Bajocian ammonoids from Pumani River area (Ayacucho, Peru): Palaeobiogeographical and palaeoenvironmental implications for the Arequipa Basin

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ABSTRACT

Deposits of the Socosani Formation in the Pucayacu and Pumani sections (Ayacucho Department, Peru), along several kilometres, have yielded Upper Bajocian ammonoid fossil-assemblages characterized by the occurrence of juvenile individuals belonging to endemic or pandemic genera, such as *Megasphaeroceras* and *Spiroceras* respectively. In addition, certain Bajocian genera relatively common in the Mediterranean-Caucasian Subrealm, but very scarce in the Eastern Pacific Subrealm, such as the strigoceratid *Cadomoceras* and the phylloceratid *Adabofoloceras*, occur in this area. According to the taphonomic, palaeoecological and palaeobiogeographical evidence from the Pumani River area, the maximum deepening, relative sea-level rise and oceanic accessibility of a Bajocian–Bathonian, second-order, transgressive/regressive facies cycle in the marine Arequipa Basin were reached during the Late Bajocian Niortense Biochron. However, synsedimentary regional tectonics in the Pumani River area disturbed this general deepening/shallowing cycle of the Arequipa Basin, particularly during the Late Bajocian post-Niortense time-interval of the Garantiana and Parkinsoni biochrons.

1. Introduction

Bajocian ammonoids seem to be scarce in the Peruvian central Andes, although there are well-developed marine deposits in the southern areas of Peru (Westermann et al., 1980; Riccardi et al., 1992; Palacios, 1994; Alvan, 2009; Carlotto et al., 2009; Giraldo, 2010; Alvan et al., 2012). A Bajocian stratigraphic succession of high biostratigraphic completeness, within the southern Peruvian areas belonging to the Arequipa Basin, crops out in the area of Pumani River (Ayacucho Department), 300 km SE of Lima (Fig. 1A). It is located 17 km S of Totos, in the boundary between the provinces of Victor Fajardo (Vilcanchos and Sarhua districts) and Huanca Sancos (Lucanamarca District). The Pucayacu Section studied by Westermann et al. (1980) and a new Pumani Section located 2 km southward have yielded significant information of the high Bajocian biostratigraphic completeness in this area (Fig. 1C).

The primary aim of the present work is to focus on the composition and structure of the Bajocian ammonoid associations at the outcrops of the Pumani River area (Pucayacu and Pumani sections), calibrated in units of European standard chronozones, in order to interpret the successive palaeoenvironmental changes and their implications in sequence stratigraphy of the Arequipa Basin.

2. Geological setting

In the Peruvian central Andes, structural highs gave rise to two distinctive depositional areas, the Pucara Basin in the North and the Arequipa Basin in the South, during the Early Jurassic. The Totos-Paras structural high, southerly delimited by the Abancay-Andahuaylas-Totos fault system (AAT in Fig. 1B), was a prolongation of the Cusco-Puno High, defined by the Cusco-Lagunillas-Mañazo and the Urcos-Sicuani-Ayaviri fault systems (CLM and USA in Fig. 1B), due to Early Jurassic sinistral transtensive tectonic (Carlotto et al., 2009). In the northern area of Totos and Paras, the Chunumayo Formation is composed of Toarcian-Bajocian marine deposits, mainly limestones, 200–500 m thick, and overlies volcanic rocks of the Permo-Triassic Mitu Group. Above the Chunumayo Fm, there are 300 m of the Yura Group (Middle-Upper Jurassic) corresponding to fluvial-deltaic deposits (Carlotto et al., 2009; Giraldo, 2010; Giraldo et al., 2010).

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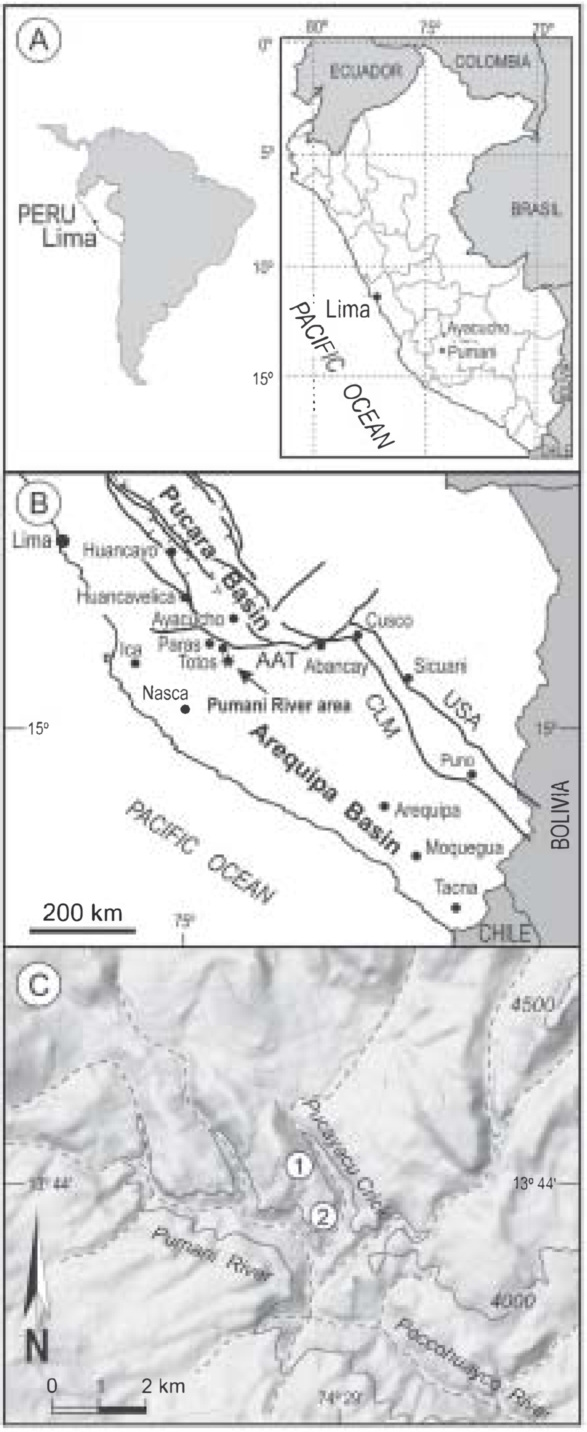


Fig. 1. A) South America map showing the location of the Pumani River area in southern Peru (Ayacucho Department). B) Middle Jurassic palaeogeographical distribution of the Arequipa and Pucara basins (after Carlotto et al., 2009) with the location of the Pumani River area. Abbreviations of the fault systems: AAT: Abancay-Andahuaylas-Totos, CLM: Cusco-Lagunillas-Mañazo, USA: Urcos-Sicuani-Ayaviri. C) Topographic location of the Pucayacu (1) and Pumani (2) sections.

Middle Jurassic deposits reach thicknesses greater than 2000 m southward of the Arequipa Basin, developed in deeper depositional environments going from shelf deposits to slope turbidites with olistolith development. In the type area of the Socosani Fm, late Bajocian starved deposits of the upper Socosani Fm overlie shallow-marine limestones and are overlain by thick Bathonian and early Callovian turbidite deposits of the Puente Fm (Vicente, 1981, 1989; Vicente et al., 1982; Alvan, 2009). In the southern areas of Totos and Paras, as shown below, the Bajocian deposits represent deep marine environments from shelf deposits to slope turbidites with olistoliths, reaching thicknesses greater than 900 m. They are assigned here to the Socosani Formation (Yura Group; Jenks, 1948; Benavides, 1962; Vicente, 1981, 1989, 2006; Jaillard et al., 1990; Carlotto et al., 2009), instead to the Chunumayo, Puente and Cachios formations as in the previous regional studies (Fig. 2).

In the Pumani River area (Figs. 3 and 4A), grey and brown limestones with microfilaments (*Bositra* sp.) of the Socosani Fm represent Aalenian and Early Bajocian open marine platform to slope deposits. Distinctively, grey calcareous slump deposits and redeposited sediments, including metric blocks of brown calcareous sandstones, indicative of slopes occur within the calcareous interval in the Pumani Section, as well as microbial laminae and centimetric, domical structures in the uppermost levels, indicative of sedimentary starvation (Fig. 4E–F). The occurrence in this lithostratigraphic unit of ammonites belonging to the Aalenian/Bajocian boundary in the Pumani River area is reported below for the first time. This calcareous interval of the Socosani Fm represents the southward equivalent of the Chunumayo Fm developed through a shallow platforms system as meridional margin of the Pucara Basin at the Totos-Paras structural high.

Two lutaceous stratigraphic intervals well differentiated, surpassing 700 m in thickness, overlie the calcareous interval and crop out in the area between the Pumani River and the Pucayacu Crick. They belong to the upper Socosani Fm and underlie the calcareous sandstones of the Puente Fm observable in the east side of the Pucayacu Crick (Fig. 4C). These lutaceous intervals are also older than the Cachios Fm present 2 km southward, in the north side of the Condoray Hill and the south side of the Poccohuayco River (Fig. 1C).

The lower lutaceous interval consists of brown, black and green shales with intercalations of limestones and calcareous sandstones, varying between 50 and 200 m in thickness (Fig. 4B). Grey carbonate concretions, locally compressed by gravitational diagenetic compaction with deformed millimetric laminae and septarian cracks of calcite cementation indicative of syndepositional earthquake-induced shaking (Pratt, 2001), are common in the lower part of this stratigraphic interval (Fig. 4G). Brown ferruginous concretions of calcareous sandstones occur in the upper part of this interval and the lower part of the following one (Fig. 4H). Both types of concretions, spherical or ellipsoidal in morphology and decimetric in size, are indicative of sedimentary reworking and redeposition from older sediments.

The upper lutaceous interval is composed of grey, green and yellow shales with intercalations of calcareous sandstones, where at least middle Upper Bajocian, Garantiana Zone, marine deposits surround isolated megablocks of lowermost Upper Bajocian, Niortense Zone, marine deposits of similar lutaceous facies (for biochronostratigraphic differences between ammonoids of the Niortense and Garantiana zones, see below). These megablocks reach several hundred metres long and tens of metres in thickness (Fig. 4C–D). Synsedimentary, soft-sediment folded calciturbidites and slump deposits are common. Associated with extensive and thick beds of calcareous sandstones, locally occur decimetric or metric beds of arkosic sandstones with rounded detrital quartz grains and angular pebbles of Jurassic limestones, identified as olistostromes. These olistostromes should be the ?Bathonian continental sandstones mentioned by Westermann et al. (1980, photo 3) in the west side of the Pucayacu Crick. Differential criteria for the identification of olistostromes and texturally similar melanges were discussed by Hsü (1974) and Cieszkowski et al. (2009, 2012).

Westermann *et al.* 1980		Carlotto *et al.* 2009	This paper			Age	
Yura Group	Cachios Formation	Yura Group	Yura Group	Puente Fm	Marly limestones and calcareous sandstones	Bathonian	Middle Jurassic
		Chunumayo Fm		Socosani Fm	Upper lutaceous interval Lower lutaceous interval	Bajocian	
Pucara Group	Chunumayo Fm				Calcareous interval	Aalenian	

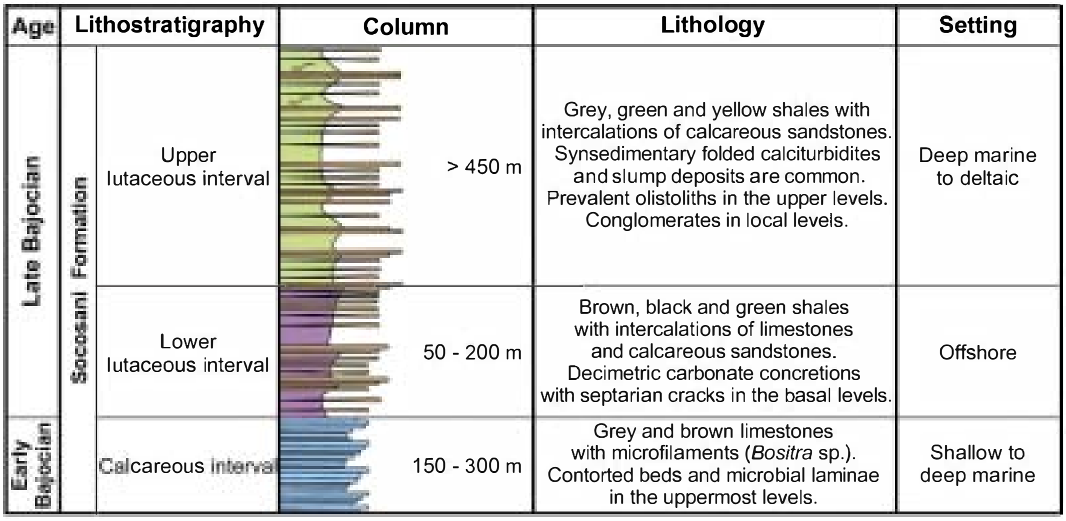
Fig. 2. Lithostratigraphic units distinguished in the Aalenian-Bathonian deposits of the Pumani River area by Westermann et al. (1980), Carlotto et al. (2009) and in this paper.

The uppermost megablocks of this interval, observable on a distance of several kilometres and interpreted as olistoliths, correspond to Late Bajocian and probably Bathonian deep-water slope and basinal deposits. The occurrence of ammonites belonging to the Bajocian/Bathonian boundary interval at the top of the Socosani Fm in the Pucayacu Crick is described and figured below for the first time.

In the Pumani River area, the Bajocian beds of limestones and calcareous sandstones represent turbulence-related sedimentary events, associated with tractive bottom currents, whereas the lutaceous intercalations correspond to background-sedimentation time-intervals on the seafloor. Both centimetric to decimetric lithologic phases may contain evidence for sedimentary and taphonomic reworking, associated with scours. *Thalassinoides* burrows occur in some levels. The successive decametric parasequences progressively show less distinctive development and become more fine-grained, from the Aalenian-Lower Bajocian calcareous interval towards the top of the Socosani Fm. Thickening and coarsening upwards sequences of metric thickness are common and contain resedimented ammonoids. Thinning and fining upwards sequences show lesser development and they are commonly associated with slump deposits, reworked concretions and reelaborated ammonoids. The decimetric or metric olistostromes with detrital quartz grains and the decametric olistoliths composed of, and included within, deep-water slope and normal basinal deposits probably are due to synsedimentary regional tectonics.

3. Ammonoid taphonomic analysis

Ammonoid associations are dominated by reworked elements (i.e. resedimented and reelaborated elements *sensu* Fernandez-Lopez, 1991, 1995, 2007, 2008). Reelaborated internal moulds (i.e. exhumed and displaced before their final burial) are locally common, showing structural discontinuity with, and darker colour than, the including deposit. Resedimented shells, displaced on the seafloor before their burial, are dominant. Criteria to identify reelaborated ammonoids are: the petrographic difference between the sedimentary infilling and the enclosing sedimentary rock; the presence of a structural discontinuity between the sedimentary infilling and the enclosing rock; the presence of inverted geopetal infilling, disarticulation surfaces along the boundary between contiguous chambers of the phragmocone or between the phragmocone and the body chamber, and fracture surfaces or abrasion surfaces on the internal mould. Reelaborated ammonoids, as early concretionary internal moulds, usually maintain their original shape without traces of extensive compression by diagenetic compaction. The occurrence of reelaborated ammonoids implies



Age	Lithostratigraphy		Column	Lithology	Setting
Late Bajocian	Socosani Formation	Upper lutaceous interval	> 450 m	Grey, green and yellow shales with intercalations of calcareous sandstones. Synsedimentary folded calciturbidites and slump deposits are common. Prevalent olistoliths in the upper levels. Conglomerates in local levels.	Deep marine to deltaic
		Lower lutaceous interval	50 - 200 m	Brown, black and green shales with intercalations of limestones and calcareous sandstones. Decimetric carbonate concretions with septarian cracks in the basal levels.	Offshore
Early Bajocian		Calcareous interval	150 - 300 m	Grey and brown limestones with microfilaments (*Bositra* sp.). Contorted beds and microbial laminae in the uppermost levels.	Shallow to deep marine

Fig. 3. Age, column, lithology and depositional setting of the three Bajocian subdivisions of the Socosani Fm in the area of Pumani River.

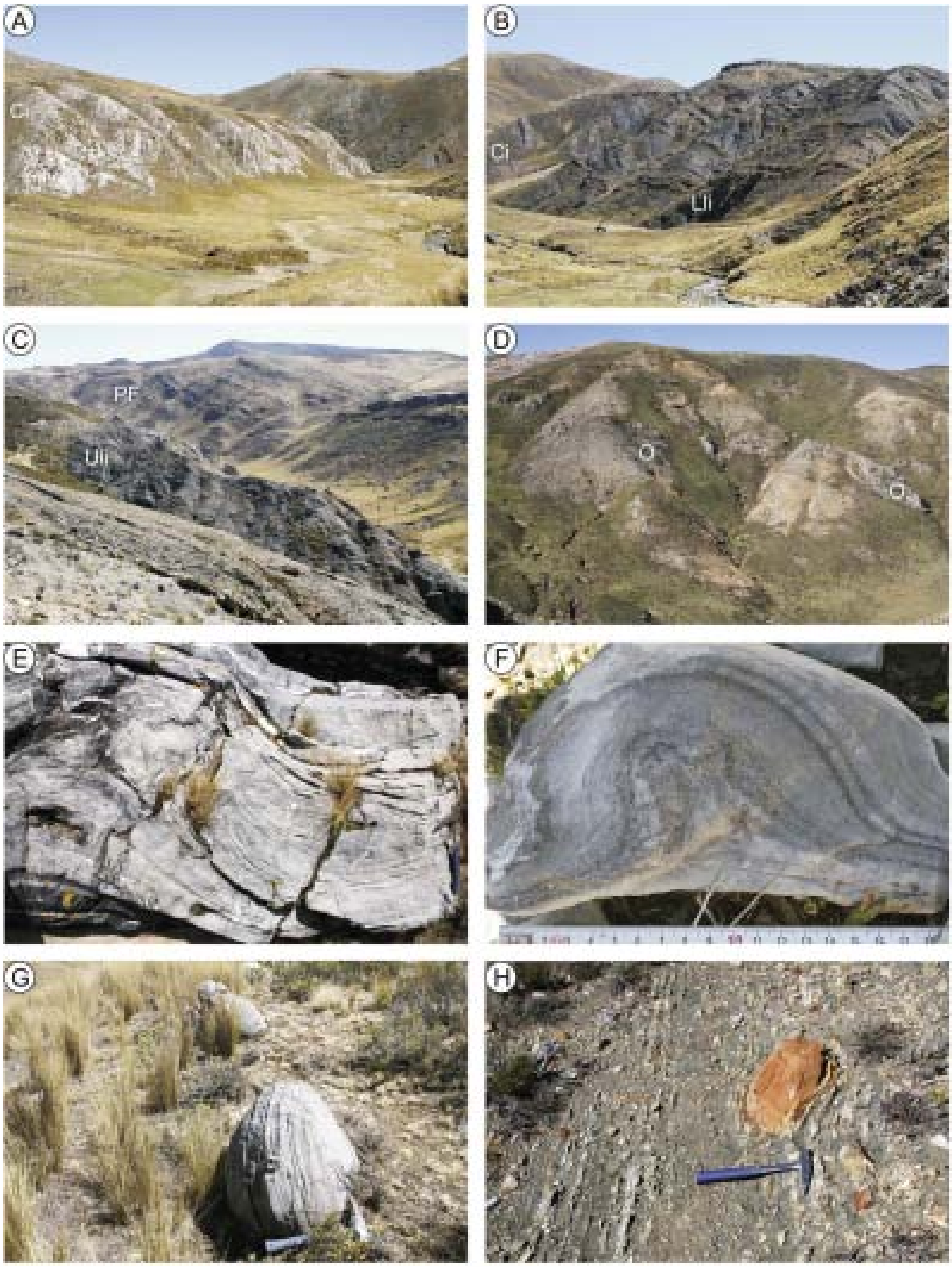


Fig. 4. A) Outcrop of the Bajocian calcareous interval (Ci) of the Socosani Fm on the south side of the Pumani River. B) Outcrop of the Bajocian calcareous interval (Ci) and the lower lutaceous interval (Lli) on the north side of the Pumani River. C) Outcrop of the upper lutaceous interval (Uli) of the Socosani Fm, in the Pumani Section on the west side of the Pucayacu Crick, and the prograding succession from marly limestones to calcareous sandstones of the Puente Fm (PF) on the east side of the Pucayacu Crick. D) Outcrop of the upper part of the upper lutaceous interval on the east side of the Pucayacu Crick, with several decametric olistoliths (O), above the Pucayacu Section represented in Fig. 5A and northward equivalent of the uppermost part of the upper lutaceous interval at the Pumani Section represented in Fig. 5B. E) Contorted beds interpreted as slump deposits at the top of the calcareous interval in the Pumani Section. F) Detail of synsedimentary, soft-sediment folded laminae of calciturbidites at the top of the calcareous interval in the Pucayacu Section. G) Grey carbonate concretion at the base of the lower lutaceous interval in the Pumani Section. H) Brown ferruginous concretion of calcareous sandstones at the upper part of the lower lutaceous interval in the Pucayacu Section.

that tractive current flows or winnowing affected the burial of the concretionary internal moulds.

Taphonomic features of the Bajocian ammonoid assemblages include the relative abundance of reelaborated, homogeneous but incomplete, concretionary internal moulds and resedimented hollow ammonoids, bearing no traces of abrasion, bioerosion or encrusting organisms.

Hollow ammonoids (i.e., ammonoid shells showing no sedimentary infill in the phragmocone) are dominant and indicative of predominant conditions of high rate of sedimentation and high rate of sediment accumulation (Fernandez-Lopez, 2008). These hollow ammonoids are usually compressed by gravitational diagenetic compaction (Fig. 5C–D, 10N) and are associated to expanded sections, although they are locally common as resedimented elements included in calcareous concretions (Figs. 5A, 9I, 9M–N, 9T–U). Reelaborated, hollow ammonoids preserved as homogeneous concretionary internal moulds of the body chamber or of fragmentary whorls, maintaining their tridimensional volume and shape, are only locally present (Figs. 5B and 9C–D, 9K–L, 10C, 10F–G). These diverse preservational features of the ammonoids shells imply only punctual episodes of low rates of positive net sedimentation, due to sedimentary bypassing, among dominant episodes of high rates of sediment accumulation by turbulence-related sedimentary events and high rate of sedimentation, during the development of expanded sections in deep-water marine environments.

4. Ammonoid biostratigraphy and chronostratigraphy

Bajocian ammonoids are scarce in the Socosani Fm at the Pumani River area, particularly in the calcareous interval, although they are locally common in the lutaceous intervals (Fig. 6). New field samplings and the revision of earlier collections provided several hundreds of Bajocian ammonoids of this area. The uppermost Aalenian Malarguensis Biozone and lowermost Bajocian levels can be identified by the occurrence of *Puchenquia (Gerthiceras)* cf. *mendozana* Westermann [Macroconch] and *Tmetoceras* cf. *flexicostatum* Westermann [M] in the lower part of the calcareous interval, according to the biostratigraphic data obtained in Argentina and Chile (Riccardi and Westermann, 1991). Above, several specimens of *Pseudotoites* [M and m] and *Sonninia* [M] characterize the Laeviuscula Zone, whereas higher and sparse specimens of *Chondromileia* [M and

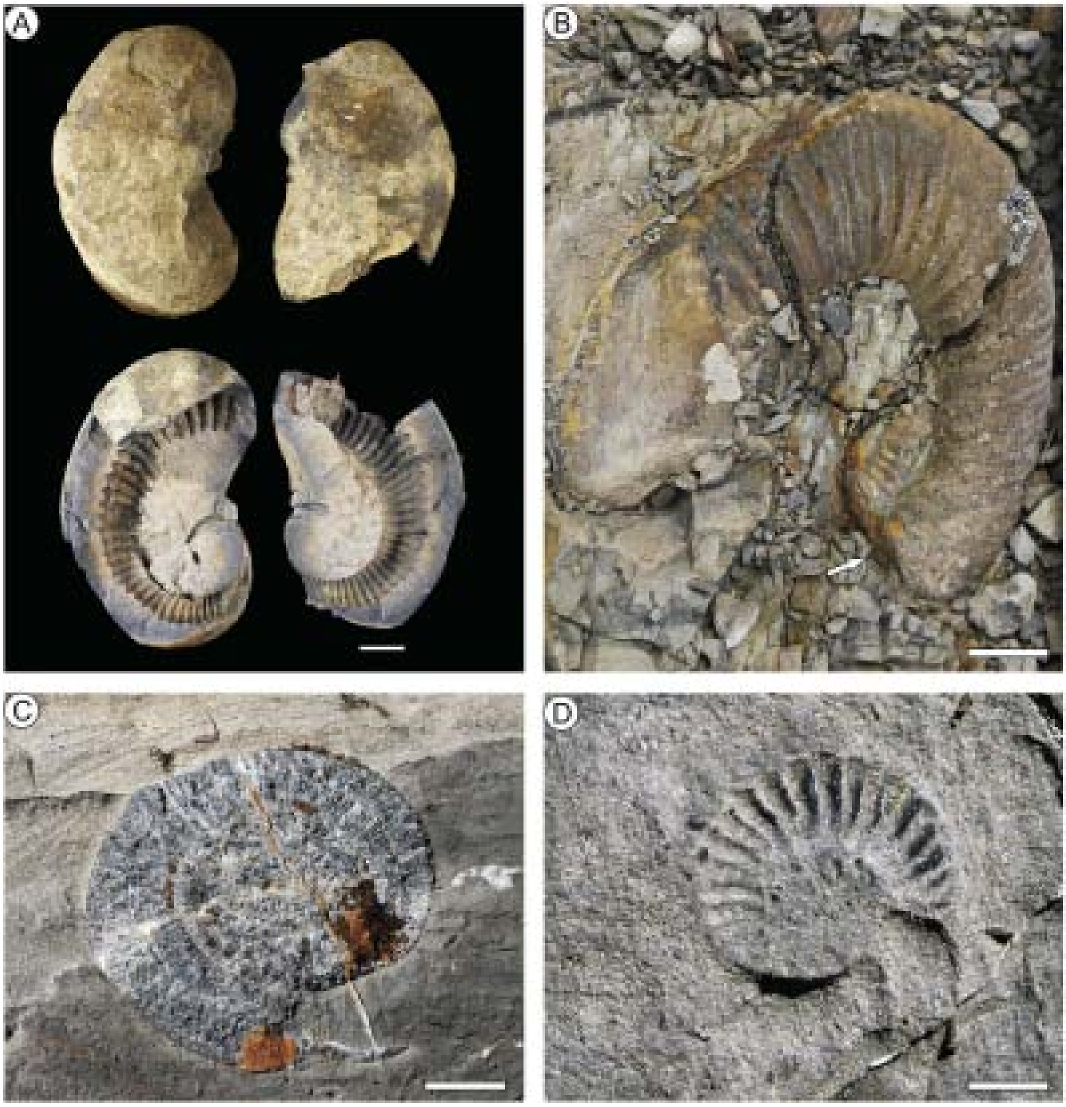


Fig. 5. Bajocian ammonites from the Socosani Fm. A) *Spiroceras orbignyi* (Baugier and Sauze). Specimen C112, upper lutaceous interval. External mould of a resedimented shell preserved as hollow ammonites (i.e., without sedimentary infill in the phragmocone, Fernandez-Lopez, 1997, 2008) and included in a calcareous concretion. Latex casts shown in Fig. 9T–U. B) *Prorsisphinctes* sp. Specimen C121, upper lutaceous interval. Reelaborated, fragmentary and concretionary internal mould, showing a textural and structural discontinuity with the sedimentary matrix (arrowed). C) *Skirroceras* sp. Specimen N294, calcareous interval. Resedimented shell preserved as hollow ammonites and hollow phragmocone (i.e., without septa, Seilacher et al., 1976; Maeda and Seilacher, 1996) continuously filled with macrocrystalline calcite. D) *Pelekodites* sp. Specimen N293, calcareous interval. External mould of a resedimented shell preserved as hollow ammonites, compressed by gravitational diagenetic compaction. Scale bar equals 10 mm.

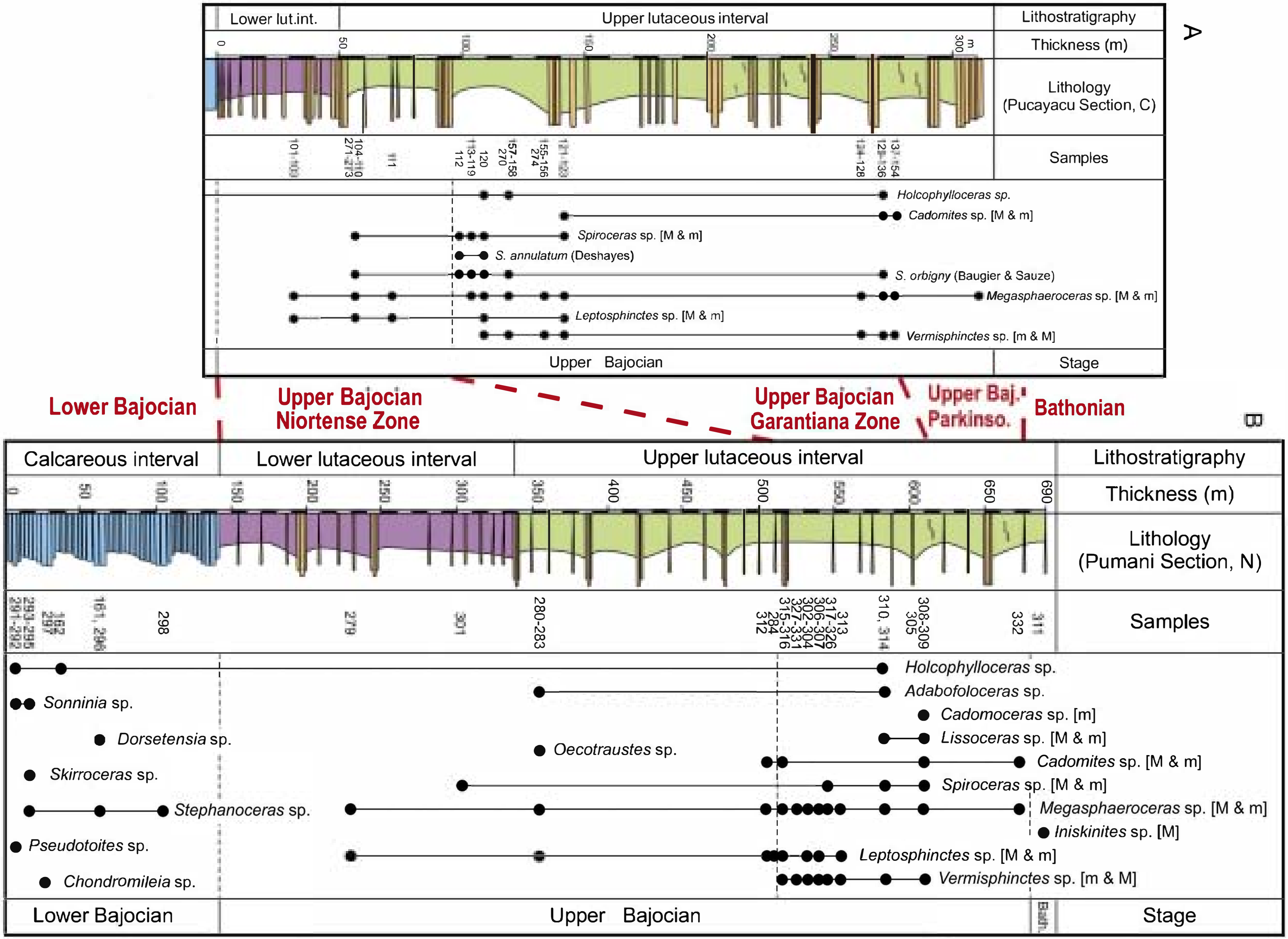


Fig. 6. Schematic columns showing the biostratigraphic and chronostratigraphic distribution of ammonoids in the three Bajocian lithologic intervals of the Socosani Fm at A) the Pucayacu Section and B) the Pumani Section.

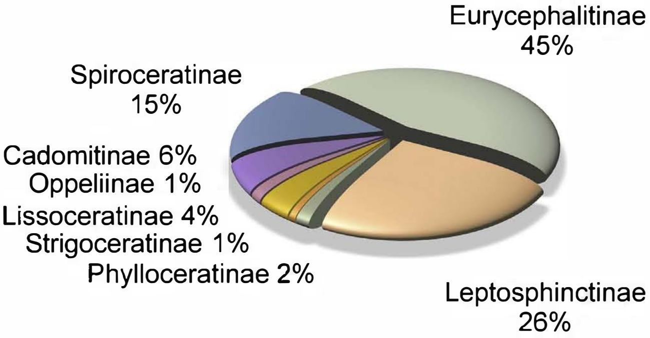


Fig. 7. Relative abundance of Upper Bajocian ammonoid subfamilies in the Pumani River area.

m], *Sonninia* [M], *Pelekodites* [m], *Stephanoceras* [M] and *Skirroceras* [m] indicate the Sauzei Zone. At the upper levels of the calcareous interval, some fragmentary specimens of *Dorsetensia* sp. [M], associated with *Stephanoceras* [M], allow the recognition of the Lower Bajocian Humphriesianum Zone.

In the lower lutaceous interval, several successive ammonoid fossil assemblages characterize the Upper Bajocian Magnum Biozone introduced for the Neuquen-Mendoza Basin (Westermann and Riccardi, 1979) as equivalent to the Rotundum Chronozone proposed in North America and to the Niortense Standard Chronozone. The taxa identified in this biostratigraphic unit indicate a time span from the latest Niortense Zone to the Garantiana Zone. The occurrence of *Megasphaeroceras* cf. *magnum* Riccardi and Westermann [M and m], *Spiroceras orbignyi* (Baugier and Sauze) (Figs. 9I and 9T–U) and *Leptosphinctes* spp. [M and m] (Fig. 10H–N) characterizes the uppermost Niortense Zone. The Garantiana Zone is recognized in the upper lutaceous interval, with *Megasphaeroceras* cf. *magnum* (Fig. 9R), *Spiroceras orbignyi, Spiroceras annulatum* (Deshayes) (Fig. 9S) and *Vermisphinctes* spp. [m and M] (Fig. 10A–G). Above, nuclei of *Cadomites* sp. are associated with fragmentary specimens of perisphinctids that may belong to *Planisphinctes* [m and M] and suggest the last Bajocian Parkinsoni Zone (as identified in the Tarapaca Basin, northern Chile, by Fernandez-Lopez and Chong Diaz, 2011). The finding of only one *Iniskinites* (Figs. 6 and 9K–L) also suggests the first Bathonian deposits including the uppermost olistoliths at the top of the upper lutaceous interval.

5. Palaeobiogeographical remarks and palaeoenvironmental implications

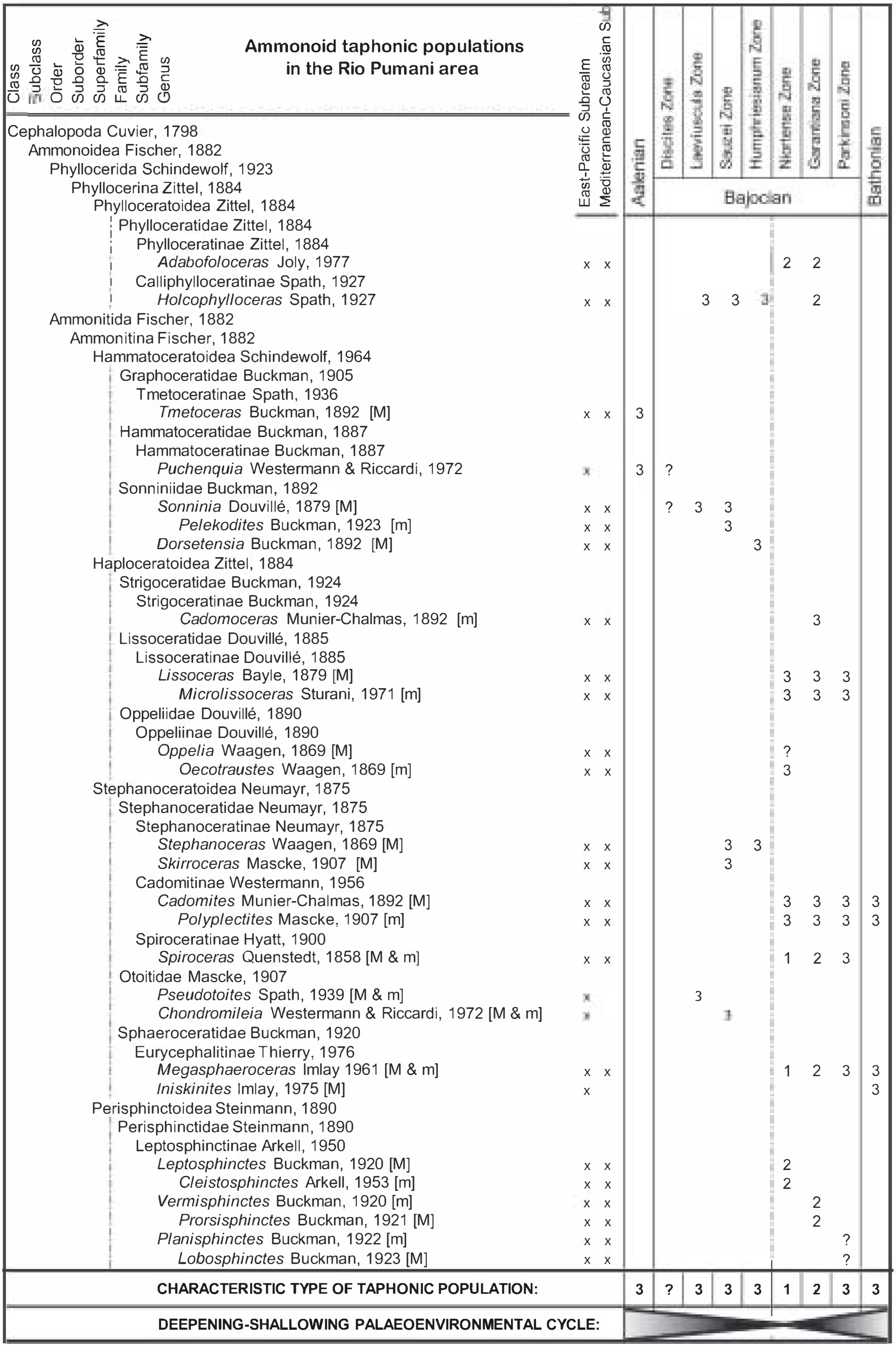
Upper Bajocian Eurycephalitinae are dominant and *Megasphaeroceras* [M and m] is the most common ammonoid genus (45%), with endemic species to the southeastern Pacific borderlands (Fig. 7). They are recorded by shells of monospecific group, showing unimodal size-frequencies distribution of positive asymmetry, dominant juveniles and dimorphism well represented (taphonic populations of type 1, as indicated in Fig. 8). Also locally common are Leptosphinctinae (26%) and Spiroceratinae (15%). *Leptosphinctes* [M] – *Cleistosphinctes* [m] display juvenile and pre-adult individuals in the lower lutaceous interval, whereas *Vermisphinctes* [m] – *Prorsisphinctes* [M] are mainly represented by adult individuals within the upper lutaceous interval. In addition, *Spiroceras orbignyi* is represented by dominant juveniles in the uppermost lower lutaceous interval and the lowermost upper lutaceous interval, whereas *Spiroceras annulatum* is very scarce and almost restricted to the lowermost upper lutaceous interval. Cadomitinae (6%), Lissoceratinae (4%), Oppeliinae (1%) and Strigoceratinae (1%) are scarce. Besides Ammonitina, Phylloceratina and Lytoceratina are extremely scarce (less than 2%).

The taphonomic, palaeoecological and palaeobiogeographical analysis of these ammonoids includes preservational features mainly related to the composition and structure of the ammonoid recorded associations, at genus level and calibrated in standard chronozones (Fig. 8), according to the model developed by Fernandez-Lopez (1997, 2000, 2011, 2013).

Most Bajocian ammonoid genera of the Pumani River area correspond to adult individuals belonging to taphonic populations of type 3 (TPT3, Fig. 8) dispersed by regional necrokinesis and/or local immigration, without evidence of sustained colonization, from more open marine or exotic oceanic areas. In contrast, Late Bajocian, monospecific populations dominated by juvenile individuals and indicative of sustained colonization by eudemic taxa (i.e., recorded in their breeding area) were abundant among the genera *Megasphaeroceras* [M and m] and *Spiroceras* [M and m] (TPT1). These ammonite populations inhabiting the Arequipa Basin belong to endemic species to the Andean Province of the Eastern Pacific Subrealm and to pandemic species of the Tethys-Panthalassa Realm, respectively. If the shells had been produced by immigrant taxa (TPT2) after active biodispersal from more marine or exotic, oceanic areas (i.e., miodemic taxa), it would probably be dominated by pre-adults of monospecific dimorphic genera. This is the case of the locally common *Leptosphinctes* [M] – *Cleistosphinctes* [m], displaying intermediate size-distribution with sorting of pre-adult ontogenic stages. The exceptional occurrence of monospecific populations, including macroconchs and microconchs such as in *Vermisphinctes* [m] – *Prorsisphinctes* [M], even with predominance of microconchs, lacking juveniles but dominated by pre-adults, suggests autochthonous biogenic production of shells by miodemic taxa too, after immigration in the Arequipa Basin by active biodispersal.

On the other hand, the occurrence of very scarce and monomorphic adult or pre-adult individuals of taxa relatively common and dimorphic in the Mediterranean-Caucasian Subrealm, such as the strigoceratid *Cadomoceras* (Fig. 9G–H) or the phylloceratid *Adabofoloceras* (Fig. 9C–F), probably correspond to species recorded in a life area without breeding and occasionally reached by passive biodispersal (parademic species) during episodes of deep marine conditions (Fernandez-Lopez and Melendez, 1996). These Peruvian parademic specimens are the oldest Bajocian Circum-Pacific records, although there are several references from younger Jurassic deposits. Poulton et al. (1994) and Evenchick et al. (2010) mentioned uppermost Middle and Upper Jurassic *Adabofoloceras* from Canada. Fernandez-Lopez and Chong Diaz (2013) reported the occurrence of *Cadomoceras* cf. *cadomensis* (Defrance in De Blainville, 1830) [m] and *Strigoceras septicarinatum* (Buckman, 1909–1930) [M] in the uppermost Bajocian Parkinsoni Zone from the Quebrada San Pedro (Antofagasta, northern Chile).

Therefore, at least six ammonoid palaeobiogeographic events of three categories have been recorded in the Arequipa Basin during the Late Bajocian: 1) Sustained colonization by endemic eurycephalitins to the Andean Province and by pandemic spiroceratins of the Tethys-Panthalassa Realm, such as *Megasphaeroceras* and *Spiroceras*, respectively. 2) Active immigration by pandemic perisphinctids of the Tethys-Panthalassa Realm, such as *Leptosphinctes* and *Vermisphinctes*. 3) Passive immigration by pandemic strigoceratids and phylloceratids of the Tethys-Panthalassa Realm, such as *Cadomoceras* and *Adabofoloceras*, respectively. These Late Bajocian bioevents of regional appearance of immigrant ammonoids and even sustained colonization should be associated with an episode of maximum deepening, maximum relative sea-level rise and highest oceanic accessibility of a Bajocian–Bathonian deepening/shallowing palaeoenvironmental cycle in the Arequipa Basin, during the Upper Bajocian Niortense Zone (Fig. 11).



Ammonoid taphonic populations in the Rio Pumani area

Class / Subclass / Order / Suborder / Superfamily / Family / Subfamily / Genus	East-Pacific Subrealm	Mediterranean-Caucasian Sub	Aalenian	Bajocian							Bathonian
				Discites Zone	Laeviuscula Zone	Sauzei Zone	Humphriesianum Zone	Niortense Zone	Garantiana Zone	Parkinsoni Zone	
Cephalopoda Cuvier, 1798											
Ammonoidea Fischer, 1882											
Phyllocerida Schindewolf, 1923											
Phyllocerina Zittel, 1884											
Phylloceratoidea Zittel, 1884											
Phylloceratidae Zittel, 1884											
Phylloceratinae Zittel, 1884											
Adabofoloceras Joly, 1977	x	x						2	2		
Calliphylloceratinae Spath, 1927											
Holcophylloceras Spath, 1927	x	x			3	3	3		2		
Ammonitida Fischer, 1882											
Ammonitina Fischer, 1882											
Hammatoceratoidea Schindewolf, 1964											
Graphoceratidae Buckman, 1905											
Tmetoceratinae Spath, 1936											
Tmetoceras Buckman, 1892 [M]	x	x	3								
Hammatoceratidae Buckman, 1887											
Hammatoceratinae Buckman, 1887											
Puchenquia Westermann & Riccardi, 1972	x		3	?							
Sonniniidae Buckman, 1892											
Sonninia Douvillé, 1879 [M]	x	x		?	3	3					
Pelekodites Buckman, 1923 [m]	x	x				3					
Dorsetensia Buckman, 1892 [M]	x	x					3				
Haploceratoidea Zittel, 1884											
Strigoceratidae Buckman, 1924											
Strigoceratinae Buckman, 1924											
Cadomoceras Munier-Chalmas, 1892 [m]	x	x							3		
Lissoceratidae Douvillé, 1885											
Lissoceratinae Douvillé, 1885											
Lissoceras Bayle, 1879 [M]	x	x						3	3	3	
Microlissoceras Sturani, 1971 [m]	x	x						3	3	3	
Oppeliidae Douvillé, 1890											
Oppeliinae Douvillé, 1890											
Oppelia Waagen, 1869 [M]	x	x						?			
Oecotraustes Waagen, 1869 [m]	x	x						3			
Stephanoceratoidea Neumayr, 1875											
Stephanoceratidae Neumayr, 1875											
Stephanoceratinae Neumayr, 1875											
Stephanoceras Waagen, 1869 [M]	x	x				3	3				
Skirroceras Mascke, 1907 [M]	x	x				3					
Cadomitinae Westermann, 1956											
Cadomites Munier-Chalmas, 1892 [M]	x	x						3	3	3	3
Polyplectites Mascke, 1907 [m]	x	x						3	3	3	3
Spiroceratinae Hyatt, 1900											
Spiroceras Quenstedt, 1858 [M & m]	x	x						1	2	3	
Otoitidae Mascke, 1907											
Pseudotoites Spath, 1939 [M & m]	x				3						
Chondromileia Westermann & Riccardi, 1972 [M & m]	x					3					
Sphaeroceratidae Buckman, 1920											
Eurycephalitinae Thierry, 1976											
Megasphaeroceras Imlay 1961 [M & m]	x	x						1	2	3	3
Iniskinites Imlay, 1975 [M]	x										3
Perisphinctoidea Steinmann, 1890											
Perisphinctidae Steinmann, 1890											
Leptosphinctinae Arkell, 1950											
Leptosphinctes Buckman, 1920 [M]	x	x						2			
Cleistosphinctes Arkell, 1953 [m]	x	x						2			
Vermisphinctes Buckman, 1920 [m]	x	x							2		
Prorsisphinctes Buckman, 1921 [M]	x	x							2		
Planisphinctes Buckman, 1922 [m]	x	x								?	
Lobosphinctes Buckman, 1923 [M]	x	x								?	
CHARACTERISTIC TYPE OF TAPHONIC POPULATION:			**3**	**?**	**3**	**3**	**3**	**1**	**2**	**3**	**3**
DEEPENING-SHALLOWING PALAEOENVIRONMENTAL CYCLE:											

Fig. 8. Chronostratigraphic distribution of ammonoid taphonic populations at genus level, characteristic types and deepening-shallowing palaeoenvironmental cycle in the Pumani River area. The occurrence of these taxa in the East-Pacific and Mediterranean-Caucasian subrealms (as distinguished by Westermann, 1993, 2000) is indicated with an asterisk. Arkell, 1950; Arkell, 1951–1959; Bayle, 1878–1879; Buckman, 1887–1907; Cuvier, 1798; Douville, 1879; Douvillé, 1890, 1885; Fischer, 1882; Hyatt, 1900; Imlay, 1961, 1975; Joly, 1977; Mascke, 1907; Munier-Chalmas, 1892; Neumayr, 1875; Quenstedt, 1856–1858; Schindewolf, 1923, 1964; Spath, 1927–1933, 1936, 1939; Steinmann, 1890; Sturani, 1971; Thierry, 1976; Waagen, 1869; Westermann and Riccardi, 1972; Zittel, 1884.

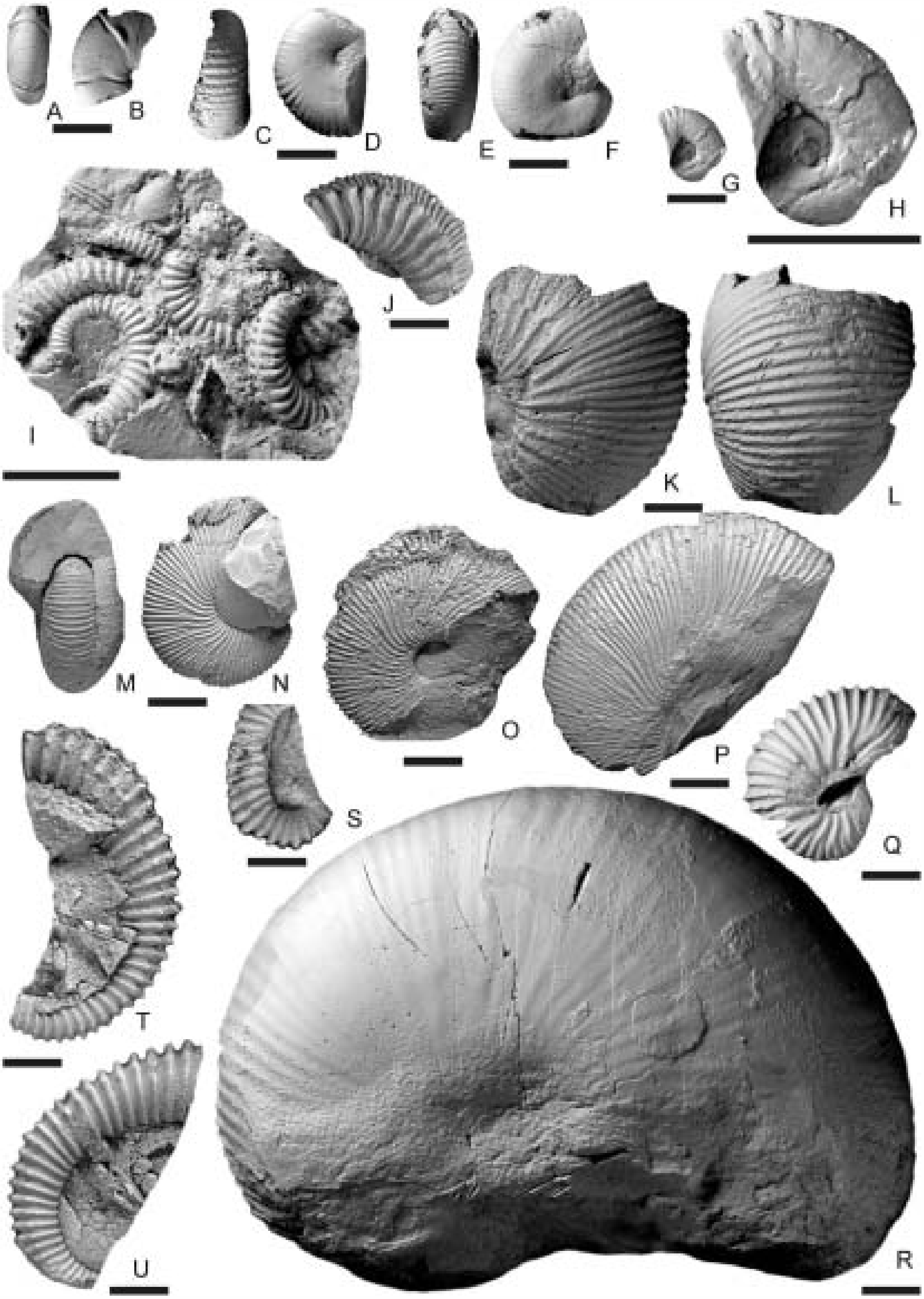


Fig. 9. Upper Bajocian and Bathonian ammonoids. A–B: *Holcophylloceras* sp., ventral and left views of whorl fragment, C270. C–D: *Adabofoloceras* sp., ventral and right views of incomplete body chamber, N280. E–F: *Adabofoloceras* sp., ventral and left views of incomplete body chamber, N310. G–H: *Cadomoceras* cf. *nepos* (Parona) [m], right views of internal mould of adult shell without peristome, N308. I: *Spiroceras* sp., latex cast of juvenile individuals in sample C271. J: *Cadomites* sp., right view of latex cast of whorl fragment, C154. K–L: *Iniskinites* sp. [M], right and ventral views of body chamber, N311. M–N: *Megasphaeroceras* sp. [M], oral and left views of pre-adult body chamber, C120A1. O: *Megasphaeroceras* sp. [M], left view of fragmentary, pre-adult body chamber, C120B5. P: *Megasphaeroceras* sp. [M], left view of incomplete, pre-adult body chamber, C120A3. Q: *Megasphaeroceras* sp. [m], left view of adult body chamber, N304. R: *Megasphaeroceras* cf. magnum Riccardi and Westermann [M], left view of adult body chamber, N331. S: *Spiroceras annulatum* (Deshayes), left view of latex cast of fragmentary shell, C112. T–U: *Spiroceras orbignyi* (Baugier and Sauze), right and left views of latex cast of resedimented, fragmentary shell, C113. All specimens of the Upper Bajocian, except Figs. K–L of the Bathonian, from Pumani (N) and Pucayacu (C) sections. The specimens were whitened with magnesium oxide prior to photography. Scale bar equals 10 mm.

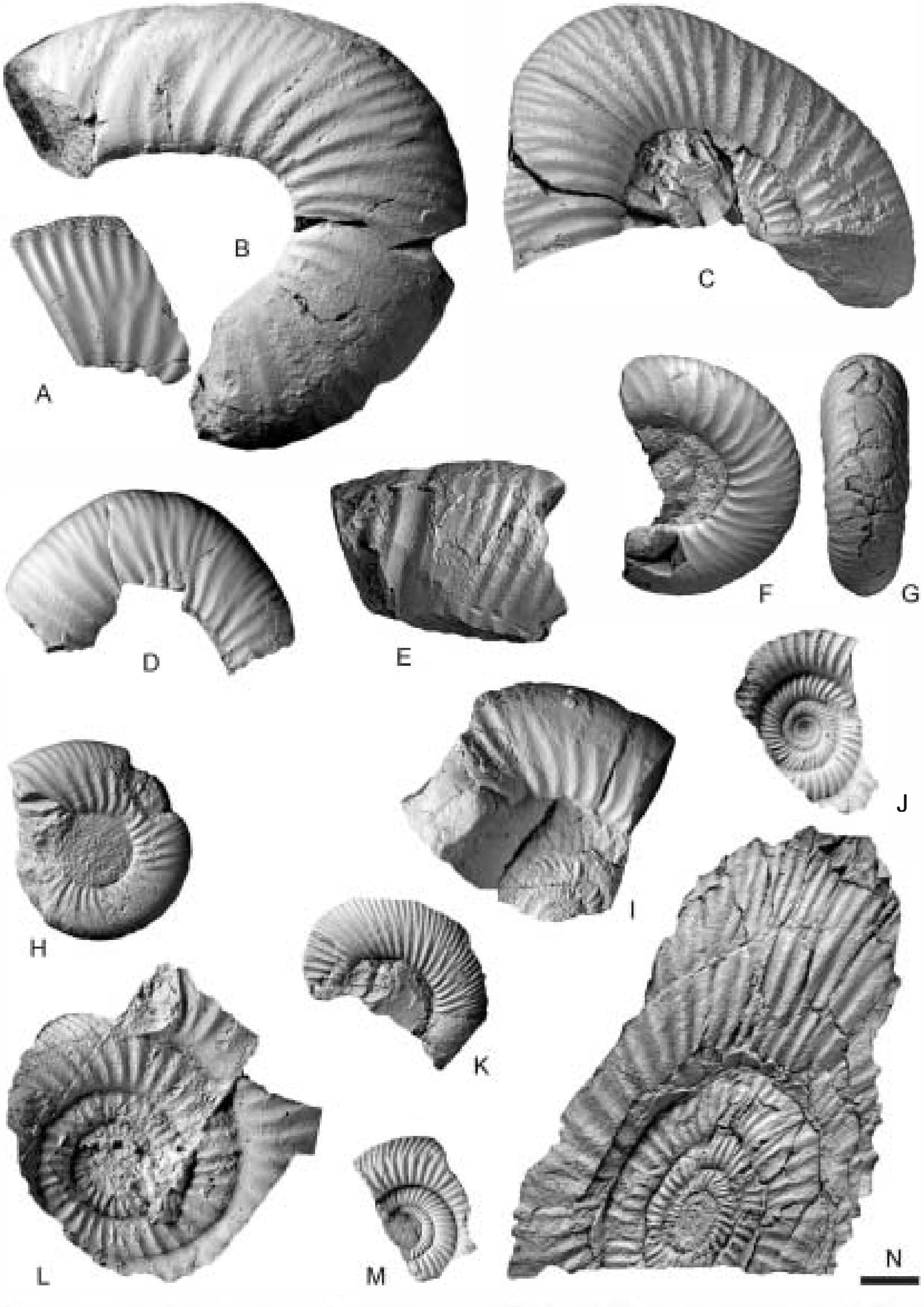


Fig. 10. Upper Bajocian ammonites. A: *Prorsisphinctes* sp. [M], right view of whorl fragment, C120X4. B: *Prorsisphinctes* sp. [M], left view of half whorl, N328. C: *Prorsisphinctes* sp. [M], right view of incomplete shell, C121. D: *Vermisphinctes* sp. [m], right view of incomplete body chamber, N317. E: *Prorsisphinctes* sp. [M], left view of whorl fragment with subcircular section, C124. F–G: *Vermisphinctes* sp. [m], right and ventral views of incomplete body chamber, C120X5. H: *Cleistosphinctes* sp. [m], right view of body chamber with lateral apophysis, N315. I: *Cleistosphinctes* sp. [m], right view of fragmentary body chamber with lateral apophysis, N284. J: *Leptosphinctes* sp. [M], left view of latex cast of inner whorls, C272. K: *Cleistosphinctes* sp. [m], right view of incomplete body chamber, N283. L: *Leptosphinctes* sp. [M], right view of latex cast of incomplete shell, C274. M: *Leptosphinctes* sp. [M], left view of latex cast of phragmocone fragment, C273. N: *Leptosphinctes* sp. [M], left view of latex cast of compressed, resedimented, incomplete shell, C111. All specimens of the Upper Bajocian from Pumani (N) and Pucayacu (C) sections. The specimens were whitened with magnesium oxide prior to photography. Scale bar equals 10 mm.

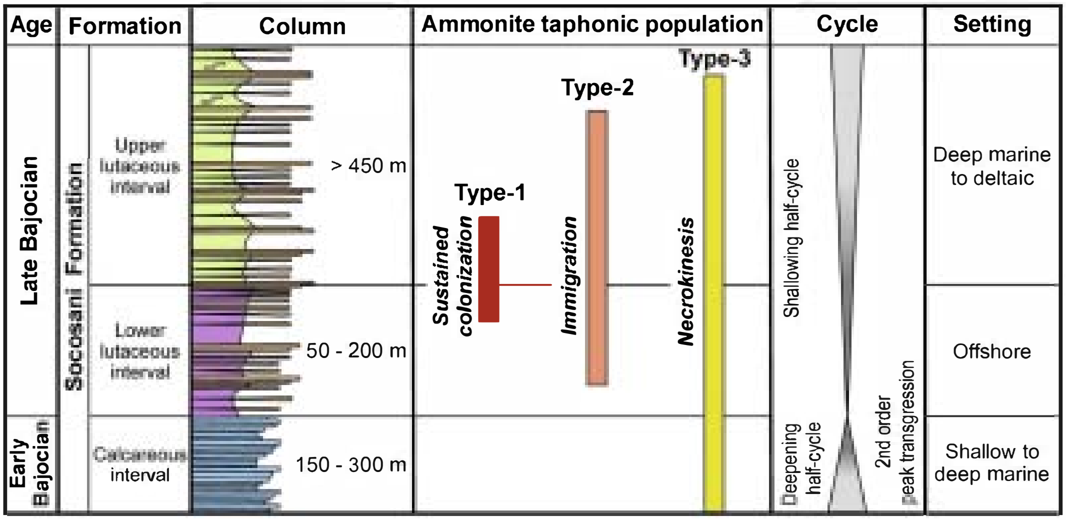


Fig. 11. Age, formation, column, ammonoid taphonic population, deepening-shallowing cycle and depositional setting of the three Bajocian lithologic intervals of the Socosani Fm in the area of Pumani River.

6. Depositional cycles and implications in sequence stratigraphy

According to the new taphonomic, palaeobiogeographical and palaeoenvironmental data presented above, the Bajocian depositional system in the area of Pumani River is interpreted as a mixed carbonate and siliciclastic ramp environment, with siliciclastic intervals of low accommodation space (lowstand and highstand systems tracts) and carbonate intervals of high accommodation space (transgressive systems tract). The carbonate deposits of the Socosani Fm, developed during an Aalenian-Early Bajocian deepening phase, represent deep marine platform to slope deposits and ended with episodes of sedimentary starvation at the earliest Late Bajocian (Niortense Biochron). On the other hand, the siliciclastic deposits of the upper Socosani Fm (the two lutaceous intervals, Fig. 11) represent a Late Bajocian shallowing phase, ending with Bathonian episodes of deep marine to deltaic sedimentation. These two phases of relative sea-level change made up a cycle of third order and include the episode of maximum deepening of a second-order, transgressive/regressive facies cycle, in the Arequipa Basin during the Early/Late Bajocian transition. Regional tectonics disturbed this general eustatic cycle in the area of Pumani River giving rise to olistoliths composed of, and included within, deep-water slope and normal basinal deposits during the Late Bajocian post-Niortense time-interval (i.e., the Garantiana and Parkinsoni biochrons).

7. Conclusions

- The changes in composition and structure of the Bajocian ammonoid recorded associations in the Pumani River area, at genus level and calibrated in units of European standard chronozones, confirm the regional changes of relative sea level drove, taphonomically and ecologically, the distribution of ammonoid shells in the Arequipa Basin.
- Taphonomic, palaeoecological and palaeobiogeographical observations in the Pumani River area indicate three categories of Late Bajocian ammonoid bioevents: passive immigration, active immigration and sustained colonization. Eudemic *Megasphaeroceras* and *Spiroceras* indicate colonization events by endemic species to the Andean Province and by pandemic species to the Tethys-Panthalassa Realm, respectively. 2) Miodemic *Leptosphinctes* and *Vermisphinctes* indicate active immigration by pandemic perisphinctids of the Tethys-Panthalassa Realm. Parademic *Cadomoceras* and *Adabofoloceras* indicate passive immigration by pandemic strigoceratids and phylloceratids of the Tethys-Panthalassa Realm.
- The Late Bajocian bioevents of ammonoid immigration and sustained colonization by *Megasphaeroceras* and *Spiroceras* were associated with an episode of maximum deepening, maximum relative sea-level rise and highest oceanic accessibility of a Bajocian–Bathonian second-order, transgressive/regressive facies cycle in the Arequipa Basin, during the Upper Bajocian Niortense Zone. However, synsedimentary regional tectonics in the area of Pumani River disturbed this general deepening/shallowing cycle of the Arequipa Basin, particularly during the Late Bajocian post-Niortense time-interval of the Garantiana and Parkinsoni biochrons.

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