1 A new species of the gondwanan genus *Cardiolaria* Munier-Chalmas in the
2 Sandbian of Northwestern Argentina: paleobiogeographic considerations

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14 Abstract. A new species of afghanodesmatid, *Cardiolaria benicioi*, is recorded
15 from Sandbian strata of northwestern Argentina. This species confirms the strong
16 paleobiogeographic relationships between the western Argentina basin and other
17 peri-Gondwanan areas. The Mid-Late Ordovician distribution of bivalves fit well
18 into the Mediterranean Province defined upon brachiopod and trilobite faunas.
19 Similitudes between Tremadocian and Floian bivalves from the western
20 Gondwana and the peri-Gondwanan areas indicates that such 'Mediterranean'
21 paleobiogeographic pattern can be traced back well into the Early Ordovician.

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24 Keywords: *Cardiolaria benicioi* nov. sp., Darriwilian, Mediterranean Province

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1. Introduction

Bivalves are uncommon in the Mid-Upper Ordovician successions of the northwestern Argentina basin. Mid Ordovician (Darriwilian-Sandbian) beds have yielded *Cadomia typa* de Tromelin, *Zaplaella capillaensis* Sánchez, and the new species *Cardiolaria benicioi*, described herein. These species are important paleobiogeographic markers and consequently are useful to elucidate faunal connections around Gondwana.

In this paper the new species *C. benicioi* is described on the basis of excellently preserved material recovered in the Sierra de Zapla of northwestern Argentina. In addition, the biogeogeographic distribution of Ordovician bivalves from western Gondwana is analyzed.

2. Geological setting and stratigraphy

Fossils come from the Capillas Formation (24°01'56"S-65°06'17"W), a thin-bedded fine-grained, green to dark grey, fossil-rich, internally homogeneous and laterally continuous interval within a thick Ordovician section that outcrops in both flanks of the Zapla anticline (Nieniewski and Wleklinski, 1950), a major structure in the Sierras Subandinas, in northwest Argentina (Fig. 1). The Sierras Subandinas form a thin-skinned thrust and fold belt in the present day foreland on northern Argentina and Bolivia (Kley et al., 1999). This abrupt region has a very dense green coverage. Due to the north-south trend of the main structures within the east propagating fold-belt, the Ordovician rocks crop out along east-west gorges, one of which is known as the Río Capillas, located ~25 km NW of the city

51 of Jujuy (Fig. 1). Along this river there are excellent quality and relatively
52 continuous exposures traversing the Sierra de Zapla (Fig. 1) that has allowed
53 stratigraphic studies (Monaldi et al., 1986; Astini, 2003; Astini et al., 2003) and
54 detailed sedimentological works on the Ordovician successions (Astini and
55 Marengo, 2006). The ~450 m thick section displays an alternation of shallow-
56 marine deltaic systems and estuarine environments, resulting from relative sea-
57 level fluctuations (Fig. 2). Collections of invertebrate faunas as well as
58 micropaleontological work have enhanced the importance of this locality
59 (Sánchez et al., 2003; Waisfeld and Henry, 2003; Albanesi et al., 2007;
60 Rubinstein et al., in press, among others). However, the recorded marginal marine
61 settings with frequent subaerial exposure (Astini and Marengo, 2006), prevents
62 proper biostratigraphic constraints of the complete sedimentary succession
63 cropping along the Río Capillas. Middle Ordovician acritarchs and related marine
64 algal forms, and spore-like microfossils were recently recorded from the Capillas
65 Formation (Rubinstein et al., in press). Based on the palynological assemblages, a
66 Dapingian age is interpreted for the upper Lagunillas Member of the underlying
67 Labrado Formation (Fig. 2), whereas the lower part of the Capillas Formation is
68 assigned to the Darriwilian (Fig. 2). Furthermore, conodont faunas recovered from
69 some carbonate-rich lenses, in a section immediately to the north of this area,
70 indicate an age not younger than late Darriwilian for the upper section of the unit
71 (Albanesi et al., 2007), which can probably reach into the Sandbian (Astini et al.,
72 2003). Both conodont faunas and facies analysis allow good correlation with other
73 sections in the Cordillera Oriental (to the west, Fig. 1), allowing to trace this
74 unique open-marine interval at a regional scale.

75 Sharply overlying a composite sandy estuarine fill referred to the Labrado
76 Formation (Fig 2), the Capillas Formation is represented by a fossil-rich fine-
77 grained laterally continuous fully marine interval, suggesting a rapid transgressive
78 shift, compatible with development of a marine flooding surface. The Capillas
79 Formation (~145 m) is a fine-grained shelfal facies association that gradually
80 coarsens and thickens up. This unit contains the only truly marine shelly fauna
81 that is not only embedded in the muddy facies within the middle section, but also
82 concentrated in few calcareous storm beds, above the fine-grained interval that
83 characterizes a maximum flooding stage. The lower section contains within the
84 laminated black shales few thin-tabular graded sandstones with parallel
85 lamination and wavy tops. The middle section is gradually to pervasively
86 homogenized with superposed bioturbation patterns, where *Phycodes* isp.
87 belonging to the *Cruziana* ichnofacies appears to be outstanding. These silty
88 mudstones contain abundant remains of bivalves and disarticulated trilobites.
89 Shell beds are mostly composed by concentrations of well preserved bivalves, few
90 trilobites and large cephalopods. Internally, they vary from disorganised and
91 poorly segregated to relatively organised, stacked and imbricated. Individual shell
92 beds show common shelter structures and geopetal cements indicating their rapid
93 burial. Fossil preservation is relatively good with weak fragmentation and scarce
94 individual abrasion in shells. Altogether, these features indicate a
95 parautochthonous origin, consistent with storm removal and nearby concentration
96 in shallow-marine environments. Few well-preserved wave ripple trains above
97 thin beds of laterally continuous sandstones allow inferring shallow subtidal
98 environments.
99

3. Paleobiogeographic considerations

Cardiolaria is a Gondwanan and peri-Gondwanan genus common in Mid-Late Ordovician (Darriwillian-Sandbian) beds from the Armorican Massif, Iberia, Morocco, and NWA (Babin and Destombes, 1990; Babin and Gutiérrez-Marco, 1991; Gutiérrez-Marco and Babin, 1999; Sá, 2008). Also, *Cardiolaria* sp. has been reported by Gutiérrez-Marco et al. (1997) from the Early Ordovician (Floian) of Central Spain. In the Sandbian strata of the northwestern Argentina *Cardiolaria* co-occurs with *Cadomia typa* de Tromelin, a Gondwanan species (Sánchez, 1986), and with the glyptarcidae *Zaplaella capillaensis* Sánchez (Sánchez et al., 2003). Glyptarcids are common dwellers in the Ordovician Gondwanan and peri-Gondwanan shelves.

All the Capillas Formation bivalves show strong paleobiogeographic affinities with those from Gondwanan and peri-Gondwanan basins (Benedetto et al., 2009). Similar paleobiogeographic affinities have been documented by brachiopods and trilobites (Benedetto, 2003, and additional references therein), and by acritarchs from the lower part of the Capillas Formation (Rubinstein et al., in press). The paleogeographic reconstruction of Sandbian time by Cocks and Torsvik (2006) (Fig. 3) shows that the existence of nearly continuous peri-continental shelves around Gondwana promoted the dispersal of bivalves. It should be noted that the pattern of occurrences of bivalve assemblages along western Gondwana during the Mid-Late Ordovician coincides with the boundaries of the Mediterranean Province defined by Spjeldnaes (1961) and refined by (Havlíček, 1989) on the basis of their brachiopod and trilobite assemblages.

124 Glyptarcoids like *Glyptarca* Hicks, *Camnantia* Cope, and *Celtoconcha*
 125 Cope, were found in Floian beds from Wales (Cope, 2002). At that time, Avalonia
 126 rifted off from the northern extent of the South American margin of Gondwana
 127 from which it was separated by a narrow Rheic Sea (Cocks and Torsvik, 2006).
 128 The gradual widening of the Rheic Ocean through the Ordovician led to place
 129 Avalonia far away from Armorica but near Baltica by the end of the Ordovician
 130 after the closure of the Tornquist Ocean (Fig. 3). However, as Sánchez and Babin
 131 (2003) stated, the bivalves of Wales show closest paleobiogeographic affinities
 132 with Iberia and the Armorican Massif during the Sandbian. Genera like *Glyptarca*,
 133 *Praeleda* Pfab, *Myoplusia* Neumayr, and *Lyrodesma* Conrad, clearly show that
 134 some bivalves were able to disperse across the wide Rheic Ocean. Noticeably,
 135 *Lyrodesma*, recorded in Wales, has been reported also from Sandbian beds of
 136 Bolivia (Sánchez and Suárez-Soruco, 1996). According to Cope (2002) bivalve
 137 larvae were only capable to migrate around Gondwana during the Early
 138 Ordovician, and they were apparently not able to cross large oceans and to
 139 colonize other continental shelves before the Mid-Ordovician, when they
 140 expanded to extra Gondwanan areas. Most of Early Ordovician bivalves seem to
 141 have been stenotopic forms, without planktotrophic larvae, which probably
 142 prevented its geographic dispersion (Sánchez and Babin, 2003).

143 It is interesting to note that though the Mediterranean Province was
 144 recognized by Sandbian times, occurrences of Early Ordovician bivalves from
 145 Gondwanan and peri-Gondwanan localities display a similar distribution. There is
 146 enough evidence supporting that the South American basins were closely related
 147 to the Mediterranean Province since the Early Ordovician (e.g. Babin and Branisa,
 148 1987; Benedetto and Sánchez, 1996; Sánchez and Babin, 2005). By the Floian, the

149 northwestern region of Argentina shared with the Mediterranean region the genera
 150 *Redonia* Rouault and *Coxiconchia* Babin, and closely related forms such as the
 151 cycloconchids *Cienagomya* Sánchez and *Fortowensia* Cope. Gutierrez-Marco et
 152 al. (2004) reported *Suria* Sánchez from late Floian strata of Peru, a genus
 153 originally described from nearly coeval beds from the Sierra de Famatina, western
 154 Argentina (Sánchez, 1997). In conclusion, according to the bivalve evidence, a
 155 western Gondwana corridor was established since the Floian and was active
 156 during most of the Ordovician.

157

158 4. Sistematic paleontology (by T.M. Sánchez)

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160 Material used in this study is housed in the paleontological collections of
 161 the Centro de Investigaciones Paleobiológicas, Facultad de Ciencias Exactas,
 162 Físicas y Naturales, Universidad Nacional de Córdoba, prefix CEGH-UNC.

163

164 Family AFGHANODESMATIDAE Scarlato and Starobogatov, 1979

165 Genus *Cardiolaria* Munier-Chalmas, 1876

166 Type species: *Cardiolaria barrandei* Munier-Chalmas, 1876

167 *Cardiolaria benicioi* nov. sp.

168 Text fig. 4

169 2003. *Cardiolaria* sp. Sánchez, Pl 4, fig. 1.

170 Derivation of name: From my grandson Benicio.

171

172 Holotype: The holotype is an internal mould of a left valve with the posterior
 173 extremity incomplete, CEGH-UNC 24072.

174 Paratypes: Six internal molds of left and right valves, CEGH-UNC 21078, and
175 24073 to 24077.

176 Type locality and age: Capillas Formation, northwestern Argentina, Darriwilian.

177 Diagnosis. *Cardiolaria* with elongate shell outline and with anterior and posterior
178 teeth of similar size.

179

180 4.1. Description. Shell outline ovate, posteriorly elongated and moderately
181 convex. Maximal high placed at the subumbonal region. Prosogyrous beak placed
182 in the anterior third of the valve. Eight anterior teeth and 15-20 posterior teeth.

183 The posterior teeth are similar in size to those of the anterior one but some of the
184 posterior series decrease abruptly in size below the umbo. These smaller posterior
185 teeth overlap the anterior teeth sub-umbonally. A small edentulous space below
186 the umbo separates both dental series. Anterior teeth not chevroned; anterior
187 subumbonal teeth diverging from the dorsal to the ventral part of the valve (Fig. 4,
188 4). Posterior teeth with ample chevron angles; most distal posterior teeth in zig-
189 zag (Figs. 4, 3 and 6). Adductor anterior muscle scar fringed on its internal margin
190 by a myophoric buttress. Posterior adductor scars smaller than the anterior ones but
191 deeply impressed. In the absence of well preserved external moulds, there is not
192 evidence of the shell ornament, but some poorly preserved external moulds show
193 only growth lines. Shell length ranges from 8 to 22 mm.

194

195 4.2. Discussion. *Cardiolaria benicioi* nov. sp. is distinguished from *C. beirensis*
196 (Sharpe, 1853) and the type species by its elongate outline shell and the size of the
197 anterior teeth with regard to the posterior ones. *C. barrandei* described and
198 illustrated by McAlester (1968) has a strongly inflated, rounded outline shell, and

199 preserve three large anterior teeth and several smaller posterior teeth. McAlester
 200 (1968) stated that the subumbonal dentition is not preserved in this material.
 201 However, Babin (in Babin and Gutiérrez-Marco, 1991) noted that a single
 202 specimen from the type locality shows an edentulous space beneath the umbo
 203 between the two dental series. *C. benicioi* differs from *C. barrandei* in the shell
 204 outline, in the less inflated shell, and in the number and relative size of the
 205 anterior teeth. Moreover, impressions of adductor muscles in *C. barrandei* are
 206 stronger than those of the *C. benicioi*. *C. beirensis*, described and figured by
 207 Bradshaw (1970) and Babin and Gutiérrez-Marco (1991) clearly differs from *C.*
 208 *benicioi* in its rounded shell outline and both the size and form of the anterior and
 209 posterior teeth. Bradshaw (1970) suggested that differences in shell outline can not
 210 be diagnostic for species identification because this feature is of little value in
 211 distorted faunas. It is important to note that although the specimens of *C. benicioi*
 212 show a chaotic position and are densely packed, shells are not deformed.

213

214 5. Additional comments

215

216 The specimen CEGH-UNC 24073 (Fig. 4, 5) shows some trace fossils
 217 preserved as epirelief on the internal mould. Although there are few records of
 218 similar trace fossils in the Ordovician, their form and size resemble those formed
 219 by annelids whose most common Paleozoic trace is *Vermiforichnus* Cameron
 220 (1969) to which can be tentatively assigned. The traces on the *C. benicioi*
 221 specimen are short, almost straight, unbranched epirelief tubules, displayed along
 222 the, and parallel to the surface of internal moulds. Because neither external
 223 moulds nor shells are preserved there is not evidence of shell borings.

224

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Figure captions

- 355 Figure 1. Map of a part of the Sierras Subandinas showing location of the
 356 fossiliferous level.
- 357 Figure 2. Stratigraphy of the Capillas Formation and location of fossiliferous
 358 level.
- 359 Figure 3. Paleogeographic reconstruction for the Sandbian simplified from Cocks
 360 and Torsvik (2006). ARM, Armorique, PE, Perunica, PRE, Precordillera.
- 361 Figure 4. *Cardiolaria benicioi* nov. sp. 1. Left valve, Holotype, CEGH-UNC
 362 24072. 2. Incomplete left valve, CEGH-UNC 21078. 3. Right valve, CEGH-UNC
 363 24075. 4. Detail of dentition, same specimen of the figure 2. 5. Right valve,
 364 CEGH-UNC 24073. Arrows indicate the traces possibly made by *Vermiforichnus*.
 365 6. Left valve, CEGH-UNC 24074. 7. Left valve, CEGH-UNC 24076. 8. Right
 366 valve, CEGH-UNC 24077. Scale bars: 5 mm.

Research highlights

- * Additional data confirms relationships along western Gondwana during the Ordovician
- * The Mediterranean Province was first defined for the late Ordovician
- * The Mediterranean Province existed since the early Ordovician