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Palynostratigraphy of Middle Cambrian to lowermost Ordovician stratal sequences in the High Zagros Mountains, southern Iran: Regional stratigraphic implications, and palaeobiogeographic significance

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Abstract

A palynological investigation of Cambro-Ordovician stratal sequences in the High Zagros Mountains of southern Iran permits the definition of a series of successive acritarch assemblage zones of chronostratigraphic significance, much improving the current knowledge of the Lower Palaeozoic stratigraphy of this important area for oil exploration. The five acritarch assemblage zones can be readily correlated with previously established palynostratigraphic schemes constrained by co-occurrence of independent age evidence, confirming the utility of organic-walled microfossils for the detailed biostratigraphic characterization of sedimentary units. The proposed biozonation will facilitate accurate dating of the southern Iranian Cambrian sequences during future drilling of deep test oil wells. Acritarch assemblage zone I (Middle Cambrian), occurs at the base of Member C of the Mila Formation; assemblages zone II (late Middle to earliest Late Cambrian) extends through the middle and upper part of the same lithostratigraphic unit; zone III (early Late Cambrian in age) characterizes the lower part of the Ilebeyk Formation; zone IV (middle Late Cambrian up to Cambrian/Ordovician transitional levels) occurs in the middle and upper part of the Ilebeyk Formation; finally, acritarch assemblage zone V ranges through the basal part of the Zardkuh Formation and proves an early Tremadocian age for the latter unit. The Mid-Late Cambrian acritarch associations show a marked Avalonian palaeobiogeographical affinity, also sharing a high proportion of taxa with typical Baltican and North Africa–Gondwanan assemblages; on the other hand, they are clearly different from known Laurentian (North America) fossil microphytoplankton suites. These results are in general agreement with current palaeogeographical models which place Avalonia, Baltica, and the North African part of Gondwana, all at relatively high southern palaeolatitudes, in contrast with the sub-equatorial position of Laurentia. However, the presence of many typical "Avalonian" taxa in the Iranian Mid-Late Cambrian assemblages would suggest a closer position of Iran to Avalonia than currently envisaged. The observed breakdown of acritarch biogeographic differentiation in earliest Ordovician times possibly represents a major disruption of oceanic current patterns and a lessened palaeolatitudinal thermal gradient.

Keywords: acritarchs; biostratigraphy; Middle-Late Cambrian; Tremadocian; palaeobiogeography; High Zagros Mountain Range; Iran

1. Introduction and historical perspective

An almost complete sequence of Cambrian through Lower Ordovician strata is exposed in the Zagros Basin, southern Iran, cropping out in three main localities: Zardkuh (Tang-e-Ilebeyk section), Kuh-e-Garreh (Tang-e-Darreh Doon section) and Kuh-e-Dinar (Tang-e-Putak section), immediately southwest of the Zagros Crush Zone, a zone of intense faulting and tectonic disturbance (Fig. 1). These remote areas are very difficult to access and were first surveyed during early expeditions by J.V. Harrison in the years 1930–31 (Bakhtiary mountains survey; Harrison et al., 1932) and in 1933–34 (Kuhgalu country survey; Harrison et al., 1935), and later by A. Setudehnia and A. Kheradpir, in 1971–75. These early surveys included the geological mapping, lithostratigraphic description, and preliminary, low resolution, biostratigraphic dating of the Palaeozoic units in these areas, which are known for their potential as important

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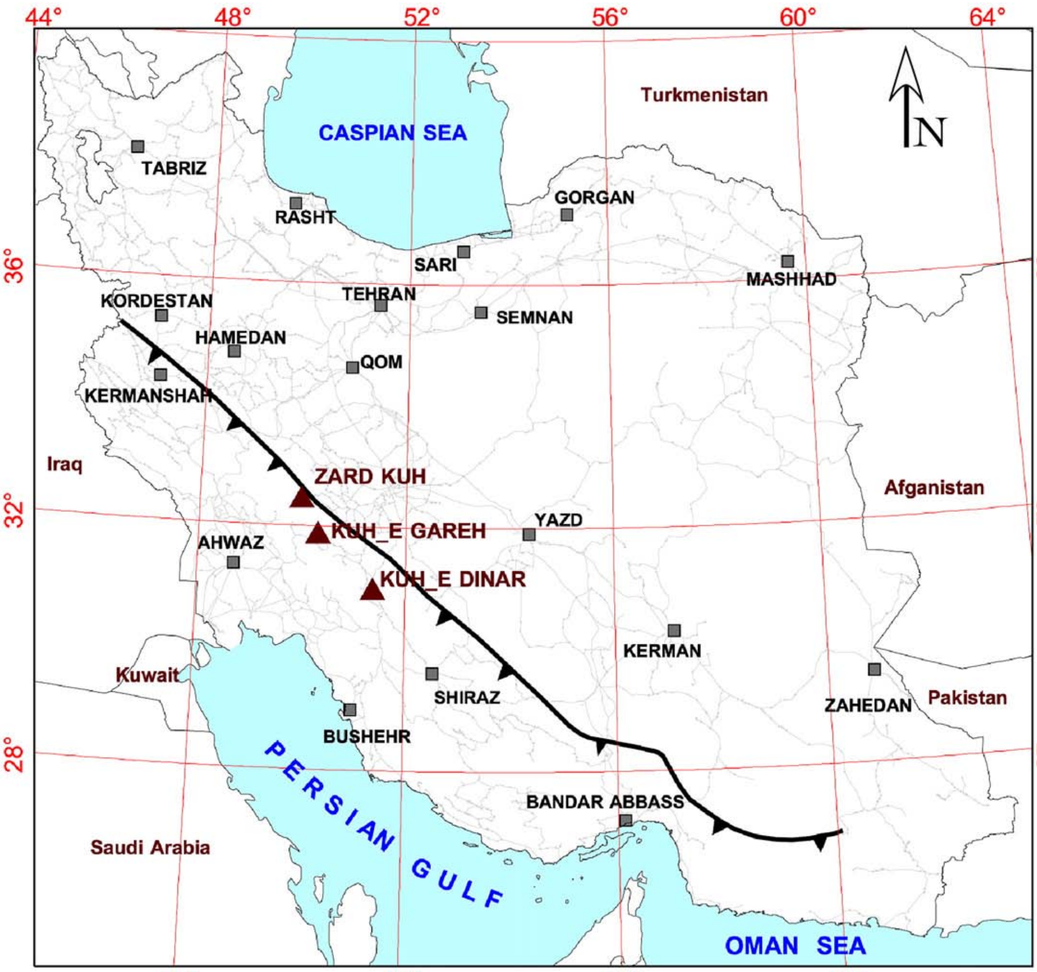

Fig. 1. Geographic setting and location of study sections.

hydrocarbon reservoirs. Before the present study, the stratigraphic relationships between the Mila Formation, the underlying Zaigun and Lalun formations and the overlying Ilebeyk and Zardkuh formations were imprecisely known.

The Early Palaeozoic (Cambrian–Ordovician) palaeogeographic position of the terrane or terrane assemblage comprising the Iranian plate is also uncertain; palaeomagnetic data are not available in this area, and (macro)palaeontological data are still scarce or not adequately discussed in terms of taxonomic and palaeogeographic significance (Popov, pers. comm., 2007). Although a certain consensus seems to exist on the fact that Iran has been part of the Gondwana palaeocontinent at some time during the Palaeozoic (Scotese and McKerrow, 1990 and references therein), the few and old available previous reports on Cambrian faunas of the study area (e.g., King, 1930) refer to a clear non-European faunal affinity, *de facto* excluding a peri-Gondwanan Cambrian palaeoposition for the Iranian terrane. One of the authors of the present paper (Ghavidel-syooki) investigated the Zardkuh area (and in particular the Tang-e-Ilebeyk section) in 1982, collecting a complete series of palynological surface samples from the Zardkuh and Ilebeyk formations in order to improve the biostratigraphic datings and existing plaeobiogeographic concepts. Herein, we report the results of such palynological analyses with the aims of:

1) refining the biostratigraphic dating of the Mila, Ilebeyk and lowermost Zardkuh formations;
2) establishing a local palynozonation that may be used for the identification of the Cambrian–Ordovician formations in the subsurface of southern Iran during oil exploration deep drilling test wells in the future;
3) assessing the palaeobiogeographic significance of southern Iranian Cambrian–Ordovician palynological assemblages.

2. Regional stratigraphy

In the study area (Fig. 1), the Precambrian and Lower Palaeozoic strata have been subdivided into the Barut, Zaigun, Lalun, Mila, Ilebeyk, Zardkuh, and Seyahou formations. The present analysis concerns only three of these formations (Mila, Ilebeyk, Zardkuh; Fig. 2), but we give here a brief description of all the pre-Permian units cropping out in this little known area of Iran.

The Barut Formation (Upper Proterozoic–lowermost Cambrian) is well-exposed in Kuh-e-Dinar where it reaches 150 m in

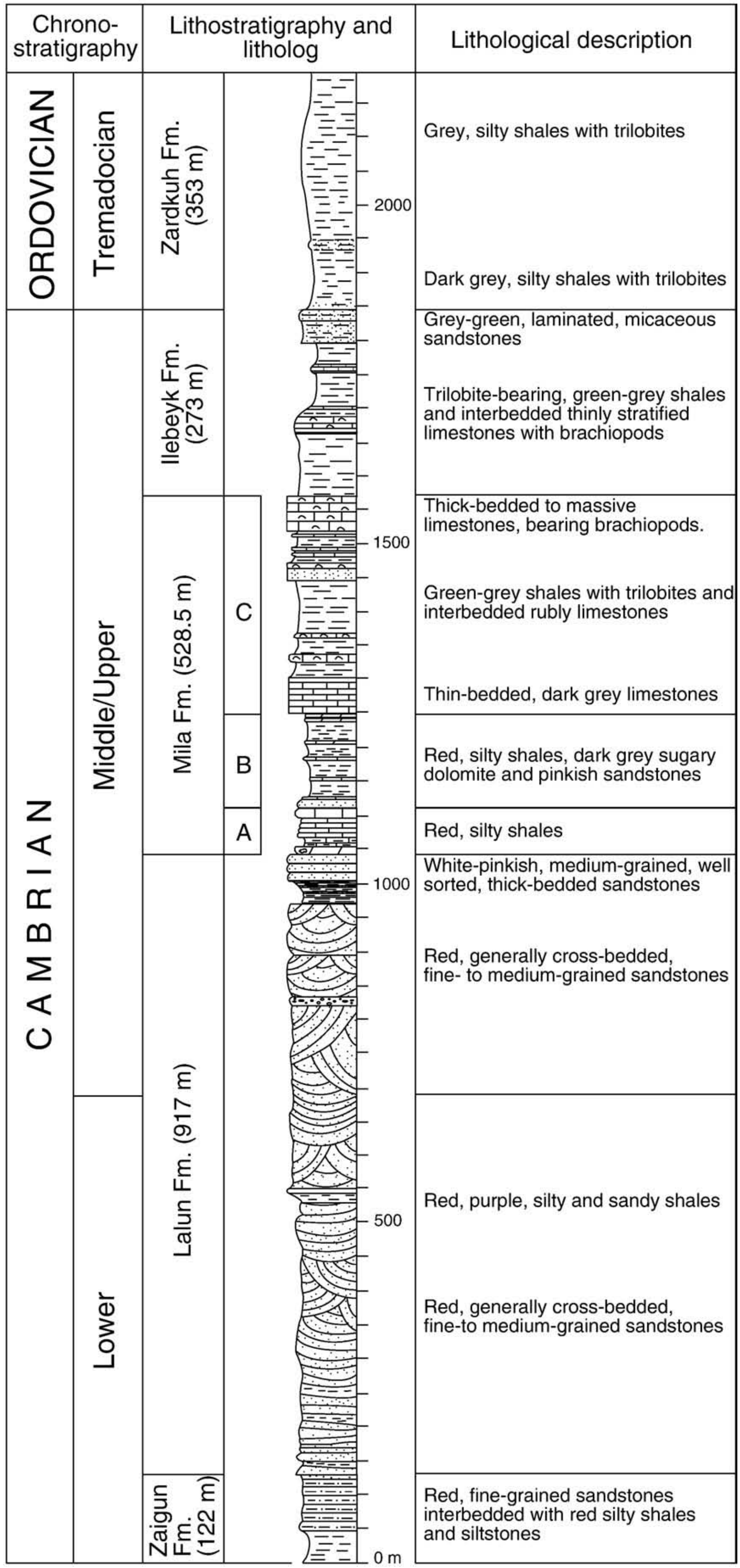

Fig. 2. Composite lithological log, lithostratigraphy, and major chronostratigraphic attributions of study sections.

thickness, and consists mainly of dolomite beds interbedded with red and purple shales. This unit is unfossiliferous in the study area, however, a Late Proterozoic–earliest Cambrian age has been proposed by Setudehnia (1975) based on lithological correlation with the Barut Formation outcrops in northern Iran.

The Zaigun Formation is well represented at Kuh-e-Garreh and Kuh-e-Dinar, where it reaches 122 m in thickness, and it is absent in the Zardkuh Mountains (Setudehnia, 1975). This stratigraphic unit is mainly composed of varicoloured (red/purple and green/blue) micaceous and fissile shales, becoming more sandy in the upper part, where there are characteristic interbeds of fine-grained, red sandstones within a shaly matrix. Both the lower and upper contacts of the Zaigun Formation are conformable and transitional with the underlying (Barut) and overlying (Lalun) formations. The Zaigun Formation is also unfossiliferous and it has been assigned to the latest Proterozoic–Early Cambrian based on its stratigraphic position and lithological correlation with equivalent formations in northern Iran (Setudehnia, 1975; Stöcklin et al., 1964).

The Lalun Formation crops out in Kuh-e-Dinar, Kuh-e-Garreh and adjacent mountains, where it is represented by 917 m of reddish/brown sandstones, but not in the Zardkuh area. Its lower contact with the underlying Zaigun Formation is conformable and rather transitional, its upper boundary with the Mila Formation is quite sharp, commonly identified at the top of a pinkish-white weathered sandstone body. Although the Lalun Formation is unfossiliferous in the study area, its age has been determined as Early Cambrian based on the analysis of equivalent strata in northern Iran (Setudehnia, 1975).

The succeeding Mila Formation is well represented in Kuh-e-Garreh, Zardkuh and adjacent mountains (e.g., Kuh-e-Lajin and Kuh-e-Sabzu), but substantially reduced in Kuh-e-Dinar, where its entire upper portion is missing. The total thickness of this formation has been estimated in 523.5 m. Three members have been recognized within the Mila Formation: the lower Member “A” (72 m-thick in Tang-e-Putak and Kuh-e-Dinar; not exposed in Zardkuh Mountain) consists of unfossiliferous dark grey-brown dolomites interbedded with red, silty shales. The succeeding Member “B” is represented in the three localities of Kuh-e-Dinar, Zardkuh and Kuh-e-Garreh; it consists of unfossiliferous, slightly weathered red and green shales and siltstones with dolomite interlayers in the middle part, its thickness varying from 26 m in Kuh-e-Dinar, to 102 m in Kuh-e-Garreh. The top of this member is covered by scree and soil, while being faulted at the base (Setudehnia, 1975). The best exposure and most complete section (321.5 m-thick) of the Member “C” of the Mila Formation is in Tang-e-Ilebeyk of Zardkuh Mountain. The same stratigraphic unit is progressively reduced in thickness from Kuh-e-Garreh (104 m) to Tang-e-Putak (42.7 m). In these two latter localities, a disconformity truncates the upper portion of this member, bringing it in direct contact with sandstones and shales of Early Permian age (Ghavidel-syooki, 1988, 1993, 1997). Member “C” of the Mila Formation consists of abundantly fossiliferous green-grey to olive-grey shales, sandstones and limestones. In Tang-e-Ilebeyk, the lower 239.5 m of this member contain a typical Middle Cambrian invertebrate skeletonized fauna consisting of trilobites, *Dorypygella* sp., *Solenoparia* sp., *Nisusia* sp., *Paradoxides* sp.; brachiopods, *Obolus* sp., *Lingulella* sp., and the hyolitid *Circotheca* sp. (Setudehnia, 1975). The upper 82.2 m of member “C” of the Mila Formation yields an upper Cambrian fauna, including *Billingsella* sp., *Billingsella* cf. *B. rhomba, Eurudagnostus* sp., *Agnostus* sp., *Coosina* sp., *Loganellus* sp., *Labiostria* sp., and *Circotheca* sp. aff. *C. jamsella.*

The Ilebeyk Formation is well-exposed in Tang-e-Ilebeyk of Zardkuh, but it is not present in Kuh-e-Garreh and Kuh-e-Dinar (Setudehnia, 1975). This formation has a thickness of 273 m and consists of shales and sandstone with a few limestone stringers. Trilobites have been collected in the uppermost 33.5 m of this formation, including *Saukia iranicus*, *Plectotrophia* sp., *Saratoga latefrons*, *Idahoia* sp., *Calvinella* sp., *Baltagnostus* sp., *Coosia* sp., *Meeria* sp., *Circotheca* sp., *Lotagnostus* sp., *Pseudoagnostus* sp., *Chaungia* sp., and *Labiostria* sp. Based on this trilobite fauna, the formation has been assigned to the Upper Cambrian (Setudehnia, 1975).

The Ilebeyk Formation is conformably overlain by the 340 m-thick Zardkuh Formation, consisting of shales interbedded with fine-grained sandstones. This formation only occurs in Tang-e-Ilebeyk of Zardkuh Mountain and it is traditionally subdivided into two members: a 90 m-thick, sandier lower member with a characteristic trilobite-yielding horizon at 12.2 m above the base of the formation, and a 250 m-thick, predominantly shaly upper member. The trilobite fauna characteristic of the lower member contains the species *Dikelokephalina* cf. *D. asiatica* which indicates an Early Ordovician age (Kobayashi, 1934; Setudehnia, 1975; Kim and Choi, 2000). Because the contact between the Ilebeyk and the Zardkuh formations is sharp and well defined lithologically, the Cambrian–Ordovician boundary is traditionally drawn at the base of the Zardkuh formation (Setudehnia, 1975). The upper member of the Zardkuh Formation is characterized by the occurrence of graptolites such as *Didymograptus* cf. *D. extensus*, *Temnogratus* sp., and *Schizograptus* sp., which confirm an Early Ordovician age for the formation (Setudehnia, 1975). Previous palynological study of the Zardkuh Formation also indicates a Tremadocian through Arenigian age (assemblages O1 through O4 of Ghavidel-syooki, 1997).

Finally, the 185 m-thick Seyahou Formation consists mainly of shales with intercalation of sandstones and siltstones; it yields a non-diagnostic skeletonized fauna comprising *Sinorthis* sp., *Obolus* sp., and *Lingulella* sp., and rich acritarch assemblages indicating a Middle to Late Ordovician age (Ghavidel-syooki, 1997). The Ordovician stratigraphic units (Zardkuh and Seyahou formations) are disconformably overlain over the entire study area by the Early Permian Faraghan Formation (Ghavidel-syooki, 1993, 1996, 1997). Therefore, a major hiatus exists between the Seyahou Formation (Late Ordovician) and Faraghan Formation (Early Permian).

3. Materials and methods

A total of 80 surface samples have been analyzed. Forty-one samples were collected from the more complete Tang-e-Ilebeyk section of Zardkuh, covering the entire stratigraphic interval of interest (Mila, Ilebeyk, and lowermost Zardkuh formations):

they all proved palyniferous. Another 16 productive samples were collected from Member C of the Mila Formation in the Tang-e-Darreh Doon section at Kuh-e Garreh. Twenty-three samples coming from the Mila Formation at Kuh-e Dinar (Tang-e Putak section) were barren.

The samples are indicated herein by the National Iranian Oil Company code number preceded by the prefix AS (for the samples from Zardkuh) or AKS (for the samples from Kuh-e-Garreh).

Palynomorphs were extracted from shale and siltstone samples by standard palynological procedures, including removal of carbonates and silicates by hydrochloric and hydrofluoric acids, and density separation of the organic residues in 30 ml of saturated zinc bromide solution. Organic residues were then sieved through 15 µm nylon mesh sieves. Palynological concentrates were mounted on glass slides for optical microscopy and on metallic stubs for extensive SEM examination.

Productive samples yielded well-preserved and abundant palynomorphs with acritarchs dominating the assemblages, but also including algal clusters, scolecodonts and rare chitinous graptolite debris. These palynomorphs range in colour from yellow to orange brown, indicating an intermediate degree of thermal maturity of the organic matter. All slides pertaining to this study are housed in the palaeontological collections of the Exploration Directorate of the National Iranian Oil Company under the sample numbers AS-2500 to AS-2930 and AS 2301–AS2500 as well as AKS2385-AKS2480.

4. Biostratigraphy

The palynoflora of the Mila, Ilebeyk and lowermost Zardkuh formations is composed of 41 acritarch species, one algal cluster, and one scolecodont species (Plates 1–5). Only the acritarch assemblages are considered in this paper; they are stratigraphically significant and allow an informal biozonation for the Zagros Basin (Figs. 3, 4) consisting of five local assemblage zones in ascending stratigraphic order, as follows.

4.1. Acritarch assemblage zone 1

This assemblage zone occurs in the lowermost 42 m of Mila Formation's Member C (Figs. 2, 3). It is characterized by the co-occurrence of *Eliasum jennessii, Retisphaeridium dichamerum* and *Retisphaeridium howellii.* The known stratigraphic range of *E. jennessii* is restricted to the Middle Cambrian; it is in fact a characteristic component of Martin and Dean (1988) Zone AO-1 of eastern Newfoundland, correlated to the lower part of the *Paradoxides paradoxissimus* trilobite Zone. The two *Retisphaeridium* species typically occur in Lower to Middle Cambrian strata in eastern Newfoundland (Martin and Dean, 1981, 1983, 1984 and 1988), and in Western Canada and southern Alberta (Staplin et al., 1965), although *R. dichamerum* has been recorded also from the Upper Cambrian strata (*P. spinulosa* Zone) of the Anglo-Welsh area by Downie (1984). Accordingly, the present informal acritarch zone is here attributed to the Middle Cambrian; it is probably correlatable at least in part (Fig. 4) with acritarch Zone AO-1 of Martin and Dean (1988). It follows that Members A and B of the Mila Formation (barren in both macrofauna and palynoflora) should be considered at least Middle Cambrian or older in age, based on their stratigraphic occurrence. This is in agreement with what was previously proposed by Setudehnia (1975).

4.2. Acritarch assemblage zone II

This zone extends through a thickness 252 m of Member C of the Mila Formation in Tang-e-Ilebeyk of Zardkuh (Figs. 2, 3). Its base is defined by the first appearance of several diagnostic taxa such as *Cristallinium ovillense*, *Timofeevia lancarae, Timofeevia pentagonalis, Timofeevia phosphoritica, Timofeevia microretis*, and *Vulcanisphaera turbata*; its top coincides with the base of the succeeding zone. The above mentioned acritarch species are characteristic components of different Middle to Late Cambrian acritarch suites described from several localities worldwide, such as Belgium and France (Ribecai and Vanguestaine, 1993); East European Platform (Volkova, 1990); Morocco (Vanguestaine and Van Looy, 1983); Libya (Albani et al., 1991); and eastern Newfoundland (Martin and Dean, 1988; Parsons and Anderson, 2000).

The species *Timofeevia pentagonalis*, *T. microretis*, and *Vulcanisphaera turbata* have their independently dated FADs (First Appearance Datums) in an interval between the latest Middle Cambrian to the early Late Cambrian (base of upper A2 acritarch Zone; Martin and Dean, 1988). This is also in general agreement with observations of similar assemblages in coeval stratal sequences in western Missouri, United States (Wood and Stephenson, 1989), and in the Alborz Range of northern Iran (Ghavidel-Syooki, 2006).

A very similar acritarch assemblage of inferred earliest Late Cambrian age has been described in northwestern Libya by Albani et al. (1991).

The discussed acritarch assemblage shares many diagnostic forms, and thus should be considered as correlatable with the acritarch Zone *Timofeevia pentagonalis–Vulcanisphaera turbata* defined by Vanguestaine and Van Looy (1983) in the High-Atlas of Morocco, ranging from the upper part of the Middle Cambrian (*Paradoxides forchhammeri* trilobite Zone), up to an interzone between the *Olenus* and the *Parabolina spinulosa* trilobite Zones (lower Upper Cambrian; cf. Martin and Dean, 1988, Fig. 10). This age assignment is assumed to be valid for the present acritarch zone II (Fig. 4), and is also consistent with macrofaunal fossil evidence reported by Setudehnia (1975).

4.3. Acritarch assemblage zone III

This assemblage zone occurs through a thickness of 63 m in the Ilebeyk Formation (Figs. 2, 3). Its base is marked by the first appearance of *Timofeevia?* sp., *Leiofusa stoumonensis*, *Cristallinium cambriense,* and by the inception of abundant *Leiosphaeridia* spp. (Figs. 2, 3). Many taxa characteristic of the preceding assemblage range into the lower part of the present zone but gradually disappear before its top. This evident reduction in taxonomic diversity (together with the sudden

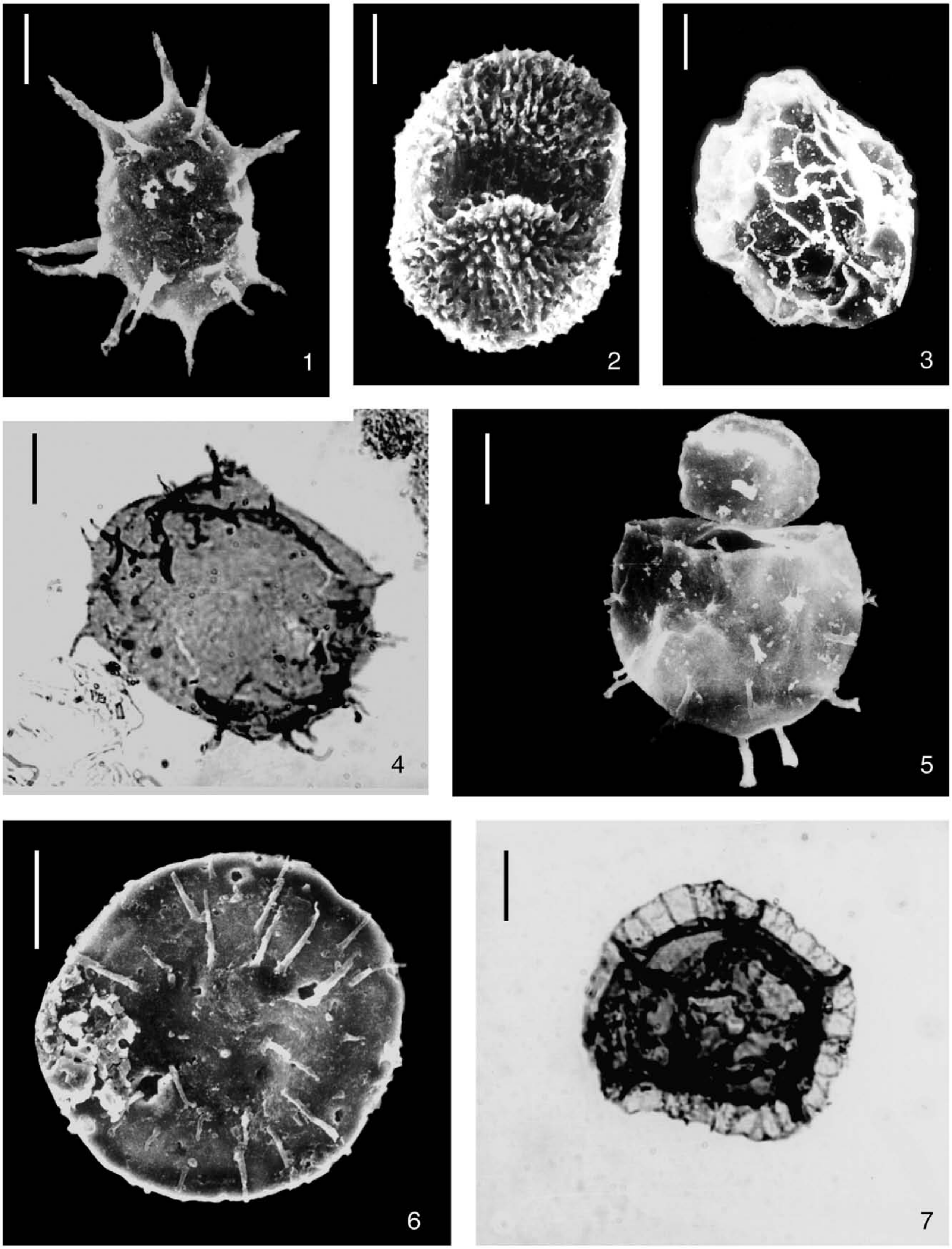

Plate I *(caption on page 107)*.

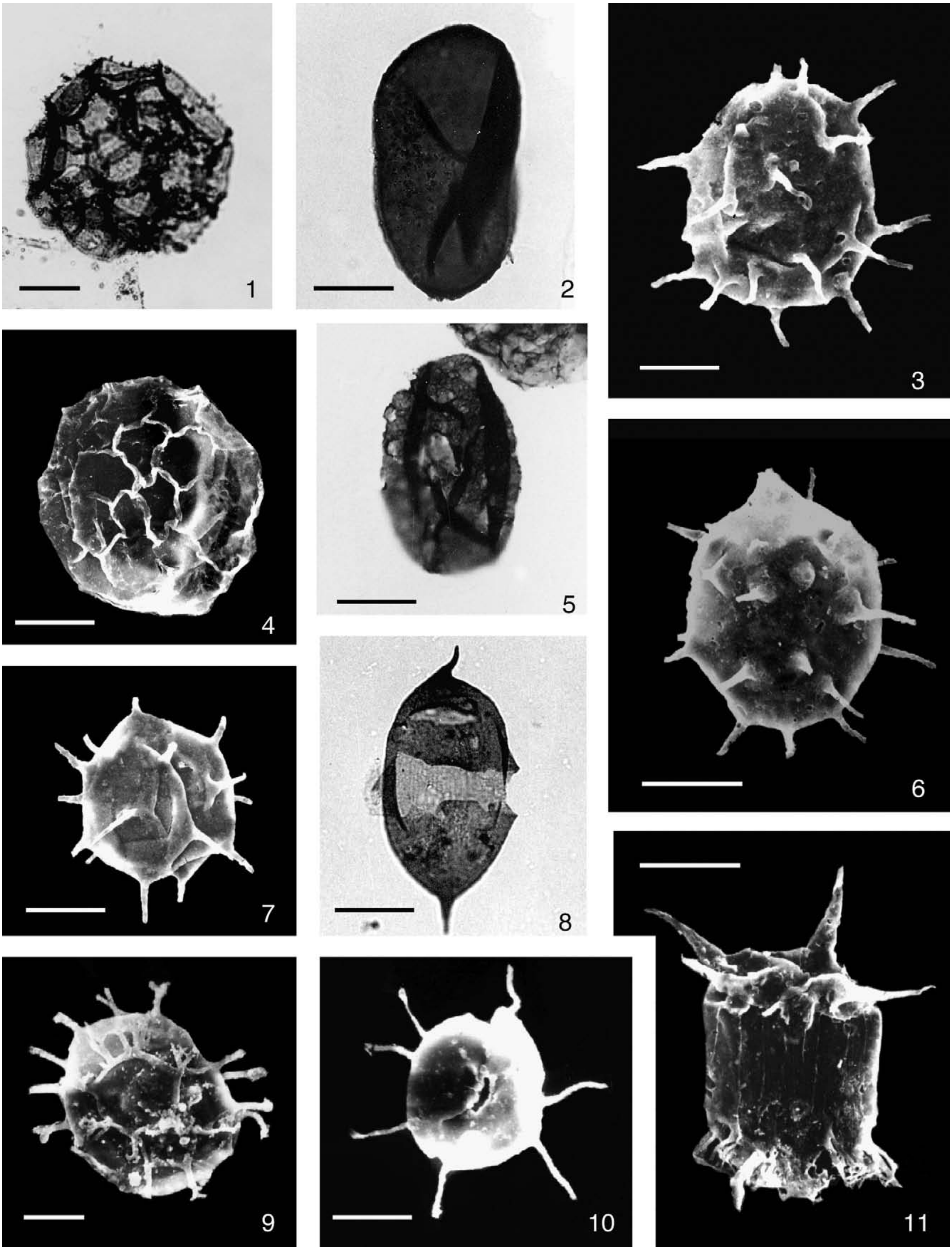

Plate II *(caption on page 107)*.

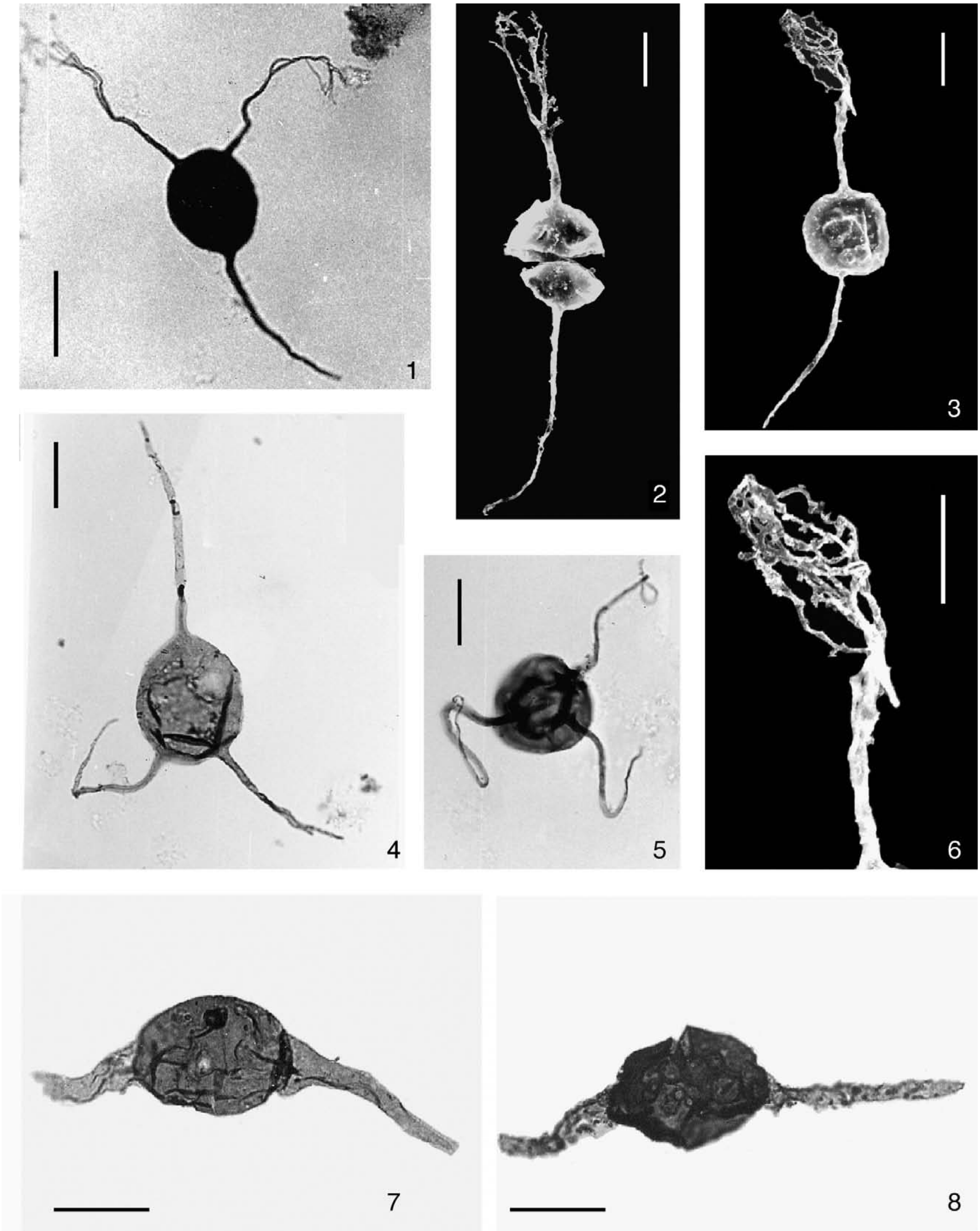

Plate III *(caption on page 107)*.

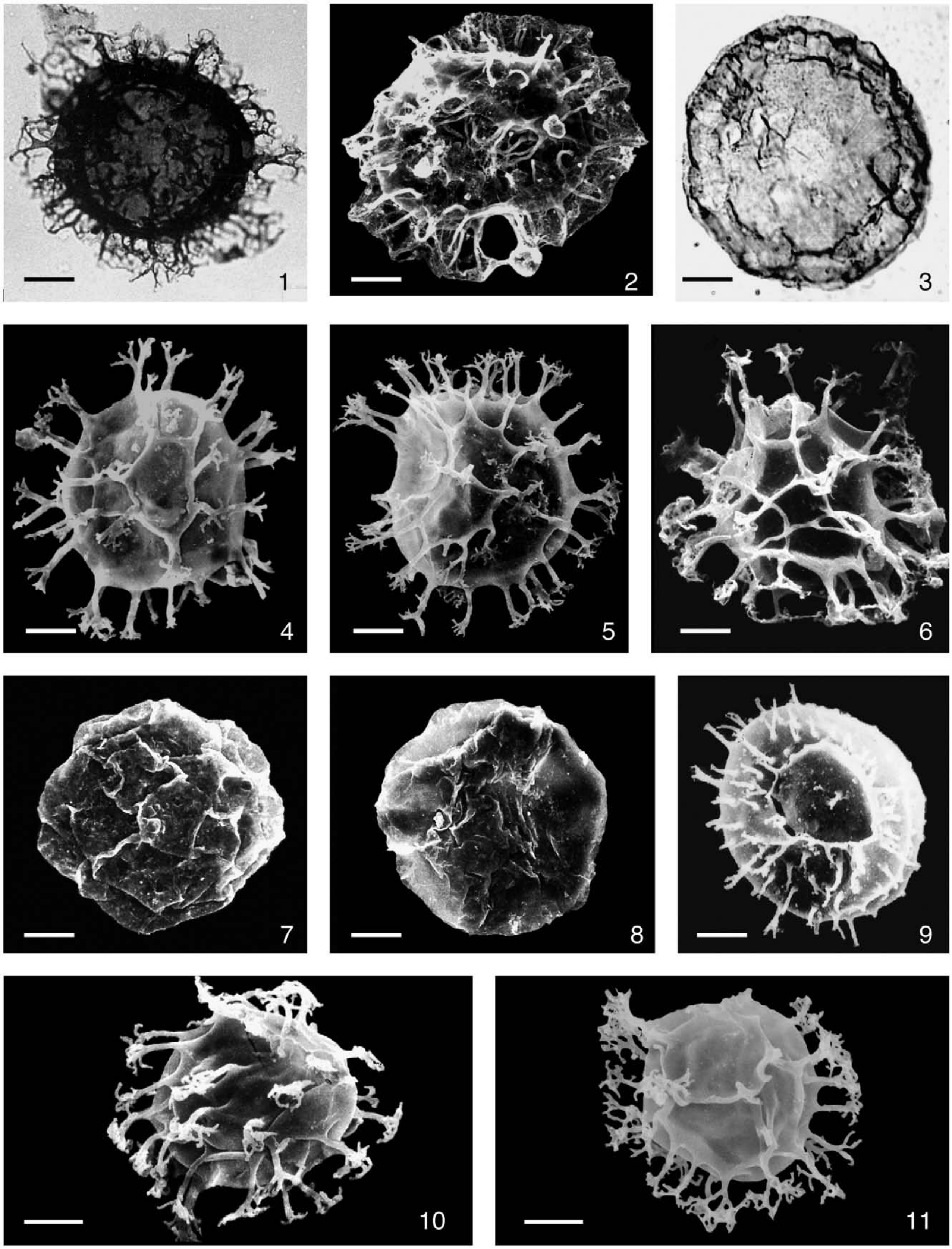

Plate IV *(caption on page 107)*.

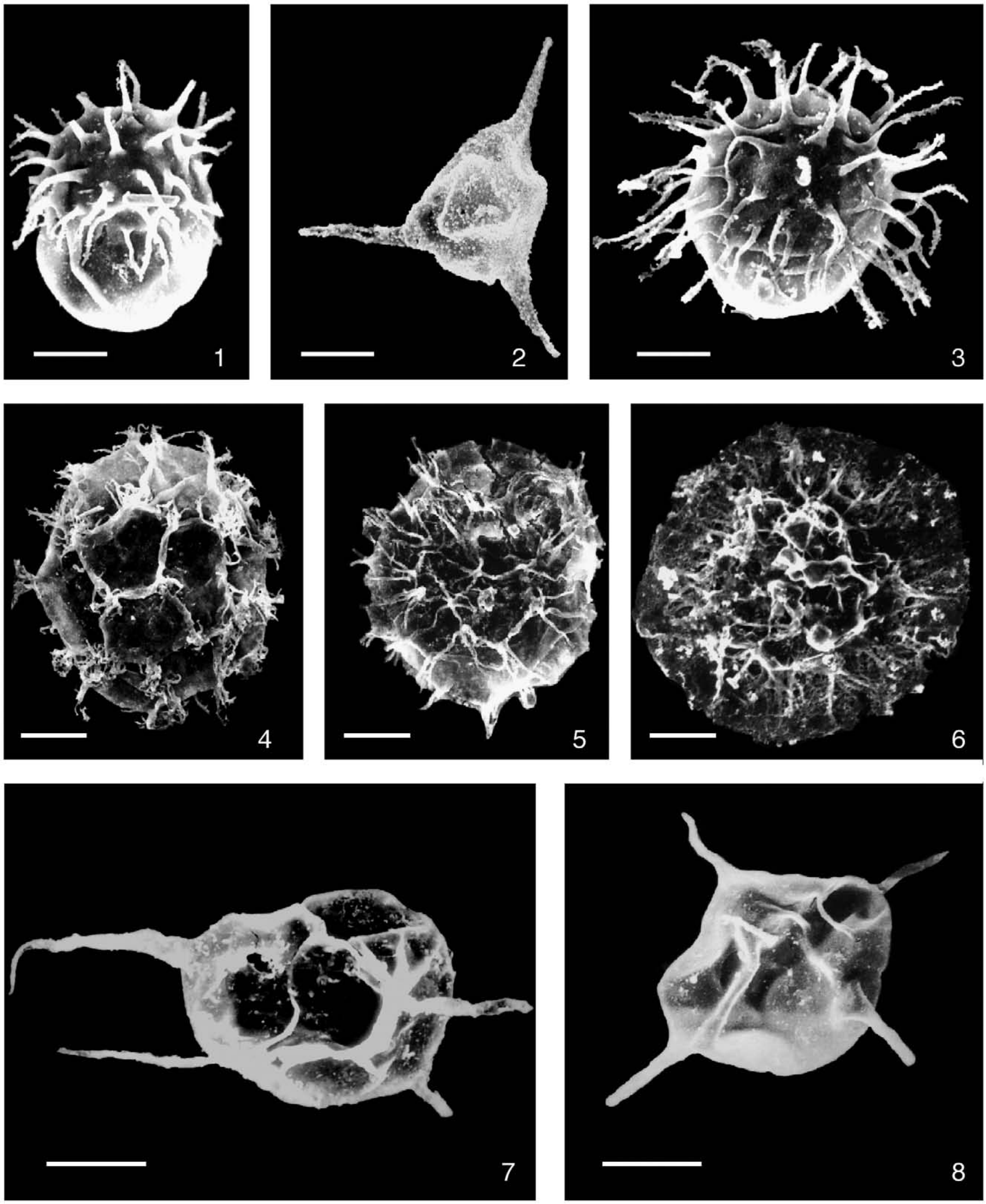

Plate V. Scale bars equals 10 μm.

1, 3. *Trunculumarium revinium* (Vanguestaine) Loeblich and Tappan, 1976.
2. *Veryhachium dumontii* Vanguestaine, 1973.
4. *Vulcanisphaera turbata* Martin *in* Martin and Dean, 1981.
5. *Vulcanisphaera africana* Deunff, 1961.
6. *Vulcanisphaera cirrita* Rasul, 1976.
7, 8. *Veryhacium mutabile* Di Milia, Ribecai and Tongiorgi, 1989.

appearance of leiospherids) is also a characteristic feature of zone III. The known stratigraphic range of *L. stoumonensis* is restricted to the Upper Cambrian: independently verified Upper Cambrian occurrences of this species are those from eastern Newfoundland (*Olenus* to *Parabolina spinulosa* trilobite Zones: Martin and Dean, 1988; Parsons and Anderson, 2000) and from the Stavelot Massif of Belgium (*P. spinulosa–Leptoplastus trilobite* Zones; Ribecai and Vanguestaine, 1993). *Cristallinium cambriense* is a very commonly reported acritarch species from Lower Cambrian through Tremadocian sediments worldwide (see detailed geographic and stratigraphic summary occurrences in Vecoli, 1996 and in Vanguestaine, 2002). Consequently, a Late Cambrian age, possibly early Late Cambrian, is suggested for the present assemblage zone, which may be equivalent to subzone A3a of palynofloral Zone A3 of Martin and Dean (1988; Fig. 4).

4.4. Acritarch assemblage zone IV

The base of this zone is defined by the inception of numerous taxa, namely: *Acanthodiacrodium achrasii*, *Cristallinium randomense*, *Cymatiogalea aspergillum*, *Cymatiogalea bellicosa*, *Cymatiogalea membranispina*, *Dasydiacrodium caudatum*, *Dasydiacrodium obsonum*, *Impluviculus multiangularis*, *Impluviculus* sp., *Veryhachium dumontii, Trunculumarium revinium*, *Vulcanisphaera africana*, and *Lusatia dendroidea* (Figs. 2, 3). The present zone extends through a thickness of 240 m in the Ilebeyk Formation, its top being coincident with the base of the succeeding zone V. The majority of the acritarch species listed above are chronostratigraphically significant, and typically co-occur in Upper Cambrian sediments in numerous localities worldwide.

The stratigraphic ranges of *Dasydiacrodium obsonum*, *D. caudatum*, *Cristallinium randomense*, *Trunculumarium revinium*, and *Veryhachium dumontii* are well documented from different palaeogeographic areas and consistently occur within stratal sequences correlated to a chronostratigraphic interval comprised between the *Parabolina spinulosa* and the *Peltura* trilobite zones. This has been demonstrated in eastern Newfoundland (A3–A5 acritarch Zones of Martin and Dean, 1988; RA5-RA7 acritarch palynofloras of Parsons and Anderson, 2000), in the High Atlas of Morocco (acritarch zone 7 of Vanguestaine and Van Looy, 1983), and in the Rocroi Massif of France and the Stavelot Massif of Belgium ("Stoumont assemblage" and acritarch Zone 5 of Ribecai and Vanguestaine, 1993; Vanguestaine, 2002). The co-occurrence of taxa typically described from Upper Cambrian through lowermost Ordovician

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Plate I. Scale bars equals 10 µm. (*see on page 102*)

1. *Acanthodiacrodium achrasii* Martin, 1973.
2. *Acantodiacrodium angustum* (Downie) Combaz, 1967.
3. *Cristallinium cambriense* (Slavíková) Vanguestaine, 1978.
4. *Acanthodiacrodium ubui* Martin, 1969.
5. *Cymatiogalea bellicosa* Deunff, 1961.
6. *Baltisphaeridium* sp. cf. *B. crinitum* Martin *in* Dean and Martin, 1978.
7. *Cymatiogalea membranispina* Deunff, 1961.

Plate II. Scale bars equals 10 µm. (*see on page 103*)

1. *Cristallinium randomense* Martin *in* Martin and Dean, 1981 *emend*. Martin *in* Martin and Dean, 1988.
2, 5. *Eliasum jennessii* Martin *in* Martin and Dean, 1984.
3. *Dasydiacrodium obsonum* Martin *in* Martin and Dean, 1988.
4. *Cristallinium ovillense* (Cramer and Diez) Martin *in* Martin and Dean, 1981.
6. *Dasydiacrodium caudatum* Vanguestaine, 1973.
7. *Impluviculus* sp.
8. *Leiofusa stoumonensis* Vanguestaine, 1973.
9. *Cymatiogalea aspergillum* Martin *in* Martin and Dean, 1988.
10. *Impluviculus multiangularis* (Umnova) Volkova, 1990.
11. *Ladogella rommelaerei* (Martin) Di Milia, Ribecai and Tongiorgi, 1989.

Plate III. Scale bars equals 10 µm. (*see on page 104*)

1–6. *Lusatia dendroidea* Burmann, 1970 emend. Albani, Bagnoli, Ribecai and Raevskaya, 2007.
7, 8. *Orthosphaeridium*? *extensum* Parsons and Anderson, 2000.

Plate IV. Scale bars equals 10 µm. (*see on page 105*)

1, 2. *Timofeevia microretis* Martin *in* Martin and Dean, 1981.
3. *Saharidia fragilis* (Downie) Combaz, 1967.
4, 5. *Timofeevia phosphoritica* Vanguestaine, 1978.
6. *Timofeevia lancarae* (Cramer and Diez) Vanguestaine, 1978.
7. *Retisphaeridium dichamerum* Staplin, Jansonius, and Pocock, 1965.
8. *Retisphaeridium howellii* Martin *in* Martin and Dean, 1983.
9. *Stelliferidium* sp.
10. *Timofeevia* sp.
11. *Timofeevia pentagonalis* (Vanguestaine) Vanguestaine, 1978.

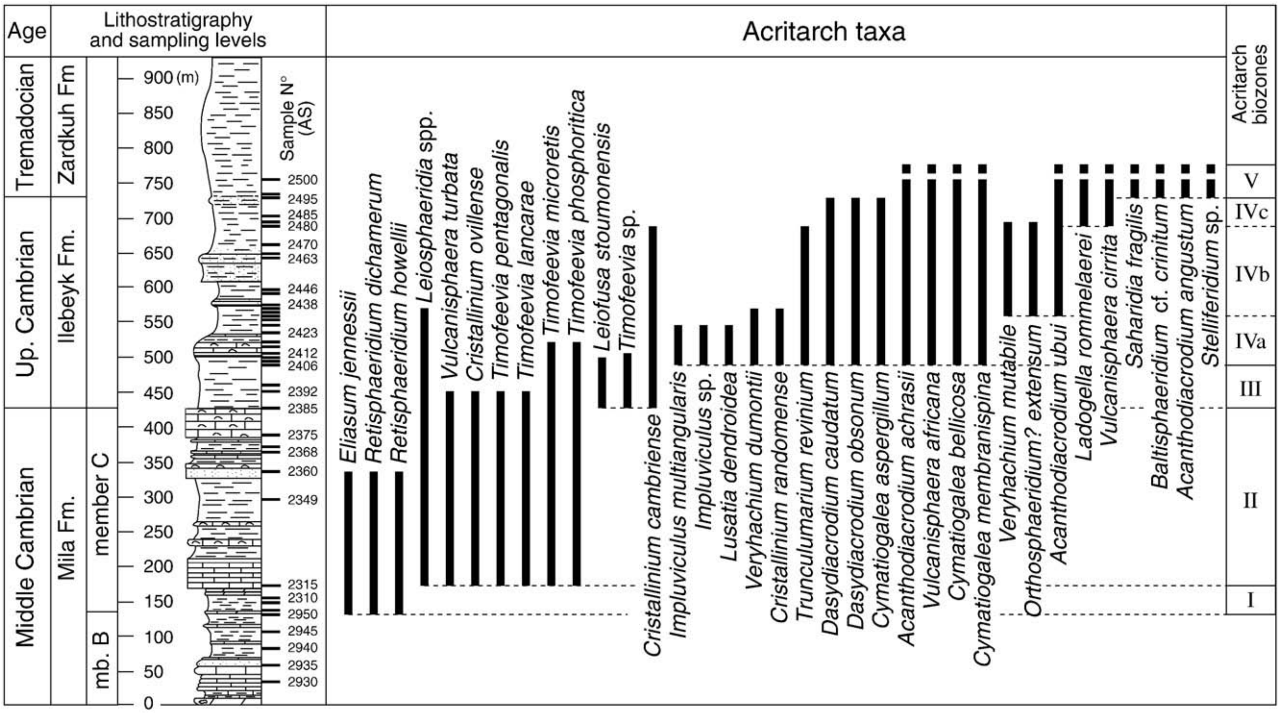

Fig. 3. Stratigraphical distribution of acritarch taxa from the Cambrian (Mila and Ilebeyk formations) and lowermost Ordovician strata (Zardkuh Formation) in Zagros Basin, Southern Iran, and proposed biozonation.

transitional strata such as *Acanthodiacrodium achrasii*, species of *Cymatiogalea* and *Impluviculus*, and *Vulcanisphaera africana* support the above correlation. Similar assemblages to that defining the present zone occur in the Algerian Sahara (HM/A acritarch assemblage of Vecoli, 1996) and in the Ghadames Basin (northwestern Libya and southern Tunisia: *T. phosphoritica–D. caudatum* acritarch zone of Vecoli, 1999).

The present zone IV is thus assigned to a chronostratigraphic interval ranging from middle Upper Cambrian up to Cambrian/Ordovician transitional levels (Figs. 3, 4). Based on distributional patterns of its constituents, the zone can be subdivided into three sub-zones (Fig. 3). A first subzone (IVa) is characterized by the occurrence of abundant *Lusatia dendroidea* showing a high morphological intraspecific variability (see Plate III Figs. 1–6), as well as by the occurrence of the genus *Impluviculus*. The precise chronostratigraphic value of these taxa is uncertain (although evidencing a definite Late Cambrian age). However, in the study area, the stratigraphic level defined by their co-occurrence seems to have good potential for correlation across the basin. The subzone IVb is defined by the disappearance of *Lusatia* and *Impluviculus*, as well as *Veryhachium dumontii* and *Cristallinium randomense*, and by the inception of *Veryhachium mutabile*, *Orthosphaeridium extensum*, and *Acanthodiacrodium ubuii*. The FADs of these three latter species are not highly significant, and *V. dumontii* and *C. randomense* have been reported to co-occur elsewhere together with *T. revinium*, *C. aspergillum*, and *D. caudatum* (in eastern Newfoundland: Martin and Dean, 1988 and in Morocco: Vanguestaine and Van Looy, 1983). For these reasons, it remains difficult to appreciate the chronostratigraphic value of this sub-assemblage which may reflect local palaeoenvironmental conditions. Finally, the disappearance of *T. revinium*, *V. mutabile*, and *O. extensum*, together with the inception of *Ladogella rommelaerei* and *Vulcanisphaera cirrita*, can be used to define a third subzone (IVc) within zone IV.

4.5. Acritarch assemblage zone V

This zone extends through 68.4 m in the basal part of the Zardkuh Formation (Figs. 2, 3); its base is defined by the first appearance of *Saharidia fragilis, Acanthodiacrodium angustum, Baltisphaeridium crinitum, Cymatiogalea cylindrata*, and *Cymatiogalea sp*. The top of the zone cannot be defined in the present study. *Vulcanisphaera africana*, *Acanthodiacrodium achrasii*, *Cymatiogalea bellicosa*, and *C. membranispina* persist from the previous zone. An important feature is the absence of the most typical Upper Cambrian taxa, all disappearing at the zone's lower boundary.

Acanthodiacrodium angustum is a diagnostic Tremadocian taxon; this species has been widely reported from Tremadocian-aged strata worldwide, and a detailed list of occurrences is given in Vecoli (1999, p. 28). There is now sufficient evidence to prove that the FAD of *A. angustum* lies at a stratigraphical level close to the Cambrian–Ordovician boundary. The lowermost record of this species is from an horizon within the *Cordylodus proavus* conodont Zone in the Kallavere Formation of Estonia (Volkova, 1990, and see discussion in Vecoli, 1999, p. 28). The accompanying taxa, *S. fragilis*, *B. crinitum*, *V. africana*, and the various *Cymatiogalea* species, although ranging downwards in Upper to uppermost Cambrian strata, are characteristically abundant in typical Tremadocian acritarch assemblages in North Africa (Algeria, Tunisia, and

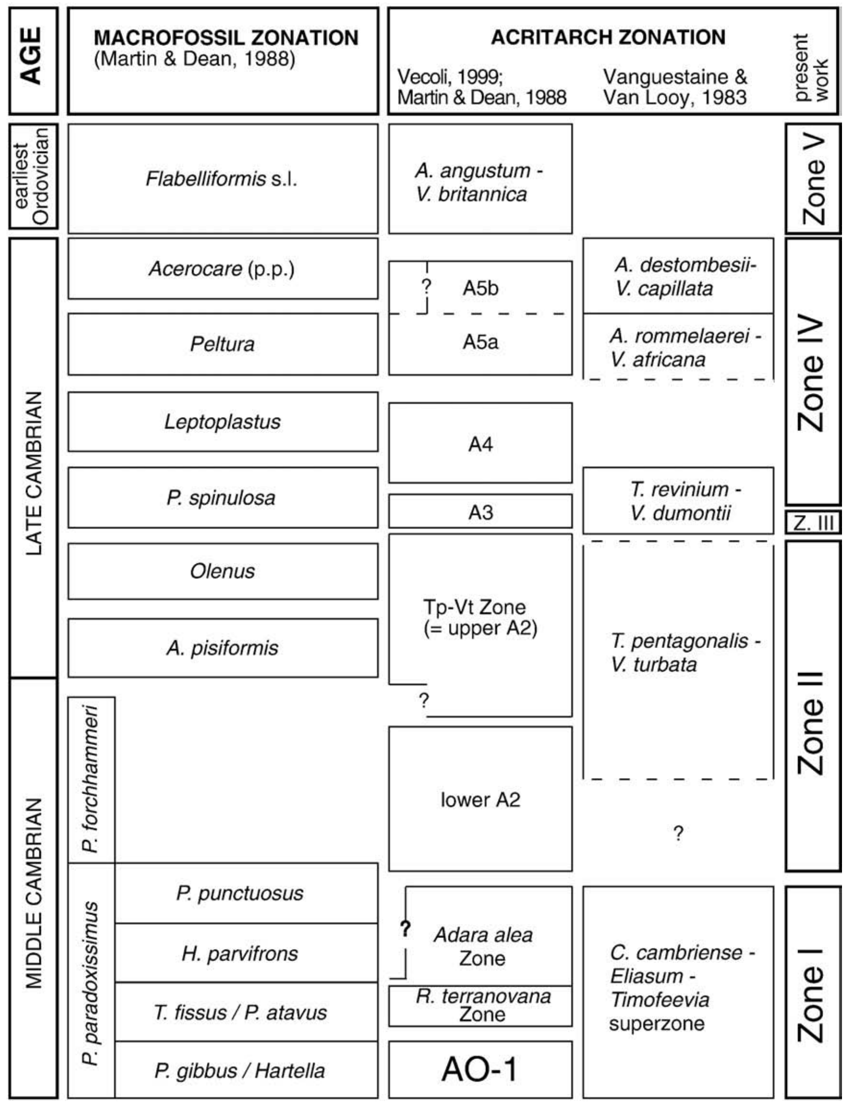

Fig. 4. Chronostratigraphic correlation of described Iranian assemblages with macrofossil zonation and previously established Middle Cambrian through earliest Ordovician acritarch zonations.

Libya: Vecoli, 1996, 1999, 2004; Morocco: Elaouad-Debbaj, 1988), central Europe (Martin, 1973, 1977), and the Baltic area (Tongiorgi in Bagnoli et al., 1988; Volkova, 1990).

Accordingly, there are sufficient elements for an age assignment of the present zone to the earliest Ordovician (early Tremadocian), and for correlation to the *Acanthodiacrodium angustum–Vulcanisphaera britannica* assemblage zone defined in the Tremadocian of North Africa by Vecoli (1999; Fig. 4).

5. Palaeobiogeography

Cambrian to earliest Ordovician palaeogeography is poorly constrained by palaeomagnetic data; evidence for continental separation during this time is mainly based on stratigraphic and tectonic considerations, and degree of similarity among faunal assemblages (e.g., trilobites; review in Scotese and McKerrow, 1990, 1991). Although the existence of four main continental blocks separated by oceanic basins is generally accepted (Laurentia, Baltica, Siberia, and Gondwana; Fig. 5), their relative palaeolongitudinal position (cf. Dalziel, 1997) and the position of some of the smaller terranes remains controversial because of the scarcity of firm data (Scotese and McKerrow, 1990, p. 4). As discussed by the latter authors, Iran is generally considered to have formed part of the Gondwana palaeocontinent during at least a part of the Palaeozoic; it is generally shown, during Cambrian to Silurian times, to be positioned in tropical palaeolatitudes along the margin of Gondwana, forming one of the so-called “peri-Gondwana” terranes (Fig. 5). However it is interesting to note (at least from an historical viewpoint) that in an old study, King (1930) found no similarities between Cambrian macrofaunas from the Zagros Basin of southern Iran and coeval association from southern European, thus discounting a Gondwanan palaeobiogeographical affinity for southern Iran.

The palaeobiogeographic value of acritarchs has been repeatedly demonstrated; although acritarch bioprovincialism appears to be most pronounced during mid-Ordovician times (Vavrdová, 1974; Li, 1987; Tongiorgi and Di Milia, 1999; Vecoli, 1999; Servais et al., 2003), the factors controlling

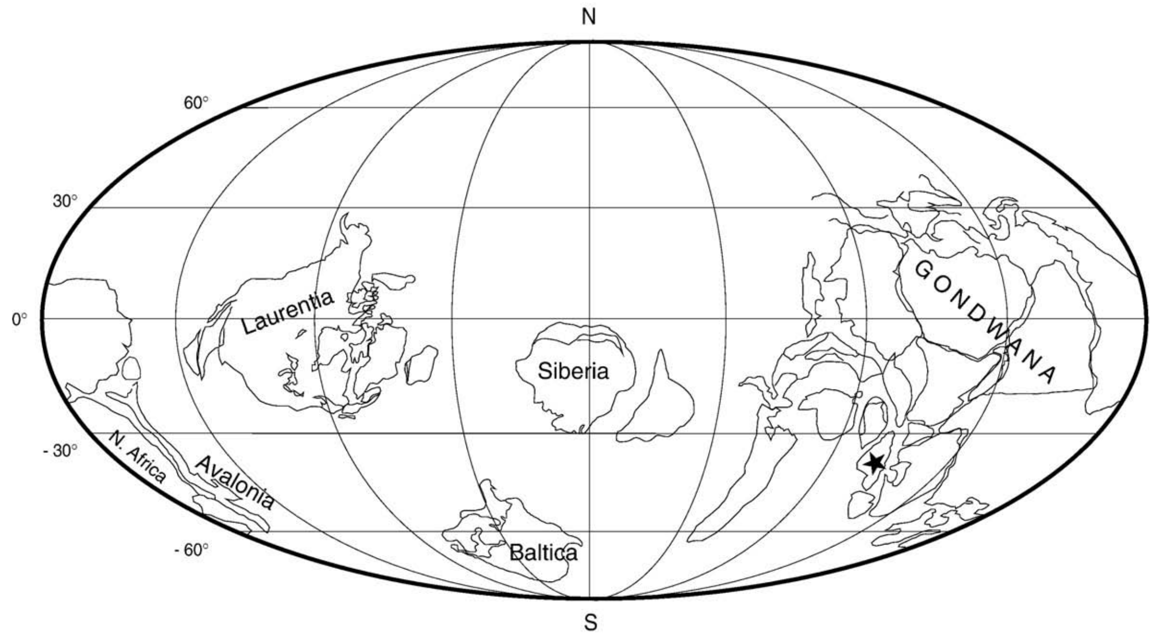

Fig. 5. Palaeogeographical model of continental mass distribution during Cambrian times (based on the map of Scotese and McKerrow, 1991 modified according to further data from Williams, 1997; Moczidlowska, 1997; Cocks and Torsvik, 2005) showing position of study area (star) and other localities discussed in text. Present results are consistent with a Gondwanan palaeogeographical affinity for Iran, but point to a more southerly, higher palaeolatitudinal position (closer to Avalonia).

acritarch provincialism (primarily palaeolatitude in combination with water masses barriers) must have acted also during the Cambrian, as discussed by Moczydlowska (1997).

In the present analysis, we compare the Mid-Late Cambrian to earliest Ordovician acritarch assemblages of southern Iran with coeval suites described from localities belonging to well defined palaeocontinental settings (constrained by independent evidence) in an attempt to evaluate their potential as palaeobiogeographical indicators, and to verify the consistency of our data with existing palaeogeographic maps. Mid-Late Cambrian to basal Ordovician acritarchs from East European Platform (Baltica), eastern Newfoundland (Avalonia, peri-Gondwana), and North Africa (part of core Gondwana) are comprehensively described by Volkova (1990), Martin and Dean (1988), and Albani et al. (1991) and Vecoli (1996), respectively. North American Cambrian–Ordovician acritarchs have been less intensively studied, published information being almost totally restricted to Cambrian assemblages from Missouri and Arkansas (Wood and Stephenson, 1989), and to rare isolated minor reports (e.g., Staplin et al., 1965).

Additional data available are those by Vanguestaine (1973, 1978; Belgium), Ribecai and Vanguestaine (1993; Belgium and northern France), Downie (1984; British Isles), all Avalonian localities, and those by Welsch (1986) for Finmark (Baltica). A comprehensive study of Middle and Late Cambrian acritarchs by Moczydlowska (1998), concerns the Upper Silesia region in southern Poland, which palaeogeographically belongs to the Avalonia terrane. Further punctual and isolated records of Cambrian acritarchs exist, but which are not significant for the scope of the present discussion; these records are listed in the relatively recent compilation by Molyneux et al. (1996), and will not be considered in further detail here. Finally, acritarch data from Mid-Upper Cambrian of Siberia are very poor and do not permit any meaningful comparison (Raevskaya, 2005 and pers. comm., 2007), and hence are not taken into consideration in the present discussion.

Table 1 shows the shared occurrence of acritarch species between the present assemblages and those representative of Baltica, Avalonia, North Africa (part of core Gondwana), and Laurentia, subdivided into three time slices, Middle and Late Cambrian, and earliest Ordovician. The data shows that only two cosmopolitan species (*Timofeevia phosphoritica* and *Vulcanisphaera turbata*) are shared between the study assemblage and the only Cambrian Laurentian assemblage described in the literature (Wood and Stephenson, 1989). On the other hand, a high proportion of species are shared between the Iranian assemblages and those described from Baltica and Avalonia both in Mid-Late Cambrian and Early Ordovician times, and similarities tend to increase passing from Late Cambrian to earliest Ordovician. The presence in the Iranian assemblage of highly polymorphic morphotypes of *Lusatia* and *Veryhachium mutabile* (two taxa previously known to only occur in Baltican localities) is in support of a similar palaeolatitude of Iran and Baltica. However, the most pronounced microforal affinities of the present Middle to Late Cambrian Iranian assemblages are with Avalonia. This is demonstrated by the presence of some morphologically distinctive taxa which are exclusively shared between these two areas, and do not occur in Baltican or other Gondwanan localities: *Retisphaeridium howellii*, *Eliasium jennessii*, *Orthosphaeridium*? *extensum*, *Cymatiogalea aspergillum,* and *Timofeevia microretis*. The present data is in general agreement with proposed palaeogeographical models showing the position of major continental masses and their drift trajectories from Late Cambrian to Early Ordovician times (e.g., Scotese and McKerrow, 1991; Williams, 1997; Moczydlowska, 1997; Cocks and Torsvik, 2005, 2007).

Table 1
Comparison of Mid-Late Cambrian and basal Ordovician southern Iranian acritarch assemblages with other published coeval acritarch assemblages. Origin of published data discussed in text; paleogeographical position of localities showed in Fig. 5

	Middle Cambrian				Upper Cambrian				Earliest Ordovician (Tremadocian)			
Iranian acritarchs	Baltica	Avalonia	Gondwana	Laurentia	Baltica	Avalonia	Gondwana	Laurentia	Baltica	Avalonia	Gondwana	Laurentia
E. jennessii		■										
R. dichamerum		■		■								
R. howellii		■										
V. turbata				■		■	■	■				
C. ovillense	■	■	■		■	■	■					
C. cambriense	■	■	■		■	■	■					
C. randomense					■	■	■					
T. pentagonalis	■	■			■	■						
T. phosphoritica	■	■	■	■	■	■	■	■				
T. lancarae	■	■	■		■	■	■					
T. microretis						■						
L. stoumonensis					■	■						
I. multiangularis					■	■			■	■		
L. dendroidea					■							
V. dumontii					■	■	■					
T. revinium					■	■	■					
D. caudatum					■	■	■				■	
D. obsonum						■					■	
C. aspergillum						■					■	
C. membranispina										■	■	
C. bellicosa										■	■	
V. africana						■	■			■	■	
V. mutabile					■						■	
O? extensum						■					■	
A. ubui						■	■		■	■	■	
A. achrasii						■	■			■	■	
A. angustum									■	■	■	
L. rommelaerei						■	■					
S. fragilis					■	■	■		■	■	■	
B. crinitum									■	■	■	

Although the difference in palynofloral composition between the Laurentian asemblage and the North African–Gondwanan, Avalonian and Baltican ones may be a result of sample bias, due to the few study published for Laurentia, the peculiar taxonomic composition of the Cambrian North American acritarch assemblages supports a wide palaeolatitudial and geographical separation between these palaeocontinents, as previously noted by Molyneux (in Molyneux et al., 1996), and in accordance with the "wide ocean model" (Williams, 1997).

The high similarities with Avalonian acritarch assemblages, however, may indicate that Iran was located further south along the North Africa–Gondwanan margin, than indicated in the maps of Scotese and McKerrow (1991, and Fig. 5), hence it was probably closer to Avalonia. This would also explain the evident Baltican affinties, considering the comparable palaeolatitudes of Avalonia and Baltica during Cambrian times. A markedly increased similarity of acritarch assemblages in latest Cambrian and earliest Ordovician times between Baltica, Avalonia, and North Africa–Gondwana is well known (e.g., Martin and Dean, 1981, 1984; Vecoli, 1996, 1999). Although the lack of data on Laurentian earliest Ordovician acritarchs somewhat limits a more rigorous interpretation, the acritarch bioprovinciality breakdown observed at the Cambrian–Ordovician transition and earliest Ordovician probably reflects a modification of the current pattern due to the southward movement of Gondwana and the northward drift of Baltica, and the shrinking of the Iapetus ocean between Baltica and Laurentia, contributing to the breakdown of water-mass barriers.

6. Discussion and conclusions

This study represents the first comprehensive micropalaeontological (palynological) investigation of the Cambrian rock units of the Zagros Basin in southern Iran. Previous works based on macrofaunal analyses (mainly trilobites) had permitted a broad assignments of the Mila and Ilebeyk formations to the Middle-Upper Cambrian by means of isolated findings in a few stratigraphical levels, but did not result in any workable biostratigraphical schemes.

The present recognition of five, well characterized acritarch assemblage zones demonstrates the utility and potential of organic-walled microfossils for detailed biostratigraphic characterization of sedimentary units, and will permit accurate dating of the southern Iranian Cambrian sequences during future drilling of deep-test oil wells. Acritarch assemblage zone I is Middle Cambrian in age and occurs in the basal part of Member C of the Mila Formation. Assemblages zone II extends through ca. 250 m in the middle and upper part of member C of the Mila Formation and correlates to the late Middle to earliest Late Cambrian. Zone III characterizes the lower part of the

Ilebeyk Formation and is early Late Cambrian in age. Assemblage zone IV is present in the middle and upper part of the Ilebeyk Formation, and can be assigned to a chronostratigraphic interval ranging from middle Late Cambrian up to Cambrian/Ordovician transitional levels. Finally, acritarch assemblage zone V extends through the basal part of the Zardkuh Formation and proves an early Tremadocian age for the latter unit.

There are no detailed sedimentological analysis of the Iranian Cambrian sediments; however the abundance and diversity of the recovered acritarch associations indicate a marine, inner neritic depositional palaeoenvironment for the rocks comprising the Mila and Ilebeyk formations, according to accepted models of microphytoplankton distribution along the onshore–offshore transect (e.g., Vecoli, 2000, 2004). The well-preserved organic matter in the palynological residues, and the yellow to brown colour of the palynomorphs suggest a Thermal Alteration Index of 3–4 (mature), suggesting generation of hydrocarbon for these Cambrian units.

From a palaeobiogeographic point of view, the Mid-Late Cambrian acritarch associations show a marked Avalonian affinity, as well as sharing a relatively high proportion of taxa with typical Baltican and North Africa–Gondwanan assemblages. On the other hand, the described Laurentian (North America) microphytoplankton assemblages are substantially different from the Iranian ones. These results support the currently accepted palaeogeographical models which place Laurentia in sub-equatorial position, and are also in agreement with current hypotheses of acritarch distributional patterns being mainly influenced by palaeolatitudal climate belts, and the distribution of water-mass barriers (Vavrdová, 1990; Vecoli, 1999; Servais et al., 2003; Vecoli and Le Hérissé, 2004). In this context, the Baltican, North Gondwanan, and Avalonian assemblages represent a cool to cold water microphytoplankton biogeographic realm, in opposition to a warm water, sub-equatorial realm indicated by the North American Cambrian acritarchs (e.g., Wood and Stephenson, 1989; Molyneux et al., 1996). Data on earliest Ordovician acritarch global distributional patterns suggest a palaeobioprovinciality breakdown, possibly linked to plate motion-induced redistribution of water masses and to lessened thermal palaeolatitudinal gradients. Although many details on acritarch palaeobiogeography and their controlling factors remain to be worked out, the present study confirms the potential of these organic-walled microfossils as effective tools for palaeogeographic and possibly for palaeoceanographic reconstructions, in addition to their unquestionable biostratigraphic value.

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Appendix 1. List of taxa cited in text and in the range chart (Fig. 3), with author-names

Genus *Acanthodiacrodium* Timofeev, 1958 emend. Deflandre and Deflandre-Rigaud, 1962
- *Acanthodiacrodium achrasii* Martin, 1973
- *Acanthodiacrodium ubui* Martin, 1969
- *Acanthodiacrodium angustum* (Downie) Combaz, 1967

Genus *Baltisphaeridium* Eisenack, 1958 ex Eisenack, 1959 emend. Eiserhardt, 1989
- *Baltisphaeridium* sp. cf. B. *crinitum* Martin *in* Dean and Martin, 1978

Genus *Cristallinium* Vanguestaine, 1978
- *Cristallinium ovillense* (Cramer and Diez) Martin in Martin and Dean, 1981
- *Cristallinium cambriense* (Slavíková) Vanguestaine, 1978
- *Cristallinium randomense* Martin in Martin and Dean, 1981 emend. Martin in Martin and Dean, 1988

Genus *Cymatiogalea* Deunff, 1961 emend. Deunff, Górka and Rauscher, 1974
- *Cymatiogalea aspergillum* Martin in Martin and Dean, 1988
- *Cymatiogalea bellico*sa Deunff, 1961
- *Cymatiogalea membranispina* Deunff, 1961

Genus *Dasydiacrodium* Timofeev, 1959 ex and emend. Deflandre and Deflandre-Rigaud, 1961
- *Dasydiacrodium caudatum* Vanguestaine, 1973
- *Dasydiacrodium obsonum* Martin in Martin and Dean, 1988

Genus *Eliasum* Fombella, 1977
- *Eliasum jennessii* Martin in Martin and Dean, 1984

Genus *Impluviculus* Loeblich and Tappan, 1969 emend. Martin, 1977
- *Impluviculus multiangularis* (Umnova) Volkova, 1990
- *Impluviculus* sp.

Genus *Ladogella* Golub and Volkova, 1985 emend. Di Milia, Ribecai and Tongiorgi, 1989
- *Ladogella rommelaerei* (Martin) Di Milia, Ribecai and Tongiorgi, 1989

Genus *Leiofusa* Eisenack, 1938 emend. Combaz, Lange and Pansart, 1967
- *Leiofusa stoumonensis* Vanguestaine, 1973

Genus *Leiosphaeridia* Eisenack, 1958
- *Lesiosphaeridia* spp.

Genus *Lusatia* Burmann, 1970
- *Lusatia dendroidea* Burmann, 1970 emend. Albani, Bagnoli, Ribecai and Raevskaya, 2007

Genus *Orthosphaeridium* Eisenack, 1968 emend. Kjellström, 1971
- *Orthosphaeridium? extensum* Parsons and Anderson, 2000

Genus *Retisphaeridium* Staplin, Jansonius and Pocock, 1965
- *Retisphaeridium dichamerum* Staplin, Jansonius and Pocock, 1965
- *Retisphaeridium howellii* Martin in Martin and Dean, 1983

Genus *Saharidia* Combaz, 1967
- *Saharidia fragilis* (Downie) Combaz, 1967

Genus *Stelliferidium* Deunff, Górka and Rauscher, 1974
- *Stelliferidium* sp.

Genus *Timofeevia* Vanguestaine, 1978

Timofeevia lancarae (Cramer and Diez) Vanguestaine, 1978
Timofeevia microretis Martin in Martin and Dean, 1981
Timofeevia pentagonalis (Vanguestaine) Vanguestaine, 1978
Timofeevia phosphoritica Vanguestaine, 1978

Genus *Trunculumarium* Loeblich and Tappan, 1976
Trunculumarium revinium (Vanguestaine) Loeblich and Tappan, 1976

Genus *Veryhachium* Deunff, 1954 emend. Sarjeant and Stancliffe, 1994
Veryhachium dumontii Vanguestaine, 1973
Veryhachium mutabile Di Milia, Ribecai and Tongiorgi, 1989

Genus *Vulcanisphaera* Deunff, 1961
Vulcanisphaera africana Deunff, 1961
Vulcanisphaera cirrita Rasul, 1976
Vulcanisphaera turbata Martin in Martin and Dean, 1981

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