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Middle-Late Cambrian acritarchs from the Zardkuh area in the High Zagros Mountains, southern Iran: Stratigraphic and paleogeographic implications

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Abstract

The excellent preservation of the acritarchs, their great abundance, diversity and good stratigraphic control permit establishment of a detailed Middle and Late Cambrian acritarch biozonation. A total of 56 palynomorph species form the basis of 10 local acritarch assemblage zones. Assemblage zones I-II occur in the lower and middle parts of the Member C of the Mila Formation and suggest Early-mid Middle Cambrian; assemblages zones III-IV appears in the upper part of the Member C of the Mila Formation and the lower part of Ilebeyk Formation and encompass latest Middle and earliest Late Cambrian; acritarch assemblage zones V-IX occur in the middle and upper parts of the Ilebeyk Formation and characterize Late Cambrian; finally, acritarch assemblage zone X appears in the basal part of the Zardkuh Formation and proves to have an early Tremadocian age. Amongst the Late Cambrian acritarch assemblages of Laurentia only the two cosmopolitan species of *Timofeevia phosphoritica* and *Vulcanisphaera turbata* are shared with coeval strata in the High Zagros Mountains. Iranian acritarch assemblages show a marked Gondwanan paleobiogeographical affinity, share a high proportion of taxa with typical Baltican and North Africa–Gondwanan assemblages, and are different from known Laurentian microphytoplankton suites. These results are in general agreement with paleogeographical models that place Avalonia, Baltica, and the North African part of Gondwana, at relatively high southern paleolatitudes, whereas Laurentia occupies a sub-equatorial position. Four new acritarch species, namely *Leiosphaeridia iranense*, *Navifusa reticulata*, *Ooidium zagrosensis*, and *Veryhachium ilebeykensis* are described.

Keywords: Acritarch biozonation; Middle-Late Cambrian; Mila Formation; Ilebeyk Formation; High Zagros Mountains.

Introduction

The biostratigraphic zonation of the Cambrian in different paleocontinents is based mainly on trilobites. The major divisions are based on a succession of *Paradoxides* trilobites with subdivisions mostly

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provided, where possible by olenids and agnostids (e.g., in Baltica and Avalonia). In northern Gondwana, the divisions are based mainly on a succession of paradoxidid and solenopleuridid trilobites [17]. In the current Cambrian subdivisions, the Middle Cambrian is equivalent to the undefined Cambrian Series 3 [32]. The base of Series 3 has not been defined, although the proposed limit first appearance datum (FAD) of *Ovatoryctocara granulata* and of *Oryctocephalus indicus* approximately coincides with the classic Lower-Middle Cambrian boundary, and the top is defined as the lower boundary of the Furongian Series. In the Late Cambrian, the major divisions are also based on the succession of trilobites with subdivisions mostly provided from the Late Cambrian trilobite zonation at Manuels Rivers and Random Island, eastern Newfoundland, Canada [20]. The Cambrian paleogeographic position of the Iranian Platform is also uncertain since paleomagnetic data are not available in this area, and macro-paleontological data are still scarce or not adequately discussed in terms of taxonomic and paleogeographic significance [14]. A certain consensus seems to exist that Iran was part of the Gondwana paleocontinent at some time during the Paleozoic [11, 13, 39]. The few available old reports on Cambrian faunas of the study area [16] refer to a clear non-European faunal affinity, in fact, excluding a peri-Gondwanan Cambrian paleoposition for the Iranian terrane. Acritarchs are a polyphyletic planktonic organic-walled cyst and provide further data for determining Cambrian paleobiogeography. They have proven to be a useful compliment to trilobites in correlation across Avalonia, Baltica, and northern Gondwana. Acritarchs generally can be extracted in great numbers from any fine-grained siliciclastic rock that was deposited under normal marine conditions. They provide a means for detailed sampling, and locally may provide the only fossil age constraints. The Cambrian acritarch zonations have been proposed for Gondwana [14, 28, 43, 47]; for Avalonia [20, 21, 28, 29, 31, 33, 42] and for Baltica [24, 49, 51]. Molyneux et al. [27] established a correlation between the acritarch

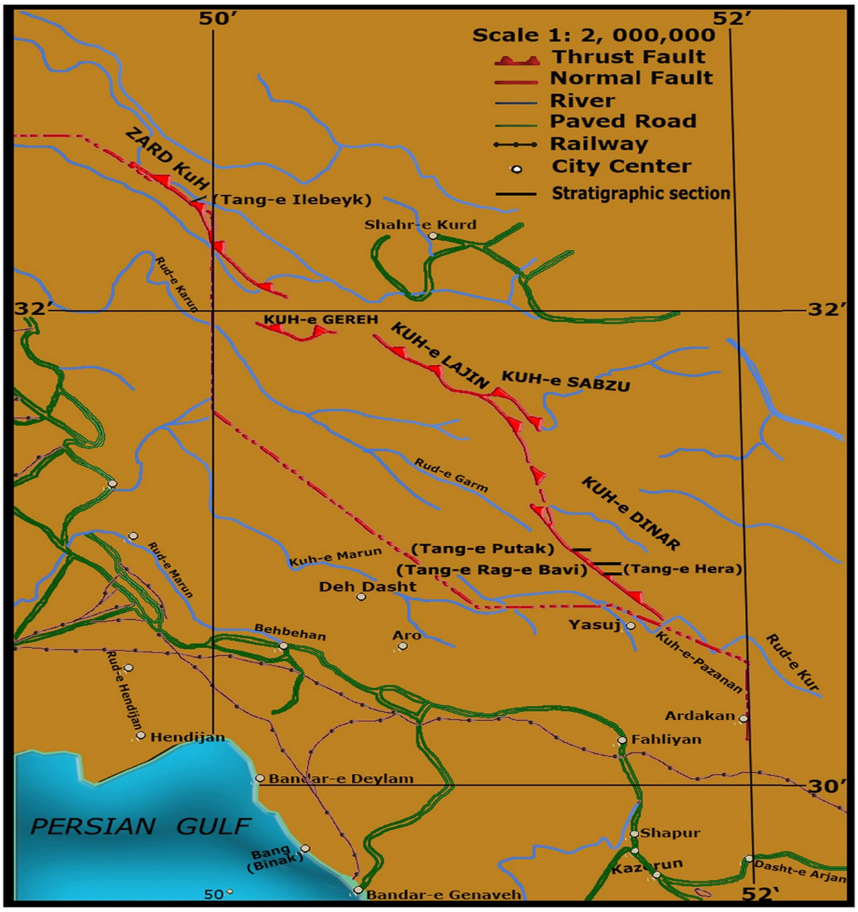

Figure 1. Location map of study area and connection to adjacent cities.

zones of Baltica and Avalonia. They found two problems from the use of these biozones in Middle Cambrian chronostratigraphy: a) in Avalonia and Baltica, the Cambrian Series 3 stratigraphic record includes significant hiatuses [29]; and b) there are identification problems with some of the diagnostic acritarch species, e.g., *Cristallinium* and *Timofeevia* [29]. In Iran, a primarily Cambrian acritarch biozonation was established on the Ilebeyk Formation, in the Chal-i Sheh area, the High Zagros Mountain, southern Iran [11] and the Cambrian succession of Kuh-e Kharbash, in Deh-e Molla, Eastern Alborz Mountain, northern Iran [13]. An important acritarch biostratigraphy was recently established on the Cambrian succession (Mila and Ilebeyk formations) and the lowermost part of the Zardkuh Formation (Early Ordovician), the High Zagros Mountains, southern Iran [14]. This study has proven that acritarch taxa are a useful compliment to trilobites in correlation across Avalonia, Baltica, and northern Gondwana. In the High Zagros Mountains, there is an almost complete Cambrian outcrop in the stratotype of the Ilebeyk Formation and other adjacent localities (Fig. 1), comprising siliciclastic rocks of non-marine (Zaigun and Lalun formations) and marine deposits (Mila and Ilebeyk formations). The Mila Formation is well represented in Kuhe-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 measured 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 Kuhe-Garreh. The top of this member is covered by scree and soil while being faulted at the base [40]. 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). 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. The upper 82.2 m of Member C is characterized by Upper

Cambrian fauna [40]. 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 [40]. 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. Based on this trilobite fauna, the formation has been assigned to the Upper Cambrian [40]. 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. The trilobite fauna characteristic of the lower member contains the species *Dikelokephalin*a cf. *D. asiatica* which indicates an Early Ordovician age [40]. 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 lower member of the Zardkuh Formation [40]. Because these sequences have favorable lithologies for palynological investigations, the Cambrian rock units of the study area were sampled several times for precise acritarch biozonation (Fig. 3). Thus, the present study aimed to: i) analyze Middle-Late Cambrian deposits in the Zagros Mountains; ii) establish acritarch regional correlations; iii) determine the age relationships of the Mila and Ilebeyk formations using acritarchs from the study area; and iv) verify paleogeographic position of the study area (e.g., Gondwana, Avalonia, Siberia, and Baltic and Laurentia paleoplates) during the Cambrian period.

Materials and Methods

A total of 44 surface samples were collected from the whole stratigraphic interval of the Cambrian succession (Zaigun, Lalun, Mila, Ilebeyk and the lowermost part of the Zardkuh formations). The collected samples are designated herein by code numbers preceded by prefixes MG-01 to MG-22 and MHS-01 to MHS-22 (Fig. 3). Palynomorphs were extracted from shales, siltstones, fine-grained sandstones and argillaceous limestones, using standard palynological procedures, which included the removal of carbonates and silicates by hydrochloric and hydrofluoric acids and density separation of the organic residues in 30 ml of a saturated zinc bromide solution. The organic residues were then sieved through 15 μm nylon mesh sieves. Extensive scanning electron and transmitted light microscopic examinations were applied on selected specimens during the study. All samples proved to be palyniferous

Table 1. Quantitative distribution of the different groups of palynomorphs throughout the Middle-Late Cambrian (Mila and Ilebeyk formations) and earliest lower Ordovician (Tremadoc).

List of encountered acritarch taxa in present study		MG-1	MG-2	MG-3	MG-4	MG-5	MG-6	MG-7	MG-8	MG-9	MG-10	MG-11	MG-12	MG-13	MG-14	MG-15	MG-16	MG-17	MG-18	MG-19	MG-20	Total
1	*Cristallinium ovillense*	3	5	10	5	3																26
2	*Comasphaeridium silesiense*	1	20	100	25	9																155
3	*Retisphaeridium dichamerum*	1	8	10	12	15																46
4	*Eliasum hutchinsonii*	38	15	15	16	10																94
5	*Leiosphaeridia crassa*	10	33	50	10	15	75	10	20													223
6	*Siphonophycus typicum*	20	35	300	210	2	30	10	9													616
7	*Timofeevia lancarae*	65	85	100	67	540	620	803	21													2301
8	*Vulcanisphaera cantabrica*					2310	3400	220	100													6030
9	*Adara alea*					13	8	3	1													25
10	*Protoleiosphaeridium rugulosum*					7	15	1	2													25
11	*Stelliferidium distinctum*					15	12	9	1													37
12	*Cristallinium cambriense*					70	80	15	4	36	20											225
13	*Symplassosphaeridium cambriense*					1	5	12	5	12	14	24	20	56								149
14	*Retisphaeridium ovillense*					8	10	14	15	11												58
15	*Leiofusa stoumonensis*								10	18	2	5	1	2								38
16	*Veryhachium ilebykensis* n.sp.								20	10	4	1	4									39
17	*Timofeevia phosphoritica*								1	2	2	5	4	5	4	2	3					28
18	*Trunculumarium revinium*								2	1	3	10	18	5		18	2					59
19	*Timofeevia pentagonalis*								10	2	40	50	42									144
20	*Vulcanisphaera turbata*								30	400	200	100	50	40	10	300	80					1210
21	*Cymatiogalea virgulata*									70	6	10	20									106
22	*Cymatiogalea aspergillum*									1	2	25	6	6								40
23	*Lusatia dendroidea*									175	47	65	8	10	2							307
24	*Actinotodissus archasii*									60	21	75	120	110	100	70	16	40	12	1		625
25	*Ninadiacrodium caudatum*									40	5	35	32	64	44	80	100		16	32		448
26	*Leiosphaeridia iranense* n.sp.									1	2	25	5	14	5	10	11	9	20	1		103
27	*Vulcanisphaera cirrita*									7	37	5	1	1	5	3	2	5	1	1		68
28	*Vulcanisphaera africana*									10	50	40	10	8	10	14	4	4	2	8		160
29	*Stelliferidium cortinulamorphum*									10	5	250	124	50	30	60	75	20	5	15		644
30	*Ninadiacrodium dumontii*									45	78	15	5	50	20	20	2					235
31	*Dasydiacrodium obsonum*									35	23	55	28	8	16	8	16					189
32	*Baltisphaeridium crinitum*									20	5	5	8	3	3	1	1					46
33	*Impluviculus multitriangularis*												2	8	1	2						13
34	*Navifusa punctata*												2	1		1	1					5
35	*Polygonium* sp.												1	9	12	6	2					30
36	*Navifusa reticulata* n. sp												2	3	5	3	2					15
37	*Orthosphaeridium extensum*													20	6	1	4					31
38	*Ladogella saharica*													2	4	3	1					10
39	*Veryhacium mutabile*													15	12	10	12					49
40	*Acanthodiacrodium ubuii*													14	10	12	3					39
41	*Elenia armillata*															2	1	1				4
42	*Ladogella rommelaerei*															8	10	144				162
43	*Ladogella rotundiformis*															30	16	80	40	180		346
44	*Striatotheca randomensis*															2	1	2	1	1		7
45	*Veryhachium lairdii*															1	4	1	2			8
46	*Vulcanisphaera tuberata*															10	6	20	12	24		72
47	*Dasydiacrodium angulare*																	80	10	2		92
48	*Cristallinium randomense*																	24	31	1		56
49	*Ladogella intermedia*																		11	20		31
50	*Ooidium clavigerum*																		22	5		27
51	*Ooidium rossicum*																		10	5		15
52	*Ooidium zagrosensis* n. sp.																		16	10		26
53	*Claxiella izhoriensis*																		15	10		25
54	*Cymatiogalea gorkae*																		4	3		7
55	*Acanthodiacrodium angustum*																			10	1	11
56	*Vulcanisphaera britanica*																			10	24	34
		138	201	585	345	3018	4255	1097	251	966	566	800	513	504	299	677	375	430	230	339	25	15614

and yielded well-preserved and abundant palynomorphs with dominant acritarch assemblages, algal clusters, empty sheaths of cyanobacteria, and chitinous graptolite remains in Member C of the Mila, Ilebeyk and lowermost part of the Zardkuh formations. It is worth mentioning here that benthic cyanobacteria (e.g., *Siphonophycus typicum*), which occur as empty sheaths, were extremely abundant in samples of the basal part of Member C of the Mila Formation (MG-01 to MG-02), and their abundance decreases upwards (Table 1). Furthermore, the chitinous graptolite remains are restricted only to sample MG-02 of Member C of the

Mila Formation, which may correspond to the basal part of the Middle Cambrian (Table 1). The observed acritarch taxa ranged from yellow to orange-brown, indicating an intermediate degree of thermal maturity in this part of the High Zagros Mountains. All samples and slides related to this study are deposited in the Iranian Natural History Museum, Department of Organization Environment (DOE) under accessions MG-01 to MG-22 and MHS-99 to MHS-120 (Fig. 3).

Acritarch biostratigraphy

The biostratigraphic study of the Mila and Ilebeyk formations, and lowermost Zardkuh Formation is based on detailed sampling for acritarchs from the type section of the Ilebeyk Formation, providing information on the first appearance datum (FAD) and last appearance datum (LAD) of diagnostic taxa. The study section is in Tang-e Ilebeyk, which its base is located at 49°56'10"E and 32°27'34"N and the top at 49°56'55"E and 32°27'52"N. Member C of the Mila Formation and the Ilebeyk, Zardkuh and Seyahou formations are well exposed in the Tang-e Ilebeyk, on the southern flank of Zardkuh Mountain (Fig. 2). Member C has a sharp contact with Member B and begins with nodular rubbly

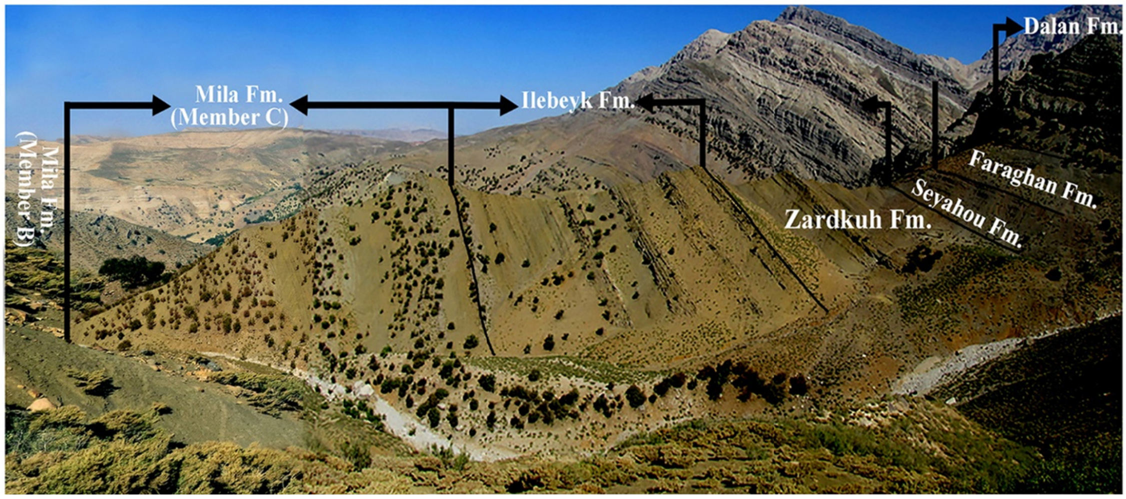

Figure 2. Outcop of Paleozoic rock units (Mila, Ilebeyk, Zardkuh, Seyahou, Faraghan and Dalan formations) in Tang-e Ilebeyk, Zardkuh Mountain, the High Zagros Mountains, southern Iran.

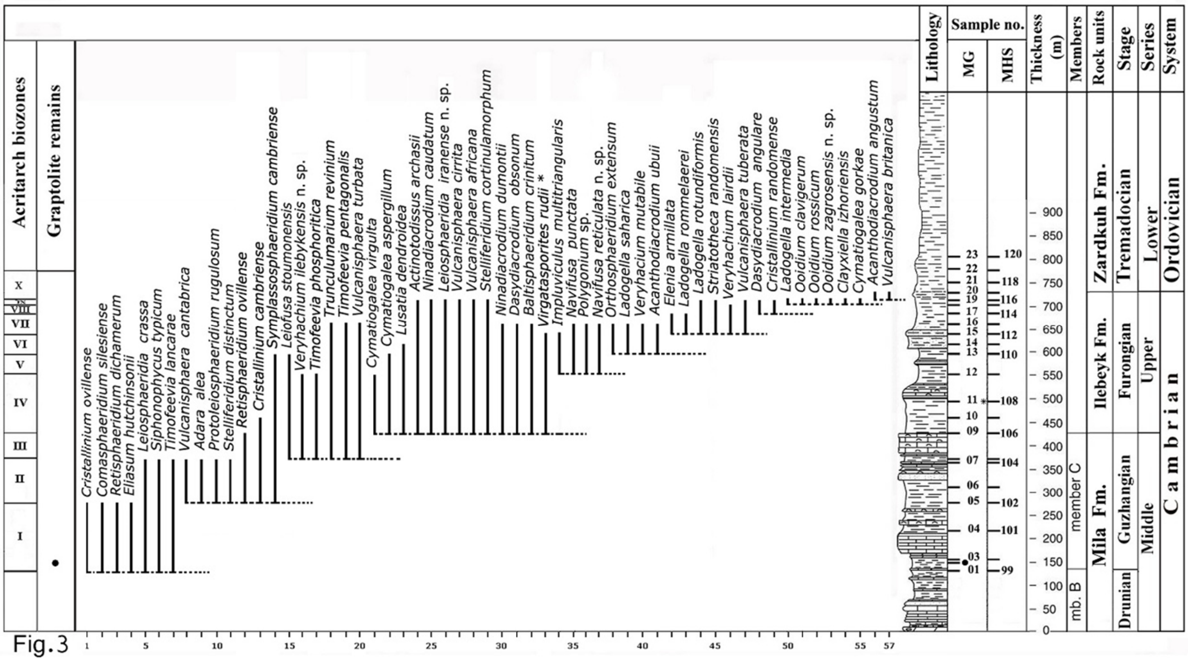

Figure 3. Stratigraphical distribution of acritarch taxa from the Cambrian (Mila and Ilebeyk formations) and lowermost Ordovician strata (Zardkuh Formation) in the Zagros Mountains, southern Iran.

limestone at the base and increases in shale and mudstone content up-section. A total of 56 acritarch species (28 genera), one cyanobacteria species (*Siphonophycus typicum*), and one cryptospore species (e.g., *Virgatasporites rudii*) were identified. The distributions of the species are shown in Figure 3. Scanning electron and transmitted light microphotographs were prepared for selected palynomorphs and presented in Plates I-VII. The observed acritarch taxa were arranged in ten biozones. These acritarch assemblage zones and their biostratigraphic ages are discussed below in ascending stratigraphic order.

1. Acritarch assemblage zone I

This assemblage zone is marked by the first appearance datum (FAD) of acritarch and cyanophyte taxa, namely *Cristallinium ovillense, Comasphaeridium silesiense, Retisphaeridium dichamerum, Eliasum hutchinsonii, Timofeevia lancarae, Leiosphaeridia crassa* and *Siphonophycus typicum*, which some of them extend through the succeeding zone (Fig. 3, MG-01 to MG-05). This assemblage zone extends within a 135 m thickness in Member C of the Mila Formation. This Member consists of interbedded olive gray shales and thin to medium bedded nodular limestones, which contain trilobites, and brachiopods in some horizons (Fig. 3). Amongst the collected surface samples from this interval, the sample MG-02 contains graptolites, whose chitinous remains are illustrated in Plate VI, M. Amongst the acritarch taxa, *Cristallinium ovillense, Comasphaeridium silesiense, Retisphaeridium dichamerum* and *Eliasum hutchinsonii* are restricted to this assemblage zone and the others extend into the succeeding zone. Previously, these acritarch taxa have only been recorded from the Middle Cambrian in southeast Turkey [10], Newfoundland of Canada [20, 21], Morocco [43], Norway [52], Poland [24], Belgium [44]; Russia [51], Libya [47, 48], Iran [14], Ireland [42] and Spain [28]. The majority of organic walled microphytoplankton taxa are common in the Middle Cambrian, but *Leiosphaeridia crassa* and *Siphonophycus typicum* are long ranging taxa that extend from the Neoproterozoic to the Middle Cambrian [25]. This informal acritarch zone is attributed to the Middle Cambrian and probably correlates, at least in part, with acritarch zone AO of Middle and Upper Cambrian acritarch and trilobite zonation at Manuels Rivers and Random Island, eastern Newfoundland [21], the IMC2 acritarch biozone of acritarch assemblages from the Oville and Barrios Formations, northern Spain [28] and the SK1 acritarch assemblage of Russia [34, 51] (Table 3 this paper). It follows that Members A and B of the Mila Formation (barren in both macrofauna and microflora) should be considered at least Middle Cambrian or older, based on their stratigraphic position. This is in agreement with what was previously proposed [40].

2. Acritarch assemblage zone II

This assemblage zone is characterized by the first appearance datum (FAD) of the acritarch taxa: *Vulcanisphaera cantabrica, Adara alea, Protoleiosphaeridium rugulosum, Retisphaeridium ovillense, Cristallinium cambriense, Symplassosphaeridium cambriense,* and *Stelliferidium distinctum* (Table 1; Fig. 3, MG-05 to MG-08). Some characteristic taxa of assemblage zone 1 also range into the lower part of this assemblage zone, but gradually disappear before its top. This assemblage zone includes 95 m thickness of Member C of the Mila Formation. It consists of alternations of olive-gray shales, sandstones and thin to medium-bedded, nodular limestones (Figs. 2, 3). This part of Member C contains a typical Middle Cambrian skeletonized, invertebrate fauna bearing the trilobites *Dorypygella* sp., *Solenoparia* sp., *Nisusia* sp., *Paradoxides* sp., *Obolus* sp.; brachiopod *Lingulella* sp., and the hyolitid *Circotheca* sp. [40]. Amongst the acritarch taxa *Vulcanisphaera cantabrica, Adara alea, Protoleiosphaeridium rugulosum* and *Stelliferidium distinctum* are confined to this assemblage zone and the other species continue into the succeeding zones. *Vulcanisphaera cantabrica* is extremely abundant (Table 1) and was originally recorded from the Middle Cambrian base of the Genestosa Member (Oville Formation) from the Cantabrian Mountains, northern Spain, and restricted to the IMC2 acritarch assemblage zone from the Oville and Barrios Formations, northern Spain [28]. *Adara alea* is another Middle Cambrian taxon, except for record of the lower Upper Cambrian acritarchs from Upper Silesia, Poland [24], this species has recorded from Middle Cambrian of southeast Turkey [10], Canada [21, 31], Russia [34, 51]; North Africa [47, 48], northwest Wales [9, 33, 55], Ireland [42], Algerian Sahara [45] and northern Spain [28]. *Protoleiosphaeridium rugulosum* is restricted to Middle Cambrian, the Oville and Barrios formations, northern Spain [28]. The other acritarch taxa (*Cristallinium cambriense, Symplassosphaeridium cambriense,* and *Stelliferidium dis*tinctum) are long ranging (Middle Cambrian–Early Ordovician) and are cosmopolitan, recorded from England [33, 35], Morocco [43], Newfoundland [21, 31], Sweden [8], SW Spain [22], Russia [51], western Libya and southern Tunisia [47], northwest Wales [9, 33, 55], and northern Spain [1]. It is probably correlatable, at least in part, with the A1

Table 2. Paleogeographical distribution of the stratigraphically significant acritarchs from the Mila and Ilebeyk formations in the High Zagros Mountains, southern Iran (for comparison, locality, a selection of references is used): 1. Sosinsk Formation, southern Turkey [10]; 2. Mila and Ilebeyk formations, the High Zagros Mountains, Iran [14]; 3. Oville and Barrios formations, northern Spain [28]; 4. Túnel Ordovícico del Fabar, Cantabrian zone, northern Spain [1], Playón and Umbria Pipeta formations, southern Spain [22]; 5. Solanas Formation, [7]; 6. MacLean Brook Formation, Nova Scotia [29]; 7. Manuels River and Elliot Cove formations, Newfoundland [20, 21]; 8. Booley Bay Formation, Ireland [42]; 9. Maentwrog and Ffestiniog Flags formations, Wales [55]; 10. Shoot Rough Road Shales, the Comley area, Shropshire, England [42]; 11. Revin Group, Belgium, Vanguestaine [44]; 12. Silesia, Poland, [24]; 13. Various formations in Russia [51]; 14. Kistedal Formation, northern Norway, [52]; 15.The United States, Bonneterre and Davis formations [54].

Number	Acritarch taxa in present study	Middle Cambrian																					
		Gondwana				Amorica				Avalonia					Baltica							Siberia	Laurentia
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	*C. ovillense*	+	+					+		+	+	+			+	+			+	+	+		
2	*C. silesiense*	+				+	+			+		+				+	+						
3	*R. dichameru*	+			+	+				+	+	+	+	+	+		+					+	+
4	*E. hutchinsonii*										+	+											
5	*L. crassa*														+	+							
6	*S. typicum*														+	+							
7	*T. lancarae*	+	+			+		+	+	+		+			+			+		+	+	+	+
8	*V. cantabrica*					+																	
9	*A. alea*	+	+			+			+	+	+	+	+	+	+		+		+	+			
10	*P. rugulosum*					+																	
11	*S. distinctum*					+		+			+		+										
12	*R. ovillense*		+			+				+			+		+						+		
13	*C. cambriens*	+	+			+	+		+	+	+	+	+		+		+	+	+	+	+	+	
14	*S.cambriense*		+		+	+		+	+		+												
15	*L. stoumonensis*																						
16	*V. ilebeykensis* n.sp.																						
17	*T. phosphoritica*																						
18	*T. revinium*																						
19	*T. pentagonalis*																						
20	*V. turbata*																						
21	*C. virgulata*																						
22	*C. aspergillum*																						
23	*L. dendroidea*																						
24	*A. archasii*																						
25	*N. caudatum*																						
26	*L. iranense* n.sp.																						
27	*V. cirrita*																						
28	*V. africana*																						
29	*S. cortinulamorphum*																						
30	*N. dumontii*																						
31	*D. obsonum*																						
32	*B. crinitum*																						
33	*I. multitriangularis*																						
34	*N. punctata*																						
35	*Polygonium* sp.																						
36	*N. reticulata* n. sp.																						
37	*O. extensum*																						
38	*L. saharica*																						
39	*V. mutabile*																						
40	*A. ubuii*																						
41	*E. armillata*																						
42	*L. rommelaerei*																						
43	*L. rotundiformis*																						
44	*S. randomensis*																						
45	*V. lairdii*																						
46	*V. tuberata*																						
47	*D. angulare*																						
48	*C. randomense*																						
49	*L. intermedia*																						
50	*O. clavigerum*																						
51	*O. rossicum*																						
52	*O. zagrosensis* n. sp.																						
53	*C. izhoriensis*																						
54	*C. gorkae*																						
55	*A. angustum*																						
56	*V. britanica*																						
	CS=2V/a+b	3.96%				28.5%				35%					23.40%							8.89%	

Number	Acritarch taxa in present study	Upper Cambrian																					
		Gondwana				Amorica				Avalonia					Baltica							Siberia	Laurentia
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	*C. ovillense*																						
2	*C. silesiense*																						
3	*R. dichameru*																						
4	*E. hutchinsonii*																						
5	*L. crassa*																						
6	*S. typicum*																						
7	*T. lancarae*																						
8	*V. cantabrica*																						
9	*A. alea*																						
10	*P. rugulosum*																						
11	*S. distinctum*																						
12	*R. ovillense*																						
13	*C. cambriens*																						
14	*S.cambriense*																						
15	*L. stoumonensis*	+			+			+		+	+		+	+	+	+			+	+	+	+	
16	*V. ilebeykensis* n.sp.										+												
17	*T. phosphoritica*	+					+	+		+	+	+	+	+			+		+	+	+		+
18	*T. revinium*	+				+					+		+	+			+		+	+	+		
19	*T. pentagonalis*	+			+					+		+	+	+	+		+		+	+	+	+	
20	*V. turbata*	+			+	+		+		+	+	+	+	+	+	+		+	+	+	+	+	+
21	*C. virgulata*	+				+				+	+		+	+							+	+	
22	*C. aspergillum*				+					+	+		+	+			+						
23	*L. dendroidea*	+			+	+					+			+		+	+		+	+		+	
24	*A. archasii*	+			+	+					+		+	+			+					+	
25	*N. caudatum*	+			+	+	+			+	+		+	+				+	+	+			
26	*L. iranense* n.sp.																						
27	*V. cirrita*				+							+	+			+							
28	*V. africana*	+	+		+	+	+	+			+		+	+				+	+	+	+		
29	*S. cortinulamorphum*	+											+					+					
30	*N. dumontii*	+			+	+		+		+	+		+	+		+	+	+		+		+	
31	*D. obsonum*	+			+	+							+			+						+	
32	*B. crinitum*										+							+	+	+			
33	*I. multitriangularis*	+			+	+					+				+			+	+	+		+	
34	*N. punctata*					+																	+
35	*Polygonium* sp.	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
36	*N. reticulata* n. sp.																						
37	*O. extensum*				+						+		+	+					+	+			
38	*L. saharica*	+																					
39	*V. mutabile*				+						+						+						
40	*A. ubuii*	+			+						+		+								+		
41	*E. armillata*										+				+			+	+	+			
42	*L. rommelaerei*	+									+		+	+			+	+					
43	*L. rotundiformis*	+									+			+	+		+		+	+			
44	*S. randomensis*										+												
45	*V. lairdii*								+		+		+										
46	*V. tuberata*	+									+		+										
47	*D. angulare*																					+	
48	*C. randomense*	+			+					+	+		+	+	+		+	+			+	+	
49	*L. intermedia*										+												
50	*O. clavigerum*										+												
51	*O. rossicum*	+			+						+			+				+	+	+	+		
52	*O. zagrosensis* n. sp.																						
53	*C. izhoriensis*										+				+	+	+		+	+			
54	*C. gorkae*										+												
55	*A. angustum*																						
56	*V. britanica*																						
	CS=2V/a+b	20%				17.86%				38.62%					14.51%							8.93%	

Number	Acritarch taxa in present study	earliest Ordovician (Tremadoc)																					
		Gondwana				Amorica				Avalonia					Baltica							Siberia	Laurentia
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	*C. ovillense*																						
2	*C. silesiense*																						
3	*R. dichameru*																						
4	*E. hutchinsonii*																						
5	*L. crassa*																						
6	*S. typicum*																						
7	*T. lancarae*																						
8	*V. cantabrica*																						
9	*A. alea*																						
10	*P. rugulosum*																						
11	*S. distinctum*																						
12	*R. ovillense*																						
13	*C. cambriens*																						
14	*S.cambriense*																						
15	*L. stoumonensis*																						
16	*V. ilebeykensis* n.sp.																						
17	*T. phosphoritica*																						
18	*T. revinium*																						
19	*T. pentagonalis*																						
20	*V. turbata*																						
21	*C. virgulata*																						
22	*C. aspergillum*																						
23	*L. dendroidea*																						
24	*A. archasii*																						
25	*N. caudatum*																						
26	*L. iranense* n.sp.																						
27	*V. cirrita*																						
28	*V. africana*																						
29	*S. cortinulamorphum*																						
30	*N. dumontii*																						
31	*D. obsonum*																						
32	*B. crinitum*																						
33	*I. multitriangularis*																						
34	*N. punctata*																						
35	*Polygonium* sp.																						
36	*N. reticulata* n. sp.																						
37	*O. extensum*																						
38	*L. saharica*																						
39	*V. mutabile*																						
40	*A. ubuii*																						
41	*E. armillata*																						
42	*L. rommelaerei*																						
43	*L. rotundiformis*																						
44	*S. randomensis*																						
45	*V. lairdii*																						
46	*V. tuberata*																						
47	*D. angulare*																						
48	*C. randomense*																						
49	*L. intermedia*																						
50	*O. clavigerum*																						
51	*O. rossicum*																						
52	*O. zagrosensis* n. sp.																						
53	*C. izhoriensis*																						
54	*C. gorkae*																						
55	*A. angustum*	+			+	+	+		+		+		+	+				+	+	+			
56	*V. britanica*	+			+								+		+	+							
	CS=2V/a+b	71.42%				0%				0%					28.57%							0%	

acritarch zone of Manuels Rivers and Random Island, eastern Newfoundland [21], the IMC3 acritarch biozone of from the Oville and Barrios formations, northern Spain [28] and lower part of the Sk2A acritarch biozone of Russian workers [49, 51] (See Table 3 in this study).

Table 3. Chronostratigraphic correlation of described Iranian acritarch assemblages (Mila and Ilebeyk formations) with macrofaunistic and microfloristic coeval zones in the other parts of the World.

AGE	MACROFOSSIL ZONATIN	ACRITARCH ZONATION					present work
	(Martin & Dean, 1988)	Volkova & Kir'janov, 1995; Raevskaya, 2005	Vanguestaine' & Van Looy, 1983	Palacios, 2015	Martin & Dean, 1988; Parsons & Anderson, 2000	Vecoli, 1999; Martin & Dean, 1988	
earliest Ordovician	*Flabelliformis* s.l.				RA 10b	*A. angustum-V. britannica*	Zone X
LATE CAMBRIAN	*Acerocare* (p.p.)				RA 10a		Zone IX
					RA 9		
					RA 8		Zone VIII
					RA 7b		Zone VII
					RA 7a		
	Peltura	Vk 4B			RA 6b		Zone VI
			A. rommelaeri - *V. africana*		RA 6a	? A5b	Zone V
		VK 4A			A 5a	A5a	
	Leptoplastus	VK 3			A 4	A4	Zone IV
	P. spinulosa	VK 2B	*T. revinium* - *V. dumontii*		A 3b	A3	Zone III
		VK 2A			A 3a		
	Olenus	VK 1B	*T. pentagonalis* - *V. turbata*		Upper A 2	Tp-Vt Zone (= Upper A2)	
	A. pisiformis	VK 1					
MIDDLE CAMBRIAN	*P. forchhammeri*	SK 2	*C cambriense* - *Eliasum/Timofeevia*	IMC 6	Lower A 2	Lower A2	Zone II
		SK 2A		IMC 5			
	P. paradoxissimus: *P. punctuosus*	SK 1		IMC 4	A 1	? *Adara alea Zone*	
	H. parvifrons			IMC 3			
	T. tissus/ P. atavus			IMC 2	A O	*R.terranovana Zone*	Zone I
	P. gibbus/Hartella	?		IMC 1	A 0- 1	Ao-1	
		KB	*A. umbonulata* - *S. compressa*	?			

3. Acritarch assemblage zone III

This assemblage zone is marked by the first appearance datum (FAD) of the acritarch taxa *Leiofusa stoumonensis, Vulcanisphaera turbata, Timofeevia pentagonalis, Timofeevia phosphoritica, Trunculumarium revinium* and *Veryhachium ilebeykensis* n. sp., which all continue into succeeding zones (See Table 1; Fig. 3, MG-08 to MG-13). This assemblage zone occurs in 55 m thickness of the upper part of Member C of the Mila Formation and lowermost part of Ilebeyk Formation. It consists of interbedded olive-gray shales and thick-massive bedded limestones. This interval contains an abundant upper Cambrian skeletonized invertebrate fauna including: *Billingsella* sp., *Billingsella* cf. *B. rhomba*, *Eurudagnostus* sp., *Agnostus* sp., *Coosina* sp., *Loganellus* sp., *Labiostria* sp., and *Circotheca* sp. aff. *C. jamsella*. Amongst the acritarch taxa, *Leiofusa stoumonensis, Vulcanisphaera turbata* and *Trunculumarium revinium* are characteristic of the early Late Cambrian. Previously, these acritarch taxa have been recorded from the Late Cambrian of Belgium [44], Norway [52], Canada [20, 21, 31], Italy

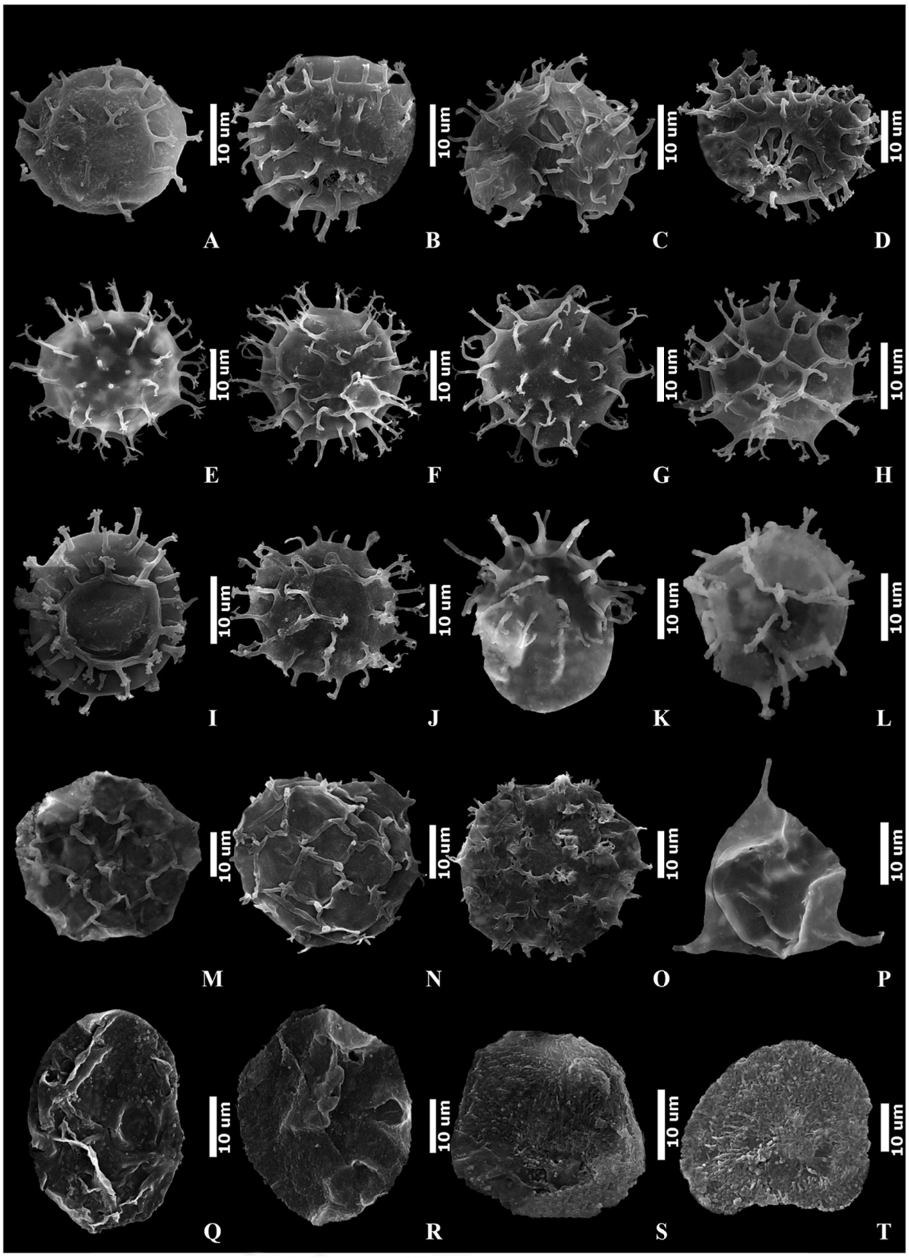

Plate I

Plate I. A, B, C, D, I. *Stelliferidium cortinulamorphum* [33]; E, F, G. *Stelliferidium* cf. *distinctum* [35]; H. *Timofeevia pentagonalis* [44]**;** J. *Timofeevia phosphoritica* [44]; K. *Trunculumarium revinium* [44]; L. *Cymatiogalea virgulata* [21]; M. *Retisphaeridium dichamerum* [44]; N, O. *Vulcanisphaera cantabrica* [28]; P. *Veryhachium mutabile* [9]; Q, R. *Eliasum hutchinsonii* [21]; S, T. *Protoleiosphaeridium rugulosum* [28].

[7], Russia [27, 51], Libya and southern Tunisia [47], Belgium and France [38], England [9, 33, 55], northern Spain [28], southeast Poland and western Ukraine [15], Oman [26], Ireland [42] and Iran [14]. The other acritarch taxa (*Timofeevia pentagonalis* and *Timofeevia phosphoritica*) are long ranging species (Middle Cambrian–Early Ordovician) and are cosmopolitan, recorded from southwest Spain [22], western Libya [47] and Poland [24]. This assemblage zone is probably correlatable, at least in part, with the upper A2 to A3 acritarch zones of Canada [21, 31], the VK I to VK 2B acritarch zone of Russian workers [27, 49, 51], and *V. turbata -T. phosphoritica* to *N. dumontii -T. revinium* assemblage zones of Newfoundland in Canada [43],

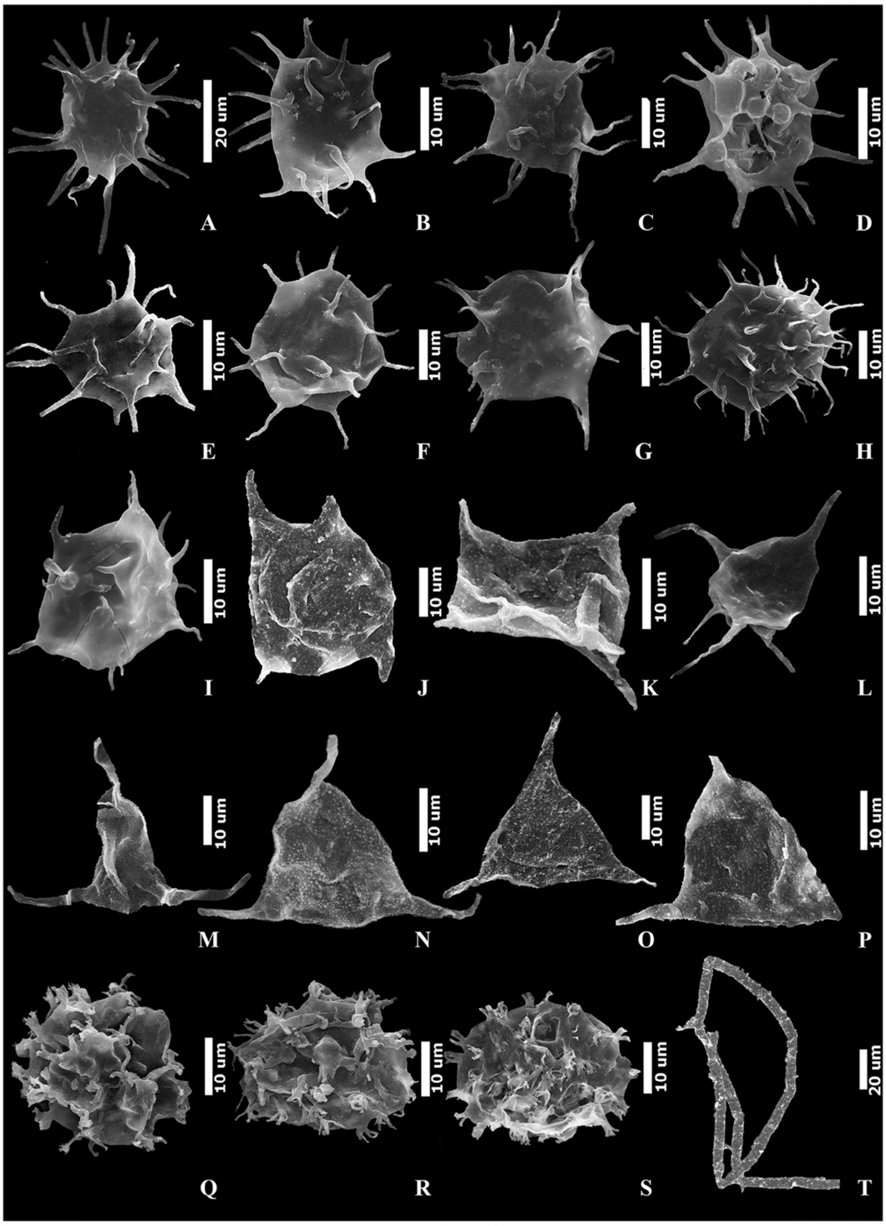

Plate II

Plate II. A, B, C, D. *Actinotodissus achrasii* [33]; E. *Polygonium* sp.; F. *Acanthodiacrodium ubuii* [20]. G, H. *Dasydiacrodium obsonum* [21]; I, L. *Ninadiacrodium caudatum* [34]; M, N, O, P. *Ninadiacrodium dumontii* [34]; J, K. *Ninadiacrodium* sp.; Q, R, S. *Vulcanisphaera turbata* [20]; T. *Siphonophycus typicum* [23].

Russia and Morocco, respectively (Table 3). The sudden appearance of *Veryhachium* (*Veryhachium lairdii* and *Veryhachium ilebeykensis*) is also a characteristic feature of this acritarch assemblage zone.

4. Acritarch assemblage zone IV

This assemblage zone is marked by the FAD of an acritarch assemblage and one cryptospore (*Virgatasporites rudii*). The this assemblge includes *Cymatiogalea virgulata, Cymatiogalea aspergillum, Lusatia dendroidea, Actinotodissus archasii (= Acanthodiacrodium archasii), Ninadiacrodium caudatum, Baltisphaeridium crinitum, Leiosphaeridia iranense n. sp., Vulcanisphaera cirrita, Vulcanisphaera africana, Stelliferidium cortinulamorphum, Ninadiacrodium dumontii,* and *Dasydiacrodium obsonum*. Most taxa in this assemblage range into the succeeding zones (See Table 1; Fig. 3, MG-09 to MG-

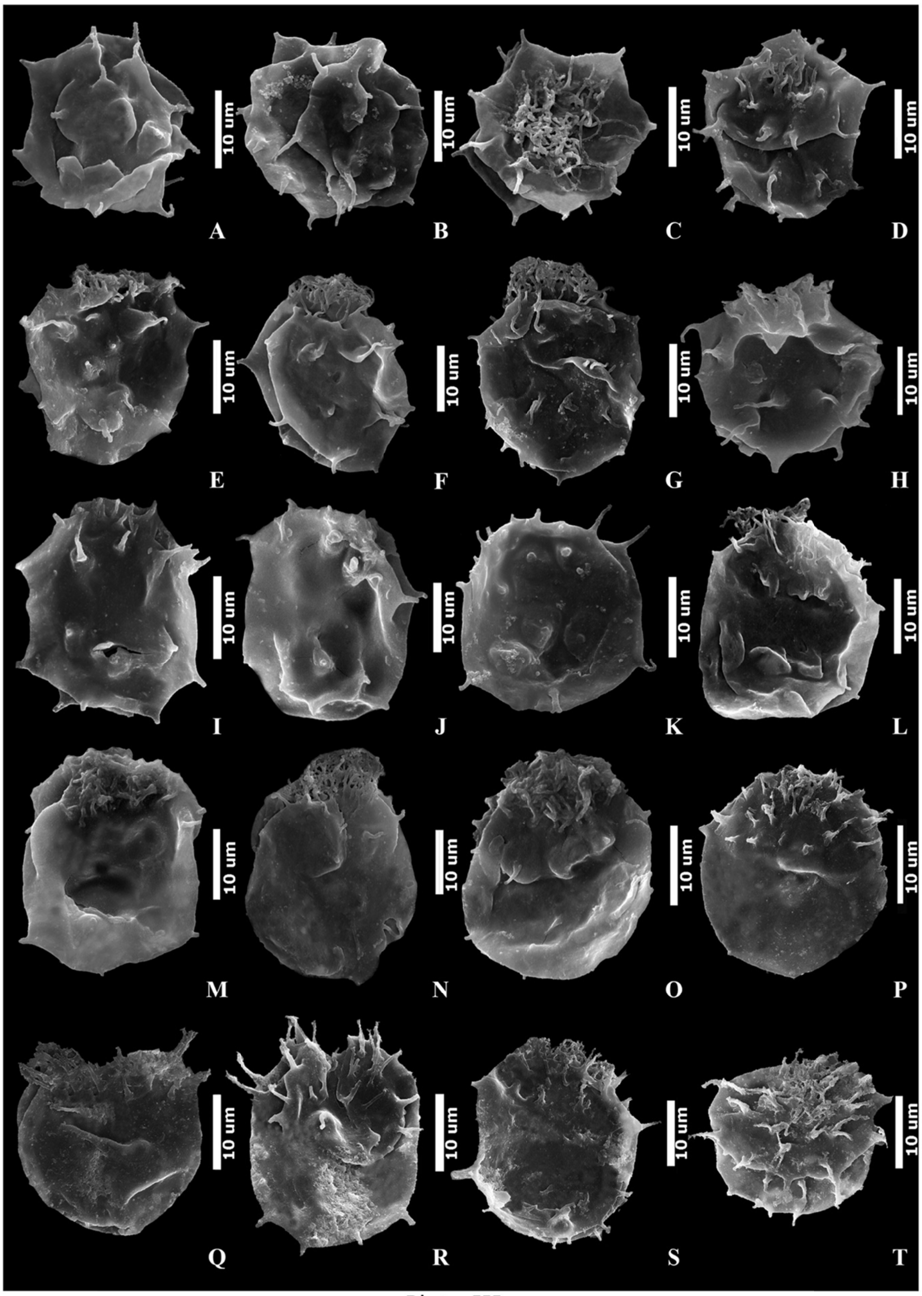

Plate III

Plate III. A, B. *Vulcanisphaera tuberata* [9]; C, D, E, F, G, H, T. *Ladogella intermedia* [31]; I, J, K. *Ladogella saharica* [46]; L, M, N, O. *Ooidium clavigerum* [31]; P. *Ooidium rossicum* [19]; Q. *Calyxiella izhoriensis* [31]; R, S. *Ladogella rommelaerei* [21].

19). This assemblage zone occurs in 122.5 m thickness of the Ilebeyk Formation. It consists of shales interbedded with fine-grained sandstones (Fig. 3). Trilobites have been collected from the uppermost 33.5 m of the 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 the trilobite fauna, the formation has been assigned to the upper Cambrian [40]. Amongst the acritarch taxa, *Lusatia dendroidea, Ninadiacrodium caudatum, Ninadiacrodium dumontii, Dasydiacrodium obsonum, Cymatiogalea aspergillum* and *Stelliferidium cortinulamorphum* are well documented from different paleogeographic regions in the Late Cambrian of Spain

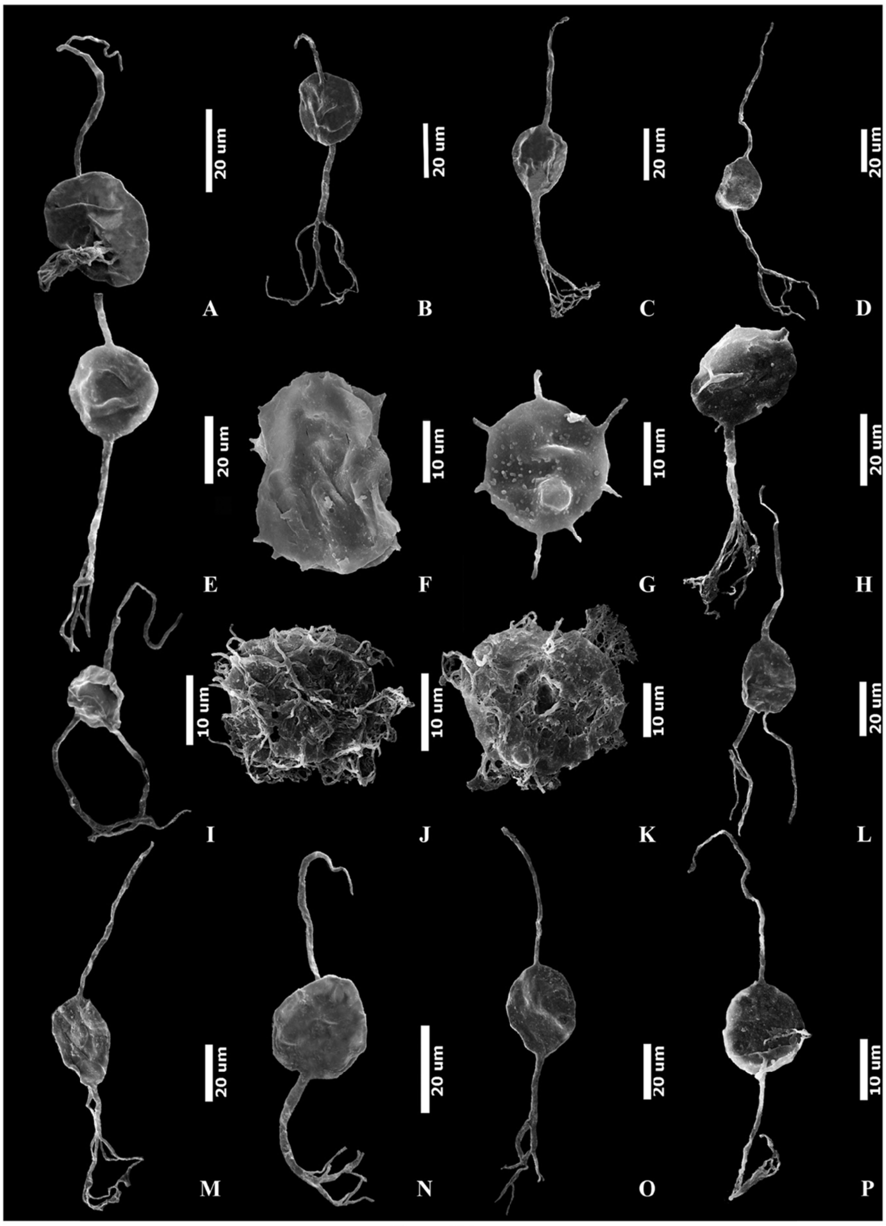

Plate IV

Plate IV. A, B, C, D, E, H, I, L, M, N, O, P. *Lusatia dendroidea* [2]; F. *Dasydiacrodium* sp. aff. *D. angulare* [34]; G. *Impluviculus multiangularis* [33]; J. *Vulcanisphaera africana* [33]; K. *Vulcanisphaera cirrita* [35].

[1], Sweden [37], North Africa [47, 48], Belgium [38, 44], England [9, 33, 55], Iran [13, 14], Canada [21, 31], Russia [23, 27, 34, 51], southeastern Poland and western Ukraine [15], Germany [4], and Italy [8]. These taxa consistently occur within stratal sequences correlated to a chronostratigraphic interval between the *Parabolina spinulosa* and *Peltura* trilobite Zones. The other acritarch taxa (*Actinotodissus archasii, Baltisphaeridium crinitum, Leiosphaeridia iranense* n. sp., *Vulcanisphaera cirrita,* and *Vulcanisphaera africana*) are long ranging (Late Cambrian–Early Ordovician) and cosmopolitan. They have previously been recorded from the lower Ordovician of France and England [36], and Canada [21], and the Late Cambrian to Early Ordovician of Russia [23, 51] and Iran [13]. A characteristic feature of this assemblage zone is the first appearance of galeate acritarchs (e.g., *Cymatiogalea* and *Stelliferidium*), which first appear in the L1–L3 acritarch assemblage zones of England [33], Canada [21, 31], and Russia [34, 49, 51]. In uppermost

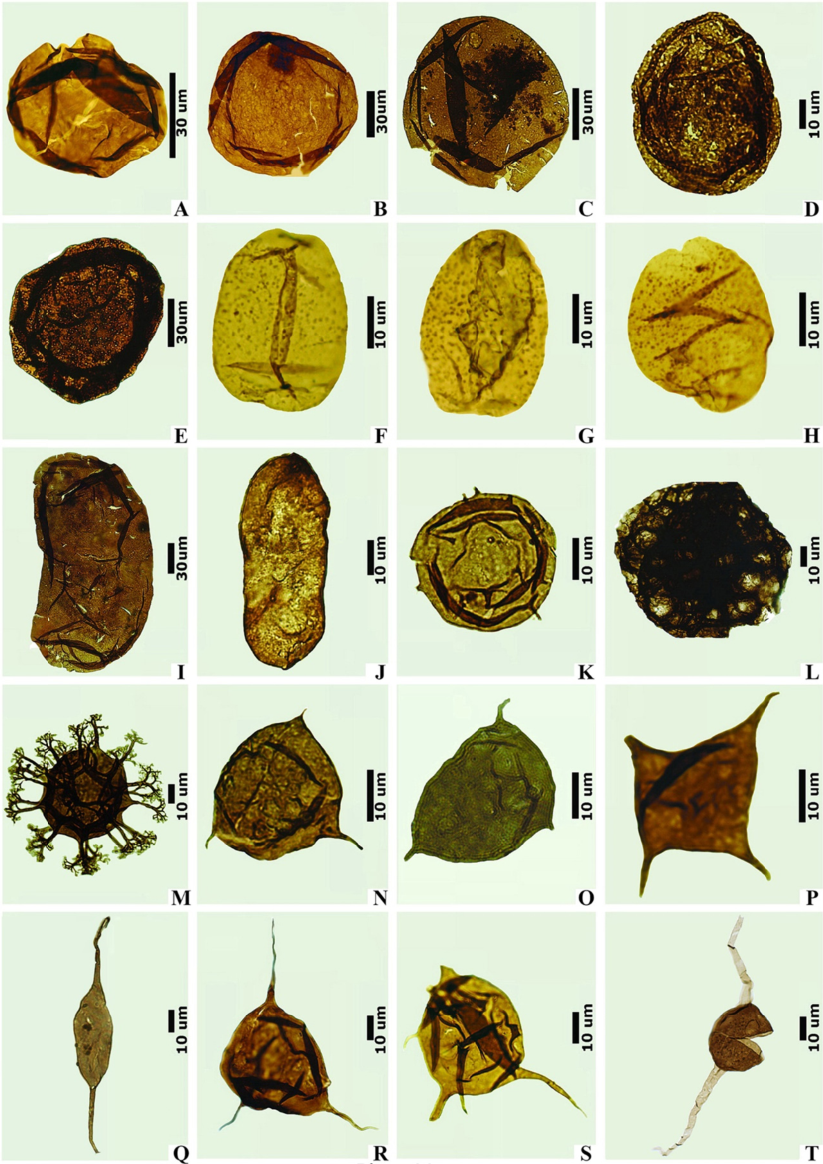

Plate V

Plate V. A, B, C. *Leiosphaeridia crassa* [50]**;** D, E. *Leiosphaeridia iranense* n.sp.; F, G, H. *Eliasum hutchinsonii* [21]; I, J. *Navifusa punctata* [18]; K. *Baltisphaeridium crinitum* [21]; L. *Symplassosphaeridium cambriense* [28]; M. *Timofeevia lancarae* [44]; N, O. *Veryhacium ilebeykensis* n. sp.; P. *Veryhachium lairdii* [9]; Q. *Leiofusa stoumonensis* [44]; R, S. *Veryhachium mutabile* [8]; T. *Orthosphaeridium? extensum* [31].

Cambrian and lower Ordovician acritarch assemblages, galeate taxa become common components globally. Another feature of this assemblage zone is appearance of the cryptospore *Virgatasporites rudii*, which was originally introduced as *Leiosphaeridia* sp. from the Tremadocian near the Hassi-Messaoud Oilfield in Algeria [45]. It was later recorded from Middle Ordovician (Darwillian) in southeast Turkey [30] and the Late Cambrian from northern Spain [1]. This assemblage zone is probably correlatable, at least in part, with A4 microflora zones of Canada [21, 31], acritarch zone 7 in the High Atlas of Morocco [43], and "Stoumont assemblage" or acritarch zone 5 in the Rocroi Massif, France and Stavelot, Belgium [38]. This assemblage zone may also correlate with the VK3 acritarch zone of Russian workers [34, 49, 51], the VI–VIII acritarch zones of Poland and Ukraine [15], and the L1–L3 acritarch zones of the Comley area, Shropshire, England [33] (See Table 3).

5. Acritarch assemblage zone V

This assemblage is characterized by the FAD of the acritarchs: *Navifusa punctata*, *Navifusa reticulata* n. sp., *Polygonum* sp., and *Impluviculus multigranular*. This assemblage zone extends within a 40 m thickness of the Ilebeyk Formation. It consists of olive-gray shales interbedded with thin bedded limestones. Most of the acritarch taxa in the preceding assemblage zones (zones III and IV) continue into this zone (See Table 1; Fig. 3, MG-12 to MG-16). Amongst acritarch taxa, only *Impluviculus multitriangularis* characterizes the Late Cambrian and the other taxa (*Navifusa punctata*, *Polygonium* sp., and *Navifusa reticulata* n. sp.), are recorded for the first time from the Ilebeyk Formation. Previously, *Impluviculus multitriangularis* has been recorded within a chronostratigraphic interval between the *Parabolina spinulosa* and *Peltura* trilobite Zones from Russia [27, 51], western Ukraine [49], northern Spain [1] and Iran [14]. *Polygonium* sp., has been recorded from Late Cambrian of northern Spain [1] and Iran [14], and *Navifusa punctata* from the Late Ordovician [Sandbian] of the U.S.A [18]. Therefore, chronostratigraphic range of *Navifusa punctata* should be considered Late Cambrian to Late Ordovician.

6. Acritarch assemblage zone VI

This assemblage zone is marked by the FAD of the acritarch taxa *Orthosphaeridium extensum, Ladogella saharica, Veryhachium mutabile,* and *Acanthodiacrodium ubuii* (See Table 1; Fig. 3, MG-13 to MG-16). This assemblage zone includes 43m thickness of the Ilebeyk Formation. It comprises interbedded silty gray shales and thin-bedded limestones. Amongst the acritarch taxa, *Orthosphaeridium extensum, Veryhachium mutabile,* and *Ladogella saharica* are well documented from different paleogeographic areas and occur consistently within stratal sequences correlated to a chronostratigraphic interval between the *Parabolina spinulosa* and *Acerocare* trilobite Zones. They have been recorded from Late Cambrian of Newfoundland in Canada [20, 21, 31], northern Spain [2], Russia [51], France [38], Sweden [37], North Africa [46, 47, 48], and Iran [14]. *Acanthodiacrodium ubuii* is a long ranging taxon (Late Cambrian–Early Ordovician). It has previously been recorded from Early Ordovician of Norway [52]; Late Cambrian, the RA5 to RA10a acritarch microflora zones of Newfoundland in Canada [31], and the Late Cambrian of Iran [14] (See Table 3*).*

7. Acritarch assemblage zone VII

This assemblage zone is characterized by the FAD of acritarch taxa, consisting of *Elenia armillata, Ladogella rommelaerei, Ladogella rotundiformis, Striatotheca randomensis, Veryhachium lairdii,* and *Vulcanisphaera tuberata* (See Table 1; Fig. 3, MG-15 to MG-17). This assemblage zone extends within 42 m thickness of the Ilebeyk Formation. It comprises interbedded silty gray shales and thin-bedded limestones. Amongst the acritarch taxa, *Elenia armillata, Ladogella rotundiformis* and *Striatotheca randomensis* are well documented from different paleogeographic areas and occur consistently within the upper Cambrian stratal sequences that are correlated to a chronostratigraphic interval between the *Peltura* and *Acerocare* trilobite Zones. Previously, these acritarch taxa have been recorded from the Late Cambrian of Russia [49, 50, 51], Sweden [41], Newfoundland in Canada [31], Poland [15], and France [38].

The other acritarch taxa (*Ladogella rommelaerei*, *Veryhachium lairdii*, and *Vulcanisphaera tuberata*) are long ranging species (Late Cambrian–Early Ordovician). Previously, they have recorded from Newfoundland in Canada [20, 21, 31], Öland in Sweden [37], France [38], England [9, 33], and North Africa [45, 46, 47, 48].

8. Acritarch assemblage zone VIII

This assemblage zone is defined by the FAD of the acritarchs *Cristallinium randomense* and *Dasydiacrodium angulare* (See Table 1; Fig. 3, MG-17 to MG-19). This assemblage zone is present in 20 m thickness of the Ilebeyk Formation. It consists interbedded silty gray shales and thin-bedded limestones (Fig. 3).

Cristallinium randomense [20] is common in assemblage zone VIII and extends from MG-17 to MG-19 in the Ilebeyk Formation (See Table 1; Fig. 3). The species has been recorded from the Upper Cambrian of the Elliott Cove Formation, Random Island, eastern Newfoundland, RA4–RA10a microflora zones in Canada [31]; *Parabolina spinulosa* Zone of Estonia [27]; Zone to lower Tremadocian of Norway [52]; *Peltura scarabaeoides* Zone at Degerhamn *Acerocare*, Sweden [37]; acritarch assemblage zone 5 in Belgium [38]; IVa acritarch assemblage subzone in southern Iran [14]; A3a acritarch assemblage zone from the MacLean Brook Formation, southeastern Cape Breton Island, Nova Scotia, Canada [29]; Comley area, Shropshire, England [33]; and Severnaya Zemlya, High Arctic of Russia [34]. It has also been recorded from the lower Upper Cambrian of the Sosnowiec Formation, Upper Silesia, southern Poland [24] (See Table 3 in this study).

Dasydiacrodium angulare [34] is common to abundant in assemblage zone VIII and extends from MG-17 to MG-19 (Fig. 3) of the Ilebeyk Formation. This species has previously been recorded from the upper Cambrian Kurchavinskaya Formation, Severnaya

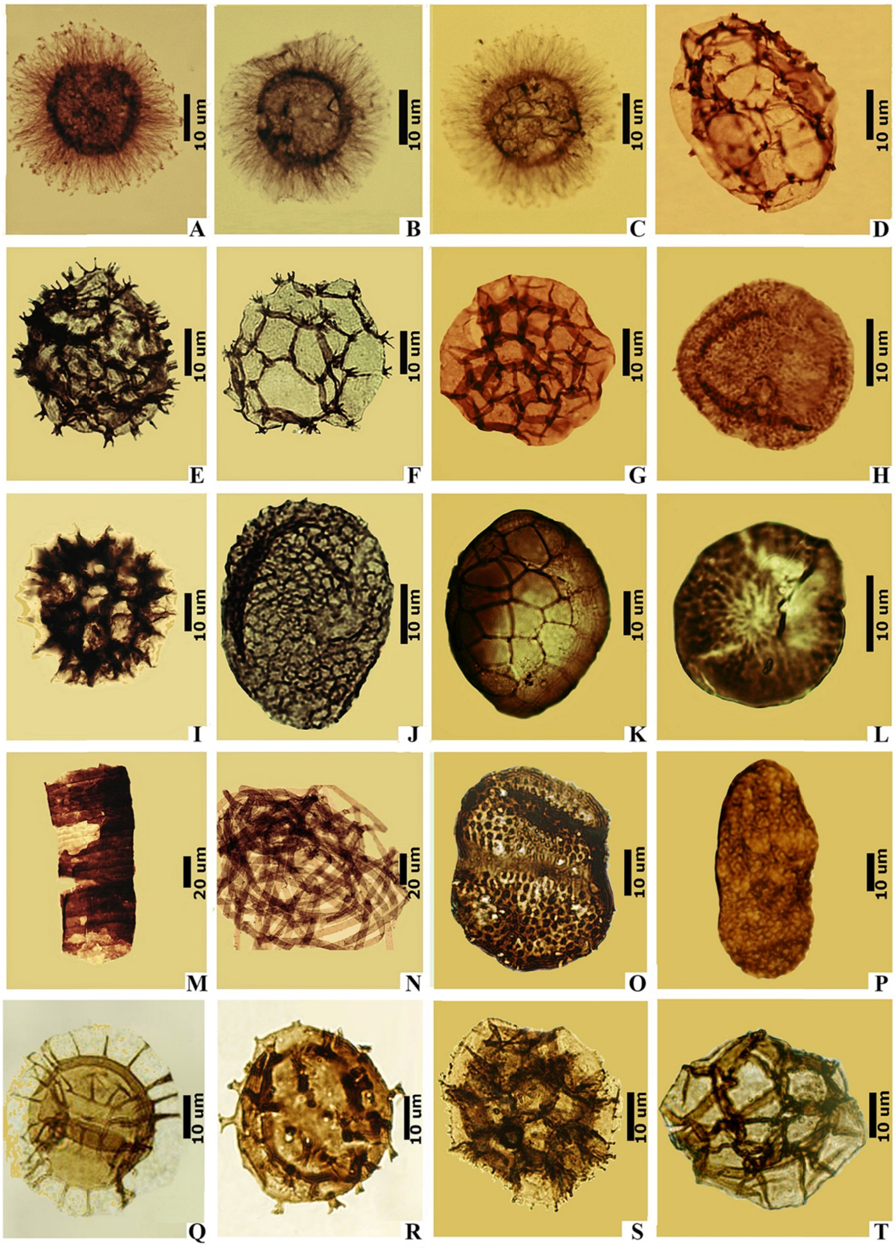

Plate VI

Plate VI. A, B, C. *Comasphaeridium silesiense* [24]; D, E, F. *Vulcanisphaera cantabrica* [28]; G. *Retisphaeridium dichamerum* [28]; H. *Protoleiosphaeridium rugulosum* [28]; I. *Adara alea* [20]; J. *Retisphaeridium ovillense* [42]; K. *Cristallinium ovillense* [20]; L. *Virgatasporites rudii* [1]; M. Chitinous graptolite remains; N. *Siphonophycus typicum* [23]; O. *Acanthodiacrodium angustum* [9]; P. *Navifusa reticulata* n. sp.; Q. *Cymatiogalea gorkae* [35]; R. Vulcanisphae*ra britannica* [36]; S. *Cristallinium randomense* [20]; T. *Cristallinium cambriense* [44].

Zemlya, Russian High Arctic [34, 49, 51].

9. Acritarch assemblage zone IX

The assemblage zone is characterized by the FAD of the acritarch taxa, including *Calyxiella izhoriensis*, *Cymatiogalea gorkae*, *Ladogella intermedia*, *Ooidium clavigerum*, *Ooidium rossicum*, and *Ooidium zagrosensis* n. sp., and complete disappearance of the acritarch taxa of preceding zones (See Table 1; Fig. 3, MG-18 to MG-19). This assemblage zone extends within 12.5 m thickness of the Ilebeyk Formation. It comprises yellow-green, laminated, micaceous sandstones with a bed of gray-green, fissile, highly micaceous shale (Fig. 3). Amongst the acritarch taxa,

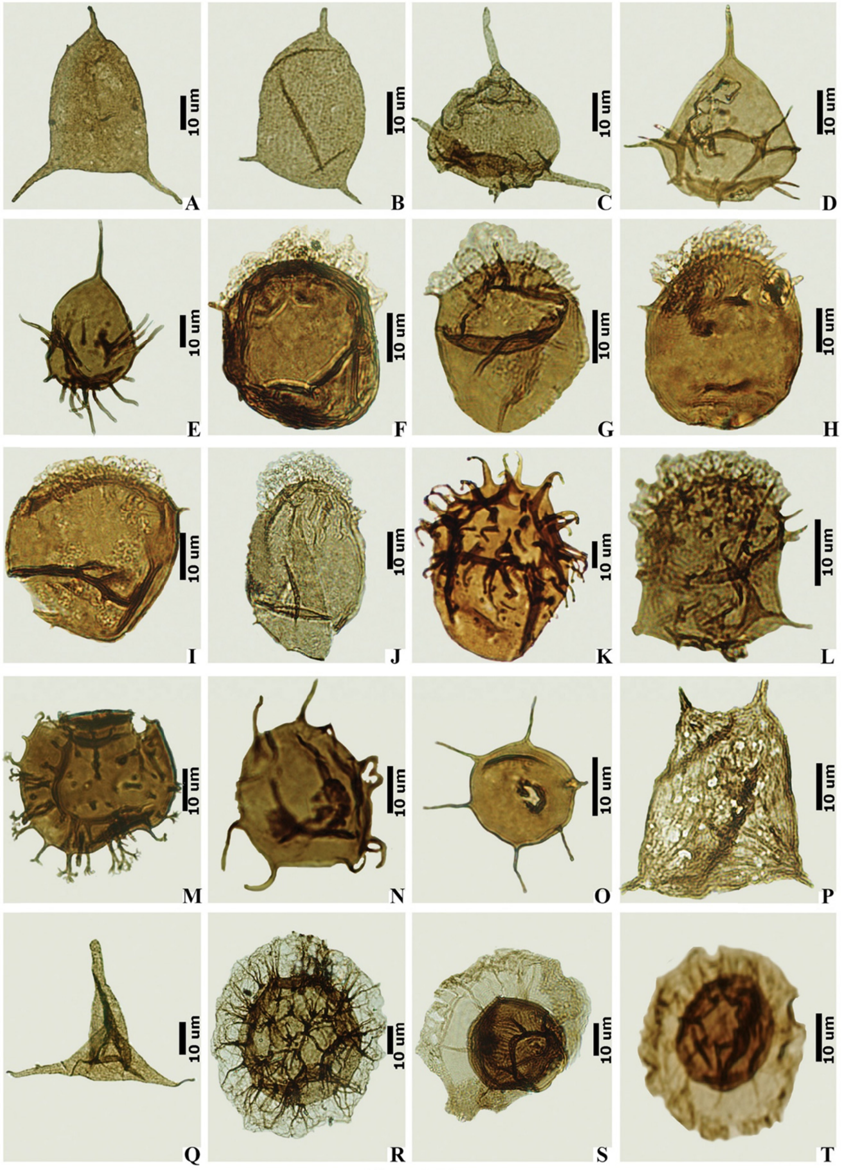

Plate VII

Plate VII. A, B, C, Q. *Ninadiacrodium dumontii* [34]; D, E. *Ninadiacrodium caudatum* [34]; F, G, H, I. *Ooidium zagrosensis* n. sp.; J. *Ooidium clavigerum* [31]; K. *Trunculumarium revinium* [44]; L. *Ladogella rommelaerei* [7]; M. *Cymatiogalea aspergillum* [21]; N, O. *Impluviculus multiangularis* [33]; P. *Striatotheca randomensis* [31]; R. *Vulcanisphaera africana* [33]; S, T. *Elenia armillata* [31].

Ladogella intermedia and *Ooidium clavigerum* are well documented from different paleogeographic areas and consistently occur within the upper Cambrian stratal sequences correlated to the *Acerocare* trilobite Zone. Previously, these acritarch taxa have been recorded from the upper Cambrian RA7b to RA10a, or RA8 and RA9 microflora zones of the Elliott Cove Formation, Random Island, eastern Newfoundland in Canada [31]. *Calyxiella izhoriensis* is also well documented from different paleogeographic areas, but consistently occurs within the upper Cambrian stratal sequences correlated to the chronostratigraphic interval between the *Peltura* and *Acerocare* trilobite Zones. This species has been recorded from Late Cambrian of different parts of Russia [49, 51], Sweden [37, 41], and the Elliott Cove Formation, eastern Newfoundland in Canada (RA6a to RA10a microflora zones) [31]. *Ooidium rossicum* has also recorded from the upper Cambrian of Russia [19, 49, 51], Norway [52], and Random Island, eastern Newfoundland, Canada, RA9 to RA10a microflora zones [31]. *Ooidium rossicum* has been recorded from the Tremadocian of Belgium [38] and the Cambro-

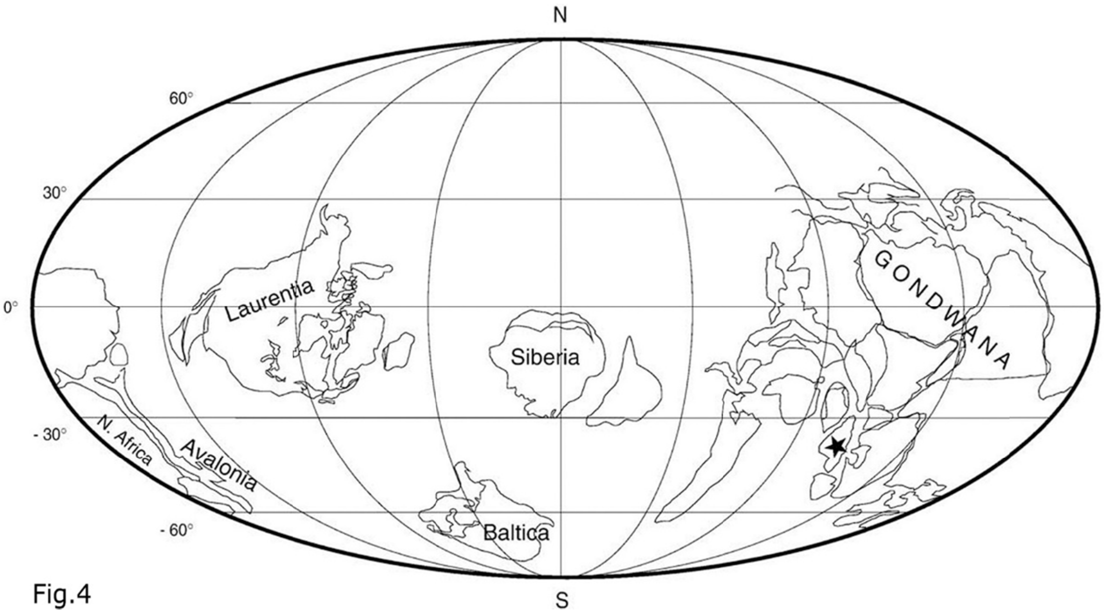

Figure 4. Paleogeographical model of continental mass distribution during Cambrian times based on the map of [39] modified according to further data from [6, 14, 53] showing position of study area (star) and other localities discussed in text. Present results are consistent with a Gondwanan palaeogeographical affinity for Iran, but point to a more southerly, higher paleolatitudinal position [14].

Ordovician of North Africa [47] and northern Iran [13]. *Cymatiogalea gorkae* is a long ranging taxon (Late Cambrian–Early Ordovician) of this assemblage zone and present also in the RA5 to RA10 acritarch microflora zones of the Random Island, eastern Newfoundland in Canada [31].

10. Acritarch assemblage zone X

The assemblage zone is characterized by the FAD of the acritarch species, comprising (See Table 1; Fig. 4, MG-19 to MG-20). This assemblage zone is present in 15 m of the basal part of the Zardkuh Formation. It comprises green-gray, fissile, micaceous shales interbedded with green, fine-grained, micaceous sandstones (Figs.3, 4). Because the contact between the Ilebeyk and the Zardkuh formations is a sharp and well-defined lithological boundary, the Cambrian-Ordovician boundary is traditionally placed at the base of the Zardkuh Formation [40]. Both *Acanthodiacrodium angustum* and *Vulcanisphaera britannica* have been widely recorded from Tremadocian aged strata worldwide [47]. These species have previously been recorded from Tremadocian strata in England [36]; Iran [12]; the *Cordylodus proavus* conodont Zone in the Kallavere Formation of Estonia [51]; and Algerian Sahara [45]. There is sufficient evidence for an age assignment of the present zone to earliest Ordovician (early Tremadocian), and for correlation of the *Acanthodiacrodium angustum-Vulcanisphaera britannica* assemblage zone with the Early Ordovician (Tremadocian), HM/C acritarch assemblage of the Argiles d' El Gassi Formation in Algeria, North Africa [45] (See Table 3 in this study).

Systematic paleontology of acritarchs

In this study, palynomorphs extracted and identified from the Mila, Ilebeyk and lowermost part of the Zardkuh formations are illustrated on Plates I-VII. The observed palynomorph taxa and their relative abundances are given in Table 1 and their stratigraphic occurrences are given in Fig. 3. Full descriptions were provided only for four new acritarch species, namely *Leiosphaeridia iranense* n. sp., *Navifusa reticulata* n. sp., *Ooidium zagrosensis* n. sp., and *Veryhachium ilebeykensis* n. sp .

Group Acritarcha [9]

Genus *Leiosphaeridia* [9]

Type species. *Leiosphaeridia baltica* [9]

Leiosphaeridia iranense n. sp. [Plate V; D, E]

Holotype. Plate V; E

Dimensions. Vesicle diameter 61 (85.5)114 µm; crater form 1 (1.25) 1.5 µm; 20 specimens were measured.

Type stratum. Ilebeyk Formation, Tang-e Ilebeyk, southern flank of Zardkuh Mountain, the High Zagros Mountains, southern Iran.

Etymology. Refers to Iran, the country where it was recorded for the first time

Description. Vesicle is spherical with uniform wall, bearing numerous pores on the surface of the vesicle. It is only present in the flattened state. Vesicle wall is thin with major compressional folds. This species differs from *Leiosphaeridia baltica* and other species of *Leiosphaeridia* in densely pores on the whole vesicle wall. No excystment was observed.

Occurrence. This species occurs in the Ilebeyk Formation from the samples MG-09 to MG-19 with Late Cambrian age.

Genus *Navifusa* [18]

Type species. *Navifusa navis* [18]

Navifusa reticulata n. sp. (Plate VI, P)

Holotype. Plate VI, P

Type stratum. Ilebeyk Formation, the type locality in Tang-e Ilebeyk, southern flank of Zardkuh Mountain, High Zagros Mountains, southern Iran.

Etymology. From the Greek reticule means bearing reticules; the name is considered feminine.

Dimensions. Vesicle length 52 (55.5) 59 µm; vesicle width 25 (26) 27 µm; lumen diameter 1.2 (1.5) 1.9 µm; 15 specimens were measured.

Description. Elongate fusiform vesicle, where vesicle is straight with polar ends broadly rounded and lacking processes. The vesicle surface is covered by densely reticulate ornamentation in which lumen ranges from 1.2 µm to 1.9 µm. Some specimens have a few folds. This species differs from *Navifusa navis* and other related species of *Navifusa* in having reticulated ornamentation and its occurrence in the Cambrian deposits.

Occurrence. This species appears in the samples MG-12 to MG-16 of the Ilebeyk Formation.

Genus *Ooidium* [19]

Type species. *Ooidium rossicum* [19]

Ooidium zagrosensis n. sp. (Plate VII, F, G, H, I)

Holotype. Plate VII, H

Type stratum. This species is present within the Ilebeyk Formation in sample MG-17 to MG-19, High Zagros Mountain Ranges, southern Iran.

Etymology. Refers to the Zagros Mountain ranges which extends from NW to SE Iran, where it was `recorded for first time.

Dimensions. Vesicle length 32 (35.5) 39 µm; vesicle width 28 (29.5) 31 µm; processes length 4 (4.25) 4.5 µm; 25 specimens were measured.

Description. *Ooidium zagrosensis* n. sp., has an ellipsoidal to oval vesicle in outline, frequently broader at one end and sometimes shows folds at various orientations. A mass of tangled thread-like trabeculae occupies one pole, while the other pole is psilate and without any processes. This species differs from *Ooidium rossicum* in the absence of striations at the equatorial region and the absence of granulate ornamentation.

Occurrence. This species appears in the sample MG-17 to MG- 19 of the Ilebeyk Formation

Genus *Veryhachium* [9]

Type species. *Veryhachium trisulcum* [9]

Veryhachium ilebeykensis n. sp. (Plate V, N, O)

Synonymy. *Veryhachium* sp. A, 2000 Parsons and Anderson, Plate 10, figs. 14, 12

Holotype. Plate V, N

Type stratum. The Member C of the Mila Formation in the sample MG-08 to MG-13, southern flank of Zardkuh Mountain, Tang-e Ilebeyk, the High Zagros Mountains, southern Iran.

Etymology. Refers to the Ilebeyk Formation, where the species was first discovered.

Dimensions. Vesicle length 28 (35) 42 µm; vesicle width 24 (26) 28 µm; large spine 2.2 (7.7) 13.2 µm; medium spine 2.4 (6.7) 11.2 µm; small spine 1.4 (1.8) 2.2 µm.; 12 specimens were measured.

Description. Vesicle varies from triangular with convex sides to straight sides. From each corner of vesicle arises a very short tapering process, which is in communication with vesicle cavity freely. The body surface is smooth, or shagrinate to slightly granulate. This species differs from *Veryhachium trisulcum* in very short processes and convex sides.

Occurrence. This species is present in the sample MG-08 in Member C of the Mila Formation and extends in MG-13 in the lowermost part of Ilebeyk Formation, the High Zagros Mountains, southern Iran.

Paleobiogeography

Acritarchs are organic-walled microfossils interpreted as phytoplanktonic organisms that occur in marine sedimentary rocks spanning at least ca. 1.7 Ga of Earth history. They have been used successfully for biostratigraphic purposes, particularly in Lower Paleozoic and Neoproterozoic strata. In addition to their significance for revealing the early evolution of the biosphere and marine ecosystems, acritarchs can contribute substantially to the recognition of the paleobiogeographic affinities of different paleocontinents and their tectonic history. The present study revealed that taxonomically diverse and well-preserved acritarchs occur throughout the Middle-Late Cambrian succession in the High Zagros Mountains, southern Iran. Acritarch associations are a good scientific tool for chronostratigraphy and stratigraphic relationships, as well as thermal alternation index. Furthermore, a number of studies have indicated that marine phytoplanktonic assemblages vary in composition, diversity, and abundance, both overall abundance and relative abundance of components, in relation to their position along an onshore-offshore gradient [48]. Among acritarch populations, samples from offshore shelf facies contain the most abundant and diverse assemblages, whereas assemblages from nearshore and deep-water basinal facies have lower diversity. In the context of genetic sequence stratigraphy, the onshore-offshore model implies that the diversity and abundance of marine palynomorphs (acritarchs and chitinozoans) are likely to reach a maximum at, or close to, a marine-flooding surface in offshore shelf settings. Conversely, correlative marine assemblages from more proximal settings are likely to be less diverse, consisting principally of sphaeromorph acritarchs and other widely occurring species such as *Veryhachium trispinosum* [26].

Cambrian to earliest Ordovician paleogeography is poorly constrained by paleomagnetic data and continental separation during this time interval is mainly based on stratigraphic, tectonic, and faunal assemblage considerations [39]. Cambrian paleocontinents with up-to-date records of acritarchs comprise Baltica, Siberia, Gondwana (with marginal assembly of microplates referred to as Avalonia and Armorica) and Laurentia, which are separated by oceanic basins (See Table 2). However, their relative paleolongitudinal position [6] and the position of some of the smaller terranes is still controversial because of the scarcity of firm data [39]. As it was discussed [14], it is interesting to note, at least from a historical viewpoint, in an old study [16] found no similarities between Cambrian macrofaunas from the Zagros Basin of southern Iran and coeval association from southern Europe, thus discounting a Gondwanan paleobiogeographical affinity for the High Zagros Mountains, southern Iran. In terms of Cambrian paleobiostratigraphy, almost complete middle–upper Cambrian acritarch assemblages have been documented from Random Island, Newfoundland [20, 21, 31] and in the East-European Platform [49, 51]. Acritarch records from other areas include Middle-Late Cambrian acritarchs in the High Arctic of Russia [34]. There are well preserved acritarchs of the Cambrian System from Series 2 to Furongian in south-eastern Poland and western Ukraine [15], whole Cambrian acritarchs from Upper Silesia, Poland [24], Middle and Late Cambrian acritarchs in the Booley Bay Formation, County Wexford, Ireland [42], Middle Cambrian–Furongian acritarchs in southeastern Cape Breton Island, Nova Scotia, Canada [29], Middle-Late Cambrian in the Al-Bashair Member of the Andam Formation Oman [26], Middle-Late Cambrian in the Zagros Mountains, southern Iran [14], Middle Cambrian acritarchs from the Oville and Barrios formations, northern Spain [28], Late Cambrian acritarchs from the Túnel Ordovícico del Fabar Cantabrian Zone, northern Spain [1], and Late Cambrian acritarchs from the Comley area, Shropshire, England [33].

Comparison of the present Cambrian acritarch taxa from the High Zagros Mountains with the four Cambrian paleocontinents proves their utility for biostratigraphy, paleogeography and global correlations. Table 2 shows the shared occurrences of acritarch species between the present assemblages and those representative of Baltica, Siberia, Gondwana (with marginal assembly of microplates referred to as Avalonia and Armorica) and Laurentia, subdivided into three time slices, Middle and Late Cambrian, and Early Ordovician (Table 2). The data shows throughout Europe, acritarch genera of *Cristallinium, Comasphaeridium, Eliasum, Retisphaeridium, Stelliferidium, Timofeevia, Lusatia, Vulcanisphaera, Leiofusa, Trunculumarium, Ninadiacrodium, Acanthodiacrodium* (=*Actinodiscus*s) and *Dasydiacrodium* are important components of Mid-Late Cambrian acritarch assemblages. An acritarch assemblage has described from the upper Cambrian Bonneterre and Davis formations of Missouri and Arkansas in the United States [54] that apparently has little similarity with coeval assemblages from Newfoundland and Europe and only two cosmopolitan species (e.g., *Timofeevia phosphoritica* and *Vulcanisphaera turbata*) are shared between the study assemblages and the upper Cambrian Laurentian acritarch assemblage.

For paleobiogeographic evaluations of acritarch taxa, the author selected the Coefficient Similarity (CS) of Clark and Hartleberg [5] because it was successfully used by [3] when he evaluated the provincialism of lower Paleozoic conodonts. The Coefficient Similarity is expressed as: $CS = 2v / a + b$, where v is the number of species in common between the two compared areas, a and b is the total number of species recorded in each area. This CS was applied for the acritarch taxa encountered in this study and previously published assemblages of coeval age from Gondwana (e.g., Libya, Algeria, Morocco, Tunisia, Turkey, Jordan, Arabian Peninsula, Turkey, and Iran), microplate of Armorica (Belgium, Spain, Italy, and France), Avalonia (Nova Scotia, Newfoundland, Ireland, and Wales), Baltican (Poland, Ukraine, Norway, Sweden, Estonia, and Russia), Siberian and Laurentian paleocontinents (Table 2). By using the CS, the identified acritarch species of Middle Cambrian of the High Zagros Mountains are 67.46 % in common with Gondwana (including of marginal microplates of Gondwana such as Avalonia and Armorica), 23.65 % in common with Baltica, 8.89

% in common with Siberia, and nothing in common with Laurentia. The CS was also used for the Late Cambrian acritarch taxa of the study area, which are 76.48 % in common with the Gondwana, 14.51 % in common with Baltica, and 8.93 % in common with Siberia. The CS values show various similarities between the study area and selected assemblages of other paleocontinents. The changes in the CS values suggest the possibility of provincialism among Late Cambrian acritarchs. On the other hand, a high proportion of species are shared between the Iranian assemblages and those described from Avalonia, in Mid-Late Cambrian times. This may indicate that Iran was located further south along the North Africa-Gondwanan margin than indicated in the maps by Scotese and McKerrow [39] (Fig. 4). Hence, it was probably closer to Avalonia. As is apparent from Table 2, similarities tend to increase passing from Late Cambrian to Early Ordovician time. The present data are in general agreement with proposed paleogeographical models showing the position of major continental masses and their drift trajectories from Late Cambrian to Early Ordovician times [6, 39, 53]. Furthermore, the presence of *Lusatia dendroidea* and *Veryhachium mutabile* in the Late Cambrian Iranian assemblages (these two taxa had previously been known to occur only in Baltican localities) supports a similar high paleolatitude for Iran and Baltica. 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 [54]. However, there are still many places which need to be worked in order to present a model for global acritarch distribution in the Cambrian. Therefore, the paleobiogeographical utility of acritarchs for this time seems to be still immature.

Results and Discussion

This study represents the first comprehensive microfloristic and macrofaunistic investigation of the Cambrian rock units of the High Zagros Mountains in southern Iran. Previous works based on macrofaunal analyses (mainly trilobites and brachiopods) had permitted a broad assignment of the Zaigun and Lalun formations based on stratigraphical positions to Late Proterozoic–Early Cambrian and the Mila and Ilebeyk formations to the Middle-Late Cambrian by means of isolated findings of macrofauna in a few stratigraphical levels, but did not result in any workable biostratigraphical schemes. The present study resulted in:

1) Although, the lower part of the Mila formation is barren in palynomorph entities, but two diagnostic trilobite such as *Mysopsolenites* sp., and *Redlichia* sp., were found in the lower part of this Formation, indicating late Early to early Middle Cambrian. Up to now, these two species have been reported from Jordan, Morocco, and Iberia of west Gondwana and they are indicative of Early Cambrian (Series 2). The presence of these trilobites in the A and B Members of Mila Formation signify relationship of the Zagros Mountains to the Gondwanan paleoplate during this time interval.

2) Ten acritarch assemblage zones were established in Member C of the Mila and Ilebeyk formations and lowermost part of Zardkuh Formation; acritarch assemblage zones I-II occur in the lower and middle parts of the Member C of the Mila Formation and suggest early-mid Middle Cambrian; acritarch assemblages zones III-IV appear in the upper part of the Member C of the Mila Formation and the lower part of Ilebeyk Formation and encompass latest Middle and earliest Late Cambrian; acritarch assemblage zones V-IX occur in the middle and upper parts of the Ilebeyk Formation and characterize Late Cambrian; finally, acritarch assemblage zone X ranges through the basal part of the Zardkuh Formation and proves to have an early Tremadocian age.

3) The thermal maturation of organic matter in the sedimentary structures and facies associations is *in situ* in the depositional setting of study area. Since the distribution of acritarchs and their sizes in the depositional environments suggest neither selective distribution of microplankton nor distinctive planktonic communities occupying nearshore and offshore shallow-shelf environments. The color of acritarchs varies from yellow to orange-brown and represents a Thermal Alteration Index of 3-4 (mature), suggesting possible generation of hydrocarbon for the Mila and Ilebeyk formations in the High Zagros Mountains.

4) For paleobiogeographic evaluations of acritarch taxa, the author selected the Coefficient Similarity (CS) [5]. By using the CS, the identified acritarch species of the Middle Cambrian of the High Zagros Mountains are shown to be 67.46 % in common with Gondwana (including of marginal microplates of Gondwana, such as Avalonia and Armorica), 23.65 % in common with Baltica, 8.89 % in common with Siberia, and nothing in common with Laurentia. The CS was also used for the Late Cambrian acritarch taxa of the study area, which are 76.48 % in common with Gondwana, 14.51 % in common with Baltica, and 8.93 % in common with Siberia and nothing in common with Laurentia. The CS values show various similarities between the study area

and selected assemblages of other paleocontinents. The changes in the CS values suggest the possibility of provincialism among Middle-Late Cambrian acritarchs. On the other hand, a high proportion of species are shared between the Iranian assemblages and those described from Avalonia, both in Mid and Late Cambrian (35–38.62 %), and may indicate that Iran was located further south along the North Africa–Gondwanan margin and probably closer to Avalonia than indicated in the maps [39] (Fig. 4).In brief, the Iranian acritarch associations share a higher proportion of taxa with Gondwanan acritarch assemblages (67.46-76.48 %) than other paleocontinents (e.g. Laurentia, Baltica and Siberia).

5) The occurrence of *Lusatia dendroidea* and *Veryhachium mutabile* in the Late Cambrian Iranian acritarch assemblages supports a similar paleolatitude for Iran and Baltica as well as Avalonia since these two acritarch species were previously restricted to Baltican paleoplate.

The acritarch bioprovinciality breakdown is observable at the Cambrian-Ordovician transition and earliest Ordovician which probably reflects a modification of the contemporaneous pattern due to the southward movement of Gondwana and the northward drift of Baltica, shrinking of the Iapetus ocean between Baltica and Laurentia, resulting to the breakdown of water-mass barriers.

6) The cryptospore species of *Virgatasporites rudii* is recorded for the first time from the Late Cambrian of the High Zagros Mountains. This species was originally introduced as *Leiosphaeridia* sp. from the Tremadocian near the Hassi-Messaoud Oilfield in Algeria. Later on, it was recorded from Middle Ordovician (Darwillian) in southeast Turkey [30] and the Late Cambrian of northern Spain. In addition to the four new acritarch species, fifteen acritarch taxa are recorded for the first time from the Mila and Ilebeyk formations, consisting of *Elena armillata, Striatotheca randomensis*, *Dasydiacrodium angulare*, *Ladogella saharica*, *Ladogella rotundiformis*, *Ladogella intermedia*, *Ooidium clavigerum*, *Stelliferidium cortinulamorphum, Symplassosphaeridium cambriense*, *Adara alea*, *Vulcanisphaera cantabrica*, *Siphonophycus typicum*, *Leiosphaeridia crassa*, *Comasphaeridium silesiense* and *Protoleiosphaeridium rugulosum*.

7) There is 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 paleoenvironment for the rocks comprising the Mila and Ilebeyk formations, according to accepted models of microphytoplankton distribution along the onshore–offshore transect.

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