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Ammonoid biostratigraphy and paleobiogeography of Lower Jurassic sections from Sonora  
(northwest Mexico) and their tectonic implications

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**Abstract**

The Antimonio terrane is a tectonostratigraphic unit known from the northwestern part of Sonora state of Mexico, where it is developed on the Proterozoic to Permian basement of the Caborca block. The Upper Permian to Lower Jurassic El Antimonio Group, which includes the Lower Jurassic Sierra de Santa Rosa Formation, is its most extensive stratigraphic unit. Biostratigraphic dating of the thick Lower Jurassic sedimentary succession is crucial for the reconstruction of the basin evolution and tectonic history. However, the Early Jurassic ammonite faunas have only been partially treated in previous works; therefore a comprehensive paleontological and biostratigraphical study was carried out.

Ammonoids were collected from sections exposing the Sierra de Santa Rosa Formation, including Sierra del Álamo (type locality of the El Antimonio Group), Sierra de Santa Rosa, Pozos de Serna, and Sierra la Jojoba. From 455 moderately preserved specimens, a total of 49 taxa were distinguished, 29 of them identified at the species level, which belong to 22 genera.

The ammonoid assemblages represent three stages of the Lower Jurassic, from the Upper Hettangian through the Sinemurian to the Lower Pliensbachian. Provincialism of the fauna tests the recently developed North American regional ammonoid zonation: out of eleven relevant zones, eight were recognized and documented in the studied sections. Stratigraphically from oldest to youngest, these include the Upper Hettangian *Rursicostatum* Zone, the Lower Sinemurian *Involutum* and *Leslei* Zones, and the Upper Sinemurian *Carinatum* Zone that are identified in Sierra del Álamo. *Paltechioceras*-dominated

assemblages of the uppermost Sinemurian Harbledownense Zone also occur, besides Sierra del Álamo, in the sections at Pozos de Serna and Sierra de Santa Rosa, whereas the lowermost Pliensbachian Imlayi Zone is only represented at Pozos de Serna. The Lower Pliensbachian Whiteavesi and Freboldi Zones occur in sections at Sierra de Santa Rosa and at Sierra la Jojoba. In the latter zone, *Fuciniceras perplicatum* permits correlation between local sections and represents the first appearance of hildoceratids in North America, only known from the Upper Pliensbachian elsewhere.

Although the original proximity of the Antimonio terrane and localities in Nevada is predicted by the Mojave-Sonora megashear hypothesis, paleobiogeographic analyses using multivariate methods revealed only modest similarity of the ammonoid faunas and lend more support for the alternative tectonic model of earlier, pre-Jurassic dextral displacement along the California-Coahuila transform. The early appearance of the hildoceratid *Fuciniceras* at Sonora and the coeval absence at Nevada also supports our findings. Similarities with coeval faunal from the Insular and Intermontane superterrane of the Canadian Cordillera strengthen arguments for their origin at much lower paleolatitudes and large scale northward displacement as postulated by the Baja BC hypothesis.

**Keywords:** El Antimonio Group; Caborca block; Lower Jurassic; ammonoids; biostratigraphy; Mojave-Sonora megashear

## 1. Introduction

Studies of Jurassic ammonoid assemblages have contributed to understanding the complex geology of the western Cordilleran orogen of the Americas by providing a highly resolved biostratigraphic framework (e.g. Smith et al., 1988) and faunal distribution data for analyses of paleogeographic and tectonic linkages of allochthonous terranes (Smith and



Tipper, 1986). In northwestern Mexico's Sonora state, Early Jurassic ammonoids are relatively diverse and abundant in the Antimonio terrane (Stanley and González-León, 1995). This distinct tectonostratigraphic unit includes the Upper Permian to Lower Jurassic El Antimonio Group. This more than three-kilometre-thick stratigraphic unit is in tectonic contact with the underlying Proterozoic crystalline basement complexes and Paleozoic passive margin sedimentary sequences of the Caborca terrane (Campa and Coney, 1983). The Caborca block, comprising the Antimonio and the Caborca terranes together, is one of the most controversial elements in Cordilleran tectonic reconstructions (e.g. Lawton et al., 2017).

In the El Antimonio Group the locally fossiliferous Lower Jurassic sequence is assigned to the Sierra de Santa Rosa Formation that is more than one-kilometre-thick. Although its ammonoid fauna was discovered 90 years ago (Keller, 1928; Jaworski, 1929; Burckhardt, 1930), the few subsequent studies were focused on either single localities only (Linares et al., 1997; Lucas et al., 1999) or the placement of the Triassic-Jurassic system boundary (González-León et al., 1996). Significantly, however, Taylor et al. (2001) reported the biostratigraphy of the type section in the Sierra del Álamo area and incorporated it into their Hettangian-Sinemurian North American regional zonation.

In this paper we build on our preliminary studies (Pálffy and González-León, 2000) and attempt a comprehensive biostratigraphic overview of Lower Jurassic ammonoid assemblages. Material collected from six measured sections of the Sierra de Santa Rosa Formation in four disjunct outcrop areas of the Antimonio terrane (Sierra del Álamo, Sierra de Santa Rosa, Pozos de Serna, and Sierra la Jojoba) (Fig. 1B). These successions are used to test the applicability and correlation potential of the Lower Jurassic North American regional zonal schemes (Smith et al., 1988, Taylor et al., 2001) that take into account the previously known Cordilleran sections but rely heavily on a few sections with the most detailed record for each stratigraphic interval. Our work also resolves some local geological problems, such

as the age of the sequence at Sierra de la Jojoba. Detailed paleontological descriptions of all taxa will be published separately elsewhere. Photographic illustration in this work is therefore restricted to the biostratigraphically most diagnostic species.

Another objective of this study is to use a paleobiogeographic analysis of the studied ammonoid faunas to constrain conflicting models of the tectonic evolution of the Caborca block. Previously, Late Triassic coral faunas (Stanley and González-León, 1995) and Early Jurassic bivalves (Damborenea and González-León, 1997; Scholz et al., 2008) from the El Antimonio Group were employed in assessing similarities with various other allochthonous terranes in the North American Cordillera, in order to shed light on the validity and timing of hypothesized large-scale displacements. Two alternative tectonic models postulate that the Caborca block was involved in a large-scale sinistral movement, but during different time intervals: either in the Middle to Late Jurassic along the Mojave-Sonora megashear (MSM, Fig. 1A) (Anderson and Silver, 2005) or earlier, in the Permian and Triassic along the California-Coahuila transform (CCT) (Dickinson and Lawton, 2001). In contrast, Poole et al. (2005) suggest that the Caborca block did not move significantly and its Proterozoic basement is a largely autochthonous promontory of southwestern Laurentia.

Assessing Early Jurassic faunal similarity provides a crucial test for these competing models. Their disparate predictions are tested through comparison with coeval faunas from other terranes and areas, especially in Nevada, lying on the opposite, cratonward side of assumed strike-slip faults (Fig. 1A). In the context of another controversial issue in Cordilleran tectonic evolution, the Baja-British Columbia (or Baja-BC) hypothesis (Irving 1985; Hildebrand 2015), we assess faunal similarity with terranes in British Columbia (Wrangellia, Stikinia and Cadwallader) to gauge their proximity to the Antimonio terrane in Early Jurassic time.

## 2. Geological setting

### 2.1. Tectonic setting

The North American Cordillera, as a long-lived and still active orogenic belt, is one of the geologically most complex areas of the North American continent. It includes our study area in northern Sonora, other areas with major Jurassic ammonoid fossil localities in the southwestern US and farther afield in British Columbia, with which paleogeographic links will be assessed. The geological setting, including the tectonic evolution and stratigraphy of the study area, is outlined here based on a recent summary (González-León et al., 2017).

Tectonic complexities of the Cordilleran orogen are intimately linked to the evolution of the active Pacific margin (Dickinson, 2009). The western margin of Laurentia was affected by northwest-southeast directed truncation of Proterozoic and Paleozoic sequences at the ancient continental margin during the late Paleozoic (Stevens et al., 2005), between the Antler and Sonoma orogenic phases (Lawton et al., 2017). The initiation of a new subduction zone during the Early Permian resulted in the development of a magmatic arc along the Laurentian continental margin. Arc magmatism ceased by Middle to Late Triassic time and reactivated during the Early Jurassic. Consequently, the tectonic setting of the El Antimonio basin of Sonora has been interpreted as a fore-arc basin (Stanley and González-León, 1995; González-León, 1997; Lucas et al., 1999; González-León et al., 2005). Alternatively, a retroarc setting was proposed to better explain the presence of old detrital zircon populations derived from the North American craton (Hodges et al., 2017). Terranes, defined as distinct tectonostratigraphic units, are key elements of modern Cordilleran tectonic models (Coney et al., 1980) and numerous terranes have been accreted to the western Laurentian continental margin since the late Paleozoic (Colpron et al., 2007).

Due to difficult access and relatively sparse data, several aspects of the tectonic evolution of Sonora are still controversial. Some confusion pertains to the two related terrane names found in recent literature on the geological history of Sonora, the Antimonio and Caborca terranes. By some authors, the Antimonio terrane is regarded as an allochthonous terrane lying structurally above the Caborca terrane composed of a Proterozoic basement and a thick succession of Paleozoic strata (Stanley and González-León, 1995). The El Antimonio Group was suggested to be thrust along with the Upper Permian Monos Formation over the Caborca terrane, which was part of the North American craton, at some time in the Carboniferous to Late Jurassic interval. The two terranes together are often referred to as Caborca block (Lucas et al., 1999; Gonzalez-Leon et al., 2009; Goodell et al., 2017; Lawton et al., 2017).

Silver and Anderson (1974) first suggested that from the Middle to Late Jurassic the Caborca block was transported southeastward along the supposed Mojave-Sonora megashear (MSM), which conceivably formed the southwestern margin of the North America plate (Anderson and Silver, 2005) (Fig. 1A-B).

Tectonic reconstructions based on constraints from plate geometry and restoration of various Mexican terranes of diverse origin indicate that much of the area of Mexico is built up of crustal blocks that moved to their current position relative to the stable inner part of Laurentia some time after the Carboniferous (Dickinson and Lawton, 2001). Although several different models attempted to resolve the controversy, the precise age, the scale and the trace of the displacements remain debated. Stone and Stevens (1988) considered Caborca as a basement block reaching its position by a late Paleozoic displacement, whereas Anderson and Silver (2005) and Anderson (2015) suggest a Late Jurassic movement along the trace of the Mojave-Sonora megashear. Despite their differences, most variants of the different models assume that the kinematics of the suspected movement was transverse and sinistral (Dickinson and Lawton, 2001; Anderson and Silver, 2005; Anderson and Nourse, 2005;

Scholz et al, 2008; Amato et al., 2009; Colpron and Nelson, 2009; Anderson 2015; Riggs et al, 2016; Lawton et al., 2017; González-León et al., 2017). Contrary to the previous studies, the movement itself was questioned by Poole et al. (2005), who suggest that the Caborca block is an “autochthonous promontory of southwest Laurentia”.

## 2.2. Stratigraphic setting

The most complete Lower Jurassic sections in Sonora are the outcrops of the Sierra de Santa Rosa Formation of the El Antimonio Group in Sierra del Álamo, and the younger part of the eponymous formation in Sierra de Santa Rosa (Fig. 1B). These sections yielded the majority of the ammonoid fauna reported here.

As understood in current lithostratigraphic schemes in a broader stratigraphic context, the stratigraphic succession in Sierra del Álamo is composed of the Permian Monos Formation (Cooper and Arellano, 1946) which is disconformably overlain by the Upper Permian to Lower Jurassic El Antimonio Group (González-León et al., 2005) (Fig. 2). In accordance with the interpreted fore-arc tectonic setting of the El Antimonio basin (Stanley and González-León, 1995; González-León, 1997; Lucas et al., 1999; González-León et al., 2005), much of the Lower Jurassic Sierra de Santa Rosa Formation was deposited in deep-water environments and records an increased rate of sedimentation following the initiation of Jurassic arc magmatism at ca. 200 Ma (González-León et al., 2017).

The studied sections are described in detail in recent publications by González-León et al. (2005, 2017) and Scholz et al. (2008) to provide context for the new paleontologic and biostratigraphic data. Along two measured sections in Sierra del Álamo, González-León (1980) first reported a 3.4-km-thick stratigraphic succession, where based on their age, two informal members were distinguished: an Upper Triassic lower member, and a Lower Jurassic upper member. González-León et al. (1996) and Lucas et al. (1997) later recognized

the Permian-Triassic and Triassic-Jurassic boundaries here. The Triassic-Jurassic transition and system boundary have also been discussed in details by González-León (1997), Lucas and Estep (1999) and González-León et al. (1996; 2000).

González-León (1997) subdivided this unit into 21 informal units that form 14 (numbered I to XIV) unconformity-bounded sequences (Fig. 2). The framework of these sequences is used for all further descriptions below. Lucas and Estep (1999) revised the lithostratigraphic scheme for the Antimonio Formation and subdivided the unit, in ascending order, into the Antimonio, Río Asunción, and Sierra de Santa Rosa Formations (Fig. 2). Subsequently, González-León et al. (2005) grouped the new lithostratigraphic units into the El Antimonio Group and assigned sequences X to XIV to the Sierra de Santa Rosa Formation, which encompasses the Lower Jurassic beds studied here (Fig. 3).

The Triassic-Jurassic boundary in the El Antimonio Group is equated to a sequence boundary between sequences IX and X (González-León, 1997; Lucas and Estep, 1999; González-León et al., 2000), which results in a disconformity at the Triassic-Jurassic boundary, and an incomplete succession where Lower Hettangian strata are entirely absent. Sequence X comprises up to 60 m of fining-upwards siliciclastic strata, in its higher part interbedded with calcareous mudstone and bioclastic limestone beds (González-León et al., 1996) (Fig. 3). The base of Sequence XI consists of coarse-grained fluvial sediments, which grade upward into sandstone and siltstone, intruded by a thick dioritic intrusion, which is followed by alternating calcareous mudstone and siltstone. The basal conglomerate of Sequence XII is fining upwards into sandstone alternating with sandy coquina beds, followed by a massive mudstone/siltstone unit, interbedded with fossiliferous tuffaceous and bioclastic limestone beds. Sequences XIII and XIV together encompass 615 m; the middle part of Sequence XIII consists of turbidite beds whereas the overlying Sequence XIV comprises mostly terrigenous strata devoid of fossils.

Although the upper part of the Sierra de Santa Rosa Formation in Sierra del Álamo is missing due to faulting (González-León et al., 2005), it crops out in Sierra de Santa Rosa (Fig. 1C) where Lower Jurassic rocks were first reported by Keller (1928) and Flores (1929). The age assignment was confirmed by Jaworski (1929) who also published a faunal list of molluscs from here. After these pioneer studies, Hardy (1981) mapped the area extensively, named the Sierra de Santa Rosa Formation and subdivided the here ca. 1460 m thick formation into the informal lower, middle, and upper members; this terminology is still in use. The formation rests on Proterozoic basement above a tectonic contact due to overthrusting, and the Jurassic succession is overlain by much younger volcanic rocks (Fig. 1C).

According to Hardy (1981), the lower member includes alternating beds of cross-bedded sandstone and calcareous mudstone, interbedded with pebble conglomerate with volcanic clasts, and sandy limestone. Typical lithologies of the middle member include blue-grey limestone, mollusc-bearing sandy shale, interbedded with sandstone or mudstone, tuffaceous at some levels. Upsection finer-grained sandstone and limestone become dominant. Both the shale and limestone beds yield abundant and relatively well-preserved fossils. The upper member is lithologically variable, including calcareous shale and sandstone interbedded with volcanogenic conglomerate and limestone beds.

Three sections in the Sierra de Santa Rosa were measured and described by Damborenea and González-León (1997). Part of the ammonoid fauna studied here was also collected by us from these sections (Fig. 4). Section 3 is located in the southwest part of Sierra de Santa Rosa, Section 4 is 3 km further east, whereas Section 5 is 9 km further north (Fig. 1C). Sections 3 and 4 are in tectonic contact with the Proterozoic basement.

Another incomplete Lower Jurassic succession of the Sierra de Santa Rosa Formation is exposed at the locality of Pozos de Serna, 50 km further west from Sierra de Santa Rosa (Fig.

1B). The steeply west-to-southwest-dipping section is disconformably overlying Proterozoic carbonates according to Lucas et al. (1999), or they are in fault contact (González-León et al., 2005).

The ~750 m thick stratigraphic section (Fig. 5), which was first reported in detail by Lucas et al. (1999), represents the upper part of the lower member and most of the middle member of the Sierra de Santa Rosa Formation. Due to thrust faulting, Proterozoic limestone covers the top part of the middle member. A 120 m thick unit of conglomerate and coarse-grained sandstone forms the lowermost preserved part of the Jurassic. The mudstone-dominated middle member disconformably overlies the lower member.

The age of the section at this locality has been debated. Based on ammonoid biostratigraphy, Beauvais and Stump (1976) first suggested a Late Jurassic (Oxfordian-Kimmeridgian) age. The revision of Linares et al. (1997) indicated an Early Pliensbachian age. In contrast, Calmus et al. (1997) proposed a Sinemurian to Bajocian-Bathonian age and subsequently Lucas et al. (1999) assigned the succession to the uppermost Sinemurian.

The Sierra la Jojoba section, where parts of the Sierra de Santa Rosa Formation crop out, is located approx. 40 km northwest of Sierra de Santa Rosa (Fig. 1B), and is tectonically sandwiched between Proterozoic and younger Jurassic or Cretaceous(?) strata. Occurrence of the bivalve *Weyla* (*Weyla*) *mexicana* (Jaworski) and some ammonite fragments were first reported by Keller (1928), indicating a Jurassic age. More recent studies found that the bioclastic limestone contains bivalves (*Weyla alata*, *W. titan*, and *Pholadomya* cf. *voltzi*; Scholz et al., 2008). Hardy (1981) also assumed a possible Jurassic age for the San Luis Formation that overlies the Sierra de Santa Rosa Formation, based on lithological similarities. However, Radelli (1990) claimed, in agreement to Kienast and Rangin (1982) that the detrital and volcanic series belongs to the Lower Cretaceous. The succession is 110 m thick but its base is not observable in the outcrop (Fig. 6). It consists of massive calcareous shale and



siltstone and interbedded sandy limestone and calcareous sandstone, with occasional conglomerate interbeds. At the top of the measured Sierra de la Jojoba section the Sierra de Santa Rosa Formation is unconformably overlain by a thick series of unfossiliferous conglomerate, quartzite, and volcanic and volcanosedimentary rocks.

### 3. Material and methods

A total of 455 ammonoid specimens form the basis of this study, obtained during several successive field campaigns. Two of the authors (JP, CMGL) and other members of a field party collected the majority of the specimens in 1999, augmenting earlier material from the same, previously measured sections. Stratigraphic occurrences are referred here using numbered levels (L), where the number is derived from the field numbers that are not necessarily in sequence. All material are housed at the Estación Regional del Noroeste, Instituto de Geología, Universidad Nacional Autónoma de México in Hermosillo, with collection numbers with the prefix ERNO. In 2018 additional specimens were collected by the first author (DS).

As the majority of specimens are flattened internal molds, poor preservation often hindered species level identification. Latex casts were made of specimens preserved as external molds. Ammonium-chloride coating was applied to specimens prior to photography. Systematic descriptions will be presented in a forthcoming publication, on the basis on the unpublished thesis of Szűcs (2018).

Biostratigraphic analysis is based on the stratigraphically ordered occurrences of the identified taxa in the six measured stratigraphic sections. A conventional approach is used in applying the concept of North American regional standard zones developed from biostratigraphic analyses of key Cordilleran sections (Smith et al., 1988; Taylor et al., 2001)

because provincialism precludes unambiguous assignment of international standard zones developed in Northwest Europe (i.e. Dean et al. (1961) for the Early Jurassic.

The assessment of paleobiogeographic affinity utilizes a literature-based compilation of ammonoid occurrence data from the North American Cordillera. In order to contribute to debates of controversial large scale terrane movements before or after deposition of fossiliferous Early Jurassic strata, we assembled ammonoid distribution data as a presence-absence matrix at a substage resolution in three time slices (latest Hettangian–Early Sinemurian, Late Sinemurian, Early Pliensbachian) from the Walker Lake terrane in Nevada (Taylor, 1998, 2000; Taylor et al., 2001; Hou, 2014; Porter et al., 2014; Caruthers et al., 2018), the Cadwallader terrane in the Taseko Lakes map area, British Columbia (Smith and Tipper, 2000; Macchioni et al., 2006; Longridge et al., 2006, 2008a, b; Hou, 2014), from the Stikine terrane in northwest British Columbia (Thomson and Smith, 1992; Pálffy and Schmidt, 1994; Johannson et al., 1997), and from Wrangellia terrane in Haida Gwaii (formerly Queen Charlotte Islands), British Columbia (Pálffy, 1991; Pálffy et al., 1994; Smith and Tipper, 1996; Longridge et al., 2008c). Our selection was guided by the aim of including the most complete fossiliferous sections from where recent taxonomic studies are available and obtaining representative coverage for meaningful comparison between the Antimonio terrane, outboard terranes of the Canadian Cordillera and an onboard terrane from Nevada. The occurrence data table is available as Supplementary material.

For calculation of similarity, we utilized a suite of appropriate binary coefficients (Jaccard, Dice, Simpson and Raup-Crick indices), recommended for paleobiogeographic studies and described in detail by Shi (1993) and Hammer and Harper (2006). The Jaccard index is a widely used and recommended coefficient (Shi, 1993) but it is sensitive to large differences in diversity. The Dice index involves normalization to reduce sensitivity to disparate diversities and sample sizes, thus it produces a greater range in values while

retaining the order of similarities. The Simpson index differs in its relative emphasis on presences and disregard for absences in small samples (Hammer and Harper, 2006), thus it may highlight incomplete sampling. The Raup-Crick index is the most mathematically sophisticated among these four, loosely interpreted as a randomization test for probability of equality among the samples (Hammer and Harper, 2006). After pairwise tabulation of resulting similarity indices, cluster analysis was performed using the unweighted paired-group method with arithmetic averages (UPGMA) and experimenting with the above four similarity indices as distance measures (Shi, 1993; Hammer and Harper, 2006). UPGMA is useful to visualize in cladograms the faunal similarity through hierarchical grouping. Multivariate data analyses were carried out using the software package PAST (Hammer et al., 2001).

## 4. Results

### 4.1. Ammonoid biostratigraphy

The stratigraphic distribution and ranges of ammonoid taxa are presented in Figs. 3–6, beside lithological columns of six measured sections published in González-León et al. (2005, 2017) and Scholz et al. (2008), ranging in age from Late Hettangian to Early Pliensbachian. The suggested correlation and temporal relationships of the sections are shown in Fig. 7. A short description of the ammonoid zones recognized in the studied sections is given here, using the North American regional standard zonal schemes of Taylor et al. (2001) for the Hettangian and Sinemurian, emended by Longridge et al. (2006), and that of Smith et al. (1988) for the Pliensbachian. Our results are summarized in a composite range chart (Fig. 8).

The oldest unit proven in the studied material is the uppermost Hettangian *Rursicostatum* Zone, with its zonal index *Paracaloceras rursicostatum* (Frebald). This zone is only

documented from Sierra del Alamo, from Levels 1, 2 and 11 that represent calcareous mudstone and bioclastic limestone layers within Sequence X (Fig. 3). The characteristic species occurring in the zone are *Badouxia* cf. *mexicana* Taylor, Guex and Rakús (Fig. 9.1-2), *B.* cf. *castlensis* Longridge, *Nevadaphyllites* cf. *microumbilites* Taylor, and *Paracaloceras* cf. *rursicostatum* (Frebald).

The zonal index of the Involutum Zone of the Lower Sinemurian, *Coroniceras involutum* Taylor, is not known from Sonora. This zone is only documented from Sierra del Alamo, from Levels L3-L4 comprising calcareous mudstone and siltstone within Sequence XI. The zone is characterized by the first appearance of *Arnioceras* sp., *Eolytoceras* sp. and *Coroniceras* aff. *truemani* (Vialli), followed by the first appearance of *Arnioceras* aff. *arnouldi* (Dumortier), *A.* aff. *humboldti* Hyatt (Figs. 9.3, 9.4, 9.8) and *Coroniceras* aff. *gaudryi* (Reynès) (Fig. 9.9).

Although the zonal index *Bartoliniceras leslei* Taylor, Guex and Rakús is not found in the studied material, the Leslei Zone is well documented from Levels L5-L7 in Sequence XI at Sierra del Alamo (Fig. 3). The zone is characterized by the first appearance of *Caenisites* aff. *brooki* (Sowerby), *Phylloceras* cf. *costatoradiatum* (Fig. 10.12), dominated by late-appearing species of *Arnioceras* of which *A.* aff. *densicosta* (Figs. 9.5-7), *A.* aff. *oppeli* (Fig. 9.11) and *A.* cf. *miserabile* also appear here, as well as *Phylloceras* cf. *frondosum*.

The Upper Sinemurian Carinatum Zone is restricted to bioclastic limestone layers Levels L8-L9 in Sequence XII from Sierra del Alamo (Fig. 3). The zone is characterized by the first appearance of an ammonite resembling the index fossil, *E. carinatum*, together with *E. wendelli* Taylor, Guex and Rakús (Figs. 9.10, 10.6) and *E.* cf. *longicella* (Quenstedt). This zone is clearly dominated by specimens of *Epophioceras*, which agrees well with the characterization of the zone by Taylor et al. (2001).

In the studied material, the next higher Corinnae Zone could not be proven. However, from the same section Taylor et al. (2001) reported an assemblage assigned to this zone, therefore their data is shown in Fig. 3 indicated by blue colour.

The uppermost Sinemurian Harbledownense Zone is widespread and well documented from the sections of Sierra del Alamo (Fig. 3: Level L10 in Sequence XIII), Pozos de Serna (Fig. 5: L12), and Section 3 of Sierra de Santa Rosa (Figs. 4A: L26 in the lower member). The zone is characterized by the first appearance of *Paltechioceras* cf. *boehmi*, ammonites resembling the index species *P.* cf. *harbledownense* (Fig. 10.13), *Palaeoehioceras* sp. and Echioceratidae gen. et sp. indet.

The lowermost Pliensbachian Imlayi Zone is documented only from Pozos de Serna (Fig. 5, Levels L13-16). The zone is characterized by the first appearance of the ammonites resembling the index species *Pseudoskirroceras imlayi* (Fig. 11.4), dominated by specimens of *Polymorphites* cf. *confusus* (Quenstedt) (Figs. 10.3-5) and also contains the first appearance of species of *Gemmellaroceras* and *Metaderoceras*, in agreement with the original definition of the Imlayi Zone by Smith et al. (1988).

The overlying Lower Pliensbachian Whiteavesi Zone is documented from the middle member in Sections 4 and 5 of Sierra de Santa Rosa (Fig. 4B: Levels L28-L31; Fig. 4C: L24). The zone is characterized by the first appearance of *Dubariceras silviesi* (Hertlein) (Figs. 10.15, 11.7) which is almost restricted to the Whiteavesi Zone and the appearance of *Metaderoceras evolutum* Fucini (Figs. 11.1, 11.3), *M. gemmellaro*i Levi (Figs. 11.2, 11.6), *M.* cf. *brutum* (Wiedenmayer) and *Reynesocoeloceras* cf. *indunense* (Meneghini) (Fig. 10.11) and Liparoceratidae.

The youngest unit distinguished in the studied sections is the Frebaldi Zone at the top of the Lower Pliensbachian. This zone is widespread as it is documented from Sections 3, 4 and 5 of Sierra de Santa Rosa (Fig. 4A: Levels L25, L27; Fig. 4B: L17-L21, LE2911-18; Fig. 4C:

L22-L23) and Sierra de la Jojoba (Fig. 6). The zone is characterized by the first appearance of the index fossil *Dubariceras freboldi* Dommergues, Mouterde and Rivas, together with the earliest Hildoceratidae species, *Fuciniceras perplicatum* (Fucini) (Figs. 10.9, 10.14) as well as *F. sp. A*, *F. sp. B*, *Metaderoceras cf. mouterdei* Frebold (Fig. 11.5). *Prodictyloceras sp.* (Fig. 10.10) and *P. cf. colubriforme* also appear, as the youngest form of the fauna.

#### 4.2. Diversity and paleobiogeography

The studied ammonoid faunas from Antimonio terrane have been compared with coeval assemblages from the Walker Lake terrane in Nevada, the Intermontane superterrane of the Canadian Cordillera (especially two of its component terranes, the Cadwallader terrane of southern and the Stikine terrane of northwestern British Columbia), and the Wrangellia terrane (part of the Insular superterrane). All four tectonostratigraphic units comprise fossiliferous Lower Jurassic marine, probably arc-related sedimentary rocks but their ammonoid diversity is different and changes through time. Even though zonal resolution is possible, diversity would remain limited and excessively variable in small temporal units, due to vagaries of sedimentary facies and preservation. However, it has been possible and insightful to distinguish three broader time slices for our analyses, as local assemblages were aggregated into latest Hettangian–Early Sinemurian, Late Sinemurian, and Early Pliensbachian bins for optimal, substage-level temporal resolution. The oldest interval is the most diverse both in the Antimonio terrane (16 species) and in the total fauna (89 species). Only 8 Late Sinemurian and 11 Early Pliensbachian species from El Antimonio area reflecting a general drop in diversity (34 and 31 species in total, respectively). Similar trends and somewhat higher diversity are observed in Nevada (39, 16, and 8 species per interval, respectively). The Intermontane superterrane has an exceptionally high latest Hettangian–Early Sinemurian diversity due to abundant and well-preserved faunas known from the

Taseko Lakes map area of Cadwallader terrane. The next two time slices are well represented by assemblages from Stikinian localities, similar to Sonoran faunas in their diversity values. Overall moderately high and even diversity (28, 20, and 25 species, respectively) characterizes Wrangellia as known from the Haida Gwaii (Queen Charlotte Islands).

Diversity and its differences determine sample size and disparity between regions thus influences values of various similarity indices, listed in Table 1. The Jaccard index yielded low values with subdued variability, reflecting its sensitivity to large differences in diversity (Shi, 1993). The Antimonio terrane displays both its lowest and highest similarity with Wrangellia, in the Late Sinemurian (0.12) and Early Pliensbachian (0.42), respectively. The first value is the lowest absolute value among all terrane relationships, whereas the maximum (0.42) is registered between Wrangellia and Stikinia (Intermontane) in the Early Pliensbachian. The Dice index produced the same order of similarities but with a greater range in values, being less sensitive to disparate diversities and sample sizes. For both indices, the highest similarity score to Antimonio terrane is registered for the Intermontane superterrane in the two older time slices and for Wrangellia in the youngest one. On the contrary, Nevada scores the lowest similarity in both the oldest and youngest interval.

The Simpson index differs in its relative emphasis on presences and disregard for absences in small samples (Hammer and Harper, 2006) such as the Antimonio terrane in our dataset, thus it may highlight incomplete sampling. Indeed, both the lowest and the highest similarity with respect to the Antimonio terrane is registered for a different one of the three other terranes in the three time slices. The Raup-Crick index is the most mathematically sophisticated among these four, loosely interpreted as a randomization test for probability of equality among the samples (Hammer and Harper, 2006). It produces the largest range of values and signals consistently moderate values between Antimonio and Nevada (0.24 to

0.38) which nevertheless represent the lowest score among terrane relationships for the latest Hettangian–Early Sinemurian and the highest one for the Early Pliensbachian.

These experiments with different coefficients permitted an informed choice of a distance measure. As follows from the above, the Dice index is a suitably conservative choice for the uneven dataset at hand. A consistent feature of the cladograms (Fig. 12A-C) for all three time slices that the Antimonio terrane occupies a separate branch at the lowest node, whereas the nearest unit is variably Nevada, the Intermontane superterrane, and Wrangellia terrane, for the three successive time slices. Cladograms of different distance measures differ to various degrees (see Supplementary material). Shared among many but especially noticeable for the clustering based on the Raup-Crick index is that Nevada is not situated on the most closely similar branch with respect to the Antimonio terrane (Fig. 12D-F).

## 5. Discussion

### 5.1. Correlation and age of the sections

A biostratigraphic correlation of the six studied sections is proposed in Fig. 7 and outlined in detail below. Sierra del Alamo is the stratigraphically oldest and longest section among the examined localities (Fig. 7). Six zones are represented here, one from the uppermost Hettangian and five from the Sinemurian stage. The oldest zone, the uppermost Hettangian *Rursicostatum* Zone, contains six taxa from three levels (Figs. 3, 8). The lowest documented Sinemurian unit is the *Involutum* Zone, represented by three taxa from five levels. The overlying Lower Sinemurian *Leslei* Zone is the most diverse zone with 9 taxa from five levels. There is a transitional interval between the *Involutum* and *Leslei* Zones, with three taxa from five levels, which cannot be unambiguously assigned to either of these zones. The Upper Sinemurian is also present here with two zones, the *Carinatum* and the *Harbledownense* Zones, with five taxa from three levels.



The section of Pozos de Serna (Figs. 5, 7) is subdivided into two zones that span two stages. The uppermost Sinemurian Harbledownense Zone is documented by a single level with only one taxon, whereas the overlying Imlayi Zone from the lowermost Pliensbachian yielded five taxa from four levels. The presence of the Harbledownense Zone permits correlation of the basal part of Pozos de Serna with the upper part of the section of Sierra del Álamo.

Three sections were measured at the localities of Sierra de Santa Rosa. The informal lower member of the Sierra de Santa Rosa Formation in Section 3 (Fig. 4A), the oldest one, is assigned to the uppermost Sinemurian Harbledownense Zone, with three taxa present at a single level. The two fossiliferous levels yielding six taxa from the overlying middle member is assigned to the uppermost Lower Pliensbachian Freboldi Zone. The intervening two biozones cannot be proven in the unfossiliferous parts of the section. The basal part of Section 3 correlates with the lowermost part of Pozos de Serna and the upper part of Sierra del Álamo, all belonging to the Harbledownense Zone.

The youngest Section 4 (Fig. 4B) is represented by two Lower Pliensbachian zones: the Whiteavesi Zone is known from ten levels with six taxa, and the Freboldi Zone from six levels with seven taxa. Only this latter part of the section is correlatable with the upper part of Section 3.

Section 5 (Fig. 4C) is of broadly the same age as Section 4, but the Whiteavesi Zone is more poorly developed here with only one taxon from a single level, whereas the Freboldi Zone is better represented by five taxa from two levels.

These three neighbouring sections were first compared by Hardy (1981), who proposed a lithological correlation shown in Fig. 4. However, ammonite biostratigraphy now permits a more accurate correlation as presented here. The most reliable marker is the occurrence of *Fuciniceras perplicatum* (Figs. 10.9, 10.14) from Levels 27, 21 and 22 (Fig. 4). The resulting

correlation significantly differs from Hardy's, by a few tens and up to 100 m of difference, and suggests diachronism of the lithological boundary between the informal members. However, if we consider the very first appearance of the genus *Fuciniceras* in each section, we can resolve the contradiction between the informal members, as Level 23 of the Section 5 indicates a *Fuciniceras* occurrence within the middle member, as in the other sections.

Besides ammonoids, bivalves constitute the other abundant and well-studied group of macrofossils in the Sierra de Santa Rosa Formation (Damborenea and González León, 1997; Scholz et al., 2008). A Pliensbachian age assignment from bivalve assemblages from sections in the Sierra de Santa Rosa (Damborenea and González León, 1997) is also in good agreement with the ammonoid-based results.

Apart from biostratigraphy, U-Pb dating of detrital zircons from sandstone beds in the Sierra de Santa Rosa Formation has been used to obtain independent numeric age constraints on 10 samples (González-León et al. 2005; 2009; Hodges et al., 2017). Clearly useful to identify provenance of the sediments, the youngest age group in volcanically derived zircons was also interpreted as the depositional age of the sandstone beds, assuming coeval arc volcanic activity nearby (Hodges et al., 2017). However, this approach can only be followed with caution, as evidenced by one sample from the oldest Jurassic part of the Sierra del Álamo section that only yielded pre-Jurassic detrital zircons (González-León et al., 2009), suggesting that a conservative interpretation would permit determination of a maximum depositional age. The other nine samples with detrital zircon U-Pb data were obtained from the Sierra de Santa Rosa, where Hodges et al. (2017) distinguish three distinct clusters of youngest grains, and interpret them to represent three regional magmatic pulses at 199, 192, and 180 Ma. The oldest of these were inferred from samples from the lower member in Section 3 and, using the calibrated time scale of Ogg and Hinnov (2012), correspond to the Early Sinemurian, whereas our ammonoid biostratigraphy implies Late Sinemurian age.

Three samples with youngest zircons of ca. 192 Ma, which translates into Late Sinemurian, originated from the top of the lower member and the base of the middle member in Section 4, and the base of the upper member in Section 3, respectively. Contradictory ammonoid biostratigraphic age assignments suggest Early Pliensbachian ages at all three levels. Resolution of these discrepancies is offered partly by using the biostratigraphic correlation proposed above (Fig. 4), as an improvement over the lithologic correlation of the sections (Hardy, 1981), partly by emphasizing that the youngest detrital grains provide only maximum age constraints rather than true depositional ages, as demonstrated by the oldest Jurassic sample from Sierra del Álamo. All three samples yielding a 180 Ma cluster of youngest detrital zircons (Hodges et al., 2017) originate from the upper member in the area northeast of Rancho San Carlos, several km away from the measured sections and separated from them by a thrust fault (Hardy, 1981). The uppermost part of the formation here also differs in thick-bedded, shallow marine limestone facies with abundant reef-forming corals but lacking ammonoids. Therefore, a Toarcian age of this part of the formation does not contradict our data. In the lack of ammonoids from, these detrital zircon U-Pb ages suggest extension of the age range of the Sierra de Santa Rosa Formation into the Toarcian. Considering its age that postdates the Early Toarcian global environmental and biotic crisis, its significance may lie in revealing recovery not from the end-Triassic mass extinction (Hodges et al., 2017) but rather from the later but also significant Early Toarcian extinction event.

## *5.2. Applicability of North American Lower Jurassic ammonoid zonal schemes*

According to Page (2017), "the 'meaning' of the Jurassic 'Standard Zones' are chronozones and not biozones – they have been explicitly so since Oppel's day, and as the stratigraphical building blocks of all 'modern' Jurassic stages, they must still be." With this in mind, and recognizing the differences between Tethyan (European) and East Pacific (western

North American) faunas, the regional standard ammonoid zonal schemes developed for North America have been also used in a largely chronostratigraphic sense. Therefore, as new ammonoid-bearing sections are evaluated, the performance of the regional zonation should be reassessed.

Historically, Smith et al. (1988) were the first to propose a regional standard ammonoid zonal scheme for the Pliensbachian Stage and set the agenda to develop similar schemes for the entire Lower Jurassic in North America. Based on 20 reference sections from Alaska to Nevada, Smith et al. (1988) established 5 Zones, with assigned stratotypes in British Columbia, in good agreement with the 5 Northwest European Standard Zones. Pálffy et al. (1994) made a step towards a Sinemurian zonation, and Jakobs et al. (1994) formally erected a Toarcian zonation for the North American Cordillera. Later, based on 14 reference section from Alaska to Sonora, Taylor et al. (2001) established 18 Zones as standard North American ammonoid zonation for the Hettangian (11 Zones) and Sinemurian (7 Zones) stages, where 15 Zones are assigned to a stratotype section in Nevada. Compare to 3 Hettangian and 6 Northwest European standard zones, it is not surprising to see that some of their zones and subzones are mainly applicable for local subdivision in Nevada and Oregon only, and less useful for long-distance, Cordillera-wide correlation purposes, as indicated by the following contradictions encountered in this study.

Taylor et al. (2001) also worked on the type section of Sierra del Alamo, where immediately above the Triassic-Jurassic boundary, which is marked by a disconformity, they report *Sunrisites sunrisense* (Guex), figured in González-León et al. (1996, pl. 1, figs. 1-2), which indicates the Upper Hettangian Sunrisense Zone. Somewhat surprisingly, this level is not represented in the material available for this study. Although Longridge et al. (2008a) did not question the identification, there may be some taxonomic confusion or, alternatively, an

undetected hiatus in the section to explain the lack of superjacent upper Hettangian Morganense and Mineralense Zones.

The Rursicostatum Subzone of Taylor et al. (2001) was elevated to zone status by Longridge et al. (2006). This zone is correlated with the upper part of the Angulata Zone of the Northwest European standard zonation (Fig. 8).

The Trigonatum Zone cannot be proven in the studied material, as *Coroniceras* does not occur in Sonora together with any specimens of *Paracaloceras* or *Badouxia*. This may result from collection failure or lack of preservation in suitable facies in this interval. However, unambiguous Trigonatum Zone is also lacking from Lower Sinemurian sections reported by Hou (2014) from Five Card Draw (Nevada) and Last Creek (British Columbia), furthermore Pálffy (1991) from Haida Gwaii, also known as the Queen Charlotte Islands, (British Columbia). Thus, the correlation potential of this zone appears low. This zone is correlated with the lower part of the Bucklandi Zone of the Northwest European standard zonation (Fig. 8).

The next higher Involutum Zone is present in Sonora, but it is difficult to distinguish from the overlying Leslei Zone. Forms originally thought to be restricted to one or the other zone occur mixed here, which might be an effect of low sampling or there might be a transitional unit between the Involutum and Leslei Zones, as *Arnioceras* seems to appear earlier than *Coroniceras*. The zone is correlated with the upper part of the Bucklandi Zone of the Northwest European standard zonation (Fig. 8).

Although the Leslei Zone was originally subdivided into lower and upper parts or subzones (Taylor et al., 2001), their difference is not noticeable here, which is in agreement with the description of the Sierra del Alamo section in Taylor et al. (2001). *Arnioceras* is more diverse in our collection, although none of its species was figured from this section in

Taylor et al. (2001). The zone is correlatable with the Semicostatum and Turneri Zones of the Northwest European standard zonation (Fig. 8).

The Carinatum Zone is well represented in Sonora by *Epophioceras* spp., in good agreement with the earlier reports, but the next higher Corinnae Zone with diagnostic oxynoceratids was not found in the material studied here, perhaps caused by sampling failure. Note that oxynoticeratids relatively rare in North America (Hue, 2014; Howarth, 2013), as the only diverse appearance of the group reported from the Huayacocotla basin, Mexico (Meister et al., 2005). The authors consider it as a deep-water 'embayment-like structure of the eastern Pacific (Panthalassian) rim' with mainly Tethyan/NW European affinities and endemic elements (Meister et al., 2005). The Carinatum Zone is correlated with the lower part of the Obtusum Zone of the Northwest European standard zonation (Smith et al., 1988). Originally, Taylor et al. (2001) introduced the Jamesi Zone with its type section and only occurrence in the Sierra del Álamo. The name-bearer species, *Asteroceras jamesi*, was erected in the same publication (Taylor et al., 2001) but later synonymized with *Euerbenites corinnae* by Blau et al. (2002), hence the zonal name needs to be emended as Corinnae Zone, as it is shown on Fig. 3., in blue colour. However, as Hou (2014) and Porter et al. (2014) noted, this unit cannot be unambiguously demonstrated in either Nevada or elsewhere, hence it would be reasonable to demote it to subzone rank. Its lack of documentation in our studied material may be caused by sampling failure. The Carinatum Zone sensu stricto is correlated with the lower part of the Obtusum Zone of the Northwest European standard zonation or, with the inclusion of Corinnae Subzone (*ex* Jamesi Zone), it may be broadly equivalent to the entire standard Obtusum Zone and possibly also part of the Oxynotum Zone (Fig. 8).

The Harbledownense Zone was not described from the Sierra del Álamo section by Taylor et al. (2001). However, it has a remarkably good correlation potential, both among the three sections in Sonora and beyond, to several other localities in the Cordillera. In spite of

being widespread, subzonal subdivision as proposed by Taylor et al. (2001) does not seem possible in Sonora. The occurrence of *Paltechioceras* spp. provide solid ground for correlation with the Raricostatum Zone of the Northwest European standard zonation (Fig. 8).

The faunal content of the lowermost Pliensbachian Imlayi Zone is in good agreement with the original description of Smith et al. (1988) from British Columbia. An interesting local feature of the zone at Pozos de Serna is the dominance of small sized *Polymorphites*. Their assemblage is almost monospecific and the number of specimens is remarkably high. A section in Italy at Furlo Pass, described by Venturi et al. (2005, 2007) yields a quite similar Tethyan fauna. The zone is correlated with the Jamesoni Zone of the Northwest European standard zonation (Fig. 8).

The next higher Whiteavesi Zone is well represented in Sierra de Santa Rosa, strongly dominated by *Metaderoceras* and *Reynesocoeloceras*, which are other genera showing strong Tethyan affinity (Fig. 8).

The youngest zone documented in this study, the Frebaldi Zone in the upper part of the Lower Pliensbachian revealed interesting new features. The earliest representatives of Hildoceratidae first appear here, including *Fuciniceras*, which previously was only reported from the Upper Pliensbachian Kunaie Zone in North America. *Fuciniceras perplicatum* was described from probably coeval strata in Tuscany (Italy) in the Tethyan realm (Blau and Meister, 2011). Based on the occurrence of genus *Productylioceras*, this zone also appears at Sierra la Jojoba and the zone is correlated with the Davoei Zone of the Northwest European standard zonation (Fig. 8).

### 5.3. Ammonoid paleobiogeographic constraints on tectonic models

Increasingly well-known Early Jurassic faunas of North America have afforded analyses of paleobiogeographical similarities, to test evolving and controversial tectonic models of

terrane interactions (e.g. Taylor et al., 1984; Smith and Tipper, 1986; Smith, 2006). New data from the El Antimonio Group in Sonora help address one long debated problem, the origin of the Caborca block and its proposed large-scale displacement. Data compiled for our quantitative paleobiogeographic analysis selectively focuses on the Walker Lake terrane in Nevada, part of the Jurassic Luning sedimentary basin and often referred to in previous works as part of Sonomia (e.g. Taylor et al., 1984). This area lies on the opposite (northeast) side of the proposed strike-slip faults MSM and CCT (see Fig. 1A). Here we compared them together with other terranes from the western Canadian Cordillera, now at significantly higher latitude which may have been subjected to post-Early Jurassic northward tectonic transport (Aberhan, 1999). The selected localities from these allochthonous terranes represent the richest and best-studied ammonoid faunas from the Lower Jurassic of North America.

Two problems apparently confound straightforward interpretation of multivariate analyses of ammonoid distribution data. The results of pairwise comparison of terranes or expressing their similarity using cluster analysis is affected by the choice of similarity index (Table 1). On the other hand, the three time slices analysed did not yield strictly consistent results in the degree of similarity between terranes within the Early Jurassic, neither is there any clear trend of temporal changes in similarity between certain terranes (Fig. 12). Many of these observations can be accounted for by the presence of better preserved assemblages at a few localities, restricted to certain intervals in the stratigraphy of some terranes. These faunas received more attention to taxonomic research, resulting in more extensive faunal lists (e.g. the Early Sinemurian of Taseko Lakes in Cadwallader terrane or the Early Pliensbachian of Haida Gwaii in Wrangellia), that is clearly reflected in the apparent diversity pattern in time and space.

Due to the varying sensitivity of similarity indices to sample sizes and their differences, the “monograph effect” of the richest and best-studied faunas somewhat distorts the



coherence of coefficient-based analyses and introduces similar biases into the cluster analyses. However, the degree of divergence in our results is not excessive and with due consideration to the properties of similarity indices and the confounding factors, meaningful interpretation to inform tectonic models is possible.

A primary goal of our approach is to assess the degree of similarity of the Antimonio and Walker Lake terranes, as Sonora and Nevada lie on opposite sides of proposed sinistral strike-slip faults (Fig. 1A). The MSM model suggests Middle or Late Jurassic movement of several hundred kilometres along this fault (Anderson and Silver, 2005), thus predicting the highest similarity between Early Jurassic Sonoran and Nevadan localities. An alternative model proposes earlier, Permian to Triassic movement along the CCT fault (Dickinson and Lawton, 2001), which would be reflected by less similarity between Sonoran and Nevadan assemblages, commensurate with a distance comparable to that in the present day.

Early Jurassic proximity and resultant high similarity between the Antimonio and Walker Lake terranes is not born out from either the pairwise or the cluster analyses. Overall, our results provide more support to the CCT rather than the MMS model. The conservative, quasi-autochthonous Caborca block model suggested by Poole et al. (2005) is also congruent with our results, as its prediction about the Early Jurassic position is similar to that of the CCT model. However, most studies provide independent geological evidence for some form of large-scale sinistral displacement, such as the recently proposed model of Lawton et al. (2017) that reconstructs the Caborca block as the southwest part of the broad Southwestern Laurentian Borderland (SLaB), truncated by sinistral translation in Permian-Triassic time, thus also compatible with our results. Independently, earlier paleobiogeographical studies on Late Triassic corals and Early Jurassic bivalves from the Antimonio terrane offered tentative support for the MSM hypothesis (González-León and Stanley, 1995; Scholz et al., 2008). However, based on several other lines of geological evidence, Amato et al. (2009) found little

support for large-scale Late Jurassic displacement along the suspected trace of MMS and suggested pre-Jurassic translation instead.

As faunal similarity with Nevada is shown to be modest contrary to the expectations from the MSM model, perhaps similarly significant is the finding of higher scores in several indices and intervals (Table 1) for ties with the outboard terranes of the Canadian Cordillera, a pattern confirmed by the cladograms of Fig. 12. Sonora is the most southerly region along the Cordilleran margin of North America with robust Early Jurassic ammonoid distribution data. Its similarity with both Stikinia and Wrangellia, i.e. the outboard Intermontane and Insular superterrane of oceanic volcanic arc affinity in the Early Jurassic, lends further support to their original low latitude paleogeographic position, strengthening previous arguments (Taylor et al., 1984, Smith and Tipper, 1986, Aberhan, 1999; Smith, 2006). The large, perhaps as much as 3000 km, right-lateral northward transport of the Canadian Cordilleran terranes after the mid-Cretaceous has been formulated as the Baja-BC hypothesis with several alternatives for the magnitude, trace and timing of the displacement (e.g. Irving, 1985; Umhoefer, 1987; Butler et al., 2001; Hildebrand, 2015). Paleobiogeographic analysis of Early Jurassic faunal data from different terranes thus can provide evidence for both pre-Jurassic sinistral and post-Jurassic dextral large-scale displacement in the complex tectonic history of the Cordilleran orogen.

## 6. Conclusions

The ammonoid assemblages studied from six stratigraphic sections in the Sierra de Santa Rosa Formation in Sonora represent three stages of the Lower Jurassic, from the Upper Hettangian through the Sinemurian to the Lower Pliensbachian. Provincialism of the fauna warrants the use of the recently developed North American regional ammonoid zonation. Eight zones were recognized and documented in the studied sections.

The oldest, uppermost Hettangian Rursicostatum Zone is found in the type section of the formation in the Sierra del Álamo area, occurring above the disconformity marking the Triassic-Jurassic system boundary. We could not confirm the previously reported presence of the older Sunrisensis Zone. Overlying strata yielded several species of *Arnioceras*, together with common *Coroniceras* and *Caenisites*, which together indicate the Lower Sinemurian Involutum and Leslei zones. The appearance of *Epophioceras* marks the Carinatum Zone from the lower part of Upper Sinemurian, whereas poorly preserved echioceratids higher upsection indicate the Harbledownense Zone. Between these, no collections were obtained from levels previously assigned to the still poorly known Jamesi (or Corinnae) Zone, introduced based on this section by Taylor et al. (2001).

The section at Pozos de Serna yielded *Paltechioceras* and the higher part is dominated by small polymorphitids, permitting assignment to the Harbledownense Zone of the uppermost Sinemurian and the Lower Pliensbachian Imlayi Zone, respectively.

*Paltechioceras* dominate the oldest assemblage in the Sierra de Santa Rosa, which is assigned to the Harbledownense Zone. The middle member yielded *Metaderoceras*, representing the Lower Pliensbachian Whiteavesi Zone, whereas the upper member is characterized by *Metaderoceras*, *Dubariceras* and *Fuciniceras*, which together represent the Freboldi Zone. The poorly known section in Sierra la Jojoba yielded *Productylioceras* sp., assigned to the Lower Pliensbachian Freboldi Zone.

Correlation of the three sections in Sierra de Santa Rosa, where three informal members were previously established, is possible using *Fuciniceras perplicatum* as a marker species, yielding a more reliable biostratigraphic correlation compared to the originally proposed lithologic one. The Early Pliensbachian occurrence of *Fuciniceras* also represents the oldest known record of hildoceratids from North America. Previously reported detrital zircon ages from sandstone beds in the Sierra de Santa Rosa Fm. are best interpreted as maximum age

constraints, because if taken at face value as depositional ages, they in some cases contradict with the ammonoid biostratigraphic age of the unit. However, detrital zircon ages from a nearby reef section with no ammonoids collected are significant in extending the age of the Sierra de Santa Rosa Fm. into the Toarcian.

Using a substage-level compilation of occurrence data from the best known North American sections, Early Jurassic ammonoids from the El Antimonio Group were analysed together with assemblages from the Walker Lake terrane in Nevada and outboard terranes of the Canadian Cordillera, the Stikine, Cadwallader and Wrangellia terranes, using multivariate methods. Both pairwise comparison using multiple similarity indices and cluster analysis yielded results somewhat confounded by disparate sample sizes but generally revealed only modest similarity with Nevada, contrary to predictions of the MSM tectonic model. More support is found for along the CCT fault. The coeval absence of the early hildoceratids at Nevada also supports pre-Jurassic displacement, otherwise the inferred proximity during the Lower Jurassic would warrant its presence at Sonora and Nevada as well. Higher degree of similarity with the Insular and Intermontane superterrane of the Canadian Cordillera argues for more southerly Early Jurassic position of coeval oceanic island arcs and thus lends support for the Baja BC hypothesis. Taken together, further faunal evidence for large-scale pre-Jurassic sinistral and post-Jurassic dextral displacements underlines the complexity of Cordilleran tectonic evolution.

Building on these results, further studies are planned to test the North American regional ammonoid zonation using quantitative biostratigraphic methods, and to investigate paleobiogeographic affinities with coeval faunas from the Sierra Madre Oriental, South America and the westernmost Tethys to re-assess the role of the Hispanic Corridor in ammonoid migration and dispersal.

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### Figure captions

**Fig. 1.** Location maps of the studied sections in Sonora, northwest Mexico, and the distribution of Cordilleran tectonostratigraphic terranes compared in this work. **A:** Index map showing the extent of the Caborca block, other terranes with significant Early Jurassic

ammonoid faunas, the assumed trace of the Mojave-Sonora megashear (MSM) and the California-Coahuila transform (CCT). **B:** Location of the studied sections and distribution of El Antimonio Group outcrops within the Caborca block. PS: Pozos de Serna; SA: Sierra del Álamo; SJ: Sierra la Jojoba; SR: Sierra de Santa Rosa. **C:** Geological map showing the location of the studied sections in Sierra de Santa Rosa (after González-León et al., 2017).

**Fig. 2.** Litho- and chronostratigraphic subdivision of El Antimonio Group in the studied sections in Sonora (after González et al., 2017). Perm.: Permian; Trias.: Triassic; L.: Lower; U.: Upper; Het.: Hettangian; Sin.: Sinemurian; Pli.: Pliensbachian; Fm.: Formation; S.S.R.: Sierra de Santa Rosa.

**Fig. 3.** Ammonoid biostratigraphy of the Upper Hettangian and Sinemurian part of Sierra de Santa Rosa Formation at Sierra del Álamo. Lithologic column of the measured section after González-León (1997), where X-XIII refer to unconformity-bounded sequence numbers and numbers from 16-20 are informal units of the sequences (see more details at Fig. 2). The legend is shown in Fig. 6.

**Fig. 4.** Ammonoid biostratigraphy of the Upper Sinemurian and Lower Pliensbachian part of Sierra de Santa Rosa Formation at Sierra de Santa Rosa. Lithologic columns after Damborenea and González-León (1997). **A:** Section 3; **B:** Section 4; **C:** Section 5. The legend is shown in Fig. 6.

**Fig. 5.** Ammonoid biostratigraphy of the Upper Sinemurian and Lower Pliensbachian part of Sierra de Santa Rosa Formation at Pozos de Serna. Lithologic column of the measured section after Scholz et al. (2008). The legend is shown in Fig. 6.



**Fig. 6.** Ammonoid biostratigraphy of the Lower Pliensbachian part of Sierra de Santa Rosa Formation at Sierra la Jojoba. Lithologic column of the measured section after Scholz et al. (2008).

**Fig. 7.** Bio- and chronostratigraphic correlation of the studied Lower Jurassic sections in Sonora. PS: Pozos de Serna; SR: Sierra de Santa Rosa; SJ: Sierra la Jojoba; U.: Upper; L.: Lower; Z.: Zone; Rurs.: Rursicostatum; Inv.: Involutum; Car.: Carinatum; Har.: Harbledownense; Whi: Whiteavesi.

**Fig. 8.** Composite zonation and relative stratigraphic ranges of ammonoids from the studied Lower Jurassic sections in Sonora. North American regional standard zones (NA Z.) are used and approximately correlated with the Northwest European standard zones (NW Eu. Z.). Other abbreviations: L.: Lower; U.: Upper, Rurs.: Rursicostatum; C.: Canadensis; T.: Trigonatum; Inv.: Involutum; Car.: Carinatum; Cor.: Corinnae; Har.: Harbledownense; Whi.: Whiteavesi.

**Fig. 9.** Biostratigraphically significant latest Hettangian and Sinemurian ammonoids from the Sierra de Santa Rosa Formation, Sierra del Álamo section. All specimens are natural size and coated with ammonium chloride. **1-2:** *Badouxia* cf. *mexicana* (Taylor, Guex and Rakús), Rursicostatum Zone, latest Hettangian (**1:** ERNO-8728, Level 1; **2:** ERNO-8729, Level 2); **3, 4, 8:** *Arnioceras* aff. *humboldti* (Hyatt), Leslei Zone, Early Sinemurian (**3:** ERNO-8730, Level 4; **4:** ERNO-2926, Levels 4 or 5; **8:** ERNO-8731, Level 5); **5-7:** *Arnioceras* aff. *densicosta* (Quenstedt), Involutum Zone to Leslei Zone, Early Sinemurian (**5:** ERNO8732, Level 6; **6:** ERNO-8733, Level 6; **7:** ERNO-8734, Level 6); **9:** *Coroniceras* aff. *gaudryi* (Reynès), Involutum Zone, Early Sinemurian (ERNO-8735, Level 5); **10:** *Epophioceras wendelli* (Taylor, Guex and Rakús), Carinatum Zone, Late Sinemurian (ERNO-8736, Level

8); **11**: *Arnioceras* aff. *oppeli* (Guérin-Franiatte), Leslei Zone, Early Sinemurian (ERNO-2932, Level 6, Unit 18).

**Fig. 10.** Biostratigraphically significant Sinemurian and Early Pliensbachian ammonoids from the Sierra de Santa Rosa Formation. All specimens are natural size and coated with ammonium chloride. **1, 2, 8**: *Polymorphites* sp., Imlayi Zone to earliest Freboldi Zone, Early Pliensbachian, Pozos de Serna (**1**: ERNO-8737, Level 16; **2**: ERNO-2888, Level 13; **8**: ERNO-8738, Level 16); **3-5**: *Polymorphites* cf. *confusus* (Quenstedt), Imlayi Zone to earliest Freboldi Zone, Early Pliensbachian, Pozos de Serna (**3**: ERNO-8739, Level 13; **4**: ERNO-2891 A, Level 13; **5**: ERNO-8740, Level 16, **a**: lateral view, **b**: oblique ventral view); **6**: *Epophioceras wendelli* (Taylor, Guex and Rakús), Carinatum Zone, Late Sinemurian, Sierra del Álamo (ERNO-8741, Level 8, **a**: lateral view, **b**: lateral view of counterpart); **7**: *Fuciniceras* sp. A, Freboldi Zone, Early Pliensbachian, Sierra de Santa Rosa, Section 4 (ERNO-8742, Level 21, **a**: lateral view, **b**: lateral view of counterpart); **9, 14**: *Fuciniceras perplicatum* (Fucini), Freboldi Zone, Early Pliensbachian, Sierra de Santa Rosa (**9**: ERNO-2902, Section 4, Level 21; **14**: ERNO-8743, Section 3, Level 27); **10**: *Prodactylioceras* sp., Freboldi Zone, Early Pliensbachian, Sierra la Jojoba (ERNO-8744, *ex situ*); **11**: *Reynesocoeloceras* cf. *indunense* (Meneghini), Freboldi Zone, Early Pliensbachian, Sierra de Santa Rosa, Section 3 (ERNO-8745, Section 3, Level 25, **a**: lateral view, **b**: ventral view); **12**: *Phylloceras* cf. *costatoradiatum* (Geyer), Leslei Zone, Early Sinemurian, Sierra del Álamo (ERNO-8746, Level 6); **13**: *Paltechioceras* cf. *harbledownense* (Crickmay), Harbledownense Zone, Late Sinemurian, Sierra de Santa Rosa, Section 3 (ERNO-8747, Level 26); **15**: *Dubariceras silviesi* (Hertlein), Whiteavesi Zone, Early Pliensbachian, Sierra de Santa Rosa, Section 4 (ERNO-2925, Level 18, **a, b**: lateral view of part and counterpart, **c**: ventral view).

**Fig. 11.** Biostratigraphically significant Early Pliensbachian ammonoids from the Sierra de Santa Rosa Formation. All specimens are natural size and coated with ammonium chloride. **1**, **3**: *Metaderoceras evolutum* (Fucini), Sierra de Santa Rosa (**1**: ERNO-8748, Section 4, Level 28, early Whiteavesi Zone, **a**: oblique ventral view, **b**: lateral view; **3**: ERNO-2919, Section 5, Level 22, Whiteavesi Zone); **2**, **6**: *Metaderoceras gemmellaroi* (Levi), Whiteavesi Zone, Sierra de Santa Rosa (**2**: ERNO-8749, Section 4, Level 29; **6**: ERNO-8750, Section 5, Level 22, **a**: lateral view, **b**: ventral view); **4**: *Pseudoskirroceras* cf. *imlayi* (Smith and Tipper), Imlayi Zone, Pozos de Serna (ERNO-8751, Level 13); **5**: *Metaderoceras* cf. *mouterdei* (Friebold), Frieboldi Zone, Sierra de Santa Rosa, Section 4 (ERNO-8752, Level 19); **7**: *Dubariceras silviesi* (Hertlein), Whiteavesi Zone, Sierra de Santa Rosa, Section 4 (ERNO-8753, Level 30) **a**: lateral view, **b**: lateral view of rubber cast counterpart).

**Fig. 12.** Dendrograms expressing similarity of Early Jurassic ammonoid faunal assemblages from Sonora with other areas in North American Cordillera: Nevada (Walker Lake terrane), the Intermontane superterrane (including Cadwallader and Stikine terranes in British Columbia) and Wrangellia terrane. Assemblages compiled at substage level, cluster analysis performed using UPGMA method and Dice index (A–C) and Raup-Crick index (D–F) (Hammer and Harper, 2006).

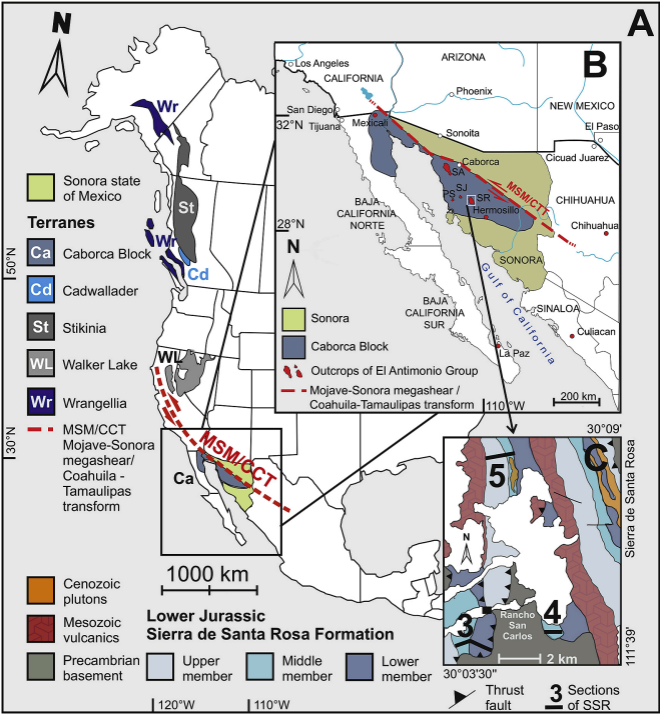
**Table 1.** Values of our binary coefficients expressing faunal similarity between the Antimonio terrane in Sonora, Walker Lake terrane in Nevada, the Intermontane superterrane and Wrangellia terrane in British Columbia, during three substages in the Early Jurassic. Jaccard index: first column, lower left; Dice index: first column, upper right; Simpson index: second column lower left; Raup-Crick index: second column, upper right.

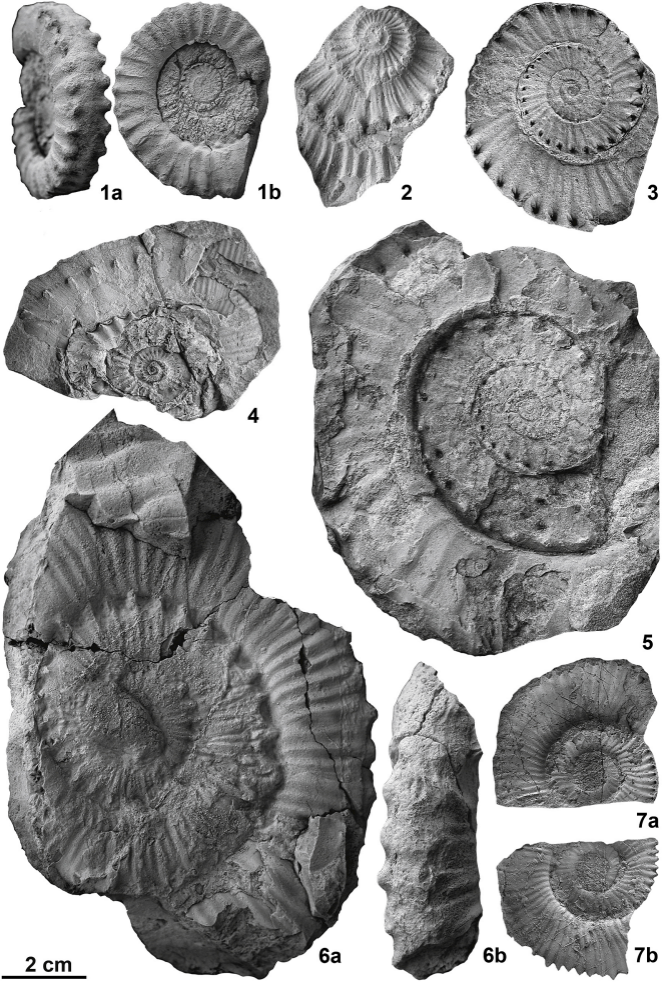
	Dice				Raup-Crick				
	Antimonio	Nevada	Intermontane	Wrangellia	Antimonio	Nevada	Intermontane	Wrangellia	
Antimonio	1.00	0.32	0.35	0.39	1.00	0.38	0.23	0.01	Early Pliens- bachian
Nevada	0.19	1.00	0.60	0.42	0.38	1.00	0.96	0.53	
Intermontane	0.21	0.43	1.00	0.59	0.36	0.75	1.00	0.73	
Wrangellia	0.24	0.27	0.42	1.00	0.64	0.88	0.92	1.00	
Antimonio	1.00	0.33	0.38	0.21	1.00	0.37	0.71	0.03	Late Sinemurian
Nevada	0.20	1.00	0.42	0.44	0.50	1.00	0.69	0.06	
Intermontane	0.23	0.26	1.00	0.43	0.38	0.63	1.00	0.71	
Wrangellia	0.12	0.29	0.27	1.00	0.38	0.50	0.75	1.00	
Antimonio	1.00	0.25	0.36	0.27	1.00	0.24	0.80	0.46	latest Hettangian- Early Sinemurian
Nevada	0.15	1.00	0.33	0.36	0.44	1.00	0.00	0.15	
Intermontane	0.22	0.20	1.00	0.38	0.75	0.38	1.00	0.10	
Wrangellia	0.16	0.22	0.23	1.00	0.38	0.43	0.54	1.00	
	Jaccard				Simpson				

**Table 1.** Values of four binary coefficients expressing faunal similarity between the Antimonio terrane in Sonora, Walker Lake terrane in Nevada, the Intermontane superterrane and Wrangellia terrane in British Columbia, during three substages in the Early Jurassic. Jaccard index: first column, lower left; Dice index: first column, upper right; Simpson index: second column lower left; Raup-Crick index: second column, upper right.

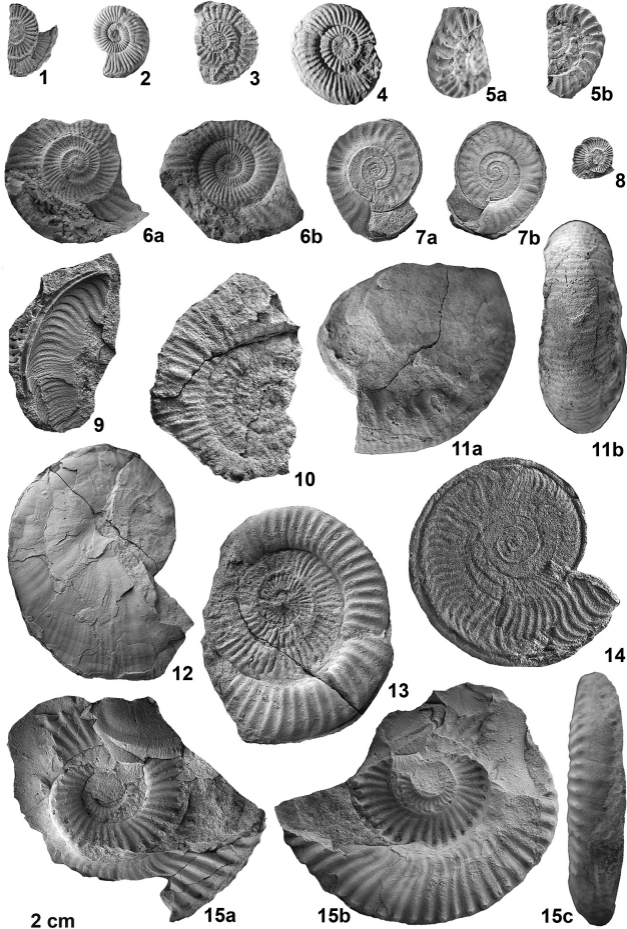
**Highlights:**

- *Fuciniceras* represents the oldest known record of hildoceratids from North America
- Coeval absence of early hildoceratids at Nevada endorse pre-Jurassic displacement
- This study does not support Late Jurassic movement of the Mojave-Sonora Megashear
- Pre-Jurassic sinistral movement supported along the California-Coahuila transform
- High affinity with Canadian terranes support Baja-British Columbia hypothesis

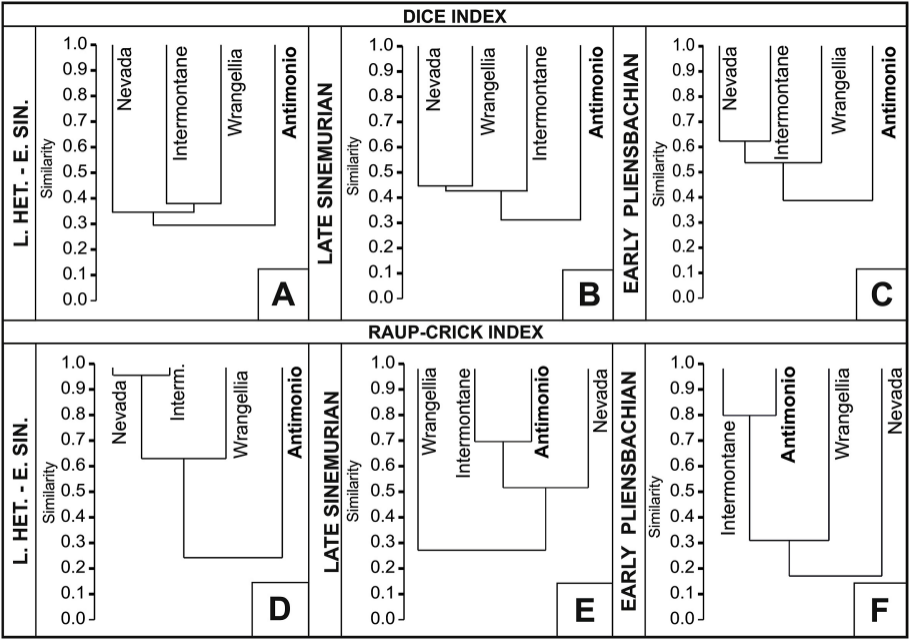




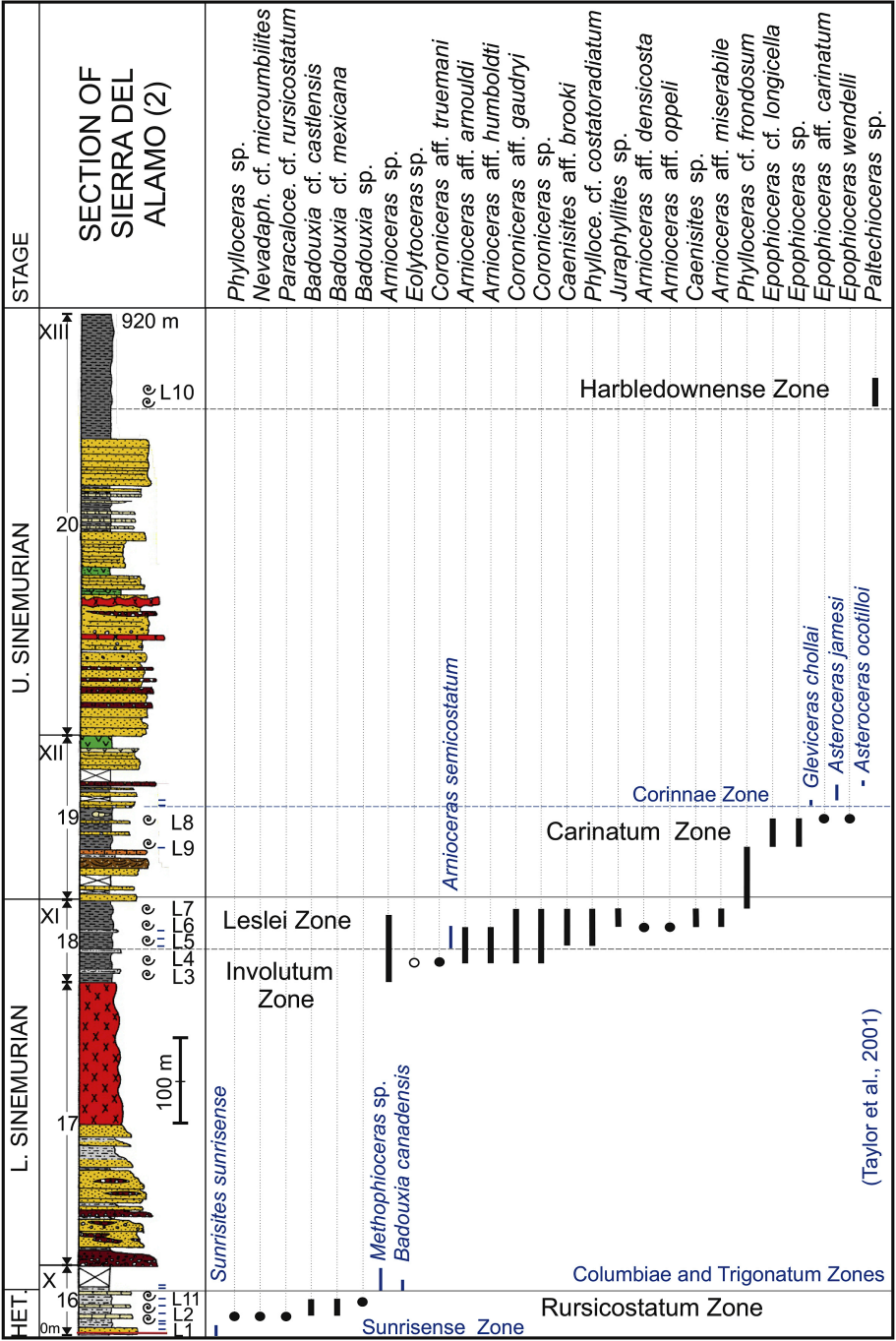


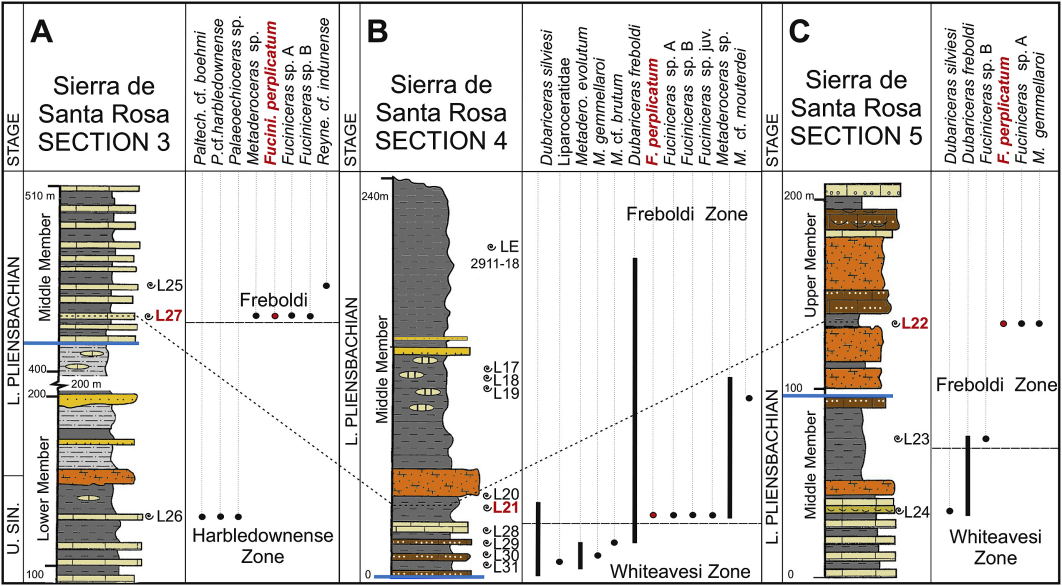


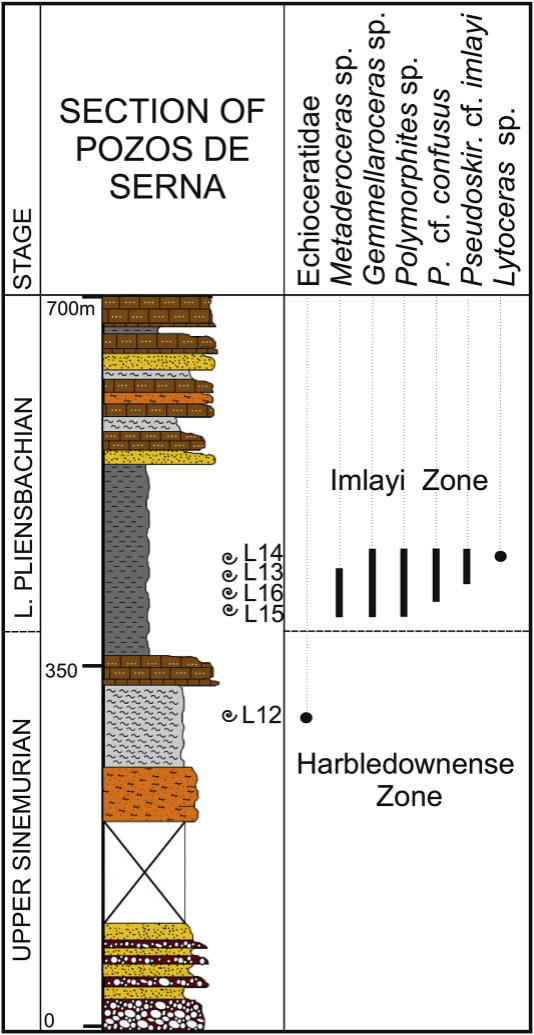


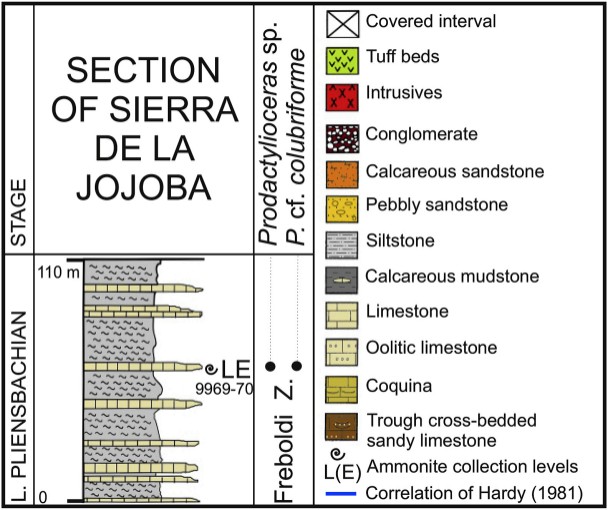


System	Stage	Locality	Formation	Sequence				Total [m]	
					[m]	Unit	[m]		
Lower Jurassic	L. Pli.	Sierra de la Jojoba	S.S.R. Fm.	-				110	
	L. Pli.	Sierra de Santa Rosa	Sierra de Santa Rosa Fm.	Upper		225		773	
	L. Pli.			Middle		128			
	U. Sin.			Lower		420			
	L. Pli.	Pozos de Serna	S.S.R. Fm.	-				700	
	U. Sin.								
	U. Sin.	Sierra del Alamo	Sierra de Santa Rosa Fm.	<b>XIV</b>	150	<b>21</b>	150		1070
				<b>XIII</b>	465	<b>20</b>	465		
				<b>XII</b>	115	<b>19</b>	115		
	L. Sin.			<b>XI</b>	280	<b>18</b>	60		
	<b>17</b>					220			
U.Het.		<b>X</b>	60	<b>16</b>	60				
Perm. Trias.			Rio Asuncion Fm.	<b>VII -IX</b>		<b>12-15</b>		450	
			Antimonio Fm.	<b>I -VI</b>		<b>1-11</b>		1878	
Perm.			Monos Fm.	-					









U. H.	SINEMURIAN							L. PLIENSBACHIAN		
Ru.Z.	Col.Z.	T.Z.	Inv. Z.	Les.Z.	Car.Z.	Cor.Z.	Har.Z.	Imlay Z.	Whi.Z.	Freboldi Z.
	<b>ALAMO</b>									
							<b>PS</b>			
							<b>SR3</b>			
								<b>SR4</b>		
								<b>SR5</b>		
									<b>SJ</b>	

U. HET.	SINEMURIAN							L. PLIENSCHACHIAN			STAGE	TAXA	
	Ang. Z.	Bucklandi. Z.		S.Z.	T.Z.	Obtusum Z.	O.	R.Z.	Jame. Z.	Ibex. Z.	Dav. Z.		NW.Eu.Z.
	Rurs. Z.	C. Z.	T. Z.	Inv. Z.	Leslei Z.	Car. Z.	Cor. Z.	Har. Z.	Imlay Z.	Whi.Z.	Freboldi Z.	NA. Z.	
													<i>Phylloceras</i> sp.
													<i>N.phyllites</i> cf. <i>microumbilites</i>
													<i>Paracaloc.</i> cf. <i>rursicostatum</i>
													<i>Badouxia</i> cf. <i>castlensis</i>
													<i>Badouxia</i> cf. <i>mexicana</i>
													<i>Badouxia</i> sp.
													<i>Amioceras</i> sp.
													<i>Eolytoceras</i> sp.
													<i>Coroniceras</i> aff. <i>truemani</i>
													<i>Amioceras</i> aff. <i>arnouldi</i>
													<i>Amioceras</i> aff. <i>humboldti</i>
													<i>Coroniceras</i> aff. <i>gaudryi</i>
													<i>Coroniceras</i> sp.
													<i>Caenites</i> aff. <i>brookii</i>
													<i>Phylloc.</i> cf. <i>costatoradiatum</i>
													<i>Juraphyllites</i> sp.
													<i>Amioceras</i> aff. <i>densicosta</i>
													<i>Amioceras</i> aff. <i>oppeli</i>
													<i>Caenites</i> sp.
													<i>Amioceras</i> aff. <i>miserabile</i>
													<i>Phylloceras</i> gr. <i>frondosum</i>
													<i>Epophioceras</i> cf. <i>carinatum</i>
													<i>Epophioceras</i> <i>wedelli</i>
													<i>Epophioceras</i> cf. <i>longicella</i>
													<i>Epophioceras</i> sp.
													<i>Paltechioceras</i> sp.
													<i>Paltechioceras</i> cf. <i>boehmi</i>
													<i>P.</i> cf. <i>harbledownense</i>
													<i>Palaeoechioceras</i> sp.
													Echioceratidae gen. et sp. in.
													<i>Gemmellaroceras</i> sp.
													<i>Polymorphites</i> sp.
													<i>Polymorphites</i> cf. <i>confosus</i>
													<i>Pseudoskirroceras</i> cf. <i>imlayi</i>
													<i>Lytoceras</i> sp.
													<i>Metaderoceras</i> cf. <i>brutum</i>
													<i>Metadero.</i> cf. <i>gemmellari</i>
													<i>Metaderoceras</i> <i>evolutum</i>
													<i>Reynesocoelo.</i> cf. <i>indunense</i>
													Liparoceratidae gen.et.sp.ind.
													<i>Dubariceras</i> <i>silviesi</i>
													<i>Dubariceras</i> <i>freboldi</i>
													<i>Fuciniceras</i> <i>perplicatum</i>
													<i>Fuciniceras</i> sp. A
													<i>Fuciniceras</i> sp. B
													<i>Fuciniceras</i> sp. juv.
													<i>Metaderoceras</i> cf. <i>mouterdeii</i>
													<i>Productylioceras</i> sp.
													<i>P.</i> cf. <i>colubriforme</i>



