
Trilobite-based biostratigraphic model (biofacies and biozonation) for the Middle Cambrian carbonate platform of the Argentine Precordillera

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ABSTRACT

A preliminary biostratigraphic model that combines trilobite biofacies and biozonation is proposed for the early Marjumian (Middle Cambrian) of the Precordillera of western Argentina. This interval involves a variety of paleogeographic–paleoenvironmental settings across the carbonate platform, ranging from its interior to exterior areas beyond the platform margin and including both open-marine and near-shore environments. This model is based on three stratigraphic sections of the basal part of the Alojamiento Formation, which crops out in the Cordón del Alojamiento (Provincia de Mendoza) and Cordón de Santa Clara (Provincia de San Juan); and three sections of the Soldano Member of La Laja Formation in the Sierra Chica de Zonda (Provincia de San Juan). Three biofacies were recognized on the basis of trilobite associations that show a marked environmental distribution: 1) The Ptychagnostidae Biofacies is represented by an assemblage exclusively dominated by agnostoids, most of them belonging to *Ptychagnostus*; this assemblage occurs in mudstones and calcareous shales deposited below storm wave-base seaward of the platform margin; 2) the Peronopsidae Biofacies also developed in the external areas but it occurs in limestones deposited between fair-weather and storm wave-base; this assemblage is likewise dominated by agnostoids, but instead belonging to *Peronopsis*, with the rest of the fauna comprising polymeroids (Dolichometopidae, Oryctocephalidae, Zacanthoididae and Alokistocaridae); 3) the Alokistocaridae Biofacies occurs in grainstones, mudstones and calcareous shales deposited between fair-weather and storm wave-base under changeable conditions located near the platform margin and in the interior. It is dominated by alokistocarids whose relative abundance increases landward from 52% to 58% and to 95%. The remaining components belong to Dorypygidae, Zacanthoididae and Oryctocephalidae; Eodiscidae and Peronopsidae comprise minor proportions in the most seaward location. Due to the contrasting, environmentally mediated associations, these sections belong to three essentially synchronous biozones erected previously for the Middle Cambrian of western Laurentia, the *Ptychagnostus gibbus*, *Oryctocephalus* and *Ehmaniella* Biozones.

KEYWORDS | Trilobite Biofacies. Middle Cambrian. Carbonate Platform. Argentine Precordillera.

INTRODUCTION

Any biostratigraphic analysis must take into account the temporal as well as the spatial distribution of the fossils under study. In this ‘dual biostratigraphy’ (Ludvigsen et al., 1986), the temporal aspect is recorded by the stratigraphic extension of species based on their presence–absence record, which can be used to erect a scheme of successive biozones. By contrast, the spatial component is made evident as facies-controlled faunal associations that represent primary biotic communities, providing it can be established that taphonomic processes have not biased their composition. Although biozones are usually based on species because they yield the highest resolution, individual biofacies are typically defined at the generic or familial level because these taxonomic levels have a sufficiently persistent stratigraphic duration for broad patterns to be revealed, with the assumption that species included within these groupings shared similar ecological requirements (Pratt, 1992). Biofacies are defined on the basis of relative abundance, with the dominant taxon or taxa chosen as the nominative group or groups. This practice has proved enlightening for other fossil marine invertebrates besides trilobites, such as conodonts (Zhang and Barnes, 2002), rhynchonelliformean (‘articulate’) brachiopods (Zhan et al., 2002) and bivalves (Damborenea and Manceñido, 2005), as well as entire faunas (Lebold and Kammer, 2006).

The first biofacies scheme for the Cambrian of the Precordillera of western Argentina was proposed by Bordonaro (1990) who grouped the 65 trilobite species then documented into two biofacies. These included a biofacies representing a restricted inner platform and another representing the outer platform and slope, following the models developed for the Laurentian Cambrian by Palmer (1973, 1981; Palmer and Halley, 1979) and Robison (1976), even though the link between both biofacies was unknown at the time. Later, Bordonaro (2003a) recognized in the upper Middle Cambrian portion –the Marjuman (or Marjuman) stage in Laurentian usage– that the inner platform is recorded in the Precordillera Oriental by La Laja Formation (Fm) and the outer platform is represented by the Alojamiento Fm exposed in the Precordillera Occidental. Both lithostratigraphic units are laterally equivalent. Bordonaro and Banchig (2007) defined three penecontemporaneous trilobite biofacies in the Alojamiento Fm that reflect the interfingering between the platform margin and the outer platform environments. Research in progress concerning the detailed taxonomy of the trilobites from the Soldano Member of La Laja Fm has revealed in the same chronostratigraphic interval an association of alokistocarid taxa similar in relative abundance and affinity to those comprising the Alokistocaridae Biofacies in the Alojamiento Fm.

In this paper we distinguish the associations of trilobites that inhabited simultaneously a series of environments in a transect across the platform from its near-shore setting to seaward of its margin. We erect a tripartite biofacies and biozonation scheme for the Precordilleran carbonate platform that is comparable to the distributions exhibited by other late Marjuman faunas of Laurentia.

STUDY AREA

The study area consists of a northeast–southwest transect that cuts transversally the entire Precordillera of Argentina and ties together exposures of La Laja Fm in the Precordillera Oriental of the province of San Juan with those of the Alojamiento Fm in the Precordillera Occidental and the Precordillera Mendocina, between the provinces of San Juan and Mendoza (Figs. 1A–C). Exposures of the Soldano Member of La Laja Fm were examined at three localities in the Precordillera Oriental: (1) cerro Tres Marías at the northern extremity of the Sierra de Marquesado; (2) quebrada de Zonda; and (3) quebrada La Laja, the last two in the northern half of the Sierra Chica de Zonda. Exposures of the Alojamiento Fm were studied at three relatively nearby localities at: (4) cerro Santa Clara in the Cordón de Santa Clara, which constitutes the southernmost extension of the Precordillera Occidental of San Juan; (5) quebrada de Aguilera; and (6) quebrada del León, both in the Cordón del Alojamiento which is located in the northern sector of the Precordillera Mendocina. These six areas can be correlated to provide a transect across the Middle Cambrian carbonate platform (Fig. 2).

METHODOLOGY

The collections were made from intervals of similar age, uniform lithology and similar stratigraphic thickness: cerro Tres Marías (35 m), quebrada de Zonda (30 m), quebrada La Laja (20 m), cerro Santa Clara (20 m), quebrada de Aguilera (30 m) and quebrada del León (40 m). In cerro Tres Marías, quebrada de Zonda and quebrada La Laja the sampled beds are grainstones, whereas in cerro Santa Clara and quebrada de Aguilera they are grainstones–packstones and packstones–wackestones, respectively; in quebrada del León they are mudstones–calcareous shales. The same lithofacies is taken to have been deposited in a similar setting. Therefore, we consider that major differences between localities in the percentages of taxa recorded must represent different trilobite communities corresponding to different environments. The uniformity of lithofacies through the intervals studied indicates that these environments were temporally stable, arguing that we did not mix faunas from different environments that fluctuated at each locality

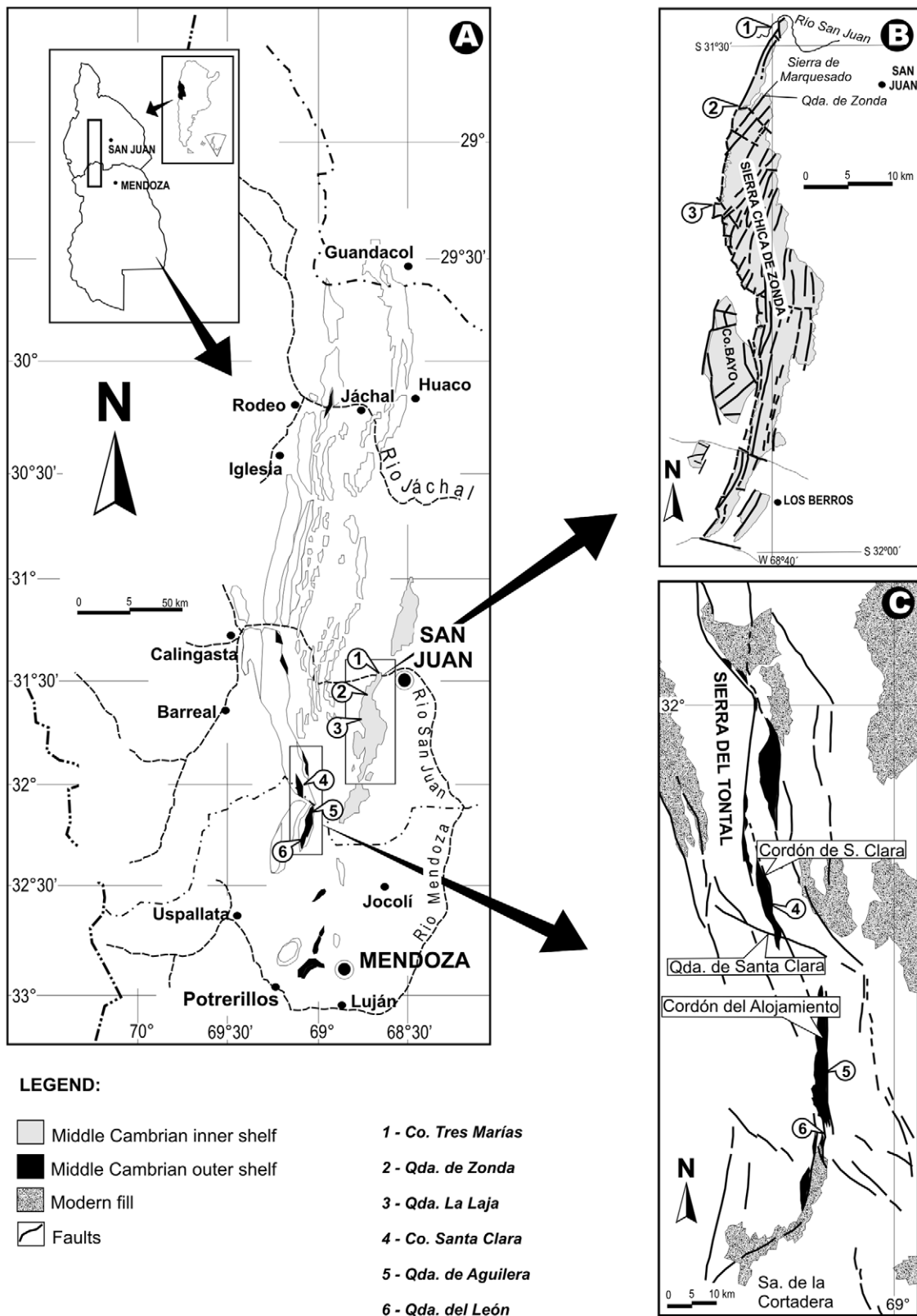


FIGURE 1 | A) Regional location map of the transect between the Precordillera Oriental and the Precordillera Occidental of San Juan and Mendoza provinces. B) Map showing the localities of La Laja Formation. C) Map showing the localities of the Alojamiento Formation.

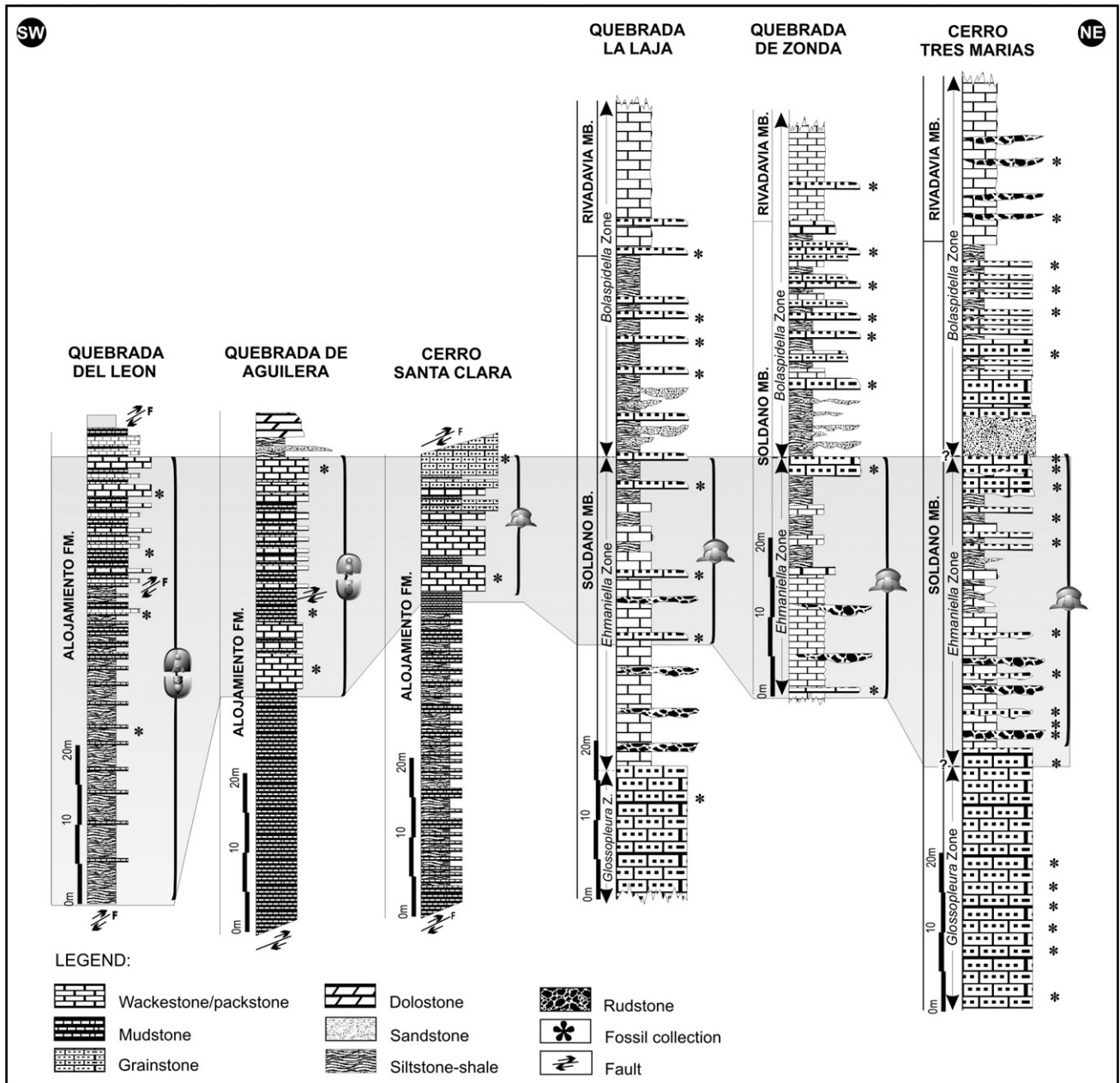


FIGURE 2 | Correlation of stratigraphic sections of the lower part of the Alojamiento Fm in cerro Santa Clara, quebrada de Aguilera and quebrada del León, and the upper part of the Soldano Member of La Laja Formation in cerro Tres Marias, quebrada de Zonda and quebrada La Laja. The shaded pattern comprises strata with early Marjumian (Middle Cambrian) trilobites, shown by schematic drawings of an agnostoid cephalon and pygidium and a ptychoparioid cranidium. The datum for the cross-section is the highest occurrence of trilobites belonging to the *Ptychagnostus gibbus*, *Oryctocephalus* and *Ehmaniella* biozones.

The trilobites we collected from the Alojamiento Fm and Soldano Member were identified at least to the generic level. Biofacies were determined according to their relative abundance expressed as percentages. Our database consists of 12 genera collected from six sections. Each collection comprises some 50 or more individuals, yielding 625 identifiable specimens. Most polymeroid specimens counted are represented by cranidia because the pygidia are small, except in macropygous taxa like corynechochides; counts of agnos-

toids are represented more or less by equal numbers of cephalon and pygidia. Due to the nature of the sampling and the relative uniformity of lithofacies in each interval, and because the interval under study is comparatively brief, it is not necessary to perform more complex statistical treatment such as a cluster analysis. Rather, relative abundances portrayed with pie diagrams suffice to show the percentages of families in each section. The biofacies are recognized on the basis of visual appreciation of pie diagrams (Fig. 3).

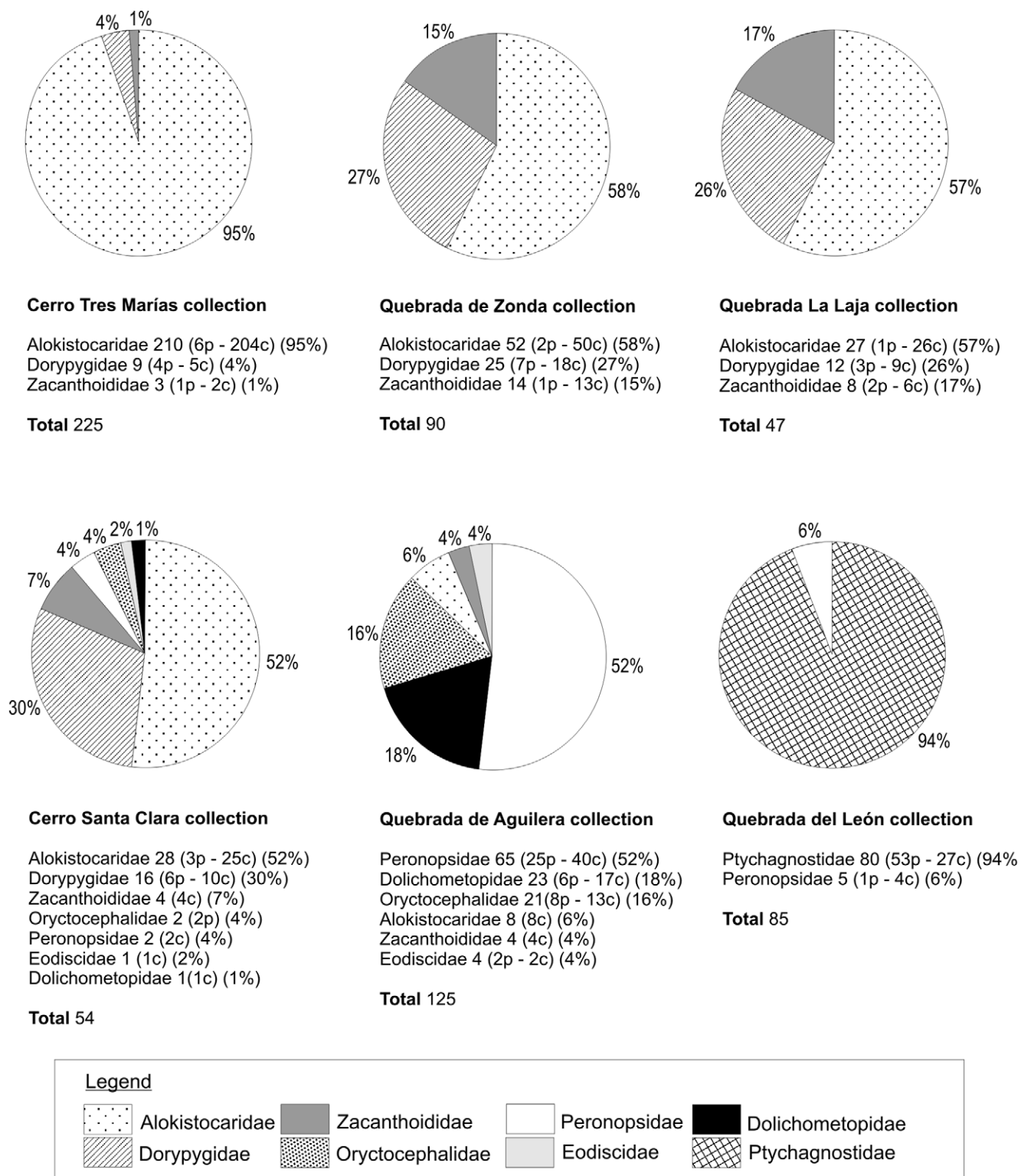


FIGURE 3 | Pie diagrams showing the relative abundance of each trilobite family for each locality over the stratigraphic interval of interest (lower Alojamiento Formation, upper Soldano Member of La Laja Formation). Numbers in parentheses represent cranidia and pygidia.

STRATIGRAPHY

Alojamiento Formation

This unit, first named by Harrington (1971), was redefined by Banchig and Bordonaro (1997, 1998) who modified its boundaries, detailed its lithological composition, and determined its age to be Middle Cambrian to questionably Late Cambrian on the basis of trilobites in both the Cordón del Alojamiento and the Cordón de Santa Clara. The succession consists in general of thin-bedded black limestones and argillaceous limestones with interbedded calcareous shales, massive chert-bearing dolomites and minor quartzose grainstones and quartz arenites. All three sections record a shallowing-upward trend, shown by thin-bedded limestones in the lower part and barren dolomites and dolomites with cross-laminated sandstones in the upper part (Fig. 2). In the lower part of each section Bordonaro and Banchig (2007) recognized three lithofacies linked by their fossil content, this fact demonstrating lateral variations and their interfingering in a north–south sense.

Lithofacies

Bioclastic grainstones–packstones. These grey-colored limestones occur exclusively, but commonly, in the lower part of the section at cerro Santa Clara where they are irregularly interbedded with light brownish-grey to yellowish argillaceous mudstone. Fossils consist of disarticulated trilobite sclerites mostly representing adults (holaspides), forming coquinas with conspicuous whole to fragmented cranidia and pygidia. Diversity is high, including taxa belonging mainly to Alokistocaridae, Dorypygidae and Zacanthoididae, along with scarcer elements of Oryctocephalidae, Peronopsidae and linguliformean (phosphatic, ‘inarticulate’) brachiopods. In the upper part this lithofacies passes into massive, light-grey fossiliferous grainstones. The trilobite fauna in these also belongs to Alokistocaridae, Dorypygidae and Zacanthoididae.

Bioclastic wackestones–packstones. This lithofacies occurs in the eastern tectonic slice of the Cordón del Alojamiento, where it shows a gradual upward change in bedding style from lenticular and planar laminated to planar thin-bedded. These dark-grey limestones contain an abundant fauna represented by fragmented sclerites including *Peronopsis*, *Bathyriscus* and *Tonkinella*, as well as linguliformean brachiopods and siliceous sponge spicules.

Mudstones and calcareous shales. These lithofacies also occur in the western tectonic slice of the Cordón del Alojamiento. There they comprise dark-grey to black shale and calcareous shale with interbedded dark-grey

mudstones, whose fossil content consists predominantly of deformed agnostoids belonging to *Ptychagnostus*. This sector shows a coarsening- and thickening-upward trend, with gradation from calcareous shales to lenticular-bedded mudstones.

Environment

The occurrence of grainstones–packstones only at cerro Santa Clara, and the upward transition to massive dolomites and then sandy limestones culminating in quartz arenites, suggests a gradual shallowing-upward to relatively high-energy conditions at the top. These grainy fossiliferous limestones record the onset of regression, probably associated with the progradation of a fair-weather wave-dominated system of sandy bars and shoals located near the platform margin.

Packstones–wackestones were deposited below fair-weather and above storm wave-base where bioclastic beds accumulated during conditions of agitation whereas mud settled out from suspension during fair-weather times. These conditions of alternating hemipelagic sedimentation and storm wave action characterized a paleogeographic location near the margin of the carbonate platform facing the open sea, perhaps in an upper-slope setting. The upward increase in bedding thickness is indicative of progressive shallowing.

The association chiefly of calcareous shales with subordinate lenses and thin beds of mudstone suggests a low-energy setting characterized by dominantly hemipelagic fall-out. This setting is interpreted to have been open-marine seaward of the platform margin, below the influence of storm wave-base.

The environments envisioned for these three penecontemporaneous lithofacies range from that dominated by higher energy under shallow-water conditions, as seen in the most eastern and northern section (cerro Santa Clara), to lower energy areas of greater depth, as observed in the most western and southern section in the Cordón del Alojamiento.

La Laja Formation

This unit was redefined by Bordonaro (1980) and subdivided into four members, with the Soldano, Rivadavia and Juan Pobre members comprising the Middle Cambrian portion. The succession is composed in general of black limestones and laminated argillaceous limestones, with interbedded calcareous shales and minor quartz arenite (Bordonaro, 2003b). The part under consideration is the upper half of the Soldano Member whose age is early Marjumian. Outcrops at the three localities exhibit

minor differences in lithofacies and fossil content which are interpreted as due to small-scale lateral environmental changes (Fig. 2). The Soldano Member at these localities also shows an apparent upward shallowing, made evident by thin-bedded limestones in the lower part and calcareous shales with fine-grained glauconitic sandstone near the top in quebrada de Zonda and quebrada La Laja. In the northernmost section, at cerro Tres Marías, this sandy carbonate interval is replaced by cross-stratified quartz arenites. These sandstones occur at the base of the *Bolaspidella* Zone.

Lithofacies

Mudstones. These grey, locally peloidal and bioturbated limestones are thin- and lenticular-bedded with bedding contacts planar or burrowed. They contain scarce disarticulated trilobite sclerites.

Calcareous shales. Yellowish brown, thin-bedded to laminated, calcareous silty shales contain no fossil remains. They often overlie grainstones and are commonly interbedded with mudstones as irregular and lenticular layers.

Bioclastic grainstones–packstones. These thick-laminated limestones are mostly lenticular-bedded, have planar to undulating bases, and are irregularly intercalated with mudstones and calcareous shales. Fossil content consists of disarticulated trilobite sclerites, generally of adults (holaspides) representing a relatively low-diversity fauna. They form coquinas of cranidia and pygidia, which are sometimes complete but in most beds they are fragmented to varying degrees. Typical is an association of one or two species belonging to two or three alokistocarid genera. Less common are representatives of Dorypygidae and Zacanthoididae.

Environment

This lithofacies association is indicative of sedimentation in the protected, low-energy interior of the carbonate platform, between fair-weather wave-base and storm wave-base, in water depths of less than a few dozen meters (Pratt and Bordonaro, 2007). This is evidenced by the dominance of lime mud with subordinate amounts of clay, which was then bioturbated and pelleted. In this setting populations of trilobites established themselves under favorable ecological conditions such as nutrient availability. Storms frequently reworked the bottom, which disturbed this stability and suspended the mud and sclerites which were later redeposited with the passing of the storms. Depending on the intensity and number of turbulent events, sclerites are preserved whole or fragmented. With the return of stable conditions, deposition of lime mud

continued, accompanied by some land-derived clay, via hemipelagic fall-out.

SYSTEMATIC PALEONTOLOGY

We present here a summary of the family-level categories that are represented in the Alojamiento and La Laja formations. Species-level taxonomy is in preparation. Specimens are deposited in the paleontological collections of the Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales of the Centro Regional de Investigaciones Científicas y Técnicas, Mendoza (IANIGLA-PI prefix) and the paleontological collections of the Universidad Nacional de San Juan (PIUNSJ prefix).

Order: Agnostida SALTER, 1864

Suborder: Agnostina SALTER, 1864

Family: Peronopsidae WESTERGÅRD, 1936

Remarks: The Peronopsidae are represented in the Alojamiento Fm by sporadically common specimens assigned to *Peronopsis* HAWLE and CORDA, 1847 (Figs. 4Q, R). This genus is broadly defined and contains over 100 species possessing ‘primitive’ agnostoid characters (Laurie, 2004).

Family: Ptychagnostidae KOBAYASHI, 1939

Remarks: Laurie (2004) provided the most recent discussion of the concept of this family. Locally abundant specimens from the Alojamiento Fm are assigned to *Ptychagnostus* JAEKEL, 1909. This is a broadly defined genus that may include species that are not closely related (Westrop et al., 1996), but here almost all specimens seem to belong to a single species, *P. intermedius* (TULLBERG, 1880) (Figs. 4N–P), with some left under open nomenclature as *Ptychagnostus* sp. indet.

Suborder: Eodiscina KOBAYASHI, 1939

Family: Eodiscidae RAYMOND, 1913

Remarks: The eodiscids are represented in the Alojamiento Fm by scarce, poorly preserved specimens assigned with question to *Pagetia* WALCOTT, 1916 (Fig. 4I–J).

Order: Corynexochida KOBAYASHI, 1935

Family: Dorypygidae KOBAYASHI, 1935

Remarks: This family contains robust corynexochids whose pygidia bear relatively stout marginal spines. Two genera occur in both the Soldano Member and Alojamiento Fm: *Kootenia* WALCOTT, 1889 (Fig. 4K) and *Olenoides* MEEK, 1877 (Fig. 5F), which are separated

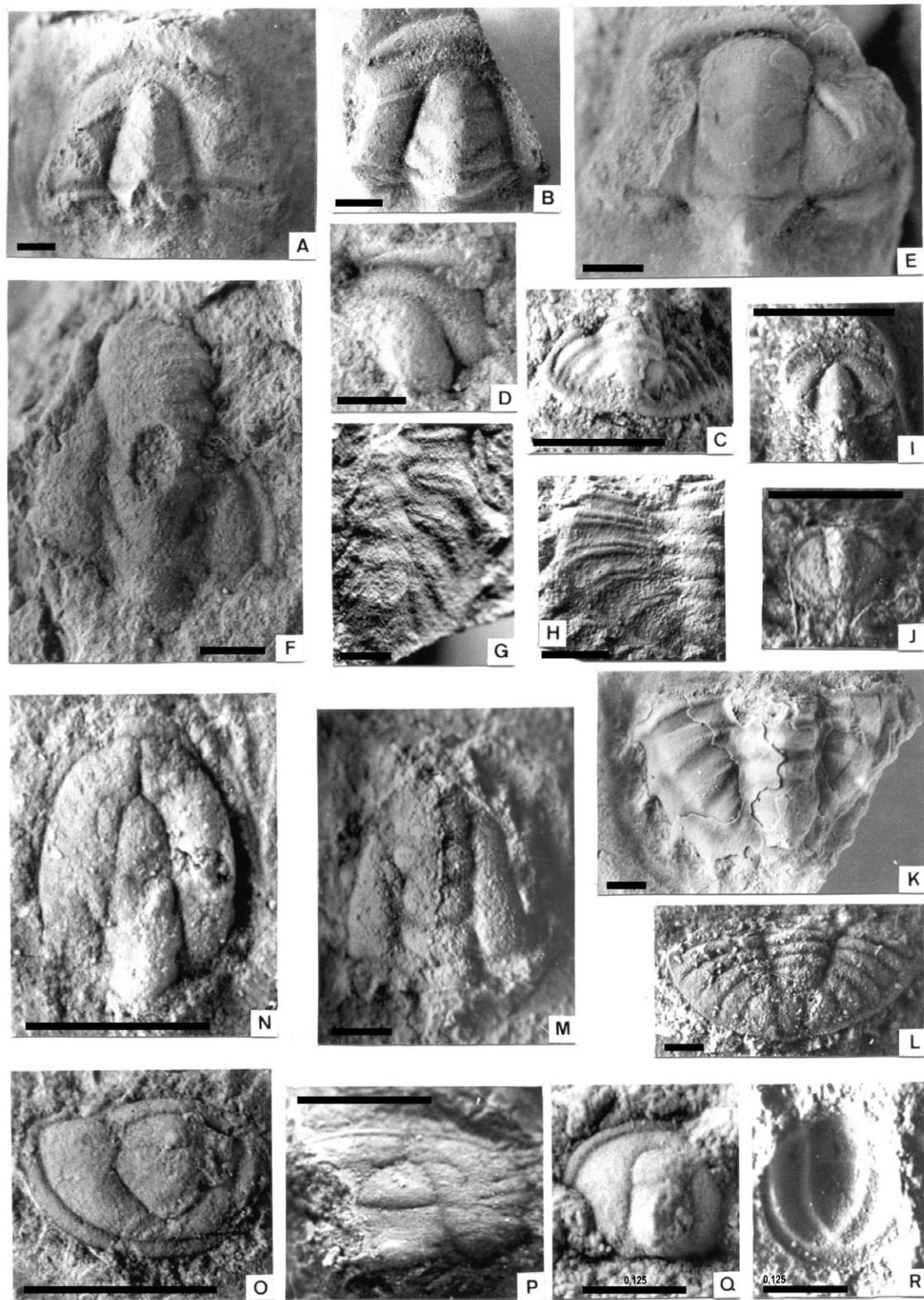


FIGURE 4 | Trilobites from the lower Alojamiento Formation. A, B) *Elrathiella?* sp. indet.; A) IANIGLA-PI: 1504, cranidium; B) IANIGLA-PI: 1501, cranidium. C) *Ehmaniella* sp. indet., IANIGLA-PI: 1531, pygidium. D) Alokistocaridae gen. et sp. indet., IANIGLA-PI: 1508, cranidium. E) *Zacanthoides* sp. indet., IANIGLA-PI: 1514, cranidium. F, H) *Bathyriscus* sp. indet.; F) IANIGLA-PI: 1580, cranidium; G) IANIGLA-PI: 1579, pygidium; H) IANIGLA-PI: 1588, pygidium. I, J) *Pagetia?* sp. indet.; I) IANIGLA-PI: 1523, cranidium; J) IANIGLA-PI: 1617, pygidium. K) *Kootenia* sp. indet. IANIGLA-PI: 1520, pygidium. L, M) *Tonkinella* sp. indet.; L) IANIGLA-PI: 1608, pygidium; M) IANIGLA-PI: 1607, cranidium. N–P) *Ptychagnostus intermedius*; N) IANIGLA-PI: 1541, cephalon; O) IANIGLA-PI: 1542, pygidium; P) IANIGLA-PI: 1554, cephalon. Q, R) *Peronopsis* sp. indet.; Q) IANIGLA-PI: 1540, cephalon; R) IANIGLA-PI: 1567, pygidium cast. Scale bar: A–P: 0.25 cm; Q and R: 0.125 cm.

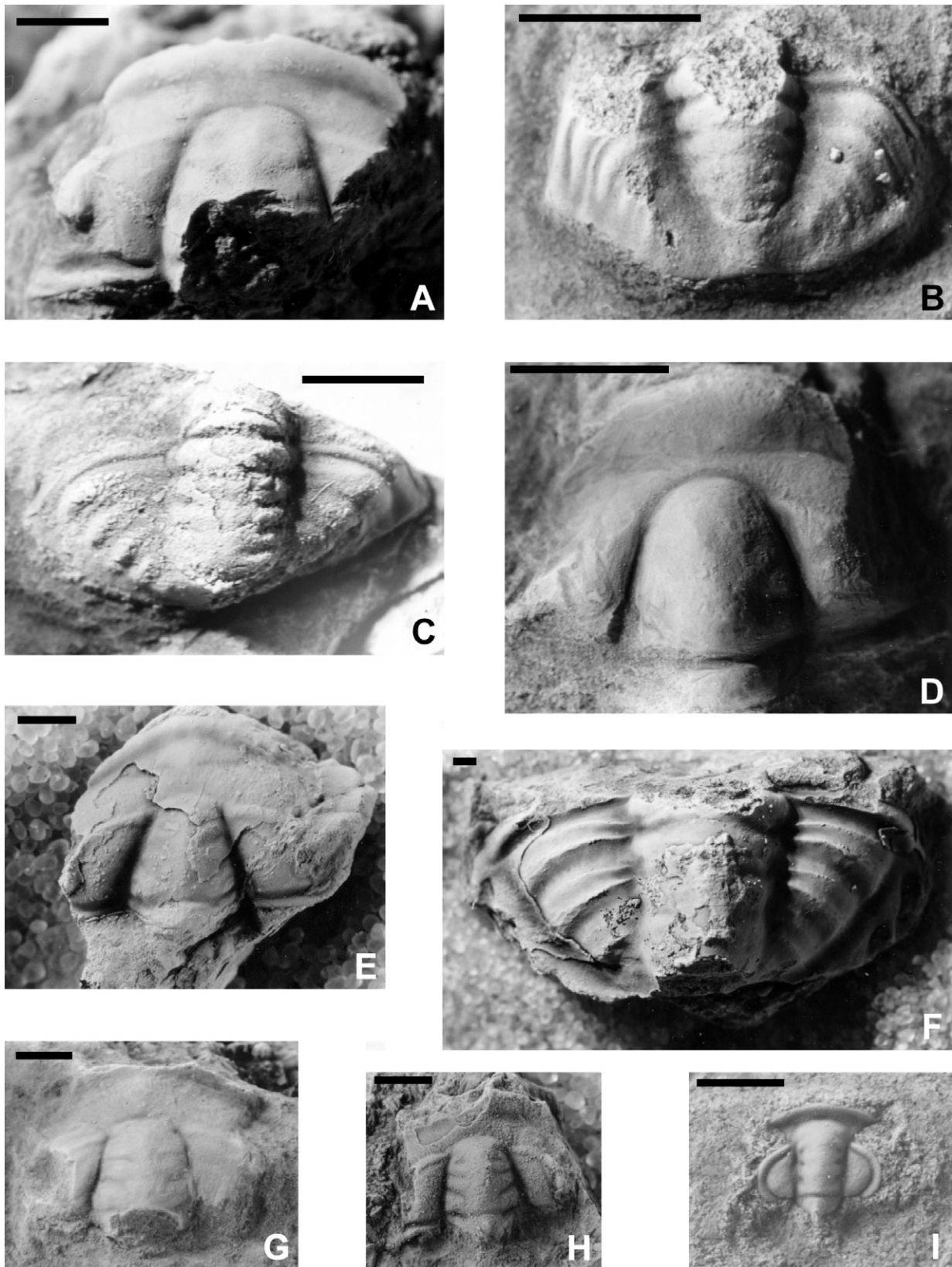


FIGURE 5 | Trilobites from the upper Soldano Member of La Laja Formation. A–C) *Ehmaniella* sp. indet. A) PIUNSJ: 220, cranidium. B) PIUNSJ: 287, pygidium. C) PIUNSJ: 288, pygidium. D) *Elrathiella* sp. indet. PIUNSJ: 226, cranidium. E) *Altiocculus* sp. indet., PIUNSJ: 247, cranidium. F) *Olenoides* sp. indet., PIUNSJ: 199, pygidium. G) *Alokistocare* sp. indet., PIUNSJ: 254, cranidium. H) *Ehmaniella?* sp. indet., PIUNSJ: 246, cranidium. I) *Zacanthoides* sp. indet., PIUNSJ: 168, cranidium. Scale bar: 0.25 cm.

mainly on the basis of relative length of the pygidial spines and nature of the furrows on the pleural fields. These genera contain over 100 named species and some appear intermediate between the two genera (Sundberg, 1994).

Family: Zacanthoididae WALCOTT, 1888

Remarks: This group is represented in both the Soldano Member and Alojamiento Fm by rare to moderately common specimens attributable to *Zacanthoides* WALCOTT, 1888 (Figs. 4E, I).

Family: Dolichometopidae WALCOTT, 1916

Remarks: In the Alojamiento Fm are fairly rare specimens belonging to *Bathyriscus* MEEK, 1873 (Figs. 4F–H).

Family: Oryctocephalidae BEECHER, 1897

Remarks: Moderately rare specimens in the Alojamiento Fm are assigned to *Tonkinella* MANSUY, 1916 (Figs. 4L, M). This genus has been recently revised by Sundberg (2006) whose concept we follow here.

Order: Ptychopariida SWINNERTON, 1915

Suborder: Ptychopariina RICHTER, 1933

Family: Alokistocaridae RESSER, 1939

Remarks: We follow Sundberg (1999) in the definition of this family. Four genera (Figs. 5A–E, G) are common in the Soldano Member: *Alokistocare* LORENZ, 1906, *Altiocculus* SUNDBERG, 1994, *Ehmaniella* RESSER, 1937 and *Elrathiella* POULSEN, 1927. Two genera (Figs. 4A–C) are recognized in the Alojamiento Fm: *Elrathiella* POULSEN, 1927 and *Ehmaniella* RESSER, 1937. We largely follow Sundberg (1994) in the concepts of these taxa.

BIOSTRATIGRAPHY

Biofacies

The trilobite associations in the six measured sections show a marked environmental control and we recognize three coeval biofacies within the early Marjumian interval (Figs. 6A–C).

Alojamiento Formation

A total of 263 identifiable cranidia and pygidia collected from the three localities were grouped into three faunal associations (Bordonaro and Banchig, 2007).

Alokistocaridae Biofacies. Members of this family reach the greatest percentage of the faunal association (52%). *Ehmaniella* and *Elrathiella* predominate, along with *Kootenia*, a few indeterminate zacanthoidids, and scarce representatives of *Tonkinella*, *Peronopsis*, *Pagetia*? and possible dolichometopids. This biofacies occurs in bioclastic grainstones and packstones that crop out in the easternmost tectonic slice, located in the cerro de Santa Clara.

Peronopsidae Biofacies. This is dominated by the agnostoid *Peronopsis* which comprises 52% of the association. This taxon is accompanied by *Bathyriscus* and *Tonkinella*, a few indeterminate alokistocarids, scarce indeterminate zacanthoidids and eodiscids, as well as possible dorypygids. This biofacies occurs in the packstone–wackestone lithofacies of the basal Alojamiento Fm in the intermediate tectonic slice of the Cordón del Alojamiento at quebrada de Aguilera.

Ptychagnostidae Biofacies. This biofacies is characterized by an overwhelming dominance (94%) of *Ptychagnostus*, mainly as *P. intermedius*, with a few *Ptychagnostus* sp. indet., plus rare *Peronopsis*. This association is found in laminated mudstones and black calcareous shales of the westernmost tectonic slice exposed in the upper reaches of quebrada del León.

La Laja Formation

We recovered 362 specimens from three localities, most of them coming from the bioclastic grainstone–packstone lithofacies.

At cerro Tres Marías, the northernmost of all tectonic slices, of 225 specimens Alokistocaridae comprise 95%, Dorypygidae 4% and Zacanthoididae 1%. In quebrada de Zonda, which is in the intermediate tectonic slice, of 90 specimens 58% belong to Alokistocaridae, 27% to Dorypygidae and 15% to Zacanthoididae. From quebrada La Laja, in the southernmost tectonic slice, 47 specimens show an almost identical faunal composition: 57% Alokistocaridae, 26% Dorypygidae and 17% Zacanthoididae.

Alokistocaridae include *Alokistocare*, *Altiocculus*, *Ehmaniella* and *Elrathiella*. While we consider this comparable to the Alokistocaridae Biofacies found in the Alojamiento Fm, generic composition does differ somewhat. Minor components are *Kootenia* (or *Olenoides*) and a few indeterminate zacanthoidids.

Biofacies and Environment

The Alokistocaridae Biofacies is constrained to grainstones and packstones in the Santa Clara, La Laja, Zonda

and Tres Marías localities, indicating relatively shallow-water and moderately high-energy, well-oxygenated conditions with adequate nutrients. This fact accords with the presence of benthic polymeroid trilobites of large size and globose form, such as alokistocarids and dorypygids, whose robust morphology offered resistance to mechanical destruction. The proportion of alokistocarids increases towards the north, which suggests an environmental control: perhaps either decreasing bathymetry or a greater availability of nutrients, or both. This interpretation is supported by the increasing proportion of calcareous shales with interbedded grainstones at cerro Tres Marías.

The high diversity at cerro de Santa Clara (eight families) as well as in quebrada de Aguilera (seven families) is not due to the mixing of different biofacies, but rather was the response to the particular environmental setting at the outer part of the platform. The ecological reasons for this have yet to be determined, but similarly increased diversity near the platform margin was observed by Robison (1976), Pratt (1992) and Melzak and Westrop (1994).

By contrast, the Peronopsidae and Ptychagnostidae biofacies, expressed in the two localities in the Cordon del Alojamiento, are found in muddy limestones. These were deposited in successively deeper settings west and southwest of the platform margin.

Biofacies Correlation

Similar biofacies associations have been recognized in Marjumian strata in several areas of Laurentia. Robison (1976) subdivided the carbonate platform of Utah and Nevada into two, an open-shelf assemblage and a restricted-shelf assemblage. Among the trilobites of the open shelf are species belonging to *Bathyriscus*, *Olenoides*, *Zacanthoides*, *Kootenia*, *Oryctocephalus*, *Elrathina*, *Peronopsis*, *Pagetia*, *Ptychagnostus* and *Onymagnostus*. The fauna of the restricted shelf is dominated by *Ehmaniella*, *Kootenia*, *Poliella*, *Spencella*, *Zacanthoides* and *Alokistocare*. Similarly, Young and Ludvigsen (1989), in their discussion of species described by Rasetti (1951) from the comparatively deep-water Stephen Fm and Burgess Shale of the southern Canadian Rocky Mountains, recognized a *Bathyriscus* Biofacies dominated by *Bathyriscus*, *Ogygopsis* and *Olenoides* plus minor proportions of *Elrathina* and *Zacanthoides*. Sundberg (1991, 1994) described various alokistocarid genera from Utah and Nevada, and although he did not conduct a biofacies study *per se*, it is apparent that there exists an alokistocarid-dominated platform-interior association containing a smaller proportion of dolichome-topids, zacanthoidids, oryctocephalids and dorypygids.

These patterns indicate that some species appear to have relatively broad environmental tolerances while others

seem more restricted. In any case, wide platforms bordered by ramp-like margins were not separated into distinct entities with no ecological overlap. On the other hand, in down-slope transported boulders in the basal part of the Cow Head Group of western Newfoundland, Young and Ludvigsen (1989) encountered three biofacies representing outer platform–upper slope environments: (1) blocks of grainstone belonging to the *Zacanthoidid–Pagetia* Biofacies dominated by *Zacanthoides*, *Pagetia*, *Parkaspis*, *Peronopsis* and *Elrathina*; (2) blocks of packstone and wackestone belonging the *Bathyriscus* Biofacies with *Bathyriscus* as the main element along with rare *Peronopsis* and *Eoptychoparia*; and (3) blocks of mudstone and packstone belonging to the *Onchocephalites* Biofacies with abundant *Onchocephalites* accompanied by *Peronopsis*, *Onymagnostus* and *Bathyriscus*. These biofacies appear to represent, before slumping, a more closely spaced mosaic compared to the broad pattern observed by Robison (1976).

What controlled trilobite distribution is unclear, but it would have been one or more factors such as nutrition, reproduction constraints, temperature and sediment type. Most of these trilobites were probably deposit-feeders, although it is unknown how specialized they were (see also Hughes, 2001). Nevertheless, these examples reveal that the genera and families comprising the trilobite biofacies in the Alojamiento and La Laja Fms show generally similar environmental distributions to those in Laurentia. Thus, by comparison, we can assign our Alokistocaridae Biofacies to the relatively shallow platform while the Ptychagnostidae and Peronopsidae biofacies represent the external, off-platform (or outer-shelf) region (Figs. 6B, C).

Biozones

Given that biozones are considered temporal manifestations, either partial or total, of biofacies (e.g., Ludvigsen et al., 1986; Westrop, 1986, 1992, 1995; Pratt, 1992), a single biofacies could potentially yield a number of biozones. Robison (1976) erected three synchronous biozonal schemes, one for the restricted shelf, and two for the open shelf, one based on polymeroids and the other agnostoids. Here we recognize only one biozone in each biofacies. This is because, at present, we have not yet completed the taxonomy at the species level necessary for a more refined biozonation. In part this is due to the degree of fragmentation and deformation present in much of the material, as well as the taxonomic difficulties involved with many early ptychoparioids. Apart from recognizing the widely distributed *Ptychagnostus gibbus* Biozone based on the occurrence of *Ptychagnostus intermedius* in the Alojamiento Fm (Bordonaro and Banchig, 2007), for the time being we base our biozonal assignment on several conspicuous and temporally persistent

genera and adopt existing biozones defined in other areas of Laurentia (see Robison, 1976; Palmer, 1981; Sundberg, 1994, 2006).

***Ehmaniella* Biozone**

This biozone was redefined by Robison (1976) as a restricted-shelf assemblage in western Laurentia based on faunas mainly in the Great Basin. However, he noted that *Ehmaniella* is common also in the Burgess Shale (Rasetti, 1951) where, instead, it occurs in deeper water, off-platform setting. The *Ehmaniella* Biozone is characterized by the dominance of *Ehmaniella* accompanied by *Kootenia*, *Zacanthoides* and *Alokistocare*. It represents a relatively long time span that includes the *Ehmaniella*, *Bolaspis*–*Glyphaspis*, *Ehmania* and *Parehmania* biozones defined by Schwimmer (1975). Sundberg (1994) adopted this concept of an extended *Ehmaniella* Biozone and subdivided it into the *Proehmaniella*, *Elrathiella*, *Ehmaniella* and *Altiocculus* sub-biozones. Sundberg (1999) noted that *Alokistocare* is limited to the *Ehmaniella* Sub-biozone at the base of the ‘marjumiid biomere’ of the earliest Marjumian (see also Ludvigsen and Westrop, 1985; Palmer, 1998) or the base of the (proposed) Topazian (or Topazan; Sundberg, 2005). He differentiated this genus from older taxa considered to be alokistocarids that have been grouped under *Amecephalus* and are restricted to the *Plagiura* and *Glossopleura* biozones belonging to the base of the (proposed) Delamarian (or Delamarian; Palmer, 1998).

The abundance of alokistocarids of Marjumian aspect in Cerro Santa Clara indicates that the Alojamiento Fm belongs to the extended *Ehmaniella* Biozone, but it is not yet possible to narrow this down to subzones comparable to those defined in the Great Basin because of the difficulty in determining the diagnostic species. Nonetheless, the presence together of *Elrathiella*, *Tonkinella* and *Ehmaniella* suggests that these strata belong to the *Ehmaniella* and *Altiocculus* sub-biozones in the middle part of the biozone (Sundberg, 1994). Similarly, we provisionally recognize species belonging to *Ehmaniella* and *Elrathiella*, plus *Altiocculus cataractensis*, in the Soldano Member which are indicators of the *Elrathiella* and *Ehmaniella* sub-biozones.

***Oryctocephalus* Biozone**

This subdivision was erected by Robison (1976) as a temporally extended polymeroid ‘assemblage zone’ for somewhat deeper water lithofacies of the outer platform of western Laurentia in order to replace the *Bathyriscus*–*Elrathina* Biozone of Rasetti (1951). It is equivalent to a succession of agnostoid biozones in the same general setting. Among the polymeroids that charac-

terize this biozone are *Alokistocare*, *Bathyriscus*, *Kootenia*, *Ogygopsis*, *Olenoides*, *Oryctocephalus*, *Elrathina* and *Zacanthoides*. The agnostoids *Ptychagnostus* and *Peronopsis* and the eodiscid *Pagetia* are associated only in the upper part of the biozone. Schwimmer (1989) recognized *Glyphaspis*, *Alokistocare* and *Peronopsis* as representatives of the *Oryctocephalus* Biozone in the Conasauga Fm of Georgia, in eastern Laurentia. Due to the abundance of *Peronopsis* associated with *Pagetia*? in Quebrada de Aguilera, as well as co-occurrence of oryctocephalids, *Bathyriscus*, *Zacanthoides* and alokistocarids, we consider that the Alojamiento Formation in this locality belongs to the *Oryctocephalus* Biozone.

***Ptychagnostus gibbus* Biozone**

Robison (1976, 1982) created this biozone as the interval between the first appearance of the eponymous species and the first appearance of *Ptychagnostus atavus*. He considered it correlative with the *Ptychagnostus gibbus* Biozone of Sweden (Westergård, 1946). In western Laurentia the biozone contains an association of other species of *Peronopsis* and *Ptychagnostus*, notably among which is the cosmopolitan *P. intermedius* which is restricted to that biozone. *Ptychagnostus intermedius* is a conspicuous element in the Alojamiento Fm (Bordonaro and Banchig, 2007), confirming that the *Ptychagnostus gibbus* Biozone in that unit was synchronous with the uppermost *Oryctocephalus* and *Ehmaniella* biozones (Palmer, 1981; Sundberg, 1991).

CONCLUSIONS

We propose a model of ‘dual biostratigraphy’ for a transect across the Marjumian (Middle Cambrian) carbonate platform that developed on the ancient Precordilleran continental margin. The biofacies recognized here were more or less synchronous and indicate, as do the lithofacies, a fundamental polarity of the sedimentary basin from the (present-day) northeast to southwest. The biofacies distribution enables a paleogeographic reconstruction of the carbonate platform that includes three belts: the platform interior (Soldano Member of La Laja Fm), a promontory formed by the shallow platform margin (Alojamiento Fm in Cerro Santa Clara) and seaward of the platform margin (Alojamiento Fm in Quebrada de Aguilera and Quebrada del León).

The Alokistocaridae Biofacies is recognized in the Alojamiento Fm in Cerro Santa Clara and in the Soldano Member in Quebrada de La Laja, Quebrada de Zonda and Cerro Tres Marías. Thus it was distributed both in the platform interior and along the shallow platform margin, and characterized the bathymetric zone between fair-weather

wave-base and storm wave-base. The varying proportions of alokistocarids indicate ecological differences probably governed by nutrient supply related to the input of fine terrigenous material which was greater in the innermost part of the platform near the coast. The Peronopsidae Biofacies, on the other hand, represents somewhat deeper water conditions at and below storm wave-base located seaward of the platform margin. The Ptychagnostidae Biofacies indicates even deeper water beyond the margin, the most distal setting, which is observed in the westernmost outcrops of the Alojamiento Fm.

Within this spatial framework we recognize the same early Marjuman biozones as those erected in North America. The platform interior and margin strata fall into the upper half of the *Ehmaniella* Biozone, while the deeper water strata beyond the margin belong to the upper part of the *Oryctocephalus* and the *Ptychagnostus gibbus* biozones. These three zones were broadly synchronous.

This is the first dual biostratigraphic model of regional application yet formulated for the Precordilleran continental margin. It shows strong faunal affinities to Laurentian carbonate shelves, with both endemic and pandemic taxa. *Alokistocare*, *Altiocculus*, *Ehmaniella* and *Elrathiella* are endemic Laurentian polymeroid genera which in the Precordillera are found only in the platform interior. On the other hand, both endemic Laurentian taxa like *Bathyriscus* and *Zacanthoides* and the cosmopolitan genera *Olenoides*, *Kootenia* and *Tonkinella* share the outer and marginal parts of the carbonate platform. Pandemic agnostoids belonging to *Ptychagnostus* and *Peronopsis* and the eodiscid *Pagetia?* occur only in settings communicated with the open ocean.

This approach to biostratigraphy serves to differentiate trilobite associations that inhabited simultaneously a variety of environments in a single basin during a limited time span. In this way any faunal similarities with other regions can be recognized and it can be determined if the presence or absence of taxa involved a response to biogeographic factors or local environmental conditions. This method eliminates the error of assuming that the presence or absence of a taxon was controlled exclusively by time or that a species could live in all areas without regard to environmental conditions. The advantages of 'dual biostratigraphy' are as well shown by the Middle Cambrian of the Argentine Precordillera as they are for Laurentia.

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