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New insights on Lower Ordovician (Floian) reefs from the Argentine Precordillera: Biostratigraphic, sedimentologic and paleogeographic implications

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Author Statement

"**New insights on Lower Ordovician (Floian) reefs from the Argentine Precordillera: biostratigraphic, sedimentologic and paleogeographic implications**" by Mestre, Ana, Heredia, Susana, Moreno, Florencia, Benegas, Leandro, Morfil, Andres and Soria, Tatiana.

Dear editor:

A detailed description of the diverse contributions to the work is shown.

Dr. Ana Mestre: Conceptualization, methodology, conodont and microfacies analysis, writing - review and editing. Supervision. Funding acquisition and project administration.

Dr. Susana Heredia: Conceptualization, methodology, conodont analysis, writing - review and supervision.

Lic. Moreno, Florencia: Conceptualization, methodology, conodont and microfacies analysis, writing - review and editing.

Lic. Leandro Benegas: Methodology, conodont and microfacies analysis, Figure editing.

Lic. Andres Morfil: Methodology, conodont and microfacies analysis, Figure editing.

Dr. Soria, Tatiana: Methodology, conodont and microfacies analysis.

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New insights on Lower Ordovician (Floian) reefs from the Argentine Precordillera: biostratigraphic, sedimentologic and paleogeographic implications

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Abstract

The shallow carbonate facies of the middle part from the San Juan Formation that outcrops in the Central Precordillera is studied in the present contribution in order to assess conodont biostratigraphy and sedimentology. Three facies and five microfacies were recognized in the Niquivil and Talacasto sections. These facies represent three genetically-related depositional facies from distal to proximal, and include from shallow subtidal facies below wave action to shoal and reef facies. This reef and shoal facies is recorded for the first time at the Talacasto section. The reef framework consists mainly of calcimicrobes in consortia with pulchrilaminids, calathids and lithistid sponges conforming a microbial-metazoan matrix-supported reef. The pulchrilaminid *Zondarella communis* Keller and Flügel, present in these reef facies, is here assigned for first time to the late Floian (Early Ordovician), *Oepikodus intermedius* conodont Zone. In this sense, the Precordilleran reefs represent the latest Floian record of pulchrilaminids compared to the worldwide records for these Early Ordovician reef-builder organisms. This provides crucial information for understanding the dispersal pathways of these organisms, and allows a paleogeographic reconstruction of the western margin of Gondwana in the Early Ordovician.

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1. Introduction

During the Early-Middle Ordovician, the Precordillera (NW Argentina) was mainly occupied by an extensive shallow-water mixed platform, on which a carbonate system was developed in the central part of the basin, in the current province of San Juan.

The San Juan Formation is a Lower-Middle Ordovician classic unit from the Precordillera. It was redefined by Keller *et al.* (1994) as composed by limestone and marly limestone with rich open marine fossils at La Silla section (Central Precordillera) (Beresi, 1986; Herrera and Benedetto, 1991; Beresi and Rigby, 1993; Vaccari 1994; Sánchez et al., 1996; Carrera, 1997). Different carbonate and mixed carbonate facies in the San Juan Formation were recognized by Cañas (1999), Keller (1999), Mestre (2014) and Soria et al. (2017), among others. The Ordovician reef shallow facies from this classic unit was studied by several authors (Cañas and Keller, 1993; Keller and Bordonaro, 1993; Carrera and Cañas, 1997; Cañas and Carrera, 2003) who provided different information about reef facies, which are mainly composed by microbial, lithistid sponges, calathids and *Zondarella communis* Keller and Flügel, 1996 (pulchrilaminids by Stearn et al., 1999).

Reefs are defined as calcareous deposits created by essentially in-place sessile organisms (Riding, 2002). The skeletal reef ecosystems became dominant in the latest Middle–Late Ordovician in the world. In contrast, Early Ordovician reefs were dominated by microbial components, together with calathids and lithistid sponges (Church, 1974; Toomey and Nitecki, 1979; Pratt and James, 1989; Cañas and Carrera, 1993, Li et al., 2015). The earliest occurrence of pulchrilaminids in the Early Ordovician reefs was documented in South China, and then in Laurentia (Toomey and Nitecki, 1979; Pratt and James, 1982; Adachi et al., 2011, 2012). Furthermore, Keller

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and Flügel (1996) described the genus *Zondarella* (included later in the Order Pulchrilaminida by Webby, 2012) which was involved in the upper reef horizon from the Argentine Precordillera. This reef horizon would have developed during the Dapingian times (early Middle Ordovician) (Lehnert and Keller, 1993; Keller and Flügel, 1996, Albanesi et al., 2003; Cañas and Carrera, 2003).

In the Central Precordillera, the distribution of the upper reef horizon that includes the reef-builder *Zondarella communis* is restricted to the north part of this region (Cañas and Carrera, 2003), and its presence southward still remains unknown. For this reason, the exploration of the new areas and sections in the Central Precordillera where this reef facies is present is an imperative assignment for increasing the knowledge on the distribution and paleoenvironment analysis of this important facies in the Ordovician Precordillera basin.

The *Tripodus laevis/Baltoniodus triangularis* Zone (early Dapingian) was recorded through the upper strata of the San Juan Formation which overlies the upper reef horizon in the Niquivil section (Mango and Albanesi, 2018a), contrary to a previous record that assumed the upper reef horizon as correlative with the *T. laevis* and *B. navis* zones (Dapingian) in the same section (Albanesi et al., 2003; 2006). This controversy led to restudy the conodont biostratigraphy of this reef horizon.

The aim of this contribution is to carry out biostratigraphic and sedimentologic studies on the middle part of the San Juan Formation in the Niquivil (31°00’30,87’’S – 68°46’11,80W) and Talacasto (30°24’20,63’’S – 68°41’07,70’’W) sections (Fig. 1) at the Central Precordillera where the reef and shoal facies are developed, in order to provide an assessment of biostratigraphic and paleogeographic significance of these facies in a regional and global context.

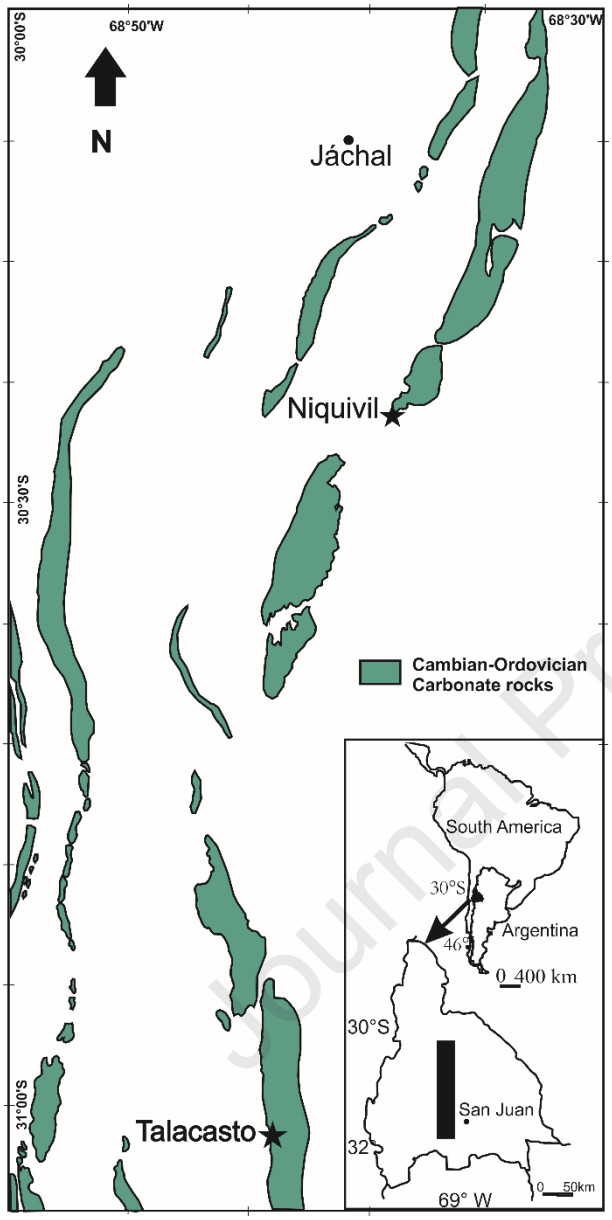

Figure 1: Location map of the study sections from the Central Precordillera. The black stars indicated the Niquivil and Talacasto sections.

2. Geological setting

The Precordillera is located in western Argentina and extends through the provinces of La Rioja, San Juan, and Mendoza, where Cambrian-Ordovician carbonate

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and siliciclastic successions are developed in a shelf environment. The San Juan Formation represents the youngest carbonate unit that is followed by a transitional diachronous succession that consists of nodular marlstones, parted limestones interbedded with black shale, or only black shale through the Lower to Middle Ordovician (Baldis et al., 1982; Keller, 1999; Astini, 2003; Mestre and Heredia, 2013; Mestre, 2014). The oldest conodonts recovered from the San Juan Formation demonstrate a late Tremadocian age for the base of this unit, recording the *Paltodus deltifer* Zone (Keller et al., 1994; Albanesi et al., 1998). The top of the San Juan Formation has been dated at several localities. In the northern and south sections, conodonts rendered a Lower Ordovician age (*Oepikodus intermedius* Zone) for the transitional beds between the San Juan Formation and the black shale of the overlying Gualcamayo Formation (Heredia et al., 2009; Soria, 2017), whereas elsewhere in central sections, conodonts have proved a Darriwilian age for the upper limestone beds of the San Juan Formation (Lehnert, 1995; Albanesi et al., 1998; Heredia and Mestre, 2011; 2013; Mestre, 2012; 2014; Heredia et al., 2017).

The reef facies were first mentioned in the Precordillera by Baldis et al. (1981) in the Upper Cambrian La Flecha Formation. After that, the Upper Cambrian thrombolithic microbialites were recorded in the La Silla Formation (Keller, 1999; Cañas, 2002). The most recent study in the La Silla Formation describes a reef mound, where the *Amsassia argentina* Carrera *et al*. (coral-like organism) constitutes the main framework builder organism together with a complex microbial consortium, and these organisms belongs to the latest Cambrian–Early Ordovician (Carrera et al., 2017).

In the San Juan Formation, diverse organic buildups have been recorded including the microbialites-sponge reefs and “stromatoporoid”-sponges-receptaculite reefs in the lower and upper part of this unit (Cañas and Carrera, 1993; Cañas and

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Keller, 1993; Keller and Bordonaro, 1993; Carrera and Cañas, 1996; Keller and Flügel, 1996), as well as in the "Ponón Trehué" Formation (Lehnert et al., 1998) at the southernmost of Cuyania.

Cañas and Carrera (2003) presented a summary of the Ordovician Precordilleran reefs, describing two Tremadocian reef types and two Middle Ordovician reef types. The Middle Ordovician reefs are composed by the Microbialite-*Zondarella*-*Calathium* reefs, present in the middle part of the San Juan Formation at the Central Precordillera, and the *Zondarella*-dominated reefs, present in the upper part of the San Juan Formation at the Eastern Precordillera. However, both were included in upper reef horizon (Keller, 1999; Lehnert and Keller, 1993; Cañas and Carrera, 2003).

Based on the conodont assemblages recovered from the Microbialite-*Zondarella*-*Calathium* reefs and *Zondarella*-dominated reefs in Central and Eastern Precordillera accordingly, Lehnert and Keller (1993) constrained these levels from the *Baltoniodus navis* to *"Amorphognathus" variabilis* zones (Middle Ordovician). However, in the Río Sasso section, these authors recorded the oldest conodont association with isolated *Zondarella* sp., indicating the *Oepikodus intermedius* – *Baltoniodus triangularis* zones for these levels. Also, Lehnert et al. (1998) proposed the *Oepikodus intermedius* Zone for the upper biostromal complex present in the "Ponón Trehué" Formation. On the other hand, Albanesi et al. (2006) proposed the *Tripodus laevis* and *Baltoniodus navis* conodont zones (Dapingian) for the Microbialite-*Zondarella*-*Calathium* reefs.

3. Methods

This study is based on detailed field observations and laboratory analyses of thin and polished sections. The Niquivil and Talacasto sections were logged for the

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153 construction of lithological columns of the shoal and reef facies from the San Juan
154 Formation (Fig. 2). Also, twenty-two rock samples were collected from these facies. In
155 the Micropaleontology Laboratory, forty thin and polished sections were made in order
156 to identify fossils and analyze the distribution of shoal components. A petrological
157 investigation of the thin and polished sections was performed using Leica DM2700
158 microscopes and Lanset binocular microscopes.

159 Fifteen conodont samples were collected from shoal and reef facies in the
160 Talacasto section on the same levels sampled by Soria et al. (2013), and five samples
161 were productive for conodonts. Also, eleven beds previously studied by Albanesi et al.
162 (2003, 2006) were resampled (Fig. 2, Table 1). From these, only 6 samples were
163 productive for conodonts. Initially, 1–2 kg of each sample was dissolved in diluted
164 formic acid with additional material processed if needed, following the Stone (1987)
165 methods. The insoluble fraction of each sample was picked for conodonts resulting in
166 recovery of *ca.* 200 identifiable and fragmented conodont elements. Conodonts are
167 housed in the collection of the INGEO at the Universidad Nacional de San Juan, under
168 the code-MP.

169

170 **4. Conodont biostratigraphy**

171 In order to date the shoal and reef facies recognized in the Talacasto and
172 Niquivil sections (Figs. 1, 2, Table 1), samples from these levels were examined for
173 their conodont content. The conodont assemblages recovered from samples belong to
174 the *O. intermedius* Zone, late Floian (Early Ordovician). The zonal key conodont *O.*
175 *intermedius* Serpagli, is accompanied by the more abundant species
176 *Bergstroemognathus extensus* Serpagli, *Juanognathus variabilis* Serpagli, few
177 specimens of *Cooperignathus aranda* (Cooper), and the typical Gondwanan conodont

178 species *Erraticodon patu* Cooper (Heredia et al., 2013), as well as a few more long-
179 ranging taxa (Fig. 3).

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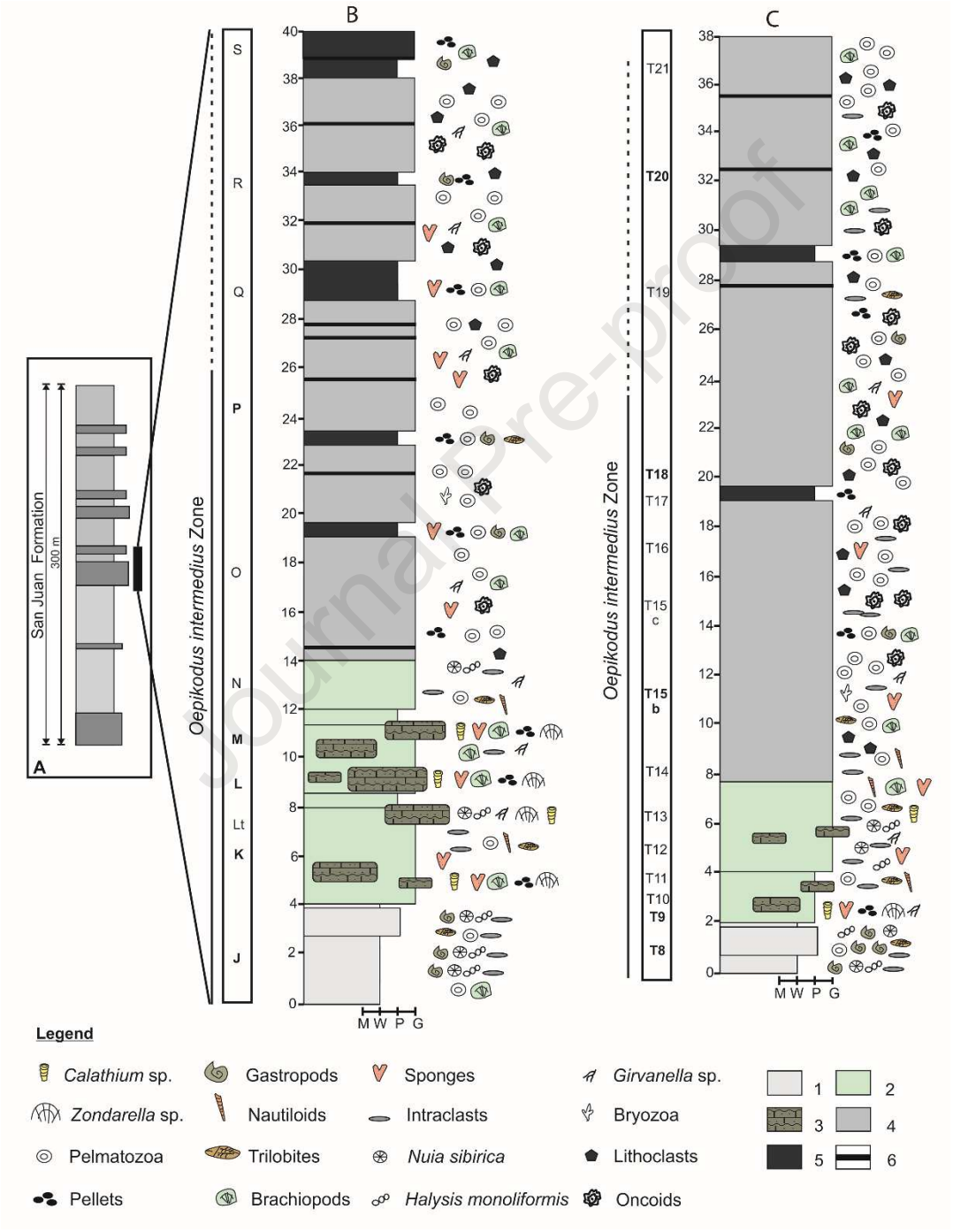

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183 **Figure 2:** Stratigraphy column of the shoal and reef facies from Niquivil (B) and
184 Talacasto sections (C) (vertical scale in meters). The samples in bold font are the

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productive conodont samples. A- Schematic stratigraphic column of the San Juan Formation. The microfacies are represented by 1- Nodular biointraclastic wackestone-packstone, 2- Biointraclastic packstone-grainstone, 3- Microbial-Skeletal boundstone, 4- Intrabioclastic grainstone, 5- Peloidal packstone-grainstone, 6- Chert.

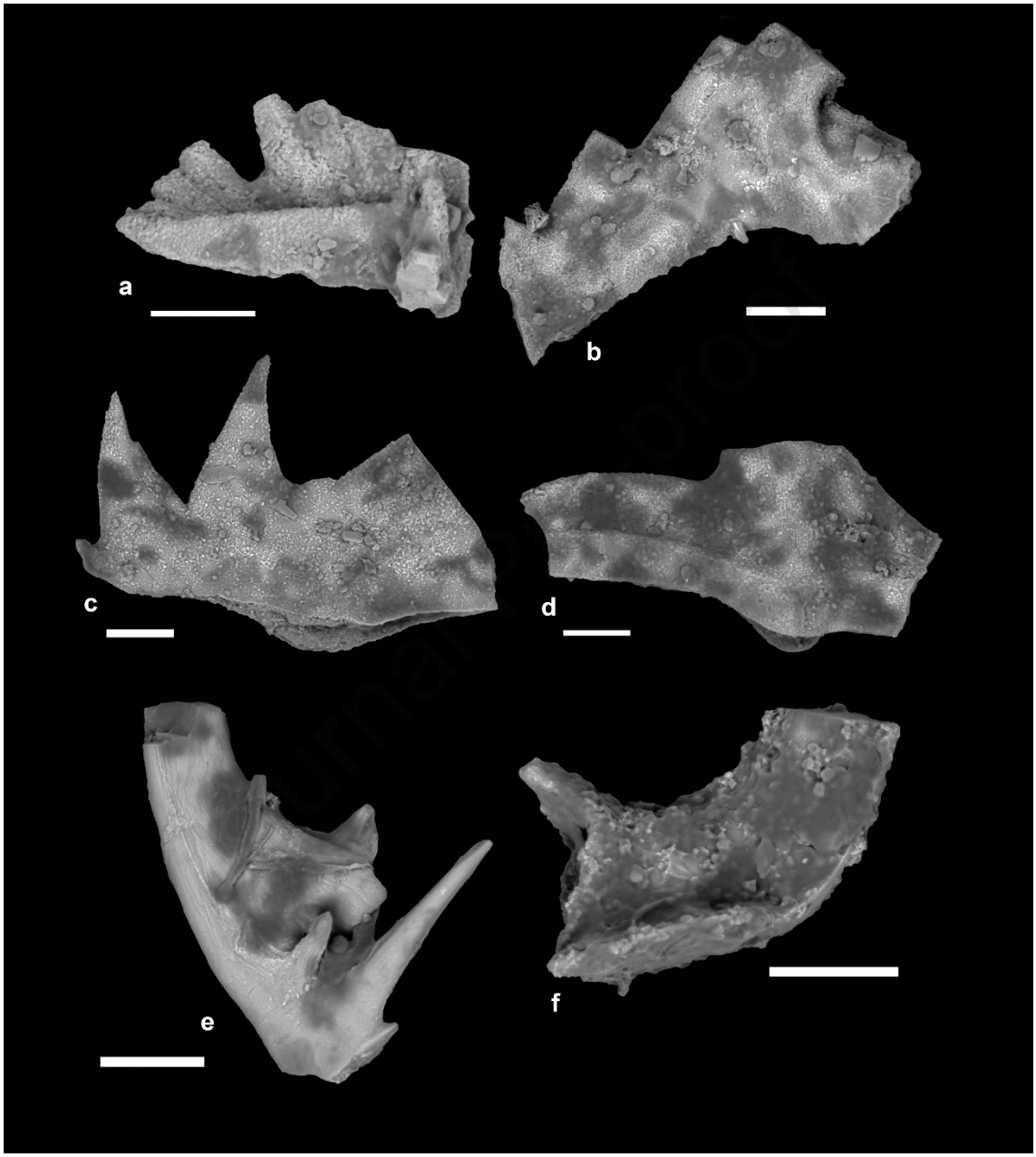
The *Oepikodus intermedius* Zone has already been recorded in several sections in the San Juan Formation by Sarmiento (1990), Lehnert (1993, 1995), Albanesi et al. (1998), Soria et al. (2013, 2017), Soria (2017) and Mango and Albanesi (2018b). Moreover, the conodont *O. intermedius* was recorded in the Huanghuachang section (Wang et al., 2009), South China (Li et al., 2010), Russia (Dubinina and Ryazantsev 2008) and Spitsbergen or the Svalbard Islands (Lehnert et al., 2013).

In this contribution, like in those papers of Soria et al. (2013, 2017) and Mango and Albanesi (2018b), the *Oepikodus intermedius* Zone is considered as an interval zone. Its lower boundary is indicated by the first occurrence of the eponymous conodont, and its upper boundary is marked by the first record of the conodont *T. laevis* or *Triangulodus brevibasis* (Seergeva), which matches with the last occurrence of the *O. intermedius* (Mango and Albanesi, 2018a,b).

The *O. intermedius* Zone may be correlative with the upper part of the *O. evae* Zone from South China (Wang et al., 2018), the upper part of the *R. andinus* Zone from North America (Midcontinent) (Ethington and Clark, 1981; Ross et al., 1997), the *Trapezognathus diprion* and *Microzarkodina* sp. A or upper *O. evae* Zone from Baltoscandia region (Bagnoli and Stouge, 1997; Viira, 2001), and the upper *O. evae* Zone from Newfoundland (Johnston and Barnes, 1999) (Fig. 4).

The species *B. extensus* has been recorded in North America, China, Australia and Argentina with an age range equivalent to middle-late Early Ordovician, from the

210 *Prioniodus elegans* to the *O. intermedius* zones (Zhen et al., 2001). Lehnert (1993)
211 extends the upper limit of its biostratigraphic range to the *J. jaanussoni* / *O.* aff. *O.*
212



213

214 **Figure 3:** Microphotographs of scanning electron microscope. The bar indicates 0.1
215 mm. specimens a-b from Niquivil section and c-f from Talacasto section. (a) *Oepikodus*
216 *intermedius* (Serpagli), Pa element, P sample, INGEO-MP 3573 (1); (b-c)
217 *Bergstroemognathus extensus* (Graves and Ellison), (b) Pb element, P sample, INGEO-
218 MP 3571 (1); (c) S element, T18 sample, INGEO-MP 1953 (1); (d) *Cooperignathus*

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aranda (Cooper), M element, T18 sample, INGEO-MP 1954 (1); (e) *Erraticodon patu* Cooper, Sc element, T15b sample, INGEO-MP 1851 (4); (f) *Juanognathus variabilis* (Serpagli), S element, T20 sample, INGEO-MP 1955 (2).

lanceolatus Association which is probably equivalent to the *B. triangularis/B. navis* Zone. However, Mango and Albanesi (2018a) interpreted that the subsequent conodont association *"P." nogamii/P. gracilis/A. jemtlandica* Association proposed by Lehnert (1993) is correlative with the *T. laevis/B. triangularis* Zone, restricting the *B. extensus* biostratigraphic range to the Early Ordovician as in the worldwide record.

4.1 Biostratigraphic discussion

The conodont fauna retrieved from the reef and shoal facies in this contribution is in agreement with those previously published (Soria et al. 2013; 2017, Mango and Albanesi, 2018b) and our own conodont data from the middle part of the San Juan Formation in the Central and Eastern Precordillera sections. However, this new conodont biostratigraphic data is highly contrasting with the previous conodont biostratigraphy of this reef facies in the Niquivil section, which was considered as developed during Dapingian times, *T. laevis* and *B. navis* zones (Albanesi et al., 2003, 2006; Cañas and Carrera, 2003).

In the Niquivil section, Albanesi et al. (2003, 2006) verified the first occurrence of *T. laevis* 20 m below the reef facies from the H1 sample to the N sample, and the presence of the *B. navis* only in the K sample which is located in the shoal and reef facies (Albanesi et al., 2006, Fig. 6, 7). On the other hand, Mango and Albanesi (2018a) in a recent conodont biostratigraphic study in the same section, recorded the first

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occurrence of *T. laevis* at least 20 m above the reef facies; additionally, these authors state the absence of *B. navis* in this section, contrary to the previously registered data by Albanesi et al. (2003; 2006). Nevertheless, the incoherence in the record of these important index conodonts was not discussed by Mango and Albanesi (2018a). Consequently, the late Floian age (*O. intermedius* Zone) recorded here for the reef and shoal facies in the Niquivil section is strongly supported by the biostratigraphic proposal of Mango and Albanesi (2018a).

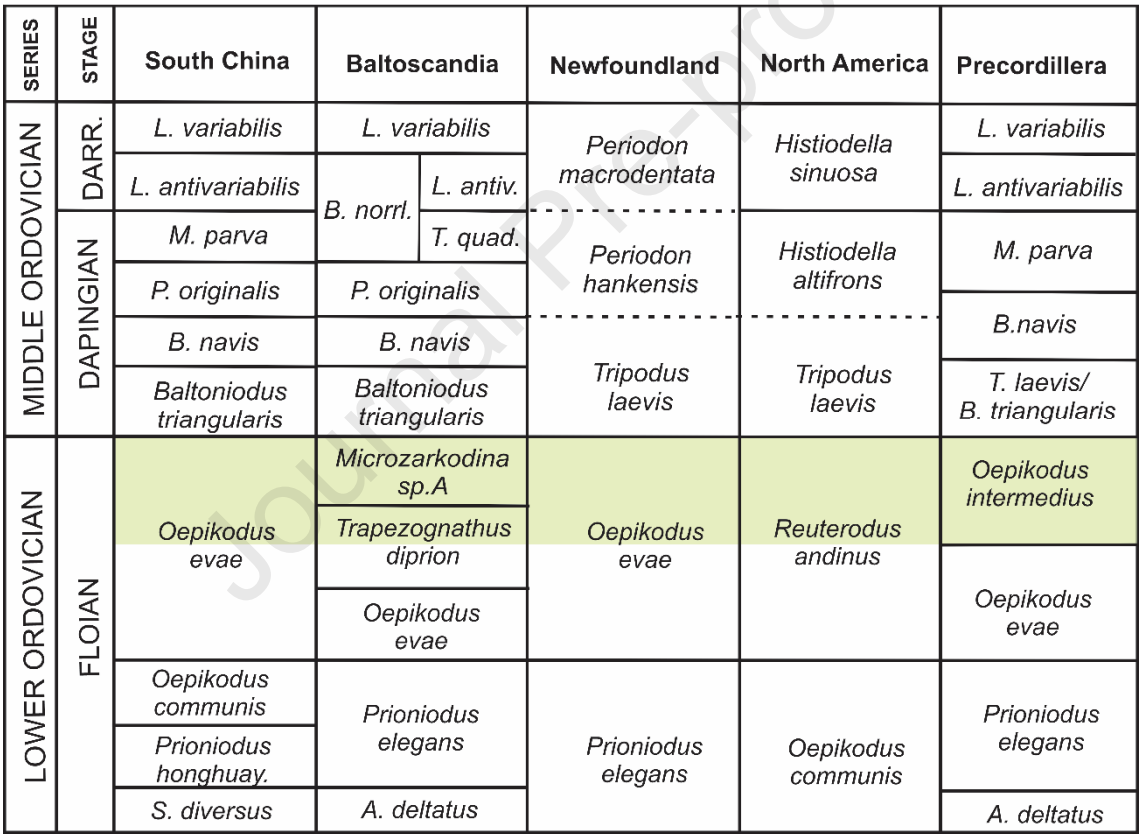

Figure 4: Conodont biostratigraphic correlation across the Lower/Middle Ordovician boundary between the Precordillera (Albanesi and Ortega, 2002, Soria et al. 2013, 2017; Heredia et al., 2017; Mango and Albanesi, 2018 a, b), South China (Wang et al., 2018), Baltoscandia (Bagnoli and Stouge, 1997; Löfgren and Zhang, 2003), Newfoundland (Johnston and Barnes, 1999; Stouge, 2012), North America (Ethington and Clark, 1982;

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Ross et al., 1997). The shadow area shows the study precordilleran reefs age. *A., Acoudus; B., Baltoniodus; L., Lenodus; M., Microzarkodina; P., Paroistodus; S., Serratognathus; T., Tripodus.*

5. Depositional facies

The description of carbonate microfacies is carried out using the classification of Dunham (1962). Based on textures/fabrics, sedimentary structures, key components and fossil contents, five microfacies were recognized in the middle part of San Juan Formation in both sections studied, which represent three genetically - related depositional facies from distal to proximal, including from shallow subtidal facies below wave action to shoal banks facies (Table 2).

***5.1 Facies 1 – Shallow subtidal*:** This facies mainly includes greenish nodular wackestone-packstone (M1) (Fig. 5a-b), it is dominantly thinly irregular to nodular bedded with thin interbeds of silty shale, and it has a high concentration of gastropods.

***Nodular biointraclastic wackestone-packstone* (M1):** The M1 microfacies is generally light to medium grey with diverse and abundant robust fauna, and with little evidence of fossil erosion. The carbonate component consists of gastropods (Fig. 5c-d), calcareous algae (*Halysis monoliformis*) and calcareous microproblematica (*Nuia síbirica*), intraclasts, trilobites and brachiopods.

The variety of textures, inorganic sedimentary structures, and distribution of siliciclastics are often obscured by pervasive bioturbation. Based on the diverse faunal assemblage, limited abrasion of the particles and robust fossil morphologies, as well as

the abundance of fine siliciclastic sediment and an intense bioturbation, this facies is interpreted as a normal marine shallow subtidal environment below wave action (Holland, 1993; Mángano and Droser, 2004). The high concentration of gastropods can be used as a paleobathymetric proxy, where the abundance peaks are associated to inferred lowstand intervals (Lindskog et al., 2015).

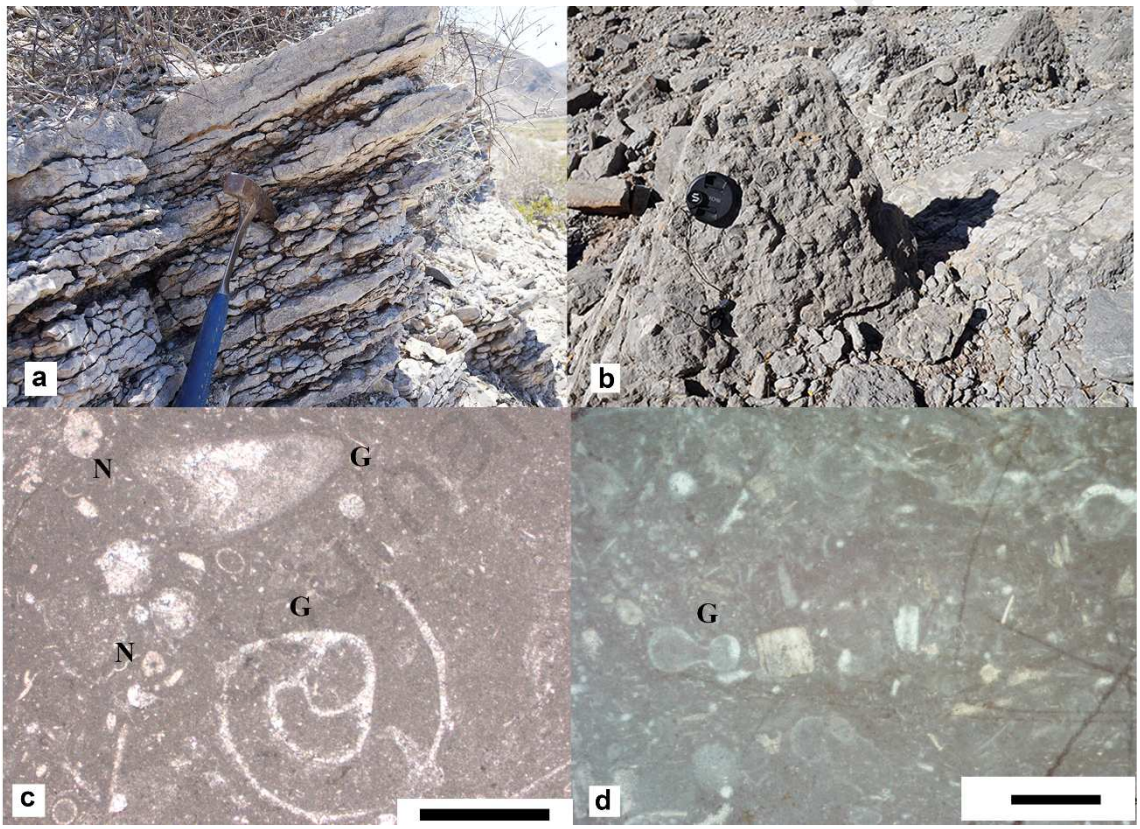

Figure 5 (colour online): Facies 1, Shallow subtidal below of the wave action. (a) Nodular bed outcrop from the Niquivil section, the hammer is 27 cm long. (b) High concentration of gastropods on the strata surface, scale represent 6 cm, Talacasto section. (c) Photomicrographs of the microfacies M1, (**G**) gastropods, (**N**) *Nuia síbirica*, scale 1 mm, J sample, Niquivil section. (d) Photograph of a cut slab of the microfacies M1, (**G)** gastropods, scale 0.5 mm, T8 sample, Talacasto section.

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297 ***5.2 Facies 2 - Shoal and reef facies:*** This facies is dominantly represented by two
298 microfacies including biointraclastic packstone-grainstone (M2) and Microbial-skeletal
299 boundstone (M3) (Fig. 6a, c, Fig. 7a-c, Fig. 8a).

300 ***Biointraclastic packstone-grainstone*** **(M2):** This microfacies is composed by light to
301 medium grey fine to very coarse well sorted grainstone. The most common carbonate
302 components are pelmatozoan ossicles, intraclasts, *Halysis monoliformis* and *Nuia*
303 *síbirica*, trilobites and brachiopods (Fig. 6b).
304 The stenohaline components dominating microfacies M2 indicate an open marine
305 environment, with bedding features suggesting common transport and reworking due to
306 wave action in the inner platform setting. The microfacies could have formed in
307 extensive coastal shoals or fringing banks (Read, 1985).
308 ***Microbial-Skeletal boundstone*** **(M3):** This microfacies only occurs in the lower levels
309 studied in the San Juan Formation (Fig. 2) and represents the main microfacies of the
310 biogenic structure. The reefs components consist of calcimicrobes, pulchrilaminids (*Z.*
311 *communis*) (Fig. 6c, Fig. 7c-d), lithistid sponges and *Calathium* sp. (Fig. 6d). It also
312 contains cyanobacteria, calcareous algae, and microproblematica, such as *Girvanella* sp.
313 *Renalcis?* sp., *N. síbirica*, and *H. monoliformis* (Fig. 8b-c), while brachiopods,
314 trilobites, nautiloids
315 and pelmatozoan ossicles are poorly represented. Microbes produce soft mats that trap
316 particulate sediment resulting in matrix-supported reefs (Riding, 1991; 2000; 2002). In
317 general, this type of reefs consists of a framework of microbes of light grey micrite,
318 with dispersed pulchrilaminids, *Calathium* sp. and lithistid sponges, conforming cluster
319 reefs (Riding, 2002) where essentially skeletons in place are adjacent, but not in contact.
320 The reefs range in shape as they can be small balls, domes and bells (up to 2.5 m in

height) with a nodular and laterally discontinuous texture (Fig. 6a, c, Fig. 7a-b, Fig. 8a). The

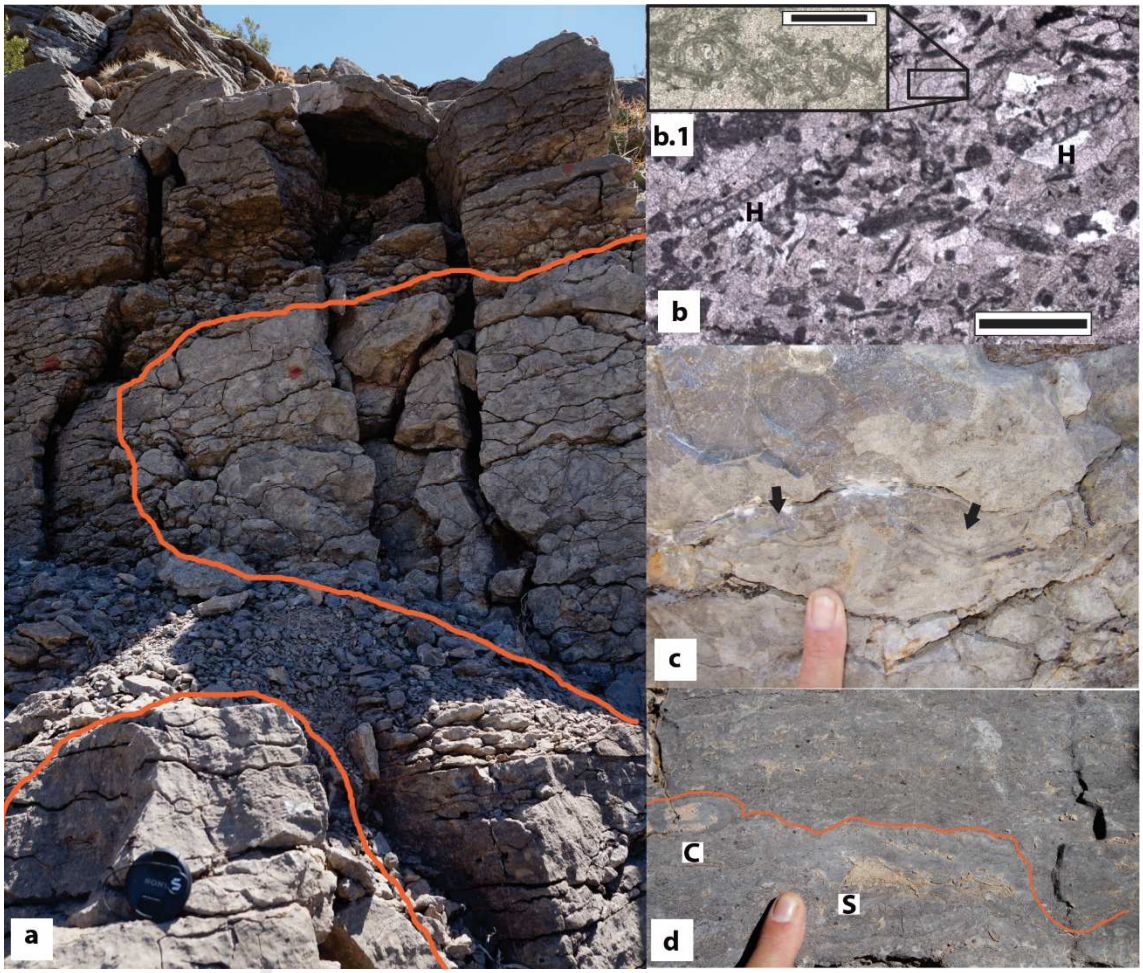

Figure 6: Facies 2, Shoal and reef facies. (a) Outcrop of the relation between M2 and M3 in the Niquivil section**,** scale represent 6 cm. (b) Photomicrographs of the microfacies M2, (**H**) *Halysis monoliformis***,** scale 1 mm, (b.1) details of *Girvanella* sp. filaments, scale 200 µm, T11 sample. (c) Detail of *Zondarella communis* indicate with black arrow, the finger is 3 cm long. (d) Outcrop of the irregular and diffuse limits between the M1 and M3 in the Talacasto section**,** (**C**) *Calathium* sp., (**S**) sponge, the finger is 3 cm long.

microfacies M3 is developed in a shallow subtidal environment, a normal marine setting with good circulation, and exposed to intermittent periods of high energy interbedding with the M2 microfacies.

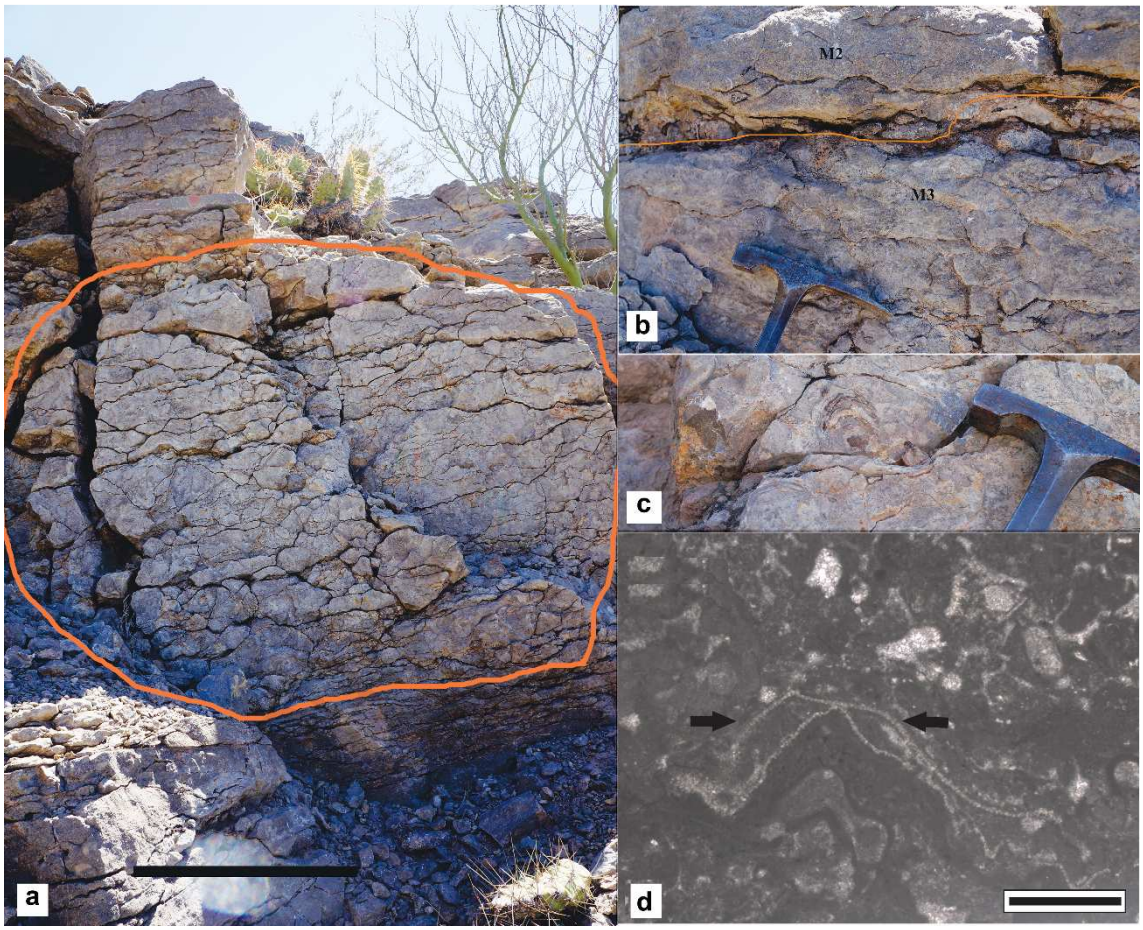

Figure 7: Facies 2 - Shoal and reef facies. (a) Outcrop of the relation between M2 and M3, reef with ball-shape, scale represent 1 m**,** Niquivil section. (b) Outcrop of the clear and well-defined limits between the M2 and M3**,** the hammer is 15 cm long, Niquivil section. (c) Detail of *Zondarella communis*, the hammer is 15 cm long, (d) Photomicrographs of the microfacies M3, *Zondarella communis* indicate with black arrow, scale 1 mm, L sample, Niquivil section.

345 ***5.3 Facies 3 - High energy shoal banks*:** This facies mainly includes two microfacies,
346 the intrabioclastic grainstone (M4) and peloidal packstone-grainstone (M5), which
347 display shallowing-up cycles in the shoal setting with an increase in the amount of
348 siliciclastic sediment such as lithics and quartz lithoclasts (Fig. 9a-b and Fig. 10a-b).

349

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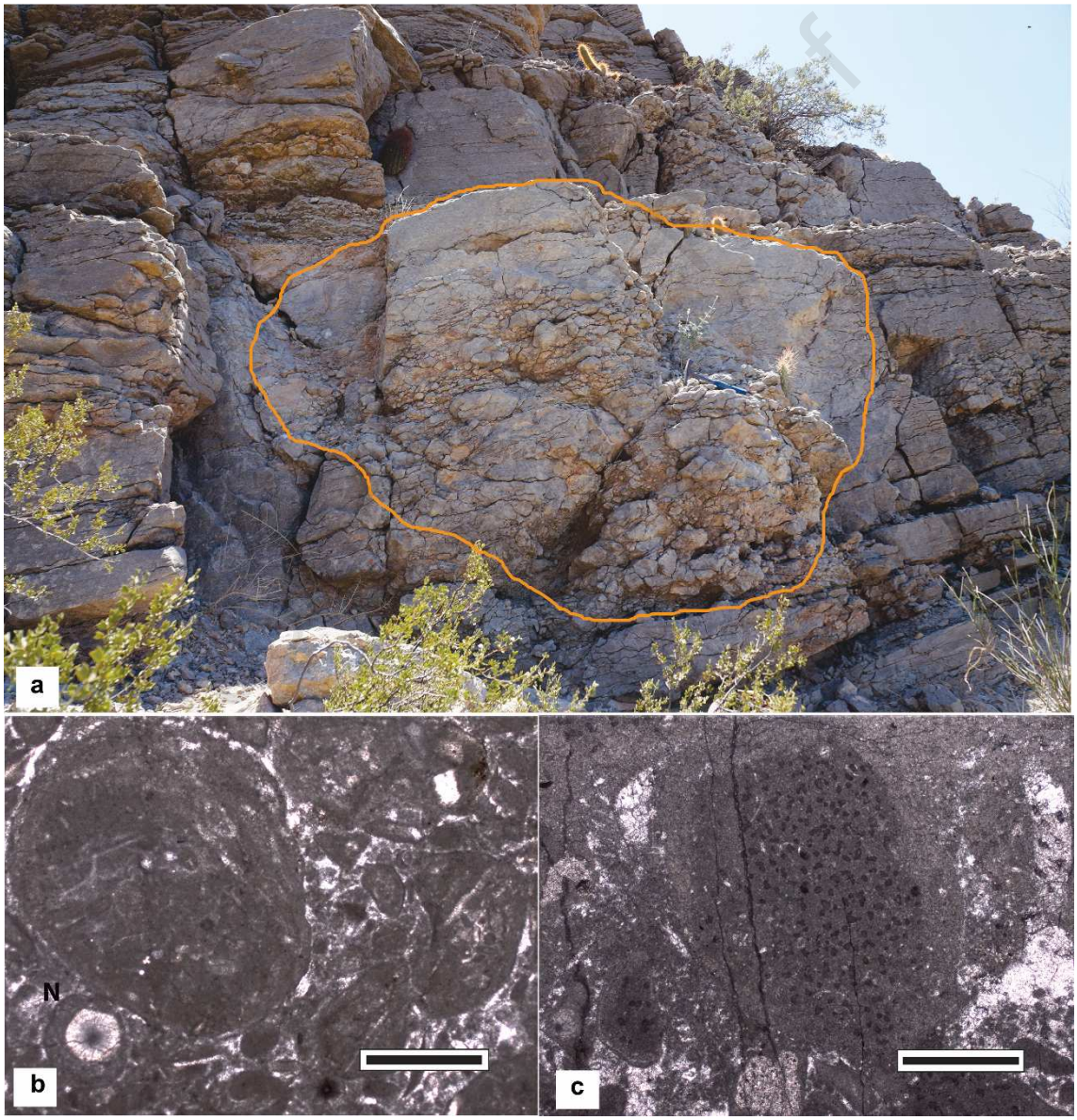
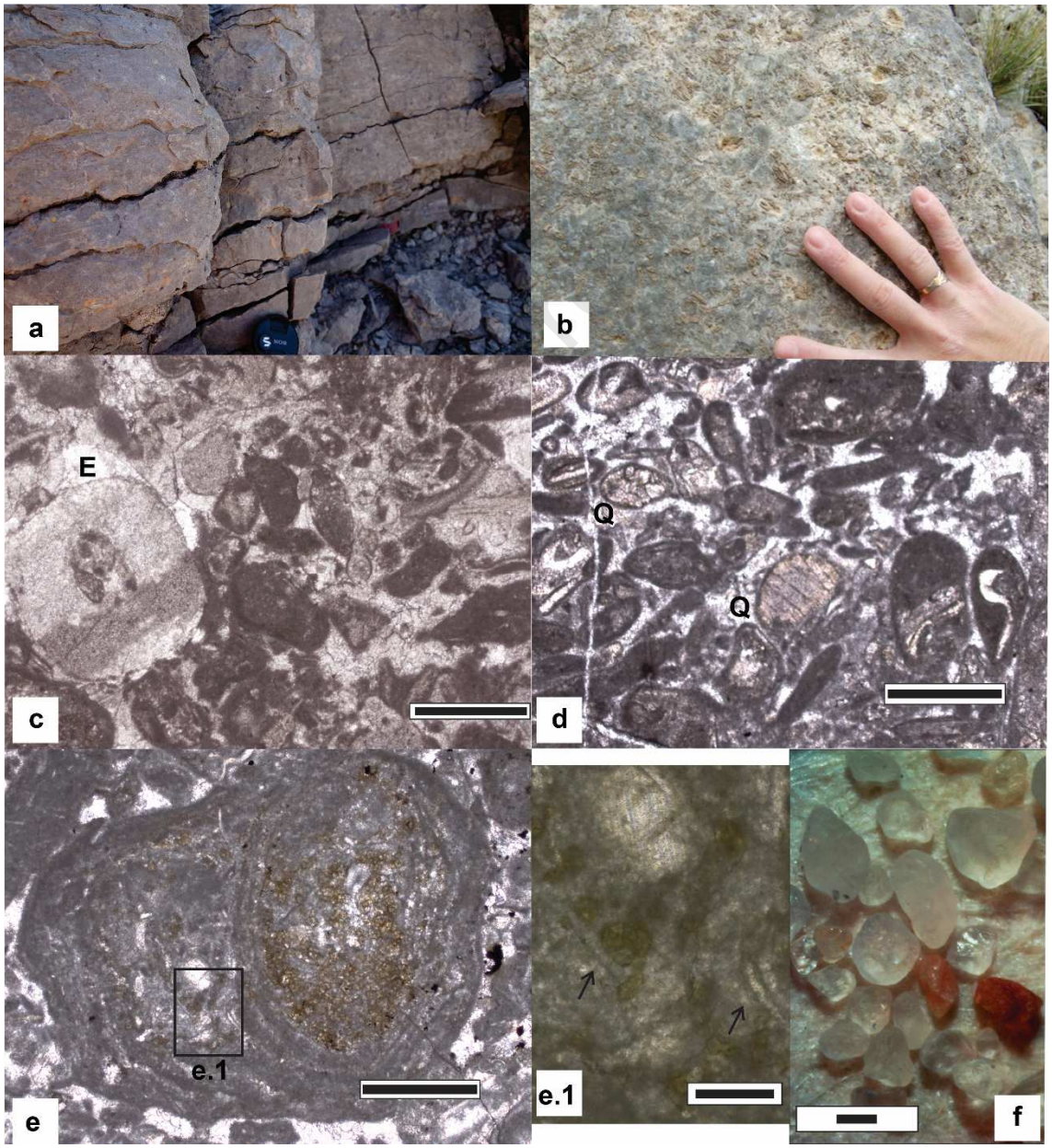


351

352 **Figure 8:** Facies 2 - Shoal and reef facies. (a) Outcrop of the relation between M2 and
353 M3, reef with bell-shape, the hammer is 27 cm long, Niquivil section. (b)

354 Photomicrographs of the microfacies M3, *Girvanella* sp. balls and (**N**) *Nuia sibirica*,
355 scale 1 mm, T10 sample, Talacasto section. (c) Photomicrographs of the microfacies
356 M3, *Girvanella* sp. and *Renalcis?* sp., scale 1 mm, T10 sample, Talacasto section.

357 ***Intrabioclastic grainstone*** **(M4):** Microfacies M4 is light to reddish grey in color with
358 thin to very thick tabular beds, erosive base and sharp top in amalgamated and stacked
359



360

361 **Figure 9 (colour online):** Facies 3 - High energy shoal banks. (a) Outcrop of the
362 amalgamated and stacked beds, Niquivil section, scale represent 6 cm. (b) High

363 concentrations of pelmatozoan ossicles and articulate stems on the strata surface in the
364 Talacasto section, the finger is 7 cm long. (c) Photomicrograph of the microfacies M4,
365 (**E**) pelmatozoan ossicles and intraclast, scale 1 mm, P sample, Niquivil section. (d)
366 Photomicrographs of the microfacies M4, intraclast and (**Q**) quartz lithoclast, scale 1
367 mm, T14 sample, Talacasto section. (e) Photomicrographs of the microfacies M4,
368 *Girvanella* sp. oncoids, scale 1 mm, (e.1) details of *Girvanella* sp. filaments, scale 200
369 µm, T15b sample, Talacasto section. (f) Quartz and lithic lithoclast recovered from
370 insoluble residue of conodont process, scale 0.5 mm, T14 sample, Talacasto section.

371 beds. It comprises intraclasts, pelmatozoan ossicles (Fig. 9c), G*irvanella* sp., oncoids
372 (Fig. 9e), lithoclasts (Fig. 9d, f), *Calathium* sp., sponges, brachiopods, bryozoans, and
373 bioclastic fragments, with moderately to grain-supported and well-sorted textures.
374 Diagenetic chert and iron oxide staining bioclasts are also observed.

375 The dominating stenohaline pelmatozoans indicate an open marine environment
376 suggesting common reworking and transport due to wave action. This largely encrinitic
377 facies represents extensive pelmatozoan meadows, whose sediment was locally
378 reworked into shoal banks and bars by wave action and/or storm events (Aigner, 1985;
379 Ausich, 1997; Batten Hender and Dix, 2008). The oncoids in this microfacies rarely
380 exceed 2 mm in size and show a range of shapes, with nuclei of particles encrusted with
381 asymmetric sets of crinkly and thinly laminated micrite, or with slightly denser layers of
382 *Girvanella* filaments forming a laminated or meshwork fabric. The sets of laminae are
383 frequently disconformable, likely indicating episodic rotation of oncoids (Fig. 9E)
384 (Batten Hender and Dix, 2008). Many intraclasts and bioclasts within this facies possess
385 brownish rust-stained margins encrusted by *Girvanella* (Fig. 9c-d).

386

Peloidal packstone-grainstone **(M5):** This microfacies is mainly light grey to grey in color, and it shows thin to medium tabular beds. It consists predominantly of moderately-sorted peloids, and it has minor bioclasts and intraclasts. It displays sharp-erosive bases and burrowed tops, planar lamination and low-angle cross-stratification (Fig. 10A-B). Iron oxide nodules are developed on the strata surfaces. Rare fossil fragments of pelmatozoan, brachiopods and trilobites are present.

The presence of planar lamination and low-angle cross-stratification with well-sorted peloids is dominant over the grain-supported textures (Fig. 10c-d). This indicates high-energy and wave-agitated environments during deposition conforming shoal banks and bars (Batten Hender and Dix, 2008; Hamon and Merzeraud, 2008; Zhang et al., 2015a,b; Chen et al., 2016; Gou et al., 2018).

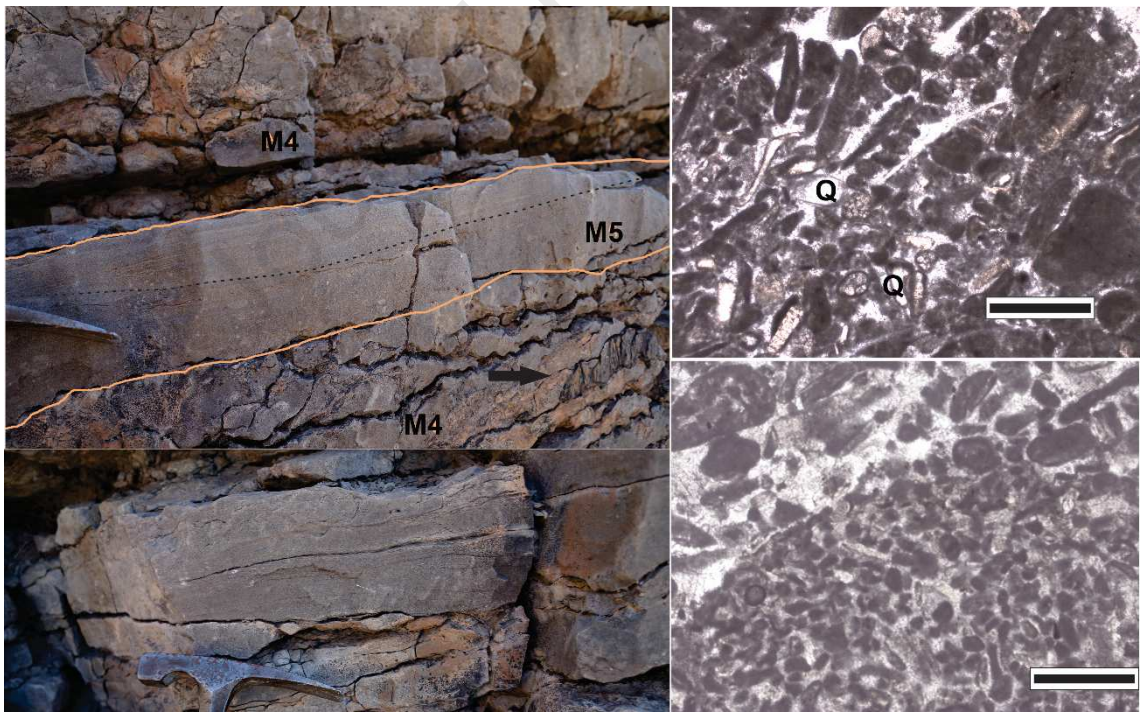


Figure 10: Facies 3 - High energy shoal banks. (a-b) Outcrop of the thin to medium tabular beds, with sharp-erosive bases, planar lamination and low-angle cross-stratification, (a) scale represent 6 cm. (b) the hammer is 15 cm long. (c-d)

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Photomicrographs of the microfacies M5, peloids and (**Q**) quartz lithoclast, scale 1 mm. (c) T16 sample, Talacasto section. (d) N sample, Niquivil section.

6. Comparison between the Niquivil shoal and reef facies and the Talacasto equivalent beds

In recent years, many authors have made contributions about Ordovician reef and shoal facies providing exensive discussions and new ideas on the origin, distribution and composition of the facies and reef frame-organisms (Adachi et al., 2011; Carrera et al., 2017; Hong et al., 2017; Li et al., 2015, 2017, 2018, among others). The most recent contribution about these topics from the Precordillera was that of Cañas and Carrera (2003) who studied the La Silla, Niquivil and San Roque sections from the Central Precordillera.

The Niquivil section is here restudied in order to compare it to the Talacasto section for first time, showing differences in the distribution, morphology and fauna composition in the shoal and reef facies (Fig. 2). Moreover, the comparision between them allows the recognition of subtle variations in the environment conditions during the growth of the reefs.

The stratigraphic levels analyzed in the Niquivil section are 40 m thick, whereas in the Talacasto section is 38 m thick (Fig. 2). The reefs facies are embedded in the base of the shoals (biointraclastic packstone-grainstone) in both sections. The Niquivil reefs present variable dimensions from 2.5-3.5 m in width and 1.5-2.5 m in height, with clear and well-defined limits (Fig. 6a, Fig. 7a-b and Fig. 8a), whereas the size in the Talacasto reefs varies from 0.5-1 m in width and 1-1.5 m in height, and the limits are irregular and diffuse (Fig. 6d).

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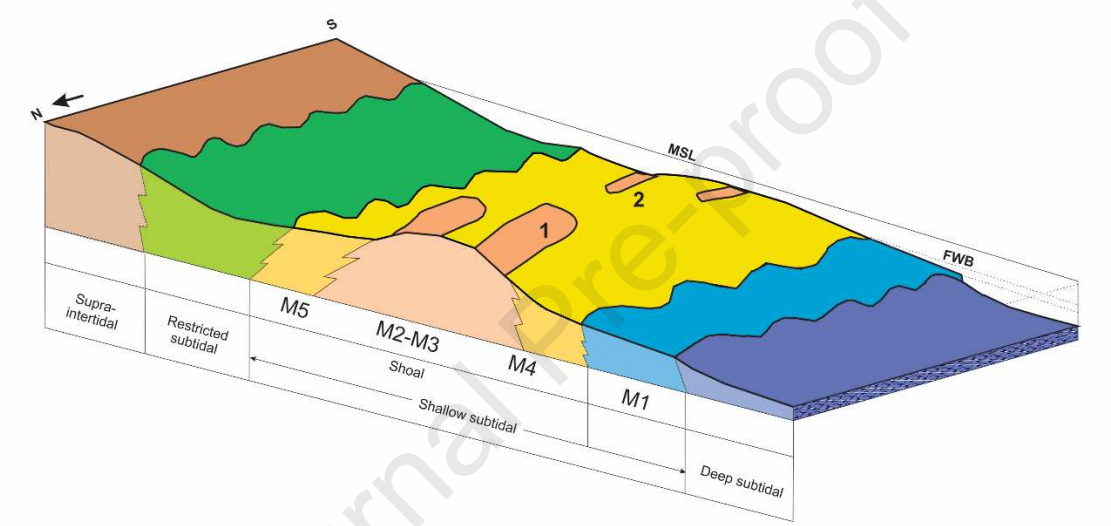
427 The skeletal components observed in the Niquivil reef facies consist specially by
428 *Zondarella communis*, *Calathium* sp., sponges, whereas nautiloids, gastropods,
429 brachiopods, trilobites and pelmatozoan ossicles are scarce. On the other hand, the
430 Talacasto reef facies is characterized by sponges (as main component) and *Calathium*
431 sp. The *Zondarella communis* specimens are small and scarce as well as the
432 brachiopods, gastropods, trilobites and pelmatozoan ossicles, which are rare or absent.
433



434

435 **Figure 11:** Carbonate platform depositional model for the San Juan Formation in the
436 study areas. The platform displays a gentle transition from shallow to deeper
437 depositional environments. The subdivision of the carbonate platform is based on
438 Pomar (2001). FWB- fair-weather wave base, MSL – medium sea level, **1-** Niquivil, **2-**
439 Talacasto sections**.**
440

441 A detailed study of the framework of the reef facies and its relation to the reef-
442 builder organism should be carried out in the future in order to resolve the interaction
443 between the reef-builders and the real nature of the *Zondarella communis*, due to the
444 fact that the latter is interpreted as pulchrilaminids (Webby, 2012) or by microbial
445 generation, like stromatolite (Cañas and Carrera, 2003).

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In the present report, a comparative analysis of reef and shoal facies between the Niquivil and Talacasto sections is developed in order to show that the differences between these reef communities were essentially controlled by the bathymetry and morphology of the platform (Fig. 11). Although sea-level fluctuation is an important variable that controls regional reef development, it is estimated that energy change is a first-order factor that controls reef growth (Zhang et al., 2015b, 2016). Based on this statement we interpret a probable shallower depositional environment in the Niquivil section compared to the Talacasto section.

7. Depositional model and environmental significance

The vertical distribution of the facies and microfacies in the middle part of San Juan Formation in the Talacasto and Niquivil sections and their arrangement from shallow subtidal below wave action to shoal and reef settings, suggest that these beds represented an open-ocean, relatively high-energy carbonate platform, and denote that their shallowest depositional position occurred in the upper *O. intermedius* Zone (uppermost Floian). Therefore, it is possible to recognize three evolutionary stages in the build of the shoal banks.

Stage 1 (Fig. 12) is represented by Facies 1 (Nodular biointraclastic wackestone-packstone) where the high fauna diversity, the intensity of bioturbation and the interbedding fine silty shale observed in this facies, suggest low energy conditions in the subtidal environment below the fair water wave base in the photic zone due to the presence of *H. monoliformis* and *N. síbirica.*

Gradual regression during Stage 2 (Fig. 12) is represented by Facies 2, where the increase of the wave action produced the intraclast and bioclast reworking in this

deposit characterized by the biointraclast packstone-grainstone microfacies (M2). The accumulation of carbonate material by wave action building shoal bars presumably parallel to the shoreline in the inner platform settings (Flügel, 2010) generated protection and a relatively shallow environment. In these conditions, the reef grew on the shoals, and its framework consisted of open microbialites colonies with *Zondarella communis*, *Calathium* sp. and sponges as reef-builders (M3 microfacies). The spaces between this organic framework were filled by carbonate mud, giving as a result matrix-supported reefs (Riding, 1991; 2000; 2002).

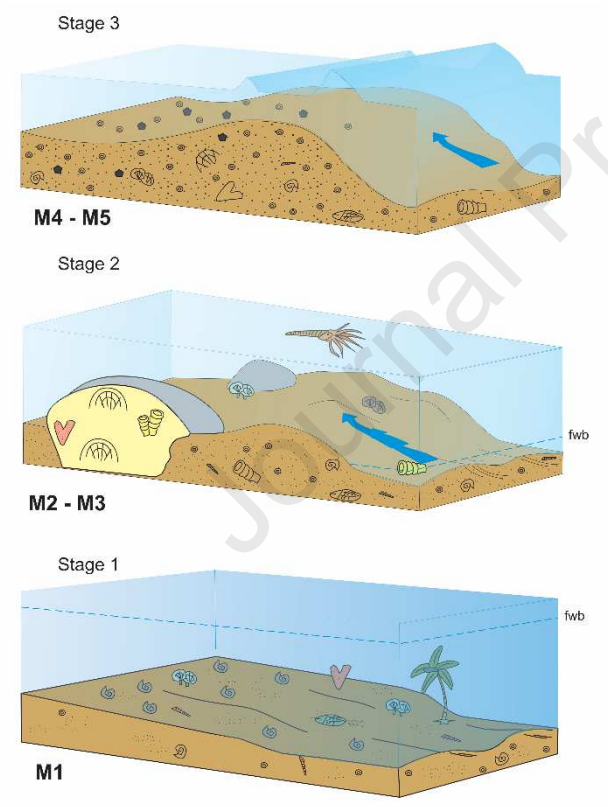

Figure 12: Dynamic facies model, showing distribution of facies and timing of the arrangement from shallow subtidal below wave action to reef and shoal, recognizing three evolutionary stages in the built of the shoal banks (for legends see Fig. 2).

The reefs of the San Juan Formation could have formed in 6 to 12 m water depths due to the presence of *Calathium* sp. (Nitecki 1972; Kaya and Friedman, 1997),

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485 in a normal marine environment with good circulation, and subjected to intermittent
486 periods of high energy in the shallow subtidal shoal setting.

487 Subsequently, the gradual increase of energy in shallower environments
488 produced that the reefs were covered by coarse carbonate and lithic material developing
489 high energy shoal banks represented by Facies 3 (Stage 3, Fig. 12). The microfacies M4
490 and M5 are interbedding and they conform the thickest facies in the stratigraphical
491 levels studied.

492 Recent studies have attempted to calibrate the absolute depths of the lithofacies
493 and biofacies in a well-constrained Upper Ordovician stratigraphic interval of the
494 classic Cincinnati Arch region (northern Kentucky and southern Ohio), indicating the
495 orientation and gradient of an ancient gently dipping carbonate ramp (Brett et al., 2015).
496 The conclusion was that the cross-bedded grainstone that represent shoal-type
497 environments are within the 6 - 18 m depth range, in agreement with estimates of
498 normal wave base in epeiric seas which is of 5 - 15 m (Brett et al., 1993).

499 A regression trend is recognized in the shoal and reef facies from the
500 Precordillera, which is composed by successions of coarsening-up and thickening-up
501 strata that reflects a gradual shallowing-upward evolution during the *O. intermedius*
502 Zone (late Floian).

503

504 **8. Paleogeographic significance of the Precordilleran late Floian shoal and reef**
505 **facies**

506 The late Floian (late Early Ordovician) regression trend registered in the shoal
507 and reef facies studied here has already been documented by Nielsen (2003, 2011) and
508 Haq & Schutter (2008) for Baltoscandia and Laurentia. Nielsen (2003) proposed an

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abruptly sea-level lowering in this time interval, the Latest Billingen Stage (Baltoscandian) or Basal Whiterock (Laurentia) after the *Evae* highstand cycle. This regression event is recorded in other regions where the carbonate and siliciclastic coarse deposits were developed. Agematsu and Sashida (2009) registered late Floian (*T. larapintinensis Zone*) shoal to backshoal deposits from the Sibumasu Terrane (Thailand), and Astini et al. (2004) verified a late Floian deltaic progradation to the top of the Acoite Formation in the Eastern Cordillera during the *T. diprion- B.* cf. *triangularis* Zone (Carlorosi et al., 2013).

An overview of the Precordilleran Ordovician reefs was made by Cañas and Carrera (2003) proposing three reef types: 1- Thrombolithic reef dominating during the Upper Cambrian and the of most Tremadocian; 2- Microbialite-metazoan reef in the late Tremadocian; 3- Microbialite-*Zondarella*-*Calathium* reef and *Zondarella*-dominated reef in the early Middle Ordovician (Dapingian). These two types of Middle Ordovician reefs are present in different regions of the Precordillera. The Microbialite-*Zondarella*-*Calathium* reef is located in the Central Precordillera, and the *Zondarella*-dominated reef has been described for the Eastern Precordillera (Cañas and Carrera, 2003). These authors considered a microbial origin for *Zondarella*, opposed to the interpretation proposed by Keller and Flügel (1996), Stearns et al. (1999), Zhen and Pickett (2008), Webby (2012) and Hong et al. (2018). In the present contribution the followed criterion is that proposed by Webby (2012) who consider *Zondarella* as Pulchrilaminid (hypercalcified sponges).

The reef facies studied in the present report coincides with the Microbialite-*Zondarella-Calathium* reef proposed by Cañas and Carrera (2003). However, the new biostratigraphic and sedimentologic information allows indicating an accurate late Floian age (later *O. intermedius* Zone) for the reef facies, improving the knowledge of

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paleoenvironmental and paleogeographic distribution of the pulchrilaminid (*Z. communis*) for this time interval.

The conodont information from the *Zondarella*-dominated reefs (Eastern Precordillera) reports that these reefs appear immediately below carbonate beds that represent at least the *Lenodus variabilis* Zone (Mestre, 2014; Heredia et al., 2017) or more likely the *L. antivariabilis* Zone (Heredia and Mestre, 2017), proposing a latest Dapingian to earliest Darriwilian age (Fig. 13) for these reefs, in agreement with the previous age suggested by Lehnert and Keller (1993).

Cañas and Carrera (2003) suggested that the San Juan Formation reef sequences correspond to the globally recognized reef-forming phases 1 to 3 proposed by Webby (2002). Nevertheless, the Middle Ordovician reefs correspond to phase 4, which includes Dapingian-Early Darriwilian reefs. We propose that the Microbialite-*Zondarella*-*Calathium* reef corresponds to the upper part of the phase 3 and the *Zondarella*-dominated reef to the upper part of the phase 4 (Fig. 13). The new biostratigraphic location of the Precordilleran pulchrilaminids (*Z. communis*) provides a new insight on the paleogeographic distribution of this restricted group of "hypercal-cified sponges".

The oldest encrusting pulchrilaminid (genus *Pulchrilamina*) was reported from the Tremadocian to the early Floian in the provinces of Hubei and Guizhou, South China (Zhu et al., 1993; Adachi et al., 2011) (Fig. 13, 14). The *Pulchrilamina* have also been recorded in North America (in the states of Texas and Oklahoma) from early Floian strata, where they are the main framework-builders exhibiting large domical forms (Toomey and Ham, 1967; Toomey, 1970; Toomey and Nitecki, 1979; Toomey and Babcock, 1983; Webby, 1986, 2002) (Fig. 12, 13). Moreover, this genus was

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558 reported in Newfoundland from early Floian strata (Pratt & James, 1989) (Fig. 13, 14)
559 and reef-derived clasts of probable Floian-Dapingian age (Pohler and James, 1989) that
560 were not taken in consideration due to their reworked origin.

561 The youngest record of pulchrilaminids as that proposed by Webby (2012), is
562 represented by *Ianilamina kirkupensis* Pickett and Zhen, from the central New South
563 Wales (Australia), as an isolated occurrence in early Darriwilian limestone lens related
564 to a volcanic arc setting. Zhen and Pickett (2008) inferred that *Ianilamina kirkupensis* is
565 the most similar species compared to *Z. communis* from Argentina (Keller and Flügel
566 1996). The main differences between them are the well-developed pores in the laminae
567 of the *Ianilamina* that have not been observed in *Zondarella.* However, the frequent
568 disruption in the laminae of this former species could be equal to the *Ianilamina* pores,
569 and the presence of encrusting bryozoan in both species allow a close comparison
570 between them (Zhen and Pickett, 2008).

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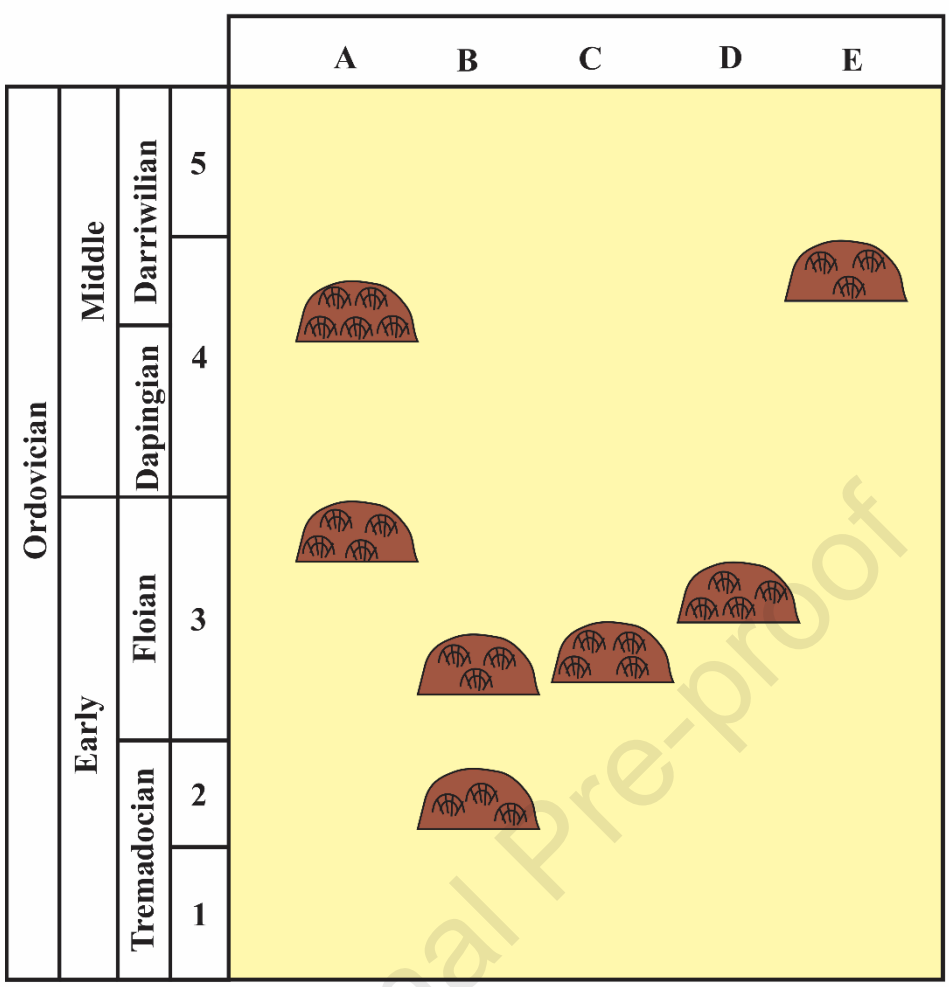

Figure 13: Scheme of vertical distribution of the Early-Middle Ordovician pulchrilamiloid reefs and its location in the division of Webby (2002) of the Ordovician reef-building phases. A- Precordillera (this study); B- South China (Zhu et al., 1993; Adachi et al., 2011); C- North America (Toomey and Nitecki, 1979; Toomey and Babcock, 1983); D- Newfoundland (Pratt and James, 1989); E- Australia (Zhen and Pickett, 2008).

The late Floian pulchrilaminids from the Precordillera represent the youngest record of this reef-builder organism in the Early Ordovician (Fig. 13, 14). The latest Early Ordovician time was interpreted by Webby (2012) as a doubtful evolutionary period for Early Ordovician pulchrilaminids. This new record provides crucial information on early skeletal reefs, increasing the knowledge for the reconstruction of

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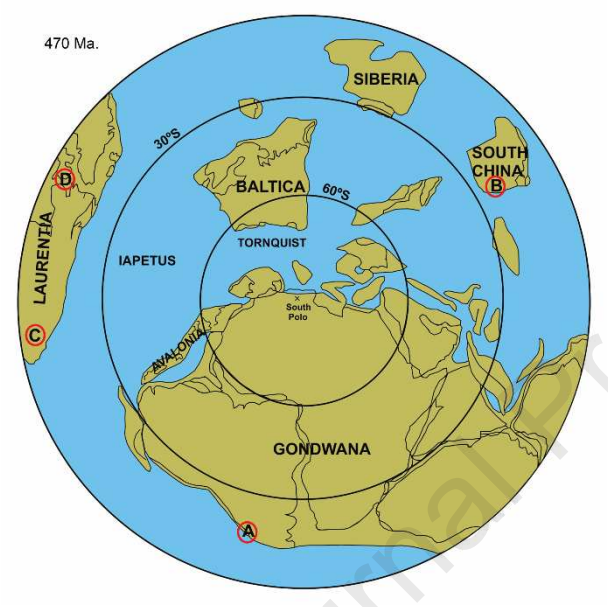
584 the evolutionary trends of these reef-builder organisms and their distribution during the
585 Early and Middle Ordovician on the western margin of Gondwana.

586 Another important datum verified here is the increasing lithic input from the
587 base to the top in the shoal facies. The size, shape and composition of the lithics (Fig.
588 9f) allow inferring a mature and relatively proximal continental area of provenance.

589



590

591 **Figure 14:** Global distribution of Early Ordovician pulchrilaminid reefs. A-
592 Precordillera; B- South China; C- North America; D- Newfoundland. (Modified from
593 Cocks and Torsvik, 2002).

594 The Precordillera is considered as an allochthonous terrane that docked to the
595 western margin of Gondwana during Middle Ordovician (Benedetto, 1993; Astini et al.,
596 1995; Thomas and Astini, 1996, 1999; Thomas et al., 2002). The allochthonous model
597 is supported, between other arguments, by a progressive change in biogeographic
598 affinities of the Precordilleran fauna from the late Cambrian to the Ordovician times,
599 from entirely Laurentian fauna to mainly Gondwanan fauna. On the basis of the
600 variations in the proportion of Laurentian to Gondwanan elements, four biogeographic

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601 evolution stages were proposed for the Precordillera terrane (Benedetto et al., 1999).
602 They are: Laurentian stage (Cambrian-Tremadocian), isolation stage (Floian-
603 Dapingian), pre-accretion stage (Darriwilian-Katian), and finally the Gondwanan stage
604 (Hirnantian-Silurian). The isolation stage was achieved when the Precordillera was
605 disconnected from the Laurentian continental margin and before it reached the
606 continental margin of Gondwana. The abundance and type of lithoclasts recovered from
607 the shoal facies during the supposed isolation stage would suggest the connection to a
608 mature continent during the late Floian.
609

610 **9. Conclusions**

611 This research implicated an integral analysis of field observations, thin sections, and
612 conodont biostratigraphic data, in order to study the facies, depositional environment
613 and accurate age of the San Juan Formation middle part shallow facies that was
614 deposited during the Early Ordovician in the Central Precordillera. The conclusions are
615 summarized as follows:

616 • Three facies and five microfacies were recognized in the Talacasto and Niquivil
617 sections, which represent three genetically-related depositional facies from distal
618 to proximal, including from shallow subtidal facies below wave action to shoal
619 and reef facies.
620 • A regression trend is recognized in the Precordilleran shoal bank setting,
621 composed by a succession of coarsening-up and thickening-up strata that reflects
622 a gradual shallowing-upward evolution during the *O. intermedius* Zone.
623 • The reef facies is recognized for the first time at the Talacasto section,
624 representing the most southern record of this facies from the Central
625 Precordillera.

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- The reefs consist of a microbial micrite framework in consortium with *Zondarella communis* (pulchrilaminids), *Calathium* sp. and sponges, conforming microbial-metazoan matrix-supported reefs.
- A comparison between the shoal and reef facies from the Talacasto and the Niquivil sections is presented for the first time. The differences between the reef communities led to infer a probable shallower depositional environment in the Niquivil section compared to the Talacasto section.
- The pulchrilaminid (*Zondarella communis*) present in these reef facies is accurately assigned for the first time to the *Oepikodus intermedius* Zone, indicating a late Floian age for this reef-building organism.
- The record of this Precordilleran pulchrilaminids represents the youngest evidence for this reef-framer organism compared to the worldwide records of the Early Ordovician age.
- In a global context, the pulchrilaminid reefs from the San Juan Formation match phases 3 and 4 of Webby's (2002) division of Ordovician reef-building phases.
- The present study of the Precordilleran Early Ordovician reefs increases the knowledge about the dispersal pathways of the pulchrilaminds during the Ordovician, and provides crucial information for understanding the paleogeographic reconstruction of the western margin of Gondwana in the Early Ordovician.

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654 was based on the Graduate Thesis of Lic. Leandro Benegas and Andres Morfil, San
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656

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991 **Table 1:** Conodont distribution in the Niquivil and Talacasto sections.

	Niquivil section						Talacasto section				
	J	**K**	**L**	**M**	**P**	**S**	**T8**	**T9**	**T15b**	**T18**	**T20**
Ansella jemtlandica											X
Berg. extensus	X	X	X	X	X		X	X		X	
Cooperig. aranda							X	X	X	X	
Cornuodus longibasis	X	X					X	X			
Drepanodus arcuatus	X	X			X		X	X			
Drepanoistodus forceps	X										
Erraticodon patu									X		
Juanognathus jaanussoni						X			X		X
Juanognathus variabilis	X				X		X	X		X	X
Oepikodus evae							X				
Oepikodus intermedius	X				X		X	X			
Oistodus striolatus			X	X		X	X	X	X		X
Paroistodus parallelus		X					X	X		X	
Periodon flabellum	X				X		X	X	X		
Protop. leonardii	X	X	X		X		X	X	X		
Reutterodus andinus							X				
Rossodus barnesi	X						X	X		X	X
Scolopodus krummi			X				X	X		X	
Semiac. potrerillensis			X			X					X
Triangulodus sp.						X			X	X	

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993 **Table 2:** Carbonate facies and microfacies of the shoal and reef facies from the San
994 Juan Formation.

Facies and Microfacies		Lithology	Components	Siliciclastics	Texture and geometry	Interpretation
Facies 1	**M1- Nodular Biointraclastic wackestone-packstone**	Light to medium grey, fine skeletal wackestone-packstone, diverse and abundant robust fauna, little evidence of fossil erosion.	Gastropods (up to 80 %), intraclasts, minor brachiopods, *Halysis monoliformis*, *Nuia síbirica*, trilobites, and pelmatozoan ossicles. Rare peloids	Thin interbeds of silty shale	Dominantly thinly bedded; irregular to nodular. Shales occur as thin discontinuous laminae or burrow fill.	Shallow subtidal below wave action, occasionally storm reworked deposit.
Facies 2	**M2- Biointraclastic packstone-grainstone**	Light to medium grey, fine to very coarse grainstone, well sorted	*Nuia síbirica*, *Halysis monoliformis*, pelmatozoan ossicles, oncoids, cortoids, intraclasts, peloids, trilobites, brachiopods, nautiloids, gastropods and ostracods	Silt to fine sands are rare to scarce, quartz	Coarse and tabular bedded with sharp to erosive bases, massive and occasionally cross-bedding.	Moderate to high energy shoals bank, highly winnowed.
	M3-Microbialite-skeletal boundstone	Light grey, peloidal micrite	Microbial (*Girvanella* sp., *Renalcis?* sp, among others), *Zondarella communis*, Sponges, *Calathium* sp., brachiopods, trilobites, pelmatozoan ossicles. peloids	Absent	Irregular to nodular, lateral discontinuous beds, domical to bell shapes	Reefs matrix supported, shallow subtidal in the shoal (M2), moderate energy.

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Facies 3	**M4- Intrabioclastic grainstone**	Light to reddish grey, medium to very coarse grained grainstone, diagenetic chert and iron oxide staining bioclasts	Pelmatozoan ossicles and articulate stems, *Girvanella* sp., oncoids intraclasts, fragmented *Calathium* sp., sponges, brachiopods, bryozoans, bioclastic fragments, peloids	Fine to very coarse quartz and lithic clasts	Thin to very thick tabular beds, thickest beds are continuous; erosive base and sharp top, amalgamated and stacked beds	High to moderate energy, shoal banks, shallowing-up cycles, hardground development
	M5- Peloidal packstone-grainstone	Light grey fine grainstone to packstone diagenetic chert and nodules iron oxide	Peloids, pelmatozoan ossicles, sponges, brachiopods, gastropods and trilobites	Fine to very coarse quartz and lithic clasts	Thin to medium tabular beds, sharp, erosive bases. Burrowed tops; planar lamination, low-angle cross-stratification, locally amalgamated	

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New insights on Lower Ordovician (Floian) reefs from the Argentine Precordillera: biostratigraphic, sedimentologic and paleogeographic implications

- The shallow facies of the middle part from the San Juan Formation were studied.
- Reef and shoal facies were recorded for the first time at the Talacasto section.
- Reef framework consists of calcimicrobes, pulchrilaminids, calathids and sponges.
- *Oepikodus intermedius* conodont Zone (Early Ordovician) was recorded.
- The pulchrilaminid *Z. communis* is assigned for first time to the late Floian.

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Dear Editor of the Journal of South American Earth Sciences:

We declare that we have no conflict of interest.

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