olcostephanus* (*O.*) *leanzai*. Since then all the constituent faunas have been monographed (Aguirre-Urreta & Rawson 2002, 2003); as a result, two of the subzonal names have changed (Fig. 3).

The base of the zone, and of the *H. neuquensis* Subzone, is marked by the first appearance of the genus *Holcoptychites*. The lowest forms (*H.* cf. *recopei* (Douvillé) and *H.* sp. nov.) are poorly preserved; higher in the subzone *H. magdalenae* (Douvillé) appears, then *H. neuquensis* (Douvillé) (Fig. 6b, c).

The middle subzone is characterized by more compressed *Holcoptychites* originally assigned to *H. compressum* Leanza & Wiedmann. That species is now regarded as a junior subjective synonym of *H. agrioensis* (Weaver) (Fig. 6d) so the name of the subzone has had to be changed (Aguirre-Urreta & Rawson 2003).

The base of the highest subzone is marked by the abrupt replacement of *Holcoptychites* by *Olcostephanus* – the fourth, and final, invasion of the basin by that genus. The fauna is one of the most widespread ones in the basin. The index species was initially identified as *Olcostephanus leanzai* (Giovine), but Aguirre-Urreta & Rawson (2002) showed that *O. (O.) leanzai* is a junior subjective synonym of *O. (O.) laticosta* (Gerth) (Fig. 6a) and thus changed the subzonal name to the *laticosta* Subzone. Apart from the index species, a single *O. (O.) boesei* (Riedel) is recorded, while in the upper part of the subzone *O. (Jeannoticeras) agrioensis* Aguirre-Urreta & Rawson also occurs. Seven fragments of an indeterminate neocomitid are known from the highest 2 m of the zone (Aguirre-Urreta & Rawson 2002) and may be the predecessor of the *Hoplitocrioceras* of the zone above.

Aguirre-Urreta & Rawson (2003) have proposed Agua de La Mula as the standard reference section for the *neuquensis* Zone and its three subzones.

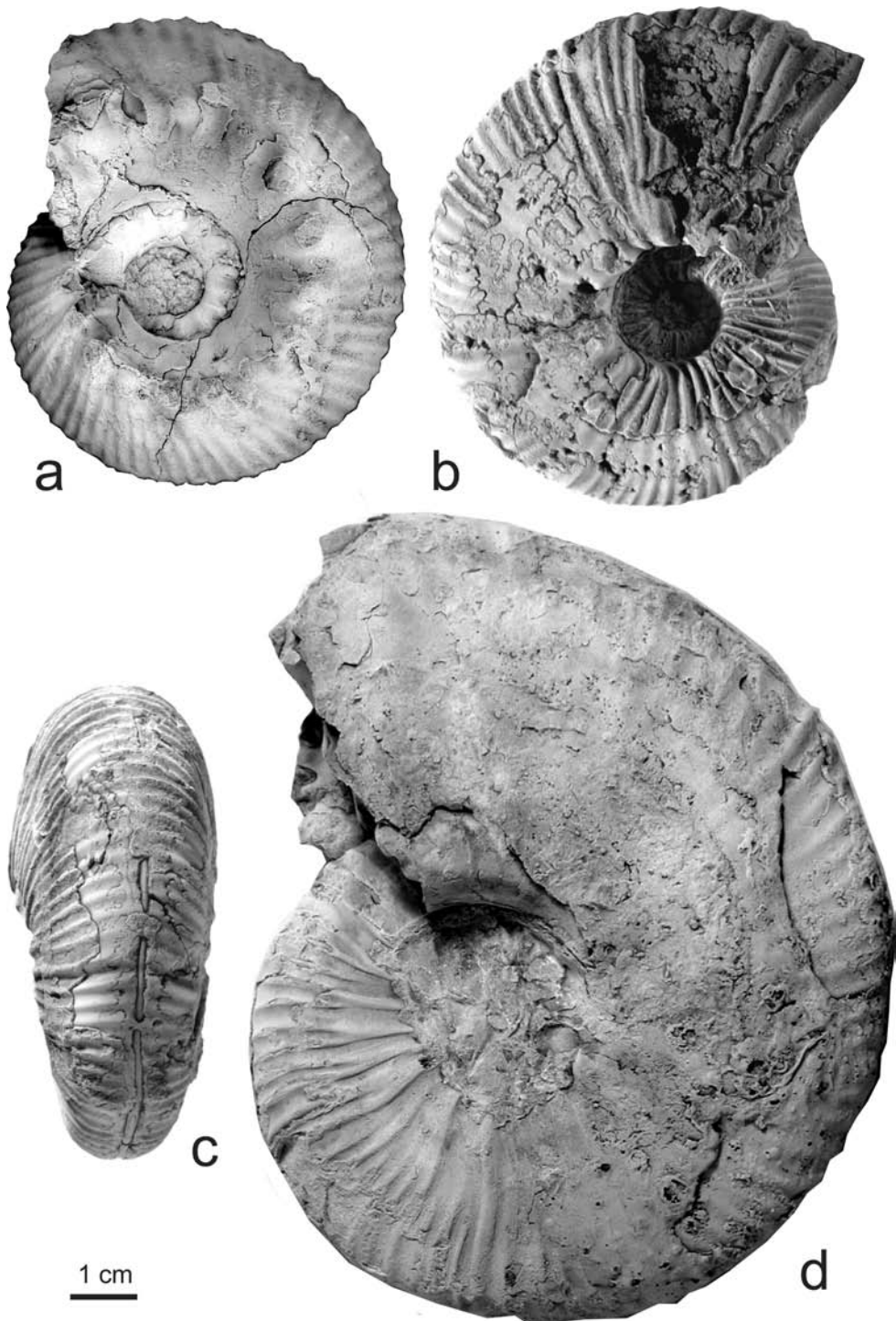


Fig. 6. Hauterivian index ammonites from the Agrio Formation. (a) *Olcostephanus (Olcostephanus) laticosta* (Gerth) (CPBA 17311). (b) & (c) *Holcoptychites neuquensis* (Douvillé) (holotype EM 2001). (d) *Holcoptychites agrioensis* (Weaver) (CPBA 20011.2). EM, Repository of the University Claude Bernard, Lyon, France.

The Hoplitocrioceras gentilii Assemblage Biozone (Aguirre-Urreta & Rawson 1997)

Proposed for the middle part of the *Holcoptychites neuquensis* Zone of previous authors, the base of the zone is marked by another turnover at family level, the neocomitid genus *Hoplitocrioceras* replacing *Olcostephanus*. *Hoplitocrioceras* may be endemic to the basin.

The *gentilii* Zone was divided into the *Hoplitocrioceras* sp. nov. and *H. gentilii* (Fig. 7a) subzones by Aguirre-Urreta & Rawson (1997), reflecting the evolution from more inflated, strongly tuberculate *Hoplitocrioceras* to more compressed forms. The fauna has since been monographed and the former '*H. sp. nov.*' named as a new species, *H. giovinei* (Fig. 7b, c), by Aguirre-Urreta & Rawson (2001). As a result, the name of the subzone was also revised (see Fig. 3). Agua de La Mula was proposed as the standard reference section for the *gentilii* Zone and its two subzones.

The only other ammonites recorded from the *Hoplitocrioceras* beds are two specimens of *Olcostephanus* (*Olcostephanus*) *variegatus* (Paquier) from the upper part of the *giovinei* Subzone (Aguirre-Urreta & Rawson 2002, fig. 5a–c).

The Weavericeras vacaensis Assemblage Biozone (Aguirre-Urreta & Rawson 1997)

Hoplitocrioceras is abruptly replaced by the desmoceratid(?) genus *Weavericeras*, which extends through the highest part of the Pilmatué Member of the Agrio Formation, up to the base of the Avilé Member. The two genera overlap in the lowest bed in the *vacaensis* Zone. *Weavericeras* (Fig. 7g) shows some variation in degree of inflation, but we have yet to investigate whether this has any stratigraphic significance. The genus was proposed by Leanza & Wiedmann (1980) who figured a single specimen and listed previous illustrations by Weaver (1931) and Giovine (1950).

The Spitidiscus riccardii Assemblage Biozone (Aguirre-Urreta, Gutiérrez Pleimling & Leanza 1993)

The zone was proposed for blue-black shales with *Spitidiscus* at the base of the Agua de la Mula Member, immediately overlying the Avilé Member. There appear to be at least two species, *S. riccardii* (Leanza & Wiedmann 1992; Aguirre-Urreta 1995) (Fig. 7e, f) and an undescribed form (Aguirre-Urreta & Rawson

1997, p. 456, fig. 6e–g), but despite extensive searches we have yet to find both in the same section and therefore remain uncertain of the order of occurrence. The shales are widespread, but at many localities *Spitidiscus* is either absent or flattened in the shale and easily missed. Elsewhere solid body chambers are common, sometimes with some phragmacone.

The Crioceratites schlagintweiti Consecutive-Range Biozone (Aguirre-Urreta & Rawson 1993)

Proposed for the lower part of the former *Crioceratites andinum* Zone to include those beds immediately above the *riccardii* Zone in which the earliest Crioceratitidae appear, *Crioceratites schlagintweiti* (Giovine) (holotype refigured by Riccardi 1988, plate 8, figs 1 & 2; Aguirre-Urreta 1993, plate 4, fig. 3) (Fig. 7i) and *C. apricus* (Giovine) (holotype refigured by Riccardi 1988, plate 7, figs 3–5; Aguirre-Urreta 1993, plate 3, fig. 7). The fauna awaits revision.

The Crioceratites diamantensis Consecutive-Range Biozone (Aguirre-Urreta & Rawson 1993)

Proposed for the upper part of the former *Crioceratites andinus* Zone. The first appearance of the index species *C. diamantensis* (Fig. 7h) defines the base of the zone. *Crioceratites andinus* (Gerth) also occurs: the holotypes of both species were refigured by Aguirre Urreta (1993, plate 3, fig. 8, plate 4, fig. 1). Other specific names are also available, and the whole fauna awaits revision. But in comparison with the underlying forms, these later *Crioceratites* are more compressed and involute, showing a tendency to recoil.

At Pichaihue some *Crioceratites* occur in the highest beds of this zone, but are different from the *diamantensis*–*andinus* group and look more like European Barremian forms.

The Paraspiticeras groeberi Local Range Biozone (Aguirre-Urreta & Rawson 1993)

The base of the zone is marked by the first appearance of *Paraspiticeras* (Fig. 7d), a few metres above the *Crioceratites*-bearing beds. Only the index species is known.

At Mina San Eduardo, Pichaihue, Puesto Ponce and Loma Tilhué, only a few fragments

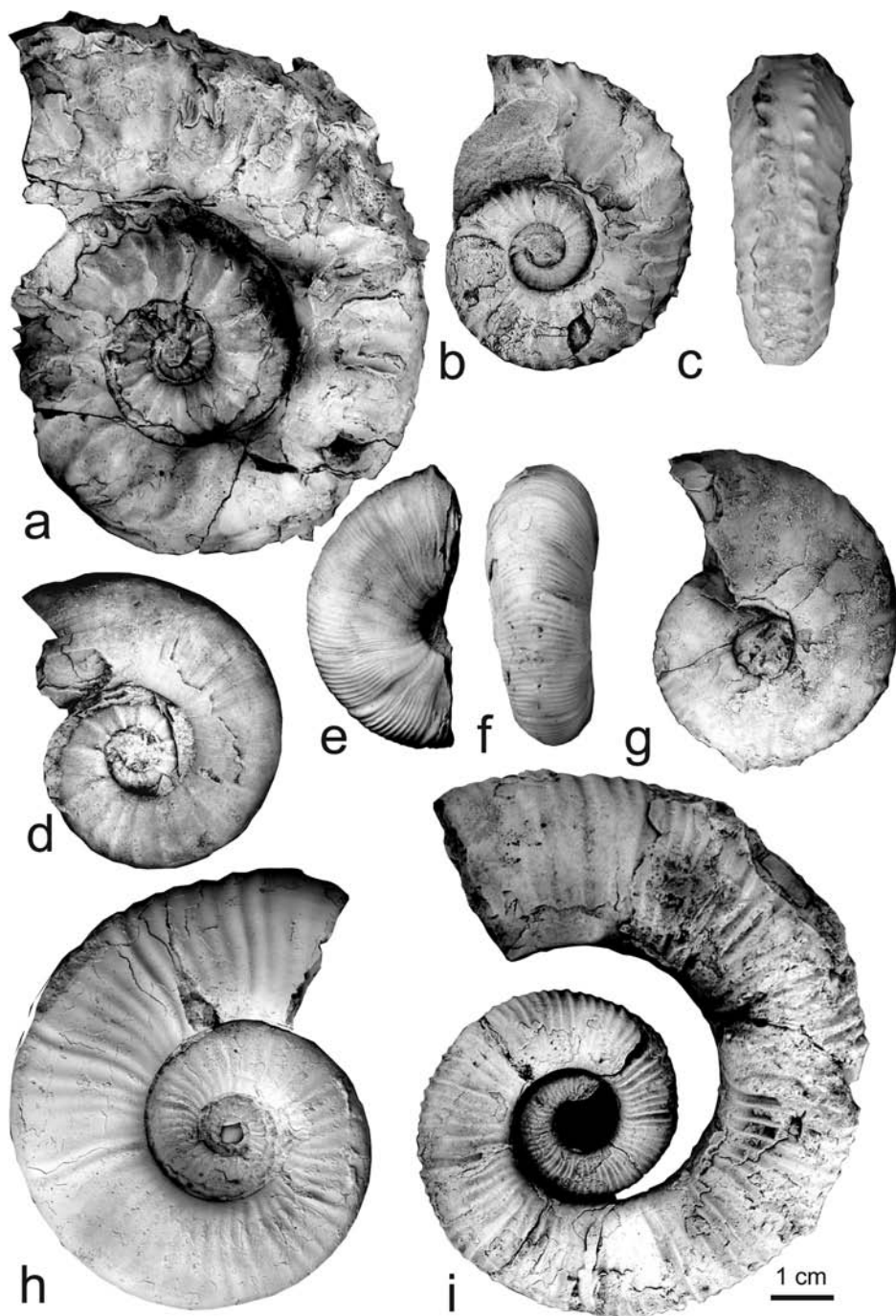


Fig. 7. Hauterivian and Early Barremian (?) index ammonites from the Agrio Formation. (a) *Hoplitocrioceras gentilii* Giovine (CPBA 19187). (b) & (c) *Hoplitocrioceras giovinei* Aguirre-Urreta & Rawson (CPBA 19234). (d) *Paraspiticeras groeberi* Aguirre-Urreta & Rawson (CPBA 17312). (e) & (f) *Spitidiscus riccardii* Leanza & Wiedmann (CPBA 17026). (g) *Weavericeras vacaensis* (Weaver) (CPBA 17313). (h) *Crioceratites diamantensis* (Gerth) (MLP 21386). (i) *Crioceratites schlagintweiti* (Giovine) (holotype CPBA 5147). MLP, Repository of the La Plata Museum of Natural Sciences, La Plata, Argentina.

of an open coiled heteromorph ammonoid have been recovered from the highest beds of the Agua de La Mula Member, above *Paraspiticeras*. The scarcity of the fossil material and the uncertainty of its systematic assignment prevent the recognition of a new zone.

Correlation with the 'standard' succession of the Mediterranean region

The Neuquén ammonite fauna consists of an alternation of endemic and more widely distributed genera. The latter include *Spiticeras*, *Neocosmoceras*, *Neocomites*, *Karakaschiceras*, *Neohoploceras*, *Valanginites*, *Olcostephanus*, *Spitidiscus*, *Crioceratites* and *Paraspiticeras*, all of which occur also in the Mediterranean area, where the 'standard' Lower Cretaceous stages and ammonite zones were defined (see Rawson *et al.* 1996; Hoedemaeker *et al.* 2003). But most of these genera were quite long ranging and embraced numerous species, very few of which are common to both areas. Hence, only a limited number of levels can be correlated with confidence. The preliminary correlations of Aguirre-Urreta & Rawson (1997) and Rawson (1999) are updated here in the light of much new stratigraphic and taxonomic work, and are summarized in Figures 8 and 9.

In the Berriasian there are some genera in common between the Neuquén Basin and the Mediterranean region, as *Spiticeras* and *Neocosmoceras* are both well known from the latter area (Simonescu 1899; Djanélidzé 1922; Mazenot 1939). However, it is not possible at the moment to compare them at a specific level due to the lack of modern studies of the Argentine faunas. *Argentiniceras* and *Groebericeras* are also known from the Mediterranean region but with more restricted occurrences (Pomel 1889; Mazenot 1939; Hoedemaeker 1982).

There is a good correlation in the middle part of the Valanginian, at two successive levels. The *atherstoni* Subzone of the Argentine succession can be correlated with the middle part of the *campylotoxus* Zone where *O. guebhardi*, a possible synonym of *O. atherstoni*, has its acme. Just above, the Argentine *Karakaschiceras*/*Neohoploceras* faunas of the *attenuatus* Subzone (Aguirre-Urreta 1998) are so close to those of the Mediterranean area that they can be correlated confidently with the *biassalensis*–*peregrinus* subzones of the French successions.

There is then an extensive succession of faunas from the *permolestus*–*compressum* subzones where correlation is very tentative. In the

permolestus Subzone *Viluceras*, an endemic subgenus of *Olcostephanus*, is accompanied by occasional evolute *Olcostephanus* s.s. that provide a tentative link with the *nicklesi* Subzone of the Mediterranean region, which is characterized by similarly evolute *Olcostephanus* (Aguirre-Urreta & Rawson 1999b). The base of the *neuquensis* Zone appears to lie at about the base of the Hauterivian; rare *Oosterella* occur either side of the boundary in both areas, while early *Holcoptychites* appear very close to early *Spitidiscus* from the lowest Hauterivian in Europe (Aguirre-Urreta & Rawson 2003) (see Fig. 8).

A firmer correlation is provided in the *laticosta* Subzone, where the very short-ranged but widely distributed *Jeannoticeras*, a distinctive subgenus of *Olcostephanus*, occurs in the upper part. This suggests a correlation with the *jeannoti* Subzone. Such a correlation is supported by the discovery of very rare specimens of *O. (O.) variegatus*, index of the overlying *variegatus* Horizon in France, in the *giovinei* Subzone in Neuquén (Aguirre-Urreta & Rawson 2002) (Fig. 8).

Spitidiscus sp. nov. (Aguirre-Urreta & Rawson 1997, fig. 7f, g) in the *riccardii* Zone appears almost identical to forms from the *sayni* Zone in France, while *Crioceratites apicus* (Giovine) from the *schlagintweiti* Zone is virtually indistinguishable from forms in the *sayni*–*ligatus* zones. The *Crioceratites* of the *diamantense* Zone have diverged from their Mediterranean counterparts in some aspects, but like the later Hauterivian–earliest Barremian *Pseudothurmannia* they are more tightly coiled than their predecessors.

The highest zone in the Neuquén Basin has yielded only the index species, *Paraspiticeras groeberi*, provisionally dated as Early Barremian by Aguirre-Urreta & Rawson (1993).

Calcareous nannofossil biostratigraphy

Information concerning Lower Cretaceous calcareous nannofossils of the Neuquén Basin is still scarce. There have been a small number of studies with hydrocarbon exploration aims (Angelozzi 1991, 1995), and more recent papers that have focused on biostratigraphy and correlation (Mostajo *et al.* 1995; Simeoni & Musacchio 1996; Aguirre-Urreta *et al.* 1999; Concheyro & Sagasti 1999; Scasso & Concheyro 1999; Concheyro *et al.* 2002; Concheyro & Bown 2002; Bown & Concheyro 2004).

Nannofossil data compiled from several sections in the Vaca Muerta, Mulichinco and Agrio formations are presented here. They are,

AGE	WEST MEDITERRANEAN PROVINCE Hoedemaeker, Reboulet <i>et al.</i> 2003		NEUQUEN BASIN This paper	
	BIOZONE	SUB-BIOZONE (S)/ HORIZON (H)	BIOZONE	SUB-BIOZONE
B LATE HAUT.	<i>Taveraidiscus hugii</i>		<i>Paraspiticeras groeberi</i>	
	<i>Pseudothurmannia ohmi</i>		<i>Crioceratites diamantensis</i>	
	<i>Balearites balearis</i>		<i>Crioceratites schlagintweiti</i>	
	<i>Pleisiospit. ligatus</i>		<i>Spitidiscus riccardii</i>	
	<i>Subsaynella sayni</i>		<i>Weavericeras vacaensis</i>	
EARLY HAUTERIVIAN	<i>Lyticoceras nodosoplicatum</i>	<i>Olcostephanus (O.) variegatus</i> H	<i>Hoplitocrioceras gentilii</i>	<i>Hop. gentilii</i>
	<i>Crioceratites loryi</i>	<i>O. (Jeannoticeras) jeannoti</i> S	<i>Holcoptychites neuquensis</i>	<i>Olcostephanus (Olcostephanus) laticosta</i>
		<i>Crioceratites loryi</i> S		<i>Hol. agrioensis</i>
	<i>Acanthodiscus radiatus</i>			<i>Hol. neuquensis</i>
LATE VALANGINIAN	<i>Criosarasinella furcillata</i>	<i>N. (Teschentes) callidiscus</i> S	<i>Pseudofavrella angulatiformis</i>	<i>Neocomites</i> sp.
		<i>Criosarasinella furcillata</i> S		<i>Chacantuceras ornatum</i>
	<i>Neocomites peregrinus</i>	<i>Olcostephanus (O.) nicklesi</i> S		<i>Olcostephanus (Olcostephanus) atherstoni</i>
	<i>N. peregrinus</i> S	<i>Karakaschiceras attenuatus</i>		
<i>Saynoceras verrucosum</i>	<i>K. pronecostatum</i> S			
EARLY VAL.	<i>Busnardoites campylotoxus</i>	<i>S. verrucosum</i> S	<i>Lissonia riveroi</i>	<i>Olcostephanus (O.) atherstoni</i>
		<i>K. biassalensis</i> S		
	<i>Thurmanniceras pertransiens</i>	<i>Busnardoites campylotoxus</i> S		

Fig. 8. Correlation chart of the West Mediterranean and Neuquén ammonite biozones and subzones. West Mediterranean biozones after Hoedemaeker *et al.* (2003).

AGE		NEUQUEN BASIN			TETHYAN REGION		WEST MEDITERRANEAN PROVINCE		AGE
	AMMONITE BIOZONE (B)/ SUB-BIOZONE (S)	NANNOFOSSIL EVENTS	ZONE	NANNOFOSSIL EVENTS	ZONE	NANNOFOSSIL EVENTS	AMMONITE BIOZONE (B)/ SUB-BIOZONE (S)/ HORIZON (H)		
EARLY HAUTERIVIAN	<i>Paraspticerias groeberi</i> B	▼ <i>Nannoconus ligus</i>	CC5A	▼ <i>Lithraphidites bollii</i>	CC5A	▼ <i>Lithraphidites bollii</i>	<i>Taveraidiscus hugii</i> B	LATE HAUTERIVIAN	ϩ
	<i>Crioceratites diamantensis</i> B	▼ <i>Lithraphidites bollii</i>	CC4B	▼ <i>Nannoconus ligus</i>	CC4B	▼ <i>Speetonia colligata</i>	<i>Pseudothurmannia ohmi</i> B		
EARLY HAUTERIVIAN	<i>Crioceratites schlagintweitii</i> B	▼ <i>Eifellithus striatus</i>		▲ <i>Crucellipsis cuvillieri</i>		▲ <i>Crucellipsis cuvillieri</i>	<i>Balearites balearis</i> B	LATE HAUTERIVIAN	ϩ
	<i>Spitidiscus riccardii</i> B	▼ <i>Lithraphidites bollii</i>		▲ <i>Lithraphidites bollii</i>		▼ <i>Eifellithus striatus</i>	<i>Pleisioptidiscus ligatus</i> B		
EARLY HAUTERIVIAN	<i>Weavericeras vacaensis</i> B	▼ <i>Clepsilithus maculosus</i>		▼ <i>Lithraphidites bollii</i>		▼ <i>Eifellithus striatus</i>	<i>Subsaynella sayni</i> B	EARLY HAUTERIVIAN	ϩ
	<i>Hoplitocrioceras gentilii</i> S			▼ <i>Clepsilithus maculosus</i>		▼ <i>Eifellithus striatus</i>	<i>Lyticoceras nodosoplicatum</i> B		
LATE VALANGINIAN	<i>Hoplitocrioceras giovinei</i> S	▼ <i>Eifellithus windii</i>	CC4A	▼ <i>Eifellithus windii</i>	CC4A	▼ <i>Eifellithus windii</i>	<i>O. (O.) variegatus</i> H	LATE VALANGINIAN	ϩ
	<i>Olcostephanus (O.) laticosta</i> S	▲ <i>Clepsilithus maculosus</i>		▲ <i>Eifellithus windii</i>		▲ <i>Eifellithus striatus</i>	<i>O. (Jeannoticeras) Jeannoti</i> S		
EARLY VALANGINIAN	<i>Holcoptychites agrioensis</i> S			▲ <i>Wide canal Nannoconus</i>		▲ <i>Eifellithus striatus</i>	<i>Crioceratites loryi</i> S	EARLY VALANGINIAN	ϩ
	<i>Holcoptychites neuquensis</i> S			▲ <i>Eifellithus striatus</i>		▲ <i>Eifellithus striatus</i>	<i>Acanthodiscus radiatus</i> B		
EARLY VALANGINIAN	<i>Neocomites</i> sp. S						<i>N. (Teschentites) callidiscus</i> S	EARLY VALANGINIAN	ϩ
	<i>Chacantuceras ornatum</i> S						<i>Criosarasinella furcillata</i> S		
EARLY VALANGINIAN	<i>Pseudofavrella angulatifomis</i> S						<i>Olcostephanus (O.) nicklesi</i> S	EARLY VALANGINIAN	ϩ
	<i>O. (Viluceras) permolestus</i> S						<i>Neocomites peregrinus</i> S		
EARLY VALANGINIAN	<i>Karakaschiceras attenuatus</i> S		CC3B		CC3B	▼ <i>Rucinolithus wisel</i>	<i>Karakaschiceras pronecostatum</i> S	EARLY VALANGINIAN	ϩ
	<i>Olcostephanus (O.) atherstoni</i> S					▲ <i>Eifellithus windii</i>	<i>Saynoceras verrucosum</i> S		
EARLY VALANGINIAN	<i>Lissonia riverol</i> B	▼ <i>Eifellithus primus</i>		▼ <i>Eifellithus windii</i>		▲ <i>Eifellithus windii</i>	<i>Karakaschiceras biassalensis</i> S	EARLY VALANGINIAN	ϩ
	<i>Neocomites wichmanni</i> B	▲ <i>Eifellithus primus</i>		▲ <i>Eifellithus primus</i>		▲ <i>Calcalathina oblongata</i>	<i>Busnardoites campylotoxus</i> S		
EARLY VALANGINIAN	<i>Spitceras damesi</i> B	▲ <i>Haqius circumradiatus</i>		▲ <i>Haqius circumradiatus</i>			<i>Thurmanniceras pertransiens</i> B	EARLY VALANGINIAN	ϩ
	<i>Argentiniceras noduliferum</i> B	▼ <i>Crucellipsis cuvillieri</i>		▼ <i>Crucellipsis cuvillieri</i>			<i>Subthurmannia boissieri</i>		
EARLY VALANGINIAN							<i>Subthurmannia occitanica</i>	EARLY VALANGINIAN	ϩ
							<i>Berriasella jacobii</i>		

Fig. 9. Calibration of Neuquén nannofossil events against the ammonite zones, and comparison with Tethyan nannofossil events calibrated against the West Mediterranean ammonite zones. Correlation across the table is based on the ammonite correlations. Tethyan nannofossil events based on Bralower *et al.* (1989) and Bown *et al.* (1998).

from north to south: Arroyo Cienaguitas and Arroyo Loncoche (Mendoza Province), Buta Ranquil, Pampa Tril, Cerro La Parva, Mina San Eduardo, Agua de la Mula and El Marucho (Neuquén Province) (Fig. 2).

The taxonomy used here follows Bown & Concheyro (2004), where a full list of calcareous nannofossils is provided.

The basal Vaca Muerta Formation is barren of nannofossils but the formation becomes nannofossiliferous up-section, yielding moderately preserved, low-diversity assemblages dominated by *Watznaueria* (Scasso & Concheyro 1999; Bown & Concheyro 2004). In the Pampa Tril area matrix samples from a vertebrate fossil specimen yielded *Haqius circumradiatus* and *Micrantholiths hoschulzii* (Fig. 10a); their occurrence supports the Berriasian age indicated by the ammonite *Neocosmoceras* sp. found at the same level. The upper part of the formation is assigned to the Lower Valanginian based on the presence of *Eiffellithus primus* and *Eiffellithus windii*, and the absence of *Eiffellithus striatus* (Bown & Concheyro 2004).

The Mulichinco Formation is almost barren of nannofossils, with only depauperate assemblages having been reported.

The Agrio Formation yields common, moderately preserved assemblages of low to moderate diversity. Nannofossil abundance increases upwards through the Pilmatué Member, which is dated as Late Valanginian and Early Hauterivian based on the presence of *Eiffellithus striatus*, the last occurrence of *Eiffellithus windii* and the occurrence of *Clepsilithus maculosus* (Bown & Concheyro 2004).

The Avilé Member (continental or marginal marine deposits) is almost barren of nannofossils, although a poor assemblage dominated by watznauerids has been reported from the northern Mendoza Province (Angelozzi pers. Comm. 1998).

Abundance and diversity increases through the overlying Agua de la Mula Member, although the topmost beds are barren of nannofossils. This member is assigned to the Upper Hauterivian based on the absence of *E. striatus*, the last occurrence of *Cruciellipsis cuvillieri*, and the presence of *Speetonia colligata* (Fig. 10b), *Lithraphidites bollii* and *Nannoconus ligius* (Bown & Concheyro 2004).

Calcareous nannofossil bioevents

Many Early Cretaceous nannofossil species have cosmopolitan distributions, and a number of global biostratigraphic events or bioevents are recognized. However, the presence of numerous,

more geographically restricted taxa has allowed the construction of higher resolution biozonations for both the Tethyan and Boreal realms (Thierstein 1973; Sissingh 1977; Crux 1989; Bown *et al.* 1998; Jeremiah 2001). The nannocooids are the most abundant Tethyan nannofossil group, and they have been used in biostratigraphic schemes, particularly in Tethyan carbonate platform settings (Deres & Archéritéguy 1980; Perch-Nielsen 1985). However, the variability in their morphologies and poor preservation in limestones obscure their usefulness. Nannoconids are relatively frequent in the Neuquén Basin beds, and may have good potential for correlation (Bown & Concheyro 2004).

The nannofossil bioevents determined in the Lower Cretaceous of the Neuquén Basin include the first and last occurrences (FO and LO) of *Clepsilithus maculosus*, *Cruciellipsis cuvillieri*, *Eiffellithus primus*, *Eiffellithus windii*, *Eiffellithus striatus*, *Lithraphidites bollii* and '*Nannoconus*' *ligius* (Fig. 9).

The abbreviations NAZ indicate the local Neuquén ammonite zones, NASZ, for Neuquén ammonite subzones, TAZ to differentiate Tethyan ammonite zones and BAZ for Boreal ammonite zones.

Cruciellipsis cuvillieri bioevents

The FO of *Cruciellipsis cuvillieri* may not be a reliable bioevent in the Neuquén Basin as it has been recorded at different levels in different sections, usually stratigraphically higher than its true earliest Berriasian evolutionary appearance (Bown *et al.* 1998). The FO has been recorded in Berriasian sediments at Arroyo Cienaguitas (Bown & Concheyro 2004), but in Valanginian or Hauterivian sediments elsewhere: in the *wichmanni* NAZ at Pampa Tril, the *attenuatum* NASZ in Cerro La Parva, the *ornatum* NAZ at Agua de la Mula and Buta Ranquil, and the *riccardii* NAZ at Mina San Eduardo, where it is restricted to the Agua de la Mula Member. This rather inconsistent distribution may indicate that the species was at the edge of its ecological range, and excluded by unfavourable environments, or may reflect poorer preservation in the lower part of the sequence.

At Pampa Tril, the LO of *C. cuvillieri* (Fig. 10c) is recorded within the *riccardii* NAZ (Bown & Concheyro 2004); in Agua de la Mula and Mina San Eduardo the LO coincides with the base of the *schlagintweiti* NAZ, and appears to be consistent with its global extinction level, corroborating the ammonite correlation with the *sayni* TAZ of the standard Mediterranean sequences.

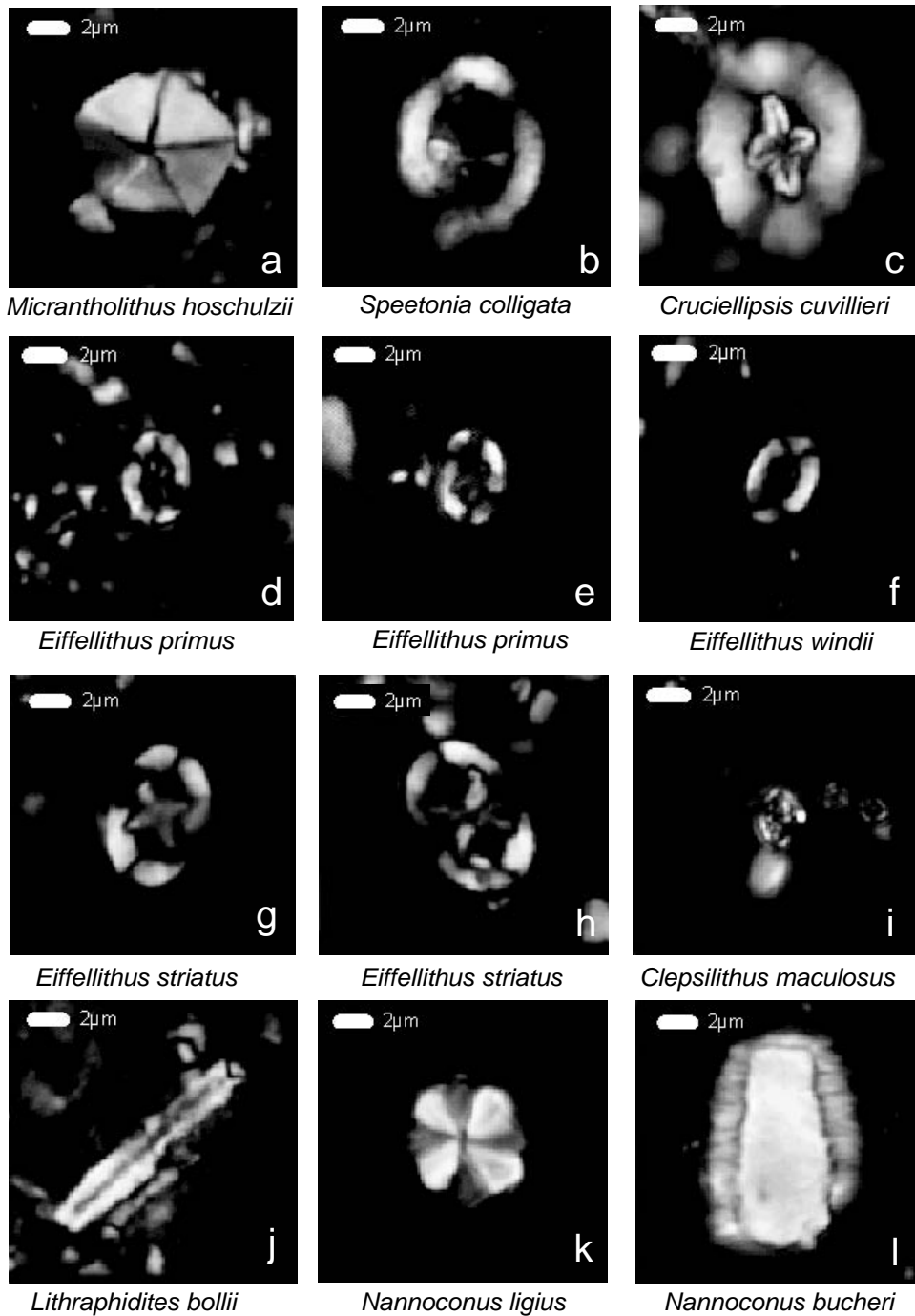


Fig. 10. Selected calcareous nanofossils from the Vaca Muerta and Agrio formations of the Pampa Tril Section. (a) *Micrantholithus hoschulzii*; PTCV6, XPL. (b) *Speetonia colligata*, PT2, XPL. (c) *Cruciellipsis cuvillieri*, PTA22, XPL. (d) & (e) *Eiffellithus primus* PT3, PT9, XPL. (f) *Eiffellithus windii*, PT16, XPL. (g) & (h) *Eiffellithus striatus*, PTA24, PTA42, XPL. (i) *Clepsilithus maculosus*, PTCV6, XPL. (j) *Lithraphidites bollii*, PTUA 16, XPL. (k) *Nannoconus ligius*, PTUA26, XPL. (l) *Nannoconus bucheri*, PTUA27, XPL, cross-nicols, polarized light. PT indicates Pampa Tril section.

Eiffellithus primus bioevents

The lowest occurrence of *Eiffellithus primus* was only recorded in the Pampa Tril area, in beds of the Vaca Muerta Formation. Its FO in Tethyan regions indicates a mid Berriasian age (Bralower *et al.* 1989), but in Pampa Tril the FO of *E. primus* (Fig. 10d, e) is in the lower *wichmanni* NAZ of the Lower Valanginian. The LO of *E. primus* occurs in the upper part of the *riveroi* NAZ and indicates a correlation with the Lower Valanginian *campylotoxus* TAZ (Bergen 1994).

Eiffellithus windii bioevents

The *E. windii* record is scattered in the studied samples, and care must be taken in distinguishing *E. windii* from the descendant species *E. striatus*. Applegate & Bergen (1989) also recognized this difficulty and chose a coccolith length of 6.4 μm as an arbitrary morphometric cut-off between these two species. Specimens smaller than this size are included in *E. windii*, and we followed this definition.

Eiffellithus windii (Fig. 10f) is found only in the Vaca Muerta Formation and the Pilmatué Member of the Agrio Formation, but is absent in many sections probably due to unsuitable coarse clastic marine facies.

The most complete record is at Pampa Tril, where the FO is in the *wichmanni* NAZ (Vaca Muerta Formation), while the LO is in the *Neocomites* sp. NAsZ (Pilmatué Member). Ranges elsewhere are shorter: at Buta Ranquil the FO is in the *angulatiformis* NasZ and the LO in the *neuquensis* NAsZ, while at Mina San Eduardo the species is recorded only in one sample in the *Chacantuceras ornatum* NasZ.

The FO of *E. windii* and LO of *E. primus* are in close proximity at Pampa Tril and these bioevents have been recorded in the upper Lower Valanginian *campylotoxus* TAZ (Bergen 1994; Bown & Concheyro 2004). The exact level of the LO of *E. windii* is not well constrained in Neuquén, but at Pampa Tril it is as high as the *Neocomites* sp. NAsZ. The same event was recorded by Bergen (1994) in the lowermost Hauterivian *radiatus* TAZ.

Eiffellithus striatus bioevents

The FO of *Eiffellithus striatus* (Fig. 10g, h) has been recorded in almost all sections. At Arroyo Loncoche, Pampa Tril, Buta Ranquil and Mina San Eduardo it occurs in the *angulatiformis* NAsZ. At Agua de la Mula the FO is slightly higher, in the *ornatum* NasZ, while at

Cienaguitas it lies above the *Neocomites* sp. beds. Bergen (1994) recorded the FO of *E. striatus* in the Upper Valanginian *trinodosum* TAZ (at about the base of the *furcillata* Subzone of the zonation used here).

At Pampa Tril the LO of *E. striatus* is recorded just below the Avilé Member, in the *vacaensis* NAZ. However, in the San Eduardo section this event occurs just above the Avilé Member (*riccardii* NAZ) (Concheyro *et al.* 2002), a level correlated with the lowermost Upper Hauterivian *sayni* TAZ by Aguirre-Urreta & Rawson (2001) and coincident with the established LO of *E. striatus* in SE France by Bergen (1994). In Agua de la Mula the LO of *E. striatus* is slightly higher, in the *schlagintweiti* NAZ.

Clepsilithus maculosus bioevents

Clepsilithus maculosus (Fig. 10i) ranges from the Lower Hauterivian (*?amblygonium-noricum* BAZs) to lowermost Barremian (lower *variabilis* BAZ) of the Boreal area (Bown *et al.* 1998; Jeremiah 2001). In the Pampa Tril section its FO is recorded in the *neuquensis* NAZ, which is correlated with the *radiatus* and *Crioceratites loryi* TAZs (Lower Hauterivian). The LO has been determined in the *vacaensis* NAZ, which probably correlates with the highest part of the *nodosoplicatum* TAZ (Upper Lower Hauterivian) (Fig. 9).

Lithraphidites bollii bioevents

Lithraphidites bollii (Fig. 10j), a Hauterivian marker (Thierstein 1971; Bergen 1994), appears sporadically in some samples from Pampa Tril, Agua de la Mula and Mina San Eduardo. At Pampa Tril we only recovered fragmentary material. Its lowest occurrence is in the lower Upper Hauterivian, at the base of the *riccardii* NAZ; its Tethyan FO is recorded in the Lower Hauterivian *loryi* TAZ (Bergen 1994). At Pampa Tril an influx of *L. bollii* is detected in the *diamantensis* NAZ, and a comparable event has been recorded also in the Boreal North Sea Basin, within the *gottschei* BAZ (Rutledge 1995).

At Agua de la Mula the distribution of *L. bollii* is sparse, but its FO is in the *schlagintweiti* NAZ and its LO in the *diamantensis* NAZ, in the upper part of the Agua de la Mula Member.

The LO of *L. bollii* may not represent the extinction level, which was recorded as uppermost Hauterivian (*angulicostata* TAZ) by Bergen (1994).

Nannoconus ligius bioevents

The problematical nannolith *Nannoconus ligius* (Fig. 10k) has been found in almost all the Agua

de la Mula Member sections. In Arroyo Cienaguillas and Arroyo Loncoche (Concheyro & Sagasti 1999) the FO of *N. ligius* is consistently above *Crioceratites diamantensis* up to the top of the section; while in Agua de la Mula, Mina San Eduardo and Pampa Tril the FO has been recorded within the *diamantensis* Zone. The LO of *N. ligius* occurs near the boundary between *diamantensis* and *groeberi* zones in some sections.

Nannoconus ligius has been recorded previously by Applegate & Bergen (1989) from the Upper Hauterivian of the Galicia Margin. Bergen (1994) extended its range from the Upper Hauterivian (*ligatus* TAZ) to the Upper Aptian of SE France and the Blake–Bahama Plateau. The constant presence of *N. ligius* in almost all the Hauterivian Agua de la Mula Member localities of the Neuquén Basin supports the stratigraphic range originally assigned for this species by Applegate & Bergen (1989).

Biogeographic significance of nannoconids in the Neuquén Basin

The presence of nannoconids, an enigmatic group of extinct nannofossils of unknown biological affinities and uncertain palaeoecology, is one of the most interesting elements of the Lower Cretaceous nannoflora of the Neuquén Basin. Their presence indicates a good marine connection with the Tethys–Caribbean seaway at this time. However, they are never as abundant in Neuquén as in contemporaneous Tethyan sequences.

Nannoconids are present in all the sections that we have studied, with the exception of Cerro La Parva. They are rare and sporadic in the Vaca Muerta Formation, and not consistently present until the Pilmatué Member of the Agrío Formation (Upper Valanginian from ammonite correlations). They are absent just beneath the Avilé Member but are consistently present and often relatively common through the Agua de la Mula Member (Angelozzi 1991, 1995; Bown & Concheyro 2004).

In Neuquén the nannoconid record indicates a significant lag-time between their evolutionary appearance in the Tethyan area (Tithonian) and their migration into ‘extra-Tethyan’ areas. But nannoconids with wide central canals, such as *Nannoconus bucheri* (Fig. 10l), *N. circularis* and *N. cf. N. circularis*, are found relatively low in the sequence (Upper Valanginian from ammonite correlations) compared with most published ranges, which are Lower Hauterivian, Barremian and higher (Perch-Nielsen 1985; Mutterlose 1996; Bown *et al.* 1998). These

earlier occurrences in Neuquén support a similar record by Gardin *et al.* (2000). However, the early occurrence of *N. circularis* is particularly puzzling as it is an atypically distinctive nannoconid, yet it has only been recorded previously from the Barremian to Aptian elsewhere (e.g. Deres & Archéritéguy 1980; Perch-Nielsen 1985).

These observations point out to the difficulties in establishing bioevents and biozones based on this enigmatic fossil group that had a restricted biogeography.

Palynomorph biostratigraphy

The oldest palynological assemblage known from the Lower Cretaceous of the Neuquén Basin was recovered from the upper part of the Vaca Muerta Formation at Mallín Quemado, c. 20 km east of Las Lajas (Quattrocchio & Volkheimer 1985). The co-occurrence of the ammonite *Spiticeras damesi* indicates a Late Berriasian age for this assemblage. The palynoflora includes dinocysts, acritarchs and miospores. The marine assemblage includes *Hystrichosphaerina neuquina* (Fig. 11a), a characteristic species of the Tithonian *Acanthaulax downei* Interval Zone, and of the Tithonian–?Early Berriasian *Dichadogonyaulax cumula* var. *curtospina* Interval Zone, and *Aptea notialis* Range Zone (Fig. 11c, d) (Quattrocchio & Sarjeant 1992; Quattrocchio *et al.* 1996, 2002). Microforaminiferal linings are also common (Fig. 11b). The terrestrial assemblages are characterized by the presence of *Araucariacites australis* (Fig. 11e), different species of *Callialasporites* (Fig. 11f) and *Classopollis*, and spores, and is comparable to equivalent assemblages recovered from the lower part of the unit and referred to the Tithonian–?Early Berriasian *Microcachrydites anctarcticus* Acme Zone (Quattrocchio *et al.* 1996) and to the Late Berriasian–?Early Valanginian Zone 1 of Quattrocchio *et al.* (2002).

The Mulichinco Formation was preliminarily studied from several different sections in the basin (Archangelsky 1977, 1980; Dellapé *et al.* 1978; Prámparo *et al.* 1995; Quattrocchio *et al.* 1999). The formation yields terrestrial and marine palynomorphs that are similar to those present in the overlying Agrío Formation, as well as marine dinocysts that are common in the Tithonian–Berriasian Vaca Muerta Formation.

There are several palynological studies on the Agrío Formation. They document principally miospores and terrestrial phytoplankton (Volkheimer & Sepúlveda 1976; Volkheimer

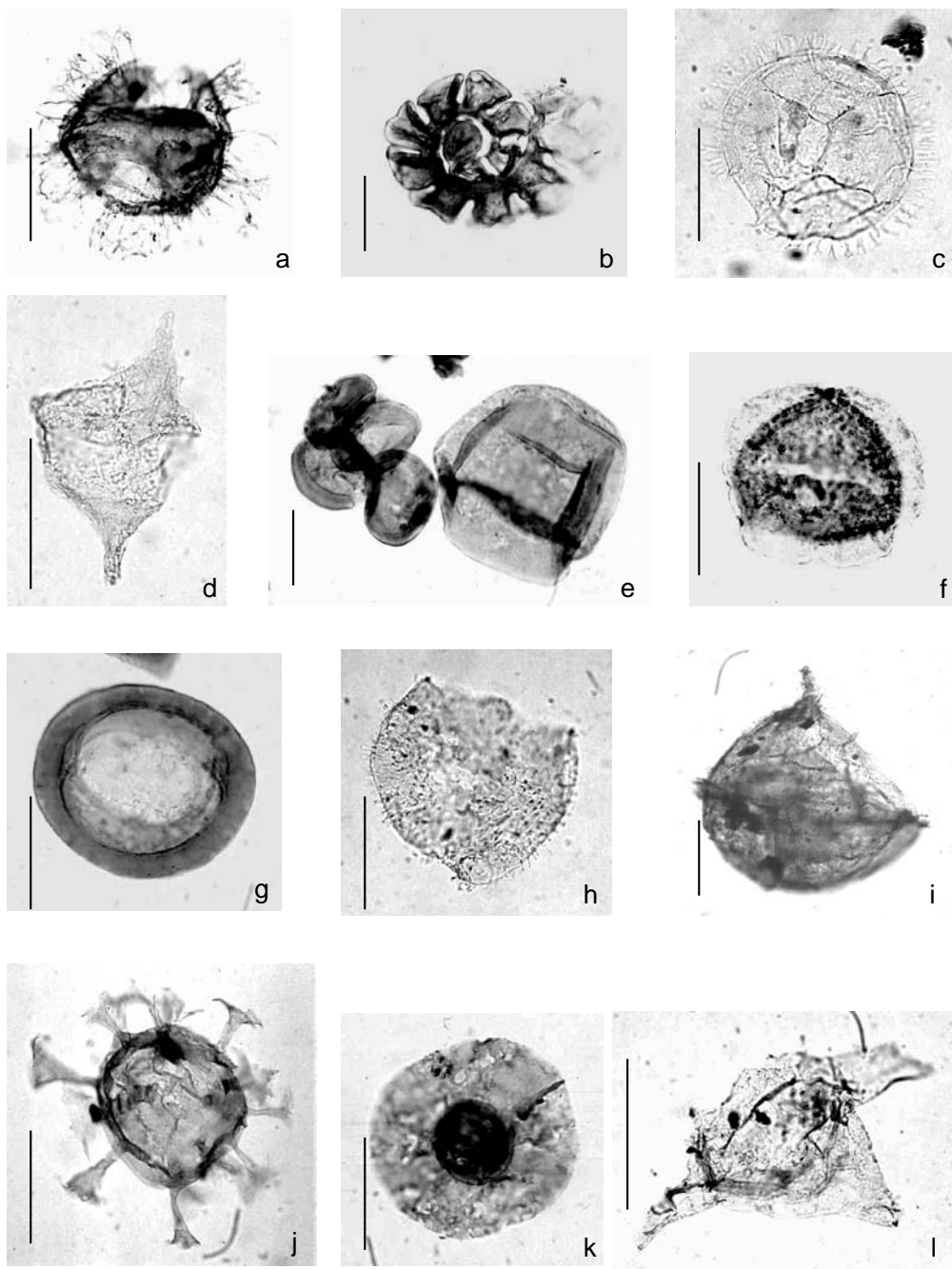


Fig. 11. Selected palynomorphs from the Tithonian–?Early Berriasian Vaca Muerta Formation (a–d) and the Valanginian–?Early Barremian Agrio Formation (e–l). (a) *Hystrichosphaerina neuquina* Quattrocchio & Volkheimer emend. Quattrocchio & Sarjeant. (b) Microforaminiferal lining. (c) *Dichadogonyaulax cumula* var. *curtospina* Quattrocchio & Sarjeant. (d) *Apta notialis* Quattrocchio & Sarjeant. (e) *Classopollis* sp. (left), and *Araucariacites australis* Cookson (right). (f) *Callialasporites trilobatus* (Balme) Dev. (g) *Cyclospheera psilata* Volkheimer & Sepúlveda. (h) *Circulodinium distinctum* (Deflandre & Cookson) Jansonius. (i) *Cribroperidinium orthoceras* (Eisenack) Davey. (j) *Oligosphaeridium complex* (White) Davey & Williams. (k) *Pterospermella australiensis* (Deflandre & Cookson) Eisenack. (l) *Muderongia staurota* Sarjeant. Scale bar is 30 μm .

et al. 1976; Archangelsky 1977, 1980; Volkheimer 1978, 1980; Dellapé *et al.* 1978; Volkheimer & Quattrocchio 1981; Volkheimer & Prámparo 1984; Prámparo *et al.* 1995; Ottone 1996; Aguirre-Urreta *et al.* 1996, 1999; Prámparo & Volkheimer 1996, 1999), but also marine dinoflagellates (Volkheimer & Quattrocchio 1981; Quattrocchio 1984*a, b*; Quattrocchio & Volkheimer 1990; Volkheimer & Sarjeant 1993; Peralta 1994, 1996, 2000; Prámparo *et al.* 1995; Aguirre-Urreta *et al.* 1996, 1999; Prámparo & Volkheimer 1996; Mostajo & Volkheimer 1997; Peralta & Volkheimer 1997, 2000; Ottone & Pérez Loinaze 2002). The continental palynomorphs are referred to the Late Valanginian–?Barremian *Cyclusphaera psilata*–*Classopollis* sp. Palynological Assemblage (Volkheimer 1980). The palynoflora also includes *Araucariacites australis*, and different species of *Callialasporites* and *Classopollis* (Fig. 11e, f). *Cyclusphaera psilata* (Fig. 11g), together with *Balmeiopsis limbatus*, a closely related form, display an exclusive Gondwanan distribution, whilst the rest of the miospore assemblage includes forms well known elsewhere (Aguirre-Urreta *et al.* 1999). There are no dinocyst zonation proposed for the Agrio Formation. The only detailed palynological study was made on the Pilmatué Member of the formation at Cerro Mesa and Cerro Negro de Covunco (Peralta 1994, 1996, 2000; Peralta & Volkheimer 1997, 2000). The marine palynomorphs of the Agrio Formation are mostly cosmopolitan, some of them long-ranging species (e.g. *Circulodinium distinctum*, *Cribroperidinium orthoceras*, *Muderongia staurota*, *Oligosphaeridium complex*, *Pterospermella australiensis*; Fig. 11h–l), with the exception of *Muderongia brachialis*, a probable local index species of the *riccardii* and basal *schlagintweiti* ammonite zones at the base of the Upper Hauterivian in the basin (Ottone & Pérez Loinaze 2002).

The La Amarga Formation includes continental sediments that crop out south of Zapala. The Bañados de Caichigüe Member yields a characteristic palynological assemblage dominated by miospores and chlorococcales (Volkheimer *et al.* 1977; Dellapé *et al.* 1978; Prámparo & Volkheimer 2000*a, b*, 2002) that may be referred also to the Late Valanginian–?Barremian *Cyclusphaera psilata*–*Classopollis* sp. Palynological Assemblage.

The Rayoso Group mostly comprises continental sediments, with common evaporitic horizons and red beds. A microflora recovered from the lower part of the group in the *Arenisca Rincón*, or Rincón Member of the Huitrín Formation (Uliana *et al.* 1975), is characteristic of

the Late Valanginian–?Barremian *Cyclusphaera psilata*–*Classopollis* Palynological Assemblage (Vallati 1996, 2000). The palynomorph assemblage of the upper part of the group, the Ranquiles Formation, includes *Cyclusphaera psilata*, *Balmeiopsis limbatus*, *Classopollis* sp. and different species of *Callialasporites*, but also angiosperm pollen grains and *Afropollis* (Volkheimer & Salas 1975, 1976; Dellapé *et al.* 1978; Archangelsky 1980; Vallati 1995, 2000). The palynomorphs are referred to the *Huitrinipollenites*–*Stephanocolpites* Palynological Assemblage (Volkheimer *et al.* 1976), probably Aptian in age.

The relationship between the continental palynological assemblages defined in the Neuquén Basin and the similar ones of central and southern Argentina was emphasized in several articles suggesting a great degree of floristic uniformity through the Lower Cretaceous in the region (Archangelsky *et al.* 1981, 1984; Prámparo 1994).

Discussion

A detailed biostratigraphic subdivision of the Berriasian–?Early Barremian marine sequences of the Neuquén Basin has been achieved using both ammonite biozones and calcareous nannofossil bioevents. Most palynomorphs are long ranging and of only limited use in regional biostratigraphy.

Correlation between the Neuquén and Mediterranean sequences and thus the accurate application of the standard stage names to the Neuquén Basin, relies on ammonite and nannofossil evidence (Figs 8 & 9). The ammonites provide firm evidence at some levels, but there are significant levels of uncertainty too. The Neuquén nannofossil species are widely distributed and many are cosmopolitan, so that the Neuquén assemblages can be directly correlated with those from the European-based stage stratotypes. Although there are only a limited number of nannofossil bioevents in the Neuquén Basin, they provide a robust independent test for the correlations indicated by ammonites.

In general, the ammonite correlations are supported by nannofossil evidence. This is especially true from the *noduliferum* to the *atherstoni* NAZs (Early Berriasian–Upper Valanginian). But the occurrence of wide-canalated nannoconids in the *angulatifformis* NAsZ could suggest a slightly younger, Early Hauterivian, age for this zone than is indicated by the ammonite correlations. However, Bown & Concheyro (2004) do not place great confidence in the calibration of these nannoconid events, while the

first occurrence of *Eifellithus striatus* at the base of the *angulatiformis* NasZ supports the ammonite correlation.

Although the base of Tethyan nannofossil zone CC4B is higher in the Neuquén Basin according to the ammonite correlations, there is a remarkably good agreement in the mid Hauterivian, particularly the LO of *Cruciellipsis cuvillieri* at the base of the *schlagintweiti* NAZ, which corroborates the ammonite correlation with the *sayni* TAZ of the European sequences. Finally, the LO of *Nannoconus ligius* in the basal part of the *Paraspiticeras groeberi* NAZ suggests a Late Hauterivian age for at least part of this ammonite zone. As noted above, Aguirre-Urreta & Rawson (1993) provisionally dated the zone as Early Barremian, but part or all could be latest Hauterivian as that is when the genus *Paraspiticeras* first appeared.

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