Proterozoic microfossils from subsurface siliciclastic rocks of the São Francisco Craton, south-central Brazil

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Abstract

Compressed organic-walled microfossils attributable to five filamentous taxa, and ten coccoidal eight, (taxa originally spheroidal forms and two originally ellipsoidal, colonial forms), all having long time-ranges in the Proterozoic, have been identified in fine-grained siliciclastic sediments in cores from four bore holes cutting subsurface equivalents of the Mesoproterozoic Conselheiro Mata Group and Neoproterozoic Bambuí Group on the São Francisco Craton in south-central Brazil. This is the first documented report of organic-walled microfossils from subsurface Proterozoic rocks of Brazil, including the first reference to occurrences of microfossils in the Conselheiro Mata Group and the Serra de Santa Helena, Lagoa do Jacaré, and Serra da Saudade Formations of the Bambuí Group. Surprisingly, microfossils in the Conselheiro Mata Group are better preserved, more diverse, and more abundant than in the younger, extremely depauperate assemblages of the Bambuí Group, possibly reflecting contrasting biostratinomic and paleoclimatic conditions. The Conselheiro Mata assemblages are dominated by fragments of filamentous microbial mats and small to medium-sized (≤ 200 µm), unornamented, simple acritarchs, none of which yet provides conclusive biostratigraphical evidence as to the age of the microfossiliferous successions. The morphologic simplicity, relatively small size, and low diversity of the microfossils in the Conselheiro Mata Group, however, are consistent with the Mesoproterozoic age attributed to this unit. Additionally, the relative proportions of planktic (sphaeromorphs) versus benthic (tubular filaments) microfossils are suggestive of fluctuations in sea level along part of the most fossiliferous bore hole. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Acritarchs; Brazil; Cyanobacteria; Micropaleontology; Proterozoic

1. Introduction

Growing interest in hydrocarbon occurrences and reserves in Proterozoic basins worldwide (Walter, 1991; McKirdy and Imbus, 1992) led the Brazilian national petroleum company, PETROBRÁS (Petrôleo Brasileiro S.A.), to investigate shows of gas in ancient cover sequences of the
São Francisco Craton (Babinski, 1986; Babinski and Santos, 1987; Babinski and Takaki, 1987; Melo et al., 1988; Santos and Babinski, 1995) in the states of Minas Gerais (MG) and Goiás (GO) in south-central Brazil. As a result of this effort, we were able to obtain fresh, relatively undeformed core material for palynological study from four bore holes, three drilled by PETROBRAS and one by the Companhia de Pesquisas de Recursos Minerais (CPRM), that furnished microfossils from two important Meso- to Neoproterozoic successions in this region (Figs. 1 and 3).

Although other papers have dealt with Brazilian Proterozoic microfossils preserved in various silicified carbonate facies (see summary in Fairchild et al., 1996), only a handful of abstracts and short notes are available on organic-walled microfossils isolated by standard palynological techniques from fine-grained siliciclastic rocks (Quadros, 1987) or carbonates (Sommer, 1971; Cruz and Lopes, 1992; Lopes, 1995). Hence, this is the first detailed report on organic-walled microfossils from maceration residues of rocks of this age from Brazil. As such, it discusses the subsurface record of benthic and planktic mi-
The SFC consists of three distinct blocks with somewhat different histories (Fig. 1): (a) the São Francisco Block (SFB), the westernmost portion, largely covered by Neoproterozoic and Mesozoic sediments, where the present study was conducted; (b) the Paramirim Corridor (PC), a narrow, 100–200-km-wide, NNW-trending band of tectonized, largely Mesoproterozoic low-grade metasediments and reactivated basement more-or-less parallelling the border of the states of Minas Gerais and Bahia; and (c) the Salvador Block (SB), east of the PC, where the oldest parts of the craton, as well as Mesoproterozoic and Neoproterozoic cover are exposed (Cordani, 1973; Brito Neves and Cordani, 1991; Trompette et al., 1992; Trompette, 1994).

The SFC (together with its eastward extension in Africa) acted as a relatively stable area during the Neoproterozoic to early Paleozoic Brasiliano and Pan-African tectonic cycles which amalgamated Western Gondwana (Brito Neves and Cordani, 1991). In Brazil, the Brasiliano cycle not only deformed and metamorphosed the fold belts (Brasília, Araçuaí, Rio Preto, etc.) surrounding the SFC and uplifted the intracratonic Paramirim Corridor but also considerably affected cover sequences on the craton, especially on the SFB (Fig. 2) (Cordani, 1973; Chemale et al., 1993; Trompette et al., 1992; Abreu, 1995).

It is these cover sequences that are of interest here. The few studies available on the subsurface geology of the SFC (Brandalise, 1980; Braun, 1988; Toledo, 1988, 1989a,b; Braun et al., 1990, 1993; Martins et al., 1993) reveal two distinct, widespread sedimentary packages, the lower, overwhelmingly siliciclastic (quartzites, pelites), separated from the overlying carbonate and fine-grained siliciclastic package by a thin rudaceous unit. In most of these studies the lower unit is correlated with the uppermost portion of the Mesoproterozoic Espinhaço Supergroup, a mostly quartzitic unit of marine and continental origin which crops out in and around the Paramirim Corridor and southward along the eastern border of the São Francisco Block. On the basis of the frequency of pelitic intercalations in the quartzites of the basal sediments of the two bore holes (1-PSB-13-MG and 1-MA-1-MG) near Montalvâ-
nia, MG, we correlate these sediments with the Conselheiro Mata Group, the topmost unit of the Espinhaço Supergroup (cf. Uhlein, 1991; Abreu, 1995; Dupont, 1995). The deepest sediments in the bore hole in Goiás (1-RC-1-GO, Fig. 2) are correlated with the Paranoá Group, equivalent to the Conselheiro Mata Group (Dardenne, 1978, 1981), with ample outcrops along the western border of the craton and already known to be microfossiliferous (see Fairchild et al., 1996).

The rest of the subsurface section is easily correlatable with the São Francisco Supergroup of Neoproterozoic age, which begins with basal rudaceous sediments, the Jequitaí Formation, considered glaciogenic, followed upward by shallow marine to paralic sediments of the Bambuí Group. The fourth bore hole (1-RF-1-MG), near Pirapora, MG, cuts through nearly 1850 m of this sedimentary package without reaching Conselheiro Mata or Paranoá equivalents.

Neither of the microfossiliferous successions has yielded direct age dates generally accepted by all. Based on general tectonic considerations, age correlations between rather widely separated, putatively equivalent Neoproterozoic glaciogenic rocks, presumptive age limits of conically laminated stromatolites, Pb–Pb age-dates on Neoproterozoic carbonates, other available but somewhat problematical geochronologic data on fine fractions of Proterozoic sediments, and a critical discussion of then available stable isotope data, Fairchild et al. (1996) accepted an age around the Mesoproterozoic: Neoproterozoic boundary for the Paranoá Group, older than 900 Ma, the inferred age of the Jequitaí glaciation, and younger than the underlying Araí Group, with a metamorphic age of at least 1170 Ma, according to Tassinari et al. (1981), but conceivably as great as 1300–1350 Ma (see Thomaz-Filho et al., 1998). Thus, the supposedly contemporaneous Conselheiro Mata Group would have to be at least this old. Indeed, tectonic and geochronological arguments regarding the Espinhaço Supergroup (in which the Conselheiro Mata Group comprises the youngest unit) strongly support an age between 1750 and 900 Ma, and most likely between 1750 and 1200 Ma for this supergroup (Abreu, 1995; Chaves and Neves, 1995; Dussin and Dussin, 1995; Thomaz-Filho et al., 1998).

Although the Bambuí Group is Neoproterozoic, there is still no agreement as to its precise age. Whereas some prefer an age around 600 Ma, based on chemostratigraphic and tectonic interpretations (Kawashita, 1996a,b; Misi and Veizer, 1998; Thomaz-Filho et al., 1998), others feel that this group must be older, such as Babinski (1993), who interprets available radiometric data as suggesting a minimum age of 690 Ma for Bambuí sedimentation, and Dardenne (1997), who admits its deposition in a foreland setting as early as 790 Ma. We side with the latter group so that until new studies can produce unambiguous results, we shall consider the age of the Bambuí Group as somewhere between 900 (the possible age of the Jequitaí glaciogenics) and 690 Ma.

### 3. Material and methods

#### 3.1. Description of the drill cores

Dark-colored, thinly laminated siltstones and shales were selected for palynological analysis from cores of four bore holes in the western part of the São Francisco craton in northwest Minas Gerais and eastern Goiás (Figs. 2 and 3). The two cores from Montalvânia, MG, 1-PSB-13-MG and 1-MA-1-MG, exhibit undeformed Mesoproterozoic and Neoproterozoic sediments. Further south, near Pirapora, MG, drill core 1-RF-1-MG recovered flat-lying Neoproterozoic sediments. Only the fourth core, 1-RC-1-GO, from Alvorada do Norte, GO, within the cratonic zone affected by Brasiliano tectonism, has deformed Mesoproterozoic and Neoproterozoic sediments.

Bore hole 1-PSB-13-MG (Montalvânia) cuts through two distinct cratonic sequences separated by a 67-m-thick conglomeratic interval between 540 and 610 m (Fig. 3). The lower unit, the Mesoproterozoic Conselheiro Mata Group, comprises 694 m of an unmetamorphosed, horizontal arenaceous package with dark, carbonaceous argillaceous-silty intercalations. Samples from 18 such intercalations, irregularly distributed between 696.8 and 1250.3 m depth, were analyzed in
Fig. 3. Generalized stratigraphic sections of the four wells whose locations are plotted in Fig. 2. Legend: 1, Fine-grained terrigenous lithologies (shales, siltstones, etc.). 2, Sandstone. 3, Conglomerate. 4, Diamictite. 5, Marl. 6, Limestone. 7, Dolostone. Inferred lithostratigraphic units: CM, Conselheiro Mata Group. P, Paranoa Group. J, Jequitaı´ Formation. SL, Sete Lagoas Formation. SH, Serra de Santa Helena Formation. LJ, Lagoa do Jacaré Formation. SS, Serra da Saudade Formation. Numbers to right of columns indicate depth (in m) of levels analyzed in this study. Fossiliferous levels are listed in Tables 1–4. After Simonetti (1994), based upon Toledo (1988, 1989a,b) and Brandalise (1980).
A series of rudaceous beds — conglomerates and breccias with argillaceous matrix, compositionally varied clasts, and occasional massive argillaceous intercalations — separates the arenaceous package from the overlying carbonates and subordinate fine-grained siliciclastics attributed to the Neoproterozoic Bambuí Group.

Bore hole 1-MA-1-MG (Montalvânia) reached a depth of 531 m and passed through, from top to bottom, a pelite-carbonate sequence, a narrow rudaceous unit, and an arenaceous unit (Fig. 3). The lower sequence, attributed to the Mesoproterozoic Conselheiro Mata Group, is made up of homogeneous quartz arenites and subordinate intercalations of carbonaceous siltstones. A polymictic conglomerate with intercalated pelitic and arenaceous laminae separates this unit from the upper sequence, which is correlated with the Bambuí Group, represented by calcarenites with occasional intercalations of calcilutites and dolostones of the Sete Lagoas Formation and marls and subordinate argillites of the overlying Serra de Santa Helena Formation. Seven samples from the Bambuí Group and three from the Conselheiro Mata equivalent were analyzed from this drill core.

Bore hole 1-RF-1-MG (Remanso do Fogo) was drilled close to Remanso do Fogo ('Bay of Fire') on the Paracatu River, where flammable gas of mixed thermochemical and biochemical origin (Melo et al., 1988) exsudes from the river bed. Beneath a thin cover of Cretaceous arenites (Uruçuia Formation), the drill core comprises 1751 m of essentially pelitic-carbonate sediments, plus a conglomerate and part of a diamictic unit at its base (Fig. 3).

The diamictites are attributed to the Jequitai Formation. The upper sequence (Bambuí Group) begins with a basal conglomerate, followed upward by four formations. The Sete Lagoas Formation, thickest of the four, is made up of carbonate shales with subordinate intercalations of calcilutites and calcarenites. It is overlain by the siltstones and sandstones of the Serra de Santa Helena Formation. This, in turn, gives way to calcarenites with intercalated shale of the Lagoa do Jacaré Formation. The uppermost unit consists of the slightly calciferous shales of the Serra da Saudade Formation. All sixteen samples analyzed from this well come from the Bambuí Group.

Bore hole 1-RC-1-GO (Rio Corrente) recovered 1175 m of pelitic sediments and carbonates of the Bambuí Group in angular unconformity above 31 m of quartzites correlated with the Paranoá Group at the western border of the craton (Fig. 3). Three formations are recognizable within the Bambuí Group: the Sete Lagoas Formation, calciferous shales with dolomitized calcilutites in its upper part; the Serra de Santa Helena Formation, shales with subordinate calcilutites at its base and subordinate calciferous siltstones at its top; and the Lagoa do Jacaré Formation, calcilutites with intercalated shales and calciferous siltstones. As most of the drill core consists of largely greenish-gray sediments, unlikely to be microfossiliferous, only five samples, all from the Bambuí Group, were analyzed.

### 3.2. Sample preparation

Potentially microfossiliferous, dark, laminated, fine-grained, predominantly siliciclastic rocks were subjected to standard chemical maceration. Samples with carbonate were generally avoided as diagenetic processes in carbonates tend to destroy organic material, including microfossils (Krylov and Tikhomirova, 1988). Given the advanced organic maturation and fragility of the organic material and in order to avoid further fragmentation and loss of microfossils, neither centrifugation nor sieving were utilized. Heavy-liquid separation using zinc chloride to eliminate inorganic particles proved inefficient and likewise was not used in this study.

Depending upon the abundance and preservation of the microfossils recovered by this process, from one to five palynological strew slides of each sample were examined by optical microscopy, as were petrographic thin sections of the microfossiliferous rock samples. A total of 110 palynological strew slides and 14 petrographic thin sections were studied. Illustrated material is deposited in the collections of the Centro de Pesquisas (CENPES), PETROBRAS, Rio de Janeiro and duplicate strew slides are deposited in the Laboratory
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of Systematic Paleontology, Departamento de Geologia Sedimentar e Ambiental, Instituto de Geociências, Universidade de São Paulo.

Table 2
Distribution of taxa in microfossiliferous levels of the Bambui and Conselheiro Mata Groups in well 1-MA-1-MG, Montalvânia, MG

<table>
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<th>Taxon</th>
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<tr>
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<td>Bambui Group (SL)</td>
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Siphonophycus sp. 1
Siphonophycus sp. 2
* cf. Polytrophicides sp.
Nostocales 1
Eosynechococcus medius
Leiosphaeridia ternata
Leiosphaeridia sp. 1
Leiosphaeridia sp. 2
Leiosphaeridia sp. 3
* cf. Glenobotrydion
P. pileiformis

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<tr>
<td></td>
<td>LJ*</td>
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Leiosphaeridia sp. 1
Leiosphaeridia sp. 3
Huroniospora sp.

* LJ, Lagoa do Jacaré formation. SH, Serra de Santa Helena formation.

4. Results and discussion

4.1. General characteristics of the microfossils

Not all of the macerated samples produced rich organic residues. While only nine of 28 sampled levels in the Bambuí Group proved to be microfossiliferous, and then, only sparsely so, 20 of the 21 levels in the older Conselheiro Mata Group turned out to be microfossiliferous (Fig. 3, Tables 1–4). Microfossil abundance, preservational quality, and morphological variety showed little relationship to depth of sampling. In both groups the organic residues consist of compressed organic-walled microfossils and associated amorphous to degraded organic matter, light gray to black in color, with mostly granular to smooth, irregular textures due to post-mortem biological and diagenetic degradation.

Most of the microfossils are very simple solitary or colonial coccolial or filamentous forms that rarely exceed 50 μm in diameter; no microfossil larger than 200 μm in diameter was observed. Palynomorphs larger than 30–40 μm in diameter are commonly partially fragmented. Tubular and cellular filamentous fossils were interpreted, respectively, as sheaths and trichomes by analogy with other similar fossil and modern cyanobacteria. For coccolial microfossils, size served to sep-
arate the prokaryotes from larger, probable eu-
karyotes in accordance with criteria discussed by
Schopf (1992a), the great majority of prokaryotes
being smaller than 25 \(\mu\)m in diameter. Intracellu-
lar inclusions, sometimes used to distinguish eu-
karyotes (Oehler, 1977), were considered as
lar inclusions, sometimes used to distinguish eu-
being smaller than 25 \(\mu\)m in diameter. Intracel-
lar inclusions, sometimes used to distinguish eu-
karyotes (Oehler, 1977), were considered as
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For the first time microfossils are documented
from the Conselheiro Mata Group and the fol-
lowing formations of the Bambui Group: Serra de
Santa Helena, Lagoa do Jacaré, and Serra da
Saudade Formations (Fig. 3). Microfossils have
previously been reported in carbonates (Sommer,
1971; Cruz and Lopes, 1992; Lopes, 1995) and
silicified peritidal carbonates of the Sete Lagoas
Formation at the base of the Bambui Group (see
Fairchild et al., 1996), but even these have not
been sufficiently illustrated.

Five filamentous taxa and ten coccoidal taxa
(eight originally spheroidal forms and two origi-
nally ellipsoidal, colonial forms), all having long
time-ranges in the Proterozoic, were identified in
this study (Tables 1–4). All but one of these taxa
were found in the Conselheiro Mata Group,
whereas only four are present in the Bambui
Group. Three taxa are common to both groups:
Eosynechococcus medius, Leiosphaeridia sp. 1, and
Leiosphaeridia sp. 3, whereas Huroniospora sp.
was observed exclusively in the Bambui Group
(Lagoa do Jacaré and Serra da Saudade
Formations).

The Conselheiro Mata microflora is much more
diverse than the Bambui microflora, as compar-
sion of well 1-PSB-13-MG (Table 1) to the other
wells (Tables 2–4) clearly shows. In this well,
three taxa (the cyanobacterium Siphonophycus sp.
1 and the acritarchs Leiosphaeridia sp. 1 and
Leiosphaeridia sp. 3) were identified in all 18
microfossilerous levels between 696.8 and 1250.3
m depth and another two (the cyanobacterium
Eosynechococcus grandis and the acritarch Pteros-
permopsimorpha pileiformis) in various levels from
top to bottom of the section. An additional three
taxa (the acritarchs Leiosphaeridia ternata and
Leiosphaeridia sp. 2 together with the cyanobac-
terium Eosynechococcus medius) are also very
long-ranging, whereas the remainder of the forms
identified in this section are restricted to single
levels (the cyanobacteria Palaeolyngbya sp. and
Nostocales 1 as well as the acritarch Form 1) or
to two to four occurrences (the cyanobacteria
Siphonophycus sp. 2 and cf. Polytrichoides sp. plus
the putative eukaryote cf. Glenobotrydion sp.).
The microflora is thus characterized by small to
medium-sized (\(\leq 200\) \(\mu\)m), morphologically sim-
ple forms (including the acritarchs) and domi-
nated by members of the common Proterozoic
taxa Siphonophycus, Eosynechococcus and
Leiosphaeridia with little variation throughout the
more than 550 m of the sampled section. Frag-
ments of filamentous (Siphonophycus) mats are
common in many of the fossiliferous levels.

As stated above, only four taxa (the probable
cyanobacteria Eosynechococcus medius and Hu-
roniospora sp. and the acritarchs Leiosphaeridia sp.
1 and Leiosphaeridia sp. 3) were identified in the
nine occurrences of Bambui microfossils, and in
practically all cases microfossils were few and
generally poorly preserved. Brasiliano tectonism
evidently affected the succession sampled in well
1-RC-1-GO, near the western margin of the cra-
ton, which accounts at least partly for the poor
preservation and scarcity of microfossils in this
well (Chemale et al., 1993). The only relatively
abundant microfossils found in the Bambui
Group occur in the Lagoa do Jacaré Formation
in well 1-RF-1-MG at the 480.7 m level and in
well 1-RC-1-GO at the 242.3 m level, and even so
these microfossils are all rather degraded. Other
levels are dominated by granular or opaque,
amorphous, fragmented organic matter with rare,
always very degraded microfossils. The 480.7 m
assemblage is composed solely of coccoidal micro-
fossils less than 20 \(\mu\)m in diameter attributable to
Huroniospora sp., many apparently preserved in
some phase of unequal cellular division resem-
bling budding (Fig. 8K, L and M). The 242.3 m
assemblage is similarly dominated by very de-
graded, granular, opaque coccoids of Huroni-
ospora sp. (Fig. 8N, O and P) but also includes
Leiosphaeridia sp. 1 and Leiosphaeridia sp. 3. Apparently only resistant forms survived deposition, diagenesis, and tectonism so that little can be inferred as to the evolutionary status, paleoecology, or chronological significance of the Bambuí microfossils. It does seem significant, nevertheless, that microfossils were detected in all four of the formations of this group penetrated by wells (Sete Lagoas, Serra de Santa Helena, Lagoa do Jacaré, Serra da Saudade Formations). This offers promise that further drilling may reveal additional microfossils in this important stratigraphic unit.

The surprising contrast in preservation, variety, and abundance of the microfossils between the Conselheiro Mata and Bambuí Groups, especially in the stable mid-cratonic region near Montalvânia (bore holes 1-PSB-13-MG and 1-MA-1-MG), is undoubtedly taphonomic in origin. Intuitively, one might expect the older, more deeply buried, Mesoproterozoic Conselheiro Mata Group to have been more ravaged by time and geologic processes than the overlying, Neoproterozoic Bambuí Group. Perhaps this unexpected situation may be due more to biostratinomic factors related to differences in sedimentation rates and climate than to diagene

4.2. Paleoenvironmental inferences based on the microfossil assemblages in the Conselheiro Mata Group

Available data on lithologies and sedimentary structures in the well cores do not allow precise definition of depositional environments represented by the fine-grained lithologies analyzed here other than indicating generally calm conditions (e.g. silty to clayey grain size; thin, plane-parallel lamination; detrital mica; carbonaceous content). However, the Conselheiro Mata microflora is sufficiently well preserved and abundant (contrary to the depauperate and degraded Bambuí microfossil assemblages) to delve further into the paleoenvironmental interpretation of many sampled levels.

Habits of the fossil microorganisms were inferred from modern morphological analogs among the simpler microbes (especially, the cyanobacteria). Thus, the greater part of the colonies found in the residues were considered as benthic forms and, when abundant (especially in the case of dense filamentous colonies), as evidence of a nearshore marine environment. On the other hand, the predominance of unicellular microfossils (especially acritarchs) over colonial forms was interpreted as evidence of offshore deposition. Where apparently benthic forms were very rare or absent, an open-water domain was inferred (Butterfield and Chandler, 1992; Petrov and Veis, 1995).

Microfossils present at all 18 levels sampled in well 1-PSB-13-MG represent varied depositional settings (Table 1). The six levels between 735.2 and 696.8 m apparently document the change from a restricted subtidal environment to an intertidal setting and finally to an open-water domain. At the 735.2 m level — the richest of all the samples investigated — the predominant microfossils are solitary coccoidal forms mostly less than 40 μm in diameter and fragments of colonies frequently associated with vestigial organic matrix. A few fragmentary filamentous masses made up of filaments of distinctly different diameters (Fig. 5A and B) are rather like some minute epiphytic species of cyanobacteria that proliferae on modern marine benthic colo-
nial cyanobacteria (Simonetti, personal observations). Solitary coccoids occasionally associated with filamentous colonies may represent cells that once occupied the now empty cylindrical sheaths (Fig. 5C); the only trichome observed within a sheath in this study was, in fact, observed in this sample (Fig. 5F). The abundance of well-preserved microfossils, the common preservation of colonial sheaths, and the possible presence of epiphytes suggest that the microbiota grew in a relatively calm nearshore environment. Indeed, a thin section cut parallel to bedding shows colonies developing in situ directly upon fine sand (Fig. 4A and B). The scarcity of acritarchs, which typically dominate oceanic domains (Hofmann, 1987), is consistent with this interpretation.

The transition to an intertidal setting is suggested by the similar microfossil assemblages from the next three samples in the succession (733.6, 731.5 and 723.4 m levels), which differ only subtly in abundance and quality of preservation. The dominant elements in all three assemblages are small solitary coccoids interpreted as individuals separated from colonies, followed by entangled filaments representing fragments of benthic mats. Planktic acritarchs greater than 40 $\mu$m are uncommon and exhibit intensely fragmented margins, perhaps the result of their permanence in the agitated waters of the intertidal zone.

Finally, in the two uppermost samples of the succession (718.85 and 696.8 m levels), a more offshore, subtidal setting is indicated by the pre-

Fig. 4. Photomicrographs of a petrographic thin section of a microfossiliferous fine sandstone of the subsurface equivalent of the Conselheiro Mata Group cut parallel to bedding from the 735.2 m level of well 1-PSB-13-MG, near Montalvânia, MG. Plain (unpolarized) light. (A) Individual filaments (small arrows) and filamentous mat (large arrow, upper right) associated with fine clasts (c) of quartz sand. Small (14 $\times$ 16 $\mu$m) acritarch (Leiosphaeridia sp. 3) visible in lower left. (B) Mat of ribbon-like filamentous sheaths (Siphonophycus sp. 1) about 3 $\mu$m across partially enveloping organic grain. Scale = 50 $\mu$m. (C) Acritarch (Leiosphaeridia sp. 3) $\approx$ 80 $\mu$m in diameter entangled in filamentous mass. Observe folds in vesicle in upper right. Scale = 20 $\mu$m (also serves D). (D) Compact cluster measuring 26 $\mu$m in greatest dimension of coccoidal microfossils. Scale as in C.
dominance of isolated acritarchs and rarity of colonial microfossils. In both samples filaments do occur but are frequently solitary, probably remnants of nearshore benthic mats.

This last situation contrasts with that inferred for the assemblage from the 927.4 m level deeper in the same well (1-PSB-13-MG). Fragments of benthic coccoidal and filamentous colonies, often associated with vestigial mucilage, predominate, and isolated coccoidal forms larger than 20 μm are rare, once again suggestive of a nearshore benthic environment. Besides these relatively common morphotypes, there also occur short fragments of cellular filaments comparable to modern trichomes of nostocalean cyanobacteria (Nostocales 1, Fig. 5G).

Nostocales 1 is also common in the samples from the 415.75 and 415.1 m levels in well 1-MA-1-MG, which, like the sample mentioned above, are dark argillaceous siltstones with submillimetric plane-parallel lamination. In these three cases this morphotype is thought to represent planktic
trichomes similar to several species of the modern genera *Anabaena* and *Nostoc*. Some species of the former genus presently occur as isolated, short trichomes a few cells long, together with other filamentous cyanobacteria, in restricted marine environments, such as lagoons and estuaries, especially under conditions favouring eutrophication (Fogg, 1987). The dominance of benthic forms allied to the scarcity of planktic elements (acritarchs) and the presence of *Anabaena*-like trichomes putatively associated with restricted marine environments may be indicative of lagoonal conditions in the three cases cited above.

The sample from the 1239.7 m level in well 1-PSB-13-MG also deserves discussion. Contrary to the majority of the samples investigated, the microflora in this sample is dominated by filaments, either as isolated individuals or as colonies within a mucilaginous matrix. These well-preserved fragments of filamentous benthic colonies point to a shallow, relatively low-energy, nearshore environment, quite possibly restricted, given the absence of significant planktic elements.

Our approach differs from the detailed faciological and paleoecological evaluation of the siliciclastic/carbonate Neoproterozoic Derevnya Formation (Siberia) carried out by Petrov and Veis (1995) and from the interesting faciological and paleoecological evaluation of the microflora of the apparently early Neoproterozoic Miroedikha Formation (Russia) made by Veis et al. (1998, 1999). Our interpretations are based mainly on intrinsic qualities of the microfossil assemblages from well cores, whereas those of Petrov and Veis (1995) and Veis et al. (1998, 1999) benefited very strongly from abundant outcrop data and sedimentary sequence analysis. Significantly, all approaches, ours as well as theirs, resulted in coherent pictures of ancient environmental settings. Our conclusions are admittedly more general but still significant in that they reinforce the value of simple morphological comparison of Proterozoic compressed microfossils as a source of paleoenvironmental information in well cores for which little sedimentological data is available.

4.3. Comparisons and chronological significance of the microfloras

The microfossils reported here together with those from 19 other occurrences known from surface outcrops on and around the CSF in the Paranóá Group, Bambuí Group, and Jequitai Formation (chert clasts within a diamicite) were recently summarized by Fairchild et al. (1995, 1996). The microfossil content of the four wells is comparable to assemblages from silicified carbonates in surface outcrops now attributed to the Paranóá Group (Fairchild and Dardenne, 1978; Subacius, 1985; Fairchild and Subacius, 1986; Simonetti and Fairchild, 1989), which, as we have said, is presumably correlative to the Conselheiro Mata Group (Dardenne, 1978; Uhlein, 1991). Common to both, as in many Proterozoic microfloras, are such taxa as *Siphonophycus*, *Eosynechococcus*, *Glenobrytidion*-like forms, and generally small leiosphaerid acritarchs. However, as befits their distinctly different depositional settings, they differ significantly in relative frequency of these elements, leiosphaerids being much more abundant in the siliciclastic subsurface sediments of the Conselheiro Mata Group.

The poor preservation, low morphological diversity, and paucity of microfossils in the Bambuí equivalent in the wells do not allow comparison with other Bambuí assemblages from surface outcrops (Fairchild et al., 1980; Fairchild and Schorscher, 1985; Cruz and Lopes, 1992; Lopes, 1995; Fairchild et al., 1996) or permit reasonable speculation as to the age of this unit.

Such is not the case, however, for the more abundant, more diverse and better preserved Conselheiro Mata assemblages. For this discussion, all 18 microfossiliferous levels in well 1-PSB-13-MG, as well as the two closely spaced assemblages from nearby well 1-MA-1-MG, may be considered as comprising a single long-lived, low-diversity microflora dominated by small leiosphaerids and tubular filaments. Despite compositional differences attributable to differing depositional settings over the nearly 600 m of section that it occupies, this microflora exhibits no detectable evolutionary innovations between the lowest and highest microfossil occurrences in this well.
Although the Conselheiro Mata microflora is extremely simple, a reasonable argument in favor of a Mesoproterozoic age may be constructed based on what is actually present and what appears to be missing in this assemblage. In spite of careful sample preparation and thorough scanning of more than a hundred prepared slides of maceration residues, no acritarchs larger than 200 \( \mu \text{m} \) in diameter, either as whole individuals or as fragments, were detected. In fact, the great majority of sphaeromorphs are less than 100 \( \mu \text{m} \) in diameter. Not a single acanthomorphic, ornamented, or otherwise complex (polygonal, vase-shaped, etc.) acritarch was observed. Nor were fragments of multicellular microscopic or macroscopic algae evident in this assemblage. Apparently, its most complex element is the disphaeromorphic acritarch *Pterospermomorpha pileiformis* (Fig. 8Q and R).

In accordance with Knoll’s (Knoll, 1996) summary of paleontological differences among the larger subdivisions of the Proterozoic, these characteristics suggest three possible time slots for this assemblage: The first, in the Mesoproterozoic, which is typified by generally non-descript leiosphaerids, with the second and third in the Neoproterozoic, in, respectively, offshore turbidites (Butterfield and Chandler, 1992), or Ediacaran-aged deposits. We feel that the latter two possibilities can safely be discarded. For example, the common presence of filamentous mat fragments at many levels in the Conselheiro Mata Group favors a relatively shallow, platformal rather than a deeper, turbiditic setting for most of the sedimentation. Moreover, the absence of any record of multicellular algae, even as fragments, or very large sphaeromorphs in the maceration residues or of Ediacaran-grade invertebrate fossils in the extensive outcrops of the Conselheiro Mata Group points to the first possibility as the most viable option.

As in the present case, small leiosphaerid acritarchs less than 500 \( \mu \text{m} \) in diameter dominate the best documented Mesoproterozoic microfossil assemblages from siliclastic rocks, according to Sergeev et al. (1981), Dismal Lakes Group (Horodyski et al., 1980), Belt Supergroup (Horodyski, 1980), and Ust’-Il’ya and Kotuikan Formations (Sergeev et al., 1995). More specifically, however, the Conselheiro Mata microflora bears particular resemblance to the shallow subtidal elements of the recently described microfossil assemblage from the presumably early Mesoproterozoic Bangemall Group of Australia (Buick and Knoll, 1999). Common to both are *Eosynechococcus, Eomicrocoleus*-like filaments (comparable to our cf. *Polytrichoides* sp.), common *Siphonophycus*, abundant *Leiosphaeridia* predominantly less than 100 \( \mu \text{m} \), and practically identical *P. pileiformis*. The absence in our assemblage of such elements of the Bangemall assemblage as the peritidal *Palaeopleurocapsa wopfneri* and the deeper subtidal megasphaeromorphic acritarch, *Crassicorium pendjariensis*, appear to reflect the greater palaeoenvironmental gamut of the Bangemall assemblage.

If the Conselheiro Mata assemblage is Mesoproterozoic in age, one might ask why the relatively large, ellipsoidal microfossil, *Archaeoellipsoides*, and the sac-like aggregate acritarch *Satka*, said to be typical of and common in Mesoproterozoic microfloras (Knoll and Sergeev, 1995; Sergeev et al., 1995; Knoll, 1996), are not present in our material. However, as mentioned for *P. wopfneri* and *C. pendjariensis*, the absence of *Archaeoellipsoides* most likely reflects differences in depositional setting, especially as *Archaeoellipsoides* is typical of silicified microfloras associated with peritidal carbonates (Golubic et al., 1995) and not of platformal siliciclastic environments such as those postulated for the Conselheiro Mata microfossils. As for *Satka*, although present in various Mesoproterozoic microfloras, this form may not be as abundant nor as cosmopolitan as originally thought. For example, in the Bangemall assemblage Buick and Knoll (1999) found only two specimens well enough preserved to warrant confident assignment to this genus.

It is tempting to suggest the temporal equivalence of the Bangemall and Conselheiro Mata assemblages based (1) on the close similarity between them; and (2) on their dissimilarity to typi-
cal Neoproterozoic microfloras. This would be in keeping with the 1750–1200 Ma age bracket generally accepted for the Espinhaço Supergroup, which includes the Conselheiro Mata Group. Also consistent with this hypothesis are the recent reports of acanthomorphic and other complex acritarchs from near the Mesoproterozoic-Neoproterozoic transition (c. 1000 Ma; Yin, 1997; Xiao et al., 1997; see also Butterfield and Rainbird, 1998), which could mean that the Conselho Mata microflora developed earlier in the Mesoproterozoic. The difference between these two biotas and the much more diverse (39 taxa) assemblages of shale-facies microfossils from the Bylot Supergroup (Canada) (Hofmann and Jackson, 1994) deserves comment, especially as this unit may have been deposited as early as 1270 Ma (middle Mesoproterozoic), which would make it potentially contemporaneous with Bangemall and Conselho Mata sedimentation. As Hofmann and Jackson (1994) pp. 7–9; acknowledge, the crucial point is the poorly constrained age of the Bylot assemblages, which could be as young as 750 Ma. In fact, these authors admit that the close similarity of their material to the Miroedikha (c. 850 Ma) and Lakhanda (c. 950 Ma) microfloras may mean that the age of the Bylot Supergroup may correspond to a more restricted interval between the present limits of 1270 and 750 Ma. It will be interesting to see if new discoveries of Mesoproterozoic microfloras from platformal settings will confirm the apparent time-significance (early to middle Mesoproterozoic) of the association of predominantly small leiosphaerids (< 100 μm) and Pterospermopsimorpha pileiformis, implicit both in Buick and Knoll’s (1999) paper on the Bangemall assemblage and in the present paper.

5. Conclusions

This is the first systematic micropaleontological study published on material recovered from well cores from Precambrian terrains in Brazil. The quality of preservation and relative abundance of the microfossils reported here are best in wells drilled in the unperturbed platform near Montalvânia, MG, which is consistent with the limits of the tectonic dominions of the São Francisco craton traced by Chemale et al. (1993). The preservational quality and abundance of the organic matter also permitted reasonably confident interpretations of probable habit and general habitat of most of the microfossils.

Microfossils are here reported for the first time from the Mesoproterozoic Conselho Mata Group and the Neoproterozoic Serra de Santa Helena, Lagoa do Jacaré, and Serra da Saudade Formations of the Bambuí Group. Somewhat surprisingly, the microfossils of the older group are much more abundant, more diverse, and better preserved than the Neoproterozoic ones. We speculate that this may be biostratigraphic in origin, perhaps reflecting generally quicker deposition and/or a cooler climate for the microfossils in the overwhelmingly siliciclastic environments of the Conselheiro Mata Group as compared to the presumably warmer settings and slower accumulation rates of the mixed carbonates and pelites of the Bambuí Group.

We interpret differences in the relative abundance of acritarchs and fragments of benthic mats as documenting changes from a restricted subtidal environment through intermediate shallow (intertidal) settings to a deeper, more open marine environment in the Conselheiro Mata Group over a thickness of about 40 m in well 1-PSB-13-MG. This is particularly noteworthy because it reinforces the potential value of even simple Precambrian microfossils, such as those studied here, in aiding paleoenvironmental interpretations, especially in lithologically monotonous well cores with few diagnostic sedimentary structures.

The few microfossil taxa identified here in the admittedly Neoproterozoic Bambuí Group are poorly preserved and exhibit broad temporal distribution which impedes them from resolving the arguments over the age of this important stratigraphic unit. The case for the microflora of the Conselho Mata Group is different, however. The dominance of small leiosphaerid acritarchs and tubular sheaths (Siphonophycus spp.) plus the presence of the disphaeromorphic acritarch P. pileiformis in this group, together with the lack of sphaeromorphs larger than 200 μm and the ab-
sence of acanthomorphs or otherwise complex acritarchs or algae — despite our intense search for such elements — are clearly consistent with a Mesoproterozoic age for this group and, furthermore, seemingly restrict it to a period prior to the explosive radiation of eukaryotes that marks the Mesoproterozoic–Neoproterozoic transition.

6. Systematic paleontology

All the microfossils observed in the present study are preserved as flattened compressions. The sizes given below are probably close to original dimensions in the case of spheroidal and ellipsoidal microorganisms but may be up to 1.57 X (or π/2) broader for the now ribbon-like, originally cylindrical filaments and slightly larger overall (by a factor of 1.2) for the now elliptical, originally ellipsoidal Leiosphaeridia ternata (Fig. 8F) here preserved with radially arranged marginal tears (see Schopf, 1992a). These size considerations have been taken into account in attributing the microfossils to paleontological taxa which were originally defined for microfossils preserved three-dimensionally in chert, such as Siphonophycus and Palaeolyngbya, as well as in designating them as prokaryotic or eukaryotic, especially as cellular ornamentation and morphological complexity, which might help in this task, are simply not evident in the microflora. Thus, on the basis of size (Schopf, 1992a) and similarity to both modern forms and other fossils, all five filamentous morphotypes (Siphonophycus sp. 1, Siphonophycus sp. 2, Palaeolyngbya sp., cf. Polytrichoides sp., and Nostocales 1) and two of the coccosoidal forms (Eosynechococcus medius and E. grandis) are here assigned to the Prokaryota as most probably Cyanobacteria, whereas seven of the eight remaining taxa (Leiosphaeridia ternata, Leiosphaeridia sp. 1, Leiosphaeridia sp. 3, cf. Glenobotrydion sp., Huroniospora sp., P. pileiformis, and Form 1) could represent either prokaryotic or eukaryotic organisms, leaving only Leiosphaeridia sp. 2, with diameters between 100 and 200 μm, as the only assuredly eukaryotic morphotype.

6.1. Filamentous microfossils

PROKARYOTA
CYANOBACTERIA
Order OSCILLATORIALES Copeland, 1936
Type species: Siphonophycus kestron Schopf, 1968, p. 671.

SIPHONOPHYCUS sp. 1
Fig. 4B, Fig. 5A–C and Fig. 6

6.1.1. Description
Originally tubular, unbranched, nonseptate, straight to slightly sinuous filaments; light gray to black, rarely opaque; surface texture smooth to incipiently granular; solitary or aggregated in masses with dozens of individual filaments, commonly within or associated with a probably mucilaginous amorphous organic matrix; filaments of distinct sizes may occur in the same mass; compressed diameter 1–10 μm (average = 4 μm; N = 314); length to several tens of microns.

6.1.2. Occurrence
Present in all microfossiliferous samples of the subsurface equivalent of the Conselheiro Mata Group, Espinhaço Supergroup, in wells 1-PSB-13-MG and 1-MA-1-MG (Tables 1 and 2).

SIPHONOPHYCUS sp. 2
Fig. 5D, E and Fig. 6
6.1.3. Description
Originally tubular, unbranched, nonseptate, straight to slightly sinuous, isolated filaments; dark gray to black, rarely opaque; surface texture smooth or granular; diameter 11–18 \( \mu \)m (average = 14 \( \mu \)m; \( N = 7 \)); fragments short, up to a few tens of microns in length.

6.1.4. Occurrence
Subsurface equivalent of the Conselheiro Mata Group, Espinhaço Supergroup: Wells 1-PSB-13-MG and 1-MA-1-MG (Tables 1 and 2).

6.1.5. Discussion
Nonseptate, unbranched, unornamented tubular filaments, abundant throughout the Proterozoic, were formerly separated on the basis of uncompressed filament diameter into three microfossil genera: *Archaeotrichion*, for tubes less than 1 \( \mu \)m, *Eomycetopsis* for tubes 2–4.5 \( \mu \)m in diameter, and *Siphonophycus*, for tubes greater than 8.3 \( \mu \)m (Schopf, 1968). In 1991, Knoll et al. suppressed the genus *Eomycetopsis* and redefined *Siphonophycus* to include tubular filaments greater than 1 \( \mu \)m in diameter, with filament diameter also being the principal characteristic for defining species. In 1994, Butterfield et al. identified five *Siphonophycus* species based on a geometric increase in diameter with arbitrary upper size limits at 2, 4, 8, 16, and 32 \( \mu \)m.

The histogram of filament diameters of our specimens of *Siphonophycus* in Fig. 6 shows two size modes, one around 2 \( \mu \)m and the other at 4 \( \mu \)m (with a possible minor mode at 10 \( \mu \)m), exactly at the limits of *S. septatum*/*S. robustum* and *S. robustum*/*S. typicum*, respectively. Remember, however, that our specimens are compressed ribbons, not tubes; hence, as explained above, they presently may be up to 1.5 times their original tubular diameters. Therefore, as it would be difficult to include our specimens in one or the other of these taxa, we prefer to designate our specimens more simply as *Siphonophycus* sp. 1 (1–10 \( \mu \)m) and *Siphonophycus* sp. 2 (11–18 \( \mu \)m). No attempt was made to differentiate the narrowest tubular filaments as *Archaeotrichion*.

*Siphonophycus* sp. 1 obviously includes the remains of more than one biological species, as it is common to see abundant 2 and 4-\( \mu \)m filaments in the same microbial mat, with the narrower form often dominating. This is also evident in Fig. 5B which shows 1–2-\( \mu \)m-broad tubes infesting a larger filament. A comparable habit is observed among living cyanobacteria in the intertidal and supratidal zones of the southern coast of the state of São Paulo, where *Lyngbya pellucida*, a similarly sized epiphyte, is commonly associated with larger filamentous cyanobacteria (Sant’ Anna et al., 1985; Sant’ Anna and Simonetti, 1992).

The size and morphology of *Siphonophycus* sp. 1 and sp. 2 suggest affinity with sheaths of diverse oscillatoriacean cyanobacteria, such as *Lyngbya*, *Blennothrix*, *Microcoleus*, among others or even with similar bacterial genera.

Genus *PALAEOLYNGBYA* Schopf, 1968

6.1.6. Description
Opaque, originally cylindrical, unbranched, unisseriate cellular trichome made up of cells apparently broader than long; trichome constricted at septa; compressed cell breadth about 2 \( \mu \)m; cell length, 0.5–1 \( \mu \)m. External sheath smooth, translucent, light gray, longer than the trichome; compressed sheath diameter 4 \( \mu \)m; specimen 60 \( \mu \)m long.

6.1.7. Occurrence
Subsurface equivalent of the Conselheiro Mata Group, Espinhaço Supergroup: Well 1-PSB-13-MG, 735.2 m level (Table 1).

6.1.8. Discussion
Although compressed, this unique specimen is essentially identical to extant members of the cosmopolitan genus *Lyngbya* (Oscillatoriaceae) in cell outline, presence of a distinct sheath, and pairing of cells (produced by asexual fission; arrow in Fig. 5F). The small original diameters of the cells (about 1.3 \( \mu \)m) and sheath (about 2.6 \( \mu \)m) of our specimen, however, fall within the known size range of morphologically similar filamentous bac-
Fig. 7. Histogram of diameters of compressed cellular fossil filaments of Nostoccales 1. Owing to the nature of the process of compression of originally ellipsoidal cells (Schopf, 1992a), the original (three-dimensional) diameters of these filaments were probably not much different from the values represented here.

6.1.11. Discussion

The described specimens were placed in Polytrichoides sp. because of the relatively narrow diameter and compact, subparallel arrangement of the constituent trichomes, typical of this genus. However, the reconstructed trichome diameter, \(<1 \mu m\), is significantly less than the size range of Neoproterozoic P. lineatus cited by Schopf (1992b); (1.6–2.5 \(\mu m\)) for three occurrences and by Knoll et al. (1991); (3–5 \(\mu m\)) for the Draken Conglomerate Formation, hence the use of ‘cf.’ prior to the genus name to indicate our reservations regarding this taxonomic assignment.

The gregarious habit of the filaments permits comparison with the fossil Eomicrocoleus crassus Horodyski and Donaldson, 1980, and the modern cyanobacterial genus Microcoleus (Phormidiaceae, Microcoleidae), characterized by the presence of several trichomes within a single, tubular sheath. Despite the similar size of our trichomes and E. crassus, our material lacks the clearly defined external sheath typical of Eomicrocoleus.

The narrow diameters of the trichomes may signify closer affinities to modern filamentous bacteria than to the cyanobacteria.

6.1.12. Description

Flattened, unbranched, constricted, uniseriate cellular trichomes; dark gray to black; surface smooth to finely granular; cells elliptical to circular, originally ellipsoidal to spheroidal; elliptical cells slightly longer than broad; breadth of cells between 3 and 10 \(\mu m\) (average = 5 \(\mu m\); \(N=42\)); cell length between 4 and 12 \(\mu m\); trichomes from 10 \(\mu m\) to several tens of microns long. One rather deformed specimen exhibits cells apparently preserved during simple binary fission.

6.1.13. Occurrence

Subsurface equivalent of the Conselheiro Mata Group, Espinhaço Supergroup: Wells 1-PSB-13-MG (927.4 m level) and 1-MA-1-MG (415.1 and 415.7 m levels) (Tables 1 and 2).
Fig. 8. Organic-walled microfossils in maceration residues from samples of a subsurface equivalent of the Mesoproterozoic Conselheiro Mata Group. Well number, depth, and slide identification are indicated within parentheses. Scale bars = 10 μm in C and R and 20 μm in G and I; bar in C is also valid for B, K–P, and S; that in G also serves H and J; that in R also serves A, D–F, Q, and T. (A) *Eosynechococcus medius*. Colony (1-PSB-13-MG, 735.2 m, C1). (B, C) *Eosynechococcus grandis*. Isolated cell (B) — (1-PSB-13-MG, 1140.0 m, B). (C) — (1-PSB-13-MG, 1140.0 m, B). (D, E) *Leiosphaeridia* sp. 3. (D) — (1-PSB-13-MG, 718.85 m, B). (E) — (1-PSB-13-MG, 735.2 m, G). (F) *Leiosphaeridia ternata*. Note radially arranged marginal splits (1-PSB-13-MG, 718.85 m, B). (G, H) *Leiosphaeridia* sp. 1. (G) — (1-PSB-13-MG, 1029.14 m, C). (H) — (1-PSB-13-MG, 1140.0 m, D). (I, J) *Leiosphaeridia* sp. 2. (I) — (1-PSB-13-MG, 1008.35 m, A). (J) — (1-PSB-13-MG, 1140.0 m, D). (K–P) *Huroniospora* sp. Note budding-like pattern in K, M and N. (K) — (1-RF-1-MG, 480.70 m, B). (L) — (1-RF-1-MG, 480.70 m, B). (M) — (1-RF-1-MG, 480.70 m, B). (N) — (1-RC-1-GO, 242.30 m, C). (O) — (1-RC-1-GO, 242.30 m, C). (P) — (1-RC-1-GO, 242.30 m, C). (Q, R) — *Pterospermoopsinorpha pileiformis*. (Q) — Inner vesicle has split. Broad, low spine-like feature in lower right is taphonomic in origin (1-PSB-13-MG, 723.4 m, B). (R) Rod-like feature in upper right is a fold in the outer envelope and not a process (1-PSB-13-MG, 1012.7 m, B2, ZnCl2). (S) Form 1. Note fine striae (1-PSB-13-MG, 723.4 m, B). (T). cf. *Glenobotrydion* sp. (1-PSB-13-MG, 1005.05 m, A).
6.1.14. Discussion

Both the cellular morphology and the dimensions of the filaments suggest that these filaments belong to the cosmopolitan family Nostocaceae. Neither akinetes (e.g. *Archaeoellipsoides* spp.) nor heterocysts, a typical feature of modern nostocaleans, were observed here.

6.2. Coccoidal microfossils

PROKARYOTA
CYANOBACTERIA
Order CHROOCOCCALES (Wettstein, 1924)
Genus EOSYNECHOCOCCUS (Hofmann, 1976)
Type species: *Eosynechococcus moorei*
EOSYNECHOCOCCUS MEDIUS (Hofmann, 1976)
Fig. 8A, Fig. 9

6.2.1. Description

Compressed elliptical (coccoidal) microfossils; colonial, occasionally isolated, or arranged in pseudofilamentous strings of three or four individuals; surface smooth or slightly granular; smaller diameter 1–6 μm (average = 4 μm) and larger, 2–9 μm (average = 6.1 μm; *N* = 28) (Fig. 9); colonies (*N* = 6) without well-defined form, made up of tens of usually contiguous individuals, some of which may be deformed by mutual compression; cell division apparently by binary fission along a plane perpendicular to the longer dimension of the cell as suggested by the common short pseudofilamentous groupings of cells.

6.2.2. Occurrence

Subsurface equivalent of the Conselheiro Mata Group, Espinhaço Supergroup: five levels in well 1-PSB-13-MG and two in well 1-MA-1-MG (Tables 1 and 2).

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Fig. 9. Comparison of compressed cell dimensions in the two species of *Eosynechococcus* (*E. medius* and *E. grandis*) identified in this study. Plotted numbers (1, 2, 3, or 4) refer to the number of measurements obtained with that specific value. Owing to the nature of the process of compression of originally ellipsoidal cells (Schopf, 1992a), the original (three-dimensional) diameters of these fossils were probably not much different from the values represented here.
EOSYNECHOCOCCUS GRANDIS (Hofmann, 1976)
Fig. 8B, C and Fig. 9

6.2.3. Description
Compressed elliptical (coccoidal) microfossils; colonial or solitary; surface smooth or granular (especially in more degraded specimens); some specimens opaque; smaller diameter, 8–14 μm (average = 11 μm; N = 17) and larger, 10–18 μm (average = 13.8 μm; N = 18) (Fig. 9); colonies (relatively) rare (N = 2), without well-defined form, made up of tens of contiguous individuals, some deformed by mutual compression; cell division apparently by binary fission along a plane perpendicular to the larger cell diameter.

6.2.4. Occurrence
Subsurface equivalent of the Conselheiro Mata Group, Espinhacõ Supergrupo: eight levels in well 1-PSB-13-MG (Table 1).

6.2.5. Discussion
These two species of *Eosynechococcus* are distinguished by their elliptical cell shape (Fig. 9) but differ in size (Hofmann, 1976). As our specimens do not exhibit radially arranged marginal tears, the originally ellipsoidal microorganisms probably underwent compression without significant distortion such that the sizes given in the descriptions above are close to the original dimensions. It is true that they are not strongly elliptical, but only two specimens of the 28 measured were circular, hence their attribution to this genus.

These fossils resemble members of the modern cyanobacterial genus *Synechococcus* (Microcystaceae, Synechococcales), typified by cylindrical to ovoidal, solitary, pseudofilamentous, or colonial cells that divide by binary fission along a plane perpendicular to the longest cell axis.

INCERTAE SEDIS
Genus LEIOSPHAERIDIA (Eisenack, 1958)

Fig. 8F

6.2.6. Description
Elliptical or more rarely circular compressed vesicles, originally ellipsoidal, without recognizable dehiscence structure; dark gray to black; walls apparently thick, always ruptured, with more-or-less radial tears at the margin of the vesicle; minor axis, 15–20 μm, and major axis, 20–31 μm (average = 22 μm; N = 10).

6.2.7. Occurrence
Subsurface equivalent of the Conselheiro Mata Group, Espinhacõ Supergrupo: Well cores 1-PSB-13-MG (four levels) and 1-MA-1-MG (2 levels) (Table 1 and Table 2).

6.2.8. Discussion
The characteristic radial pattern of marginal ruptures in the wall places these specimens firmly in the taxon *Leiosphaeridia ternata*. It also comprises putative evidence for an originally thick, resistant vesicle wall that rather than fold in upon itself upon compression, as seems to have been the case for *Leiosphaeridia* sp. 3, ruptured and flattened out, resulting in dimensions about 1.2 times the original values (Schopf, 1992a).

The dimensions of specimens identified here are similar to those described by Zang and Walter (1992; 12–73 μm) and Jankauskas et al. (1989; 30–70 μm) but are smaller than those described by Timofeev (1966; 50–80 μm).

LEIOSPHAERIDIA sp. 1
Fig. 8G, H and Fig. 10

6.2.9. Description
Compressed, elliptical, occasionally circular, or irregular, usually solitary vesicles, some apparently in various stages of binary division, rarely as colonies; dark gray to black; no recognizable dehiscence structures; surface texture irregular, intensely granular; walls relatively thick, frequently folded; colonial forms very rare, always with less than ten vesicles; vesicle diameter, 8–95 μm (average = 34; N = 219).
6.2.10. Occurrence

Present in the Bambuí Group at one level in the Sete Lagoas Formation (well 1-MA-1-MG), two levels in the Serra de Santa Helena Formation (well 1-RC-1-GO), and one level in the Lagoa do Jacaré Formation (well 1-RC-1-GO) as well as at all the microfossiliferous levels of the subsurface equivalent of the Conselheiro Mata Group, Espinhacó Supergroup, in well 1-PSB-13-MG and at one level in well 1-MA-1-MG (Tables 1, 2 and 4).

6.2.11. Discussion

Among the forms here attributable to the genus Leiosphaeridia, vesicles less than 100 μm in diameter with an irregular, granular surface texture are here grouped together as Leiosphaeridia sp. 1. Some poorly preserved forms of Leiosphaeridia sp. 3 may very well be included in this taxon especially as both taxa have similar sizes (Figs. 10 and 11) and occur together at all but one of the microfossiliferous levels of the subsurface equivalent of the Conselheiro Mata Group. Despite the evident degradational overprint in many individuals, some members of Leiosphaeridia sp. 1, for example those without prominent folds and those in the Bambuí Group, where Leiosphaeridia sp. 3 has not been detected, may represent originally different microorganisms with different preservation potentials and taphonomic behaviours. The diameters reported above are thought to correspond to original values of the uncompressed individuals.

LEIOSPHAERIDIA sp. 2
Fig. 8I, J and Fig. 10

6.2.12. Description

Irregular, circular, or elliptical opaque compressed vesicles; dark gray to black; occasionally lighter at margins; walls apparently thin, always fragmented, principally at margins; surface texture irregular, varying within a single specimen from smooth to granular and irregular; diameter, 100–200 μm (average = 131 μm; N = 14).
6.2.13. Occurrence

Subsurface equivalent of the Conselheiro Mata Group, Espinhaço Supergroup: present at four levels in well 1-PSB-13-MG and at one level in well 1-MA-1-MG (Tables 1 and 2).

6.2.14. Discussion

This taxon is the largest morphotype discovered in this study, differing from Leiosphaeridia sp. 1 in being equal to or greater than 100 μm in vesicle diameter (Fig. 10), and by variations in its surface texture. This latter condition, probably acquired taphonomically, may very well be partly due to its relatively large size, which certainly subjected the vesicles to greater post-mortem mechanical damage. Sizes cited for Leiosphaeridia sp. 2 are probably close to original dimensions. As with the other Leiosphaeridia species described here, this taxon is undoubtedly artificial, although its large size and spheroidal form almost assuredly place it among the eukaryotic phytoplankton, especially as none of the prokaryotic colonies in this microfossil assemblage could conceivably have furnished resistant, empty external sheaths of this size and character (see Fairchild, 1985; Schopf, 1992a).

LEIOSPHAERIDIA sp. 3
Fig. 4A, C, Fig. 8D, E, and Fig. 11

6.2.15. Description

Solitary or colonial (26 colonies observed) elliptical or circular compressed vesicles with no clearly evident dehiscence mechanism; light gray (translucent) to black; walls relatively thin, smooth to slightly granular, frequently with prominent compressional folds; compressed diameter, 8–140 μm, mostly 11–44 μm (average = 29 μm; N = 396).

6.2.16. Occurrence

Present in one level each in the Serra de Santa Helena and Lagoa do Jacaré Formations, Bambuí Group, well 1-RC-1-GO. Present in all microfossiliferous levels in the subsurface equivalent of the Conselheiro Mata Group, Espinhaço Supergroup, wells 1-PSB-13-MG and 1-MA-1-MG (Tables 1, 2 and 4).

6.2.17. Discussion

Leiosphaeridia sp. 3 is one of the commonest acritarchs found in our study. Indeed, it appeared, together with Siphonophycus sp. 1, in all of the microfossiliferous levels discovered in the Conselheiro Mata Group.

Compressional folds such as occur in this and other leiosphaerids have been interpreted by Schopf (1992a) as indicating compression without distortion of the original dimensions of these objects. Hence, the values given above and in Figs. 8 and 9 are probably close to the original diameters.

The morphological simplicity and broad size range of these acritarchs allow comparisons with various modern prokaryotes and eukaryotes. They may be interpreted, for example, as the mucilaginous outer envelopes of nanocysts typical of such modern cyanobacteria as Staniera and Chroococcidiopsis (Chroococcales) or as sheaths of globular colonies of Nostoc (Nostoc balls, Nostoccales). This form can also be compared with the spores (autospores) of the chlorophyte Ulva lactuca, whose walls frequently acquire folds during post-mortem degradation (Zang and Walter, 1992).

Genus GLENOBOTRYDION (Schopf, 1968)
Type species: Glenobotrydion aenigmatis (Schopf, 1968) pp. 681, 683.

cf. GLENOBOTRYDION sp.
Fig. 8T

6.2.18. Description

Colonial or isolated, elliptical or circular, translucent, compressed coccoidal microfossils bearing a distinct circular organic inclusion approximately centrally located within the microfossil; very light gray; wall smooth to finely granular, apparently thin, frequently folded; colonies (N = 2) without well-defined shape, made up of less than ten individuals, and always with vestiges of amorphous mucilage; compressed cell diameters, 12–19 μm (average = 16 μm; N = 9); diameter of inclusions, 3–5 μm.

6.2.19. Occurrence

Subsurface equivalent of the Conselheiro Mata Group, Espinhaço Supergroup: present at four

SUBSURFACE EQUIVALENT OF THE CONSELHEIRO MATA GROUP, ESPINAÇO SUPERGROUP: PRESENT AT FOUR LEVELS IN WELL 1-PSB-13-MG AND AT ONE LEVEL IN WELL 1-MA-1-MG (TABLES 1 AND 2).
levels in well 1-PSB-13-MG and at one level in well 1-MA-1-MG (Tables 1 and 2).

6.2.20. Discussion

Knoll and Golubic (1979) considered fossils of this sort as one of many taphonomic variants of populations of simple coccoidal cyanobacteria, commonly preserved in silicified benthic microbial biocoenoses, that they preferred to unite into the single paleontological species *Gloeodiniopsis lamellosus*. Inasmuch as the fossils observed here conform very closely to Schopf’s (1968) original description of *Glenobotryidion* and consist of dispersed palynomorphs rather than silicified benthic populations as in the type material, we prefer to compare them to this morphologically more informative form-genus rather than to assign them to the catch-all taxon *G. lamellosus*.

Although Oehler (1977) interpreted the internal granules in specimens of *G. aenigmatis* from the type area as vestiges of pyrenoids (proteinaceous bodies associated with chloroplasts of eukaryotic algae) on the basis of detailed studies of silicified specimens using optical and transmission electron microscopy, a similar conclusion is not warranted here in view of the small number and poorer quality of preservation of our specimens. Because of these and other preservational differences and the lack of ultrastructural studies on the inclusions, we refer these microfossils to *Glenobotryidion* with reservations.

Genus HURONIOSPORA Barghoorn, 1965 (in Barghoorn and Tyler, 1965)


HURONIOSPORA sp.

Fig. 8K–P, Fig. 12

6.2.21. Description

Circular or elliptical compressed microfossils as isolated cells or in irregular aggregates of a few closely adpressed individuals, or, rarely, as short pseudofilamentous colonies with less than ten individuals; gray to dark gray; walls always with irregular borders; surface texture granular and irregular; diameters, 3–21 μm (average = 10 μm, N = 137; Fig. 10).

6.2.22. Occurrence

Five levels in the Lagoa do Jacaré Formation and and one level (one specimen) in the Serra da Saudade Formation of the Bambuí Group. Well 1-RF-1-MG (four levels) and 1-RC-1-GO (two levels) (Tables 3 and 4).

6.2.23. Discussion

*Huroniospora* sp. is the only taxon found exclusively within the Bambuí Group in this study. This taxonomic assignment is based principally on the abundance of cells apparently preserved in the process of unequal cell division (possibly budding), as seen in Fig. 8K, M and N, and similarity in size to other occurrences of this taxon. These microfossils must have been relatively resistant as they are practically the only forms to have survived taphonomic processes affecting the Bambuí Group.

Unequal division, in which the mother-cell produced two or more smaller attached daughter cells (Fig. 8K, N), appears to have been commoner than simple binary division (Fig. 8L, O). Such budding-like reproduction occurs both among the chamaesiphonaceous (Chroococcales) cyanobacteria as well as among the fungi. Some sessile, pseudofilamentous chamaesiphonaceans have heteropolar cells that divide along a plane perpendicular or oblique to the long axis of the cell and only rarely in the middle of the cell, thus produc-
ing cells that either separate immediately or remain attached to the mother-cell to form sessile pseudofilaments. Asexual reproduction by budding is relatively common among unicellular fungi, especially among the yeasts. The comparison of the fossil material with the fungi is less certain, however, although the resistance to degradation might favor this interpretation. For the time being, however, the absence of definitive eukaryotic features in these microfossils, together with their small size and morphological simplicity, favors their interpretation as prokaryotic.

Genus PTEROSPERMOPSIMORPHA (Timofeev, 1966)
Type species: Pterospermopsimorpha pileiformis (Timofeev, 1966, p. 34).

Pterospermopsimorpha pileiformis (Timofeev, 1966)

**Fig. 8Q and R**

6.2.24. **Description**

Isolated, occasionally folded, ruptured, or fragmented, irregular, circular, or, more rarely, elliptical compressed vesicles surrounded by a larger organic envelope; vesicle dark gray to black with irregular to granular wall having smooth to irregular borders; envelope more translucent, slightly granular, with smooth to irregular margin; vesicle diameter, 11–40 µm (average = 25 µm; \( N = 14 \)); envelope slightly to much larger than vesicle, 21–60 µm.

6.2.25. **Occurrence**

Present in the subsurface equivalent of the Conselheiro Mata Group, Espinhac¸o Supergroup, at six levels (including lowest and topmost levels) in well 1-PSB-13-MG and in both fossiliferous levels of 1-MA-1-MG (Tables 1 and 2).

6.2.26. **Discussion**

These acritarchs consist of smooth-walled, unornamented inner and outer vesicles with simple folds. A possible dehiscence split is observable in Fig. 8Q, but other specimens of *P. pileiformis* do not show any other diagnostic characteristic that might allow assignment to a particular modern class or division of eukaryotic microorganisms. Given the relatively large size of some modern chroococcaceous cyanobacteria, however, a prokaryotic origin for these microfossils can not be completely ruled out. Even so, Buick and Knoll (1999, p. 755) refer to the genus *Pterospermopsimorpha* as indubitably eukaryotic. Our specimens are very similar to forms from the 700–750 Ma-old Svanbergfjellet Formation of Spitsbergen assigned to this species by Butterfield et al. (1994) and to even older specimens identified as a rare but stratigraphically important element in the ‘broadly Mesoproterozoic’ (but most likely early) Bangemall microflora of Australia by Buick and Knoll (1999). Jankauskas (1982) records it from the ca. 1350 Ma–old Zigazino-Komarovsk Formation of Russia, while Schopf (1992b) lists Mesoproterozoic occurrences of three other species of *Pterospermopsimorpha* (*P. annulare*, *P. capsulata*, *P. insolitai*). Buick and Knoll (1999, p. 750) call attention to the absence of this genus from known Paleoproterozoic microfloras. Our find thus seems to contribute to its corroboration as a potentially useful element for Mesoproterozoic biostratigraphy.

FORM 1

**Fig. 8S**

6.2.27. **Description**

A single, torn, approximately elliptical (22 × 30 µm), striated compressed vesicle; partially opaque; striae (thin, dark lines less than 0.5 µm in Fig. 8S) straight, about 1 µm apart in bands of two to four parallel striae; bands slightly divergent, parallel or perpendicular to preserved vesicle margin.

6.2.28. **Occurrence**

Subsurface equivalent of the Conselheiro Mata Group, Espinhaço Supergroup, 723.4 m level of well 1-PSB-13-MG (Table 1).

6.2.29. **Discussion**

This unique specimen, despite its torn and partially opaque condition, is the only microfossil observed in the entire study that exhibits possibly original wall ornamentation. The common Neoproterozoic acritarch *Valeria lophostriata* ex-
hibits a similarly striated surface pattern, but this species is significantly larger than Form 1 (60–700 µm), and its striae are generally much more narrowly spaced (ca. 0.25 µm) and more uniformly concentric.

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