

Palynostratigraphy of Upper Cambrian-upper Ordovician intracratonic clastic sequences, North Africa

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ABSTRACT – Detailed palynological study of subsurface sections in the Algerian Sahara (boreholes NL-2 and Uc-101) and southern Tunisia (boreholes Sn-1 and St-1) enables precise dating and intrabasinal and extrabasinal stratigraphic correlation. Most of the study samples proved palyniferous, yielding abundant, well preserved acritarchs (148 species) together with infrequent prasinophytes (2 species). Seven acritarch assemblage zones are recognizable, ranging in age from late Cambrian to late Ordovician (Ashgill) as follows: *Timofeevia lancarae*-*Cristallinium randomense* (Late Cambrian), *Timofeevia phosphoritica*-*Dasydiacrodium caudatum* (latest Cambrian), *Acanthodiacrodium simplex*-*Arbusculidium destombesii* (basal Tremadoc), *Acanthodiacrodium angustum*-*Vulcanisphaera britannica* (early Tremadoc), *Arbusculidium filamentosum*-*Coryphidium bohemicum* (late Arenig), *Frankea sartbernardensis*-*Vogtlandia ramificata* (Llanvirn), and *Evittia remota*-*Villosacapsula setosapellicula* (Ashgill) zones. Lower Tremadoc assemblages appear to be at least partially affected by environmental factors; as a consequence, the Tunisian assemblages differ somewhat from the Algerian ones. Notably, the important index species *Acanthodiacrodium angustum* is not present in the Algerian Tremadoc suites. Two important regional hiatuses are recognizable in the study area: one corresponding to the upper Tremadoc through upper Arenig, and the other to the entire Caradoc. The Tremadoc and Llanvirn represent periods of maximum abundance and diversity of the microphytoplankton.

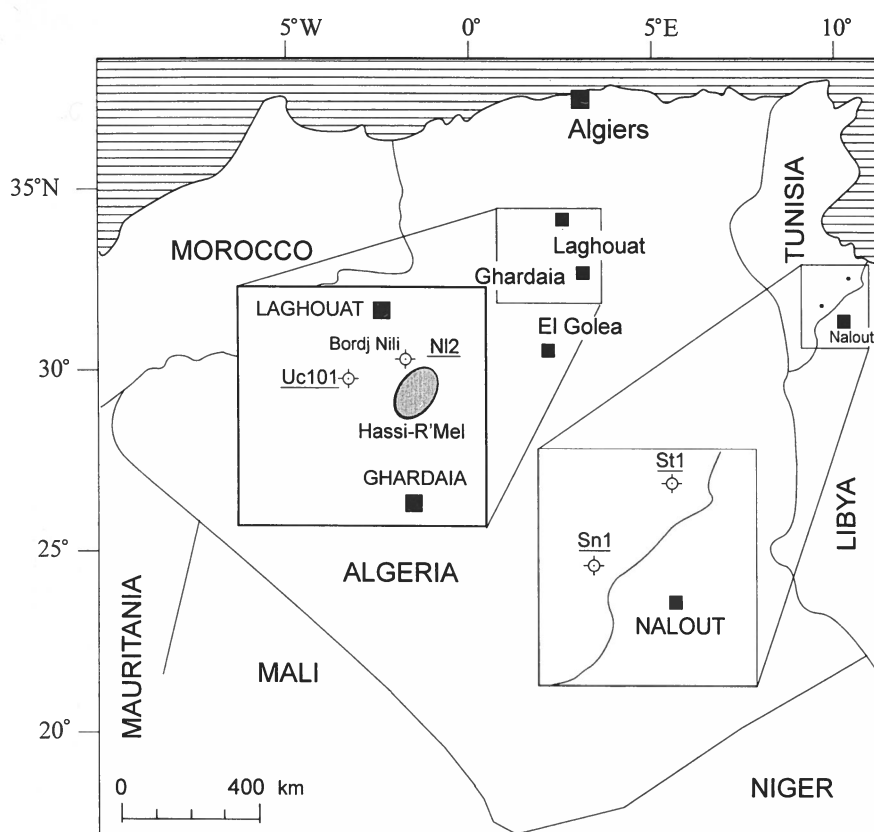
RIASSUNTO – [Palinostratigrafia delle successioni clastiche intracratoniche del Cambriano Superiore – Ordoviciano superiore del Nord Africa] – Una analisi palinologica di dettaglio di quattro sezioni stratigrafiche nel sottosuolo del deserto Algerino (pozzi NL2 e Uc101) e del sud della Tunisia (pozzi Sn1 e St1) permette datazioni precise e correlazioni stratigrafiche intra- ed extrabacinali. La maggior parte dei campioni esaminati sono risultati particolarmente ricchi di palinomorfi in buono stato di conservazione: 148 specie di acritarchi e 2 specie di alghe prasinofite sono state identificate. Sette biozone di associazione ad acritarchi di età compresa tra il tardo Cambriano e il tardo Ordoviciano (Ashgill) sono qui definite come segue: biozona a *Timofeevia lancarae*-*Cristallinium randomense* (tardo Cambriano), biozona a *Timofeevia phosphoritica*-*Dasydiacrodium caudatum* (Cambriano terminale), biozona ad *Acanthodiacrodium simplex*-*Arbusculidium destombesii* (Tremadoc basale), biozona ad *Acanthodiacrodium angustum*-*Vulcanisphaera britannica* (Tremadoc inferiore), biozona a *Arbusculidium filamentosum*-*Coryphidium bohemicum* (tardo Arenig), biozona a *Frankea sartbernardensis*-*Vogtlandia ramificata* (Llanvirn) e biozona ad *Evittia remota*-*Villosacapsula setosapellicula* (Ashgill). Alcune differenze composizionali tra le associazioni Algerine del Tremadoc inferiore e quelle coeve della Tunisia meridionale risultano probabilmente da un controllo ambientale sulla distribuzione degli acritarchi. E' degna di nota l'assenza dell'importante specie-indice *Acanthodiacrodium angustum* nelle associazioni del sottosuolo Algerino. Due importanti hiatus di estensione regionale sono individuabili nell'area studiata: il primo a livello del Tremadoc superiore - Arenig superiore, il secondo corrispondente perlopiù all'intero Caradoc. Il Tremadoc ed il Llanvirn risultano essere periodi di massima abbondanza e diversità del fitoplancton marino.

INTRODUCTION

Lower Palaeozoic subsurface clastic sequences of the Algerian Sahara and adjoining regions have been investigated palynologically mainly during the 1950s and 1960s, in conjunction with hydrocarbon exploration. However, most of the data collected by oil companies have remained confidential. The few existing published accounts on stratigraphic palynology of the Cambro-Ordovician of the Algerian Platform often do not include relevant stratigraphic and locality data (e.g., Deunff, 1961; Combaz, 1967; Jardiné *et al.*, 1974; Deunff & Massa, 1975). After the publication of the palynozonal scheme of Jardiné *et al.* (1974), there have been no further detailed palynological studies on Cambro-Ordovician Saharian

sequences despite the significant progress in acritarch biostratigraphy that has occurred over the last quarter of a century.

Early in the 1990s, a research project was initiated by one of us (D. Massa) together with palynologists of the University of Pisa (R. Albani, M. Tongiorgi, M. Vecoli), with the aim of enhancing lower Palaeozoic biostratigraphy of northern Africa, from Algeria to southern Tunisia and western Libya. This project was in cooperation with the Algerian SONATRACH and the Tunisian SEREPT oil companies. Initial results came from western Libya where Albani *et al.* (1991) documented the occurrence of Middle and Upper Cambrian marine strata. Further studies focused on acritarch-based biostratigraphy and systematics of the Cambrian-Ordovician bound-



Text-fig. 1 - Geographic setting and location of wells NI2, Uc101, Sn1, and St1.

ary interval of the Hassi-Rmel area, northwestern Algeria (Vecoli *et al.*, 1995; Vecoli, 1996; Vecoli & Playford, 1997). Recognition of an easy detectable palynological level approximating to the Cambro-Ordovician boundary, together with the new results presented herein, enable regional correlations which may assist oil exploration.

Here we report the preliminary results of a detailed palynological investigation of Upper Cambrian through upper Ordovician sequences cored by four north African boreholes; viz., NI2 and Uc101 (Hassi-R'Mel area, north-central Algeria) and Sn1 and St1 [northern Rhadames (Ghadamis) Basin, southern Tunisia].

MATERIAL AND METHODS

The material studied consists of 42 core samples from borehole NI2 (Bordj Nili, central Algeria), 15 core samples from borehole Uc101 (Oued Mehaiguene, central Algeria), 33 core samples from borehole St1 (Sidi-Toui, southern Tunisia), and 39 core samples from borehole Sn1 (Sanrhar, southern Tunisia). The samples are indicated herein with the borehole name abbreviation, followed by the sampling depth (in m): see Text-figs. 1, 2, 3. All the samples studied were cored from finer grained intervals of the various formations, so that their lithology varies from very fine-grained sandstone to siltstone and shale.

Laboratory extraction and concentration of palynomorphs was achieved using the standard palynological method outlined in Bagnoli *et al.* (1988, pp. 168-170). Most (*ca.* 80%) of the study samples proved palyniferous, yielding abundant acritarchs and rare prasinophyte phycmata. The stratigraphically lower levels of the four boreholes (i.e., Sn1-3427.0 and Sn1-3425.2, St1-2229.0, St1-2190.5, and St1-2045.0 to St1-1968.0), of supposed Middle to early Late Cambrian age, were barren or yielded only rare leiosphaerids and/or sparse fragments of indeterminate acritarchs. Some barren samples are also present at higher levels in the Algerian and Tunisian boreholes, these are: samples Uc101-3947.0 and Uc101-3938.0, Uc101-4023 and Uc101-4021.5; NI2-2972.0, and NI2-2967.5; Sn1-3094.1 and Sn1-3015.5; and St1-1404.0. The most abundant, diverse, and best preserved assemblages are those of early Tremadoc age from the Algerian boreholes (Uc101 and NI2) and the Llanvirn assemblage from borehole St1 (e.g., samples St1-1554.0 through St1-1520.5). The early Tremadoc assemblages of the Tunisian boreholes (St1 and Sn1) are also abundant and well preserved, although less diverse than the coeval Algerian ones. The Upper Cambrian assemblages are characterized by high abundance, relatively low diversity, and mediocre preservation in borehole NI2; and by low abundance, low diversity, and good

preservation in the Tunisian boreholes (Sn1 and St1). Upper Ordovician assemblages generally show high abundance but lower diversity and mediocre preservation in all the study sections.

LITHOSTRATIGRAPHY

HASSI-R'MEL AREA, ALGERIA

The stratigraphic terminology adopted herein is that indicated on the borehole logs (N12 and Uc101) provided for this study by SONATRACH. The following lithostratigraphic units are distinguished, from bottom to top (Text-fig. 2):

- *Grès de Miribel unit* (borehole N12, 3120-3095 m), predominantly quartzitic (with "tigillites" = *Skolithos*) in the lower half, with interbedded black or green micaceous, pyritic shales toward the top.

- *Grès de Bordj Nili unit* (borehole N12, 3095-3025 m), characterized by regularly alternating white quartzites and black shales rich in pyrite nodules, followed by fine-grained arenaceous beds with interbedded conglomeratic beds in the middle part. Green shales and interbedded fine-grained chloritic sandstones follow in the upper part of the unit between 3048 and 3025 m. The presence of inarticulate brachiopods and crinoids indicates a marine depositional environment.

- *Argiles d'El Gassi unit* (borehole N12, 3025-2962 m; borehole Uc101, 4132-4068 m), forming a distinct cycle beginning with coarse sandstones, followed by grey-green siltstones and shales containing graptolites of the *Rhabdinopora flabelliformis* s.l. group.

- *Argiles d'Azzel unit* (borehole N12, 2962-2908 m), truncating the Tremadoc sequence with a distinct erosional surface and consisting of grey-black, silty micaceous argillites with interbedded arenite horizons. In borehole Uc101, the Argiles d'El Gassi are followed by the essentially arenitic Grès d'Erg El Anngueur unit (4068-4025 m), which may be considered a lateral equivalent of the Argiles d'Azzel of borehole N12.

- *Argiles d'Oued Saret unit* (borehole N12, 2908-2859 m; borehole Uc101, 4025-3944 m), characterized by regular alternations of grey to black argillitic siltstones and silty argillites. This unit corresponds to the upper member of the shaly-arenitic Hassi Touareg Formation in the subdivision of the Tassili Internes of the northeastern province of the Algerian Sahara by BRP *et al.* (1964). Two ferruginous oolitic levels characterize this unit in borehole N12: one between 2909 and 2908 m, and the other near the top at 2860 m. In borehole Uc101 an oolitic horizon occurs at 3944 m. A thin dolomitic layer is found in borehole N12 at 2859 m (top of the unit).

- *Argiles Microconglomeratiques unit* (borehole N12, 2859-2695 m; borehole Uc101, 3944-3792 m), consisting of a monotonous succession of grey-black,

occasionally brown, micaceous, silty argillites containing rounded to subangular quartz grains of variable size (up to few mm) irregularly dispersed in the shaly matrix.

- *Dalle de M'Kratta unit* (borehole N12, 2695-2661 m), predominantly quartzose with interbedded black, silty argillites. According to Massa (1988), this unit is laterally continuous, albeit of variable thickness, over a large area comprising eastern Algeria and southern Tunisia, always preceding the typical "black shales" facies of the Lower Silurian. Between 2661 and 2655 m in borehole N12, a rich graptolitic fauna indicative of a Wenlock age is present.

NORTHERN RHADAMES BASIN, SOUTHERN TUNISIA

A formal lithostratigraphic nomenclature for the lower Ordovician of southern Tunisia and Tripolitania has been proposed by Massa (1988) on the basis of borehole data of the oil company SEREPT.

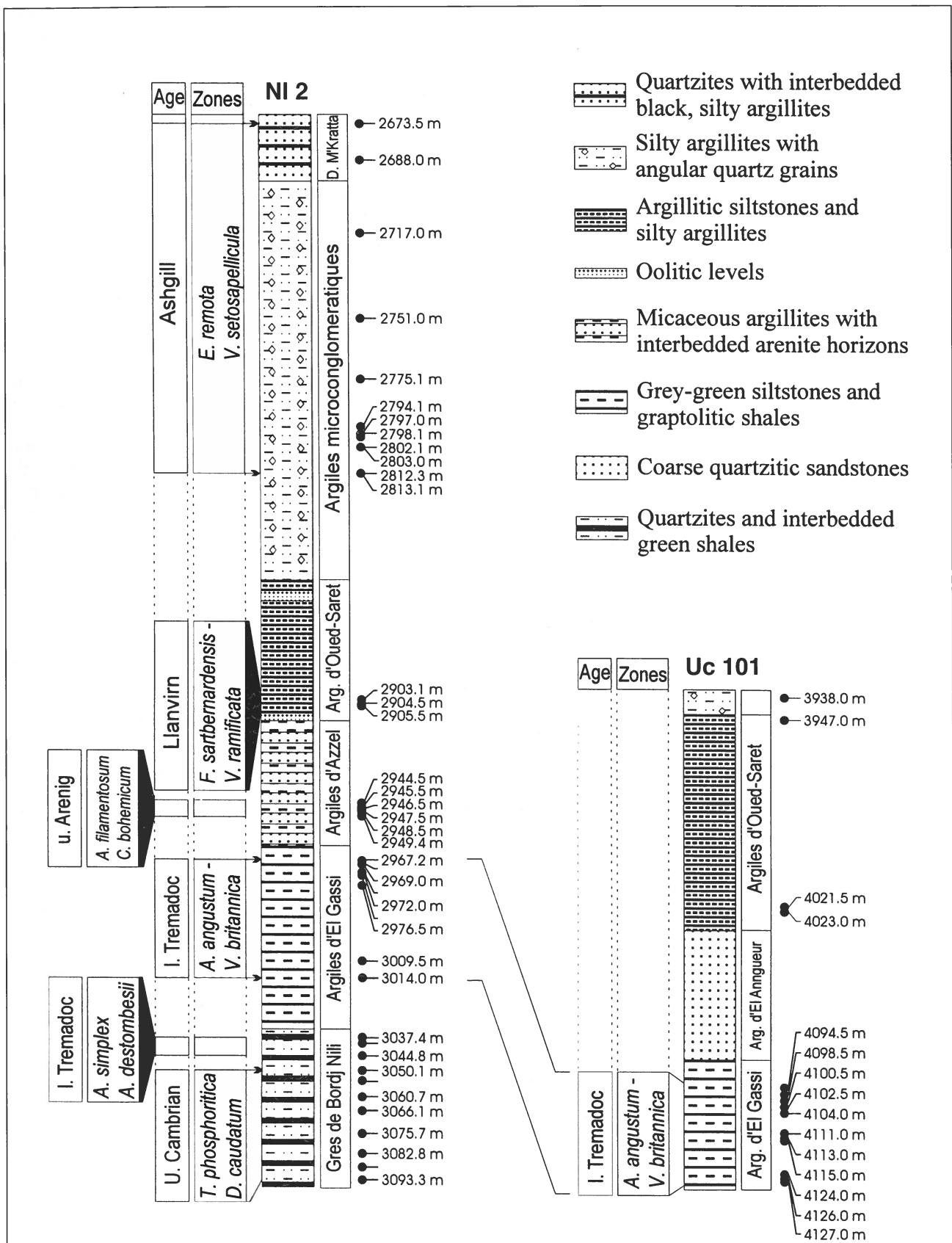
Boreholes Sn1 and St1 are considered as reference sections for the Cambrian and the Ordovician of this area. In particular, borehole St1 reached the basement, after penetrating a complete Cambrian succession.

The following formations are recognized (ascending stratigraphic order; Text-fig. 3):

- *Sidi Toui Formation* (borehole St1, 2240-1767 m; borehole Sn1, 3428-3399 m), consisting of a basal conglomerate and variably sorted, fine- to medium-grained quartzose, less commonly feldspathic sandstones interbedded with grey-black to grey-green, silty, micaceous shale. The stratification is generally subparallel, rarely cross-bedded; the shaly levels are commonly 2-4 m thick, but may reach 12 m. Pyroxenic doleritic levels (e.g., at 1967 m in borehole St1) are a noteworthy feature of the formation. According to Massa (1988; *in* Albani *et al.*, 1991) these dolerites represent sub-aqueous intraformational flows of Cambrian age which did not cause any obvious metamorphism of the intruded sediments. Tigillites (= *Skolithos*) and ferruginous oolites occur in the upper part of the section.

- *Sanrhar Formation* (borehole St1, 1767-1610 m; borehole Sn1 3399-3184 m), lithologically similar to the Sidi Toui Formation, being an essentially arenaceous unit with interbedded shales rich in pyrite and distinguished by the fairly abundant fossils (acritarchs, brachiopods, phyllocarid crustaceans) indicative of a Tremadoc age (Massa *et al.*, 1977; Massa, 1988; Termier *et al.*, 1974). In particular, Massa *et al.* (1977) and Massa (1988) reported the presence of inarticulate brachiopods of the so-called "*Tunisiglossa* and *Palaeoglossa* Community".

- *Kasbah-Leguine Formation* (borehole St1, 1610-1508 m; not cored in borehole Sn1), representing, together with the overlying unit, the onset of a new transgressive cycle. It consists of a thin, laterally dis-



Text-fig. 2 - NI2 and Uc101 boreholes: lithostratigraphy, biozonation and correlation. The Ashgill/Silurian boundary is located between 2673.5 m and 2661.0 m in borehole NI2 and at 3735.0 m in borehole UC101.

continuous sequence of unfossiliferous, coarse, ferruginous sandstones.

– *Bir Ben Tartar Formation* (borehole St1, 1508–1397 m; borehole Sn1, 3184–3097 m), characterized by ferruginous shales at the base, followed by finely stratified, grey to black, micaceous shales, very rich in organic matter (“black shale” facies) interbedded with fine-grained, texturally immature, pyritic sandstones. The presence of numerous oolitic horizons is also noteworthy. Trilobites, brachiopods, and graptolites indicative of the Llanvirn have been described from the more shaly intervals of the formation (Massa, 1988). In particular, the graptolites permit correlation with zones 6 and 7 (*Didymograptus purchisoni* and *D. bifidus*) of the British standard graptolite zonation (Massa, 1988).

– *Djeffara Formation* (borehole St1, 1397–1288 m; borehole Sn1, 3097–2977 m), characterized by irregular alternation of fine-grained, immature sandstones, siltstones, and dark gray shales, and by numerous intervals rich in coarse, angular to subangular quartz grains. A thin carbonate bed occurs in the middle part of the formation. Overall, this formation is comparable lithologically to the “Argiles microconglomeratiques” of the northern Algerian basins. Massa (1988) reported the presence of conodonts, chitinozoans, inarticulate brachiopods, and bryozoans, collectively indicative of an Ashgill age.

ACRITARCH ASSEMBLAGES AND THEIR STRATIGRAPHIC SIGNIFICANCE

Vertical distribution of acritarch and prasinophyte species in the boreholes studied enables recognition and definition of seven, distinct, stratigraphically successive assemblages (Text-figs. 2, 3).

Timofeevia lancarae – *Cristallinium randomense* assemblage zone

The most characteristic taxa of this assemblage zone are: *Timofeevia lancarae* (Cramer & Díez) Vanguetaine, 1978, *Cristallinium randomense* (Martin) Fensome, Williams, Barss, Freeman, & Hill, 1990, and *Cristallinium ovillense* (Cramer & Díez) Fensome, Williams, Barss, Freeman, & Hill, 1990. Also present are rare *Timofeevia phosphoritica* Vanguetaine, 1978 and common Leiosphaerids.

Occurrence – Borehole St1, 2155.6–2113.3 m, Sidi Toui Formation.

Discussion – The present zone can be correlated with Microflora A3 (*Cristallinium randomense*–*Verybachium dumontii*) as defined by Martin (in Martin & Dean, 1988) in eastern Newfoundland, Canada. According to Martin (in Martin & Dean, 1988), the co-occurrence of *T. lancarae* and *C. randomense* defines a stratigraphic interval equivalent, in

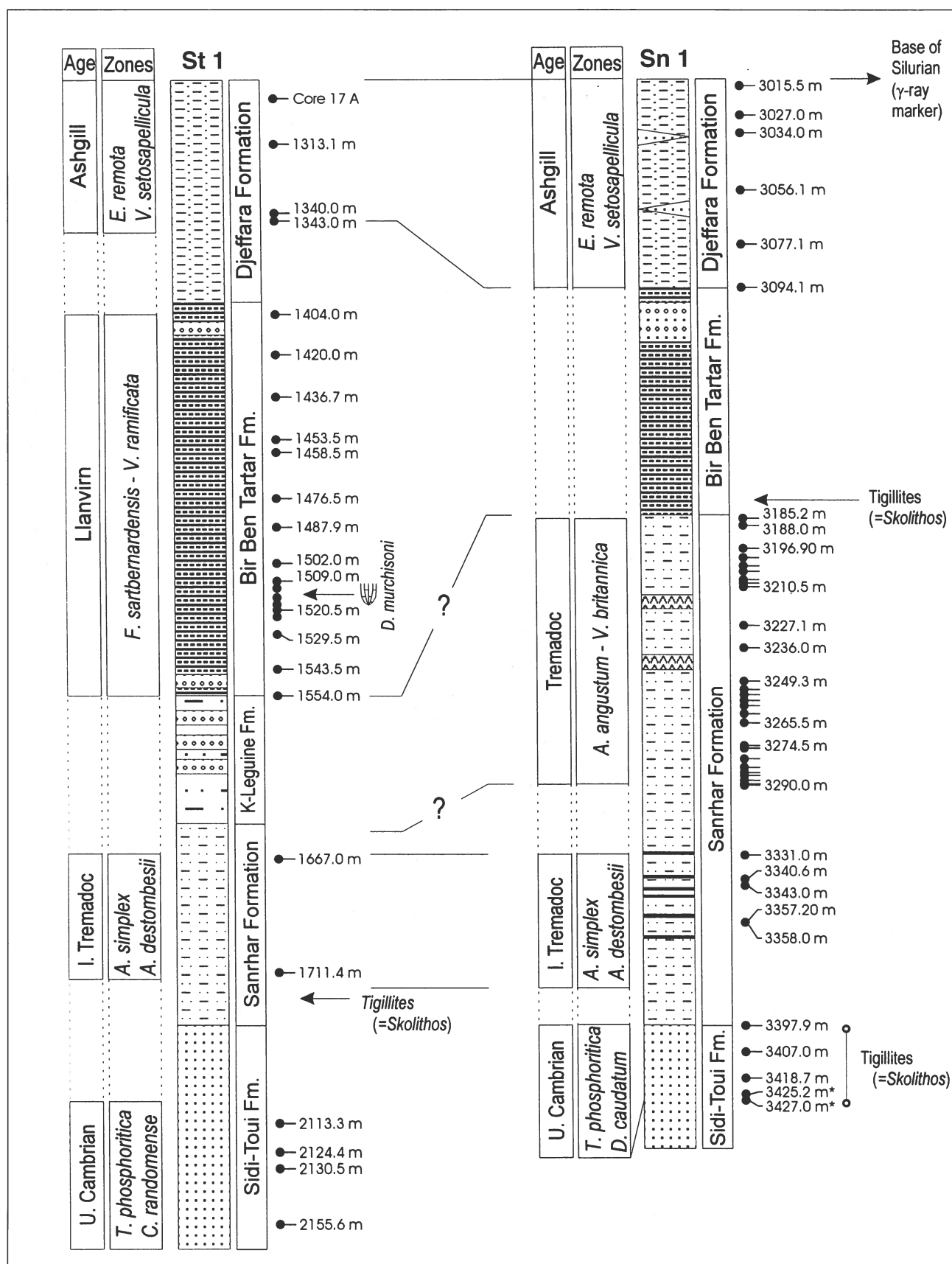
terms of trilobite zonation, with the lower part of the *Parabolina spinulosa* trilobite Zone. Upper Cambrian acritarch assemblages characterized by the co-occurrence of *T. lancarae*, *C. randomense*, *T. phosphoritica*, and *C. ovillense* have been described from North Africa (GB2 assemblage of Albani *et al.*, 1991) and from Öland, Sweden. (Tongiorgi in Bagnoli *et al.*, 1988). The GB2 assemblage was considered equivalent to the Microflora A2 (*Timofeevia pentagonalis*–*Vulcanisphaera turbata*) of Martin (in Martin & Dean, 1988), correlated to the *Olenus* trilobite Zone, while the Swedish acritarch assemblage (Tongiorgi in Bagnoli *et al.*, 1988) was attributed to a stratigraphic interval between the upper part of the *Agnostus pisiformis* trilobite Zone and the *Parabolina spinulosa* trilobite Zone. In the East European Platform, *T. lancarae* and *C. ovillense* characterize the acritarch zones VK1 and VK2 of Volkova (1990), correlated to the *Agnostus pisiformis* trilobite Zone (lower Upper Cambrian), and *Parabolina spinulosa* trilobite Zone, respectively (Volkova, 1990, 1995). From the above, it follows that the *T. lancarae*–*C. randomense* assemblage zone can be attributed to the Upper Cambrian and more precisely to a stratigraphic interval probably not older than the base of the *Olenus* Zone and not younger than the top of the *Parabolina spinulosa* Zone in terms of trilobite zonation.

Timofeevia phosphoritica – *Dasydiacrodium caudatum* assemblage zone

The introduction of *Dasydiacrodium caudatum* Vanguetaine, 1973, *Ladogella rommelaerei* (Martin) Di Milia, Ribecai & Tongiorgi, 1989, and *L. rotundiformis* Golub & Volkova, 1985 characterizes this zone. *Cymatiogalea cuvillieri* (Deunff) Deunff, 1964, *C. velifera* (Downie) Martin, 1969, *Dasydiacrodium obsonum* Martin, 1988, *Elenia armillata* (Vanderflit) Volkova, 1984, *Ooidium rossicum* Timofeev, 1957, *Phenacoon imperfectum* Vecoli & Playford, 1997, *Saharidia fragilis* (Downie) Combaz, 1967, *Stelliferidium* spp., *Vulcanisphaera africana* Deunff, 1961, and *V. capillata* Jardiné, Combaz, Magloire, Peniguel & Vachey, 1974, are also characteristic. *T. phosphoritica* persists from the previous zone. In borehole N12, the acritarch assemblage is very rich and diverse, while in borehole Sn1 is largely dominated by *D. caudatum* and *S. fragilis*, with rare occurrences of *T. phosphoritica* and *V. africana*.

Occurrence – Borehole N12, 3082.8–3050.1 m (Grés de Bordj Nili unit); borehole Sn1, 3418.7–3397.9 m (Sidi Toui Formation).

Discussion – There are close similarities between the present assemblage and the younger part (A5b) of Microflora A5 (“*Arbusculidium*” = *Ladogella rommelaerei*–*Vulcanisphaera africana*) of Martin (in Martin & Dean, 1988), correlated with the upper part of the *Peltura* and with the *Acerocare* p.p. trilobite Zones.



Ten of Martin's 14 species that compose her Microflora A5 are common to the *T. phosphoritica*-*D. caudatum* assemblage zone: viz., *Acanthodiacrodium achrasii* Martin, 1973, *Cristallinium ovillense*, *C. randomense*, *D. caudatum*, *D. obsonum*, *L. rommelaerei*, *S. fragilis*, *T. phosphoritica*, *Veryhachium dumontii* Vanguetaine, 1973, and *V. africana*. Among the taxa listed above, *C. randomense*, *D. obsonum*, *T. phosphoritica*, and *V. dumontii* are unknown from indubitably post-Late Cambrian rocks. *L. rotundiformis*, *Lophodiacrodium valdaicum* (Timofeev) Downie & Sarjeant, 1965, and *O. rossicum* are also typical indices of the uppermost Cambrian and probably do not range into the Tremadoc (Vecoli, 1996). The present acritarch zone is also closely comparable with the lower part (lacking *Acanthodiacrodium angustum*) of Volkova's (1990) VK5 zone (East European Platform) and to a lesser degree with the zone B0 of Jardiné *et al.* (1974: Algerian Sahara). These correlations facilitate attribution of the present zone to the Late Cambrian, more precisely to the upper part of the *Peltura* Zone and possibly the *Acerocare* Zone, in terms of trilobite zonation.

Acanthodiacrodium simplex-*Arbusculidium destombesii* assemblage zone

This zone is defined by the introduction of *Acanthodiacrodium baculatum* Vecoli, 1996, *A. capillatum* Vecoli, 1996, *A. complanatum* (Deunff) Umnova, 1975, *A. simplex* Combaz, 1967, *Arbusculidium destombesii* Deunff, 1968, *Stellechinatum uncinatum* (Downie) Molyneux, 1987, *Stelliferidium cortinulum* (Deunff) emend. Deunff, Górka & Rauscher, 1974, *S. furcatum* (Deunff) emend. Deunff, Górka & Rauscher, 1974, and *S. velatum* Vecoli, 1996. Also important is the absence of species of *Timofeevia*, *Ladogella*, and of ooid forms (*Ooidium rossicum* and *Phenacoon imperfectum*). *Cymatiogalea cuvillieri*, *C. velifera*, *Saharidia fragilis*, *Vulcanisphaera africana*, and *V. capillata* persist from the previous zone. In the Tunisian boreholes, the assemblage is impoverished, being largely dominated by *A. simplex*, *S. fragilis*, *S. uncinatum*, *C. cuvillieri*, and by small, nondescript acritarchs.

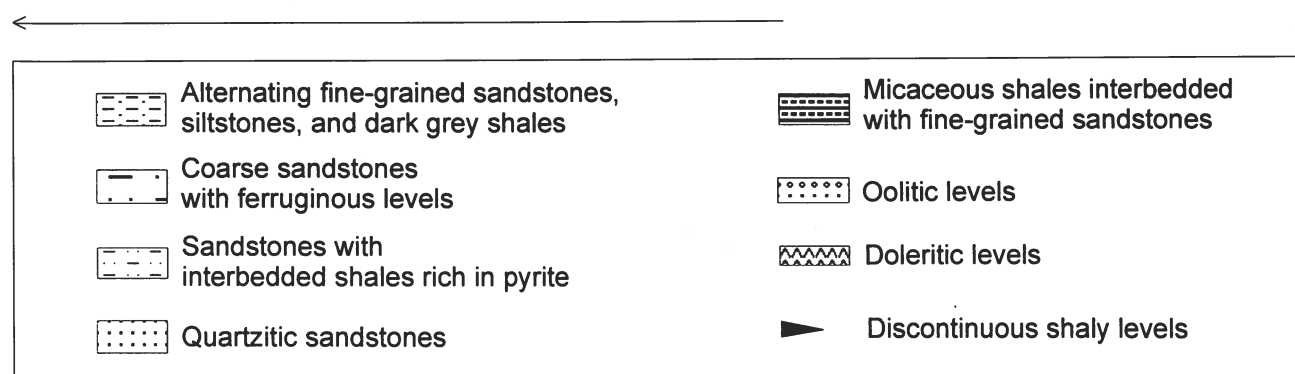
Occurrence – Borehole NI2, 3044.8-3037.4 m (Grés de Bordj Nili unit); borehole St1, 1711.4-1667.0 m (Sanrhar Formation); borehole Sn1, 3358.0-3331.0 m (Sanrhar Formation).

Discussion – Six of the nine species composing Martin's (in Martin & Dean, 1981) Microflora A6 (*Arbusculidium destombesii*-*Vulcanisphaera capillata*) occur in the present zone; viz., *Acanthodiacrodium simplex* Combaz, 1967, *Arbusculidium destombesii*, *Cymatiogalea cuvillieri*, *C. velifera*, *Eupoikilofusa squama* (Deunff) Elaouad-Debbaj, 1988, and *Vulcanisphaera capillata*. Many of these species (possibly excluding *A. simplex*) are more frequently found in Tremadoc strata, although they occur also in Upper Cambrian deposits (Martin in Martin & Dean, 1988; Martin, 1993). In Martin's Microflora A6, the lower Tremadoc is undoubtedly represented even if some of the associated macrofossils may range lower, into the *Acerocare* trilobite Zone. However, the stratigraphic range of *Arbusculidium destombesii* seems to be entirely confined to the Tremadoc. Some similarities exist with palynological B0 zone of Algeria (Jardiné *et al.*, 1974), although some of the latter's characteristic species [*Arbusculidium ornatum* (Combaz) Jardiné *et al.*, 1974, *A. ramusculosum* (Combaz) Jardiné *et al.*, 1974, and *Dasydiacrodium glabrum* Combaz, 1967] were not identified in this study.

According to the above discussion, the present zone is attributed to the lowermost Tremadoc. The presence of *Acanthodiacrodium simplex* and *Arbusculidium destombesii*, the abundance of Herkomorphitae, together with the absence of all the Upper Cambrian species that characterize the stratigraphically lower zone, strongly support this attribution.

Acanthodiacrodium angustum-*Vulcanisphaera britannica* assemblage zone

Characteristic species: *Acanthodiacrodium angustum* (Downie) Combaz, 1967, *A. formosum* Górka, 1967, *A. rotundatum* Górka, 1967, *A. ubui* Martin, 1969, *Attritaspores messaoudi* Combaz, 1967,



Text-fig. 3 - Sn1 and St1 boreholes: lithostratigraphy, biozonation and correlation. The Ashgill/Silurian boundary is located a little above 3015.5 m in borehole Sn1 and ca. at 1290 m in borehole St1.

Baltisphaeridium verutum Vecoli, 1996, *Cymatiogalea cristata* (Downie) Rauscher, 1974, *C. multarea* (Deunff) Eisenack, Cramer & Díez, 1973, *Impluviculus araneus* Vecoli & Playford, 1997, *Polygonium gracile* Vavrdová, 1966, *Stelliferidium simplex* (Deunff) emend. Deunff, Górka & Rauscher, 1974, *S. stelligerum* (Deunff) emend. Deunff, Górka & Rauscher, 1974, *Virgatasporites rudi* Combaz, 1967, and *Vulcanisphaera britannica* Rasul, 1976. Species persisting from the preceding zone: *Acanthodiacrodium complanatum*, *Arbusculidium destombesii* and species of *Stelliferidium* and *Cymatiogalea*. *A. messaoudi* and *V. rudi* are present only in borehole Sn1. The zone features a marked increase in species diversity; diacrodians and herkomorphitids dominate the assemblage. The overall diversity of the acritarch suite is higher in boreholes N12 and Uc101 than in borehole Sn1. The distinctive *Acanthodiacrodium angustum* is absent in the Algerian boreholes.

Occurrence – Borehole N12, 3014.0–2968.0 m (Argiles d'El Gassi unit); borehole Uc101, 4127.0–4094.5 m (Argiles d'El Gassi unit); borehole Sn1, 3290.0–3185.2 m (Sanrhar Formation).

Discussion – The most important feature of this zone is the presence of some diagnostic Tremadoc taxa, such as *A. ubui*, *C. cristata*, *S. simplex*, *S. stelligerum*, and *V. britannica*. All these species seem to have a widespread distribution; they are present in the Algerian boreholes as well in the Tunisian borehole Sn1. On the other hand, the morphologically distinctive and stratigraphically important *Acanthodiacrodium angustum* is present only in the latter borehole. It is postulated here that the distribution of *A. angustum* is facies-sensitive; indeed sedimentological, macropalaeontological and palynological considerations suggest a proximal, shallow water depositional environment for the Tremadoc sequences of southern Tunisia, contrasting with a more distal, deeper marine origin for the coeval Algerian sediments.

The zone clearly shows very close similarities with the early Tremadoc B1 and B2 palynological zones previously defined in the Algerian Sahara by Jardiné *et al.* (1974), and with other Tremadoc suites described in central Europe (e.g., Martin, 1973, 1977; Rauscher, 1974a, b), Baltic area (Tongiorgi *in* Bagnoli *et al.*, 1988), and Iran (Ghavidel-Syooki, 1995, 1996). A similar acritarch assemblage (Assemblage I) associated with the lower Tremadoc fossils *Cordylodus angulatus* Pander, 1856 and *Rhabdinopora* sp. was reported by Brocke (1996) from southwest China.

The presence of graptolites of the *Rhabdinopora flabelliformis* s.l. group in the associated deposits of boreholes N12 and Uc101 (Legrand, 1974) and of brachiopods of the “*Tunisiglossa* and *Palaeoglossa* Community” in the associated deposits of borehole

Sn1 (Massa, 1988) confirm a Tremadoc age for the present zone.

Arbusculidium filamentosum–*Coryphidium bohemicum* assemblage zone

Constituent species are: *Arbusculidium filamentosum* (Vavrdová) Vavrdová, 1972, *Coryphidium bohemicum* Vavrdová, 1972, *Striatotheca principalis parva* Burmann, 1970, *Barakella fortunata* Cramer & Díez, 1977, *Baltisphaeridium klabavense* (Vavrdová) Kjellström, 1971, *Dicrodiacrodium ancoriforme* Burmann, 1968 emend. Servais, Brocke & Fatka, 1996, and *Veryhachium* spp.

Occurrence – Borehole N12, 2949.4–2948.5 m and, questionably, 2947.5–2944.5 m (Argiles d'Azzel unit).

Discussion – Martin (*in* Dean & Martin, 1978) recorded *A. filamentosum*, *C. bohemicum*, and *S. principalis parva* in graptolitic deposits belonging to the *Didymograptus extensus* graptolite Zone of the Wabana Group, Bell Island, eastern Newfoundland, Canada. Co-occurrence of the above mentioned species have been reported in independently dated Arenig sediments from South China (Meitan Formation, *Didymograptus deflexus* and *Azygograptus suecicus* graptolite Zones, Li, 1987; Dawan Formation, *A. suecicus* graptolite Zone, Yin, 1995). In Europe, *A. filamentosum* is frequently associated with *C. bohemicum* in deposits of inferred or undoubted Arenig age such as the Klabava Formation of Central Bohemia (type locality; correlated with the *Tetragraptus reclinatus abbreviatus* graptolite Zone; Vavrdová, 1965, 1972, 1990), and in the Montagne Noire, France (*Didymograptus extensus* graptolite Zone; Rauscher, 1974b).

C. bohemicum has been reported from the Arenig of southwest Wales (Molyneux, 1987), and similar forms, *C. aff. bohemicum* and *C. bohemicum?*, are apparently upper Arenig index species in the Anglo-Welsh area (Molyneux, 1990; Molyneux *in* Molyneux *et al.*, 1996; Rushton & Molyneux, 1989). The lowest stratigraphic occurrence of *D. ancoriforme* correlates with the upper Arenig *Undulograptus sinodontatus/Didymograptus nexus* graptolite Zone of South China (Servais *et al.*, 1996). *Barakella fortunata* occurs in upper Arenig-lower Llanvirn strata of Morocco (Cramer & Díez, 1977), and *Baltisphaeridium klabavense* has been reported from Arenig sediments of the Montagne Noire, France (Rauscher, 1974b), Öland, Sweden (Ribecai & Tongiorgi, 1995), the Prague Basin, Czech Republic (type area; Vavrdová, 1965, 1972, 1977).

Frankea sartbernardensis–*Vogtlandia ramificata* assemblage zone

Constituent species of this zone are: *Ampullula sue-tica* Righi, 1991, *Aremoricanium rigaudiae* Deunff,

1955, *Arkonion virgata* Burmann, 1970, *Frankea sartbernardensis* (Martin) Colbath, 1986, *F. breviscula* Burmann, 1970, *F. longiuscula* Burmann, 1970, *Liliosphaeridium pennatum* (Deunff) Playford, Ribecai & Tongiorgi, 1995, *Peteinosphaeridium velatum* Kjellström, 1971 emend. Playford, Ribecai & Tongiorgi, 1995, *Stellechinatum celestum* (Martin) Turner, 1984, *Stelliferidium striatulum* (Vavrdová) Deunff, Górka & Rauscher, 1974, *Striatotheca quieta* (Martin) Rauscher, 1974, and *Vogtlandia ramificata* Burmann, 1970. *Coryphidium bohemicum*, *Dicrodia-crodium ancoriforme*, and *Baltisphaeridium klabavense* persist from the preceding (*A. filamentosum*-*C. bohemicum*) zone. In the uppermost part of the zone, the assemblage becomes impoverished and dominated by veryachiid forms and by *F. longiuscula*.

Occurrence – Borehole St1, 1554-1418.5 m (Kasbah-Leguine and Bir Ben Tartar Formations); borehole N12, 2905.0-2903.1 m (Argiles d'Oued Saret unit).

Discussion – *A. rigaudiae*, *A. virgata*, *F. breviscula*, *F. longiuscula*, *S. celestum*, and *S. quieta* are unknown from pre-Llanvirn strata. *F. sartbernardensis* also occurs commonly in Llanvirn strata of central Bohemia (Vavrdová, 1977), Morocco (Elaouad-Debbaj, 1984), Germany (Servais, 1993), and Belgium (Servais & Maletz, 1992). The lower stratigraphic limit of this species is probably very close to the Arenig-Llanvirn boundary (Vecoli *et al.*, this issue). *A. rigaudiae* and large acanthomorphs (e.g., *Baltisphaeridium? bramkaense* Górka, 1979) of this assemblage are common in the Llanvirn of Europe (Górka, 1979, 1980; Kjellström, 1971, 1976). The zone also closely resembles Zone JO-3 of Jordan (Keegan *et al.*, 1990), attributed to the Llanvirn. In borehole St1, graptolites indicative of the *Didymograptus murchisoni* Zone occur between 1558 and 1508 m, corroborating the Llanvirn age at least for the lower part of the assemblage zone.

From the above, it follows that the present assemblage is not older than Llanvirn.

Dating of the upper boundary of the zone, however, is somewhat problematical. Molyneux (1990) pointed out that *Arkonion*, *Frankea*, *Marrocanium*, *Striatotheca*, and *Dicrodia-crodium* commonly considered as indicative of Llanvirn age (e.g., Turner, 1982), have been detected also in Caradoc and possibly Llandeilan strata of Wales and eastern Ireland. Ruling out the possibility of reworking, Molyneux (1990; *in Molyneux et al.*, 1996) favoured the extension of the stratigraphic ranges of those genera up to the Caradoc. Due to current inadequacy of the acritarch database for the middle Ordovician, the problem is not easily solvable at the present state of knowledge. However, in light of the absence of indubitably Caradoc species, the present zone is here considered entirely of Llanvirn age.

Evittia remota-*Villosacapsula setosapellicula* assemblage zone

Characteristic elements of this zone are the two eponymous species together with *Actinotodissus crassus* Loeblich & Tappan, 1978, *Dactylofusa cucurbita* Jardiné, Combaz, Magloire, Peniguel & Vachey, 1974, *D. striatogranulata* Jardiné, Combaz, Magloire, Peniguel & Vachey, 1974, *Dicommopalla macadamii* Loeblich, 1970, *Leprotolypa evexa* Colbath, 1979, *Poikilofusa spinata* Staplin, Jansonius & Pocock, 1965, and *Veryhachium subglobosum* Jardiné, Combaz, Magloire, Peniguel & Vachey, 1974.

Occurrence – Borehole N12, 2813.1-2673.5 m (Argiles Microconglomeratiques and Dalle de M'Kratta units); borehole St1, 1343.0- ca.1279 m (Djeffara Formation); borehole Sn1, 3077.1-3027.0 m (Djeffara Formation).

Discussion – *A. crassus*, *D. macadamii*, *Evittia remota* [*Diexallophasis denticulata* (Stockmans & Willièr) Loeblich, 1970], *L. evexa*, and *P. spinata* have been frequently recorded from North American and Canadian Ashgill sediments (see Loeblich, 1970a, b; Loeblich & Tappan, 1978; Jacobson & Achab, 1985; Miller, 1991; Wicander *et al.*, in press). *D. cucurbita*, *D. striatogranulata*, and *V. subglobosum* are index species of the zone F of Jardiné *et al.* (1974), which was assigned to the Ashgill. The JO-1 acritarch association described by Keegan *et al.* (1990) from Jordan, also attributed to the Ashgill, is compositionally similar to the present assemblage, containing, among others, *A. crassus*, *Villosacapsula setosapellicula* (Loeblich) Loeblich & Tappan, 1976, and *Veryhachium subglobosum*. The Ashgill assemblages As1 and As2 described by Hill & Molyneux (1988) from northeast Libya both show appreciable similarity with the present assemblage, i.e., presence of *E. remota* (= *Diexallophasis denticulata*), *V. subglobosum*, and *V. setosapellicula*, prevalence of veryhachiid forms, and occurrence of species of *Cheleutochroa* Loeblich & Tappan, 1978 emend. Turner, 1984 and *Ordovici-dium* Tappan & Loeblich, 1971.

Accordingly, the present assemblage is clearly datable as Ashgill.

CONCLUSIONS

The following conclusions can be drawn:

1) The Cambrian-Ordovician transition in the Hassi-R'Mel area, Algeria, is confirmed to occur within the Grés de Bordj Nili unit, as previously indicated by Vecoli *et al.* (1995) and Vecoli (1996), and it is for the first time recognized in southern Tunisia, within the lowermost part of the Sanrhar Formation. The systemic transition is identifiable by a change from a palynoflora dominated by such distinctive

forms as *Ladogella rotundiformis*, *Timofeevia phosphorica*, *O. rossicum*, and *Phenacoon imperfectum* to a suite in which diacromorph acritarchs (e.g., *Acanthodiacrodium* spp. and *Arbusculidium destombesii*) are particularly plentiful.

2) The palynological evidence testifies to late Tremadoc-middle Arenig and Caradoc hiatuses in the study area.

3) The early Tremadoc and the Llanvirn appear times of maximum microphytoplankton diversification in north Africa.

4) Palaeogeographically, the late Arenig-Llanvirn assemblages show clear overall Perigondwanan affinities. In the early Llanvirn, several species of Baltic affinity (large *Baltisphaeridium*, *Peteinosphaeridium*, *Liliosphaeridium*, *Ampullula*) are introduced into the cold-water, Mediterranean-like *Frankea sarthbernardensis*-*Vogtlandia ramificata* assemblage. At the present state of knowledge, a meaningful palaeogeographic interpretation of the Late Cambrian-early Tremadoc and Ashgill assemblages seems hazardous.

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