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Research Paper

Mississippian-Lower Pennsylvanian foraminifers from the Sierra Nacimiento and San Pedro Mountains, North-Central New Mexico, USA ☆

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ABSTRACT

In the Sierra Nacimiento-San Pedro Mountains-Jemez Mountains of north-central New Mexico (USA), the thin succession of Mississippian sediments is termed the Arroyo Peñasco Formation, overlain by the Log Springs Formation. The Arroyo Peñasco Formation is subdivided into Del Padre Member composed of siliciclastic sediments and the overlying Espiritu Santo Member composed of carbonate sediments. Foraminifers of the Espiritu Santo Member at Lion Spring in the northern San Pedro Mountains indicate a Tournaisian age. The lower Tournaisian (= Hastarian = biozones MFZ1-4 of Poty et al., 2006 [Geological Magazine 143, 829–857]) is locally characterized by *Septaglomospiranella* ex gr. *primaeva*, *Septabrunsiina minuta* and *Tournayella* sp. The upper Tournaisian (= Ivorian = biozones MFZ5-9 of Poty et al., 2006) is characterized by *Spinoendothyra*, *Inflatoendothyra* and *Tuberendothyra*. In the Sierra Nacimiento-San Pedro Mountains-Jemez Mountains, the sediments of the Arroyo Peñasco Group are unconformably overlain by nonmarine redbeds of the Log Springs Formation (Serpukhovian/upper Chesterian). Some of the carbonate clasts of the basal conglomerate of the Log Springs Formation at Lion Spring contain late early Viséan (biozone MFZ11B of Poty et al., 2006) foraminifers and algae, including *Koninckopora* and *Paraarchaediscus*. These carbonate clasts are reworked from the underlying Arroyo Peñasco Formation (Espiritu Santo Member). In north-central New Mexico, a transgression during the Early Pennsylvanian (Morrowan) caused deposition of the shallow marine sediments of the Osha Canyon Formation. The Morrowan age of the Osha Canyon Formation is based on *Nigrispiroides* nov. gen., *Iriclinella*, *Globivalvulina*, and *Millerella*.

1. Introduction

A marine transgression during the Early Mississippian across central and northern New Mexico (then part of western Laurentia) caused deposition of shallow marine carbonate and siliciclastic sedimentary rocks that unconformably overlie an almost peneplained basement of Proterozoic and lower Paleozoic rocks (Armstrong et al., 2004). In the Sierra Nacimiento-San Pedro Mountains-Jemez Mountains of north-central New Mexico, the thin succession of Mississippian sediments is termed the Arroyo Peñasco Group, overlain by the Log Springs Fm. (Armstrong et al., 2004).

Tectonic activity during the Late Mississippian resulted in uplift, and Mississippian sedimentary rocks of the Arroyo Peñasco Group were partly or completely eroded. In the Sierra Nacimiento-San Pedro Mountains-Jemez Mountains, the sediments of the Arroyo Peñasco Group are unconformably overlain by nonmarine redbeds of the Log Springs Fm. (Serpukhovian/upper Chesterian). A transgression during the Early Pennsylvanian (Morrowan) caused deposition of the shallow marine sediments of the Osha Canyon Fm. (DuChene et al., 1977; Krainer and Lucas, 2005).

Biostratigraphy of the Mississippian succession is mainly based on foraminifers (Armstrong, 1967; Armstrong and Mamet, 1974, 1979). In the Sierra Nacimiento-San Pedro Mountains-Jemez Mountains, Armstrong (1967) dated the Arroyo Peñasco Fm. at the Pinos and Peñasco canyons sections and in the San Pedro Mountains three miles east of Regina as late Osagean to Meramecian. Armstrong and Mamet (1974) divided the Arroyo Peñasco Group of the Sierra Nacimiento and San Pedro Mountains into Espiritu Santo Fm. and Terrero Fm. (Manuelitas Mb.). Based on foraminifers, Armstrong and

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Mamet (1979) divided the section at Pinos and Peñasco canyons into Espiritu Santo Fm. (lower 27.5 m), dated as late Tournaisian (Osagean), microfossil zone 9, and Tererro Fm. (Manuelitas Mb.; upper 17 m), dated as late Viséan (late Meramecian), Mamet's microfossil zone 14. The lower part of the section in the San Pedro Mountains (lower 33 m) was ascribed to the Espiritu Santo Fm., dated as late Tournaisian (Osagean), Mamet's microfossil zone 9, and the upper part (6 m) to the Tererro Fm. (Manuelitas Mb.), dated as late Viséan (late Meramecian), Mamet's microfossil zone 14.

Here we present new data on the foraminiferal assemblage and age of the Arroyo Peñasco Fm. at Log Springs, northern San Pedro Mountains (close to the section described by Armstrong, 1967; Armstrong and Mamet, 1974) and of the Osha Canyon Fm. at Lion Spring, Sierra Nacimiento (Figs. 1, 2).

2. Mississippian stratigraphy

During the 1940s, researchers studying the upper Paleozoic strata in northern New Mexico assigned the oldest strata to the Sandia Fm. and distinguished a lower limestone member of the Sandia Fm., suggesting a pre-Pennsylvanian age for this unit (Read et al., 1944; Wood and Northrop, 1946; Read and Wood, 1947). This lower gray limestone member was described from the Sierra Nacimiento-San Pedro Mountains by Wood and Northrop (1946). Armstrong (1955) proposed the term Arroyo Peñasco Fm. for this "lower limestone member" and reported an endothyrid foraminiferan fauna of Meramecian (Viséan) age. Fitzsimmons et al. (1956) presented a list of megafossils from the type section of the Arroyo Peñasco Fm., which also indicate a Meramecian age.

Baltz, Wanek and Read (1956), Baltz and Bachman (1956), and Baltz and Read (1959) rejected the concept of the Arroyo Peñasco Fm. for the Sangre de Cristo Mountains as defined by Armstrong (1955) for the Nacimiento and San Pedro Mountains. Baltz and Read (1960) divided the pre-Pennsylvanian sedimentary rocks in the Sangre de Cristo Mountains into two new formations, the Espiritu Santo Fm. and the Tererro Fm. The Tererro Fm. was further subdivided by Baltz and Read (1960) into the Macho, Turquillo, Manuelitas, and Cowles members. Sutherland (1963) separated the basal sandstone of the Espiritu Santo Fm. of Baltz and Read (1960) and named it the Del Padre Sandstone.

Armstrong (1967) considered the Espiritu Santo and Tererro formations of Baltz and Read (1960) to be laterally equivalent successions of the Arroyo Peñasco Fm. defined by Armstrong (1955) and Fitzsimmons et al. (1956). According to Armstrong and Mamet (1974, 1979), the Macho Mb. of the Tererro Fm. is not present in the Sierra Nacimiento and San Pedro Mountains where the upper Tournaisian (lower Osagean) Espiritu Santo Fm. is overlain by the upper Viséan (upper Meramecian) Manuelitas Mb. Because of its extent and the formations that it includes, the Arroyo Peñasco Fm. was raised to group rank in north-central New Mexico by Armstrong and Mamet (1974, 1979, 1990) and Armstrong et al. (2004).

According to Armstrong et al. (2004), the Mississippian sedimentary succession in the Sangre de Cristo Mountains rests unconformably on Proterozoic metamorphic and igneous basement rocks. The Mississippian succession is termed Arroyo Peñasco Group, divided into the Espiritu Santo Fm. and overlying Tererro Fm. The Tererro Fm. is further subdivided into the (ascending) Macho, Turquillo, Manuelitas and Cowles members.

The Espiritu Santo Fm. is dated as late Tournaisian (microfossil Mamet's zone 9) based on microfossils (foraminifers). After a regressional phase during the early Viséan, interbedded carbonates and evaporites of the Macho Mb. (Mamet's zones 11 and 12) were deposited. During a transgression carbonate sedimentary rocks of

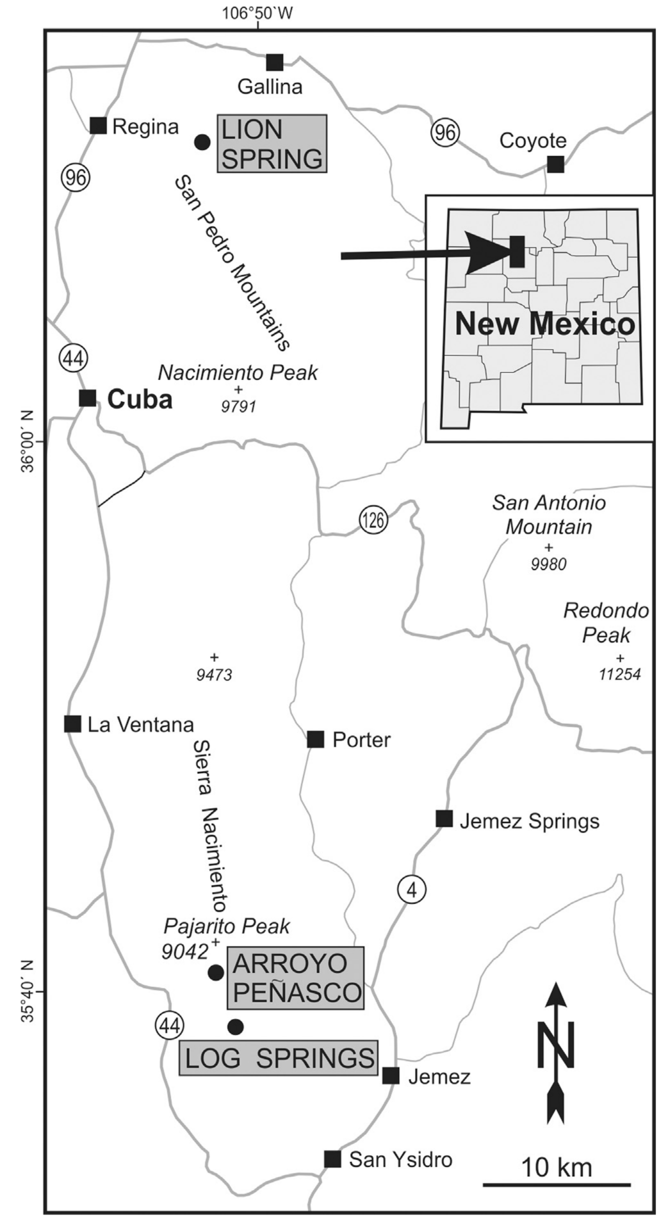


Fig. 1. Map showing locations of the studied sections in the Sierra Nacimiento and northern San Pedro Mountains in north-central New Mexico.

the Turquillo (Mamet's zones 12 and 13) and Manuelitas (zone 14) members accumulated. The Cowles Mb. is dated as Mamet's zone 16i (Armstrong et al. 2004). Krainer and Lucas (2024) pointed out that the Arroyo Peñasco Group and its subunits are too thin to be defined as a group divided into formations. The subunits ("formations") are not mappable units at most locations, so they should be regarded as of member rank (Lucas et al., 2016). Krainer and Lucas (2024) downgraded the Arroyo Peñasco Group to formation rank and proposed the following lithostratigraphic subdivision of the Mississippian succession in the Sierra Nacimiento-San Pedro Mountains-Jemez Mountains: Arroyo Peñasco Fm., subdivided into Del Padre Mb. (or Bed) and Espiritu Santo Mb. The Tererro Mb. is present in the Sangre de Cristo Mountains, but absent in the Sierra Nacimiento-San Pedro Mountains-Jemez Mountains (Fig. 3).

The Arroyo Peñasco Group in the Sierra Nacimiento-San Pedro Mountains-Jemez Mountains is overlain by the Log Springs Fm. The Pennsylvanian succession locally starts with the Osha Canyon

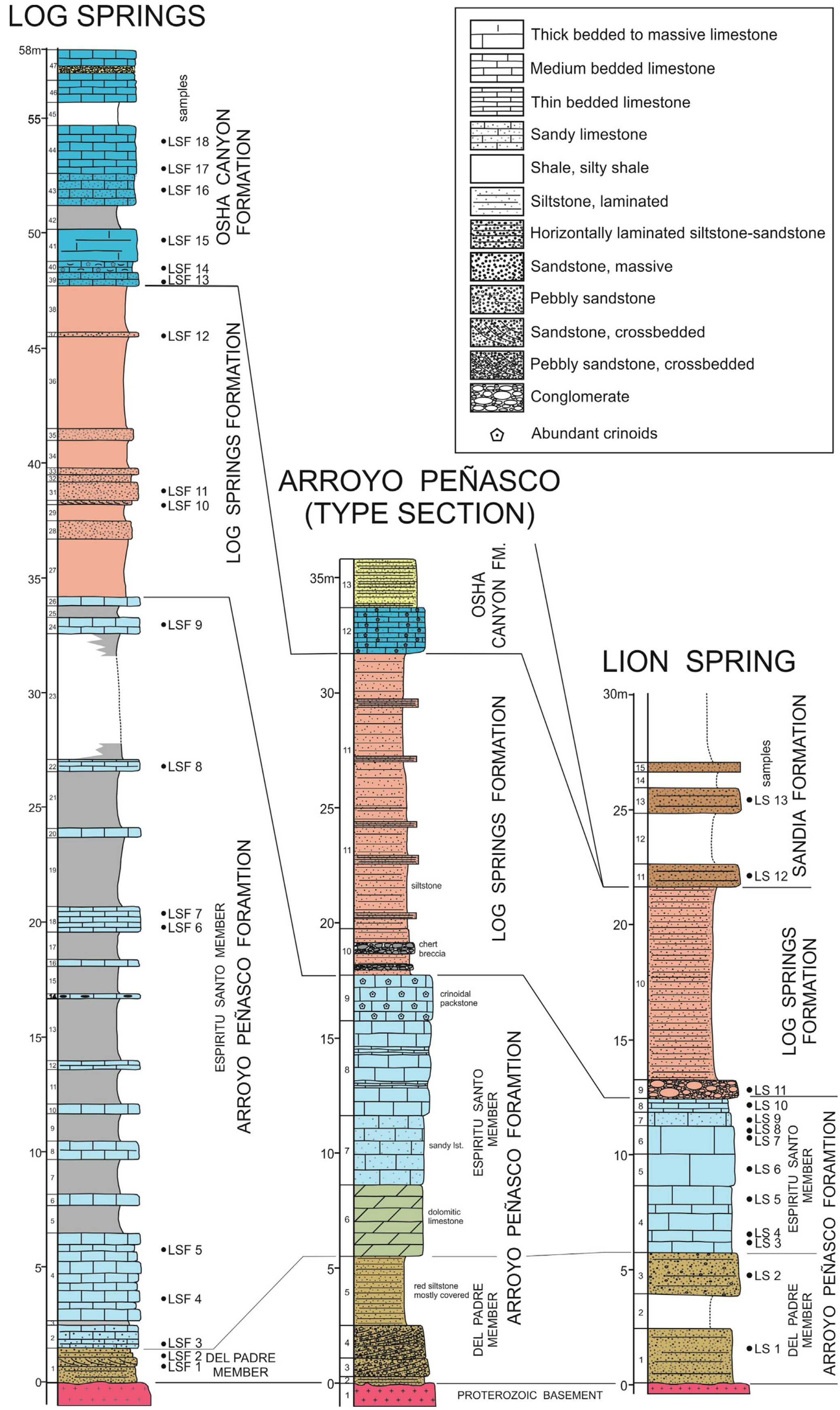


Fig. 2. Measured stratigraphic sections of the Mississippian and Lower Pennsylvanian sedimentary succession at Log Springs, Arroyo Peñasco (Sierra Nacimiento) and Lion Spring (San Pedro Mountains). The locations are shown in Fig. 1. Colors indicate the main lithofacies: gray, mudstone-shale, siltstone; brownish-yellowish colors, sandstone, conglomerate; blue, limestone; olive-green, dolomite. UTM section coordinates (from Krainer and Lucas 2024): Lion Spring, base 13, 330364E, 4004601N, top 330479E, 4004702N (NAD 27); Arroyo Peñasco, base 13, 331476E, 3946086N, top 331521E, 3946222N (NAD 83); Log Springs, base 13, 332284E, 3945207N, top 332150E, 3945643N (NAD 27).

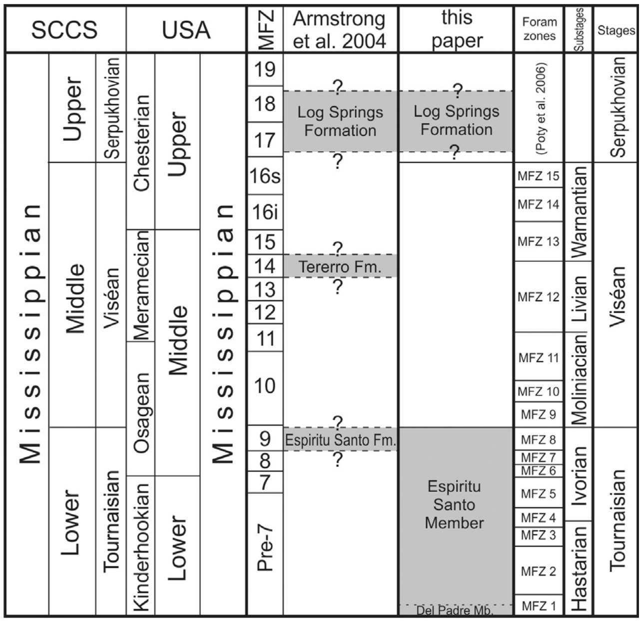


Fig. 3. Mississippian substages of the SCCS (Subcommission on Carboniferous Stratigraphy), regional substages used in the USA and stratigraphic chart for the Mississippian in the Sierra Nacimiento, Jemez and San Pedro Mountains of Armstrong et al. (2004) and this paper. Microfaunal zones (MFZ) of Armstrong et al. (2004) and Poty et al. (2006) are also shown.

Fm., but at many places the Sandia Fm. rests directly on the Log Springs Fm. (at Lion Spring) or on Proterozoic basement (Figs. 2, 3).

3. Material and methods

We studied Mississippian sedimentary rocks at Lion Spring in the northern San Pedro Mountains and at Arroyo Peñasco and Log Springs in the Sierra Nacimiento of north-central New Mexico (Figs. 1, 2). We collected rock samples from the Lion Spring and the Log Springs sections. Petrographic thin sections were prepared from sandstone samples and carbonate thin sections from limestone samples for microfacies analysis. Limestones were classified after Dunham (1962) and Embry and Klovan (1971). Foraminifers were identified from thin section photographs. We observed foraminifers in limestones of the Espiritu Santo Mb. of the Lion Spring section and of the Osha Canyon Fm. of the Log Springs section. We did not observe foraminifers in limestones of the Espiritu Santo Mb. of the Log Springs thin sections, which were mostly recrystallized.

4. Systematic palaeontology

4.1. Foraminifers of the Espiritu Santo Member (samples LS 5, LS 7, and LS 8)

In the Espiritu Santo Mb. at Lion Spring we identified the following foraminifers: *Brunsiina*? sp. (Fig. 4(A)), *Earlandia* sp. (Fig. 4(B)), *Inflatoendoyhyra* sp. (Fig. 4(C, D)), *Laxoendothyra* sp. (Fig. 4(E)), *Nodochernyshinella*? sp. (Fig. 4(F)), *Radiosphaera basilica* (Fig. 4(G)), *Radiosphaera ponderosa* (Fig. 4(H)), *Septabrunsiina minuta* (Fig. 4(I)), *Septabrunsiina* sp. (Fig. 4(J, K)), *Septaglomospiranella* ex gr. *primaeva* (Fig. 4(L-N)), *Septaglomospiranella* sp. (Fig. 4(O)), *Septatournayella* sp. (Fig. 4(P)), *Spinoendothyra spinosa* (Fig. 4(Q)), *Spinoendothyra* sp. (Fig. 4(R-U)), *Spinotournayella* sp. (Fig. 4(V)), *Tuberendothyra tuberculata* (Fig. 4(W)), and *Tuberendothyra* sp. (Fig. 5(A)).

The lower Tournaisian (= Hastarian = biozones MFZ1-4 of Poty et al., 2006) is locally characterized by *Septaglomospiranella* ex gr. *primaeva* (Fig. 4(L-N)), *Septabrunsiina minuta* (Fig. 4(I)), *Septatournayella* sp. (Fig. 4(P)), and *Spinotournayella* sp. (Fig. 4(V)) (Hance et al., 2006; Poty et al., 2014). The upper Tournaisian (= Ivorian = biozones MFZ5-9 of Poty et al., 2006) is characterized by *Spinoendothya* sp. (Fig. 4(R-U)), *Inflatoendothyra* sp. (Fig. 4(C, D)), and *Tuberendothyra* sp. (Fig. 5(A)) (see Fig. 6).

Class Calcitarcha Versteegh et al., 2009.
Order Calcisphaerales Williamson, 1881.
Family Calciphaeraceae Williamson, 1881 emend. Vachard and Téllez-Giron, 1986.
Genus ***Radiosphaera*** Reitlinger, 1957.

Type species: *Radiosphaera basilica* Reitlinger, 1957, by original designation.

Other species: See Hayward et al. (2023f).

Occurrence: Middle Devonian-Middle Carboniferous; cosmopolitan (Mamet, 2006). Rare in the latest Permian of Saudi Arabia and South China (Vachard et al., 2005; Gaillot and Vachard, 2007; Gaillot et al., 2009).

Description: Test globose with a spherical central cavity and a spinose wall, thin to thick. Wall bilayered; inner layer micritic, thin, around the central cavity; outer layer hyaline with radially arranged calcitic prisms.

Remarks: This taxon was assigned to the foraminifers (Vachard, 2016), the calcitarcha (Versteegh et al., 2009; Vachard and Le Coze, 2022), or to incertae sedis algae (Mamet, 1996a, 2006). This genus really exists as a paleobiologic entity and is not a diagenetic stage of *Eotuberina* or *Asterosphaera* (see Vachard and Clément, 1994). The nomenclatural status of the genus name is complex (Loeblich and Tappan, 1987; Mamet, 2006).

Foraminifera d'Orbigny, 1826 emend. Cavalier-Smith, 2003.
Subclass Fusulinana Maslakova, 1990.
Order Endothyrida Fursenko, 1958.
Superfamily Lituotubelloidea Miklukho-Maklay, 1963.
Family Lituotubellidae Miklukho-Maklay, 1963.
Genus ***Septaglomospiranella*** Lipina, 1955

Type species: *Endothyra*? *primaeva* Rauzer-Chernousova, 1948, by original designation.

Other species: See Hayward et al. (2023i).

Occurrence: Famennian-Tournaisian of Russian European Platform, Urals, Kuznetsk (Brenckle, 2005; Kulagina and Stepanova, 2018) and Armenia (Akopian, 1974); Strunian of Central Kazakhstan (Brenckle, 2005), Belgium and northern France (Conil and Lys, 1977), southern France (Vachard, 1974), England (Fewtrell et al., 1989), Moravia (Kalvoda, 1990), Iran (Ueno et al., 1997; Vachard, 1996), South China (Conil et al., 1988; Hance et al., 2011), Central Siberia (Bogush, 1980), Primorye (Bogush and Yuferev, 1966), USA (Montana: Sando and Mamet, 1981; Nevada: Brenckle, 1973), and Canada (British Columbia: Bamber and Mamet, 1978).

Description: Test short, inflated. Initial coiling presumably skewed, deviated perpendicularly, in relation with the terminal whorl: outer 1–1.5 whorl planispiral and slowly expanding. Septal sutures slightly depressed; periphery weakly lobate. Septa/pseudosepta short, follow the curvature of the wall and wedge-shaped through thickening at the septal join. Wall dark, single-layered and finely granular. No floor deposits. Aperture simple, basal.

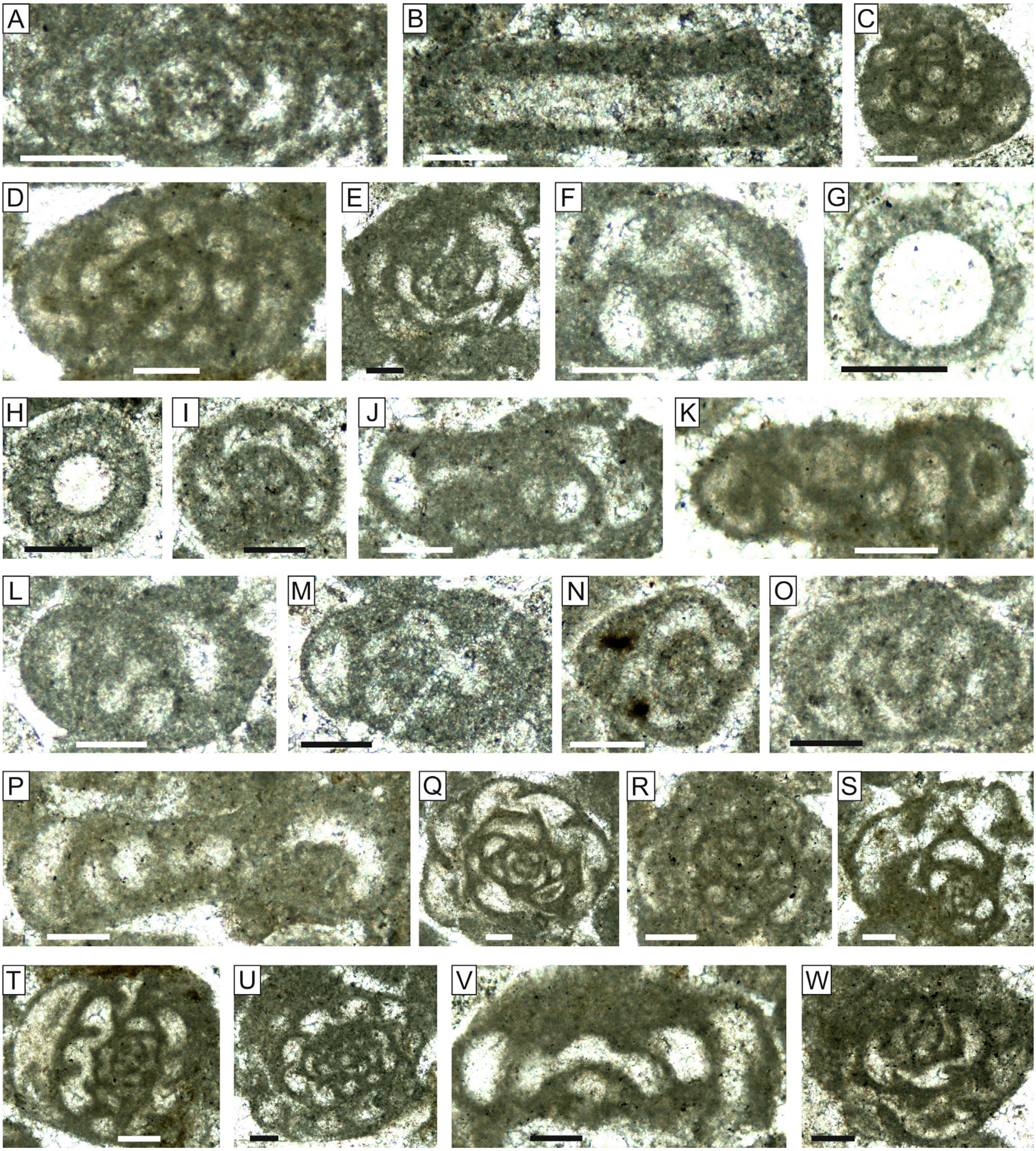
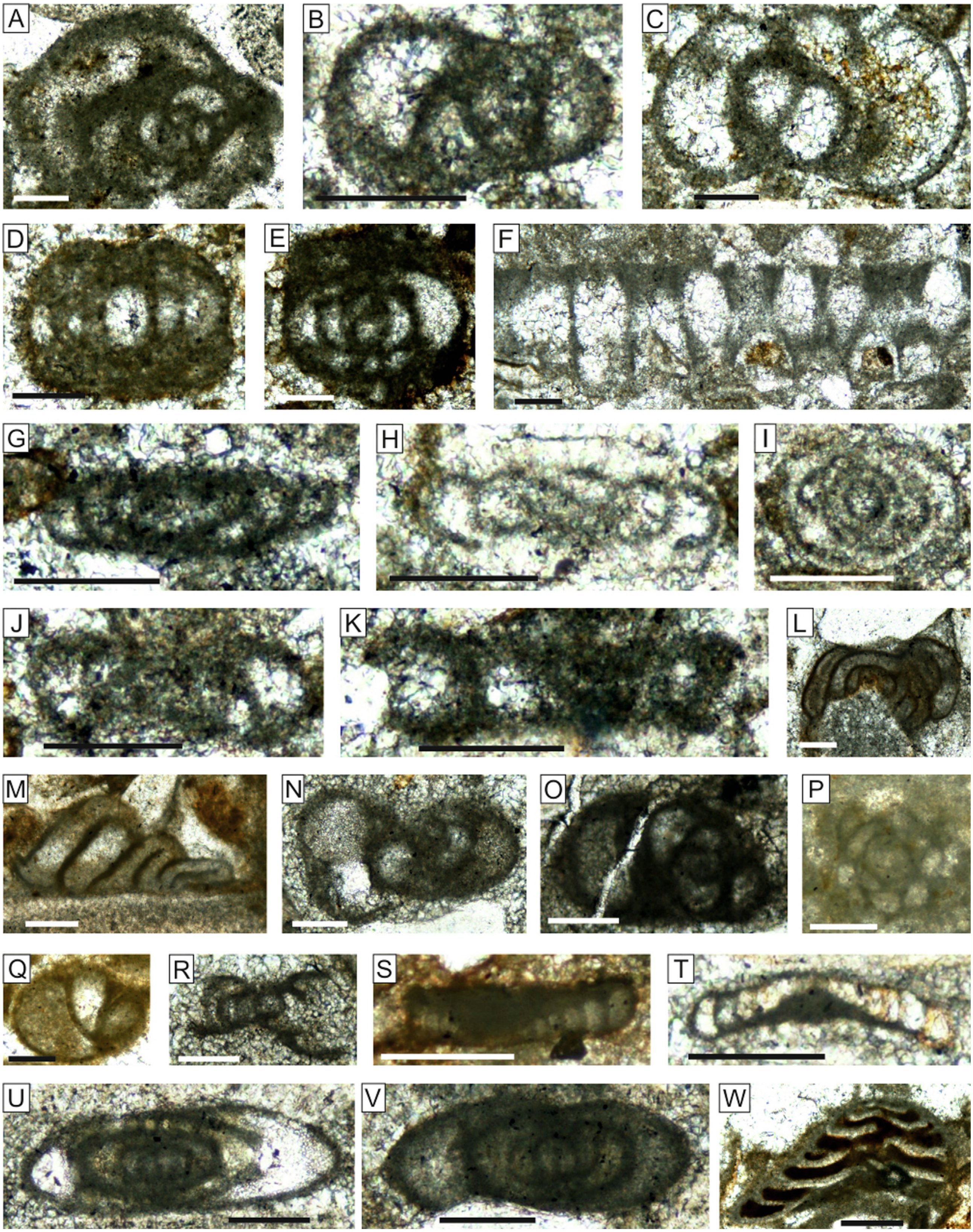


Fig. 4. Tournaisian foraminifers of the Espiritu Santo Member at Lion Spring. **A**. *Brunsiina*? sp. Subaxial section. Lion Spring. Sample LS 5-2. **B**. *Earlandia* sp. Subaxial section. Lion Spring. Sample LS 7-18. **C**. *Inflatoendoyhyra* sp. Transverse section. Lion Spring. Sample LS 8-7. **D**. *Inflatoendothyra* sp. 2. Transverse section. Lion Spring. Sample LS 8-24b. **E**. *Laxoendothyra* sp. Subtransverse section. Lion Spring. Sample LS 8-45. **F**. *Nodochernyshinella*? sp. Oblique subtransverse section. Lion Spring. Sample LS 5-1. **G**. *Radiosphaera basilica* Reitlinger, 1957. Random section. Lion Spring. Sample LS 7-14. **H.** *Radiosphaera ponderosa* Reitlinger, 1960. Random section. Lion Spring. Sample LS 7-15. I. *Septabrunsiina* ex gr. *minuta* (Lipina, 1948). Subtransverse section. Lion Spring. Sample LS 7-10. **J**. *Septabrunsiina* sp. Subaxial section. Lion Spring. Sample LS 5-3. **K**. *Septabrunsiina* sp. Subaxial section. Lion Spring. Sample LS 8-24a. **L-N**. *Septaglomospiranella* ex gr. *primaeva* (Rauzer-Chernousova, 1948). Lion Spring. L: Subaxial section. Lion Spring. Sample LS 5-5; M: Axial section. Lion Spring. Sample LS 5-4a; N: Transverse section. Lion Spring. Sample LS 7-4. **O**. *Septaglomospiranella* sp. 2. Subaxial section. Lion Spring. Sample LS 5-9. **P**. *Septatournayella* sp. 1. Subaxial section. Lion Spring. Sample LS 7-7. **Q**. *Spinoendothyra spinosa* (Chernysheva, 1940). Transverse section. Lion Spring. Sample LS 8-13. **R**. *Spinoendothyra*? sp. Subaxial section. Lion Spring. Sample LS 8-4. **S**. *Spinoendothyra* sp. 1 Transverse section. Lion Spring. Sample LS 8-12. **T**. *Spinoendothyra* sp. 3. Transverse section. Lion Spring. Sample LS 8-24. **U**. *Spinoendothyra* sp. 4. Transverse section. Lion Spring. Sample LS 8-30. **V**. *Spinotournayella* sp. 2. Subaxial section. Lion Spring. Sample LS 8-22. **W**. *Tuberendothyra tuberculata* (Lipina, 1948). Subtransverse section. Lion Spring. Sample LS 8-6. Scale bars: 100 μm.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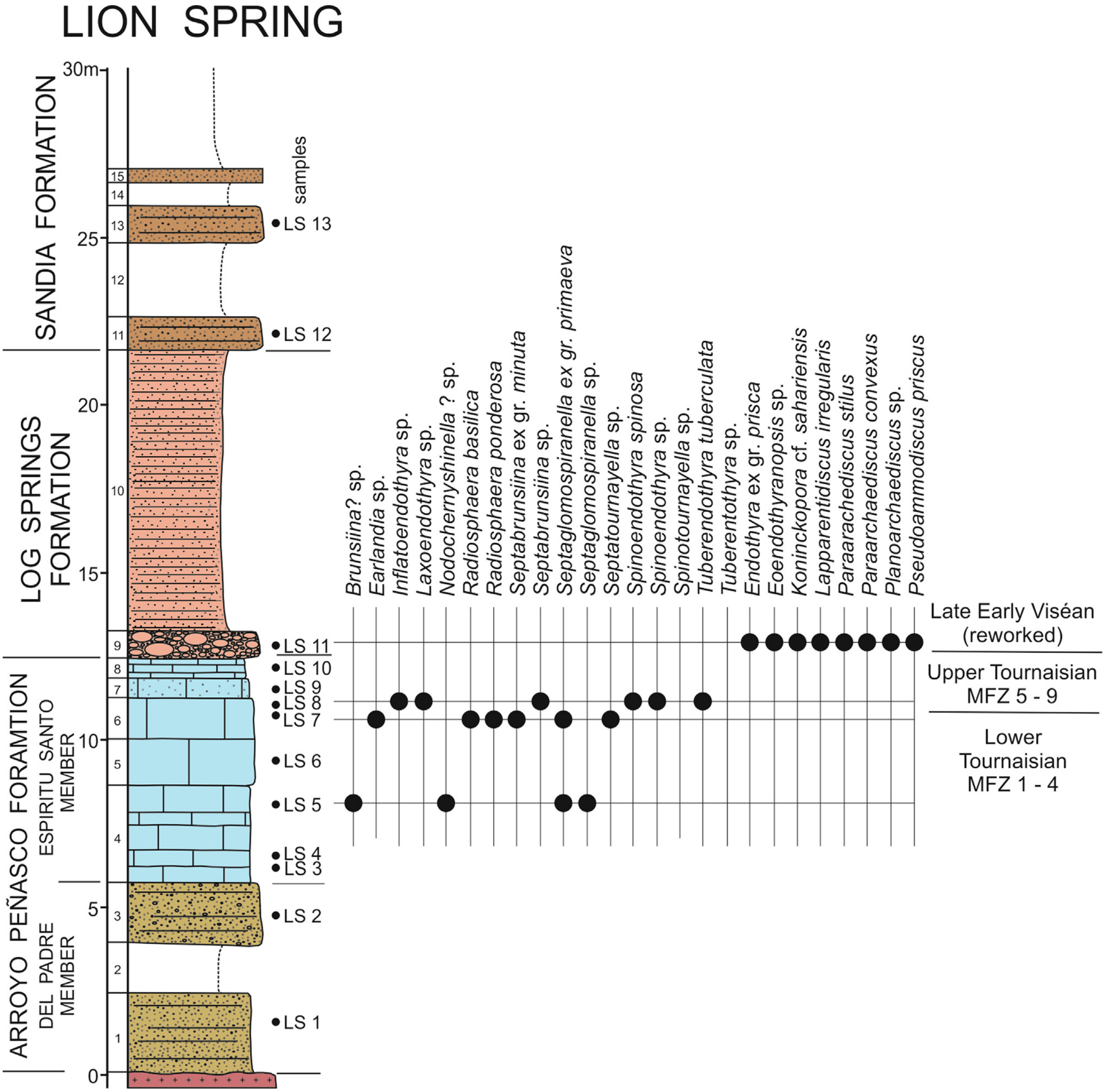


Fig. 6. Stratigraphic distribution of foraminifers in the Espiritu Santo Member of the Arroyo Peñasco Formation and the basal conglomerate of the Log Springs Formation composed of reworked clasts that contain foraminifers and the alga *Koninckopora* plotted on the Lion Spring section.

Fig. 5. Foraminifers of the Espiritu Santo Member at Lion Spring (A-C), from limestone clasts of the basal Log Springs Formation at Lion Spring (D-L) and of the Osha Canyon Formation at Log Springs (M-W). **A**. *Tuberendothyra* sp. 2. Subtransverse section. Lion Spring. Sample LS 8-27. **B**. *Endothyra* ex gr. *prisca* Rauzer-Chernousova and Reitlinger in Rauzer-Chernousova et al., 1936. Axial section. Lion Spring. Sample LS 11A-6. **C**. *Endothyra* ex gr. *prisca* Rauzer-Chernousova and Reitlinger in Rauzer-Chernousova et al., 1936. Axial section. Lion Spring-. Sample LS 11A-11. **D**. *Eoendothyranopsis* sp. 1. Axial section. Lion Spring-. Sample LS 11A-38. **E**. *Eoendothyranopsis* sp. 2. Axial section. Lion Spring-. Sample LS 11A-39. **F**. *Koninckopora* cf. *sahariensis* Chanton ex Weyer, 1968. Axial section. Lion Spring. Sample LS 11A-23. **G**. *Lapparentidiscus irregularis* Vachard et al., 2018. Subaxial section. Lion Spring. Sample LS 11A-1. **H**. *Paraarchaediscus stilus* (Grozdilova and Lebedeva in Dain and Grozdilova, 1953). Subaxial section. Lion Spring. Sample LS 11A-16. **I**. *Paraarchaediscus convexus* (Grozdilova and Lebedeva in Dain and Grozdilova, 1953). Subaxial section. Lion Spring. Sample LS 11A-20. **J**. *Planoarchaediscus* sp. Subaxial section. Lion Spring. Sample LS 11A-12. **K**. *Pseudoammodiscus priscus* (Rauzer-Chernousova, 1948). Axial section. Lion Spring. Sample LS 11A-5. **L**. *Calcivertella* sp. Axial section. Log Springs. Sample LSF 13-3. **M**. *Calcivertella* sp. Axial section. Log Springs. Sample LSF 18-6. **N**. *Endothyra* ex gr. *similis* Rauzer-Chernousova and Reitlinger in Rauzer-Chernousova et al., 1936. Oblique subaxial section. Log Springs. Sample LSF 13-9. **O**. *Endothyra* sp. Axial section. Log Springs. Sample LSF 13-7. **P**. *Eoglomospiroides* sp. Random section. Log Springs. Sample LSF 18-7. **Q**. *Globivalvulina* ex gr. *mosquensis* Reitlinger, 1950. Oblique subtransverse section. Log Springs. Sample LSF 13-4. **R**. *Iriclinella evoluta* (Reitlinger, 1950). Axial section. Log Springs. Sample LSF 13-10. **S**. *Nigrispiroides melanogaster* (Yaramazdahi and Vachard, 2019), nov. comb. Axial section. Log Springs. Sample LSF 13-4. **T**. *Nigrispiroides melanogaster* (Yaramazdahi and Vachard, 2019), nov. comb. Axial section. Log Springs. Sample LSF 13-5. **U**. *Millerella* sp. 1. Axial section. Log Springs. Sample LSF 13-1. **V**. *Millerella* sp. 2. Axial section. Log Springs. Sample LSF 13-2. **W**. *Tetrataxis* sp. Axial section. Log Springs. Sample LSF 18-3. Scale bars: 100 µm.

Septaglomospiranella ex gr. *primaeva* (Rauzer-Chernousova, 1948)
Fig. 4(L-N)

not 1940. *Endothyra primaeva* Rauzer-Chernousova – Chernysheva, p. 125, pl. 2, fig. 8.

1948. *Endothyra*? *primaeva* – Rauzer-Chernousova, p. 5–6, pl. 1, figs. 12–14.

1961. *Septaglomospiranella primaeva* var. *kazakhstanica* – Reitlinger, p. 60–61, pl. 5, figs. 9–13.

1973. *Septaglomospiranella primaeva* – Brenckle, p. 29, pl. 2, figs. 22–25, p. 29–30, pl. 3, figs. 1–5.

1974. *Septaglomospiranella primaeva armenica* – Akopian, pl. 21, figs. 7, 8.

1977. *Septaglomospiranella chernoussovensis* – Mamet in Armstrong and Mamet, p. 45, new name for *Endothyra*? *primaeva* Rauzer-Chernousova, l948.

1977. *Septabrunsiina (Septabrunsiina) educta* – Conil and Lys, p. 22, new name for *Endothyra*? *primaeva* Rauzer-Chernousova, l948, p. 22.

1978. *Septaglomospiranella primaeva* – Bamber and Mamet, p. 9.

1980. *Septaglomospiranella primaeva* – Bogush, pl. 7, fig. 2.

1981. *Septaglomospiranella primaeva* – Sando and Mamet, p. F2.

1996. *Septaglomospiranella primaeva* – Rauzer-Chernousova et al., pl. 3, figs. 9, 10.

2003. *Septaglomospiranella primaeva* – Brenckle, p. 88–89, pl. 16, fig. 7–9.

2003. *Septaglomospiranella primaeva «kazakhstanica»* – Brenckle and Milkina, pl. 1, fig. 9.

2011. *Septaglomospiranella primaeva* – Hance et al., p. 82, pl. 1, fig. 14.

2018. *Septaglomospiranella primaeva* – Kulagina and Stepanova, fig. 9.13, 9.16, 9.17, fig. 12.6, 12.8, fig. 21.11.

2018. *Septaglomospiranella* ex gr. *primaeva* – Kulagina and Stepanova, fig. 28.1, 28.3, 28.4.

2023j. *Septaglomospiranella primaeva* – Hayward et al. (not paginated).

Occurrence: Moravia (Kalvoda, 1990), Northern Eurasia (Kulagina and Stepanova, 2018), Kuznetsk (Brenckle, 2005), Armenia (Akopian, 1974). Strunian Central Kazakhstan, Central Siberia (Bogush, 1980), U.S.A. (Nevada: Brenckle, 1973), Tarim (Li, 1991). Latest Devonian of South China (Hance et al., 2011), Canada (British Columbia: Bamber and Mamet, 1978).

Superfamily Septabrunsiinoidea Conil and Lys, 1977.
Genus ***Septabrunsiina*** Lipina, 1955

Type species: *Endothyra*? *krainica* Lipina, 1948, by original designation.

Other species: See Hayward et al. (2023g).

Occurrence: Latest Devonian-early Viséan (Donbas, Russian European platform, Moscow Basin, Urals, Timan and Pripechora, Karatau, Kazakhstan, Kuzbass, Belgium, northern France, England. Germany (Conil and Paproth, 1983). Central Siberia (Bogush, 1980). Primorye (Bogush and Yuferev, 1966). Canada (British Columbia: Bamber and Mamet, 1978). U.S.A. (Utah, Alaska, Idaho, Montana, Wyoming, Mississippi, Nevada, New Mexico: Zeller, 1957; Brenckle, 1973; Loeblich and Tappan, 1987; Fewtrell et al., 1989; Rauzer-Chernousova et al., 1996; Brenckle, 2005). Mexico (Sonora: Palafox, 2011). Greece (Vachard and Clément, 1994). Northern Turkey (Dil, 1977). Turkey (Central Taurides; Dinç, 2009). Iran (Bozorgnia, 1973; Ueno et al., 1997; Vachard, 1996). South China (Conil et al., 1988; Hance et al., 2011).

Description: Test small, discoid. Initial coiling presumably skewed but obscured by high section: outer 1–1.5 whorls planispiral and slowly expanding. Septal sutures slightly depressed; periphery weakly lobate. Pseudosepta short, follow the curvature of the wall and wedge-shaped through thickening at the septal join. Wall dark, single-layered and finely granular. No floor deposits. Aperture terminal, simple, basal.

Septabrunsiina minuta (Lipina, 1948)
Fig. 4(I)

1948. *Endothyra*? *minuta* Lipina – p. 255–256, pl. 19, figs. 7, 8.

1957. *Endothyra taedia* Zeller – p. 700–701, p. 79, fig. 11, pl. 80, fig. 12.

1965. *Septabrunsiina minuta* – Lipina, p. 53–54, pl. 11, figs. 9–11, 14–29.

1980. *Septabrunsiina minuta* – Bogush, pl. 6, figs. 13–15.

1994. *Septabrunsiina* (*Septabrunsiina*) *minuta tournayelloides* – Vachard and Clément, p. 304, pl. 2, figs. 17–20.

2005. *Septabrunsiina minuta* (Lipina, 1948) – Brenckle and Hance, p. 197, pl. 1, figs. 11–19.

2005. *Septabrunsiina minuta* (Lipina, 1948) – Brenckle, p. 87–88, pl. 16, figs. 1–3.

2023h. *Septabrunsiina minuta* (Lipina, 1948) – Hayward et al. (not paginated).

Occurrence: Cherepetian of Russian platform and the Urals (Lipina, 1965). Hastarian of Belgium (Brenckle and Hance, 2005). Greece (Vachard and Clément, 1994). Moscow Basin, Utah (Brenckle, 2005). Central Siberia (Bogush, 1980). Armenia (Akopian, 1974). Canada (British Columbia: Bamber and Mamet, 1978).

Description: Test small, discoid; initial coiling glomospiroid; last four whorls nearly planispiral. Septal sutures slightly depressed. Chambers poorly inflated with a periphery smooth. Pseudosepta poorly developed in first planispiral whorl, after which they appear as short, blunt, and wedge-shaped. Wall recrystallized, granular, single-layered. No secondary floor deposits. Aperture terminal simple.

Superfamily Tournayelloidea Dain, 1953
Genus ***Tournayella*** Dain, 1953

Type species: *Tournayella discoidea* Dain, 1953, by original designation.

Other species: See Hayward et al. (2023l) (read: 2023L).

Occurrence: Latest Devonian-Tournaisian, early Viséan; Donbas, Russian Platform, Urals central Karatau (Lipina, 1965). Armenia (Akopian, 1974). Turkey (Central Taurides; Dinç, 2009). Afghanistan (Vachard, 1980; Vachard and Montenat, 1996). England (Fewtrell et al., 1989). Central Siberia (Bogush, 1980). Primorye (Bogush and Yuferev, 1966). U.S.A. (Nevada: Brenckle, 1973). Canada (British Columbia: Bamber and Mamet, 1978). Tarim (Li, 1991). South China (Ye, Lin, and Gu, 1987; Hance et al., 2011).

Description: Test discoidal, planispiral evolute with steady expansion, biconcave, with umbilical areas rather depressed. Small pseudosepta developed as slight depressions along the wall of the outer three volutions; inner volutions smooth. Periphery slightly lobate. No supplementary formations. Thus, basal micritic sediments can be present in the tests of *Septatournayella* but are not present in *Tournayella*. Wall dark, single-layered and granular with scattered lighter-colored grains; aperture terminal, simple.

Genus ***Inflatoendothyra*** Brazhnikova and Vdovenko in Vdovenko, 1972.

Type species: *Endothyra parainflata* Bogush and Yuferev, 1970, by original designation.

Other species: See Hayward et al. (2023c).

Occurrence: Northern Eurasia (Kulagina and Stepanova, 2018). Timan-Pechora (Durkina, 1984). Middle Urals (Malakhova, 1956). Central Kazakhstan (Brenckle and Milkina, 2003). Turkey (Central Taurides; Dinç, 2009). Iran (Ueno et al., 1997). Moravia (Kalvoda, 1990). South China (Hance et al., 2011). Primorye (Bogush and Yuferev, 1966). Canada (British Columbia; Bamber and Mamet, 1978). U.S.A. (Montana: Sando and Mamet, 1981; Alaska: Armstrong and Mamet, 1988); Mexico (Sonora; Palafox, 2011; Buitrón-Sánchez et al., 2012).

Description: Coiling initially skewed, changing to planispiral in last whorls, Septal sutures slightly depressed; periphery weakly lobate. Septa medium, straight, wedge-shaped through thickening at the join and at high angle to the wall. Wall dark, granular and unilayered. Basal deposits as floor cover in outer volutions. Aperture simple, basal.

Genus ***Spinoendothyra*** Lipina in Poyarkov, 1963

Type species: *Endothyra costifera* Lipina, 1955, by original designation.

Other species: See Hayward et al. (2023k).

Occurrence: Earliest Viséan of Donets Basin, late Tournaisian of the Middle Urals (Brenckle, 2005), Central Kazahstan (Brenckle and Milkina, 2003). Canada (Alberta: McKay and Green, 1963; British Columbia: Bamber and Mamet, 1978). U.S.A. (Montana: Sando and Mamet, 1981). England (Fewtrell et al., 1989). Southern France (Vachard, 1974). Northern Eurasia (Kulagina and Stepanova, 2018). Moravia (Kalvoda, 1990). Northern Turkey (Dil, 1977). Tarim (Li, 1991). South China (Hance et al., 2011).

Description: Coiling tight; initially skewed, then planispiral in last 2 whorls. Septal sutures flat; periphery smooth. Septa straight, relatively long, and at a high angle to the wall. Basal deposits mostly as small, unconnected triangular mounds in the middle of the chambers of the planispiral whorls. Wall dark, microgranular and unilayered. Aperture terminal, basal, simple.

Genus ***Tuberendothyra*** Skipp, 1969.

Type species: *Endothyra tuberculata* Lipina, 1948, by original designation.

Other species: See Hayward et al. (2023m).

Occurrence: Late Tournaisian of the Middle Urals, Volga-Urals region, Siberia, Russian Platform, England, USA (Nevada, Arizona, Colorado, New Mexico, Montana, Alaska, Canada, Alberta; Loeblich and Tappan, 1987), Canada (British Columbia: Bamber and Mamet, 1978). Mexico (Sonora; Palafox, 2011). Northern Eurasia (Kulagina and Stepanova, 2018). Southern France (Vachard, 1974). Moravia (Kalvoda, 1990). Tarim (Li, 1991). South China (Conil et al., 1988; Hance et al., 2011). Kuzbass (Colpaert et al., 2017). Primorye (Bogush and Yuferev, 1966).

Description: Coiling skewed throughout; last volution loosely coiled. Septal sutures depressed; periphery lobate. Inner septa short and wedge-shaped; outer ones long, curved, thickened slightly along the septal face and at the join, and at moderate to high angle to the wall. Basal deposits as low, unconnected mounds in a few chambers of the last volution. Wall dark, granular, unilayered, and poor coarsely perforate. Aperture simple, basal.

Genus ***Koninckopora*** Lee, 1912.

Fig. 5(F)

Type species: *Calamopora inflata* de Koninck, 1842, by original designation.

Other species: See Armstrong and Mamet, 1977; Vachard et al., 2014. *Koninckopora tenuiramosa* Wood, 1942; *K. pruvosti* Güvenç, 1966 (= *K. minuta* Weyer, 1968); *K. pruvosti* sensu Mamet and Roux, 1983 = *K. minuta* sensu Mamet and Roux, 1983 = *K. tenuiramosa* sensu stricto); *K. sahariensis* Chanton, 1965; *K. mortelmansi* Mamet, 1973. In contrast, *Koninckoporella* Mamet and Préat, 2013, with *K. pachytheca* (Mamet, 2006) and *K. acilaensis* Mamet and Préat, 2013, seems to be a diagenetic stage, not ontogenetically different from *Koninckopora.* In eastern Asia, *Koninckopora tenuiramosa* is present as far north as Japan, where it was described under the name *Koninckopora delicata* Nakai and Kato, 1981.

Description: Thallus large, conical to subcylindrical, unsegmented, stout, with cylindrical medulla. Laterals polygonal, forming continuous cell layers. Wall bilayered; an inner dark micritic layer coated by pseudofibrous yellowish calcite.

Remarks: Koninckoporaceans are probably photic algae, the assignment of which to the dasycladales is disputed, because of: (*i*) their gigantic size for an unicellular organism; (*ii*) a type of wall very rare among the true dasycladales, except for *Clypeina* (see Vachard, 2021); (*iii*) an evolution of the wall from unilayered dark microgranular walls to bilayered walls, with an additional hyaline fibrous layer; (*iv*) a very large distribution of the genus *Koninckopora,* from Alaska to NW Australia, via South China and Japan and during a very short interval of time, from middle Visean to early Serpukhovian, whereas the Carboniferous-Permian, true dasycladales have a very limited paleogeographical distribution (e.g., *Eovelebitella*, from northern Spain to Austria; *Imperiella*, from Iran to Tajikistan; and *Sinoporella*, endemic in South China); and (*v*) in NW Australia, the microfacies with abundant *Koninckopora* seems to be the deepest in the region, with a water depth of 10–20 m, when true dasycladales are rather located between 0 and 5 m (Vachard et al., 2014).

The Koninckoporaceae are almost exclusively represented by the eponymic genus. However, unilayered *Koninckopora* could be described as a new genus, more or less morphologically related with the thaumatoporellales. In contrast, *Koninckoporella* seems to be a taxon not ontogenetically different from *Koninckopora*, and *Eokoninckopora* differs totally. *Koninckopora micropora* and *K. macropora* Maslov (1956) are both considered to belong to *Epimastopora* as suggested by Weyer (1968).

Genus ***Paraarchaediscus*** Orlova 1955 emend. Brenckle et al., 1987.

Type species: *Paraarchaediscus dubitabilis* Orlova, 1955 (=?*A. stilus* Grozdilova and Lebedeva in Grozdilova, 1953; for discussion see Conil and Lys, 1968; Conil et al., 1980; Brenckle and Grelecki, 1993).

Other species: See Hayward et al. (2023d).

Occurrence: Early middle Viséan (= V1bγ = late Moliniacian = Arundian = Cf4δ = MFZ11)-earliest Moscovian, cosmopolitan; or, at least locally: Holkerian (= Livian)-Arnsbergian (early Serpukhovian) (Cózar et al., 2008; Somerville, 2008).

Description: Archaediscinae with a hyaline wall dominant upon an inner dark layer reduced to a thin inner line. Test entirely involute, oscillant, sigmoidal to aligned. Lumen at concavus stage. Nodosities absent.

Remarks: *Paraarchaediscus* can be defined as a distinct genus based on two characters: the subsisting, relatively well developed, black layer, but without buttresses, and lumina at concavus stage. However, the type species of this genus was poorly defined, never revised and possibly a synonym of *Archaediscus stilus* (see Conil et al., 1980: p. 38). On the other hand, among the true *Archaediscus* (see below), the inner line is absent or very faint in the holotype of *A. karreri*, but it can be obvious in some forms of the groups *A. gigas*, *A. karreri* and *A. enormis*. Perhaps this preservation of inner dark line can explain why Somerville et al. (1992: table 3, p. 211), Gallagher and Somerville (1997: text-fig. 8, p. 325), and Cózar (2004: text-fig. 6, p. 378, pl. 1, figs. 10, 11, 13) listed both *Paraarchaediscus @ angulatus* and *Archaediscus @ angulatus* in their tables. Other authors speak of *Paraarchaediscus @ involutus* (Somerville et al., 1992; Cózar, 2004; Gallagher et al., 2006). Both generotypes, *Propermodiscus ulmeri* and *Paraarchaediscus dubitabilis*, are very similar (Loeblich and Tappan, 1987; Laloux, 1988). Nevertheless, *Propermodiscus ulmeri* shows a last lumen at the involutus stage, whereas *Paraarchaediscus dubitabilis* is entirely at the stage concavus. Neither *Propermodiscus* nor *Paraarchaediscus* have been recently revised. However, even if Somerville (2008: p. 217) indicates that "involutus stage forms can have concavus-style suture in the outer whorls", we consider herein the two characters as generically distinct; consequently, we re-introduce the name *Propermodiscus* as different from *Paraarchaediscus* or *Glomodiscus*.

Paraarchaediscus stilus (Grozdilova and Lebedeva in Dain and Grozdilova, 1953)

Fig. 5(H)

Remarks: See Hayward et al. (2023e).

Paraarchaediscus convexus (Grozdilova and Lebedeva in Dain and Grozdilova, 1953)

Fig. 5(I)

Remarks: See Hayward et al. (2023a).

Family Eoendothyranopsidae Reitlinger in Rauzer-Chernousova et al., 1996.

Genus ***Eoendothyranopsis*** Reitlinger and Rostovzeva in Reitlinger, 1966.

Synonym: *Eomillerella* Skipp, 1969.

Type species: *Parastaffella pressa* Lebedeva, 1954, by original designation.

Other species: See Hayward et al. (2023b).

Occurrence: C_1^va-C_1^vd of Donbas; early-middle Viséan of Urals; Kazakhstan (Brenckle and Milkina, 2003); Kuznetsk Basin (Brenckle, 2005); Central Siberia (Bogush, 1980); upper MFZ9-lower MFZ11 of Belgium; cosmopolitan and very developed in North America (Brenckle, 1973, 1991; Armstrong and Mamet, 1988); Canada (Alberta: McKay and Green, 1963; British Columbia: Bamber and Mamet, 1978); ?Earliest Brigantian of Derbyshire, England (Strank, 1985).

Eoendothyranopsis sp. illustrated by Devuyst (2006: text-fig. 5.10 and text-fig. 5.11A.13), from the MFZ8 of northern Iran, constitutes a peculiar case or is probably misinterpreted and confused with a dainellid (perhaps *Lysella*).

Diagnosis: Test medium to large, nautiloid, involute, almost planispiral and shallowly biumbilicate. Periphery rounded to angular. Chambers relatively numerous, sutures poorly marked. Supplementary deposits represented by pseudochomata and an incurved spine in the last chamber. Wall brownish, thick, granular, with inclusions of light-colored calcite, sometimes with an outer tectum. Aperture terminal simple.

4.2. Foraminifers of the Osha Canyon Formation

The occurrence of foraminifers in limestones of the Osha Canyon Fm. was mentioned by Krainer and Lucas (2005), but the foraminifers were not determined. Here we present a small foraminiferal assemblage of the Osha Canyon Fm. of the Log Springs section including *Calcivertella* sp. (Fig. 5(L, M)), *Endothyra* ex gr. *similis* (Fig. 5(N)), *Endothyra* sp. (Fig. 5(O)), *Eoglomospiroides* sp. (Fig. 5(P)), *Globivalvulina* ex gr. *mosquensis* (Fig. 5(Q)), *Iriclinella evoluta* (Fig. 5(R)), *Nigrispiroides melanogaster* nov. comb. (Fig. 5(S, T)), *Millerella* sp. (Fig. 5(U, V)), and *Tetrataxis* sp. (Fig. 5(W)).

The Morrowan age of the basal Osha Canyon Fm. is based on *Nigrispiroides* nov. gen., *Iriclinella*, *Globivalvulina*, and *Millerella* (sample LSF13).

Genus ***Nigrispiroides*** nov. gen.

Derivation of the name: Latin niger, nigris: black; because of the dark umbilical filling, and ending of *Turrispiroides*, related genus.

Type and only species: *Monotaxinoides*? *melanogaster* Yarahmadzahi and Vachard, 2019, by original designation herein.

Occurrence: Morrowan of Peru; Morrowan-late Atokan of Brazil; Morrowan-early Desmoinesian of New Mexico, late Morrowan of Oklahoma; lower Atokan of Idaho; Atokan of Yukon (Canada). Late Pennsylvanian of Iran.

Diagnosis: See below, diagnosis of *Nigrispiroides melanogaster* nov. comb., by monotypy.

Description: Test low, conical, plano-convex. Spiral face evolute with weakly depressed sutures. Proloculus small to very small, spherical, followed by a tubular, undivided chamber. Lumina at concavus stage (i.e., semicircular to subcrescentic in axial section). Umbilical filling well developed in the ventral face. Wall and umbilical filling dark, microgranular. Aperture at the end of the chamber.

Nigrispiroides melanogaster (Yarahmadzahi and Vachard, 2019), nov. comb.

Fig. 5(S, T)

1976. *Monotaxinoides multivolutus* – Mamet, p. 86, fig. 4, pl. 87, fig. 4, pl. 88, figs. 1–4.

1977. No legend – Nodine-Zeller, pl. 3, fig. 26 (located below the *Ozawainella*? sp. in the figure).

1983. *Monotaxinoides transitorius* – Groves, p. 21–22, pl. 3, figs. 15–19.

1984. *Monotaxinoides transitorius* – Groves, pl. 4, figs. 10–17.

1992. *Monotaxinoides transitorius* – Groves, p. 149–150, pl. 3, figs. 27–33.

1995. *Monotaxinoides transitorius* – Altıner and Savini, p. 434, pl. 5, figs. 8–11.

1996b. *Eolasiodiscus donbassicus* – Mamet, pl. 1, fig. 27.

1997. *Monotaxinoides transitorius* – Wood et al., pl. 11, figs. 3, 7.

1998. *Monotaxinoides transitorius* – Pinard and Mamet, p. 101–102, pl. 25, figs. 16, 21.

2002. *Monotaxinoides transitorius* – Wood et al., pl. 7 fig. 19.

2015. N. gen. n. sp. = *Monotaxinoides transitorius* sensu Groves – Krainer et al., p. 21, fig. 14.11–13.

2016. *Cornuspira* sp. transitional to *Turrispiroides* (= *Monotaxinoides* auctorum) – Lucas et al., fig. 22.18–24.

2016. Miliolata similar to *Turrispiroides* – Lucas et al., p. 88–89 (no illustration).

?2017. N. gen. aff. *Turrispiroides* (= "*Monotaxinoides*" of the authors) – Krainer et al., fig. 22Aa.

2019. *Monotaxinoides*? *melanogaster* – Yarahmadzahi and Vachard, p. 114, fig. 6.1–12.

Occurrence: As for the genus *Monotaxinoides*? (with references earlier): Morrowan–early Desmoinesian of the U.S.A. (Arkansas, Idaho, New Mexico, Oklahoma, Texas), Canada, Peru; and early?–middle? Gzhelian (but possibly reworked from the Moscovian/Kasimovian?) of Asad-Abad (Central Iran).

Measurements: D = 143–260 µm; w = 30–45 µm; H = 50–75 µm; p = 5–7 µm; n = (7)–9–12; h = 10–18 µm; s = 5–7 µm.

Diagnosis: Test low conical, plano-convex. Spiral face evolute with weakly depressed sutures. Proloculus spherical, very small. Lumina at concavus stage (i.e., semicircular to subcrescentic in axial section). Umbilical filling well developed. Aperture at the end of the chamber.

Remarks: This species is superficially homeomorphous of some so-called *Monotaxinoides* of the Americas, but it differs in its unilayered wall, and because the test wall lacks two distinct microstructures, dark-microgranular and clear pseudofibrous. *Monotaxinoides transitorius*, in the sense of Groves (1983), is relatively similar in all its parameters, but is larger (D = 218–305 μm) despite a fewer number of whorls (n = 9–10), and has a larger proloculus (p = 12–23 μm). Therefore, these false *Monotaxinoides*? of the Americas likely correspond to another species of *Turrispiroides*?. However, rare, true lasiodiscids, *Monotaxinoides* and/or *Eolasiodiscus*, and *Mesolasiodiscus* have been illustrated in the Americas, for example by Armstrong and Mamet (1977: p. 99–100, pl. 35, figs. 16–18), Groves (1992: pl. 3, figs. 34–40), and Lucas et al. (2016: fig. 11a–c).

Genus ***Iriclinella*** Malakhova, 1980.

Type species: *Endothyra spirilliniformis* var. *evoluta* Reitlinger, 1950, by original designation.

Other species: See Hayward et al. (2024). *Iriclinella fastuosa* Malakhova, 1980; *I. fastuosa* forma *minima* Malakhova, 1980; *Endothyra mameti* Igo and Adachi, 1981; ?*E. spirilliniformis* Brazhnikova and Potievska, 1948; ?*E. tatianae* Ganelina, 1956.

Occurrence: Bashkirian-early Moscovian of the southern Urals (Malakhova, 1980); southern Timan (Reitlinger, 1950), Bashkirian of Donbas (Brazhnikova and Potievska, 1948; Manukalova-Grebenyuk et al., 1969; Nemirovskaya et al., 1991). Bashkirian of Japan (Igo and Adachi, 1981).

Description: Test endothyrid, biumbilicated, with a broadly rounded periphery, with initial whorls endothyroid and slightly deviated, and adult whorls nearly planispiral and evolute. The height of whorl increases rapidly throughout growth. Secondary basal deposits faint to absent. Wall microgranular unilayered. Aperture terminal simple.

Genus ***Globivalvulina*** Schubert, 1921.

Type species: *Valvulina bulloides* Brady, 1876, by original designation.

Other species: See Hayward et al. (2021).

Occurrence: Latest Serpukhovian-latest Changhsingian; cosmopolitan.

Description: Test free, biserially coiled to biseriate. Few whorls, few chambers increasing rapidly in height. An oral valvula near the aperture. Supplementary deposits absent or very rare. Supplementary chamberlets occasionally present. Wall unilayered dark microgranular or granular with calcareous agglutinate, or bilayered with an inner pseudofibrous layer. Aperture simple basal.

Globivalvulina ex gr. *mosquensis* Reitlinger, 1950.

Fig. 5(Q)

1950. *Globivalvulina mosquensis* Reitlinger – p. 79, pl. 16, figs. 1–4.

2005. *Globivalvulina mosquensis* – Brenckle, p. 49, pl. 8, figs. 9, 10.

Description. Test composed of steadily expanding, biseriate chambers, coiled in a low, helical spire. Septal sutures flat; periphery smooth. Wall dark, microgranular along periphery with an additional hyaline-radial layer developed beneath septa. Funnel visible along base of outer chambers.

Family Ozawainellidae Thompson and Foster, 1937.

Subfamily Millerellinae Vachard, Krainer and Lucas, 2013.

Included genera: *Plectomillerella* Brazhnikova and Vdovenko in Aizenverg et al., 1983; *Millerella* Thompson, 1942; *Rectomillerella* Nguyen Van Liem, 1974; *Seminovella* Rauzer-Chernousova in Rauzer-Chernousova et al., 1951; *Novella* Grozdilova and Lebedeva, 1950; *Pseudonovella* Kireeva, 1949; *Pseudoacutella* Vachard, Krainer and Lucas, 2013.

Occurrence: Serpukhovian-Kasimovian; *Millerella*, *Pseudonovella* and *Pseudoacutella* are probably cosmopolitan but poorly known; the other genera are endemic to the Paleotethyan and Uralian Provinces.

Remarks: Ozawainellidae with a diversely developed evolute stage (i.e., short or long, terminal or initial, broad or narrow). Pseudochomata always poorly marked. Wall simple unilayered.

Genus ***Millerella*** Thompson, 1942.

Fig. 5(U, V)

Type species: *Millerella marblensis* Thompson, 1942, by original designation.

Other species: See Maslo and Vachard (1997), van Ginkel (2010), and Hayward et al. (2024).

Occurrence: Latest Serpukhovian-latest Changhsingian; cosmopolitan.

Description: Test small, planispiral, lenticular to discoid. Periphery subrounded to subcarinate. The coiling is involute to evolute in the last whorls. Proloculus small, Septa planar; perpendicular or falciform. Tunnel narrow. Chomata small or unconspicuous. Wall microgranular, unilayered. Aperture terminal, simple and basal.

5. Results

5.1. Lion Spring

5.1.1. Arroyo Peñasco Formation

At Lion Spring, in the northern San Pedro Mountains, the Proterozoic basement rocks are nonconformably overlain by a thin succession of Mississippian sedimentary rocks, divided into Arroyo Peñasco Fm. and Log Springs Fm. overlain by the Pennsylvanian Sandia Fm. (Fig. 2). The Arroyo Peñasco Fm. is 12.4 m thick and divided into Del Padre Mb. (5.7 m) and Espiritu Santo Mb. (6.7 m). The overlying Log Springs Fm. is 9.2 m thick. The section we measured is much thinner than the San Pedro section of Armstrong (1967) that he measured 3 miles (4.8 km) east of Regina.

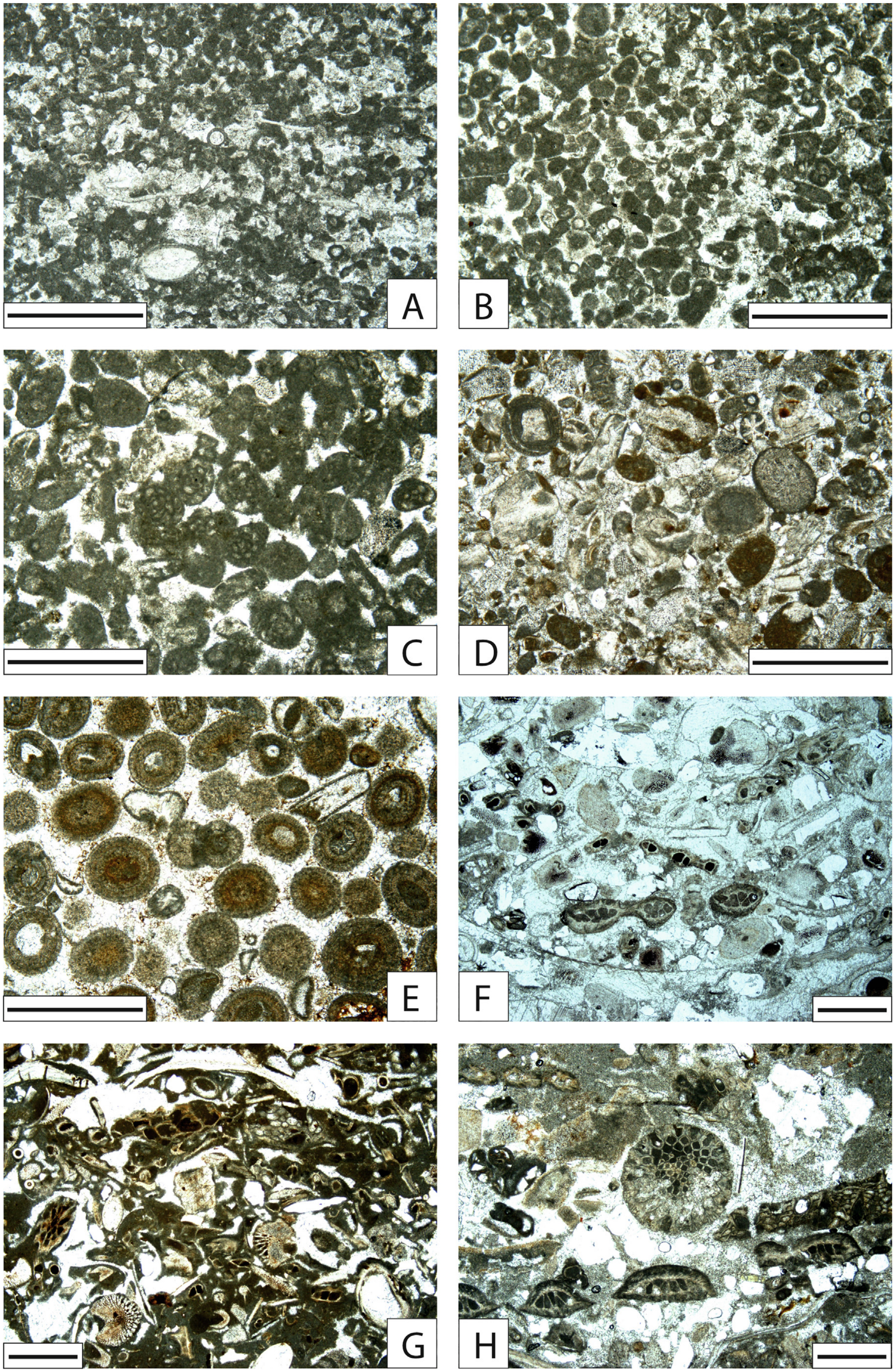
5.1.2. Del Padre Member

Lithology. At Lion Spring, the Proterozoic basement is overlain by a thin Del Padre Mb. that is poorly exposed, yellowish-brownish, coarse-grained sandstone (2.4 m), followed by a covered interval (1.5 m) and then red colored, coarse-grained pebbly sandstone (1.8 m) displaying poorly developed horizontal lamination. Individual quartz grains include pebbles and have diameters up to 1–2 cm.

Petrography. The sandstone is poorly sorted, pebbly and composed mostly of subangular grains, mostly with diameters < 1 mm, rarely up to several mm. The sandstone is composed entirely of quartz grains (quartz arenite), dominantly of monocrystalline quartz, and subordinately of polycrystalline quartz, including stretched metamorphic quartz grains. Other grain types such as feldspars, micas or rock fragments are absent. The sandstone contains some quartz cement in the form of authigenic overgrowths on detrital quartz grains, opaque cement (probably Fe hydroxides) and small amounts of matrix.

5.1.3. Espiritu Santo Member

Lithology. The Espiritu Santo Mb. is dominantly composed of indistinctly thick-bedded, gray limestone and a thin-bedded micritic limestone interval (0.6 m) on top.


A
B
C
D
E
F
G
H

Microfacies. Limestone is partly recrystallized, partly well preserved. The lowermost limestone beds (samples LS 3 and 4) are recrystallized, so the original microfacies is strongly to completely destroyed. Sample LS 3 is microsparite (recrystallized micrite) containing poorly preserved larger shell fragments, probably derived from brachiopods and ostracods. Sample LS 4 is strongly recrystallized and was probably a bioclastic wackestone. Other recrystallized limestone beds include sample LS 6 (microsparite) and LS 10 at the top of the Espiritu Santo Mb. (microsparite).

Limestone that is not recrystallized (samples LS 5, 7, 8, 9) is composed of grainstone/packstone with varying amounts of peloids, micritic intraclasts, smaller foraminifers and, subordinately, other fossils. The limestone bed of sample LS 5 is grainstone/packstone composed of abundant peloids and micritic intraclasts (Fig. 7(A)). Subordinately, shell fragments, echinoderms, ostracods and smaller foraminifers are present. Sample LS 7 also is composed of abundant peloids and micritic intraclasts, but contains many spherical grains (radiospheres), a few ostracods, smaller foraminifers and rare echinoderm fragments (Fig. 7(B)).

Sample LS 8 is poorly washed grainstone/packstone that, besides peloids and micritic intraclasts, contains abundant foraminifers (including many endothyrid species). Other fossils present are echinoderm fragments and recrystallized skeletons. This microfacies type contains small amounts of micritic matrix (Fig. 7(C)).

Sample LS 9 is grainstone/packstone composed of micritic intraclasts, abundant recrystallized skeletons, echinoderm fragments, smaller foraminifers, ostracods and rare gastropods and bryozoans.

At the Lion Spring section, the most abundant facies is grainstone/packstone with abundant peloids, micritic intraclasts, smaller foraminifers and, subordinately, other fossils. This belongs to microfacies 5 – pelletoid packstone – of Armstrong (1967). Subordinately, bioclastic wackestone (poorly preserved due to recrystallization) is present, belonging to microfacies 1 of Armstrong (1967). Microfacies 3 – oolitic grainstone and packstone – and 4 – ooid packstone with abundant bioclasts – of Armstrong (1967) are present as reworked limestone clasts in the basal conglomerate of the Log Springs Fm. We did not observe the other microfacies types listed by Armstrong (1967) in the Lion Spring section.

Armstrong (1967), in his paleogeographic reconstruction, showed that, at the beginning of deposition of the Espiritu Santo Mb., a pelletoid lime mudstone facies with a shallow marine fauna including foraminifers and ostracods covered a large area that included the Sierra Nacimiento-San Pedro Mountains and was bordered to the east (Sangre de Cristo Mountains) by intertidal and supratidal facies. The supratidal facies then prograded westward over marine carbonate muds. In the Sierra Nacimiento-San Pedro Mountains, shallow marine subtidal to intertidal pelletoid lime mudstone was deposited. During the *Endothyra spiroides* Zone, oolitic grainstone to lime mudstone (shallow marine to subtidal) was the dominant facies (Armstrong, 1967).

In the Lion Spring section, and probably also in the Arroyo Peñasco type section, the oolitic grainstone-packstone facies that is particularly characteristic of the Tererro Mb. (Manuelitas Bed) of Armstrong and Mamet (1974, 1979) and Armstrong et al. (2004), was eroded during a tectonic pulse and is present as reworked limestone clasts in the basal conglomerate of the Log Springs Fm. at Lion Spring.

5.1.4. Log Springs Formation

At Lion Spring, the base of the Log Springs Fm. is represented by a poorly exposed, coarse-grained limestone conglomerate that rests on limestone of the Espiritu Santo Mb. with an erosional base. The conglomerate is overlain by poorly exposed, reddish to partly brownish shale and siltstone with a thickness of 8.4 m. The basal limestone conglomerate is 0.8 m thick and contains limestone clasts with diameters up to 20 cm. The conglomerate is poorly sorted, clast-supported and composed of subangular clasts, including different types of carbonate rocks and matrix composed of siltstone to fine-grained sandstone.

Krainer and Lucas (2024) recognized the following carbonate clasts, many being characteristic microfacies of the Arroyo Peñasco Fm., showing that part of the Arroyo Peñasco Fm. has been reworked into the basal Log Springs Fm.:

- Oolitic grainstone containing a few recrystallized skeletons (Fig. 7(E));
- Grainstone/packstone containing peloids, rounded micritic intraclasts, rare ooids, echinoderm fragments, foraminifers and recrystallized skeletons (Fig. 7(D));
- Grainstone/packstone composed of peloids, micritic intraclasts, spherical grains, echinoderm fragments, ostracods, foraminifers and rare bryozoans;
- Fine-grained, mixed siliciclastic-carbonate sandstone composed of peloids, micritic intraclasts, quartz grains, few echinoderm fragments, rare foraminifers, skeletal grains and ooids.

Some of the carbonate clasts of the basal conglomerate contain late early Viséan (biozone MFZ11B) foraminifers and algae, including *Koninckopora* and *Paraarchaediscus*.

In these carbonate clasts we determined the following foraminifers and algae: *Endothyra* ex gr. *prisca* (Fig. 5(B, C)), *Eoendothyranopsis* sp. (Fig. 5(D, E)), *Koninckopora* cf. *sahariensis* (alga) (Fig. 5(F)), *Lapparentidiscus irregularis* (Fig. 5(G)), *Paraarchaediscus stilus* (Fig. 5(H)), *Paraarchaediscus convexus* (Fig. 5(I)), *Planoarchaediscus* sp. (Fig. 5(J)), and *Pseudoammodiscus priscus* (Fig. 5(K)).

We did not observe oolitic grainstone in the Espiritu Santo Mb., whereas grainstone/packstone containing abundant peloids is a common microfacies of the Espiritu Santo Mb.

5.1.5. Sandia Formation (Pennsylvanian)

The Log Springs Fm. is overlain by the Pennsylvanian Sandia Fm. The exposed succession is 5.4 m thick and composed of sandstone and covered intervals (Krainer and Lucas, 2024).

5.2. Log Springs

5.2.1. Arroyo Peñasco Formation

At Log Springs in the southern Sierra Nacimiento, the Mississippian Arroyo Peñasco Fm. rests on Proterozoic basement. The

Fig. 7. Thin section photographs of limestone of the Espiritu Santo Member (Lion Spring; A-C), of limestone clasts from the basal conglomerate of the Log Springs Formation (Lion Spring section; D, E) and from the Osha Canyon Formation at Log Springs (F-H). **A.** Grainstone-packstone composed of abundant peloids and micritic intraclasts, some echinoderm fragments, ostracods, foraminifers and calcispheres. Sample LS 5. **B.** Grainstone containing abundant peloids and micritic intraclasts, smaller foraminiferans and calcispheres. Sample LS 7. **C.** Grainstone-packstone containing abundant foraminifers, peloids and micritic intraclasts, and few echinoderm fragments. Sample LS 8. **D.** Grainstone-packstone containing echinoderm fragments, recrystallized skeletons, bryozoans, foraminiferans, ostracods, peloids, micritic intraclasts and rare ooids. Reworked carbonate clast from the basal conglomerate of the Log Springs Formation. Sample LS 11. **E.** Oolitic grainstone. Reworked carbonate clast from the basal conglomerate of the Log Springs Formation. Sample LS 11. **F.** Rudstone containing many quartz grains, many large bryozoan and echinoderm fragments, a few other fossils, rare intraclasts and micritic matrix. Sample LSF 13. **G.** Rudstone-floatstone in which bryozoan fragments are the most abundant fossils. Also present in small amounts are echinoderms, brachiopods, gastropods, ostracods and a few small quartz grains. Pore space is filled with micritic matrix and calcite cement. Sample LSF 18. **H.** Packstone to rudstone in which echinoderm, bryozoan and brachiopod fragments are the most abundant fossils. Quartz grains are present, too. Sample LSF 14. Scale bars: 1 mm.

Arroyo Peñasco Fm. is 34 m thick and can be divided into: (*i*) the basal, siliciclastic Del Padre Mb. (2.5 m) composed of different types of sandstone and gray, laminated sandy limestone (mixed siliciclastic-carbonate sandstone; 1 m), overlain by (*ii*) the Espiritu Santo Fm. composed of a succession of single limestone beds and thin-bedded limestone intervals separated by covered intervals that most likely represent shale/siltstone units (31.5 m). The overlying Log Springs Fm. is 13.5 m thick and composed of red siltstone and intercalated sandstone beds. Siltstone intervals are 1.2–4 m thick, and sandstone beds are 0.2–0.8 m thick. Sandstone is represented by various lithotypes including fine-grained massive sandstone, fine-grained crossbedded sandstone and coarse-grained pebbly sandstone (see details in Krainer and Lucas, 2024).

The Log Springs Fm. is overlain by the Osha Canyon Fm. (Fig. 2). DuChene (1974) defined the Osha Canyon Fm. as a new stratigraphic unit of Morrowan age that is exposed at several locations in the southern Sierra Nacimiento and Jemez Mountains. DuChene (1974) and DuChene et al. (1977) described the type section at Guadalupe Box near Osha Canyon as a 22 m-thick succession composed of fossiliferous limestone and shale. From the type section, DuChene et al. (1977) listed brachiopods and corals. Brachiopods indicate a Morrowan, probably late Morrowan age.

Krainer and Lucas (2005) described the lithofacies and limestone microfacies of the Osha Canyon Fm. at the type section. They included the fossiliferous, calcite-cemented sandstone on top of the succession in the Osha Canyon Fm. and drew the contact to the overlying Sandia Fm. at the erosional base of coarse-grained, trough-crossbedded fluvial sandstone. According to Krainer and Lucas (2005) the Osha Canyon Fm. at the type section is 27.3 m thick.

Northrop and Wood (1945) first reported a Morrowan fauna from sedimentary rocks near Guadalupe Box, which they assigned to the Sandia Fm. Read and Wood (1947) also reported a Morrowan age of limestones at the base of the upper clastic member (Sandia Fm.). Armstrong (1955) demonstrated that the Morrowan limestones unconformably rest on the Log Springs Fm. at Pinos and Peñasco canyons and at Guadalupe Box, and are unconformably overlain by the Madera Fm. (Sandia Fm.). Armstrong (1967) and Armstrong and Mamet (1974) reported a foraminiferan fauna from these limestones indicating a Morrowan age.

About 2.5 km southwest of the type section the Osha Canyon Fm. rests unconformably on Proterozoic basements rocks (granite and gneiss).

At Pinos and Peñasco canyons, the Osha Canyon Fm. consists of 9–12 m of massive fossiliferous limestone with thin shale interbeds (DuChene et al. 1977). Here the Osha Canyon Fm. unconformably overlies the Log Springs Fm. and is overlain by the Sandia Fm. with an angular unconformity.

5.2.2. Osha Canyon Formation

At Log Springs the Osha Canyon Fm. is exposed with a thickness of 10 m (Fig. 2). A similar thickness was reported from Pinos and Peñasco canyons by DuChene et al. (1977), indicating an almost complete succession of the Osha Canyon Fm. at Log Springs.

The Osha Canyon Fm. at Log Springs is mostly composed of limestone. The succession starts with sandy limestone containing abundant brachiopods (0.6 m), overlain by a fossiliferous limestone bed (rudstone) containing abundant crinoid fragments (0.5 m), followed by laminated limestone (rudstone) with crinoid fragments, brachiopods and abundant quartz grains (1.4 m) and a covered interval (1 m) probably representing shale/siltstone. Above the covered interval mixed siliciclastic-carbonate sandstone with brachiopods is exposed (1.4 m), overlain by medium-bedded fossiliferous limestone containing a few quartz grains (2.1 m), a covered interval (1 m) and medium-bedded limestone with a thin bed of carbonate conglomerate intercalated.

Microfacies. Limestone of the basal Osha Canyon Fm. at Log Springs is composed of packstone-rudstone, rudstone, and rudstone-floatstone, all containing a diverse fossil assemblage that is dominated by fragments of echinoderms (crinoids), bryozoans and brachiopods. Other fossils such as gastropods, ostracods, bivalves, foraminifers and trilobites are subordinate to rare. The following microfacies types can be distinguished (Krainer and Lucas 2024):

- Rudstone containing many quartz grains with diameters up to 5 mm, a few feldspar grains and granitic rock fragments. Fossils include fragments of bryozoans, echinoderms (crinoids) and brachiopods, a few foraminifers, rare trilobite fragments, and bivalves. The rudstone is poorly washed and contains small amounts of matrix (Fig. 7(F));
- Rudstone to floatstone in which bryozoans are the most abundant fossils, partly occurring as large colonies. Subordinately, fragments of brachiopods, echinoderms (crinoids), bivalves, ostracods, gastropods, foraminifers and rare trilobites are present. Non-skeletal grains are represented by small quartz grains. Locally, the rudstone contains micritic to pelmicritic matrix, and locally calcite cement is present (Fig. 7(G));
- Crinoid-bryozoan packstone to rudstone containing many quartz grains and rare feldspar grains. Present in small amounts are brachiopods, gastropods, ostracods, and trilobites. Also present are a few micritic intraclasts. The grains are cemented by coarse, blocky calcite (Fig. 7(H)).

The microfacies of limestones of the basal Osha Canyon Fm. at Log Springs are very similar to the microfacies types described from the type section at Osha Canyon by Krainer and Lucas (2005). The fossil assemblage indicates that the sandy limestones and limestones composed of packstone-rudstone-floatstone were deposited in a shallow, normal marine environment under moderate to high water turbulence. Thinner limestone beds composed of rudstone are interpreted as storm layers; thicker limestone units may represent carbonate sand shoals (Krainer and Lucas, 2005).

6. Discussion

Thus far, the lithostratigraphic subdivision and biostratigraphy of the Mississippian sedimentary succession in the Sierra Nacimiento and San Pedro Mountains has been based on studies by Armstrong and co-workers. Although the Mississippian succession is less than 100 m thick, Armstrong and Mamet (1974) raised the Arroyo Peñasco Fm. to group rank and divided the Mississippian into Arroyo Peñasco Group and overlying Log Springs Fm. Armstrong and Mamet (1974, 1979) divided the Arroyo Peñasco Group of the Sierra Nacimiento and San Pedro Mountains into the Espiritu Santo Fm. (including the Del Padre Sandstone Mb. at the base) and Tererro Fm. (Manuelitas Mb.).

Based on foraminifers, Armstrong and Mamet (1979) divided the section at Pinos and Peñasco canyons into Espiritu Santo Fm. (lower 27.5 m), dated as late Tournaisian (Osagean), microfossil zone 9, and Tererro Fm. (Manuelitas Mb.; upper 17 m) dated as late Viséan (late Meramecian), microfossil zone 14. The lower part of the section in the San Pedro Mountains (lower 33 m) was ascribed to the Espiritu Santo Fm., dated as late Tournaisian (Osagean), microfossil zone 9, and the upper part (6 m) to the Tererro Fm. (Manuelitas Mb.), dated as late Viséan (late Meramecian), microfossil zone 14. Unfortunately, Armstrong and Mamet (1979) listed the fossils (mainly foraminifers), but they did not present photographs of the foraminifers, which makes it impossible to evaluate their determinations. A lithologic subdivision of the Arroyo Peñasco Group into Espiritu Santo Fm. and Tererro Fm. (Manuelitas

Mb.) as proposed by Armstrong and Mamet (1974, 1979) is not possible in the field. Their subdivision is based on foraminifers, and their "formations" are biostratigraphic units, representing Mamet's microfossil zone 9 (Espiritu Santo Fm.) and Mamet's microfossil zone 14 (Tererro Fm.). Our data demonstrate that:

- The Arroyo Peñasco Group of Armstrong and Mamet (1974, 1979) and Armstrong et al. (2004) is too thin to be of group rank, therefore we downgraded the succession to formation rank (Krainer and Lucas, 2024; Fig. 2);
- A lithologic subdivision of the Arroyo Peñasco Group *sensu* Armstrong and Mamet is not possible; the subdivision of Armstrong and Mamet (1979) is based on foraminifers. Their Espiritu Santo and Tererro formations are biostratigraphic, not lithostratigraphic units;
- The foraminiferal assemblage in our studied material indicates that the Espiritu Santo Mb. at the Lion Spring section is of early (Hastarian) to late (Ivorian) Tournaisian age (Figs. 3, 6). We did not observe late Viséan foraminifers in the upper part of the succession ("Tererro Fm.") as reported by Armstrong and Mamet (1979). The Espiritu Santo Mb. at Lion Spring is very thin for the time it represents (almost the entire Tournaisian), indicating that this member represents a "condensed" succession. This is probably the result of low accommodation, which causes non-deposition, erosion and reworking of sediment, and condensation (this needs to be studied in more detail);
- Foraminifers in reworked limestone clasts of the basal Log Springs Fm., representing reworked limestone of the Espiritu Santo Mb., indicate a late early Viséan age, indicating that the Espiritu Santo Mb. extended into the Viséan (at least the late early Viséan) (Figs. 3, 6).

The Arroyo Peñasco Fm. is unconformably overlain by red beds of the Log Springs Fm., which have not provided any fossils. The Log Springs Fm. is younger than early Viséan and older than the overlying Morrowan Osha Canyon Fm. According to Armstrong et al. (2004) the Log Springs Fm. is of late Viséan to Namurian (Chesterian) age (Fig. 3). Foraminifers from limestones of the Osha Canyon Fm. at Log Springs indicate a Morrowan age, confirming DuChene et al. (1977), who stated that the brachiopod assemblage indicates a Morrowan – probably late Morrowan – age for the entire Osha Canyon Fm.

7. Conclusions

The Mississippian of the Sierra Nacimiento and the San Pedro Mountains is represented by a thin (less than 100 m) but heterogeneous succession of siliciclastic and carbonate sedimentary rocks of marine and nonmarine origin. The Mississippian succession is subdivided into the Arroyo Peñasco Fm. (composed of basal siliciclastic Del Padre Mb. and overlying Espiritu Santo Mb.) and overlying Log Springs Fm. Based on foraminifers, the Espiritu Santo Mb. of the Arroyo Peñasco Fm. at Lion Spring is of lower (Hastarian) to upper (Ivorian) Tournaisian (Kinderhookian-Osagean) age. Foraminifers in reworked carbonate clasts of the basal Log Springs Fm. indicate a late early Viséan age, indicating that the Espiritu Santo Mb. extended into the Viséan but was partly eroded.

A subdivision of the limestone facies into Espiritu Santo (late Tournaisian/early Osagean) and Tererro (late Viséan/early Chesterian), as proposed by Armstrong and Mamet (1974, 1979) and Armstrong et al. (2004), is not possible in the Sierra Nacimiento and San Pedro Mountains. The Log Springs Fm. unconformably rests on the Arroyo Peñasco Fm. and is composed of nonmarine redbeds. The Log Springs Fm. is assigned to the upper Chesterian. The Log Springs Fm. is overlain by the Lower Pennsylvanian shallow marine sediments of the Osha Canyon Fm. Limestones of the Osha Canyon Fm. at Log Springs indicate a Morrowan age. Locally, the Osha Canyon Fm. is absent (Lion Spring), and the Osha Canyon Fm. is overlain by the Sandia Fm.

CRediT authorship contribution statement

Karl Krainer: Writing – review & editing, Writing – original draft, Visualization, Investigation. **Spencer G. Lucas:** Writing – review & editing, Visualization, Resources, Investigation. **Daniel Vachard:** Writing – original draft, Visualization, Investigation.

Data availability

No data was used for the research described in the article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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