MORPHOLOGICAL DESCRIPTIONS OF LATE OLIGOCENE – EARLY MIOCENE SPORES: SAN GREGORIO FORMATION, BAJA CALIFORNIA SUR, MEXICO

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ABSTRACT
The San Gregorio Formation (Late Oligocene-Early Miocene) is part of the Paleogene and Neogene stratigraphic sequence in La Purísima region, Baja California Sur, Mexico. A borehole from this formation was analyzed with the aim of contributing continental and marine palynomorphs. This paper presents the results concerning to the continental palynomorphs, belonging to bryophyte and pteridophyte spores group. One bryophyte and eight pteridophyte spores were identified to genus level: cf. *Camarazonosporites, Cicatricosisporites, Deltoidospora, Granulatisporites*, *Leptolepidites*, *Lycopodiacidites*, *Stereisporites*, *Undulatisporites* and *Polypodiisporites*. One pteridophyte spore was identified to species level —*Lusatisporis dettmannae—,* which was the most abundant. We present systematic descriptions of the taxa recorded. These spores are associated to the Cloud Forest vegetation type.

Keywords: La Purísima, palynomorphs, fossil spores, Oligocene-Miocene.

DESCRIPCIONES MORFOLÓGICAS DE ESPORAS DEL OLIGOCENO TARDÍO-MIOCENO TEMPRANO: FORMACIÓN SAN GREGORIO, BAJA CALIFORNIA SUR, MÉXICO

RESUMEN
La Formación San Gregorio (Oligoceno Tardío-Mioceno Temprano) forma parte de la secuencia estratigráfica del Paleógeno y Neógeno en la región de La Purísima, Baja California Sur, México. Un barreno procedente de esta Formación se analizó con el objetivo de estudiar los palinomorfos continentales y marinos. En este artículo se presentan los resultados de los palinomorfos continentales, pertenecientes al grupo de esporas de briofitas y pteridofitas. Se identificaron un taxón de esporas de briofitas y ocho de pteridofitas a nivel de género: cf. *Camarazonosporites, Cicatricosisporites, Deltoidospora, Granulatisporites*, *Leptolepidites*, *Lycopodiacidites*, *Stereisporites*, *Undulatisporites* y *Polypodiisporites*. Un taxón de esporas de pteridofita se identificó a nivel de especie —*Lusatisporis dettmannae—,* la cual resultó ser la más abundante. Se presentan las descripciones sistemáticas de los taxa registrados. Estas esporas se asocian con la vegetación del tipo Bosque Mesófilo de Montaña.

Palabras clave: La Purísima, palinomorfos, esporas fósiles, Oligoceno Tardío-Mioceno Temprano.

INTRODUCTION

The Baja California peninsula is located in northwest Mexic and currently, its climate is very arid [1].The vegetation that predominates in it are mainly the desert scrub, tropical deciduous forest, oak-pine forest and oak forest are the main vegetation types [2]. During the Paleogene and Neogene (66-11.6 Ma), the southern peninsula was attached to mainland Mexico, at Cabo Corrientes, near Puerto Vallarta, Jalisco, its surface was covered by a shallow sea [3, 4]. The peninsula began the journey to its current position during the Late Miocene (12-6 Ma) as a result of the tectonic movements of the Pacific and North American plates [4, 5, 6].

Under this geological setting, sediments that gave rise to the stratigraphic sequence in the La Purísima region, Comondú, Baja California Sur (BCS) were deposited [3, 7, 8, 9, 10]. Among these, the San Gregorio Formation (SGF) was deposited during Late Oligocene-Early Miocene (27.2-22.5 Ma) [7, 8] (Figure 1). Its lithological composition consists of interbedded

phosphatic shale, silicified shale, rhyolite tuff, diatomite, phosphatic pelotoidal sandstone, and diatomaceous shale with a high content of fish remains [3, 7, 11, 12].

System	Period	Epoch	Age	Picks (Ma)	La Purísima (Hausback, 1984)
Tertiary	Neogene	Pliocene	Placenzian	3.6	La Salada
			Zanclean	5.3	
		Miocene	Messinian	7.2	
			Tortonian	11.6	
			Serravalian	13.8	Comondú
			Langhian	16.0	
			Burdigalian	20.4	Isidro
			Aquitanian	23.0	San Gregorio
	Paleogene	Oligocene	Chattian	28.1	
			Rupelian	33.9	
		Eocene	Priabonian	37.8	Tepetate
			Bartonian	41.2	
			Lutetian	47.8	
			Ypresian	56.0	
		Paleocene	Thanetian	59.2	
			Selandian	61.6	
			Danian	66.0	

Fig. 1. Paleogene and Neogene stratigraphic sequence in the La Purísima region, Comondú, Baja California Sur, Mexico.

A borehole (B4) from the SGF was analyzed in order to study continental and marine palynomorphs. The aim of this paper is to register the results concerning to continental palynomorphs belonging to the pteridophyte-bryophyte group. We show only the records and systematic descriptions of pteridophyte-bryophyte fossil spores found in the samples from borehole B4 and based on that, we bring into focus the detection of the plant palaeocummunities most probably to be associated with.

MATERIALS AND METHODS

Borehole B4 reaches a depth of 105.40 m, and was obtained in the La Purísima region at coordinates 26 º 19'03 "N and 112 ° 06'08" W, central BCS (Figure 2).

A total of 40 samples were collected and processed through standard methods for the extraction of palynomorphs [13] using hydrochloric and hydrofluoric acids, acetolysis (acetic anhydride and sulfuric acid) and flotation technic with sodium polytungstate. Permanent slides were prepared with hydroxyl-acetyl-cellulose and Canada balsam, and were deposited in the IGLUNAM palynological collection of the UNAM (Universidad Nacional Autónoma de México), Geology Institute.

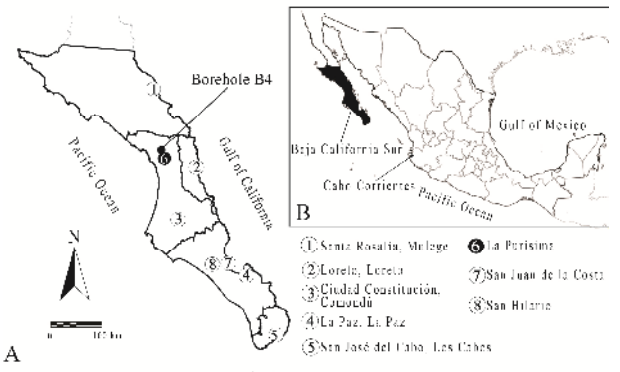

Fig. 2. A) Geographic location of Borehole B4 extraction point. **B)** Baja California Sur state on northwestern Mexico.

A slide from each sample was reviewed with an Axiolab Zeiss light microscope (LM), using x1000 objective and phase contrast. Continental and marine palynomorphs were counted in each slide. After that, the counted group of pteridophyte-bryophyte fossil spores was separated from the remainder of continental palynomorphs (Figure 3). Photomicrographs were taken in normal light and phase contrast, with an ICc1-Zeiss AxioCam and using AxioVision software, version 4.8.2. Additionally, the samples of recorded pteridophyte-bryophyte fossil spores were prepared for the scanning electron microscope (SEM) observation. The samples were dehydrated in an alcohol series; a few drops of the pollen suspension were added on the prepared stubs and then dried whit a lamp and sputter coated with gold-palladium and carbon. Specimens were examined and photographed, using a JEOL 6300 SEM at an accelerating voltage of 20 kV, at the UNAM, Geology Institute.

The morphological descriptions of the spore taxa were made following the Erdtman [14] and Punt *et al.* [15] terminologies.

RESULTS AND DISCUSSION

The SGF contains both continental and marine palynomorphs, which included more than 100 taxa. Pteridophyte-bryophyte spores represented 4% of the total continental assemblage and were recorded in 14 of the 40 samples from borehole B4. Nine trilete spores taxa and one monolete spore were counted (Figure 3). The spores determined were cf. *Camarazonosporites* Pant ex Potonié 1956 emend. Klaus 1960, *Cicatricosisporites* Potonié & Gelletich 1933, *Deltoidospora* Miner 1935, *Granulatisporites* Ibrahim 1933 emend. Potonié and Kremp 1954, *Leptolepidites* Couper 1953 emend. Norris 1968, *Lusatisporis dettmannae* (Drug) Srivastava 1972, *Lycopodiacidites* Couper, 1953 emend. Potonié 1956, *Stereisporites* Pflug 1953, *Undulatisporites* Pflug 1953 and *Polypodiisporites* Potonié 1931 in Potonié & Gelletich 1933 ex Potonié 1956.

Considering the percentages for the continental palynomorphs registered in each sample, the following ranges were obtained for each pteridophyte-bryophyte taxa: 5.6% for both cf. *Camarazonosporites* and *Cicatricosisporites*; 0.7-1.8% for *Deltoidospora;* 1.1% for *Granulatisporites;* 12% for *Leptolepidites;* 0.6-11.1% for *Lusatisporis dettmannae*; < 1% for *Lycopodiacidites*; 0.7-1.7% for *Stereisporites*.; 0.7-8.3% for *Undulatisporites*; and *Polypodiisporites* at 0.8%. *Lusatisporis dettmannae* was the most abundant of all spores.

Systematic descriptions:

Trilete spores:

Genus: ***Camarozonosporites*** Pant ex Potonié 1956 emend. Klaus 1960

Type species: ***Camarozonosporites cretaceus*** (Weyland & Krieger 1953) Potonié 1956

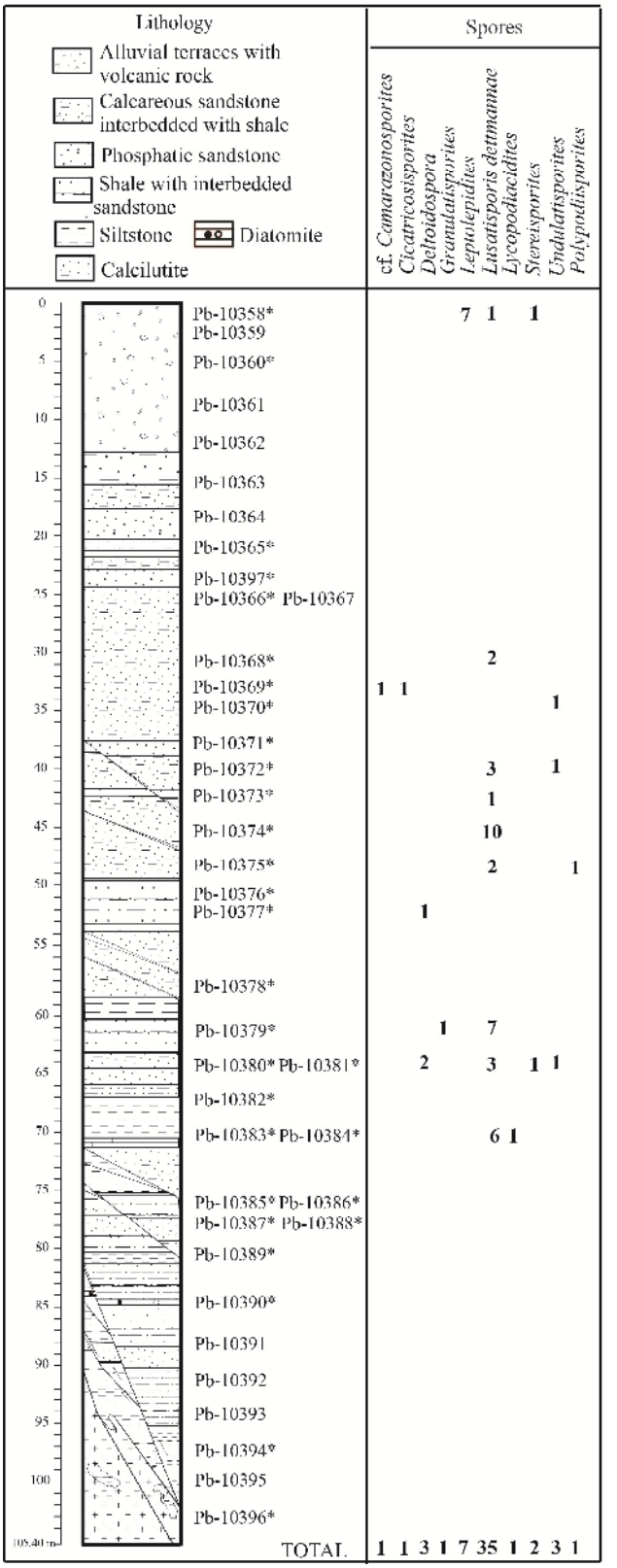

Fig. 3. Borehole B4 stratigraphic colum, San Gregorio Formation, Baja California Sur, Mexico. Pb Numbers indicate the sample number and depth. (*) = Presence of palynomorphs. The recording corresponds only to the absolute frequencies of ptheridophyte-bryophyte spores group.

cf. *Camarozonosporites* sp. (Figure 5 a-b)

Botanical affinity: ***Lycopodium***

Description: Monade, heteropolar, radiosymmetric, trilete. Amb subtriangular with rounded apices. Laesura extending all radius spore. Exine 0.6 µm thick, sculpture slightly regulate in the distal surface. Rugulae 0.3 µm wide and 2 µm long.

Dimensions: Equatorial axis = 20.1 x 23.5 um: one specimen measured.

Remarks: The distal surface of *Camarozonosporites* is regulate or hamulate, and the proximal surface is more or less smooth. It differs from *Lycopodiacidites,* as the latter is ornamented on both surfaces [16].

Other occurrences: Mexico — Middle Eocene-Late Eocene Burgos Basin, between Nuevo Leon and Tamaulipas states, Mexico [17]. South America — Middle Eocene, Llanos foothills, Colombia [18]. Europe — Middle Eocene, Eifel Formation, Germany [19]. Antarctica — Early to Middle Eocene, Wilkes Land Margin [20].

Genus: ***Cicatricosisporites*** Potonié &Gelletich 1933.

Type species: ***Cicatricosisporites dorogensis*** Potonié & Gelletich 1933

Cicatricosisporites sp. (Figure 5 c-d)

Botanical affinity: ***Anemia***

Description: Monade, heteropolar, radiosymmetric, trilete. Amb triangular obtuse concave with rounded apices. Laesura ¾ or more of radius spore. Exine 1.2-3.1 µm thick, sculputure canaliculate with irregular ribs 4-4.6 µm thick.

Dimensions: Equatorial axis = 32.25 x 32.6 µm: one specimen measured.

Remarks: In *Cicatricosisporites* the rib patterns and structure may be highly variable in nature. Some species have perforations of primary origin [16].

Other occurrences: Mexico — Middle Eocene-Late Eocene Burgos Basin, between Nuevo Leon and Tamaulipas states [17]; Late Eocene-Early Oligocene Cuayuca Formation, Puebla [21, 22, 23]; Miocene, Chiapas [24]. North America — Late Paleocene, lignites from the Red Hills Mine, Mississippi, U.S.A. [25]; Late Eocene, Jackson Group, Mississippi and Alabama, U.S.A. [26]. South America — Eocene, Esmeraldas Formation, Colombia [27]; Cenozoic, Llanos and Llanos Foothills, Colombia [28]; Middle Eocene, Llanos foothills, Colombia [18]. Europe — Late Paleocene to Eocene, Hungary [29]; Early Eocene, Belgium [30]; Middle Eocene, Messel near Darmstadt [31]; Middle Eocene, Eifel Formation, Germany [32]. Asia — Paleocene, Nomogen Formation, China [33]. Antarctica — Early to Middle Eocene, Wilkes Land Margin [20].

Genus**: *Deltoidospora*** Miner 1935

Type species: ***Deltoidospora halli*** Miner 1935

Deltoidospora sp. (Figures 4 and 5 e-f)

Botanical affinity: **Cyatheaceae**

Description: Monade, heteropolar, radiosymmetric, trilete. Amb triangular obtuse convex with rounded apices. Laesura ¾ or more of radius spore. Exine psilate 0.7-1 µm thick, usually folded.

Dimensions: Equatorial axis = 45 µm (37.3-52 µm): two specimens measured.

Remarks: *Deltoidospora* shows a psilate surface and simple laesura. The amb is characteristically triangular to convexly subtriangular [16].

Other occurrences: Mexico — From Late Eocene-Early Oligocene, Pie de Vaca Formation, Tepexi de

Rodriguez, Puebla [34]; Early Eocene-Early Oligocene, La Trinidad and La Quinta Formations, Chiapas [24]; Late Eocene-Early Oligocene, Cuayuca Formation Puebla, [21, 22, 23]; Oligocene-Miocene, La Quinta Formation, Chiapas [35]; Early-Middle Miocene, Ixtapa Formation, Chiapas [36]. North America — Eocene, Wilcox section, Louisiana, U.S.A. [37]. South America — Middle Eocene, Guys Hill Member, Chapelton Formation, Jamaica [38]; Late/Upper Miocene, Chiquimil Formation, Argentina [39].

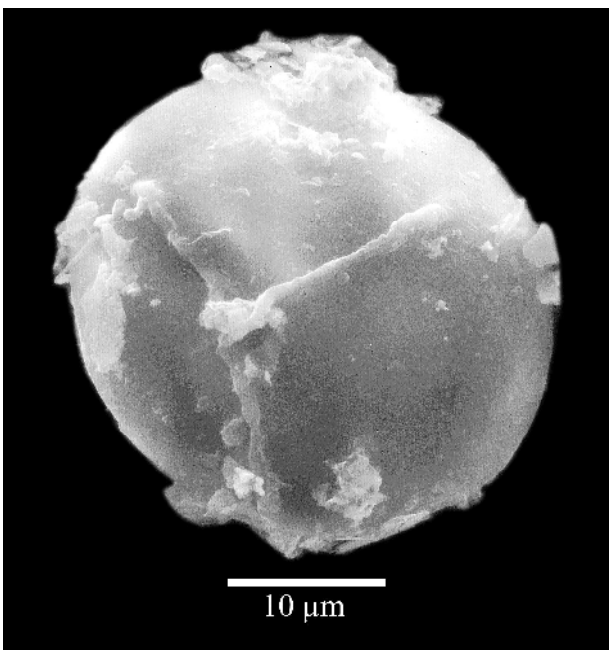

Fig. 4. Scanning electron microscope photomicrograph. *Deltoidospora* sp. (Cyatheaceae).

Genus: ***Granulatisporites*** **Ibrahim 1933 emend. Potonié and Kremp 1954**

Type species**: *Granulatisporites granulatus* Ibrahim 1933**

Granulatisporites sp. (Figure 5 g-h)

Botanical affinity: **Pteridophyta**

Description: Monade, heteropolar, radiosymmetric, trilete. Amb subtriangular with rounded apices. Laesura extending all radius spore, margo 0.99 µm thick. Aperture 2.1 µm wide. Exine 0.60 µm thick slightly microverrucate. Verrucae < 0.30 µm diameter.

Dimensions: Equatorial axis = 25 x 26.6 µm: one specimen measured.

Remarks: *Granulatisporites* presents a triangular amb evenly covered with granules [16].

Genus: ***Leptolepidites*** **Couper 1953 emend. Norris 1968**

Type species: ***Leptolepidites verrucatus*** **Couper 1953**

Leptolepidites sp. (Figure 5 i-j)

Botanical affinity: **Pteridophyta**

Description: Monade, heteropolar, radiosymmetric, trilete. Amb esferoidal. Laesura $^{2}/_{3}$ of radius spore. Exine 1 µm thick, sculpture verrugate. Verrucae from distal face 1.1 µm in diameter, and in proximal face 0.9 µm in diameter.

Dimensions: Equatorial axis = 12.9 x 14.4 µm: one specimen measured.

Remarks: This genus is characterized by an amb rounded to convexly subtriangular and by the presence of verrucae of variable size and shape; the verrucae may be smaller on the proximal surface [16].

Other occurrences: Mexico — Late Eocene-Early Oligocene, Cuayuca Formation, Puebla [21, 22]. South America — Late-Upper Miocene, Chiquimil Formation, Argentina [39]. Asia — Paleocene, Nomogen Formation, China [33].

Genus: ***Lusatisporis*** Krutzsch 1963

Type species ***Lusatisporis punctatus*** Krutzsch 1963

Lusatisporis dettmannae (Drug) Srivastava 1972 (Figure 6 a-b)

Botanical affinity: ***Selaginella***

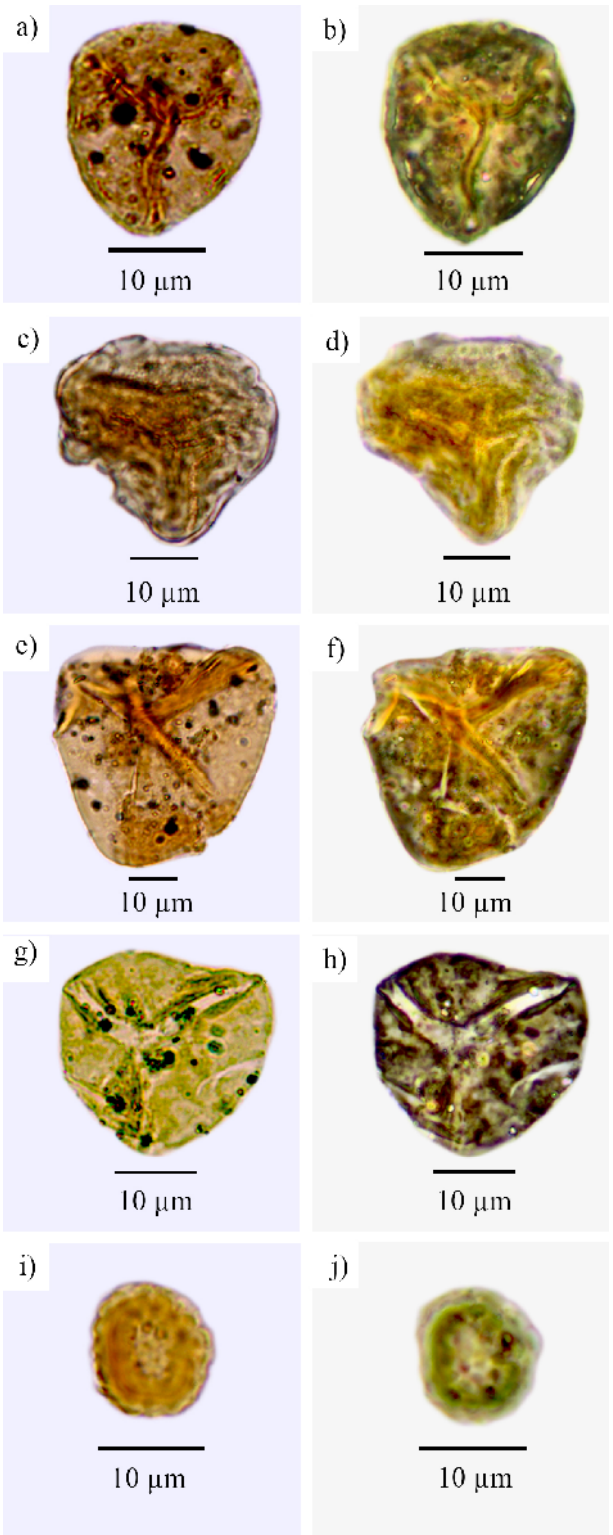

Fig. 5. LM photomicrographs. Photomicrographs in left column taken in normal light, and right column taken in phase contrast. a-b) cf. *Camarozonosporites* sp., c-d) *Cicatricosisporites* sp., e-f) *Deltoidospora* sp., g-h) *Granulatisporites* sp., i-j) *Leptolepidites* sp.

Description: Monade, heteropolar, radiosymmetric, trilete. Amb subtriangular with rounded apices. Laesura extending all radius spore. Exine psilate, 6.7 µm thick including perispore. Perispore microverrucate.

Dimensions: Equatorial axis = 31.2 µm (21.9-40.8 µm): Equatorial axis including perispore = 36.9 µm (28.6-45 µm): 12 specimens measured.

Remarks: This spore is morphologically similar to that of *Sellaginella*, rounded in polar view. Trilete, laesural arms thick, short and undulate. Exine radically wrinkled [40].

Other occurrences: Mexico — Late Eocene-Early Oligocene, Pie de Vaca Formation, Puebla [34]; Late Eocene-Early Oligocene, Cuayuca Formation, Puebla, [21, 22, 23].

Genus: ***Lycopodiacidites*** **Couper, 1953 emend. Potonié 1956**

Type species**:** ***Lycopodiacites bullerensis*** **Couper, 1953**

Lycopodiacidites sp. (Figure 6, c-d)

Botanical affinity: ***Lycopodium***

Description: Monade, heteropolar, radiosymmetric, trilete. Amb subtriangular with rounded apices. Laesura $^{2}/_{3}$ of radius spore. Exine 1.5 µm thick, sculpture rugulate on both spore surfaces. Rugulae 0.5 µm wide by 4.4 µm long.

Dimensions: Equatorial axis = 23.6 x 25.7 µm: one specimen measured.

Remarks: In *Lycopodiacidites,* the proximal surface may be smooth or ornamented [16]. In this case the proximal surface is strongly rugulate.

Other ocurrences: Mexico — During the Eocene-Oligocene in the Pie de Vaca Formation, Puebla [34]; Miocece, Ixtapa Formation, Ixtapa, Chiapas [36]; Late Miocene, Paraje Solo Formation, Veracruz [41].

Genus: ***Stereigranisporis*** (Krutzsch) Kedves 1982

Type species: ***Stereigranisporis granula*** (Krutzsch and Sontag) Kedves 1982 (in Kedves and Rusel 1982) ibid. ***Stereisporites*** Pflug 1953, subgenus ***Stereigranisporis granulus*** Krutzsch and Stong 1963 (in Krutzsch 1963)

Botanical affinity: **Briophyta**

Description: Monade, heteropolar, radiosymmetric, trilete. Amb subtriangular with rounded apices. Leaesurae ¾ or more of radius spore. Exine 0.61-1 µm thick, sculpture microverrucate to rugulate on both surfaces. Diameter verrucae 0.6 µm, sometimes come together to form rugulae 0.5-1.2 µm wide and 1.6-3.5 µm long.

Dimensions: Equatorial axis = 21.9 x 25.64 µm: one specimen measured.

Remarks: *Stereisporites* exhibits laesura short; amb circular to convexly subtriangular; distal surface may be ornamented; incipient cingulum may be present [16].

Other occurrences: Mexico— *S. crassiancoris* and *S. microgranulus-crassiexinus* were recorded as Middle Eocene-Late Eocene, in the Burgos Basin between Nuevo Leon and Tamaulipas states [17]; Late Eocene-Early Oligocene, Cuayuca Formation, Puebla [21, 22]. South America — Late-Upper Miocene, Chiquimil Formation, Argentina [39].

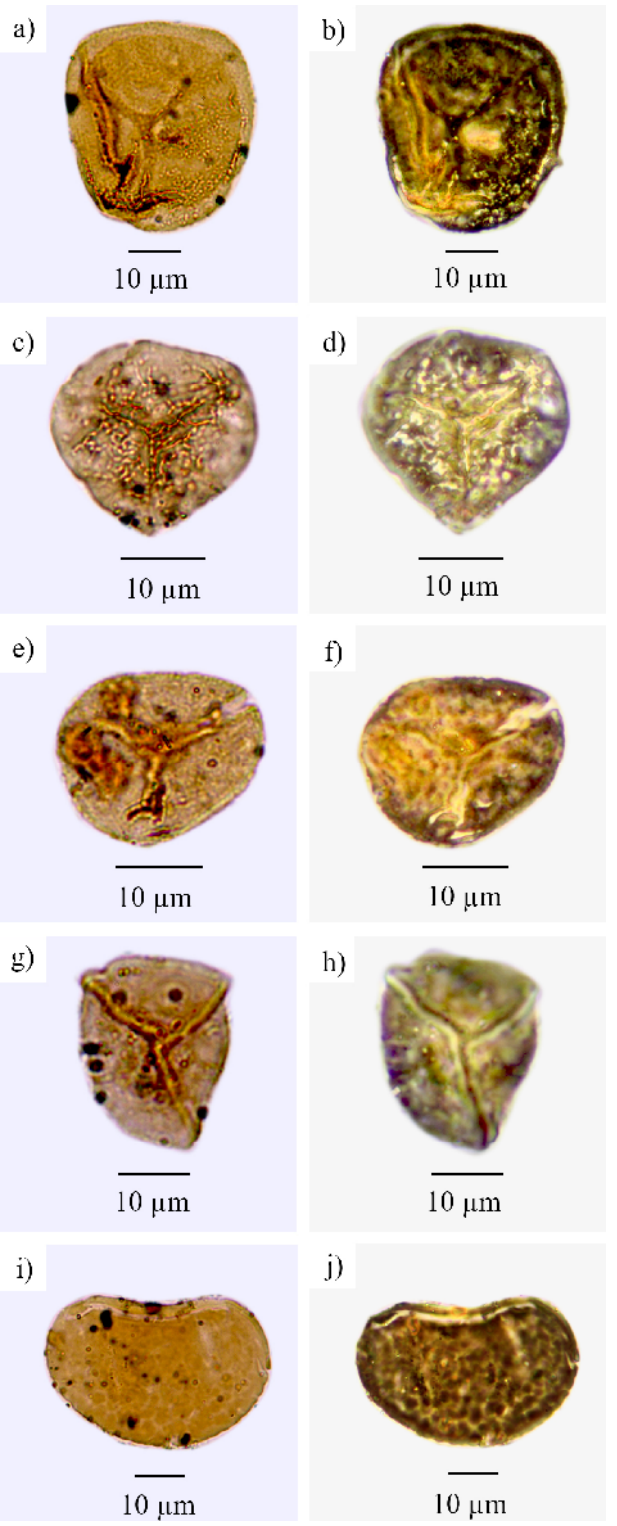

Fig. 6. LM photomicrographs. Photomicrographs in left column taken in normal light and right column taken in phase contrast. a-b) *Lusatisporis dettmannae*, c-d) *Lycopodiacidites* sp., e-f) *Stereisporites* spp., g-h) *Undulatisporites* spp. i-j) *Polypodiisporites* sp. ***Stereisporites*** spp. (Figure 6, e-f)

Genus: ***Undulatisporites*** **Pflug 1953**

Type species**:** ***Undulatisporites microcutis*** **Pflug 1953**

Undulatisporites spp. (Figure 6, g-h)

Botanical affinity: **Ophioglossaceae**

Description: Monade, heteropolar, radiosymmetric, trilete. Amb from subtriangular to triangular acute with rounded or sharpened apices. Laesura extending all radius spore, undulose. Exine 0.6-1.5 µm psilate on both spore surfaces.

Dimensions: Equatorial axis = 21.1 µm (20.75-21.45µm): three specimens measured.

Remarks: *Undulatisporites* presents a laesura simple, undulose; spore outline variable; surface psilate, smooth or scabrate [16].

Other ocurrences: South America — Middle Eocene, Saramaguacan Formation, Cuba [42]; Late-Upper Miocene, Chiquimil Formation, Argentina [39]. North America — Eocene, Wilcox section, Louisiana, U.S.A. [37].

Monolete spores:

Genus: ***Polypodiisporites*** Potonié 1931 in Potonié and Gelletich 1933 ex Potonié 1956

Type species: ***Polypodiisporites favus*** (Potonié) Potonié 1956

Polypodiisporites sp. (Figure 6, i-j)

Botanical affinity**: Polypodiaceae**

Description: Monade, heteropolar, bilateral symmetry, monolete. Laesura extending all length spore. Exine verrucate with negative reticula. Pentagonal shaped verrucae with diameter between 0.8-2.8 µm.

Dimensions: Major equatorial axis = 45 µm, minor equatorial axis = 27.9 µm: one specimen measured.

Remarks: This genus is characterized by an exine with flat, polygonal verrucate processes, forming areolate ornamentation. *Polypodiisporites* is different from *Polypodiidites,* because the latter presents verrucate or foveolate ornamentation [40].

Other occurrences: Mexico — Late Eocene-Early Oligocene Cuayuca Formation, Puebla [21, 22, 23]; Upper Oligocene, Chiapas [24]; Miocene, Ixtapa Formation, Chiapas [36]. South America — Cenozoic, Llanos and Llanos Foothills, Colombia [28]; Eocene, Esmeraldas Formation, Colombia [27]. Antarctica — Early to Middle Eocene, Wilkes Land Margin [20].

At present, pteridophyte-bryophyte spores are a major structural component of the Cloud Forest (CF) vegetation [43]. In this vegetation type, it is common to find several species of *Lycopodium, Selaginella,* Hymenophyllaceae, Pteridaceae, Polypodiaceae, Dryopteridaceae, Aspleniaceae and Cyatheaceae [43, 44]. The CF grows from temperate zones, with climates such as humid temperate with rainfall throughout the year, humid temperate with summer rains, to warm zones with climates such as humid warm with rainfall throughout the year, humid warm with summer rains, and subhumid warm with summer rains [44]. Therefore, the CF is found in areas characterized by the persistent occurrence of clouds and fog, and high atmospheric humidity [44, 45, 46], temperatures between 12 and 23° C, precipitation between 1000 and 5800 mm per year, and at altitudes between 1000 and 2500 m [45, 46, 47].

The fossil spores have been associated to CF in other mexican basin studies. In Tepexi de Rodriguez, Puebla (Pie de Vaca Formation –Late Eocene-Early Oligocene–) [34], spores associated to CF were Cyatheaceae, *Laevigatosporites, Lycopodium* and Polypodiaceae.

Also in Puebla, (Cuyuca Formation –Late Eocene-Early Oligocene–) Ramirez-Arriaga [21] and Ramírez-Arriaga *et al*. [23] relate spores as *Deltoidospora, Leptolepidites, Lusatisporis dettmannae, Retitriletes, Stereigranisporis granula, Laevigatosporites,* and *Polypodiisporites* and as well as *Momipites* complex (current *Engelhardia-Alfaroa* group) with the presence of CF. In the Izúcar de Matamoros region, Puebla (Cuayuca Formation –Late Eocene-Early Oligocene–), spores of *Camarozonosporites, Cicatricosisporites dorogensis, Chomotriletes, Deltoidospora, Hydrodictyon, Leiotriletes, Leptolepidites,*

Stereigranisporis aff. *granula, Verrucingulatisporites, Lusatisporis dettmannae* and *Polypodiisporites*, were considered as CF indicators [49].

In Chiapas (La Quinta Formation –Oligocene-Miocene–), spores associated to CF belong to Lycopodiaceae, Selaginellaceae, Equisetaceae, Cyatheaceae, Gleicheniaceae, Marattiaceae, Polypodiaceae, Pteridaceae, Vittariaceae and Schizaeaceae families [35]; while in the Pichucalco region, Chiapas (Méndez Formation –Lower-Middle Miocene–), the CF is related to *Cicatricosisporites, Cyatheaceae* and *Deltoidospora* [50].

On the other hand, in Coatzacoalcos, Veracruz (Paraje Solo Formation –Late Miocene–) the spores associated to CF were several taxa of the Cyatheaceae family [41].

CONCLUSIONS

The presence of pteridophyte-bryophyte spores, may suggest the presence of Cloud Forest, developing around the La Purísima region during the Upper Oligocene-Lower Miocene. During this time period, the Baja California peninsula was attached to mainland Mexico, and it is possible that the spores recorded, were the result of the peninsula adjoining with the Sinaloa and Nayarit states, in which CF currently exists [46, 48]. Nowadays, CF is absent in the Baja California peninsula.

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