Diversity of Crinozoa (Echinodermata: Eocrinoidea, Blastoidea, Crinoidea) from the Paleozoic of Mexico

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ABSTRACT

Paleozoic outcrops in Mexico containing echinoderms are located to the north, center and south of the country, mainly in the states of Baja California, Sonora, Chihuahua, Tamaulipas, Coahuila, Hidalgo, Puebla, Guerrero, Oaxaca, and Chiapas. These rocks correspond to marine carbonates deposited in warm shallow environments, with an approximate age of 541 to 251 Ma. Also containing a varied and diverse biota made up of phylloid algae, foraminifera (fusulinids), coralline sponges, corals, bryozoans, brachiopods, mollusks, trilobites and echinoderms. In order to know the diversity of Crinozoa from the Paleozoic of Mexico, an analysis of the species documented for the country was carried out, with the objective of contributing to the knowledge of the biostratigraphy and paleogeography of Mexico. The methodology consisted of a detailed analysis of bibliographic sources with information on echinoderms from the Paleozoic of Mexico. Cambrian eocrinoids (*Gogia, and Ubaghsicystis)* are distributed mainly in Sonora. Crinoid plates from the Carboniferous and Permian, particularly morphospecies of the genera *Cyclocaudex*, *Cyclocrista*, *Heterostelechus*, *Lamprosterigma*, *Mooreanteris*, *Pentagonopternix*, *Preptopremnum*, and *Pentaridica*, are widely distributed throughout the country. Analysis of the Mississippian-Permian biota indicates that the cosmopolitan distribution of the fauna studied in this work is due to the connections between the seas of western North America and eastern Asia. The Late Permian benthic fauna of Sonora was widely dispersed in the Tethyan realm, which stretched from western North America to North Africa and Asia. The comprehensive study of Paleozoic marine stratigraphic successions and their biotic content provided information on faunal migrations regarding the Paleozoic carbonate facies. It also contributed to reconstructing the geographical, climatological, and ecological characteristics of the Paleozoic of Mexico.

Keywords: Paleobiodiversity; invertebrates; echinoderms; paleobiogeography; Paleozoic; Mexico.

RESUMEN

Los afloramientos paleozoicos en México con equinodermos se ubican al norte, centro y sur del país, principalmente en los estados de Baja California, Sonora, Chihuahua, Tamaulipas, Coahuila, Hidalgo, Puebla, Guerrero, Oaxaca y Chiapas. Estas rocas carbonatadas marinas fueron depositadas en ambientes cálidos poco profundos, con una edad aproximada de 541 a 251 Ma. También contienen una biota variada y diversa compuesta por algas filoides, foraminíferos (fusulínidos), esponjas coralinas, corales, briozoos, braquiópodos, moluscos, trilobites y equinodermos. Con el objetivo de conocer la diversidad de Crinozoa del Paleozoico de México, se realizó un análisis de las especies documentadas para el país, con el objetivo de contribuir al conocimiento de la bioestratigrafía y paleogeografía de México. La metodología consistió en un análisis detallado de fuentes bibliográficas con información sobre equinodermos del Paleozoico de México. Los eocrinoides cámbricos (Gogia y Ubaghsicystis) se distribuyen principalmente en Sonora. Las placas de crinoideos del Carbonífero y Pérmico, en particular las morfoespecies de los géneros Cyclocaudex, Cyclocrista, Heterostelechus, Lamprosterigma, Mooreanteris, Pentagonopternix, Preptopremnum y Pentaridica, están ampliamente distribuidas por todo el país. El análisis de la biota del Misisípico-Pérmico indica que la distribución cosmopolita de la fauna estudiada en este trabajo se debe a las conexiones entre los mares del oeste de América del Norte y el este de Asia. La fauna bentónica del Pérmico tardío de Sonora estaba muy dispersa en el dominio del Tethys, que se extendía desde el oeste de América del Norte hasta el norte de África y Asia. El estudio exhaustivo de las sucesiones estratigráficas marinas del Paleozoico y su contenido biótico proporcionó información sobre las migraciones de fauna con respecto a las facies carbonatadas del Paleozoico. También contribuyó a reconstruir las características geográficas, climatológicas y ecológicas del Paleozoico de México.

Palabras clave: paleobiodiversidad; invertebrados; equinodermos; paleobiogeografía; Paleozoico; México.

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INTRODUCTION

The continents and seas have been subject to great changes in their position, shape, and oceanic characteristics, changes that were originated by the dynamics of the tectonic plates, and within this framework a numerous and diverse biota developed (Pantoja, 1970; Anderson and Silver, 1979; Baldis and Bordonaro; 1981; Campa-Uranga and Coney, 1983; Coney, 1983; Stewart *et al.*, 1984; 1990, 1999, 2002; González-León, 1986; Pérez-Ramos, 1992; Ramos and Keppie, 1999; Sánchez-Zavala *et al.*, 1999; Almazán *et al.*, 2006; Sour-Tovar *et al.*, 2007).

Paleozoic marine outcrops of Mexico exposed in the states of Baja California (La Pintas, Navas-Parejo *et al.*, 2018). Sonora (Caborca, El Chihuarruita, Sahuaral, Arivechi, Bisani, Cerros El Tule, Sierra Las Mesteñas, and Sierra Agua Verde), Chihuahua (Placer de Guadalupe-Sierra Plomosas), Tamaulipas (Cañón de Peregrina); while in south-central Mexico are exposed in the estates of Hidalgo (Calnali), and Puebla (San Salvador Patlanoaya), and in the southern region, in Guerrero (Olinalá), Oaxaca (Nochixtlán-Ixtaltepec) and Chiapas (Paso Hondo and Chicomuselo), which generally correspond to marine carbonate rocks deposited in warm shallow-water seas, these rocks have ages between 545 and 252 million years, with little representation of the Silurian, containing numerous and diverse fossils, including echinoderms (Buitrón, 1992; Buitrón *et al.*, 2008) (Figure 1).

In the areas of Caborca, Bisani, Cananea, San José de Gracia, Mazatán, and Arivechi in the state of Sonora, Cambrian sedimentary rocks with algae and invertebrates that have been studied by several authors are exposed (Cooper *et al.*, 1952; Stewart *et al.*, 1984, 1999, 2002; González-León, 1986; McMenamin, 1985, 1987; Almazán, 1989; Cuen-Romero *et al.*, 2016, 2018, 2019; Beresi *et al.*, 2019.

Also, in Sonora, there are outcrops of upper Paleozoic sequences deposited in a carbonate shallow-water platform (Cordilleran System) thrusted by oceanic basin siliciclastic and carbonate rocks (Orozco-Grajeda, 2005). The Cordilleran System rocks correspond to deposits of continental shelves in shallow seas, which developed on the western edge of Laurentia (North American Craton) (Poole *et al.*, 2005).

Paleozoic marine biota of Mexico, in general is mainly constituted by cyanobacteria algae (Cooper *et al.*, 1952; Gómez-Espinosa *et al.*, 2008; Beraldi *et al.*, 2018; Buitrón *et al.*, 2012; Vachard, *et al.*, 2017), foraminifera (Vachard, *et al.*, 1993, 1997, 2000a, 2000b, 2017; Pérez-Ramos, 2002; Gómez-Espinosa *et al.*, 2008; Buitrón *et al.*, 2012), sponges (Almazán *et al.*, 2007; Buitrón *et al.*, 2007a; Cuen-Romero *et al.*, 2013; Beresi *et al.*, 2012, 2017, 2019), archaeocyathids (Cooper *et al.*, 1953; Debrenne, 1987; Debrenne *et al.*, 1989; Buitrón *et al.*, 2000), cnidaria (Easton, 1958; González-León, 1986; Buitrón *et al.*, 2012; Villanueva-Olea 2016; Buitrón *et al.*, 2000), bryozoans (González-León, 1986; González-Mora *et al.*, 2018), brachiopods (Cooper *et al.*, 1952; Buitrón *et al.*, 2005b; Buitrón *et al.*, 2012; Jiménez *et al.*, 2018; Torres-Martínez *et al.*, 2018), hyolithids (Cooper *et al.*, 1952; MacMenamin, 1985; Buitrón *et al.*, 2017a; Devaere *et al.*, 2019), mollusks (Yochelson, 1968; Buitrón *et al.*, 2000; Gómez-Espinosa *et al.*, 2009; Buitrón *et al.*, 2012), trilobites (Cooper, *et al.* 1952; Pantoja and Robison, 1967; Robison and Pantoja 1968; Rivera, 1988; Cuen-Romero *et al.*, 2016, 2018, 2019; Sundberg and Cuen-Romero, 2021), conodonts (Brunner, 1987; Navas-Parejo, 2018; Lara-Peña *et*

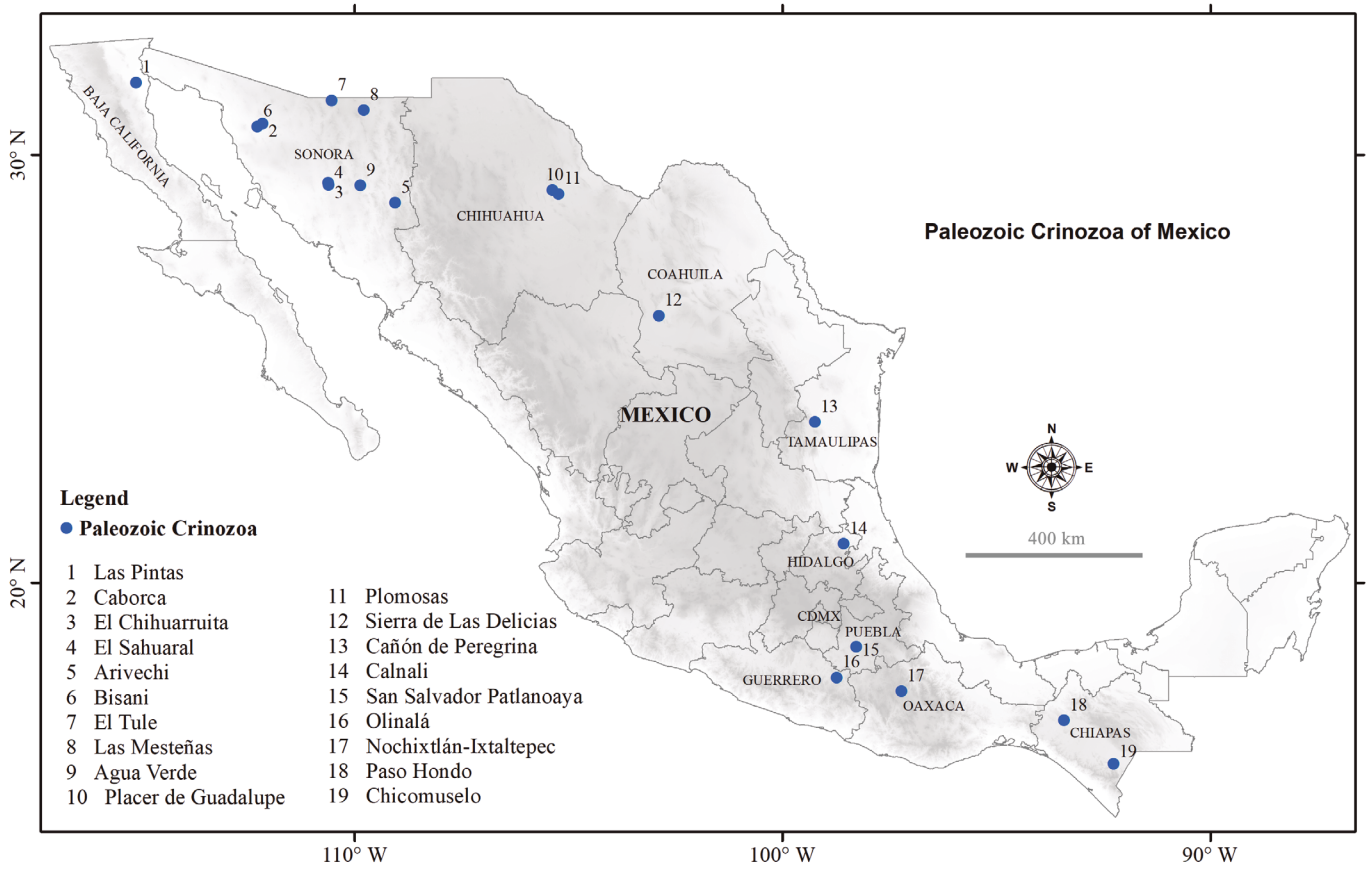

Figure 1. Map showing Paleozoic localities in Mexico containing echinoderms.

al., 2020), graptolites (Carrillo-Bravo, 1961; Peiffer-Rangin *et al.*, 1980; Rivera and Buitrón, 1986; Sour-Tovar and Buitrón 1987; Riva and Ketner, 1989; Debrenne *et al.*, 1989) and ichnofossils (Buitrón *et al.*, 2016).

The echinoderms are represented by Cambrian eocrinoids-blastoids (Nardin *et al.*, 2009; Buitrón *et al.*, 2017b, 2021) and by numerous plaques of isolated Mississippian-Permian crinoids (Strimple, 1971; Buitrón, 1977, 1992; Buitrón *et al.*, 1987, 2000, 2004, 2005a, b, 2006, 2015a, b, 2016; Buitrón and Solís, 1993; Esquivel-Macias *et al.*, 2000, 2004, 2005; Solís-Marín *et al.*, 2013), which in most cases formed encrinites (Gómez-Espinosa and Buitrón, 2017).

Considering the abundant existing information on the Paleozoic outcrops of Mexico, as well as the existing works on echinoderms, it is important to carry out an evaluation of the Crinozoa fauna for the country, with the objective of contributing to the knowledge of the biostratigraphy and paleogeography of the group.

METHODOLOGY

Previous works are the data base used for this work, an exhaustive review of the existing bibliographic references with Paleozoic Crinozoa material was performed. The information was compiled in a database and later analyzed by locality and geological age.

Exhaustive bibliographical research was done on diverse sources for echinoderms in the Paleozoic rocks of Mexico (Baja California, Sonora, Chihuahua, Tamaulipas, Hidalgo, Puebla, Guerrero, Oaxaca, and Chiapas).

The data included in this paper is organized by location, and geologic period; also, the stratigraphy, ecology and paleogeographic conditions during the sedimentation is provided (Figures 2 and 3). The classification used is based on Guensburg and Sprinkle (2003) and Wright *et al.* (2017).

CAMBRIAN ECHINODERM DIVERSITY OF SONORA

Caborca area

Sprinkle (1973) mentioned the presence of isolated plates of gogid blastoids in the Cambrian sedimentary rocks exposed in the Caborca region, located to the northwest of Sonora (Figures 1, 2). Also, Durham (1978) mentioned the possible existence of eocrinoids in the same area.

San José de Gracia, El Chihuarruita Hill

The Chihuarruita hill is located near the San José de Gracia town, 40 km to the northeast of Hermosillo, within the coordinates 29°17'05"N, 110°35'03"W (Figures 1, 2). The lower Cambrian outcrops in the region have a diverse fauna of invertebrates. Nardin *et al.* (2009) reported the presence of the eocrinoids-blastoid species assigned to *Gogia granulosa* Robison, 1965 from a bioclastic limestone. Later, Cuen-Romero *et al.* (2016) and Buitrón *et al.* (2017b) reported isolated plates of *Gogia granulosa* from the middle Cambrian Proveedora Formation (540 Ma) made up of sandstone and quartzite; and from the Buelna Formation (525 Ma) made up of limestone, shale, and sandy limestone. Also, the presence of trace fossils of the ichnogenus *Asteriacites* von Schlotheim, 1820 may correspond to an echinoderm starfish printing (Seilacher, 2007; Zamora *et al.*, 2010; Buitrón *et al.*, 2016). The biotic association allowed to establish paleogeographic relationships with Alberta (Canada), California, Nevada, Utah, and Idaho (United States of America), Spain and France (Europe), North Korea (Asia), and Australia.

San José de Gracia, El Sahuaral Hill

A middle Cambrian sedimentary sequence assigned to the El Gavilán Formation constituted by shale and oolitic limestone outcrops in the central Sonora. This unit is exposed at the Sahuaral hill, near the town of San José de Gracia, located at the coordinates 29°21'N and 110°37'W, where the eocrinoid species *Ubaghsicystis* cf. *U segurae* was described by Gil-Cid and Domínguez-Alonso (2002). The Cambrian succession of Sonora, with the presence of *Ubaghsicystis*, and sponges, hyolithids, brachiopods, and trilobites, was part of the margin from the Laurentia craton during this period (Buitrón *et al.*, 2021). Regarding the composition of the biotic community, it is inferred that the environment of deposition is a shallow-water carbonate platform with well-oxygenated tropical waters, which prevailed during the Cambrian in North America. The distribution of the Cambrian biota of San José de Gracia denotes that there was a vast faunal province that comprised northern Mexico, southwestern Canada, southeastern United States of America, Greenland, northern Europe, Antarctica and northeast Australia, which were part of the Panthalassic Ocean, Figures 1, 2.

MISSISSIPPIAN ECHINODERM DIVERSITY OF SONORA

El Bisani

The Bisani area is located in the Caborca region, in northwestern Sonora (Figures 1, 2). In this locality, Early Mississippian crinoid species were identified in the Represo Formation, corresponding to *Goniocion turgidus* Moore and Jeffords, 1968; *Fluctícharax undatu* Moore and Jeffords, 1968; and *Euloncherostigma impunitum*, Moore and Jeffords, 1968; as well as the Late Mississippian species *Pentagonomischus plebeius*, Moore and Jeffords, 1968 which were described by Moore and Jeffords (1968) from the Mississippian of the USA. The colonial coral *Lithostrotionella confluens* Easton, 1958 and the conodonts *Gnathodus cuneiformis* Mehl and Thomas, 1947 and *Gnathodus typicus* Cooper, 1939, confirmed the age of the sequence. The biota was present in in tropical shallow-water carbonate platforms seas. Due to the distribution of similar species, the region is paleogeographically related to Iowa, Kentucky, and Illinois in the United States of America, belonging to the North American Craton Province (Buitrón *et al.*, 2015a).

Sierra Las Trincheras

The Sierra Las Trincheras is located in east-central Sonora, in the coordinates 29°03'35"N and 110°35'55"W (Figures 1, 2). Buitrón *et al.* (2008) cited two crinoids species collected in a partially recrystallized massive-bedded gray limestone. Among these, the species *Rhysocamax cristatus* Moore and Jeffords, 1968 that was previously reported from Iowa and Alabama, USA (Moore and Jeffords, 1968; Raymond, 2003), from Poland (Gluchowski, 1981, 2001) and from western Siberia (Dubatolova and Dubatolova, 1984), and *Gilbertocrinus aequalis* was reported from Kentucky, USA (Moore and Jeffords, 1968).

PENNSYLVANIAN ECHINODERM DIVERSITY OF SONORA

The Pennsylvanian localities in Sonora correspond to El Tule Hill, Sierra Las Mesteñas, and Sierra Agua Verde. These Upper Paleozoic outcrops represent sequences of carbonate platform thrusted by siliciclastic and carbonate ocean basin sediments (Orozco-Grajeda, 2005). Shallow-water shelf sediments correspond to continental shelf deposits of the western edge of Laurentia (North American Craton) (Poole *et al.*, 2005).

STATE	AGE	LOCALITIES	TAXA
SONORA	PENNSYLVANIAN - PERMIAN?	Sierra Los Monos	*Pentaridica rothi* *Cyclocaudex* cf. *C. jucundus* *Cyclocaudex* cf. *C. costatus* *Preptopremnum rugosum* *Heterostelechus texanus*
	PENNSYLVANIAN	Sierra Agua Verde	*Pentagonopternix insculptus* *Pentaridica simplicis* *Cyclocaudex* sp. *Mooreanteris waylandensis* *Lamprosterigma mirificum* *Cyclocrista martini* *Preptopremnum rugosum* *Preptopremnum laeve* *Heterostelechus keithi*
		Sierra Las Mesteñas	*Cyclocaudex plenus* *Cyclocaudex insaturatus* *Cylindrocauliscus fiski* *Heterostelechus keithi* *Heterostelechus jeffordsi* *Heterostelechus texanus* *Preptopremnum laeve* *Preptopremnum rugosum* *Lamprosterigma mirificum* *Cyclocrista martini*
		El Tule Hill	*Cyclocaudex insaturatus* *Cyclocaudex jucundus* *Cyclocaudex costatus* *Cyclocrista martini* *Heterostelechus keithi* *Lamprosterigma mirificum* *Lamprosterigma erathense* *Preptopremnum laeve* *Preptopremnum rugosum*
	MISSISSIPPIAN	Sierra Las Trincheras	*Rhysocamax cristata* *Gilbertocrinus aequalis*
		El Bisani	*Goniocion turgidus* *Flucticharax undatus* *Euloncherostigma impunitum* *Pentagonomischus plebeius*
	CAMBRIAN	El Sahuaral	*Ubaghsicystis* cf. *U. segurae*
		San José de Gracia	*Gogia granulosa* *Asteriacites* sp.
		Caborca	Gogid indet.
BAJA CALIFORNIA	PENNSYLVANIAN - PERMIAN?	Las Pintas	*Preptopremnum laeve*? *Heterostelechus texanus* *Mooreanteris perforatus*

Figure 2. Taxa belonging to the localities of Sonora and Baja California states.

El Tule Hill

The El Tule Hill is located in northeast Sonora, near the border to the United States of America, in the coordinates 37°17'22" to 31°18'45"N and 110°16'00" to 110°19'00"W (Figure 1, 2). In this area, sedimentary rocks are exposed and contain a biota constituted by diverse invertebrates and calcareous algae, whose age range from Lower Mississippian to Permian. In this region, Buitrón *et al.* (2004, 2006, 2008 and 2012) identified the crinoid species *Cyclocaudex insaturatus* Moore and Jeffords, 1968; *Cyclocaudex jucundus* Moore and Jeffords, 1968; *Cyclocaudex costatus* Moore and Jeffords, 1968; *Cyclocrista martini* Moore and Jeffords, 1968; *Heterostelechus keithi* Miller, 1968b; *Lamprosterigma mirificum*, Moore and Jeffords, 1968; *Lamprosterigma erathense* Moore and Jeffords, 1968; *Preptopremnum laeve* Moore and Jeffords, 1968; *Preptopremnum rugosum* Moore and Jeffords, 1968. The species have also been reported from Ohio, Texas, and Kansas, USA (Moore and Jeffords 1968) and from the Carboniferous of Pribalkhash in Kazakhstan (Dubatolova and Dubatolova, 1984). Thanatocenosis is typical of shallow tropical seas whose species have a strong affinity to faunas of the mid-continental region in the USA and to faunas of the Eurasian-Arctic province.

Sierra Las Mesteñas

The Sierra Las Mesteñas is located in northeast Sonora, at coordinates 30°58' to 31°05'N, 109°45' to 108°52'W (Figures 1, 2). In the northeastern portion of the Sierra Las Mesteñas, marine sediments assigned to the Naco Formation are exposed. Buitrón *et al.* (2004,

STATE	AGE	LOCALITIES	TAXA
COAHUILA	MIDDLE PERMIAN	Sierra de las Delicias Las Difuntas	*Pentagonopternix coahuilensis* *Cyclocaudex typicus* *Cyclocaudex insaturatus* *Cyclocaudex* cf. *C. insaturatus* *Cyclocaudex* sp. *Floricyclus diminuta* *Floricyclus* sp. *Preptopremnum rugosum* *Preptopremnum laeve* *Preptopremnum* sp. *Heterostelechus keithi* *Cyclocaudiculus regularis* *Epicrinus torreonense*
	LOWER PERMIAN	Sierra de las Delicias Las Sardinas	*Cyclocaudex typicus* *Cyclocaudex* sp. *Preptopremnum laeve* *Epicrinus torreonense*
CHIHUAHUA	PENNSYLVANIAN - PERMIAN?	Placer de Guadalupe Sierra Plomosa	*Preptopremnum* sp. *Heterostelechus* sp.
TAMAULIPAS	PENNSYLVANIAN	Cañón La Peregrina	*Cyclocaudex costatus* *Cyclocaudex jucundus* *Cylindrocauliscus fiski*
HIDALGO		Pemuxco - Calnali	*Cylindrocauliscus fiski* *Baryschir anosus* *Cyclocaudex jucundus* *Cyclocaudex plenus* *Plummeranteris* cf. *P. sansaba*
PUEBLA		San Salvador Patlanoaya	*Stiberotaurus aestimatus* *Ampholenium apolegma* *Cyclostelechus turritus* *Lomalegnum hormidium* *Pentagonomischus plebeius*
GUERRERO		Olinalá	*Pentaridica pentagonalis* *Cyclocaudex costatus* *Cyclocaudex jucundus* *Preptopremnum rugosum*
OAXACA		Nochixtlán - Ixtaltepec	*Cylindrocauliscus fiski* *Cyclocaudex insaturatus* *Axilinucrinus angustus* *Floricyclus welleri* *Pentagonomischus* cf. *P. plebeius* *Cyclocion distinctus*
CHIAPAS		La Concordia - Chicomosuelo	*Cylindrocauliscus fiski* *Lamprosterigma mirificum*

Figure 3. Taxa belonging to the localities of Coahuila, Chihuahua, Tamaulipas, Hidalgo, Puebla, Guerrero, Oaxaca, and Chiapas states.

2008) documented the crinoid species *Cyclocaudex plenus* Moore and Jeffords, 1968*; Cyclocaudex insaturatus; Cylindrocauliscus fiski* Moore and Jeffords, 1968; *Heterostelechus keithi* Miller, 1968b*; Heterostelechus jeffordsi Miller 1968a; Heterostelechus texanus* Moore and Jeffords, 1968; *Preptopremnum laeve; Preptopremnum rugosum; Lamprosterigma mirificum and Cyclocrista martini* from the Pennsylvanian (Villanueva-Olea *et al.*, 2016).

Sierra Agua Verde

The Sierra Agua Verde is located 110 km to the northeast of Hermosillo (Figures 1, 2). In this area, a 294 m thick sequences of limestone and shale assigned to the La Joya Formation is exposed. The unit contains colonial corals of the genus *Syringopora* Goldfuss, 1826 and numerous plates and columnar fragments of crinoids of the genera: *Pentaridica* Moore and Jeffords, 1968; *Pentagonopternix* Moore and Jeffords, 1968; *Cyclocaudex* Moore and Jeffords, 1968; *Mooreanteris* Miller 1968c; *Lamprosterigma* Moore and Jeffords, 1968; *Cyclocrista*, Moore and Jeffords, 1968; *Preptopremnum* Moore and Jeffords, 1968; and *Cycloscapus* Moore and Jeffords, 1968 (Figure 4). Also, the unit contains fragments of gastropods and bryozoans. The thanatocenosis is typical of benthos in shallow tropical seas. The analysis of the distribution of the species allowed to establish paleogeographic relationships with elements of the Carboniferous biota of Texas and Kansas in the USA, belonging to the North American Craton province, (Ochoa-

Camarillo and Sosa-León, 1993; Buitrón *et al.*, 2005a, 2005b, 2007a, 2015b; Gómez-Espinosa and Buitrón, 2017; Jiménez *et al.*, 2018; Villanueva-Olea *et al.*, 2019).

PENNSYLVANIAN-PERMIAN? ECHINODERM DIVERSITY OF SONORA

Caborca-Los Monos

Los Monos Hill is located in the Caborca region in northeast Sonora (Figures 1, 2). The Monos Formation comprises more than 600 m of siltstone and sandstone that alternate with fossiliferous limestone (Cooper *et al.*, 1953), which middle part contains a diverse biota, represented by fusulinids, corals, bryozoans, brachiopods, gastropods, ammonites, and crinoids. The crinoid species in the area are *Pentaridica rothi* Moore and Jeffords, 1968; *Cyclocaudex* cf. *Cyclocaudex jucundus* Moore and Jeffords, 1968; *Cyclocaudex* cf. *Cyclocaudex costatus* Moore and Jeffords, 1968; *Preptopremnum rugosum*, and *Heterostelechus texanus*, which were previously described by Moore and Jeffords (1968) from the late Pennsylvania and Permian of Texas, USA. Some fusulinids from the Permian of Sonora are characteristic of the North American craton (Midcontinent, Glass Mountains), specifically with exotic lands of the faunal region of the North American Cordillera and related to the faunas of the Eurasian-Arctic provinces, (Buitrón *et al.*, 2004; 2007b; Vachard *et al.*, 2000b).

PERMIAN ECHINODERM DIVERSITY OF CHIHUAHUA

Placer de Guadalupe-Sierra Plomosas

In the east-central region of Chihuahua, Paleozoic rocks are exposed at Placer de Guadalupe and Sierra Plomosas-Monillas areas (Figures 1, 3). Marine and continental sedimentary rocks are exposed in the Placer de Guadalupe area (Bridges, 1965; Barboza-Gudiño *et al.*, 2016). The Plomosa Formation consists of sandstone and siltstone, containing crinoid plates of *Preptopremnum* Moore and Jeffords, 1968 and *Heterostelechus* Moore and Jeffords, 1968. The Plomosa Formation represents deposition in a marine transgression cycle deposited along the intracratonic Pedregosa Basin, which was interrupted by the first pulsations of the Appalachian Orogeny, originated by the collision of Laurentia with Gondwana during the late Permian to Middle Jurassic (Escamilla-Herrera *et al.*, 1991).

PENNSYLVANIAN ECHINODERM DIVERSITY OF TAMAULIPAS

La Peregrina canyon

The La Peregrina canyon is located in the state of Tamaulipas, in the coordinates 24°23' to 24°13'N and 99°29' to 99°19'W (Figures 1, 3). The Del Monte Formation (Pennsylvanian) consists of limestone, sandstone, and shale (Carrillo-Bravo, 1961; Buitrón *et al.*, 1998). The unit contains the crinoid species *Cyclocaudex costatus*, *Cyclocaudex jucundus*, and *Cylindrocauliscus fiski*, described by Buitrón *et al.* (1998).

PENNSYLVANIAN ECHINODERM DIVERSITY OF HIDALGO

Pemuxco-Calnali

The state of Hidalgo is located in the east-central region of Mexico. The Pemuxco area is located between the coordinates 20°36' to 20°45'N and 98°27' to 98°35'W (Figures 1, 3). The Tuzancoa Formation (Pennsylvanian) contains the crinoid species *Cylindrocauliscus fiski*; *Baryschir anosus* Moore and Jeffords, 1968; *Cyclocaudex jucundus*; *Cyclocaudex plenus*; *Plummeranteris* cf. *P. sansaba* Moore and Jeffords, 1968; previously described from Iowa, Illinois, and Kentucky, USA, (Moore and Jeffords, 1968; Arellano *et al.* 1998; Buitrón *et al.*, 2008; 2017c).

PENNSYLVANIAN ECHINODERM DIVERSITY OF PUEBLA

San Salvador Patlanoaya

In southern Puebla, the Patlanoaya Formation which consists of sandstone, tuffaceous shale, siltstone, and tuffaceous sandstone is exposed, Figures 1, 3, (Velasco de León and Buitrón. 1992; Vachard *et al.*, 2000a; Buitrón *et al.*, 2008) The unit contains the Pennsylvanian

Figure 4. Encrinite from the Pennsylvanian of the Sierra Agua Verde, Sonora, showing isolated crinoid plates and articulated crinoids. Scale line = 1 cm.

crinoid species *Stiberotaurus aestimatus* Moore and Jeffords, 1968; *Ampholenium apolegma* Moore and Jeffords, 1968; *Cyclostelechus turritus* Moore and Jeffords, 1968; *Lomalegnum hormidium* Moore and Jeffords, 1968; and *Pentagonomischus plebeius* (Moore and Jeffords, 1968).

LOWER PALEOZOIC ECHINODERM DIVERSITY OF GUERRERO

Olinalá Area

Lower Paleozoic rocks outcrop in the Olinalá region of the state of Guerrero (Figures 1, 3). These rocks are assigned to the Olinalá and Cualac Formations. The Olinalá Formation consists of 550 m of shale, sandstone, conglomerate, siltstone, and limestone. The unit contains the crinoid species *Pentaridica pentagonalis* Moore and Jeffords, 1968; *Cyclocaudex costatus*; *Cyclocaudex jucundus*; and *Preptoprennum rugosum*. These species were also described from Colorado, Texas, Kansas, and Ohio USA (Flores de Dios and Buitrón, 1982; Vachard *et al.*, 1993; González-Arreola *et al.*, 1994).

PENNSYLVANIAN ECHINODERM DIVERSITY OF OAXACA

Nochixtlán-Ixtaltepec

The Ixtaltepec Formation consists of limestone, sandstone, and shale from the Lower-Middle Pennsylvanian, exposed in the Nochitlán-Ixtaltepec area (Figures 1,3). The unit contains the crinoid species *Cylindrocauliscus fiski*, and *Cyclocaudex insaturatus* (Buitrón *et al.*, 2000; 2008). Villanueva *et al.* (2011) cited the morphospecies *Axilinucrinus angustus*; *Cyclocaudex insaturatus*; and *Floricyclus welleri* Moore and Jeffords, 1968 from the Middle Mississippian of the Santiago Formation; *Axilinucrinus angustus* was reported from the Middle Mississippian of the Ixtaltepec Formation; *Pentagonomischus* cf. *P. plebeius* Moore and Jeffords, 1968 and *Cyclocion distinctus* Moore and Jeffords, 1968 from the Early-Middle Pennsylvanian of the Ixtaltepec Formation. The analysis of the distribution of crinoids from the Lower Mississippian-Middle Pennsylvanian of Oaxaca, denotes similarity with the morphospecies of the Mid-Continental region located in east-central USA, (Villanueva *et al.*, 2011).

PENNSYLVANIAN ECHINODERM DIVERSITY OF CHIAPAS

La Concordia-Chicomosuelo

The Lower Santa Rosa Formation outcrops in La Concordia and Chicomosuelo areas of Chiapas, in the coordinates 92°03'N, 15°60'W (Figures 1, 3). The unit consists of shale interbedded with fine-grained quartzite, phyllite, shale, and conglomerate in the Aguacate River. The unit contains corals, bryozoans, bivalves, ammonites, and crinoids. The crinoid species documented are *Cilindrocaulisus fiski* and *Lamprosterigma mirificum*. These species allowed to correlate localities of the Pennsylvanian of Texas, USA (Hernández-García, 1973; Buitrón 1977; Buitrón *et al.*, 2008).

PERMIAN ECHINODERM DIVERSITY OF COAHUILA

La Concordia-Chicomosuelo

In the Sierra Las Delicias (Figures 1, 3) thirteen crinoid species were described in the Las Delicias Formation, belonging to the middle Permian species *Pentagonopternix coahuilensis* Villanueva-Olea, *et al.*, 2021; *Cyclocaudex typicus* Moore and Jeffords, 1968; *Cyclocaudex insaturatus*, *Cyclocaudex* cf. *C. insaturatus* Moore and Jeffords, 1968; *Cyclocaudex* sp., *Floricyclus diminuta* Villanueva-Olea *et al.*, 2021; *Floricyclus* sp., *Preptopremnum rugosum*, *Preptopremnum laeve*, *Preptopremnum* sp., *Heterostelechus keithi*, *Cyclocaudiculus regularis* Moore and Jeffords, 1968; *Epicrinus torreonense* Villanueva-Olea *et al.*, 2021. As well as the lower Permian species *Cyclocaudex typicus*, *Cyclocaudex* sp., *Preptopremnum laeve*, and *Epicrinus torreonense* (Villanueva-Olea *et al.*, 2021).

DISCUSSIONS

Crinoids were very abundant in the Paleozoic seas of the world; they evolved rapidly in such a way that the teak and the articular plates of the column are used as age indicators for the rocks that contain them (Stukalina, 1967, 1988; Moore and Jeffords, 1968).

At the beginning of the Cambrian period, the seas were populated by an abundant and diverse biota, which included representatives of most of the current invertebrate groups. Among the main phyla that began in the Cambrian are the Porifera, Brachiopoda, Mollusca, Arthropoda, and Echinodermata, which continued to evolve through time and thus, to be of great stratigraphic value.

During the early Paleozoic, diverse taxa of invertebrates constituted the biotic community of San José de Gracia, such as sponges, brachiopods, arthropods and echinoderms. They lived in marine environments such as in shallow, tropical, well-oxygenated waters on carbonate platforms with normal salinity, and with abundant nutrients that led to a great diversity and early evolution.

The distribution of the Cambrian biota of San José de Gracia denotes a wide faunal province that was a part of the Quay Ocean, that includes several localities in Mexico (Caborca, and Ures) and the United States of America (Idaho, Utah, and California), Europe (Italy), Asia (India, and Pakistan) and Tasmania.

Analysis of the Mississippian-Permian biota indicates that the cosmopolitan distribution of the fauna studied is due to the connections between the seas of western North America and eastern Asia (Figure 5). The benthic fauna of the Late Permian of Sonora was widely dispersed in the Tethyan sea, which stretched from western North America to North Africa and Asia. (Buitrón *et al.*, 2004, 2008).

The outcrops containing Paleozoic rocks in Mexico are found in the states of Sonora (Arivechi, Bisani, El Tule, Sierra Agua Verde, La Proveedora, Las Norias, Placeritos, Pozo Nuevo, and San José de Gracia), Chihuahua (Placer de Guadalupe), Tamaulipas (La Peregrina Canyon) located in the northern region of the country; while in the central-south zone they are exposed in the states of Hidalgo (Calnali), Puebla (San Salvador Patlanoaya), Guerrero (Olinalá), Oaxaca (Nochistlán-Ixtaltepec) and Chiapas (La Concordia, Chicomuselo and Aguacate River).

The Paleozoic rocks of Sonora are carbonate rocks deposited in a shallow-water marine environment. These rocks have an age between 541 and 251 Ma, approximately. They contain a varied and diverse biota constituted of phylloid algae, foraminifera (fusulinids), coralline sponges, corals, bryozoans, brachiopods, and crinoids, and numerous species of the genera *Cyclocaudex*, *Cyclocrista*, *Heterostelechus*, *Lamprosterigma, Mooreanteris*, *Pentagonopternix*, *Preptopremium*, *Cycloscaspus*, and *Pentaridica*.

A comprehensive study of Paleozoic marine rock sequences and their biotic content will allow to understand faunal migrations regarding the carbonate facies of the Paleozoic sequences. This knowledge will also contribute to better understand the geographical, climatological, and ecological characteristics of the Paleozoic of Mexico.

Figure 5. Possible paleogeographic location during Pennsylvanian of the sequences included in this study. 1: Las Pintas, 2: Caborca, 3: El Chihuarruita, 4: El Sahuaral, 5: Arivechi, 6: Bizani, 7: El Tule, 8: Las Mesteñas, 9: Agua Verde, 10: Placer de Guadalupe, 11: Plomosas, 12: Sierra de Las Delicias, 13: Cañón de Peregrina, 14: Calnali, 15: San Salvador Patlanoaya, 16: Olinalá, 17: Nochixtlán-Ixtaltepec, 18: Paso Hondo, 19: Chicomuselo. Paleogeographic map modified after ©2013 Colorado Plateau Geosystems, Inc.

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