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ORIGINAL PAPER

Lower Ordovician microfacies and microfossils from Cerro San Pedro (San Pedro de la Cueva, Sonora, Mexico), as a westernmost outcrop of the newly defined *Nuia* Province

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Abstract The lowermost carbonate beds of the Cerro San Pedro (San Pedro de la Cueva, Sonora State, Mexico) previously assigned to the Mississippian, belong in fact to the lower Ordovician. The limestone of this succession is often dolomitized and chertified, and displays gastropods, pelmatozoans, sponges, and trilobites as major bioclastic components. The different microfacies show that high-energy grainstones, proximal tempestites, and distal tempestites dominated the sedimentation. The paleoenvironments of deposition correspond to an inner ramp, a mid-ramp, and perhaps the upper part of an outer ramp. The strata are characterized by the incertae sedis cyanobacteria *Nuia sibirica*. A taxonomic revision and discussion of these cyanobacteria, often confused with ooidic grains, is emphasized. Some data are presented on other microfossils, such as primitive, monothalamous foraminifers: *Rauserina* sp., *Vicinesphaera* sp., and *Neoarchaesphaera* sp., leperditicopida and their endolithic microperforations, and primitive chaetetids. Compared to the contemporaneous deposits of the USA, some paleobiological components, e.g., the lithistid siliceous sponges *Archaeoscyphia*, stromatoporoids? *Pulchrilamina*, and receptaculacean algae *Calathium*, are quite rare in the studied section of Sonora, but the predominance of tempestites in the carbonate succession shows that boundstones formed before were systematically eroded and resedimented. The paleogeographic implications are the following: (1) a lower Ordovician intertropical *Nuia* Province is newly defined in the western part of the lower Ordovician intertropical belt; (2) San Pedro de la Cueva constitutes one of the westernmost outcrops of this new *Nuia* Province; (3) from Sonora, *Nuia* extends eastward as far as South China; (4) due to its westernmost paleoposition, San Pedro de la Cueva was frequently affected by tropical storms; and (5) northern lower Ordovician terranes of Mexico (Sonora, Chihuahua, and Baja California) are entirely distinct from the southern ones (Oaxaca). The paleopositions and paleogeographic connections of these northern Mexican terranes with Laurentia, Avalonia, and peri-Gondwanan parts of South America, through the Iapetus and Rheic oceans, still remain disputable or unknown.

Keywords Lower Ordovician · Carbonate tempestites · *Nuia* Province · San Pedro de la Cueva · Sonora · Mexico

Introduction

The geological record in Sonora State (Mexico) comprises a several-thousand-meters-thick Paleozoic series, which our team has investigated for a long time from both the biostratigraphic and paleoenvironmental points of view (Vachard et al. 2000a, b, c; El Albani et al. 2005; Derycke-Khatir et al. 2005; Palafox 2011; Buitrón-Sánchez et al.

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2012; Palafox et al. 2013). We have concluded that during the late Paleozoic, and especially during the Carboniferous (Vachard et al. 2000b, c; Gómez-Espinosa et al. 2008), the future area of Mexico was composed of terranes dispersed in the Rheic Ocean. The closing of this ocean amalgated these Precambrian and Paleozoic terranes from various origins, to constitute the basement of Mexico (Nance et al. 2010). Another part of this basement, in northern Mexico, is composed of the southwestern extremity of the North American Craton along the northern margin of the Iapetus and Rheic Oceans. In its southern states, Mexico includes deposits of (1) the deep bottom of the Rheic Ocean under the form of a thick flysch series named the Acatlán Complex, (2) shallow siliciclastic deposits from several microplates, including the large tectonic blocks of Oaxaquia, Chortis and Maya, and (3) some outcrops generally limited to isolated hills (San Salvador Patlanoaya, Olinalá, San Juan Ixtaltepec, Los Hornos; see Vachard et al. 2000a, b, 2004) where some fragmented, shallow, carbonate shelves were present. No part of Mexico corresponds to the southern margin (i.e., the peri-Gondwanan border) of the Rheic Ocean; these latter crop out in Colombia and Venezuela (i.e., in northern South America). The oceanic history of Mexican terranes within the Iapetus Ocean, precursor of the Rheic, is less clear during the lower Paleozoic, and especially during the transition period from Iapetus to the Rheic opening. In spite of their quite poor knowledge, some preliminary studies have suggested the crucial and crustal significance of a number of terranes in Mexico (e.g., Robison and Pantoja-Alor 1968; Pantoja-Alor 1970; Buitrón and Rivera-Carranco 1984; Sour and Buitrón 1987; Keppie et al. 1996, 2003, 2007, 2008a, b; Landing et al. 2007).

The lower Ordovician carbonate series of northern Mexico, known in the states of Baja California, Sonora and Chihuahua (Fig. 1; Table 1), have been traditionally compared to the El Paso Group of Texas and Oklahoma (USA) (Fig. 1c). Due to its academic, industrial, and economic interests, the El Paso Group, named by Richardson (1904), was accurately studied in the southeastern USA (e.g., Cloud and Barnes 1948; Hayes 1972; Wilson 1975; Toomey and Nitecki 1979; Roux 1985; Taylor et al. 2004, 2012; Pearce 2012; Lucia 2012; Sternbach 2012; Gregg and Shelton 2012; Miller et al. 2012; Fritz et al. 2012) (Figs. 1c, 2). In Baja California, Sonora and Chihuahua states, i.e., the Mexican parts of the North American Craton, there are sediments that correspond to the transition from a continental ramp (with shallow-sea carbonates) to an oceanic basin (with deposits bearing graptolites and radiolaria). The Furongian (upper Cambrian) to lower Ordovician sequences of southern Mexico in Tiñu (Fig. 1a) differ completely, indicating that as early as the early Paleozoic, the paleogeography and geodynamics of

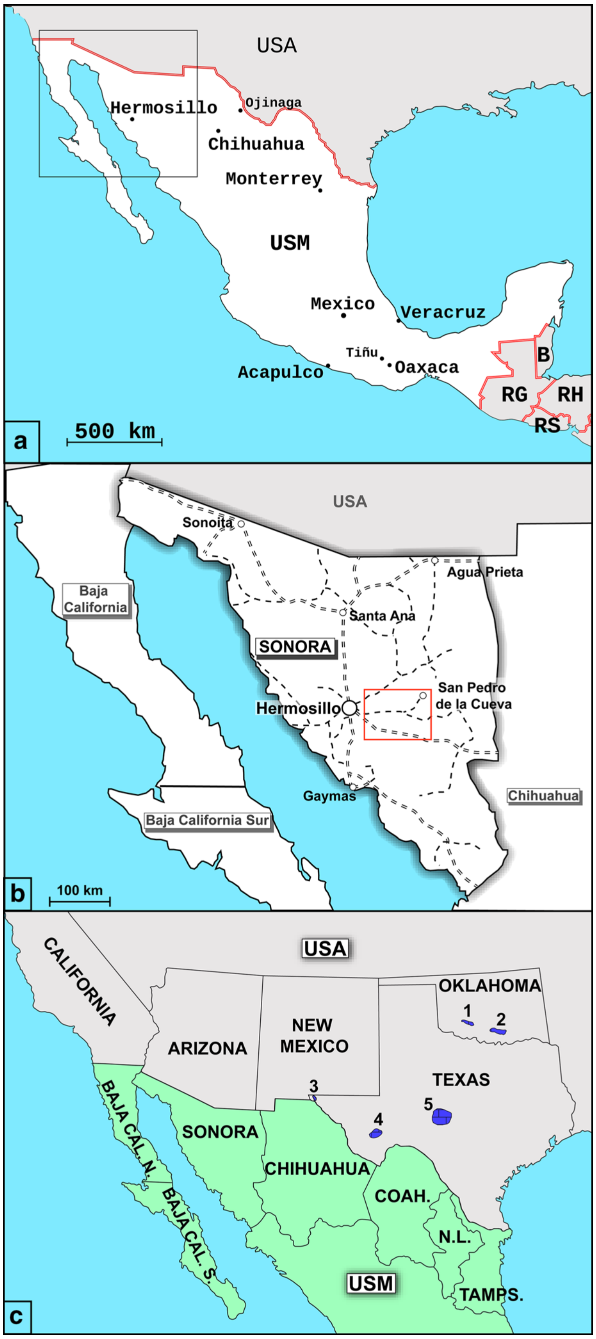


Fig. 1 Geographical maps. **a** Map of Mexico and adjacent countries. *B* Belize, *G* Republic of Guatemala, *RH* Republic of Honduras, *RS* Republic of El Salvador, *USA* United States of America, *USM* United States of Mexico. The *box* corresponds to Sonora and adjacent states. **b** Map of Sonora State in Mexico, with the main roads, main cities, and location of the studied area. The *box* corresponds to the area detailed in Fig. 3. **c** Northern states of Mexico (USM) and southern states of the USA with reference sections of the El Paso Formation (1–5) in Texas and Oklahoma (according to Toomey and Nitecki 1979, slightly modified). *Baja Cal. N.* Baja California Norte, *Baja Cal. S.* Baja California Sur, *Coah.* Coahuila, *N.L.* Nuevo León, *Tamps.* Tamaulipas, *USA* United States of America, *USM* United States of Mexico. *1* Wichita Mountains, *2* Arbuckle Mountains, *3* Franklin Mountains (i.e., the El Paso Fm stratotypic area), *4* Marathon area, *5* Llano region

Table 1 Characteristics of the Ordovician series in Sonora and other states of Mexico

State	Locality	Lithology	Thickness	Lithostratigraphy	Age	References
Sonora	Sierra López (~50 km NW of Hermosillo)	Limestone and dolostone; sandstone, siltstone, chert; intraclastic limestone	1450 m	Informal lithological units	Tremadocian (part)-Darriwilian-(hiatus) Katian	Stewart et al. (1990); Poole et al. (1995a)
	Rancho Las Norias (~40 km E of Hermosillo)	Limestone, intraclastic limestone, dolomite, and sandstone	700 m	Las Norias Formation	Tremadocian (part)-Darriwilian (part)	Vega and Araux (1987); Poole et al. (1995a); Almazan-Vazquez et al. (2006)
	Cerro Cobachi northern area (~60 km E of Hermosillo)	Limestone overlain by quartzite	330 m	Informal lithological units equivalent to Las Norias Formation	Floian (part)-Darriwilian	Vega and Araux (1987); Eguizabal-Martinez (1988); Poole et al. (1995b)
	Cerro Cobachi southern area (~60 km E of Hermosillo)	Argillite; chert	125 m	Informal lithological units (part of the Guayacan Group)	Sandbian-Katian	Peiffer-Rangin et al. (1980); Peiffer-Rangin (1987); Poole et al. (1995b)
	Barita de Sonora area (~70 km E of Hermosillo)	Mudstone, siltstone, limestone/dolostone, sandstone, intraclastic conglomerate	125 m	El Quemado Formation	Tremadocian (part)	Vega and Araux (1987); Eguizabal-Martinez (1988); Poole et al. (1995a, b)
		Argillite/shale	>100 m	El Mezquite Formation	Sandbian-Katian (part)	
		Chert	>110m	El Yaqui Formation	Katian (part)	
	Cerro Sonora (Barita de Sonora area, Sierra San Juan de Dios)	Limestone and calcareous breccia, both with *Nuia*	120 m	Cerro San Pedro Formation?	Early Ordovician?	Peiffer-Rangin (1987)
	Sierra Martinez, southern flank (~75 km E of Hermosillo)	Recrystallized dolomitic micrite, silty and sandy limestone, dolostone, some intraclastic (edgewise) conglomerate and limy siltstone overlain by quartzite	>100 m	Informal lithological units	Tremadocian (part)-Darriwilian (part)	Montijo-Gonzalez and Teran-Ortega (1988) Poole et al. (1995a)
	Sierra Agua Verde (~75 km E of Hermosillo)	Dolomitic, micrite, intraclastic conglomerate, and minor siltstone, topped by micrite, and minor cherty limestone and siltstone	900 m	Boquinete Formation	Tremadocian-Floian	Stewart et al. (1990, 1999); Ochoa-Granillo and Sosa-Leon (1993)
	Arivechi area (Sierra Chiltepin, Cerro La Sata) (~220 km E of Hermosillo)	Limestone, shale	500 m	El Santisimo Formation and lateral informal units	Tremadocian (part)-Floian (part)	Almazan-Vazquez and Fernandez-Aguirre (1987); Eguizabal-Martinez (1988); Almazan-Vazquez (1989); Poole et al (Poole et al. 1995a), Palafox (2011)

Table 1 continued

State	Locality	Lithology	Thickness	Lithostratigraphy	Age	References
Other states	Guadalupe area, Chihuahua State	Limestone, shale with chert, dolostone	>275 m	Sostenes and Solis Limestone (part) formations	Early to Late Ordovician?	Bridges (1964); Sheehan (1975); Brunner (1984); Haenggi (2001)
	Ojinaga area, Chihuahua State (Surface and subsurface data)	Limestone, shale with chert, dolostone	>10 m total thickness (unpublished)	Bliss, El Paso , Cable Canyon, Montoya formations	Early to Late Ordovician?	Reynolds (1972); Brunner (1984); Vachard and Tellez-Giron (1986)
	Baja California Norte State	Olistoliths of quartzite, limestone and chert, subordinate metaargilite and pebble conglomerate	Unknown (<250 m?)	Olistolith Rancho San Marcos Group	Floian?	Brunner (1984); Lothringer (1993)
	Oaxaca State	Dark grey to grey shales with intercalation of nodular limestone and sandstone, topped by massive sandstone	55 m	Rio Salinas Member, Tinu Formation	Tremadocian (part)	Landing et al. (2007)

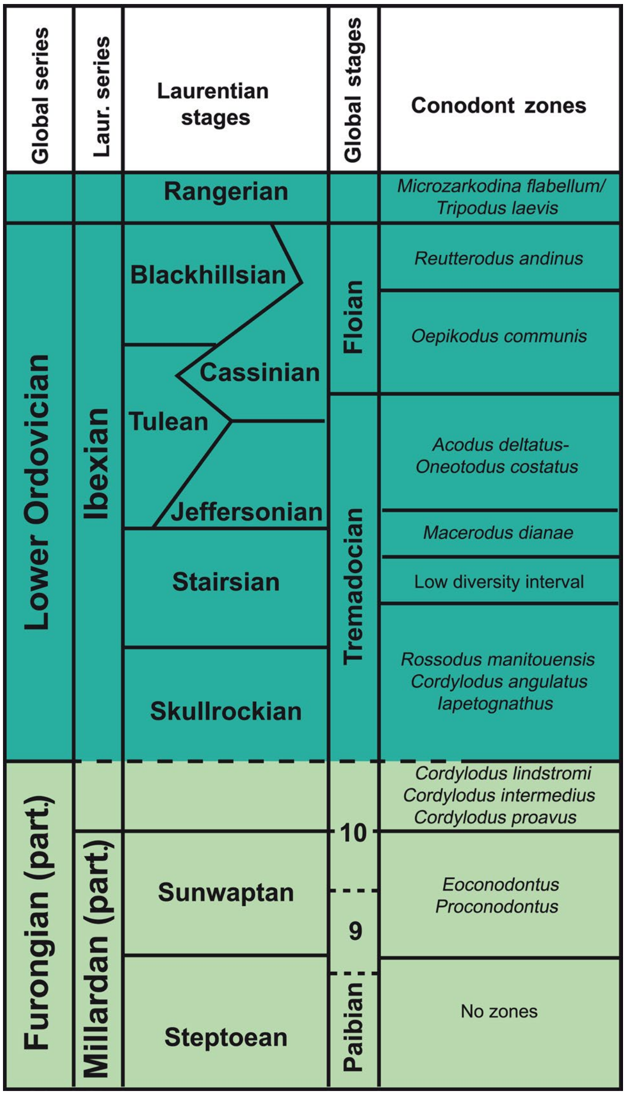


Fig. 2 Correlation scheme of uppermost Cambrian to lower Ordovician, Laurentian, and global chronostratigraphic units with conodont-based zones in North America (according to Taylor et al. 2012). The studied section, dated as lower Ordovician by *Nuia sibirica*, can be tentatively assigned to the *Macerodus dianae-Reutterodus andinus* interval (see explanations in the text)

Mexico were compartmentalized in various independent terranes.

The aims of this paper are to: (1) describe the microfacies of the poorly known Cerro San Pedro section (San Pedro de la Cueva, Sonora State, Mexico); (2) give a description of the microfaunal and algal assemblages; (3) reconstruct the depositional paleoenvironments; (4) provide new taxonomic data on the constituents discussed, especially *Nuia* and some primitive foraminifers, *Neoarchaesphaera*, *Vicinesphaera*, and *Rauserina*; (5) provide data on the lower Ordovician paleogeography of Sonora, and (6) define a tropical *Nuia* Province within the lower Ordovician Low Latitude Belt.

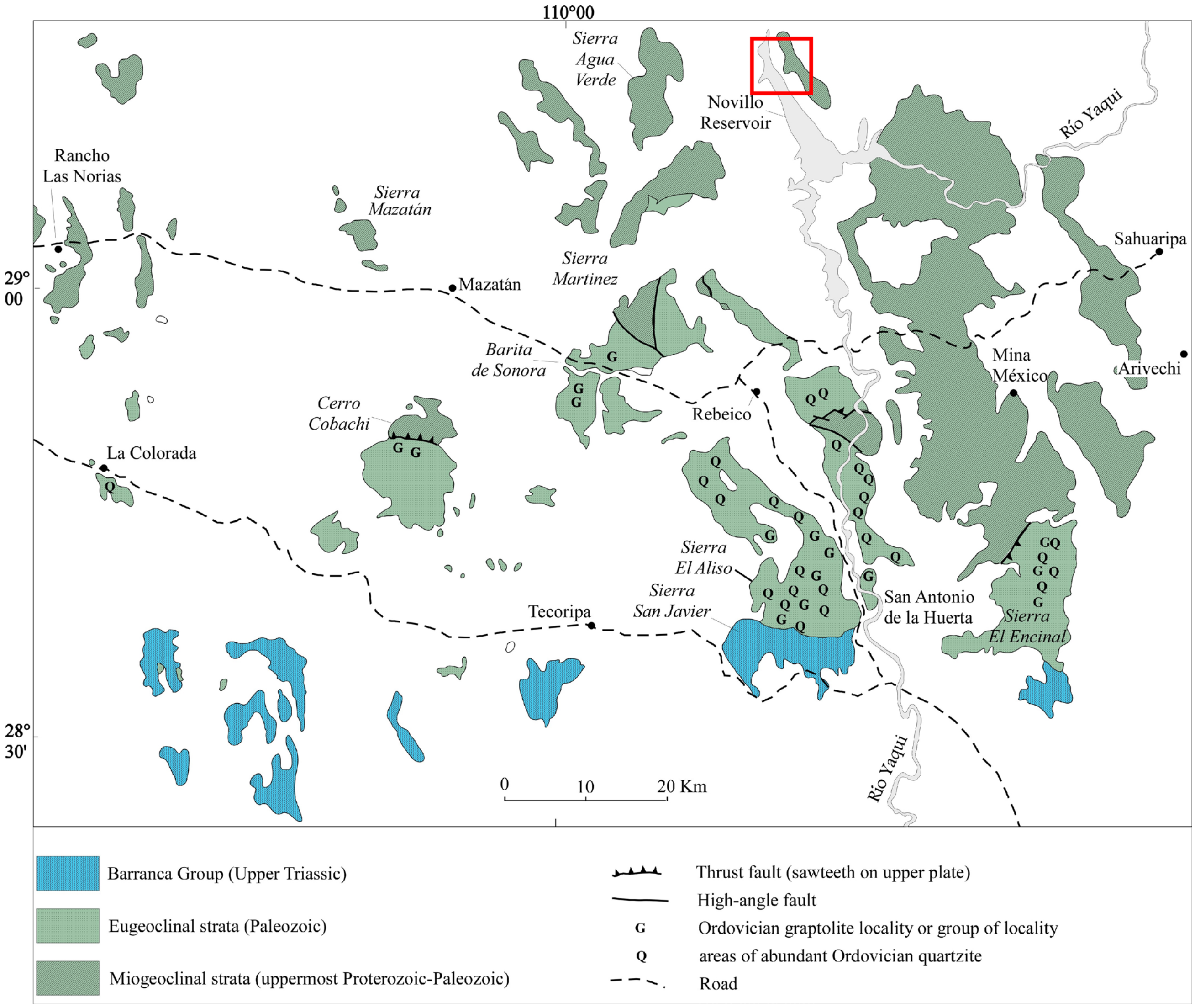


Fig. 3 Geographical map of the central part of Sonora State (Mexico) with the Paleozoic and Triassic outcrops (according to Stewart et al. 1990; slightly modified). Toponymy: *Rancho* ranch, *Cerro* hill, *Mina* mine, *Río* river, *Sierra* range. *G* Graptolites (i.e., deep oceanic deposits), *Q* quartzites (i.e., epicontinental deposits). *Boxed area* San Pedro de la Cueva area (see Fig. 4)

Ordovician successions in Sonora

The Ordovician outcrops in Sonora were mainly studied or compiled by Peiffer-Rangin (1979, 1987); Peiffer-Rangin et al. (1980), Eguizábal-Martínez (1988); Poole and Madrid (1988); Poole et al. (1995a); Stewart et al. (1990, 1999); Pérez-Ramos (1996); Page et al. (2012) and Stevens et al. (2014). They are doubtfully present in the northwestern part of the state (in the El Bisani hills; Brunner 1975, 1984; spelled Rancho Bízani by Poole et al. 1995a); relatively well known in the central part: Rancho Las Norias, Sierra San Juan de Dios, Cerro Sonora, Cerro Cobachi, Rancho La Casita, Sierra Martínez, Los Chinos, Sierra López, and the Barita de Sonora mine area (Fig. 3; Table 1), and relatively poorly known in the eastern part (Sierra Agua Verde, Cerro San Pedro, and Arivechi).

Except for a recent study in Cerro Salazar (central Sonora; Beresi et al. 2012), the lower Ordovician succession of Sonora is poorly known. This paper on the San Pedro de la Cueva area allows us to describe an equivalent of the central part of the El Paso Formation in Texas, Oklahoma, New Mexico, and Arizona (e.g., Le Mone 1969; Ethington and Clark 1964, 1971; Wilson 1975; Toomey and Nitecki 1979; Taylor et al. 2012;

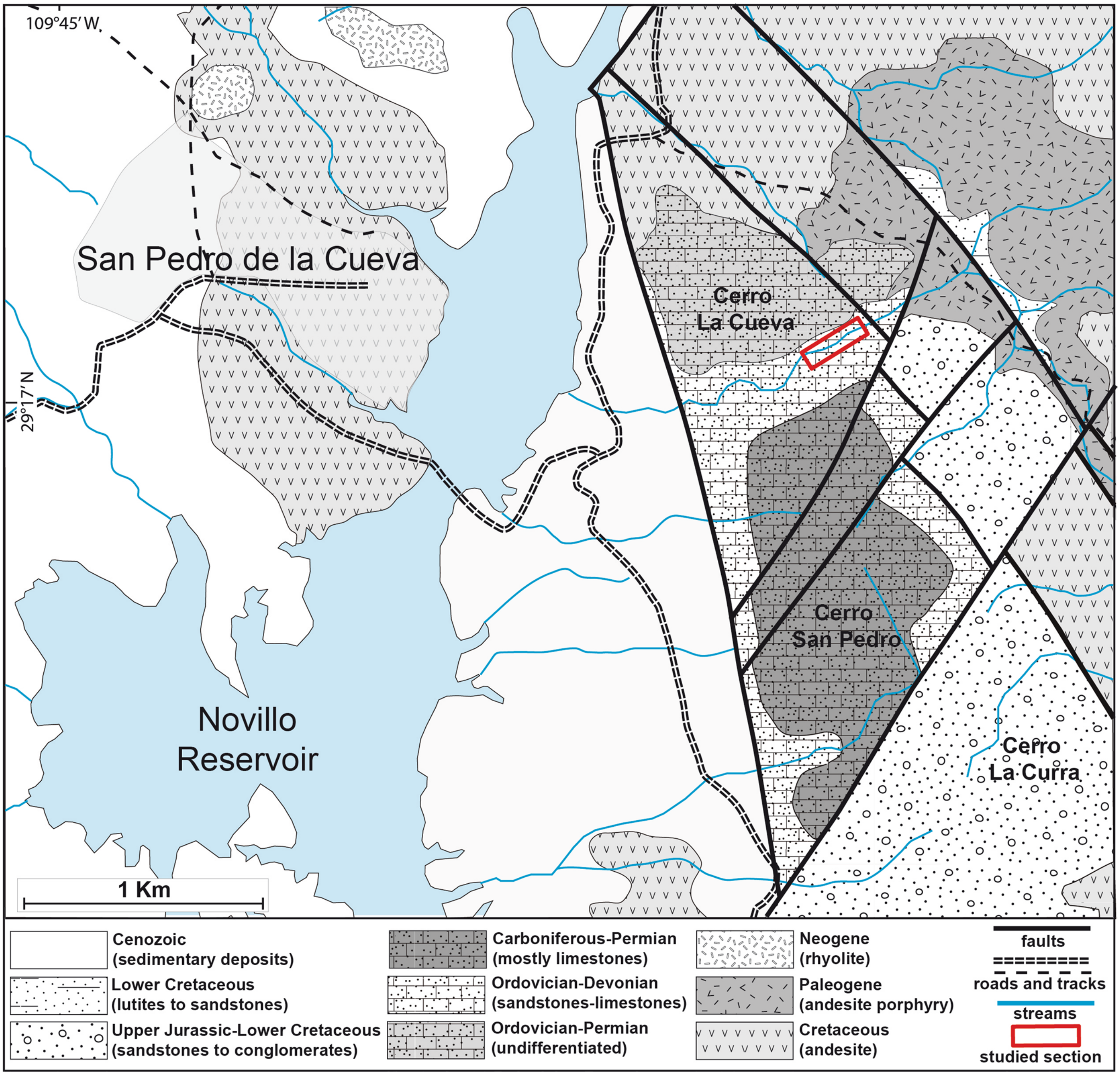


Fig. 4 Cerro San Pedro, San Pedro de la Cueva, and Novillo Reservoir. Geographical and schematic geological map (based on Garcia-Cortez and Hernandez-Morales 2010); the *red box* indicates the location of the section

Pearce 2012). Other already-known equivalents are, in the USA, the Manitou Formation in Colorado (Swett 1964; Gerhard 1972), Pogonip Group in Utah and Nevada (Wilson 1975; Carozzi 1989), and Garden City Formation in Utah (Pearce 2012). In Mexico, the El Paso Formation has also been identified in boreholes of Chihuahua State (López-Ramos 1969; Vachard and Téllez-Girón 1986; Haenggi 2001 with references therein; and this study: Table 1).

Geological setting of the studied area

The Cerro San Pedro is situated near the village of San Pedro de la Cueva (Sonora) in the northeastern border of the Novillo Reservoir (Figs. 3, 4), which impounds fresh water as far as Hermosillo, the capital of the state. It is a hill of 676 m, formed by several still poorly dated Paleozoic series (Fig. 4). Its Paleozoic sequence was initially studied by Peiffer-Rangin (1987), who assigned to it a late Tournaisian to early Viséan age. The hill was designated as Cerro El Azogue, but this name does not appear on the official maps. During a re-study of Cerro San Pedro, we were surprised to see that a part of the supposed Mississippian carbonates located at the northern edge of the hill (Peiffer-Rangin 1987, p. 52) is a lower Ordovician microfacies.

The lower Ordovician section described here is located in an arroyo (dry creek) at the foot of the Cerro San Pedro (Fig. 4). Coordinates of its base are 29°17′11″N and 109°43′41″W. The field section, oriented in a NE–SW direction with beds dipping at 48°S, shows approximately 50 m of pinkish to grayish limestone, occasionally affected by some normal faults (Fig. 5a) and/or differences of paleobathymetry (Fig. 5b). The limestone is thick-bedded (up to 2-m-thick beds), bioturbated, often wavy-bedded, chertified, or dolomitized.

Bioturbation is common in the lower part of the section (Fig. 6a, b, f), where lenses of black chert are aligned in the bedding planes (Fig. 6b, c). Obviously, the chert lenses succeeded the bioturbation (Fig. 6b). Various tempestites are recorded in this lower part of the sequence (Fig. 6c–f), whereas in the upper part of the series, biotubation, chert and tempestite are less common (Fig. 6g, h).

Compared to the lower Ordovician Boquinete Formation of the nearby Sierra Agua Verde (Ochoa-Granillo and Sosa-León 1993; Stewart et al. 1990, 1999), the studied series lithostratigraphically corresponds to Lower Carbonate Unit 2 (upper unit), dated from the upper middle Tremadocian to Floian, i.e., most probably to the *M. dianae* to *R. andinus* conodont zones (Fig. 2). Attempts at conodont extraction during this study were unsuccessful.

Microfacies and paleoenvironments

The predominant microfacies are wackestone to floatstone; they are associated with subordinate packstone and grainstone. All these microfacies contain a varied fauna, mainly composed of stenohaline forms such as gastropods, echinoderms, brachiopods, trilobites, ostracods, and siliceous sponges (Figs. 7, 8, 9, 10, 11, 12). The entire paleontological assemblage is composed of sporadic cyanobacteria *Girvanella problematica* Nicholson & Etheridge, 1878 and *Nuia sibirica* Maslov, 1954; receptaculitales *Calathium*? sp.; foraminifers *Neoarchaesphaera* sp., *Vicinesphaera* sp., and *Rauserina* sp., and various fragments of metazoans: sponges (monaxon, tetraxon, and polyaxon spicules, and entire skeletons of *Archaeoscyphia* sp.), gastropods (relatively common macluritids, bellerophontids and loxonemids), chaetetids (very rare), brachiopods (scarce), trilobites (relatively common), ostracods, leperditicopids, and echinoderms (common; mostly if not all pelmatozoans).

The microfacies and biota are characteristic of open-marine, well-oxygenated, and well-circulated conditions with normal marine salinity, deposited below the fair weather wave base (FWWB) in a deeper, open-marine shelf environment with water depths of at least some tens of meters (Wilson 1975; Flügel 2004, 2010). High-energy deposits generated by waves (grainstone) and storm (packstone to floatstone) are obvious. Silica of the chert nodules and chert bands is probably derived from numerous siliceous sponges, the presence of which is indicated by abundant sponge spicules.

Five principal types of microfacies (mf1 to mf5; Figs. 5b, 13; Table 2) were observed, which have been correlated to the standard microfacies types (SMF) and ramp microfacies (RMF) of Flügel (2004) (Table 2). First, we note that the SMF and RMF of Flügel (2004) are relatively poorly applicable to the lower Ordovician. Nevertheless: (1) due to the rarity of Flügel's microfacies SMF12 to SMF26, the innermost ramp and the intertidal and supratidal environments are almost totally absent from our material, except for an extraclast with fenestrae (Fig. 7a); (2) the different microfacies mf1A–D (Fig. 13) are located in the inner ramp, above the FWWB; under the form of bioclastic and/or micropelloidal grainstones; (3) the microfacies mf2 probably correspond to proximal tempestites because they contain predominantly photozoan bioclasts (e.g., *Nuia*, *Girvanella*, *Calathium*?), and the microfacies mf3 and mf4 probably correspond to distal tempestites because they are devoid of photozoan elements and composed of heterozoan elements (e.g., leperditicopids, gastropods, trilobites); and (4) because the deepest microfacies of Flügel (i.e., SMF1 or SMF18) are rarely observed in our material, the deposits of middle and outer ramps seem to be only represented by wackestone with monaxon spicules (microfacies mf5A), or poorly fossiliferous wackestone (mf5B).

The microfacies mf1 (Figs. 7a–d, 8a–c) are represented by various grainstones; i.e., they were deposited in agitated environments with swell, wind waves, storm waves, tidal currents and bottom currents. The shallowest environments exhibit fenestrae (only recorded as intraclasts; Fig. 7a), grainstones with ostracods (Fig. 7b), and laminites (tidalites?) with couplets of grainstone with micropellets of microbialites and grainstone with thin valves of ostracods (Fig. 7c, d), extraclastic grainstones (Fig. 7a, b), and typical bioclastic grainstones (Fig. 7c).

Under the FWWB, there are various bioclastic microfacies, but all seem to correspond to several types of tempestites. The microfacies mf2 corresponds to proximal tempestites, according to the criteria of Flügel (2004), which contain the cyanobacteria *Nuia* and *Girvanella* (Fig. 8d). As these tempestites contain photozoan bioclasts, and frequently present mixed grainstone and packstone microfacies, they probably accumulated

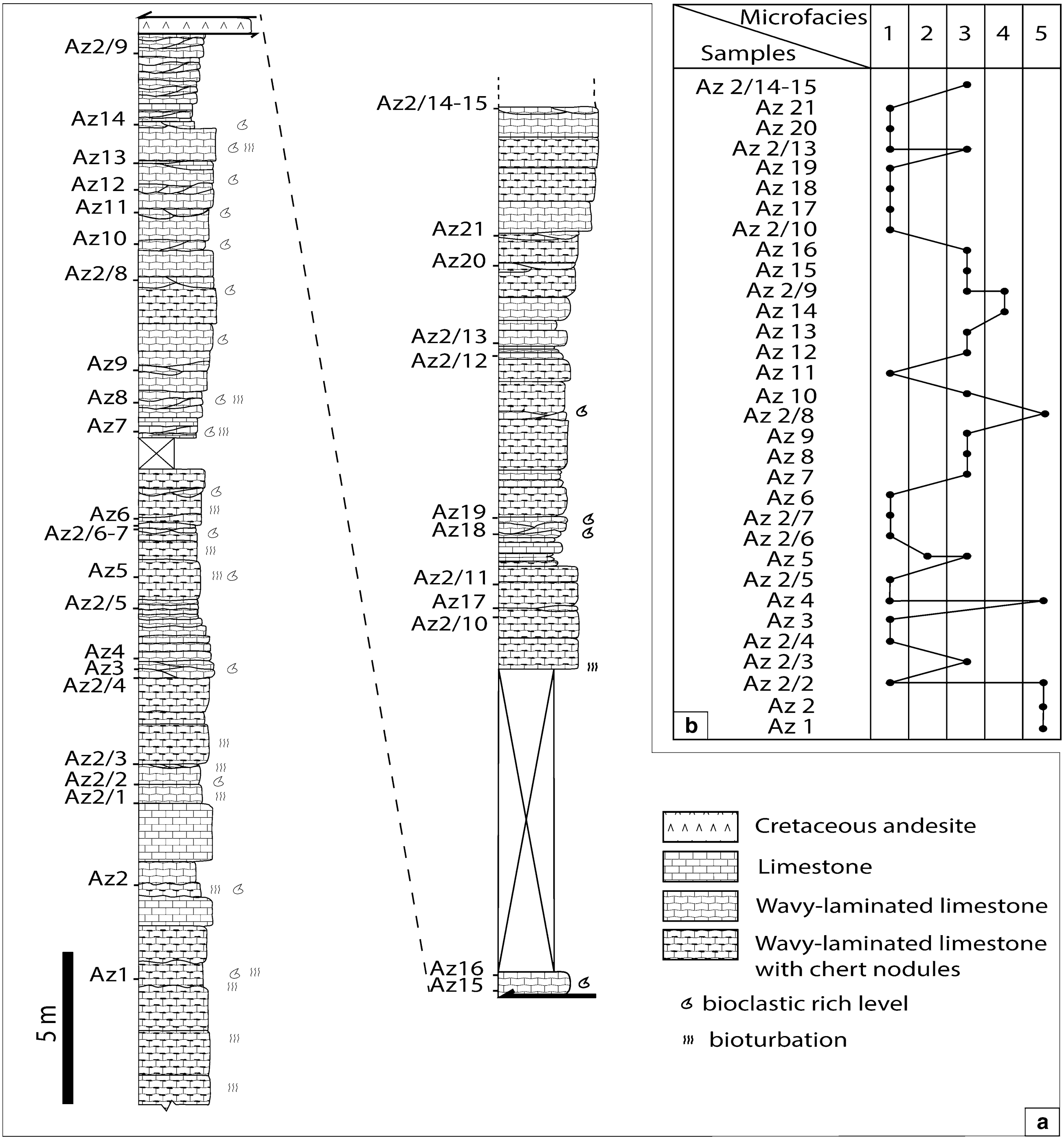


Fig. 5 Cerro San Pedro section. **a** Stratigraphical column and location of the samples (Az 1 to Az 21 and Az2.1 to Az 2/15). **b** Paleobathymetric curve according to the microfacies mf1 to mf5 (see explanations in the text, Fig. 13 and Table 2)

near the FWWB (Burchette and Wright 1992) (at a depth of approximately 10–20 m or even shallower). The paleoecology of *Nuia*, reconstructed for instance by Roux (1985), permits us to indicate that the biotopes with *Nuia* were located in shallower environments (depth 0–5 m).

The microfacies mf3 shows a heterozoan assemblage with echinoderm ossicles, ostracods, leperditicopids, gastropods and sporadic brachiopods (Figs. 10a–d, 11a–d); where pelmatozoan accumulations are relatively common, but not in the echinoderm limestones of mf4 (Fig. 12a, b). Several deposits are interpreted as tempestites because of

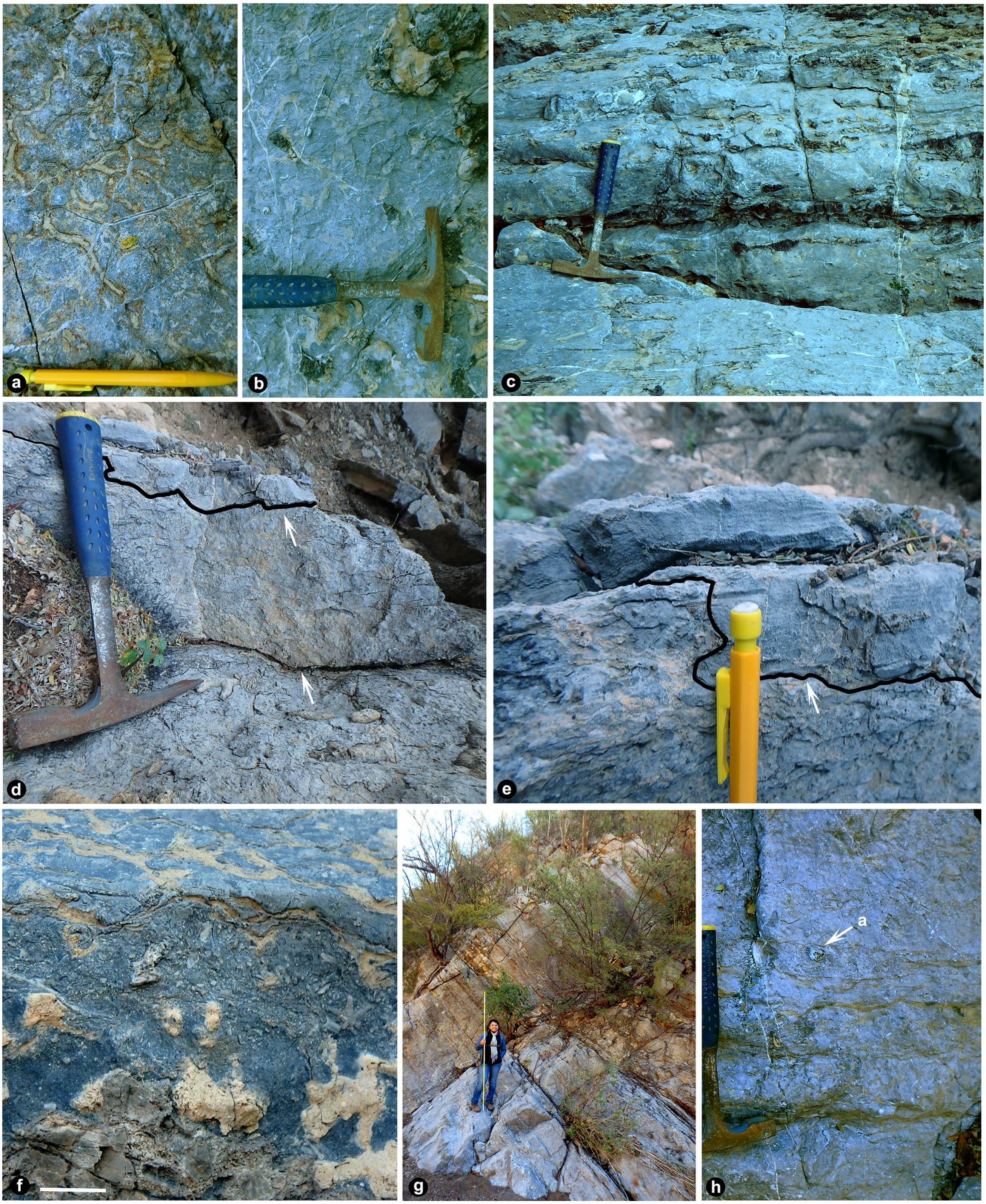


Fig. 6 Field photos. (*Scale bars*: pencil for **a**, **e** = 14 cm; hammer for **b**–**d**, **h** = 33 cm; white segment for **f** = 10 cm; measuring tape of Miss Dulce Reyes for **g** = 2 m long). **a** Numerous bioturbations; sample Az 2/1. **b** Bioturbation passing to chert; sample Az 2/4. **c** Stratified chert and a chanellized unit; sample Az2-4. **d** Erosive contact (*underlined*) between two tempestites; sample Az 2/5. **e** Tempestite passing to a laminite, with a strongly erosive contact (*underlined*); sample Az 2/7. **f** Tempestite rich in transported grains passing to an autochthonous wackestone; sample Az 2/9. **g** Upper part of the series with chert; sample Az 2/10d. **h** Uppermost part of the series without chert and with *Archaeoscyphia* (A); sample Az 2/10 g

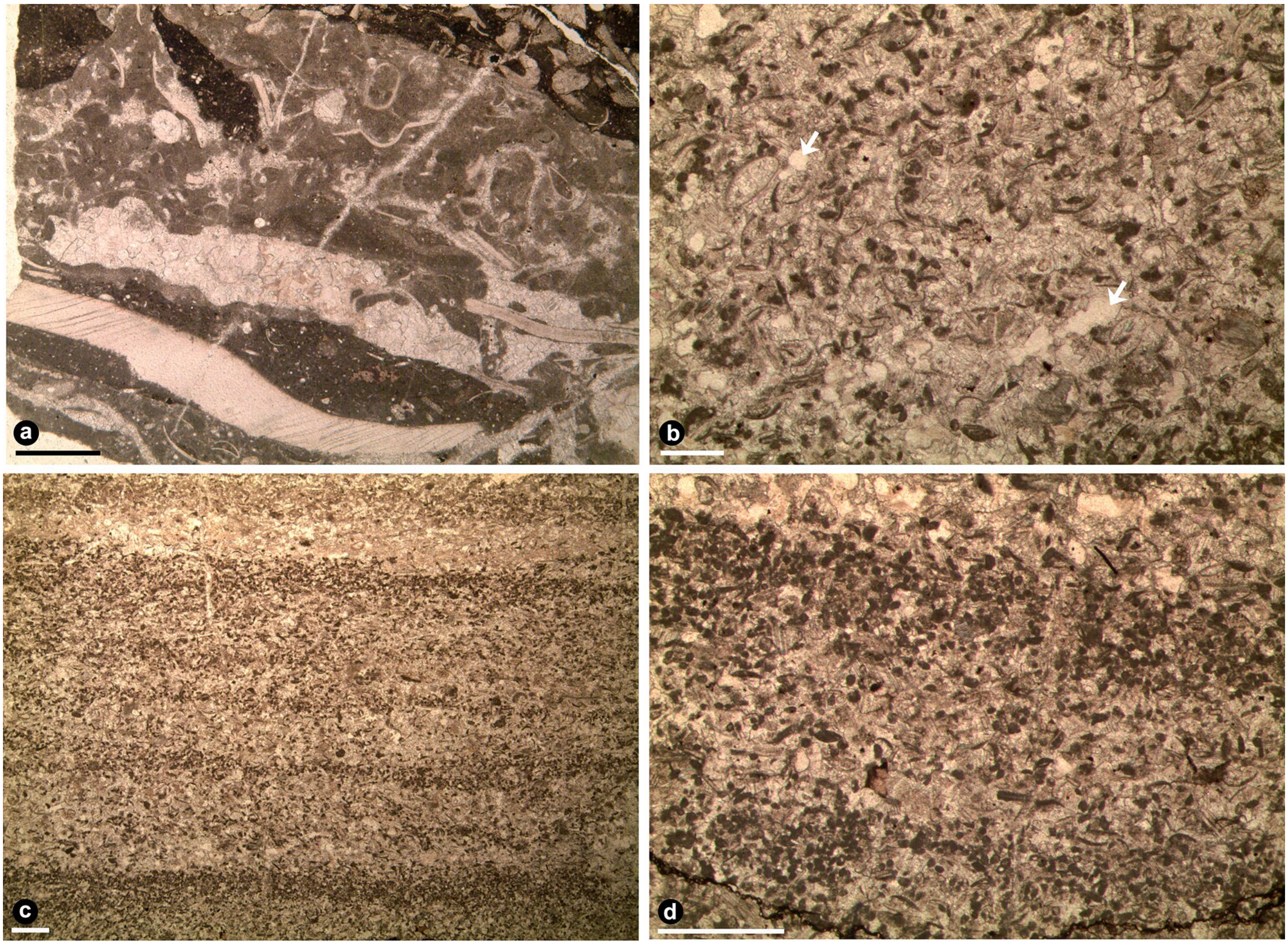


Fig. 7 mf1 microfacies (*Scale bars* 500 µm). **a** Bioclastic wackestone with fenestrae (f), as an extraclast included in a bioclastic packstone with crinoids; sample Az2-5. **b** Bioclastic grainstone with dissociated, thin valves of ostracods and rare micropellets; spots of silicification are widespread (*arrows*); sample Az2-7. **c** Planar laminated grainstone (tidalite?) with couplets of micropellets and fragments of ostracods, sample Az2-7. **d** Detail of the laminae; sample Az2-7

the abnormal concentration in bioclasts (especially, pelmatozoan ossicles) and some sedimentary features: e.g., graded bedding, bioturbation on the top of beds; erosive surfaces; mixing of packstone and grainstone (Figs. 10d, 11a–d, 12a, b); however, no hummocky stratifications were observed in the field, because the deposits consist of carbonates and not siliciclastics or mixed sediments as well as relatively atypical lower Paleozoic tempestites (Sepkoski et al. 1991). Nevertheless, hummocky beds and gutter casts are possibly present in a single microfacies (Fig. 11b). Some contacts between distinct lithologies are transitional (Fig. 11c); others are well marked (Fig. 11a, b, d); the latter are secondarily affected by pressure solution, and show stylolitic joints (Fig. 11d). Their deposits occur probably in the lower part of an inner ramp and upper part of a mid-ramp. The traditional bioconstructions with *Archaeoscyphia* of the El Paso Group were not found in situ in this study, but they contributed probably to the reworked material of a part of these tempestites (Fig. 10b), possibly located in the upper part of this paleobathymetric zone (see Wilson 1975, text-fig. IV-3 p. 99).

The microfacies mf3 and mf4 were supposedly deposited in the outer part of a mid-ramp, as far as the SWB, whereas the microfacies mf5, deposited near the SWB with wackestone with spicules (mf5A; Fig. 12c, d) and poorly fossiliferous wackestone (mf5B; Fig. 12d, e), correspond to the deepest environments of an outer mid-ramp, or was already located on an outer ramp. However, they can rapidly emerge and be reworked, (1) in agitated environments, as ellipsoidal extraclasts, which are microperforated by probable cyanobacteria (microperforations of type 1) (Fig. 8a), and (2) in tempestites, as ellipsoidal fragments of biomicrite with reworked spicules (Fig. 14d, m). Several sequence boundaries (SB) between bioclastic grainstones of mf1 and wackestones with spicules of mf5A have been observed (Fig. 9b, c). Tectonically

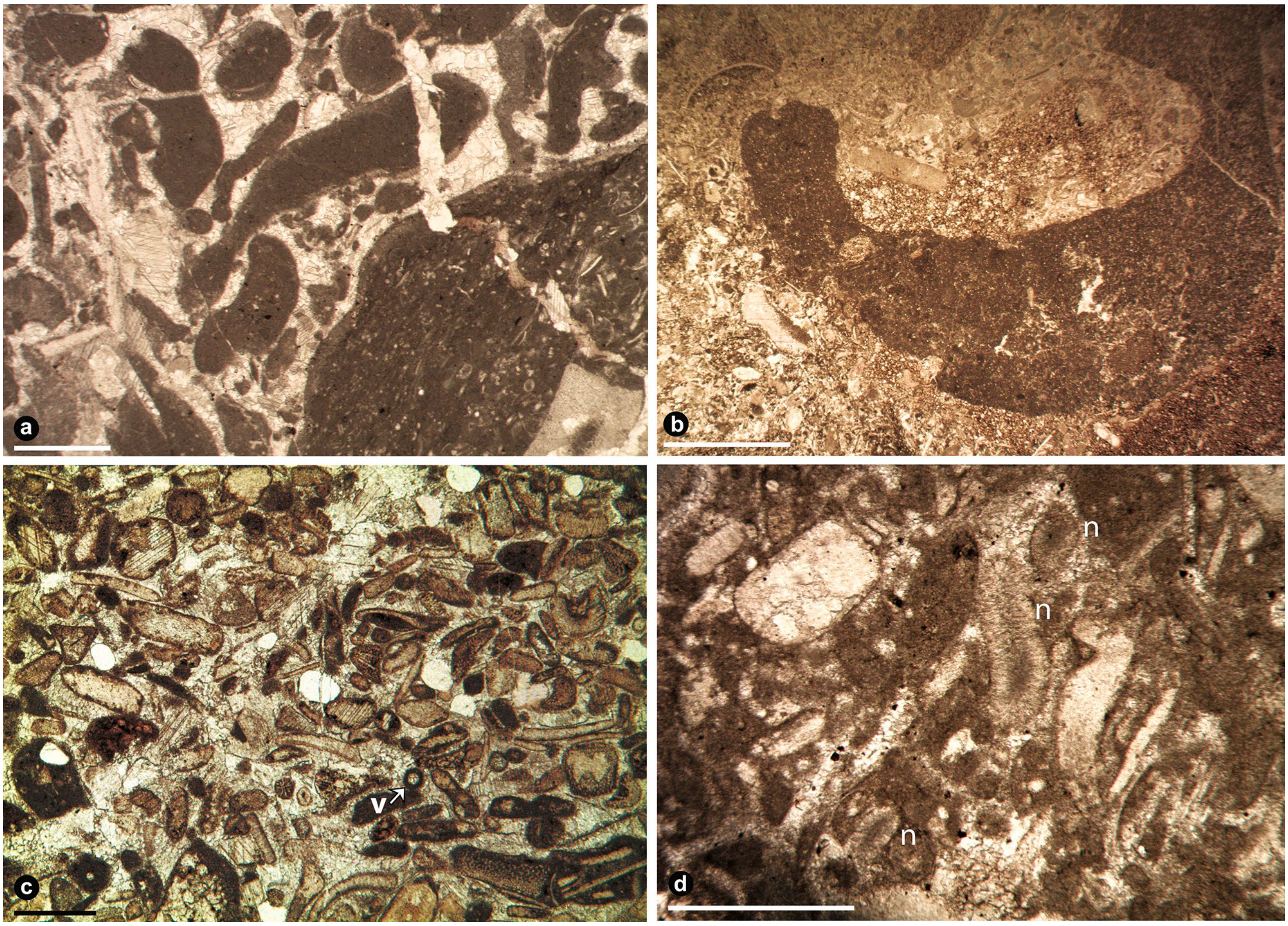


Fig. 8 mf1 and mf2 microfacies [*Scale bars* 1 mm for (**a**) 5 mm for (**b**); and 500 µm for **c**, **d**]. **a** Extraclastic grainstone where the micritic or biomicritic extraclasts are entirely surrounded by a layer generated by microperforations of type 1 (cortoid type 1 according to Flügel 2004; see Figs. 14d, 15), sample Az 3. **b** Bioclastic wackestone with a curved extraclast (chip) of microbialites (see "curled mud chips" of Wilson 1975, p. 83), sample Az 11. **c** Bioclastic and intraclastic grainstone with ostracods, echinodermal fragments, and *Vicinesphaera* (v), sample Az 2/5. **d** Bioclastic wackestone with *Nuia sibirica* (n), sample Az 6b

controlled uplift may have influenced this observed stratigraphic pattern. However, a close scrutiny of the regional stratigraphic pattern would be required in order to evaluate the tectonic influence on local to regional basin architecture.

The reconstructed paleoenvironments (Fig. 13, Table 2) are consistent with the regional paleogeographic data in central Sonora (Fig. 3), and allow to suggest that (1) the limits between the early Ordovician shallow and deep seas were located south of San Pedro, probably in Cerro Cobachi, Barita de Sonora, Sierra El Aliso, and Sierrra El Encinal, and (2) the innermost ramp and the intertidal zone are situated in the north and west of San Pedro, and could correspond to the stromatolite development known for example in the Rancho Las Norias area (Fig. 3).

Systematic paleontology

Cyanobacteria

The lower Ordovician cyanobacteria, found in the photic zone of San Pedro de la Cueva, are *Girvanella problematica* Nicholson & Etheridge, 1878, *Nuia sibirica* Maslov, 1954, and microperforations of type 1.

The tubes of *Girvanella problematica* (Fig. 14g, n) are generally numerous in a nodular thallus; they are closely packed but twisted or contorted. Their external diameter is 15–20 µm with a thin wall of 3–5 µm. Although the morphologies of the filaments of *Girvanella* are very simple and their sizes homogeneous, many species and groups of species have been proposed (Wood 1963; Perret and Vachard 1977; Mamet and Roux 1977; Héroux et al. 1977).

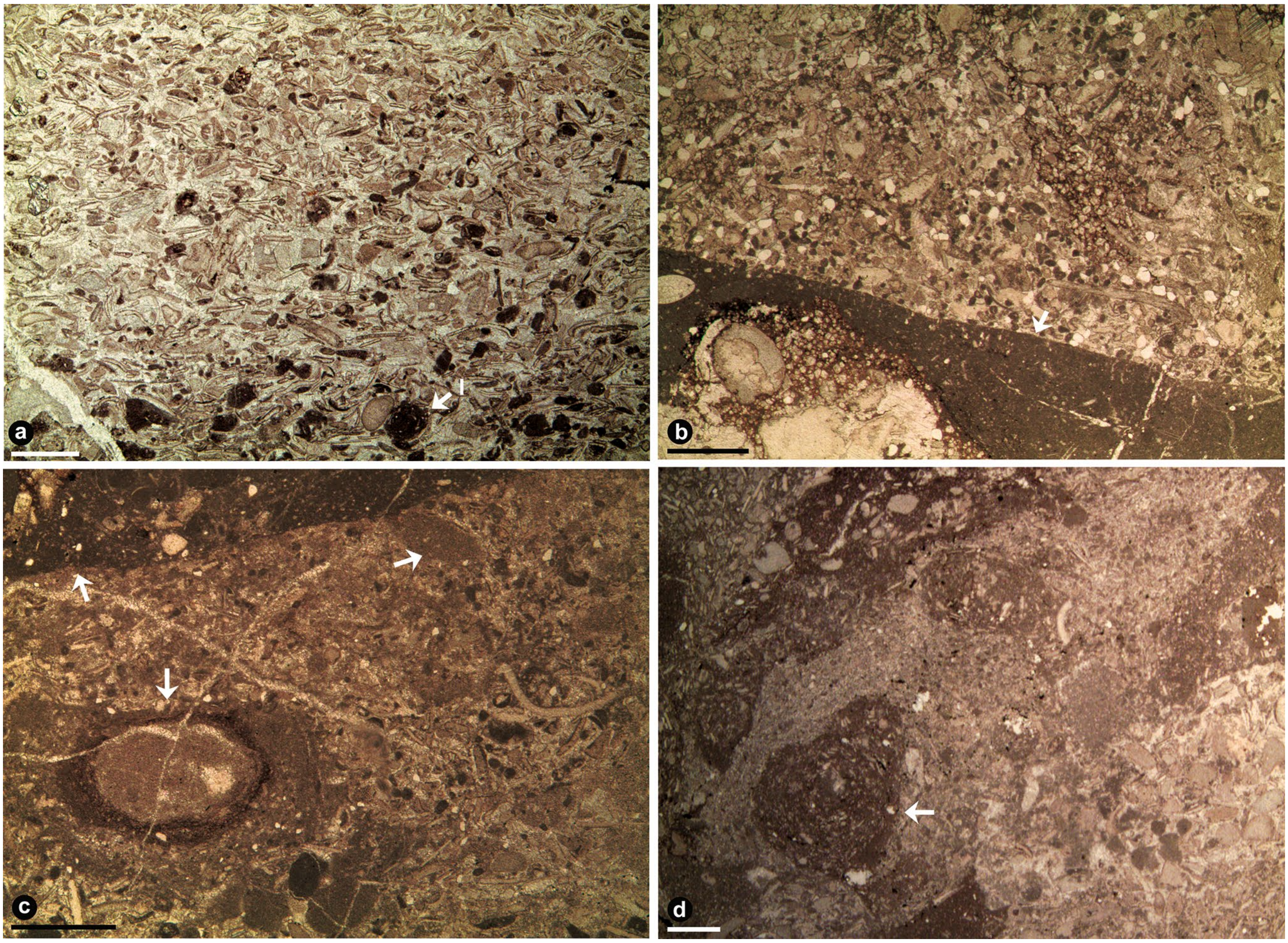


Fig. 9 mf1, mf3, and mf5 microfacies (*scale bars* 1 mm). **a** Bioclastic and intraclastic grainstone, with some small dark intraclasts widespread in the microfacies and concentrated in its lower part, sample Az2-2-1. **b** Sequence boundary (SB) between a wackestone with spicules (*bottom*) and a grainstone with pellets and quartz grains, sample Az 2/4. **c** Typical distal tempestite: bioclastic grainstone with burrows (*arrows*; see the circular swirls of skeletal debris in Flügel 2004, pl. 19, Fig. 1) passing to a bioclastic wackestone (*arrows*), sample Az 2/3. **d** Tempestite: bioclastic grainstone and bioclastic wackestone with numerous burrows (*arrow*), sample Az 2/9.1

The genus appears to have diversified into different species during the Mississippian (Tournaisian–Viséan), even when its species are under discussion (compare Perret and Vachard 1977 and Mamet and Roux 1977). In the early and middle Paleozoic, the dominant species is *Girvanella problematica*, the type species (erroneously synonymized with *G. ducii* by Mamet and Roux 1977). The range of *G. problematica* seems to be Cambrian–Devonian.

Some minute microperforations of type 1 (Figs. 8a, 14d, m, 15) are obvious around biomicritic extraclasts, which are generally sponge-spicule bearing. They are constituted of minute tubules finely distributed at their periphery, forming cortoids (see Flügel 2004). They seem similar to *Bevocastria hubbardi* Mamet & Roux, 1975 (as revised by Vachard et al. 2014) and/or the probably misinterpreted Ordovician “perforating *Girvanella*” (Klement and Toomey 1967; Riding 1975; Toomey and LeMone 1977).

Genus *Nuia* Maslov, 1954.

Type species Nuia sibirica Maslov, 1954.

Diagnosis Thallus, cylindrical to botryoid in shape, with a central, dark, cylindrical part (i.e., round in transverse section) corresponding to the emplacement of possible trichomes, and a “wall” with one layer of fine, acicular, radiate, crystals of clear calcite. So-called multilayered walls are in reality successive attached, monolayered thalli. Rare bifurcations can occur (Mamet and Roux 1982; Ross et al. 1988). Productivity can be strong to weak according to the bioaccumulations or scarce occurrences observed in microfacies.

Remarks Nuia is a taphotaxon at the sense of Lucas (2001); i.e., it is not the exact mirror of a living morphology, but a morphospecies appearing during the taphonomic process, as an early diagenetic object derived from an ontogenetic object. It is only in this sense, that the

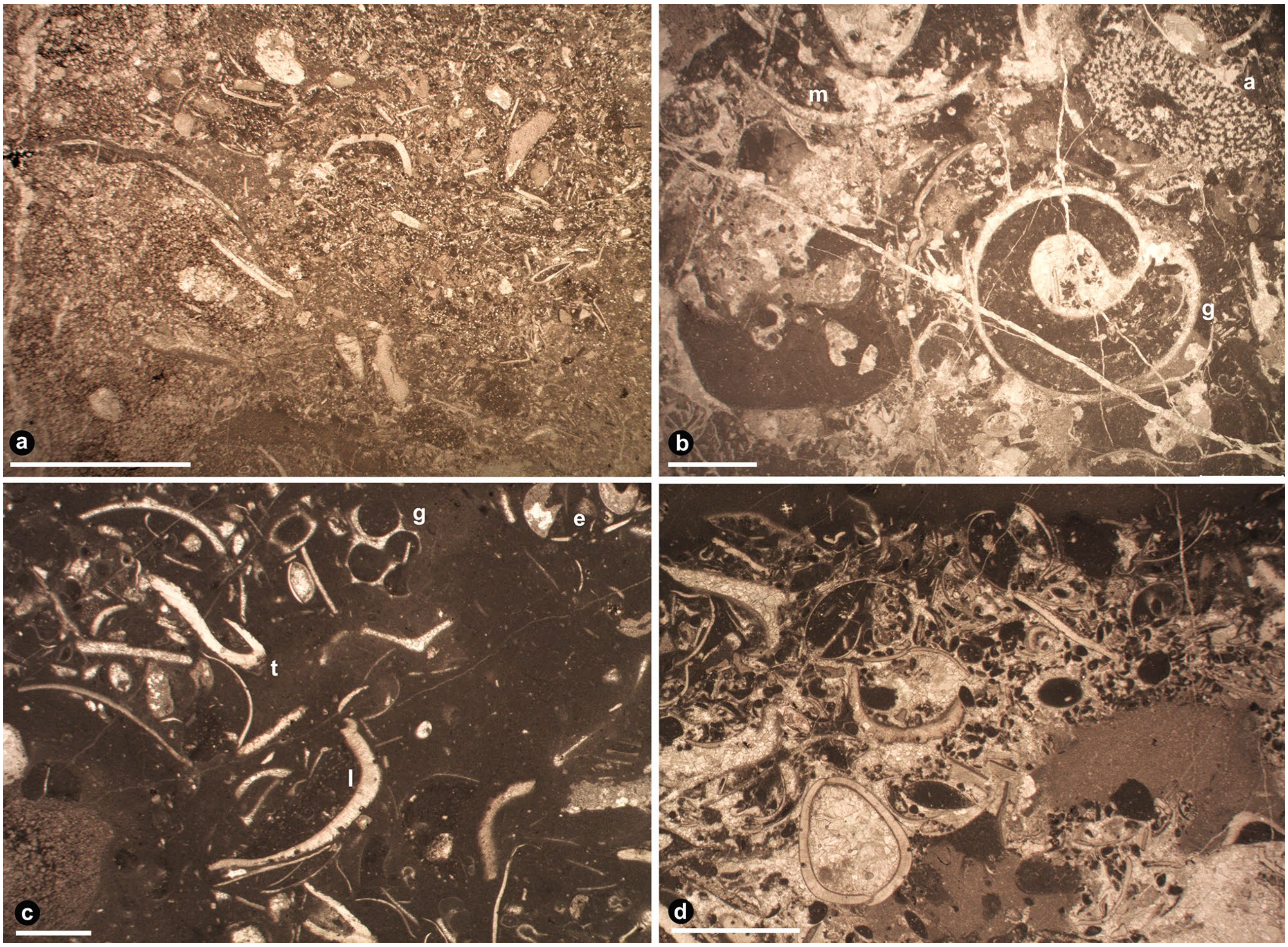


Fig. 10 mf3 microfacies (*scale bars* = 5 mm for Fig. 10a, b; 1 mm for Fig. 10c; and 2.5 mm for Fig. 10d). **a** Recrystallized, poorly bioclastic wackestone with brachiopod (*top left*) and leperditicopid (top, centre; magnified Fig. 16g), echinoderm ossicles and trilobites (*centre, right*), sample Az 12a. **b** Bioclastic wackestone with gastropods (g), other molluscs (m), and *Archaeoscyphia* (see detail Fig. 16p), sample Az 18. **c** Bioclastic wackestone with echinoderm (e), gastropod (g) and trilobite (t) remains, along with leperditicopid valves (l) with microperforations of type 2 (see Figs. 15, 18b), sample Az 8b. **d** Bioclastic grainstone (*bottom*) with a lepertidicopid showing connected valves poorly infected by microperforations of type 2 (see details Fig. 16i) passing to mudstone (*top*), sample Az 8 k

comparison of *Nuia* to *Microcodium*, ooids or microstromatolites, seems to be understandable; noting however that such interpretations are sometimes too conjectural because, for example, Paleozoic classical oolites were described as the algal genus *Bobolites* Voronova in Voronova and Radionova (1976). The observations summarized herein confirm the reconstruction sketch of *Nuia* by Vachard and Téllez-Girón (1986) as the most likely interpretation; it is re-illustrated herein (Fig. 17d). Vachard and Téllez-Girón (1986) concluded with an assignment to the cyanobacteria. Contrary to the assertion of Riding and Fan (2001); Perret and Vachard (1977) never assigned *Nuia* to the red algae. This puzzling proposal was made by Huang and Bian (1983) due to a disputable interpretation of the taphonomic transformation of the trichome mucilage. The so-called *Nuia* in the Devonian of the Urals (Shuysky 1973b) or in Belgium (Mamet and Boulvain 1992; Pratt 1995) more likely correspond to other eodiagenetic taphotaxa such as *Palaeomicrocodium* or *Tuborecta* Saltovskaya, 1981. Putative comparisons, notably with atypical, upper Cambrian ooidal grains, have also lead to misinterpretations (e.g., Ross et al. 1988, fig. 1.1–4; Spincer 1998, figs. 6.1–3, 7.1; Lothringer 1993, fig. 8).

The American outcrops with *Nuia* are well known, based on the work of Toomey and Klement (1966); Johnson (1966); Toomey (1967); Ahr (1971); Wilson (1975); Guilbault et al. (1976); Toomey and LeMone (1977); Gnoli and Serpagli (1980); Mamet and Roux (1982); Roux (1985, 1991b); Vachard and Téllez-Girón (1986); Peiffer-Rangin (1987); Ross et al. (1988); Carozzi (1989); Albertstadt and Repetski (1989); Clemons (1991); Mamet and Shalaby (1995); especially in the El Paso Group of Texas and

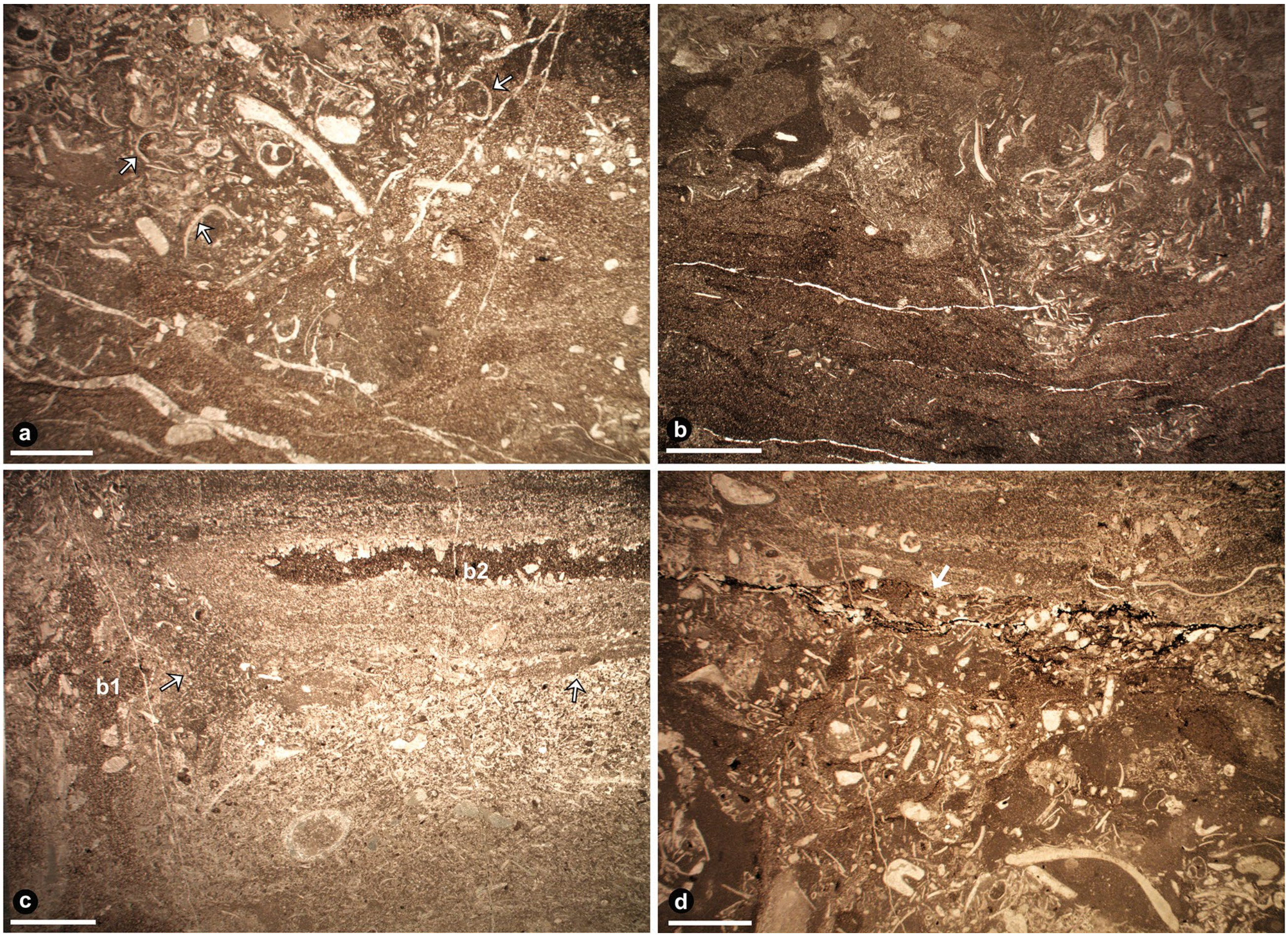


Fig. 11 mf3A and mf3B microfacies (*scale bars* 5 mm). **a** Bioclastic packstone (*left*) passing to a silty micrite (*right*), sample Az 15d. **b** Silty micrite with curved lamination (hummocky cross stratification?) passing to a bioclastic packstone/wackestone, by intermediary of a gutter-cast (?) with lag deposit, sample Az 9a. **c** Bioclastic wackestone with vertical burrow (b1) passing to a silty micrite with horizontal burrow (b2), sample Az 10a. **d** Tempestite: bioclastic wackestone overlain by a silty mudstone, sample Az 5

New Mexico (USA) and of Chihuahua (Mexico), the Hitt Canyon Formation (also called Sierrite Limestone) of the Mud Springs Mountains (New Mexico) (Karl Krainer, pers. comm., February 2015), the Pogonip Group (Nevada), the Kinblade Formation (Colorado), the Bromide Fm (Oklahoma), the Black Rock Fm (Arkansas), the subsurface rocks of Arkansas, Mississippi, Alabama and Tennessee (Alberstadt and Repetski 1989), the Saint-Lawrence Platform (New York, Vermont, U.S.A; Québec, Canada), the Sarbach beds of southern Alberta (Canada), and the San Juan Cordillera (Argentina). Additionally, *Nuia* was mentioned in Kazakhstan, Siberia, Tarim in NW China, Jiangsu and Guizhou in South China, as well as in Antarctica (Flügel 2004). By contrast, the *Nuia* mentioned in other areas have neither been illustrated nor confirmed (e.g., middle Ordovician of Scotland only mentioned but not illustrated by Ince 1984, p. 230) or obviously belong to other taxa (e.g., late Cambrian of Newfoundland in Conoglio and James (1985) or central Texas (Spincer 1998)). Consequently, they are excluded by us from the genus *Nuia*. It is noteworthy that such false *Nuia* are generally late Cambrian (Conoglio and James 1985; Ross et al. 1988; Spincer 1998), Ordovician sensu lato (Lothringer 1993), or middle Ordovician (Ince 1984; Pratt 1995) in age. As mentioned by Ross et al. (1988), no middle Ordovician *Nuia* was found in Kazakhstan by Gnilovskaya (1972) in her accurate study of the algae of this area. This confirms that *Nuia* sensu stricto is only early Ordovician in age.

Occurrence Eastern Siberia (Angara, Nyuya, Zherba, Biryuk and Lena rivers) (e.g., Maslov 1954, 1956, 1973; Reitlinger 1959; Dubatolov et al. 1985); Canada (Québec); U.S.A. (Nevada, Texas, New Mexico, Oklahoma, Utah, Colorado, Arkansas, New York, Vermont; Roux 1985 and additional references); Mexico (Chihuahua and Sonora: Vachard and Téllez-Girón 1986; Peiffer-Rangin 1987; Eguizábal-Martínez 1988); Argentina (Gnoli and Serpagli

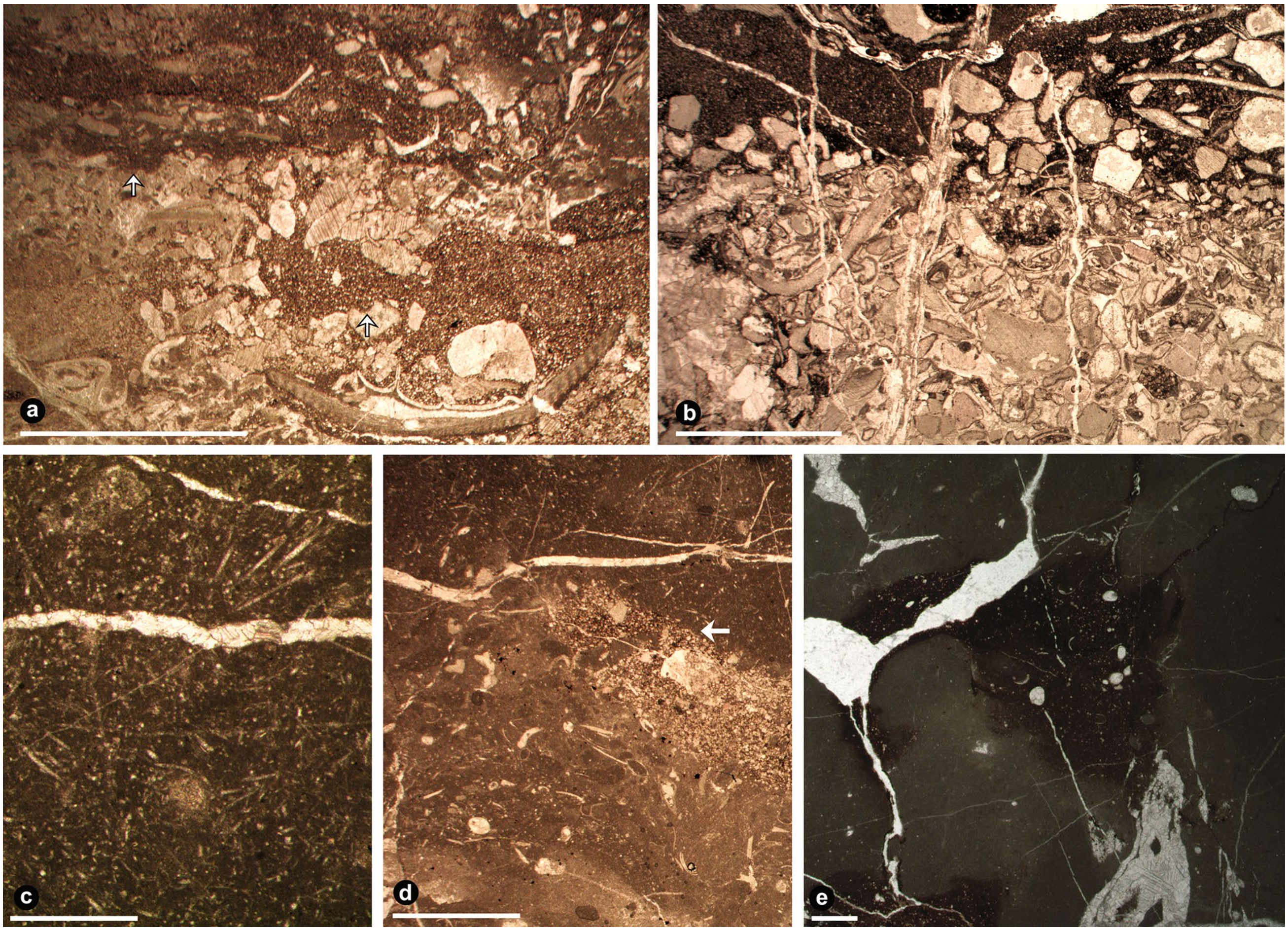


Fig. 12 mf4 and mf5A-B microfacies (*scale bars* = 5 mm for Fig. 12a, b; 1 mm for Fig. 12c; and 2.5 mm for Fig. 12d; and 500 µm for Fig. 12e). **a** Tempestite: bioclastic packstone (*bottom*) with irregular surface (*arrow*) passing to a silty mudstone (*top*), sample Az 16b. **b** Echinoderm grainstone (*bottom*) passing to an echinoderm wackestone and a silty mudstone (*top*), sample Az 21. **c** Wackestone with abundant monaxon sponge spicules, sample Az 2-/2b. **d** A poorly bioclastic wackestone overlain by a wackestone with spicules, sample Az 2c. **e** Wackestone poor in bioclasts (ostracod-rich dark areas probably represent bioturbation), sample Az 2/8

1980; Keller 1999, 2012; Astini 2001); Kazakhstan (Chu-Illi Mountains; Reitlinger 1959); China: Tarim (Riding and Fan 2001), Jiangsu (Huang and Bian 1983), Guizhou (Li et al. 2014), and Hubei (Li et al. 2015); and Antarctica (Flügel 2004).

Nuia sibirica Maslov, 1954.

Figures 8d, 14b, c, e, f, h–l, o, 16j, s, 17a–d.

1954 *Nuia sibirica* Maslov, p. 526, pl. 1, fig. 2.

1986 *Nuia sibirica* Maslov - Vachard and Téllez-Girón, p. 15–16, pl. 1, figs. 1–11 (with synonymy).

This previous synonymy list of Vachard and Téllez-Girón (1986) is completed here by the following references:

1964 algal (?) allochem-Swett, figs. 2d–f, 3a.

1966a *Nuia texana* Johnson, p. 433, pl. 57, figs. 1–7.

1970 *Nuia texana* Johnson - Young, p. 2305 (no illustration).

?1972 *Nuea* (sic) - Gerhard, p. 8 (no illustration).

1977 the possible alga, *Nuia* - Cooks and Taylor, p. 56, text fig. 10 p. 57, text fig. 40 p. 74, text fig. 44 p. 76.

non 1981 *Nuia sibirica* Maslov-Saltovskaya, p. 114, pl. 1, figs. 20, 21 (=?*Tuborecta*).

1983 *Nuia siberica* [sic] Maslov - Huang and Bian, pl. 1, figs. 1–10.

1984 *Nuia* - Beresi, text fig. p. 79, pl. 1 p. 80.

1985 *Nuia sibirica* Maslov - Dubatolov et al., p. 5 (no illustration).

1985 *Nuia sibirica* Maslov - Roux, pl. 6, fig. 8.

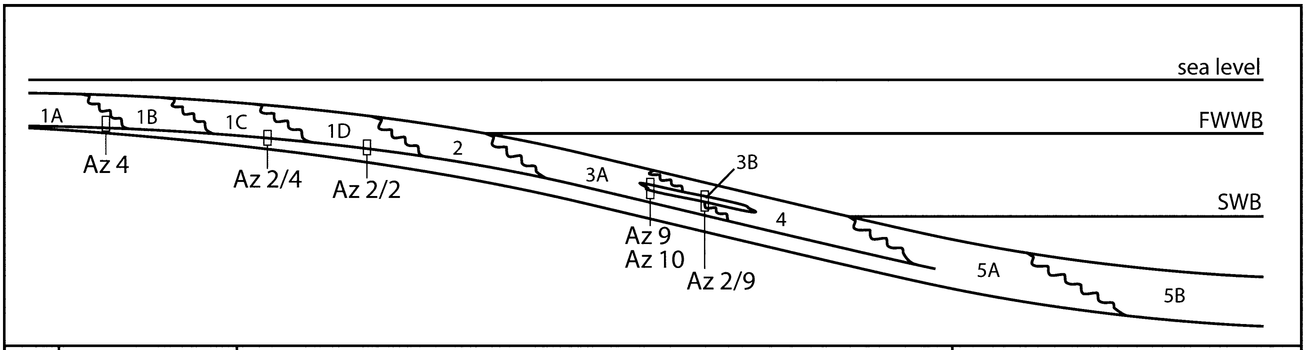
1988 *Nuia* - Ross et al., figs 4.1–4, 5.1–4.

1989 *Nuia sibirica* Maslov - Carozzi, p. 209, 210, 212, text-fig. 11–1 p. 210, text-11.2F p. 211.

1989 *Nuia* - Albertstadt and Repetski, p. 225, 227, 228, 231, 237, 238, 240, fig. 4J.

1991 *Nuia* - Clemons, p. 28–30, figs. 14, 32a–d, 46.

1991b *Nuia* - Roux, p. 351 (no illustration).



mf		Texture	Short description	Samples
1	A	grainstones	extraclasts (bioclastic limestone with fenestrae, ostracods and trilobites; wackestone with spicules, microbialitic limestones), rare echinoderms, ostracods	Az 3 (Fig. 8a), Az 4 (Fig. 14g)
	B		tidalite with micropellets and ostracods	Az 2/7 (Fig. 7b-d)
	C		slightly sandy, well washed, mostly bioclastic grainstone (trilobites, ostracods, cortoids, rare pelloids) with few lithoclasts (from e.g., mf 2)	Az 2/4 (Fig. 9b), Az 2/5 (Fig. 7a), Az 6 (Fig. 8d), Az 11 (Fig. 8b), Az 2/10, Az17-19 (Fig.10b)
	D		well washed, mostly bioclastic grainstone (*Nuia*, trilobites, ostracods, echinoderms)	Az 2/2 (Fig. 9a, 14f)
2		wackestone/ packstone	bioclastic limestone (*Nuia*, *Calathium*?, reworked *Archaeoscyphia*, echinoderms, trilobites, gasteropods), rare extraclast (from mf 5)	Az 2/6 (Fig. 14e)
3	A	wackestone/ packstone	bioturbated bioclastic limestone (trilobites, ostracods including numerous lepertidicopids, rare echinoderms, gasteropods, *Archaeoscyphia*, brachiopods) with few microperforated clasts	Az 2/3, Az 5 (Fig. 11d) , Az 7-8 (Fig. 11a), Az 10 (Fig.11c), Az 12-13 (Fig. 10a), Az 2/9 (Fig.9d), Az 15-16 (Fig. 12a), Az 2/13-15
	B	silty micrite	imput of silty micrite (with echinoderms, rare ostracods and very rare trilobites) within mf3A and mf4	Az 5 (Fig. 11d), Az 9 (Fig. 11 b), Az 2/9, Az 16 (Fig. 12a)
4		packstone	bioclastic limestone (numerous crinoids, subordinate ostracods, trilobites), rare clasts	Az 14, Az 2/9 (Fig. 9d)
5	A	wackestone/ micropackstone	bioturbated, bioclastic limestones with abundant spicules	Az 1-2, Az 2/2, Az 2/4, Az 4
	B	wackestone	impoverished wackestone with ostracodes, rare spicules	Az 2 (Fig. 12d), Az 2/8 (Fig. 12e)

Fig. 13 Composition and interpretation of microfacies and reconstructed transect of Cerro San Pedro. *Az* samples from El Azogue, *FWWB* fair-weather wave base, *mf* microfacies studied in this paper, *SWB* storm wave base. 1–5 (*left column*) refer to regional microfacies types (mf) described in the text

non 1992 *Nuia sibirica* Maslov - Mamet and Boulvain, p. 288, pl. 1, figs. 11–13, pl. 2, figs. 15,16 (more similar to microcodiaceans; probably *Palaeomicrocodium*).

1995 *Nuia sibirica* Maslov - Mamet and Shalaby, pl. 6, figs. 5–14.

?1998 *Nuia siberica* [sic] Maslov - Spincer, p. 577, 578, 580 (no illustration).

p. 1998 *Nuia* - Spincer, p. 577, 578, 580, 581, 582, 583 (non fig. 3.1–3, 6.2?, 3, 7.1–2).

1999 *Nuia* - Keller, p. 38, 40, fig. 24. 1, 5.

2001 *Nuia sibirica* Maslov - Riding and Fan, p. 803, pl. 3, figs. 4–5.

2004 *Nuia* - Flügel, pl. 98, fig. 1.

2012 *Nuia* - Pearce, p. 13, 14, 31, 32, 43, 44, 45 (no illustration).

Table 2 Comparison of the studied microfacies (mf) with the standard- (SMT) and ramp microfacies (RMF) of Flügel (2004)

mf	RMF	SMF	Environmental settings	Figures
5A	RMF1	SMF1	Outer ramp	12d, e
5B	RMF2	N/A		8a, 9b, 12c, d
4	RMF8	N/A	Mid ramp	9d
3A	RMF9	~SMF5		11 b, d, 12a
3B	RMF7	SMF10		9d, 10a, 11a, c, d, 12a
2	RMF9	~SMF5	Inner-mid transition	14e
1A	RMF24	N/A	Inner ramp (lagoonal and peritidal environments)	9a, 14f
1B	RMF22	SMF19		7a, 8b, d, 9b, 10b
1C	RMF26	N/A		7b–d
1D	RMF20	N/A		8a, 14g

2012 *Nuia siberica* [sic] Maslov - Pearce, p. 16 (no illustration).

2012 *Nuia* - Keller, p. 995 (no illustration).

2012 *Nuia* – Beresi et al., p. 334, 338, 339, Fig. 4d, n.

2013 *Nuia* - Ketner, text-fig. 15 p. 10.

non 2013 *Nuia sibirica* - Sinha and Trampisch, p. 346, pl. 2, Fig. 4 (an alga, dasycladalean or issinellacean).

2015 *Nuia* fragment - Li et al. fig 7b.

Description The morphotypes of this study are identical to those of Toomey and Klement (1966) and Johnson (Johnson 1966) from western Texas. Moreover, as suggested by Guilbault et al. (1976; figs. 1, 2), the different lower Ordovician species from the USA and Russia are probably synonymous. Moreover, all Ordovician morphospecies compiled by Shuysky (1973a, p. 68, b, p. 94–95) might be synonyms of the type species *Nuia sibirica*, due to its extreme morphological variability.

Dimensions: Maximal length (L) = 400–2000 µm; external diameter (D) = 150–250 µm; diameter of internal black part (="central cavity") (d) = 50–90 µm; thickness of calcified part ("wall") (s) = 25–50 µm; width of clear crystals (c) = 10–20 µm.

Occurrence As for the genus.

Other Algae?

The chlorophyte algae remain questionable during this period; the true Dasycladales, Chaetoporales, and Bryopsidales appear in the middle-late Ordovician (Gnilovskaya 1972; Elliott 1972; Bourque et al. 1981; Roux 1985; Poncet 1986; Mamet et al. 1992; Mamet and Shalaby 1995), and, in our opinion, neither the receptaculitales *Calathium* nor the Cambrian seletonellaceans of Kordé (1973) belong to chlorophyte algae. On the other hand, only one elianellacean (i.e., solenoporacean *auctorum*) red alga was observed (Fig. 16h).

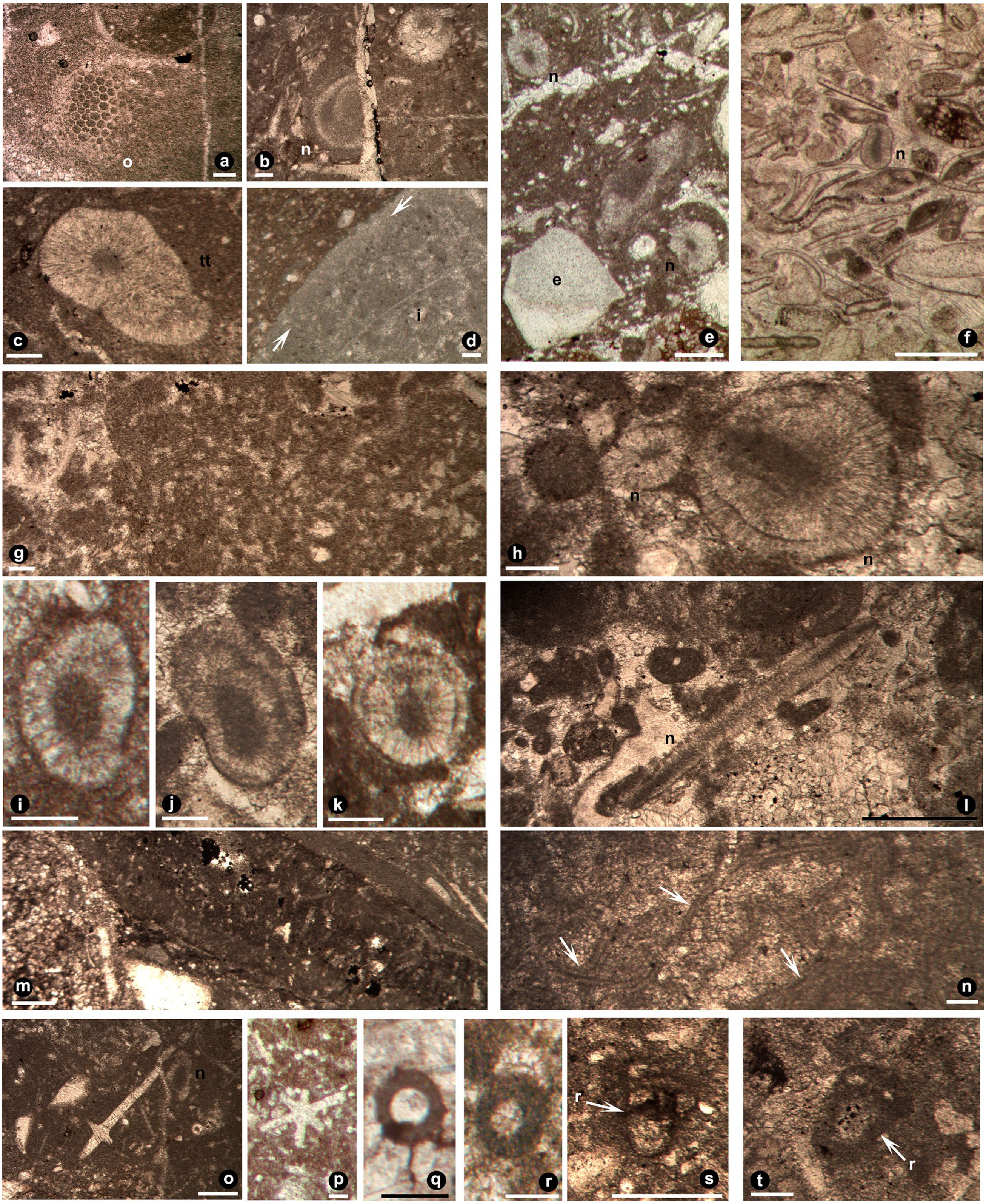
Some outer plates of receptaculitales have been observed (Fig. 18h), similar to those illustrated by Mamet et al. (1992, pl. 11, figs. 10–13, pl. 12, figs. 1–3).

Algal and/or fungal endolithic borings are common in our material. Modern endolithic microperforations, which have diameters of less than 100 µm, are produced by phototrophic (cyanobacteria, chlorophytes, and rhodophytes) and heterotrophic (bacteria and fungi) groups (Perry and MacDonald 2002; Gektidis et al. 2007). Due to light penetration as a limiting factor, many bathymetric distributions were proposed for the microendoliths (Golubic et al. 1975, 2005; Kobluk and Kahle 1977; Tavernier and Golubic 1993; Perry and MacDonald 2002; Gektidis et al. 2007; with references therein). In general, the cyanobacteria inhabit the supra- and intertidal areas, a mixed community of cyanobacteria and chlorophyta colonize shallow waters, and heterotrophic fungi and bacteria are dominantly located in deep aphotic waters.

In this study, the most abundant microperforations are spherical or ampulliform cavities, bored in the wall of a majority of the leperditicopida: type 2 microperforations (Figs. 10a–d, 15, 16f, g, i–l, 18a–c, f).

They affect always the outer surface of the wall and, apparently, do not cross through the wall. They are separated by large imperforate intervals. These microperforations affect almost all of the leperditicopid valves, but are apparently less common in our Devonian collections or in the literature (see e.g., Préat and Kasimi 1995, pl. 12, figs. 3–6; Mamet and Préat 2005, pl. 3, fig. 6, and 2007, fig. 46). On the other hand, microperforations of type 2 seem to be the consequence of an active boring in the wall of living leperditicopida, because 99% of these microperforations only affect the upper part of one or both valves. In contrast, the other types of microperforations (1, 3 and 4) affect dead, and often fragmented skeletons. These microperforations differ from those affecting the ostracod valves of the middle Ordovician of Poland (Olempska 1986), but are comparable with the Cretaceous borings described by Asgaard and Bromley (1991), which were produced while the affected rhynchonellid brachiopods were alive.

Type 3 microperforations (Figs. 15, 16k) are thin and short, and are organized in parallel series, also parallel to the surfaces of the bioclasts; they principally affect trilobite and brachiopod shell fragments.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◂**Fig. 14** Microfossils (*scale bars*: **a–d**, g, **h** = 0.100 mm; **e**, **f**, **i–k** = 0.500 mm). **a** Reticulate ostracod, tangential section, sample Az 2b. **b**, **c**, **e**, **f**, **h–l** *Nuia sibirica*. **b** Transverse section with two rings, sample Az 6. **c** Transverse section with one ring, sample Az 6a. **e** Two sections (*n*) in a bioclastic wackestone with echinodermal plates (e), sample Az 2/6. **f** One section (*n*) in a bioclastic grainstone, sample Az 2/2. **h** Oblique section with two rings and a possible bifurcation in transverse section, sample Az 6c. **i** Transverse section, sample Az2-6. **j** Oblique section with broad dark center, sample Az 6d. **k** Transverse section, sample Az2-6. **l** Longitudinal section of a not bifurcated specimen, sample Az 6e. **d** Biomicritic extraclast (i) with microperforations of type 1 (*arrows*) at the external margin with the matrix of dolomitized micrite, sample Az 2/3. **g**, **n** *Girvanella problematica* Nicholson and Etheridge (1878). **g** A set of trichomes with pellets of microbialites, sample Az 4. **n** *Girvanella problematica*, some trichomes arrowed, sample Az 10b. **m** Ellipsoidal extraclast of wackestone with short monaxon spicules, sample Az 9 k. o Hexaster spicule with a *Nuia* (*top*, *right*), sample Az 10Ba. **p** Polyaxon spicule with *Nuia* (*n*), sample Az 2/6; **q**, **r** *Vicinesphaera* sp. **q** Transverse section, sample Az 2/5. **r** Subtransverse section, sample Az 2/6. **s**, **t** *Rauserina* sp. s sample Az 14. **t** sample Az 13b

Type 4 microperforations (Figs. 15, 16e) are represented by only one perforation, similar in dimensions to type 2 but more ampulliform than subspherical, and which affects an echinoderm ossicle.

Phylum Rhizaria Cavalier-Smith 2002.

Subphylum Foraminifera d'Orbigny 1826 nom. translat. Cavalier-Smith 2002.

Remarks The oldest unquestionable foraminifers are known in the African Taoudeni Basin (Algeria-Mali) and adjacent areas (Culver 1991, 1994; Culver et al. 1996). They were found in shallow marine siltstones, which are dated from the end of the early Cambrian (e.g., Bubik 2001). Rare Cambrian foraminifers were also mentioned in Kazakhstan (Reitlinger 1959). After that, the foraminifers really begin their history during the Ordovician.

All Ordovician foraminifers are unilocular or bilocular. The most primitive forms, *Archaeochitosa*, *Chitinolagena*, *Labyrinthochitinia*, and *Maylisoria* have membranous or tectinous skeletons (Loeblich and Tappan 1987; Vdovenko et al. 1993 with references therein), and probably belong to the Allogromiata (sensu Vachard 2016). On the other hand, more evolved genera were described with an agglutinated wall and probably belong to the Astrorhizata (sensu Vachard 2016). They are, in alphabetical order, *Amphitremoida*, *Bathysiphon*, *Blastammina*, *Hemisphaerammina*, *Hyperammina*, *Lagenammina, Lakites*, *Lavella*, *Marsipella*, *Ordovicina*, *Psammosphaera*, *Pelosina*, *Rhabdammina*, *Raibosammina*, *Sorosphaera*, *Stegnammina*, *Tholosina*, *Tolypammina*, *Thurammina*, and *Thuramminoides* (e.g., Moore et al. 1952; Rauzer-Chernousova and Reitlinger 1957; Loeblich and Tappan 1964, 1987; Langer 1969; Conkin and Conkin 1979; Poyarkov 1979; Lipps 1992; Sabirov and Gushchin 2006). Paradoxically, a majority of these genera of Ordovician Astrorhizata have a type species which was described in the Holocene seas.

Recently, the importance of the genus *Amphitremoida* was highlighted by Nestell and Tolmacheva (2004) in the lower Ordovician of NW Russia, and in the lower-middle Ordovician (Floian-Darriwillian) of Argentina by Nestell et al. (2009, 2011). According to these latter authors, the middle Ordovician foraminiferal assemblage of Argentina includes the genera or morphogenera *Amphitremoida*, *Lakites*, *Lavella*, *Ordovicina* and *Pelosina*. In contrast, some other early Ordovician foraminifers mentioned in Russia are still questionable and probably confused with Devonian forms (see Sabirov and Gushchin 2006; compare with Poyarkov 1969, 1979; and see discussions in Vachard et al. 2010, p. 220 and Nestell et al. 2011, p. 606).

Three early Ordovician genera are present in our material of Sonora, *Neoarchaesphaera* sp., *Vicinesphaera* sp. and *Rauserina* sp. All these genera have a true microgranular wall and not an agglutinated wall. No bilocular or plurilocular foraminifers have been found during our study. Some authors consider nevertheless that plurilocular, coiled and uniseriate genera are present, such as "*Nodosaria*" and "*Aristorespira*" (Sabirov and Gushchin 2006 with references therein) and, since the middle Ordovician, *Reophax blackriveranus* Gutschick, 1986, or, in the Silurian *Reophax* sp. (described by Ireland 1939). We cannot confirm these reports, and, in our opinion, plurilocular forms only appear in the upper lower to lower middle Devonian (Emsian and/or Eifelian) and first become common in Givetian time (see also Poyarkov 1979; text-figs. 20–23). Moreover, "*Reophax*" *blackriveranus* possesses an organic basal layer in its wall, whereas this organic layer is unknown within the Holocene type species. It is also worth noting that the distribution of *Reophax* Montfort, indicated as Cambrian to Holocene (e.g., in Cushman and Waters 1928, p. 37), or "middle Ordovician (rare)-upper Devonian–lower Carboniferous, Permian–Holocene" by Vdovenko et al. (1993, p. 25), corresponds to the longest range registered for a plurilocular foraminifer. Moreover, the upper Devonian "*Reophax*" belong most probably to *Oxinoxis* Gutschick; the lower Carboniferous "*Reophax*" are tests of *Darjella* Malakhova and/or *Lugtonia* Cummings; and the Permian "*Reophax*" forms are tests and/or internal molds of possible *Endothyranella*, *Spireitlina* or Nodosariata. Consequently, the genus *Reophax* sensu stricto probably only appears in the Triassic.

?Class Fusulinata Fursenko 1958 emend. Vachard 2016.

?Subclass Afusulinana Vachard et al. 2010.

Order Parathuramminida Mikhalevich 1980.

Description See Vachard (2016).

Remarks About this order and its disputed assignment, see discussions in Kaczmierczak (1976); Mikhalevich (1980); Vachard (1994), (2016); Kazmierczak and Kremer (2005);

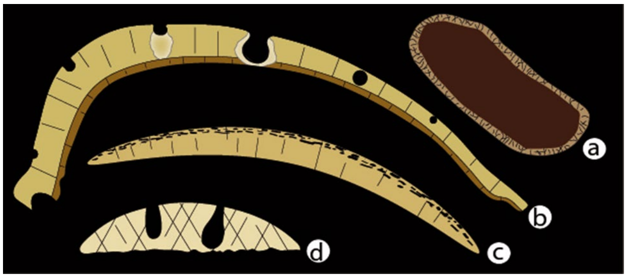


Fig. 15 Different types of microperforations. *a* Perforations of type 1; *b* perforations of type 2; *c* perforations of type 3; *d* perforations of type 4 (explanations in the text; schemes without scale to compare with microfacies figures)

Mamet (2006); Versteegh et al. (2009); Schlagwinteit et al. (2013); and herein, the paragraph devoted to *Rauserina*.

Family Parathuramminidae Bykova in Bykova and Polenova, 1955.

Genus *Neoarchaesphaera* Miklukho-Maklay, 1963.

Type species Neoarchaesphaera bykovae Miklukho-Maklay, 1963 (=*Archaesphaera magna* sensu Bykova in Bykova and Polenova 1955 non Suleimanov 1945).

Synonyms Parathurammina (part.); *Archaesphaera* (part.) auctorum.

Description Small-sized Parathuramminidae with an irregular angular-rounded to spherical profile, fairly abundant papilliform to longer protuberances apparently not perforated, broad central chamber, thin dark-microgranular wall, and inconspicuous apertures.

Remarks See discussions in Loeblich and Tappan (1987) and Vdovenko et al. (1993).

Occurrence Discovered in the lower Ordovician of Sonora. Silurian of the Urals (Pronina 1963). Relatively frequent in the Devonian with e.g., *Parathurammina* sensu Malakhova (1969, pl. 48, figs. 330–331, pl. 49, fig. 337), *Parathurammina*? sensu Racki and Sobón-Podgorska (1993, text-fig. 9a–c), and "*Thurammina* without marked projections" sensu Holcová and Slavík (2013, text-fig. p. 215).

Neoarchaesphaera sp.

Figure 16a, b, d, n, o.

Description Small parathuramminid characterized by a relatively broad chamber, 1–7 radiate protuberances in random section, in prolongation of the smooth angular corners of the chambers, and a unilayered, dark-microgranular wall. The protuberances are very short. The wall is thin, dark and microgranular. Dimensions: Outer diameter = 40–70 µm; inner diameter = 30–50 µm; wall thickness = 5–10 µm; length of protuberances = 5–10 µm; basal diameter of protuberances = 3–5 µm.

Occurrence Lower Ordovician of Sonora (very rare).

Genus *Vicinesphaera* Antropov, 1950.

Type species Vicinesphaera squalida Antropov, 1950.

Description Small parathuramminid characterized by a relatively broad spherical chamber. The wall is thick, conical to subquadratic, and with inconspicuous perforations. It is thin, dark and microgranular.

Remark Although *Vicinesphaera* was questionably reported from the Cambrian (Reitlinger 1959; Chuvashov 1965; Armstrong and Mamet 1977), its presence is indisputable in our lower Ordovician collections.

Occurrence ?Cambrian–Ordovician–Viséan; cosmopolitan.

Vicinesphaera sp.

Figures 8c, 14q, r, 16m.

Description The test is conical. The inner chamber is medium-sized and perfectly spherical. The wall is particularly thick. Dimensions: minimal diameter = 225 µm; maximal diameter = 280 µm; chamber diameter = 80 µm; wall thickness = 150 µm.

Occurrence lower Ordovician of NW Mexico (very rare).

Genus *Rauserina* Antropov, 1950.

Type species Rauserina notata Antropov, 1950.

Diagnosis Test free, monothalamous but with two or several chambers, connected by an areal, intercameral opening. External apertures are inconspicuous. Wall dark-microgranular.

Remark Rauserina is a very questionable foraminifer because: (1) its type of wall exists in many groups; e.g., in cyanobacteria such as *Girvanella*, *Halysis* Høeg, 1932 and *Tuxekanella* Riding & Soja, 1993 (see Skompski 2010), calcitarcha, tuberitinoids, parathuramminoids and irregularinoids (see discussion about all these latter taxa in Vachard 2016); (2) many similar groups of connected, minute, spherical bodies exist in Devonian *Ningbingellina* Mamet, 1998, Viséan "*Ningbingellina*" (sensu Devuyst 2006), Permian *Floritheca* Gaillot & Vachard, 2007, generally interpreted as algal spores or microproblematica; as well as some transverse sections of groups of tubular, cyanobacterial trichomes: *Halysis* and *Tuxekanella*; for instance, the *Rauserina* of Brazhnikova and Rostovceva (1966; pl. 1, Figs. 21, 22, 27–29, 32); (3) they are apparently devoid of functional apertures as well as wall microforamina allowing the passage of the pseudopodia; and (4) when they reused "*Rauserina*", Mamet et al. (1992) assigned its to the calcisphaeridae; consequently, they have made an important emendation (not mentioned in their description). Furthermore, we note that all the so-called multilocular foraminifers in the lower Paleozoic more resemble these groups of spheres than an undisputable foraminifer (Gutschick 1962, 1986; Scott et al. 2003). On the other hand, it is probable that many Paleozoic "*Sorosphaera*" do not correspond to the Holocene genus created by Brady (1879), and are most probably secondarily silicified *Rauserina*. There are *Sorosphaera bicella* Dunn, 1942; *S. bicelloidea* Stewart and Lampe, 1947; *S. colombiensis* Stewart and Lampe, 1947;

S.? *cooperensis* Conkin et al., 1968; *S. multicella* Dunn, 1942; *S. osgoodensis* Stewart and Priddy, 1941; *S. papilla* Gutschick and Treckman, 1959; *S. subconfusa* Dunn, 1942, *S. tricella* Moreman, 1930; see also *S.*? sp. of Culver, 1994 and *Psammosphaera bipartita* Ireland, 1939.

Occurrence Ordovician of Québec (Canada) and the USA (including the *Sorosphaera* spp. mentioned above). Discovered in the Ordovician of Sonora (Mexico). Silurian–lower Tournaisian (and even upper Tournaisian, according to Kulagina 2013) of Russian Platform and South Urals, Western Siberia, Donbass, Tien-Shan, and Italy.

Rauserina sp.

Figures 14s, t, 16q, r.

? 1973 *Rauserina*-Browne and Pohl, p. 195, pl. 5, figs. 4–6.

?1985 *Rauserina notata*-Dubatolov et al., p. 40 (no illustration).

?1992 *Rauserina notata* Antropov-Mamet et al., pl. 11, figs. 1–8 (with synonymy).

?1995 *Rauserina notata* Antropov-Mamet and Shalaby, pl. 5, Figs. 11, 12, 13.

Description These groups of spherical chambers have a dark microgranular wall but the median apertures were not observed. They correspond to *Rauserina* sensu Mamet et al. (1992) but also to *Webbinelloidea tholus* (Moreman, 1933) sensu Amsden et al. (1980). Length = 4400 µm; height = 200 µm; diameter of chambers = 70–100 µm; wall thickness = 7–15 µm.

Occurrence ?Ordovician–?Devonian. North America and Siberia.

Other Microfossils.

Chaetetid indet.

Figure 18l, m.

Rare specimens of small cerioid colonies with slender corallites, and perforate walls, aseptate and rare tabulae, might correspond to Lichenariidae. It is noteworthy that the primitive chaetetetids share morphological similarities with calcisponges, bryozoans and paleofavositids (tabulate corals). In contrast to the San Pedro de la Cueva section, bryozoans were relatively common in the Ojinaga-1 borehole studied by Vachard and Téllez-Girón (1986).

Ostracods and leperditicopida

Figures 7b–d, 8c, 10a, c–d, 11a–d, 12e, 14a, f, 16f, g, i, k, l, 18a–c, f, j.

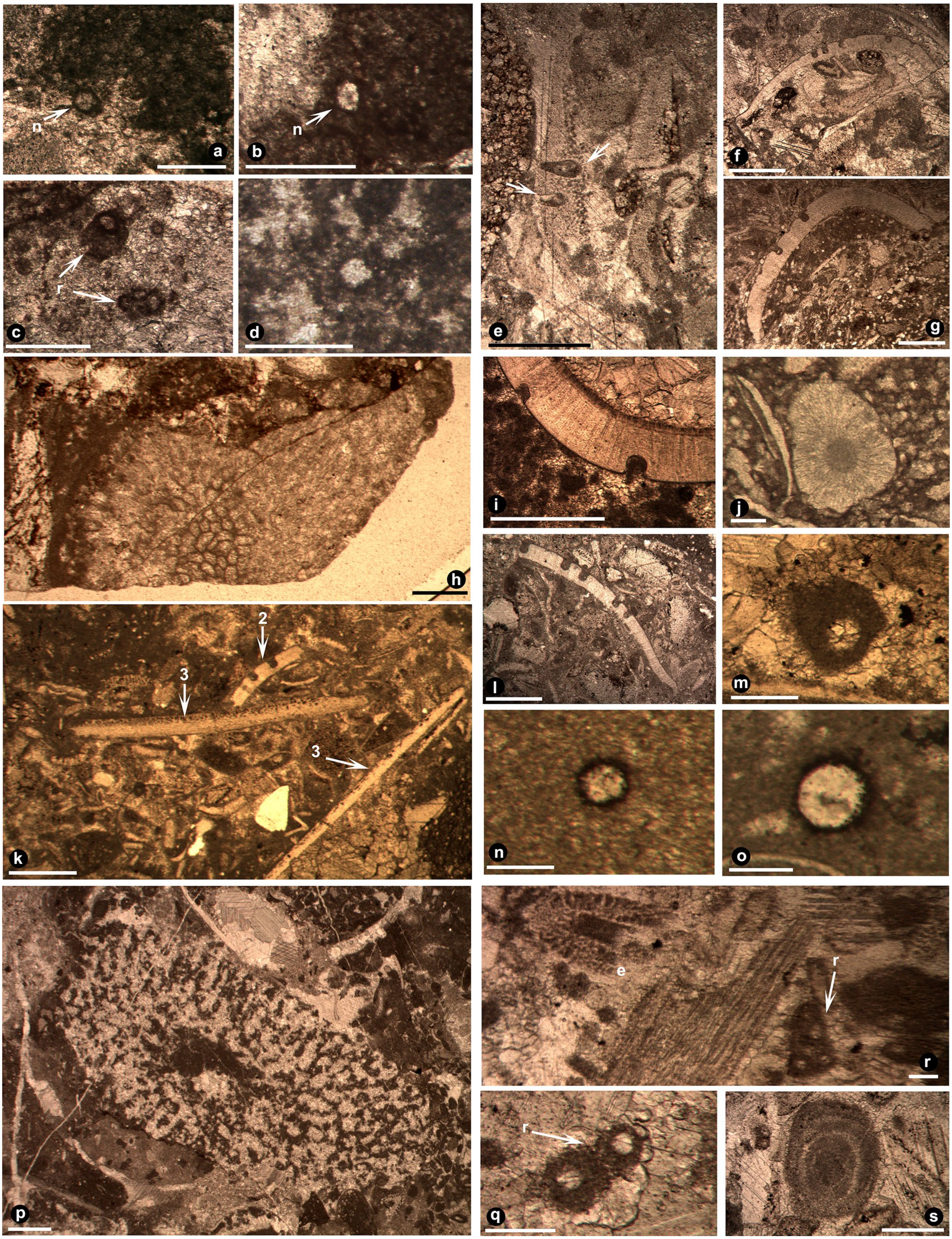
Many true ostracods were observed, as well as many leperditicopids conventionally treated as ostracods. Although leperditicopids first become common and widespread in the middle Ordovician of North America (Berdan 1984; Williams and Siveter 2008), the group is known to appear in the lower Ordovician in Baltica (Williams and Siveter 2008). It is also abundant in the lower Ordovician of San Pedro. Similarly, true ostracods are mentioned in the lower Ordovician of Argentina (Salas et al. 2007). Therefore, the areas where appear both groups, leperditicopids and ostracods, are still discussed, but Sonora seems to be a good candidate.

Echinoderm ossicles

Figures 7b–d, 8c, 9d, 10a, 11d, 12a, b, 14e, f, 154, 16e, r, 18d, e, g–i.

Echinoderm remains are locally abundant in deposits from the middle inner ramp to deeper inner ramp environments. They are mostly recrystallized and fragmented (particularly in tempestites) (Fig. 12a, b), but some retain their original shape and even some stereom details (e.g., Figure 16r). Among them, some unidentified thecal ossicles are observed (e.g., Figure 18e), but most of recognizable elements are disarticulated from pelmatozoan (stemmed) echinoderms. Various free feeding-appendage ossicles include blastozoan-like, "brachiolar" elements (simple oral groove with a low depth–width ratio, e.g., Figure 18d), together with uniserial, more typical crinoid-like "brachials". These ossicle types (Fig. 18e, i) have a deeper and narrower tripartite food groove and interestingly lack an axial canal, a diagnostic feature seen only in derived crinoids. It is worth noting that according to the diagnostic-features of blastozoans, crinoids and other echinoderms (e.g., stylophorans) advanced by Guensburg et al. (2010), it is very speculative to suggest an assignment of disarticulated elements from feeding appendages, moreover based on thin-sections, except from the depth–width ratio of oral groove, which is a subjective character. Indeed, even if indisputable crinoids have been defined from the Tremadocian (lower Ordovician) upward, Clausen et al. (2009) and Kouchinsky et al. (2010, 2015) have illustrated and discussed etched crinoid-like uniserial ossicles from lower to middle Cambrian limestones that would appear very similar to the ones discussed herein in thin section, but the affinity of which remains highly debated.

Other pelmatozoan ossicles from the Ordovician deposits of Cerro San Pedro include columnals with pentagonal lumen and outline (although slightly rounded). Lumen and outline have opposed angles. Due to partial to complete recrystallization, it is impossible to decipher the holomeric or polymeric nature of the columnals. As for brachials (sensu lato), it is impossible to definitely conclude the crinoid affinity of disarticulated columnals, as noted by Donovan (1986) (see also Clausen and Smith 2008). Only five crinoid genera are known from the early Tremadocian and two additional from the late Tremadocian, however, they already illustrate the predominant subclasses (Ausich et al. 2015). Therefore, if the crinoid affinity of some elements described herein is confirmed, they would represent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◂**Fig. 16** Microfossils (*Scale bars* **a–d**, **r**, **s** = 0.250 mm; e–g, **i**, **k**, **l** = 0.500 mm; **h**, **j** = 0.100 mm; **m–o**, *q* = 0.05 mm, *p* = 1 mm). **a–d**, **n**, **o** *Neoarchaesphaera* sp. (*n*, *arrowed*) a sample Az 15. **b** Sample Az 15a. **c** Sample Az 17. **d** sample Az 2. **n** Sample Az 2. **o** Sample Az 2. **e** Echinoderm ossicle (thecal plate?) with microperforations of type 4, sample Az 16b. **f**, **g**, **i**, **k**, **l** Leperditicopida with microperforations of type 2. **f** Sample Az 16. **g** Sample Az 12. **i** Sample Az 8i. **k** Microperforations of type 2 (2) and type 3 (3), sample Az 13. **l** Sample Az 13. **j**, s *Nuia sibirica*, **j** Typical transverse section sample Az 6. **s** Subtransverse section with two rings (see also Fig. 12d), sample Az 20a. m *Vicinesphaera* sp., sample Az 3. **p** *Archaeoscyphia* sp., oblique section (see Fig. 14b), sample Az 18a. **q**, **r** *Rauserina* sp. **q** Sample Az 19c. **r** Associated with echinoderm and brachiopod, sample Az 19b

very early representatives of this group. The presence of blastozoans is also testified by a thecal plate bearing a pectinirhomb-like structure (rhombiferan, Fig. 18g).

Paleobiogeography and Mexican terranology

Brief history of Mexican terrane studies

The tectonostratigraphic terranes of Mexico were accurately defined from Campa and Coney (1983) to Keppie et al. (2003) and Keppie (2004). As indicated by Keppie (2004, p. 769), “individual Mexican terranes have received different names (Campa and Coney 1983; Sedlock et al. 1993; Dickinson and Lawson 2001), leading to confusion and/or double-barreled names”; for example, Mixteco was proposed to replace Mixteca.

The terrane research (e.g., Coney et al. 1980; Howell 1989; Sengör and Dewey 1991; Dewey et al. 1991; Vaughan et al. 2005) has been peculiarly fruitful for the geological knowledge of Mexico. However, some weaknesses in the interpretations result from (1) an exaggeration of subdivisions of each tectonic unit interpreted as distinct terranes; (2) the history and geography, i.e., the delimitations of the terranes in space and times, are very poorly controlled; and (3) local reconstructions and palinspatic maps are largely derivative of the global reconstructions (like those, for example, of Scotese and McKerrow 1990; Dalziel 1997 and Blakey 2008). In this paper, we try to provide revised plate-tectonic reconstructions based on the paleobiogeography of *Nuia* and primitive foraminifers.

Iapetus Ocean, Rheic Ocean, and Mexican terranes

Acatlán complex and its equivalents

The Acatlán Complex (Rodríguez-Torres 1970; Ortega-Gutiérrez 1981) is unanimously interpreted as the vestige of a Paleozoic ocean, but the identity of this ocean, Iapetus, Rheic or another, and its exact location are debated (Ortega-Gutiérrez et al. 1999; Keppie and Ramos 1999; Nance et al. 2007a, b; Bozkurt et al. 2008; Morales-Gámez et al. 2008; Keppie et al. 2007, Keppie et al. 2008a, b). Long regarded as deposited up to the early Permian, and then structured by the Ouachitan orogenesis (Handschy et al. 1987; Hale-Ehrlich and Coleman 1993; Haenggi 2001; Ross 1991), the Acatlán Complex, and especially its Tecomate Fm, locally includes allochthonous elements of middle Permian age, from middle Wordian to late Capitanian (Vachard et al. 1993, 1997, 2004; Keppie et al. 2004; Sánchez-Zavala et al. 2004). Consequently, their tectonosedimentary history continues at least during the late Permian and/or early Triassic. On the other hand, as no fusulinids of middle Permian age are known in South- and Central America, the carbonate series within the Acatlán Complex correspond to olistolites coming from the North American Craton or to seamounts, insular arcs, or islands situated in the south of this craton but without connections with Perigondwana. The foraminiferal assemblages of the Oaxaquia olistolites are especially similar to those of Texas; not only with regard to the fusulinids but also the smaller foraminifers *Abadehella*, *Neoendothyra* and *Globivalvulina* ex gr. *vonderschmittti* Reichel, first found in North America in Olinalá (Vachard 1993; Vachard et al. 1993), and then re-found in Texas (Nestell and Nestell 2006; Nestell et al. 2006).

Guayacán group in Sonora

This Group (290 m thick), recorded in Central Sonora (Table 1), corresponds in our opinion to an oceanic series, probably uninterrupted, from Ordovician to uppermost Devonian. The Ordovician graptolites of this ocean in Sonora were discovered by Peiffer-Rangin et al. (1980). The uppermost Devonian was dated with brachiopods by Noll et al. (1984), and in some calciturbidites with kamaenaceans and parathuramminids by our team (unpublished data). Furthermore, many examined microfacies of Guayacán Group are rich in internal molds of radiolarians and confirmed deep-sea and/or oceanic deposits. Distally, the Guayacán Group has probably for equivalent the Marathon Formation in Texas (Young 1970) and the ophiolithic Granjeno Schist of the Sierra Madre Terrane, which overlies a basement of ca. 1 Ga, the Novillo Gneiss (Nance et al. 2007b); therefore contemporaneous of the Grenvillian basement of Laurentia and the Oaxacan Complex of the microcontinent of Oaxaquia.

Oaxaquia microcontinent

Oaxaquia was speculated with the intent to reconstruct a terrane located between Oaxaca and Tamaulipas with a Mesoproterozoic basement of ca. 1 Ga age, the Oaxacan Complex (Ortega-Gutiérrez et al. 1995). It is clear that this terrane did no more exist during the

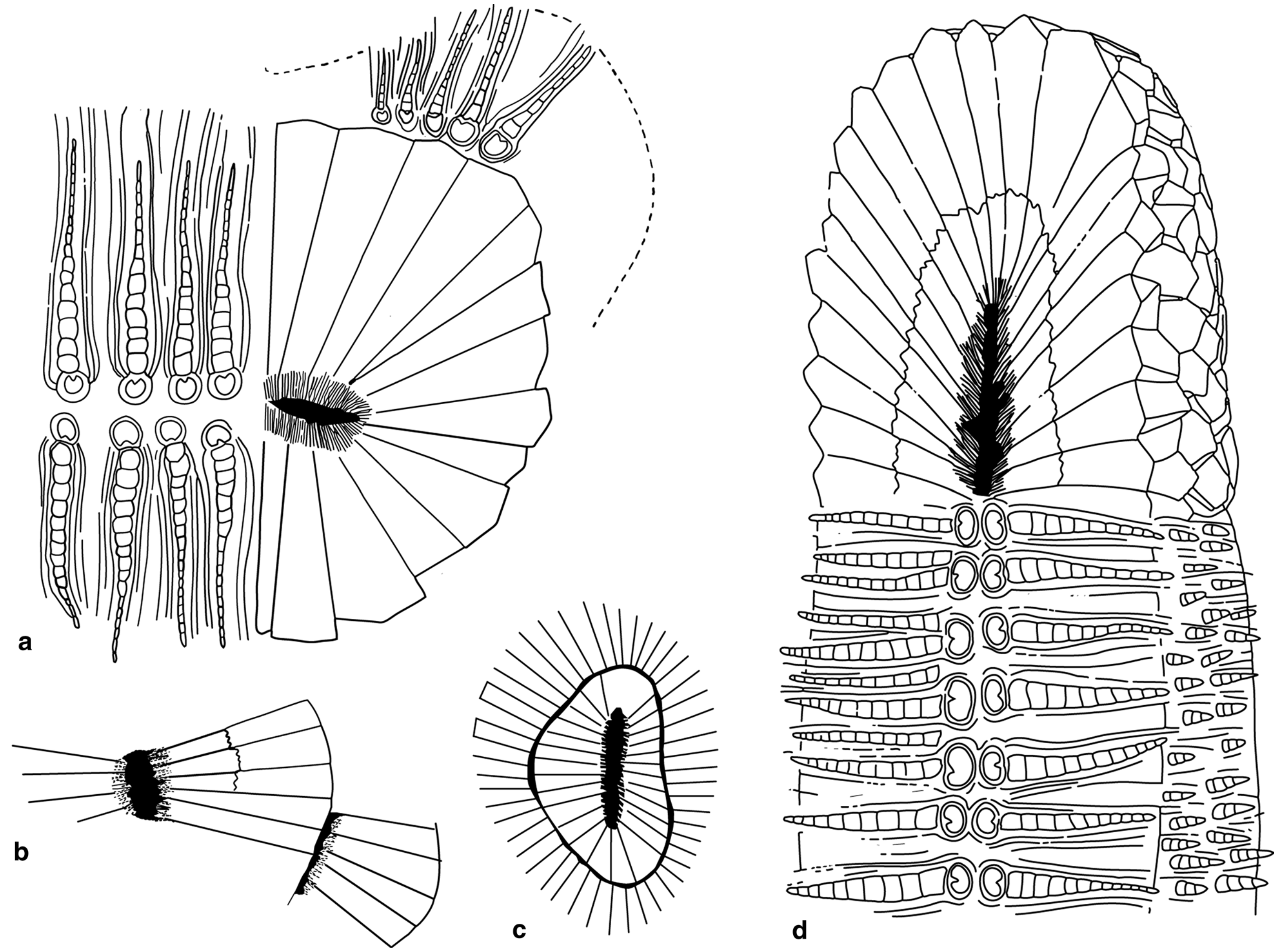


Fig. 17 Reconstructions of *Nuia*. **a**–**c** Stages of calcification. **a** In the living cyanobacteria, the heterocysts are aligned in the median plane, or at the base when a second thallus is attached on the first one. The trichomes are directed perpendicularly to the thallus axis, or arranged in fans. Their individual calcification leads to the “fibers” of calcite. **b** After disappearance of the trichomes, their richness in organic matter gives rise to a dark space, central or basal. The fibers less rich in organic matter appear in clear calcite. **c** When a second attached thallus entirely surrounds the first thallus, a complete dark space or a dark line appears. **d** Complete reconstruction of the taphotaxon (according to Vachard and Téllez-Girón 1986). Accordingly, *Nuia* is relatively similar to some Nostocales Rivulariaceae, even if all the representatives of this family are only known in fresh waters

Carboniferous–Permian, because the paleogeography of these systems appears almost similar to the modern geography of Mexico (Vachard et al. 2000a, b), with the Acatlán Complex corresponding to the oceanic bottom, and with narrow carbonate platforms, currently reworked large olistoliths or more or less preserved in situ: San Salvador Patlanoaya (Vachard et al. 2000a, b), Matzizi (Vachard et al. 2000b), Olinalá (Vachard et al. 1993; Vachard 1993; Nestell 1999), San Juan Ixtaltepec (Vachard et al. 1997), and Los Hornos (Vachard et al. 2004; Keppie et al. 2004). It must be pointed out that the Oaxaca terrane of Keppie et al. (1996) and Keppie (2004) differs from Oaxaquia, and this complicates the discussion.

The sedimentary Ordovician series of Oaxaquia (Tiñu Group or Tiñu Formation from the Oaxaca State) completely differs, in its assemblages and geological characters, from that of the northern Mexican states summarized before (Table 1). As indicated by Landing et al. (2007, p. 909): “The Tiñu Formation in Oaxaca State, southern Mexico, provides the only record of fossiliferous Paleozoic rocks south of the Laurentian successions in Sonora and Chihuahua states and Texas and north of the Gondwanan sequences in Andean Colombia and Venezuela”. The Tiñu Formation is subdivided into a lower member, the Yucachica Member (Furongian, upper Cambrian in age), and the Río Salinas Member (lower Ordovician, Tremadocian). Landing et al. (2007) have interpreted the deposits as cold-sea carbonates (due to the presence of a heterozoan association and absence of ooids and evaporites). We agree with the interpretation of a heterozoan association, but not with that of a shallow cold sea. However, Landing et al. (2007, p. 914) highlighted that the accumulation is a "trilobite and echinoderm hash". This accumulation corresponds more, in our opinion, to a middle ramp deposit, and is therefore independent of the criteria of temperature and depth only applicable to inner ramp deposits (Flores de Dios et al. 1998). This assemblage may perfectly belong to tropical or subtropical shelves, but in deeper paleoenvironments, independent of the possibilities of cool-water carbonates in tropical environments (see James 1997; Samankassou 2002; Soreghan et al. 2008).

On the other hand, the upper part of the Río Salinas "Member", although of the same marly lithology and color, displays different tectonic structures from the lower part (personal observation near the Santiago Ixtaltepec village, Guerrero, Mexico), which may correspond either to a slumping or to two different tectonic slices of different ages. Its boundary with the overlying Tournaisian Santiago Formation is also unclear. Consequently, our goal consists in the discovery of the age of the upper part of the Río Salinas "Member" and its exact limit with the overlying formation which was dated as late Tournaisian by our team. Therefore, the age of the upper part of the Río Salinas "Member" should be reassessed and the formation renamed as the current name is pre-occupied in Mexico. However, the most important problem to solve remains the detailed paleogeography of this sector of Oaxaca, because very different paleogeographic affinities were proposed by previous authors (see below).

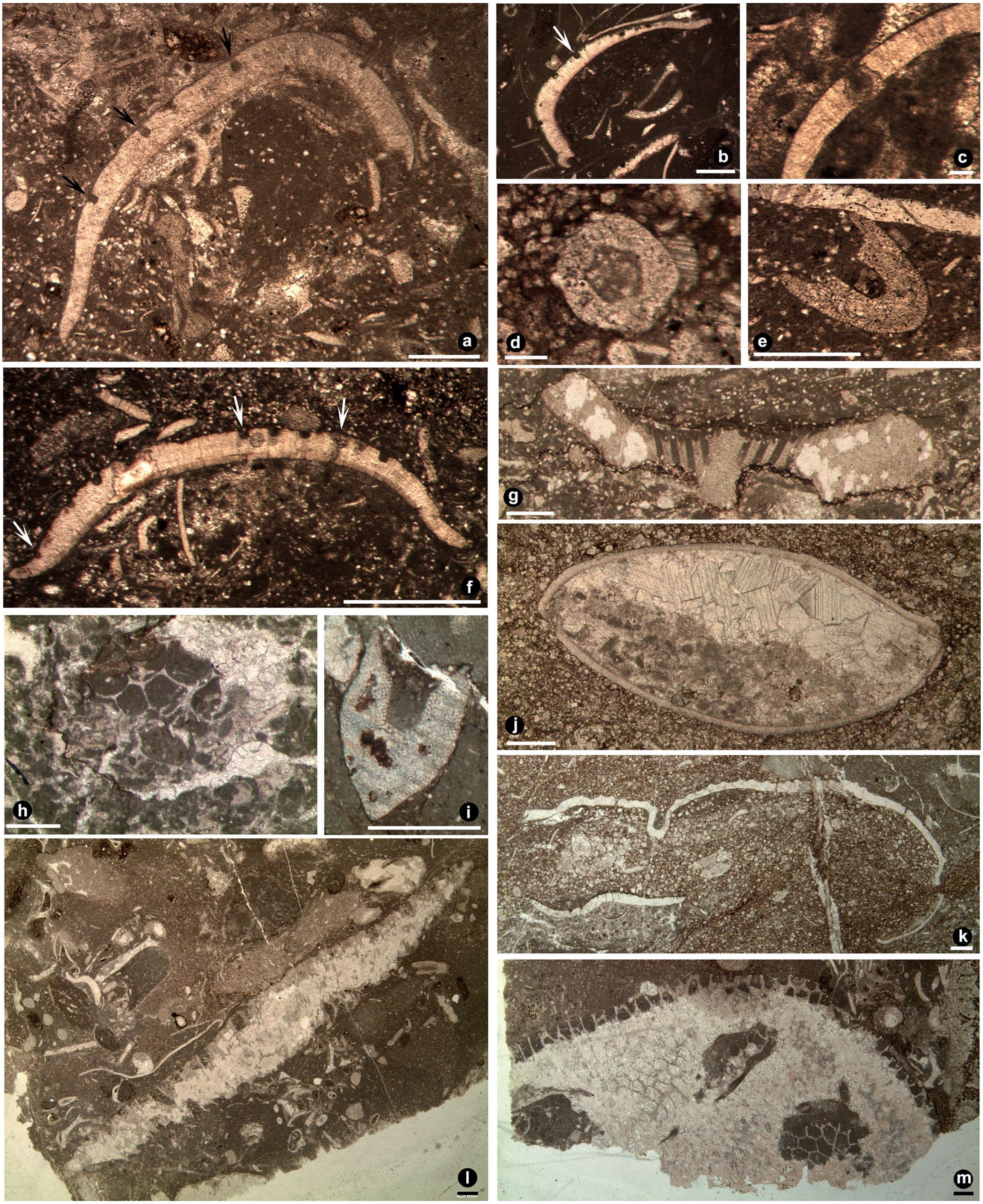
Prior to the Carboniferous, Oaxaquia might have existed, but it is currently impossible to demonstrate if (1) Oaxaquia was the oceanic bottom of the Iapetus' northern margin and became parautochthonous; or (2) Oaxaquia was the oceanic bottom of the Iapetus' southern margin, initially connected with Gondwana, and then displaced. It is possible that the oceanic bottoms of Iapetus and Rheic occupy the same areas in Mexico and were closed and opened exactly in the same areas, because the Pennsylvanian-early Permian Rheic paleogeography of Sonora (e.g., Bozkurt et al. 2008; Nance et al. 2010; Palafox 2011) existed already during the early Ordovician; and despite of the wandering of the North American craton (Cocks and Torsvik 2011, Fig. 3a–c), Sonora remained always at the extremity of this continent, and always remained the limitroph of an oceanic area. Therefore, in Sonora, the limits of the carbonate ramps and the oceanic deposits are the same during the early Ordovician (Fig. 19) as they were during the Carboniferous–Permian (see Palafox 2011), and the Iapetus and Rheic oceans had the same limits and the same extent across Sonora during the Paleozoic. This renewed paleogeography probably explains why the Acatlán Complex was first considered as having been deposited on the Iapetus and then on the Rheic oceanic bottom (Ortega-Gutiérrez et al. 1999; Nance et al. 2007a, b).

Proposed interpretations and reconstructions

Paleobiogeographical value of Nuia

The photophile and warm stenotherm characteristics of the cyanobacteria *Nuia*, and its frequent association with the Ordovician reefs permits us to indicate a tropical distribution for *Nuia*, even if the reefal ecosystems are very rarely represented during the Ordovician and only encountered in Mexico, USA, Canada and Siberia. In Mexico, the reefs built by corals, bryozoans and/or microbialites, form bars that protected lagoons where the first calcareous chlorophytes like bryopsidales and dasycladales developed, in a photozoan association with gastropods, bivalves, and the first orthoceratids (all these groups possess an aragonitic mineralization). The accumulations located in the reef-front are dominated by pelmatozoan remains (Echinodermata). In this early Ordovician tropical zone, the *Nuia* Province as defined here, was located on each part of the Equator [see the reconstructions of Roux (1991a); Poole et al. (1995a); Matte (2001) and von Raumer et al. (2003)]. The principal distribution areas of *Nuia* encompass two sectors, one from Sonora (Mexico) to Quebec (Canada) as well the western side of the North American craton; another one from Kazakhstan up to Siberia (Russia) (Gnoli and Serpagli 1980; Vachard and Téllez-Girón 1986) (Fig. 20a). The first sector corresponds exactly to the margins of Laurentia, as reconstructed for a long time (Cook et al. 1975; Petersen et al. 1976; Fig. 19). The specimens of *Nuia* from Greenland (Arctida) connect these two subprovinces or continental blocks and confirm that the three paleocontinents, Laurentia, Arctida and Siberia, were located in the early Ordovician tropical zones (Fig. 20b), with narrow connections, probably via the terranes Barentsia, Verkhoyansk, Alaska-Chukotka and Farewell (Golonka 2002; Torsvik and Cocks 2013a).

By contrast, (1) the distribution of coeval taxa of *Nuia*, *Archaeoscyphia* and *Calathium* for example, seems to be broader and includes North America, Argentina, northern Europe, Australia and China (Finks and Rigby 2003; with references therein for *Archaeoscyphia*; and Nitecki et al. 1999, for *Calathium*); this broader distribution is probably related to larval stages which did not exist in *Nuia*; and (2) the distribution of the first leperditicopids might be restricted to the western border of Laurentia (in its lower Ordovician location), in Sonora, and the southern border with the San Juan, Newfoundland and



Svarlbard localities indicated by Williams and Silvester (2008), but re-positioned in the paleomaps of Cocks and Torsvik (2011) and Torsvik and Cocks (2013b).

Therefore, several paleomaps of Dalziel et al. (1994), Keppie and Ortega-Gutiérrez (1995), Astini et al. (1995), Dalziel (1997), Golonka (2002), von Raumer et al. (2003),

◂**Fig. 18** Microfossils (*scale bars* 0.500 mm; except for **d** = 0.100 mm; and **f**, **k** = 1.000 mm). **a**–**c**, **f** Leperditicopida with spherical microperforations of type 2 (some *arrowed*; see Fig. 18**b**, **f**). **a** sample AZ 7c (see also Fig. 11a). **b** sample Az 8c. **c** sample Az 8e. **f** sample Az 9d. **d** Pelmatozoan (echinoderm) columnal (stem ossicle) with pentaradiate lumen, sample Az 7g. **e** Pelmatozoan ossicle from a free feeding appendage (arm sensu lato), sample Az 7h. **g** Echinoderm plate, *bright spots* are secondary silicifications, sample Az 2/2b. **h** Outer plate of receptaculitale *Calathium*? sp., sample Az 2/6. **i** Pelmatozoan ossicle, sample Az2-5. **j** Leperditicopida with geopetal filling, sample Az 2/15. **k** Two trilobite fragments (*top* and *bottom left*), sample Az 2/15. **l**, **m** Chaetetid indet., two fragments of colonies partly silicified, sample Az 2/14

Cocks and Torsvik (2011), and Torsvik and Cocks (2013b), reflect the biogeographic distribution of *Nuia* and, among these paleomaps, the palinspatic Earth reconstruction of Golonka (2002) is the most adequate (Fig. 20b). The maps of Bozkurt et al. (2008), Sengör et al. (2014) or Golonka (2002) indicates that the Kipchak arc is not yet connected to the Russian Craton (i.e., western Laurentia) during the early Ordovician, while it will be connected during the middle Ordovician (Sengör et al. 2014, fig. 8a, b), permitting possible connections between Siberia and Laurentia. Tarim is probably connected with the South China terranes, where *Nuia* is relatively poorly known; nevertheless, it was occasionally mentioned, whereas *Archaeoscyphia*, *Calathium* and *Pulchrilammina* are more commonly described (e.g., Adachi et al. 2011a, b; Li et al. 2014, 2015). Furthermore, Tarim and the South China terranes can be connected via the Anamia (=Indosinia/Indochina terrane) and the Mongolian (=Kazakhstanian) terranes of Torsvik and Cocks (2013a). The Chu-Ilii terrane is located on one of the Kazakhstania terranes sometimes placed near the Equator during the early Ordovician (Popov et al. 2013, fig. 10.1). Moreover, the distance between the South China-Indochina (= Indosinia = Anamia) and Gondwana paleocontinent is probably broader than indicated by Golonka (2002) or Torsvik and Cocks (2013b). In contrast, Baltica and Avalonia are related to cold temperate to subpolar waters and are separated from the *Nuia* Province by a broad branch of the Iapetus.

Harper et al. (2013) have defined a low-latitude brachiopod Province. This is larger than the *Nuia* Province defined here, because it includes the northeastern part of Gondwana (Sibumasu, Australia, eastern part of India, autochthonous Argentina, Chile, etc.), where *Nuia* is absent. Although autochthonous Argentina and Chile are effectively located in the tropical zone, they are devoid of *Nuia*, whereas the Precordillera-Argentina San Juan terrane of these authors (with *Nuia*) is located near the North American Craton. We agree with this map, nevertheless, due to the probable continuity of Laurentia and Siberia (as in the paleomap of Golonka 2002, fig. 5, for example), we bring together these two continents and we take away South Chile- autochthonous Argentina from Australia-Sibumasu.

For the Precordillera Terrane and autochthonous Argentina, the reconstructions of Astini et al. (1995), Dalziel (1997), Keller (1999, 2012), and Harper and Servais (2013) are probably the best for understanding (a) the paleolocation of its source in Laurentia; (b) the migration way of the terrane; and then (c) the location of the transform faults affecting this terrane.

Due to the paleobiogeographical comparisons suggested by Robison and Pantoja-Alor (1968) with the Argentina Precordillera, a similar Laurentian origin might be suggested for the Tiñu Terrane, preferentially to other hypotheses like: (1) a migration from Argentina to Mexico (as initially admitted by Robison and Pantoja-Alor 1968); (2) an origin from the Sierra Garzón in Colombia (as proposed in numerous papers by Keppie); and (3) the connection between Tiñu and the paleocontinent of Baltica, recently proposed by Landing et al. (2007). The first hypothesis seems to be the more convincing, because other terranes have migrated from South America to North America (see Keppie et al. 2003), displaced across South America such as the Madre de Dios terrane (southern Chile; see e.g., Ramos 1988; Hervé 1993), the fusulinids of which are related with those of Titica Lake (Peru-Bolivia border) or those of North America. We can suggest that, if Sonora shares the paleobiogeography of the North American Craton, other areas of Mexico belong clearly to another province (supercontinent or microcontinent): i.e., the peri-Gondwanan border of the Rheic ocean with affinities to Argentina or to the Oaxaquia, a block isolated within the Rheic between Laurentia and Gondwana (Dalziel 1997; Murphy et al. 2006; Landing et al. 2007; Keppie et al. 2008a, b). Oaxaquia and the Chortis and Maya blocks were interpreted as parts of the southern margin of the Rheic Ocean and show a paleobiogeographic affinity to the paleocontinent of Gondwana, or more probably a location between the two Rheic margins. Moreover, the initial location and its definitive paleogeographic emplacement remain discussed because the geological architecture of Mexico is poorly known and very complex.

Conclusions

1. The Cerro San Pedro succession (Sonora, NW Mexico) exhibits the classical microfacies in the El Paso Formation of the southern North American Craton. The northernmost outcrops of Mexico (Sonora and Chihuahua) expose some of the oldest ecosystems with cnidarian (corals), bryozoan, recptaculitales and leperditicopids from the Earth history.

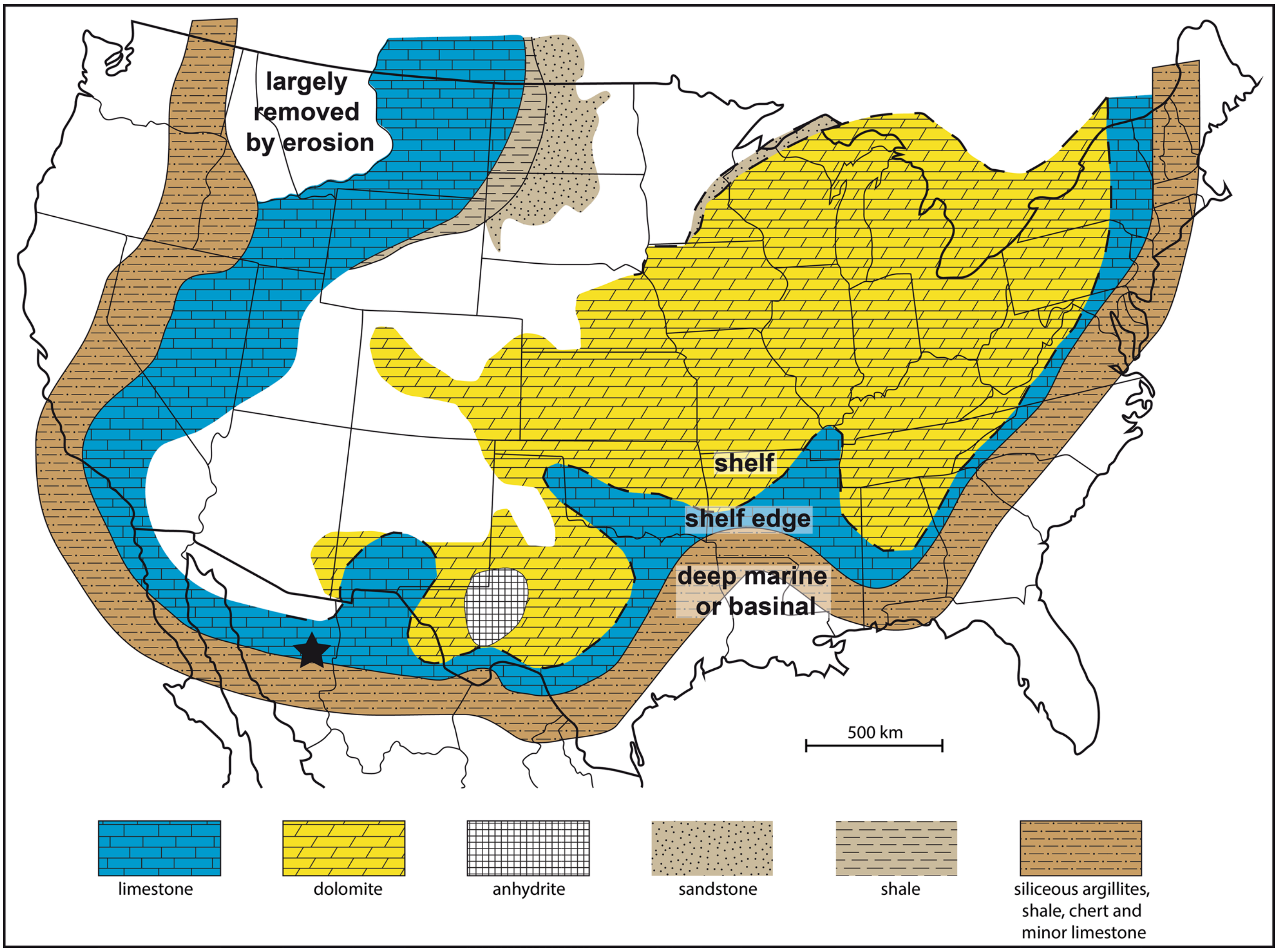


Fig. 19 Early Ordovician paleogeography of North American Craton in the USA and northern Mexico, including Sonora (modified after Cook et al. 1975; Petersen et al. 1976 and Derby et al. 2012; the *black star* indicates the studied area)

2. The reefal ecosystems, rarely represented during the Ordovician, and mainly known from the USA, Canada and Siberia are in Mexico only known as allochthonous clasts in bioclastic tempestites.
3. In the San Pedro section, the marine environments appear shallow and subtropical; and the assemblage is photozoan to heterozoan. Numerous tempestites are indicated by the accumulation of microperforated extraclasts or pelmatozoan ossicles.
4. An early Ordovician age is based on the occurrence of the cyanobacteria *Nuia sibirica*. The chlorophyte algae remain questionable during this period; the true Dasycladales, Chaetoporales and Bryopsidales appeared in the middle–late Ordovician. Consequently, the receptaculitales *Calathium*, as well as the so-called Cambrian dasycladales, most probably belong to other algal groups. On the other hand, the Vermiporellaceae, often interpreted as the first dasycladales, are more probably chaetophorales. Only one ellianacean (red? algae) was observed.
5. The oldest foraminifers of North America have been re-found during this study; moreover, they are the first Ordovician foraminifers mentioned in Mexico, with the genera *Neoarchaesphaera*, *Vicinesphaera* and *Rauserina*.
6. All these taxa have a dark-microgranular wall and not an agglutinated wall.
7. Macrofaunal fragments are classical in the El Paso Formation, especially of the *Archaeoscyphia* sponges, the gastropods and the sponge spicules. The leperditicopids are abundant and perhaps have their FAD in Sonora.
8. The endolithic perforations of the leperditicopids of Sonora need further detailed studies.
9. The cyanobacteria *Nuia* is considered here as a paleogeographic marker of the western province in the

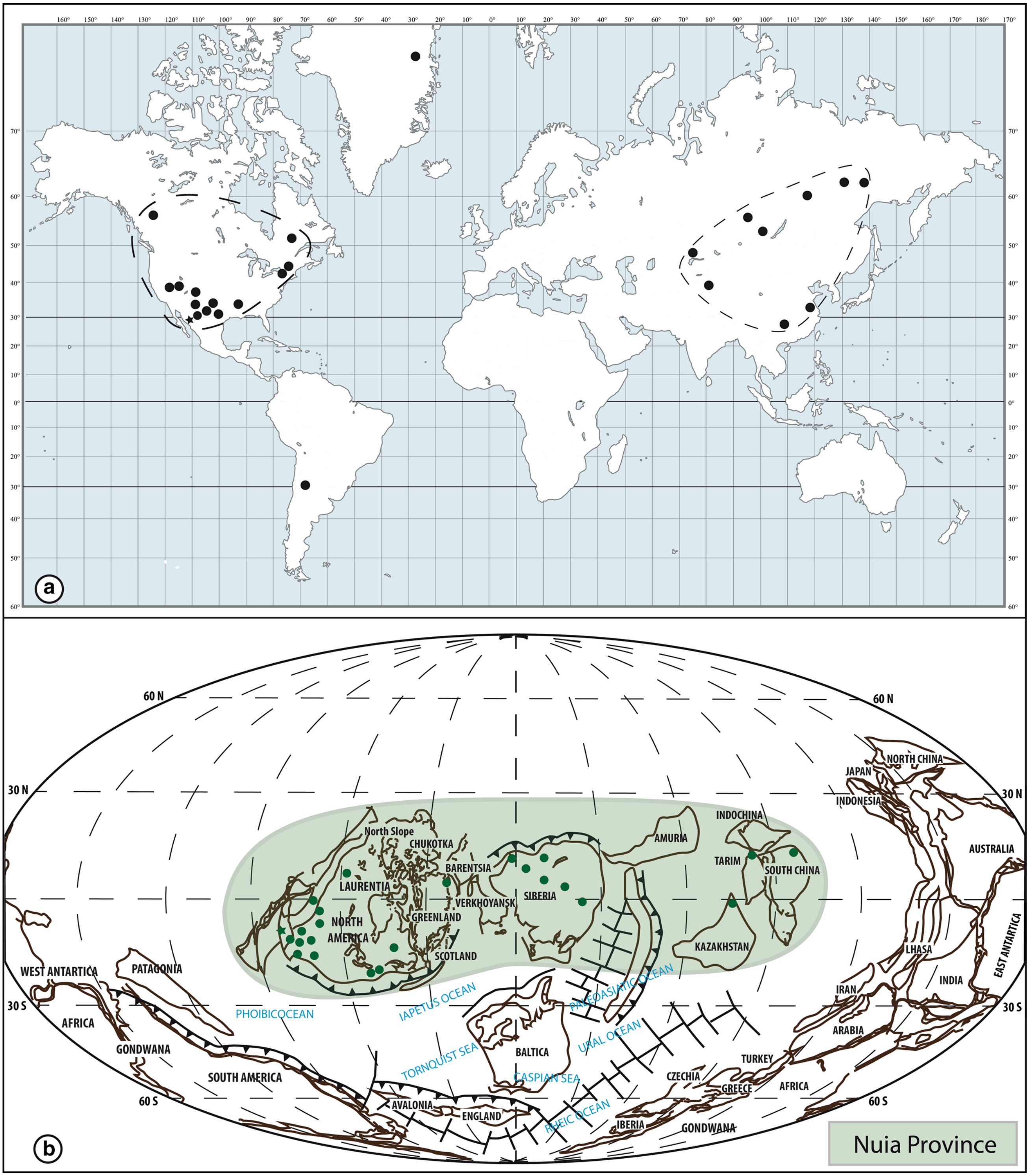


Fig. 20 Paleoprovince with *Nuia*. **a** Distribution in a modern geography (modified after Vachard and Téllez-Girón 1986). **b** The same distribution in a paleomap after Golonka (2002), with distance between the South China-Indochina and Gondwana modified (see text) and illustration of the *Nuia* Province. The *stars* in **a** and **b** indicate the new report from the studied area

tropical belt during the early Ordovician. The studied area in Sonora is considered as the westernmost part of the *Nuia* Province.

10. The Sonora shares the paleobiogeography of the North American Craton. Other areas of Mexico belong clearly to another province. As probable parts

of the northern margin of the Iapetus ocean, they have then migrated toward the Perigondwanan border; i.e., the southern margin of the Rheic ocean, and shared affinities with Argentina or blocks isolated within the Rheic between Laurentia and Gondwana. The subcontinent Oaxaquia and the Chortis and Maya blocks, which were interpreted as parts of the southern margin of Rheic ocean, probably possess paleobiogeographic affinities with the paleocontinent of Gondwana or more probably a location between the two Rheic margins. Moreover, the initial location and its definitive paleogeographic emplacement remain discussed because of the very complex geological architecture of Mexico.

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