

## Biostratigraphy of Acritarchs and Chitinozoans in Ordovician Strata from the Fazel Abad Area, Southeastern Caspian Sea, Alborz Mountains, Northern Iran: Stratigraphic Implications

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### Abstract

Sixty-four surface samples from the Lower Palaeozoic rock units (mainly Lalun, Abastu and Abarsaj formations) near Kholin-Darreh village in the Fazel Abad area, southeastern the Caspian Sea, Northern Iran, were analyzed to determine their age relationships. The samples of Lalun Formation were barren, but those of Abastu and Abarsaj formations contained well-preserved and abundant palynomorph entities, which are dominated by acritarchs (23 species belonging to 15 genera) and chitinozoans (29 species distributing among 15 genera) with remains of scolecodonts, graptolite and a few cryptospores, although not determined in detail. Based on the restricted stratigraphic range of acritarch species, an Early Ordovician (Tremadocian) age was assigned to the Abastu Formation; while based upon index chitinozoan and acritarch taxa, a Late Ordovician (Katian to Hirnantian) age was assigned to the Abarsaj Formation. Likewise, based on the presence of diagnostic chitinozoan taxa, the Abarsaj Formation can be assigned to the *Armoricochitina nigerica*, *Ancyrochitina merga*, *Tanuchitina elongata* and *Spinachitina oulebsiri* chitinozoan Biozones. These chitinozoan assemblages reflect a clear palaeobiogeographic affinity with the so-called "North Gondwana Domain". Two major hiata are present within the studied Lower Palaeozoic succession in the Fazel Abad area. The first hiatus appeared between the Lalun Formation (Early Cambrian) and the Abastu Formation (Tremadocian) and includes the Middle-Upper Cambrian Mila Formation. The second hiatus occurs between the Abastu Formation (Tremadocian) and the Abarsaj Formation (Katian-Hirnantian) and spans the interval of the Floian-Sandbian, which corresponds to uplift related to the initial stage of rifting of the Palaeo-Tethys Ocean.

**Keywords:** Acritarchs; chitinozoans; biostratigraphy; Gondwana; southeastern Caspian Sea.

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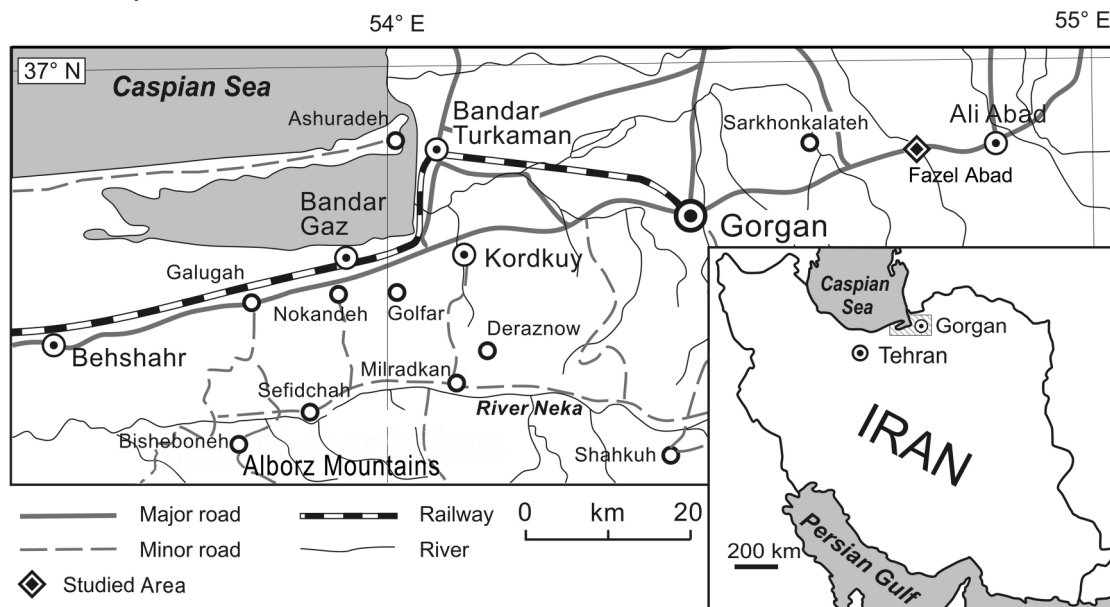
**Introduction**

The Lower Palaeozoic strata are well exposed near Kholin-Darreh village, 19 km south of Fazel Abad town, approximately 46 km southeast of Gorgan city. The road from Gorgan to Fazel Abad - Ali Abad is the principal link to the study area (Fig. 1). Herein, the Palaeozoic strata crop out along the Alestan River, where a secondary unpaved road along this river connects Fazel Abad town to Kholin-Darreh village. In this area, the Palaeozoic sequence has been divided, in ascending stratigraphic order, into the Lalun (Lower Cambrian), Abastu and Abarsaj (Ordovician), Nekarman (Silurian), Khoshyeilagh (Upper Devonian), Mobarak (Lower Carboniferous), Qezelqaleh (Upper Carboniferous), Doroud (Lower Permian), Ruteh (Middle Permian) and Nessen (Upper Permian) formations (49). Due to lack of diagnostic fossils, the precise ages of the Lalun, Abarsaj, and Abastu formations have not been determined. Hence, based on stratigraphic position, the Lalun has been assigned to the Lower Cambrian as well as the Abastu and Abarsaj formations to Ordovician (53). This paper is concerned with age determination of the Lower Palaeozoic rock units of the Fazel Abad area. Therefore, a stratigraphical column was measured and sampled in order to determine not only the age relationships of the Lower Palaeozoic rock units, but also the palaeogeographic position of this part of the Alborz Mountains, using acritarchs and chitinozoans. The encountered fauna and flora will also clarify their affiliations to the Gondwanan

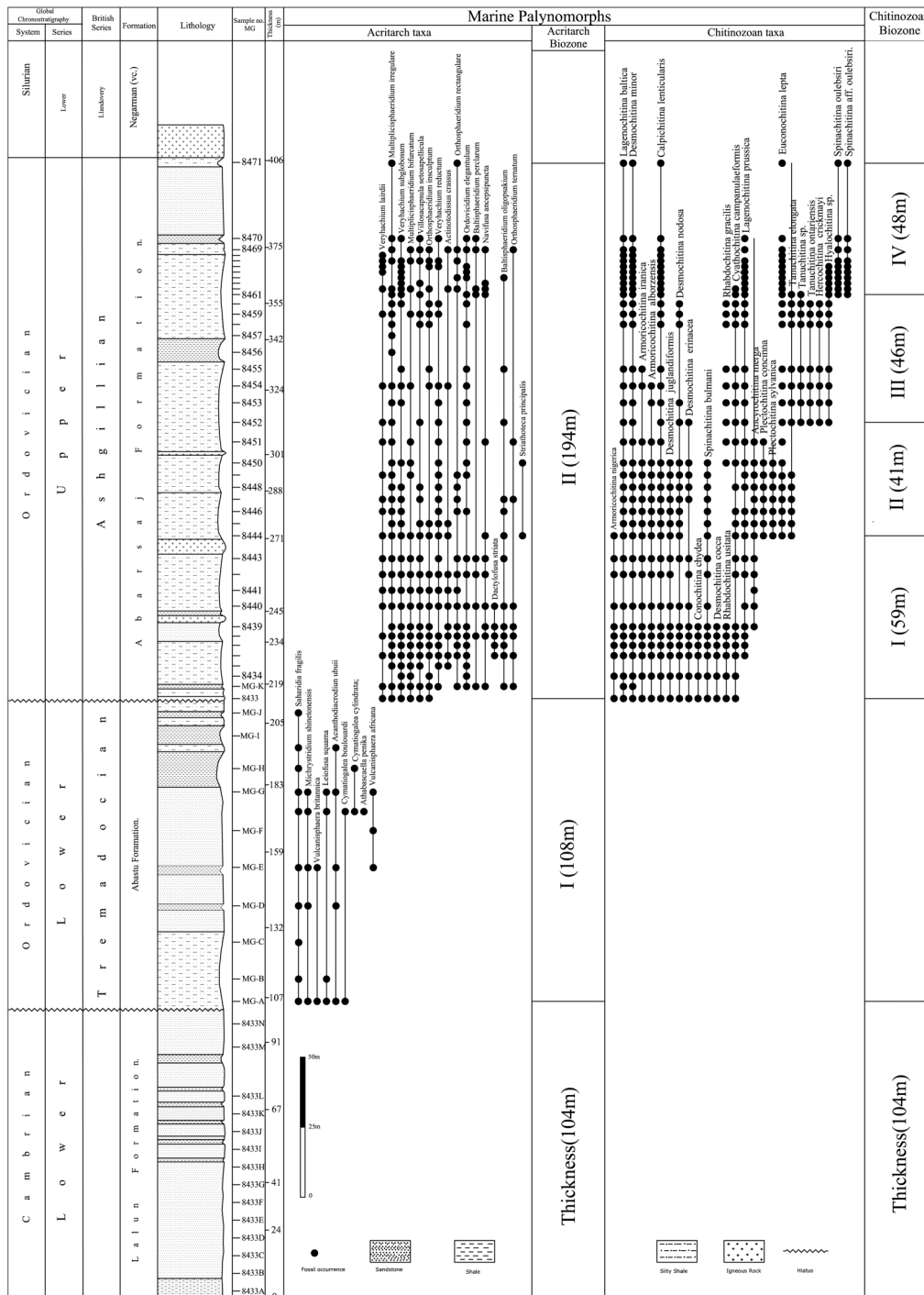
and/or Laurentia palaeo-provinces.

**Regional stratigraphic setting**

The Abastu and Abarsaj formations are well-developed at the Shahvar Mountain, northwest of Shahroud, in the eastern Alborz Mountain Ranges. A succession of these two rock units has a thickness of 1346 m and ascending stratigraphic order, it has been divided into the Abastu (581 m) and Abarsaj formations (765 m) in the Shahvar Mountain (51). The thickness of the formations substantially reduces toward the Fazel Abad area, southeastern the Caspian Sea. In the Fazel Abad area, the Lower Palaeozoic rock units have a thickness of 406 m. The author measured and sampled a stratigraphic column near the Kholin-Darreh village (36°, 45', 33" N - 54°, 48', 19. 7" E; base of the section; 36°, 45', 56. 9": N - 54°, 48', 23. 3" E; top of the section). The stratigraphic column starts from the unpaved road of Kholin-Darreh village at the base and ends near the Alestan River (Fig. 1) where the volcanic rocks of Nekarman (Soltan Maidan) Formation have clear contact with the Abarsaj Formation. The base of the Lower Palaeozoic strata is traversed by the Kholin-Darreh fault, while the upper contact of these sediments is covered by the volcanic rocks of the Nekarman Formation. Herein, the Lower Palaeozoic sedimentary rock units, in ascending stratigraphic order, are divided into the Lalun, Abastu, and Abarsaj formations. The Lalun Formation, 104 m thick, consists of reddish brown sandstones with intercalations of purple shale. Its lower contact is faulted (Fig. 2) and its top is



**Figure 1.** Location map of studied area and its connection to adjacent major cities



**Figure 2.** Lithostratigraphy and stratigraphic distributions of selected palynomorph taxa in the Abastu and Abarsaj formations near Kholin-Darreh in the Fazel Abad area, Southeastern Caspian Sea, Northern Iran.

conformably overlain by the Abastu Formation. Although this formation lacks fossils, the Middle-Late Cambrian fossils found in the overlying Mila Formation suggests that the Lalun Formation is probably Early Cambrian in age (53). The Abastu Formation is 108 m

thick and comprises an alternation of white quartzose sandstone and olive grey, micaceous shale (49). The lower contact of this rock unit is conformable with the Lalun Formation and its upper contact is marked by a purple shale horizon of the basal part of the Abarsaj

Formation. The Abarsaj Formation has a thickness of 194 m and mainly consists of olive-grey to black micaceous shale and siltstone with igneous rock (sill) in some horizons. This rock unit changes to more of a sandstone near its top. The lower and upper contacts of this Formation are apparently conformable with the Abastu and Nekarman Formations respectively. As a result of the absence of macrofossils, no palaeontological age has been previously provided for the Abastu and Abarsaj formations. However, because of being overlain by the Nekaman Formation and resting on the Lalun Formation, tentatively attributed an Ordovician age to these two formations (49)).

### Materials and Methods

Sixty-four (64) surface samples were collected for palynological study from the Lower Palaeozoic rock exposures near the Kholin-Darreh village in the Fazel Abad area. The field and laboratory descriptions of samples are shown on the stratigraphic column (Fig. 2). Each sample is designated with the National Iranian Oil Company Code number with the prefix MG and the samples include MG 8433A to MG8433N and MG-A to MG-K, as well as MG8433 to MG8471. Palynomorph entities were extracted from shale, siltstone and fine grained sandstone samples by using the standard palynological technique of treatment in HCl and HF to remove carbonate and silicate, respectively, followed by neutralizing the residue in distilled water after each acid treatment. Samples were not oxidized, and the resultant residues of each sample were treated with 30 ml of saturated zinc bromide with a specific gravity of 1.95. The remaining organic residue was then sieved through a 15 µm nylon mesh sieve in order to eliminate the finer debris and facilitate palynological analyses. Palynological preparations were then studied by using transmitted light and scanning electron microscopy. All slides used in this study are housed in the Palaeontological Collections of the Exploration Directorate of the National Iranian Oil Company under the sample numbers MG-A to MG-K, MG8433A to MG8433N and MG8433 to MG8471.

### Palynostratigraphy

Most of the studied samples contained well-preserved and abundant palynomorphs (e. g. acritarchs, chitinozoans, scolecodonts and graptolite remains) with the exception of those collected from the Lalun Formation, which are barren, consisting of a succession of red sandstone and purple shale. In general, acritarchs are more abundant than other palynomorphs. The palynomorph entities and organic debris are dark yellow

to orange-brown in color, which indicates a fairly high thermal maturity for organic materials of the Lower Palaeozoic strata (TAI = 3. 5) in this part of the Alborz Mountains. In this study, 7952 palynomorph specimens were investigated which represent 4502 acritarch specimens, 3202 chitinozoan specimens, 210 scolecodont specimens and 38 specimens of graptolites remains (Table 1). A total of 23 acritarch species (15 genera) and 29 chitinozoan species (15 genera) were identified (Fig. 2; Plates I - V). In addition, rare graptolite remains and common scolecodonts were also encountered, which have not been described in the present study. The chitinozoans permit the recognition of four biozones in the Abarsaj Formation, which are well known in the so-called "North Gondwana Domain" (40, 41). The chitinozoan biozones have been discussed below in ascending stratigraphical order along with biostratigraphic age (40, 41, 42). The identified chitinozoan taxa discussed herein are well known elsewhere (e. g. 42, 43, 18, 19); therefore, they are listed below according to the grouping of the classification scheme, which is treated herein. Likewise, the acritarch taxa discussed and illustrated herein are followed as form species and form genera under provisions of the International Code Botanical Nomenclature (I. C. B. N; 24) and are arranged alphabetically by genera under the informal *incetae sedis* "acritarch" group.

### Acritarchs

The following acritarch taxa were identified (Plates I-II):

Group Acritarcha Evitt, 1963

Genus *Acanthodiacrodium* Timofeev, 1958, emend. Deflandre and Deflandre-Rigaud, 1962

*Acanthodiacrodium ubuii* Martin, 1968 (Plate I, 2)

*Acanthodiacrodium angustum* (Downie) Combaz, 1967 (Plate I, 8)

*Acanthodiacrodium crassus* (Loeblich and Tappan, 1978) Vecoli, 1999 (Plate V, 14)

Genus *Aryballomorpha* Martin and Leiming, 1988

*Aryballomorpha grootaerii* (Martin) Martin and Leiming, 1988 (Plate I, 5).

Genus *Athabascaella* Martin, 1984, emends. Martin and Yin Leiming, 1988.

*Athabascaella penika* Martin and Yin Leiming, 1988 (Plate I, 6).

Genus *Baltisphaeridium* Eisenack, 1958 ex Eisenack, 1959 emend. Eiserhart, 1989

*Baltisphaeridium oligopsakium* Loeblich and Tappan, 1978 (Plate V, 12)

*Baltisphaeridium perclarum* Loeblich and Tappan, 1978 (Plate V, 11)

*Baltisphaeridium constrictum* Kjellström, 1971 (Plate



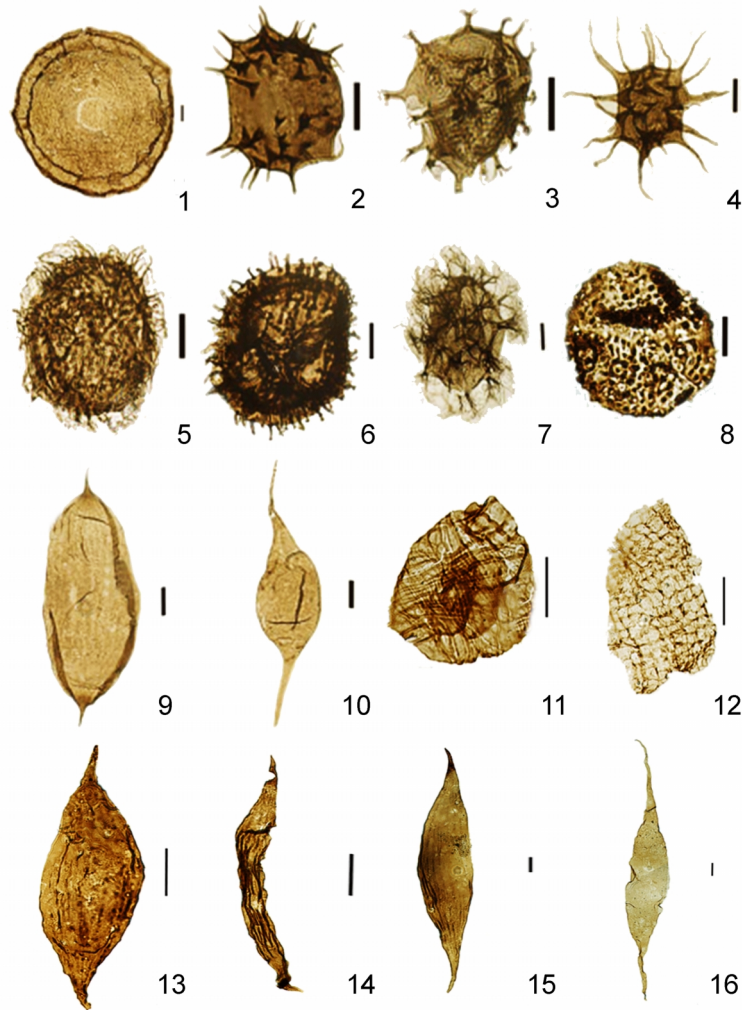


Plate I

**Plate I**

1. *Saharidia fragilis* (Downie, 1958) Combaz, 1967.
2. *Acanthodiacrodium ubuii* Martin, 1968.
3. *Vulcanisphaera britannica* Rasul, 1976.
4. *Michrystridium shinetonensis* Downie, 1982.
5. *Aryballomorpha grootaertii* (Martin) Martin and Leiming, 1988.
6. *Athabascaella penika* Martin and Leiming, 1988.
7. *Vulcanisphaera africana* Deunff, 1961.
8. *Acanthodiacrodium angustum* (Downie) Combaz, 1967.
9. *Leiofusa squama* (Deunff) Combaz, et al., 1967.
10. *Leiofusa simplex* (Combaz, 1967) Martin, 1975.
11. *Dactylofusa cabottii* (Cramer, 1971) Fensome, et al., 1990.
12. *Muzivum graziniskii* Wood & Turnau, 2001.
13. *Dactylofusa cucurbita* Jardiné et al., 1974.
14. *Dactylofusa striata* (Staplin, Jansonius, & Pocock) Fensome, et al., 1990.
15. *Dactylofusa platynetrella* (Loeblich & Tappan) Fensome, et al., 1990.
16. *Leiofusa litotes* Loeblich & Tappan, 1978.

Cramer, 1971

*Dactylofusa cucurbita* Jardiné et al. 1974 (Pate I, 13)

*Dactylofusa striata* (Staplin, Jansonius, and Pocock, 1965) Fensome, Williams, Barss, Freeman, and Hill,

1990 (Plate I, 14).

*Dactylofusa platynetrella* (Loeblich and Tappan)  
Fensome, William. Barss, Freeman and Hill, 1990

(Plate I, 15).

*Dactylofusa cabottii* (Cramer, 1971) Fensome,  
Williams, Barss, Freeman and Hill, 1999 (Plate I, 11).



Plate II

**Plate II**

1. *Orthosphaeridium insculptum* Loeblich, 1970.
- 2, 8. *Baltisphaeridium constrictum* Kjellström, 1971.
3. *Veryhachium lairdii* group Servais, T., et al., 2007.
4. *Dorsennidium hamii* (Loeblich, 1970) Stancliffe, 1994.
5. *Tylotopalla* sp.cf. *T. caelamenicutis* Loeblich, 1970.
6. *Diexallophasis denticulata* (Stockmans and Willièrè, 1962) Loeblich, 1970.
7. *Multiplicisphaeridium irregulare* Staplin et al., 1965.
9. *Orthosphaeridium rectangulare* (Eisenack, 1963) Eisenack, 1968.
10. *Baiomeniscus camurus* Loeblich, 1970.
11. *Neoveveryhachium* sp.cf. *N.carminae* (Cramer) Cramer, 1970.
12. *Veryhachium* sp. cf. *V. triangulatum* Konzalova'-Mazankova', 1969.
13. *Veryhachium strangulatum* Le Herisse, et al, 1995.
- 14, 15. *Safirotheca safira* Vavrdova', 1989.
16. *Navifusa ancepsipuncta*, Loeblich, 1970.

Genus *Diexallophasis* Loeblich, 1970.  
*Diexallophasis denticulata* (Stockmans and Williere)

Loeblich, 1970 (Plate II, 6).  
 Genus *Dorsennidium* Wicander, 1974 emend.

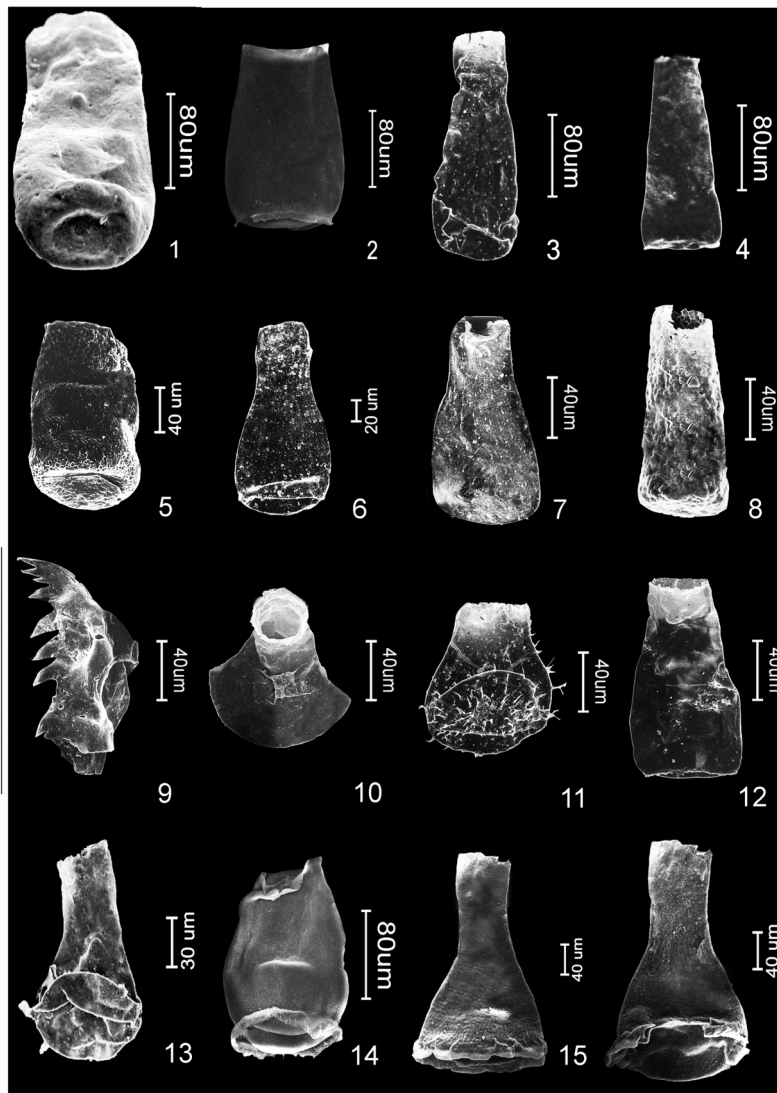


Plate III

**Plate III**

1. *Rhabdochitina usitata* Jenkins, 1967.
2. *Armoricochitina nigerica* (Bouché, 1965).
- 3, 7. *Hercochitina crickmayi* Jansonius, 1964.
4. *Tanuchitina fistolusa* Taugourdeau and de Jehkowskey, 1960.
5. *Armoricochitina iranica* Ghavidel-syooki and Winchester-seeto, 2002.
6. *Spinachitina* sp.
8. *Euconochitina moussegoudaensis* Le Herissé, et al., 2013.
9. Scolecodont form (Annelid Jaw)
10. *Euconochitina lepta* (Jenkins, 1970) Paris et al. 1999.
11. *Angochitina communis* Jenkins, 1967.
12. *Tanuchitina ontariensis* Jansonius, 1964.
13. *Plectochitina sylvanica* Jenkins, 1970.
14. *Armoricochitina alborzensis* Ghavidel-syooki and Winchester-seeto, 2002.
- 15, 16. *Cyathochitina campanulaeformis* Eisenack, 1931.



Sarjeant and Stancliffe, 1994.

*Dorsennidium hamii* (Loeblich, 1970) Sarjeant and Stancliffe, 1994 (Plate II, 4).

Genus *Leiofusa* Eisenack, 1938 emend. Combaz et al., 1967.

*Leiofusa squama* (Deunff) Combaz, Lange and

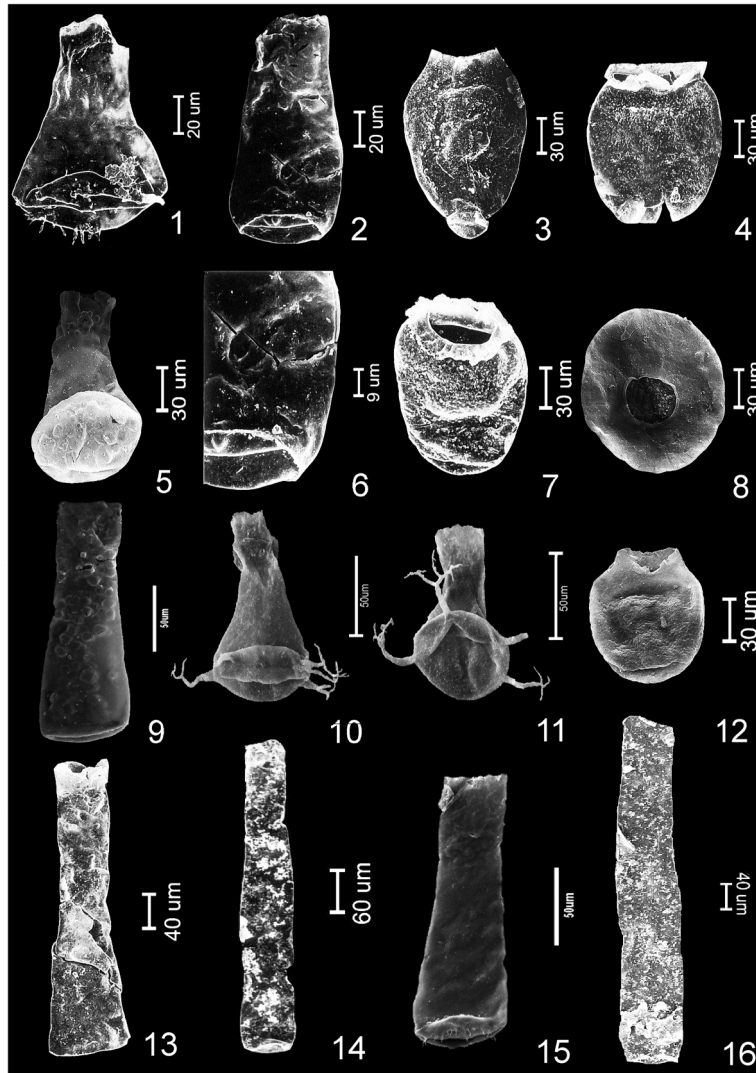


Plate IV

**Plate IV**

1. *Plectochitina concinna* Achab, 1978.
- 2, 6. *Tanuchitina ontariensis* Jansonius, 1964.
3. *Desmochitina juglandiformis* Laufeld, 1967.
4. *Desmochitina nodosa* Eisenack, 1931.
5. *Euconochitina lepta* (Jenkins, 1970) Paris et al. 1999.
7. *Desmochitina erinacea* Eisenack, 1931.
8. *Calpichitina lenticularis* (Bouché, 1965).
9. *Euconochitina moussegoudaensis* Paris in Le Herissé et al. 2013.
- 10, 11. *Ancyrochitina merga* Jenkins, 1970.
12. *Desmochitina minor* Eisenack, 1931.
13. *Spinachitina bulmani* Jansonius, 1964.
14. *Rhabdochitina gracilis* (Eisenack, 1931).
15. *Spinachitina oulebsiri* Paris et al. 2000.
16. *Tanuchitina elongata* (Bouché, 1965).

Pansart, 1967 (Plate I, 9).

*Leiofusa simplex* (Combaz, 1967) Martin, 1975  
(Plate I, 10).

*Leiofusa litotes* Loeblich and Tappan, 1978 (Plate I,  
16).

Genus *Musivium* Wood and Turnau, 2001.

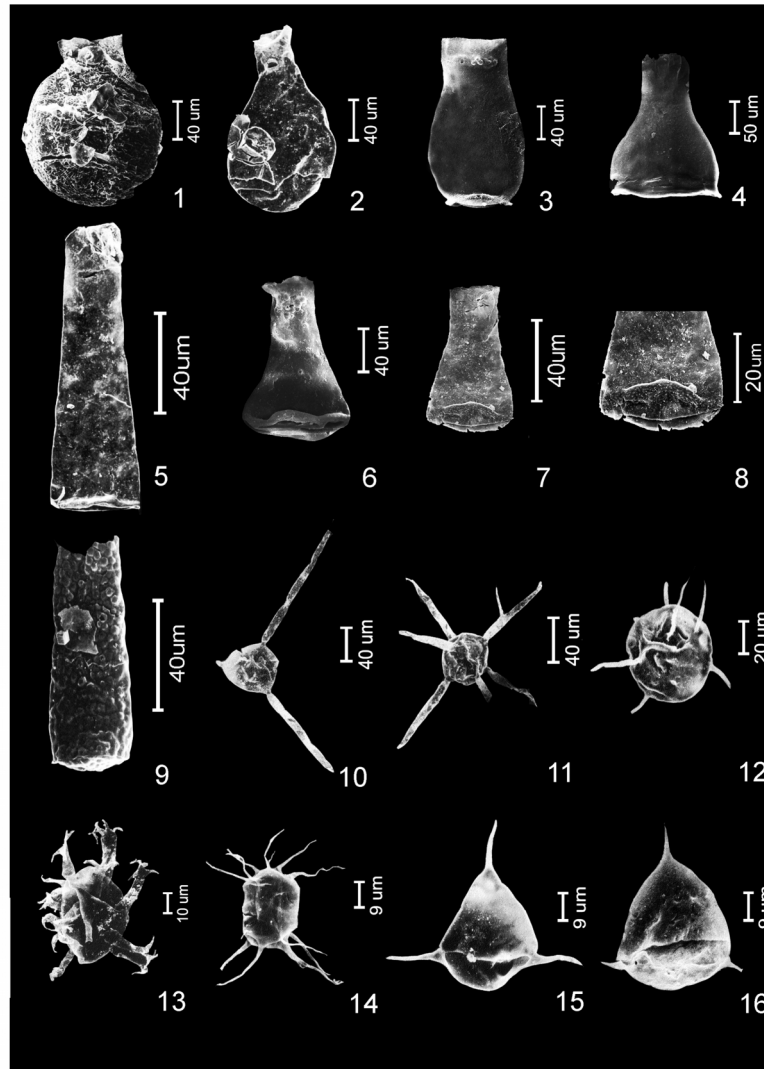


Plate V

**Plate V**

1. *Lagenochitina prussica* Eisenack, 1931.
2. *Lagenochitina baltica* Eisenack, 1931.
3. *Calpichitina lenticularis* (Bouché, 1965).
4. *Cyathochitina campanulaeformis* Eisenack, 1931.
5. *Tanuchitina fistolosa* Taugourdeau and de Jekhowsky, 1960.
6. *Euconochitina lepta* (Jenkins, 1970) Paris et al. 1999.
- 7, 8. *Spinachitina oulebsiri* Paris et al. 2000.
9. *Hyalochitina* sp.
10. *Orthosphaeridium ternatum* (Burmans, 1970) Eisenack, et al., 1976.
11. *Baltisphaeridium perclarum* Loeblich and Tappan, 1978.
12. *Baltisphaeridium oligopsakium* Loeblich and Tappan, 1978.
13. *Ordovicidium elegantulum* Tappan and Loeblich, 1971.
14. *Acanthodiacrodium crassus* (Loeblich and Tappan, 1978) Vecoli, 1999.
15. *Verhachium reductum* (Deunff, 1958) de Jekhowsky, 1961.
16. *Verhachium subglobosum* Jardine et al. 1974.

- Musivium gradziniskii* Wood and Turnau, 2001 (Plate I, 12)
- Genus *Micrhystridium* (Deflandre, 1937) emend. Staplin, 1961, emend. Lister, 1970, emend. Turner, 1984.
- Micrhystridium shinetonensis* Downie, 1982 (Plate I, 4)
- Genus *Multiplicisphaeridium* Staplin, 1961 emend. Turner, 1984
- Multiplicisphaeridium irregulare* Staplin, Jansonius and Pocock, 1965 (Plate II, 7)
- Genus *Navifusa* Combaz, Lange and Pansart, 1967 ex Eisenack, 1976
- Navifusa ancepsipuncta* Loeblich, 1970 ex Eisenack, Cramer and Diez, 1979 (Plate II, 16)
- Genus *Neoveryhachium* Cramer, 1971
- Neoveryhachium* sp. cf. *N. carminae* (Cramer) Cramer, 1970 (II, 11)
- Genus *Ordovicidium*. Tappan and Loeblich, 1971
- Ordovicidium elegantulum* Tappan and Loeblich, 1971 (Plate V, 13)
- Genus *Orthosphaeridium* Eisenack, 1968 emend. Kjellström, 1971
- Orthosphaeridium rectangulare* (Eisenack, 1963) Eisenack, 1968 (Plate II, 9)
- Orthosphaeridium insculptum* Loeblich, 1970 (Plate II, 1)
- Orthosphaeridium ternatum* (Burmman, 1970) Eisenack, Cramer and Diez, 1976 (Plate V, 10)
- Genus *Safirotheca* Vavrdova', 1989
- Safirotheca safira* Vavrdova', 1989 (Plate II, 14, 15)
- Genus *Saharidia* Combaz, 1967
- Saharidia fragilis* (Downie, 1958) Combaz, 1967 (Plate I, 1)
- Genus *Tylotopalla* Loeblich, 1970
- Tylotopalla* sp. cf. *T. caelamenicutis* Loeblich, 1970 (Plate II, 5)
- Genus *Verhachium* Deunff, 1954 emend. Sarjeant and Stancliffe, 1994
- Verhachium lairdii* (Deflandre) Deunff 1959 ex Downie 1959 (Plate II, 3)
- Verhachium reductum* (Deunff, 1958) de Jekhowsky, 1961 (Plate V, 15)
- Verhachium subglobosum* Jardiné Combaz, Magloire, Peniguel and Vachey 1974 (Plate V, 16)
- Verhachium strangulatum* Le Herisse, Al-Tayyar and van der Eem, 1995 (Plate II, 13)
- Verhachium triangulatum* Konzalova-Mazancova, 1969 (Plate II, 12)
- Genus *Vulcanisphaera* Deunff, 1961, emends. Rasul, 1976.
- Vulcanisphaera africana* Deunff, 1961 (Plate I, 7)
- Vulcanisphaera britannica* Rasul, 1976 (Plate I, 3)

### **Acritarch biostratigraphy**

The encountered acritarch taxa in the Abastu and Abarsaj formations consist of 23 acritarch species (15 genera). In this study, two local acritarch assemblage zones were recognized and are discussed in ascending stratigraphical order as follows (Fig. 2):

### **Acritarch assemblage Zone I**

This biozone is marked by the occurrence of several acritarch taxa between samples MG-A to MG-K, through a total thickness of 108 m in the Abastu Formation (Fig. 2). This acritarch assemblage zone consists of *Acanthodiacrodium angustum*, *Saharidia fragilis*, *Micrhystridium shintonensis*, *Vulcanisphaera africana*, *Vulcanisphaera britannica*, *Aryballomorpha grootaertii*, *Athabascaella penika*, *Acanthodiacrodium ubuii*, *Leiofusa simplex* and *Leiofusa squama*. From stratigraphical point of view, the acritarch species of *S. fragilis*, *M. shintonensis*, *V. britannica*, *A. grootaertii* and *A. penika* have so far been recorded from the Middle–Upper Tremadocian Shinetone Shale of England (47, 48); the Lower Tremadocian subsurface material of Algeria, the Tremadocian of Montagne Noire, France, Tremadocian, Lashkarak Formation of central to Northeastern Alborz Mountains of Iran (16); Early Ordovician of North-East China. Likewise, the acritarch species of *V. africana*, *A. angustum*, *L. simplex* and *L. squama* have been previously recorded from the Lower Tremadocian of the Algerian Sahara; the Upper Tremadocian of England; the Upper Tremadocian of Poland; the Upper Tremadocian of Belgium; and the Lower Ordovician of the Iranian Platform (17). *A. ubuii* has been recorded from the Tremadocian of Norway (62); the Upper Cambrian (Furongian) and Lower Ordovician (Tremadocian) of England (11); the Tremadocian of Belgium (35); and the Upper Cambrian (Furongian) of Newfoundland of Canada (44). *A. angustum* is a typical species of the uppermost Cambrian-lower Tremadocian strata of Belgium (6), France (35), Algeria (6), England (10) and Iran (17). Furthermore, *L. squama* (*D. squama*) has so far been reported from the Tremadocian of the Hassi-Messaoud, Algeria (6); the Tremadocian of England (11); the Tremadocian of the Kopeh-Dagh (17). Finally, *A. grootaertii* and *A. penika* have been recorded from the Early Ordovician (Tremadocian) of northeast China (36). There are no chitinozoan taxa in the Abastu Formation; therefore, based on the stratigraphic potentials of the aforementioned acritarch taxa, an Early Ordovician (Tremadocian) age is suggested for the Abastu Formation in the Fazel Abad area. Comparison of these Lower Ordovician acritarch taxa of this assemblage zone with those from other parts of the

world indicates broad similarity with those from the "Mediterranean Acritarch Province.

### *Acritarch assemblage II*

This assemblage is well defined by the disappearance of completed acritarch species Assemblage I, and appearance of the Late Ordovician acritarch taxa, consisting of *Acanthodiacrodium crassus*, *Multiplicisphaeridium irregulare*, *Orthosphaeridium insculptum*, *Orthosphaeridium ternatum*, *Orthosphaeridium rectangulare*, *Ordoviciidium elegantulum*, *Dactylofusa striata*, *Dactylofusa platynetrella*, *Dactylofusa cabottii*, *Dactylofusa cucurbita*, *Baltisphaeridium oligopsakium*, *Baltisphaeridium perclarum*, *Baltisphaeridium constrictum*, *Dorsennidium hamii*, *Tylotopalla* sp.cf. *T. caelamenicutis*, *Safirotheca safira*, *Diexaplophosis denticulata*, *Neoveryhachium* sp. cf. *N. carminae*, *Veryhachium lairdii*, *Navifusa ancepsipuncta*, *Veryhachium reductum*, *Veryhachium subglobosum* and *Musivium gradziniskii*. These are associated with the reworked Early Ordovician (Floian) acritarch taxa (e. g. *Striatotheca principalis*, *S. fragilis*, and *V. africana*), which probably originated from neighboring areas with short transport distance since they have good preservation. Amongst the aforementioned, the Late Ordovician acritarch species of this zone, *V. subglobosum* has been recorded from the Richmondian (Katian) of Oklahoma (32), Missouri (63), Algerian Sahara (28), Libya (38); the Katian of Canada (26); the Upper Ordovician of Morocco (14); Jordan (28) and Iran (20, 21); the Upper Ordovician of Czech Republic (57); the Ashgill deposits of Portugal (12). The acritarch species of *Baltisphaeridium oligopsakium*, *Baltisphaeridium constrictum*, *O. rectangulare*, *Navifusa ancepsipuncta* and *A. crassus* are typical acritarch taxa which have been recorded from the Late Ordovician elsewhere. Furthermore, some of the acritarch species of this zone, such as *Multiplicisphaeridium irregulare*, *Ordoviciidium elegantulum*, *V. lairdii* group, *V. trispinosum* group, *Orthosphaeridium ternatum* and *Dactylofusa cabottii* have been recorded from the Middle-Upper Ordovician strata of Sweden, England, the United States, Czech Republic, Saudi Arabia, China and Iran. It is worth mentioning here that *Dactylofusa cabottii* (15), is a common palynomorph in the Ordovician – Silurian shallow-water, nearshore, marine strata (63, 64). However, it has also been reported from various non-marine deposits, attributed to a possible euglenoid oldest freshwater protozoan (65). *D. cabottii* has a widespread occurrence from nearshore to marine strata; therefore, it can be tentatively placed in the marine

affinity and will remain as such until further evidence is obtained. Furthermore, *Musivium gradziniskii* (65) is another common palynomorph in the Abarsaj Formation. This species has been recorded from the Devonian, the Holy Cross Mountain and Radom – Lublin region of Poland and is assigned to Family Hydrodictyaceae of the Chlorophyta. Based on its coenobial habit and comparison with extant Hydrodictyaceae, which are found only in fresh to brackish water, the depositional environment of *M. gradziniskii* is interpreted as a very nearshore to offshore-shelf. On the other hand, based upon acritarch biostratigraphy of the *Dicellogratus complanatus* graptolite Zone from the Katian Vaureal Formation of Anticosti Island, Québec, Canada (26) and the Katian, Maquoketa Shale of Northeastern Missouri (63), all acritarch species of this assemblage zone are present in the Abarsaj Formation, indicating a Late Ordovician (Katian) age. Therefore, both the acritarch and chitinozoan taxa of this Formation are assigned to part of time slice 6a of the Katian age. It should be mentioned that the reworked acritarch taxa from the Floian-Darriwilian, as well as Sandbian are present in the *Armoricochitina nigerica* chitinozoan biozone which persists into the succeeding chitinozoan biozones of the Abarsaj Formation (Fig. 2). The important recycled acritarch species in the Abarsaj Formation are *Saharidia fragilis*, *Striatotheca principalis* and *Athabascaella penika*, which suggest the onset of erosive processes probably related to local tectonic readjustment, or alternatively the marine transgressive events from the Dapingian, Darriwilian and Sandbian. This reworked acritarch event has also been reported in Saudi Arabia, Libya, Morocco, Algeria, Turkey and the Zagros Basin of Iran (44, 20, 21). Herein, it should be mentioned that a few acritarch species such as *Dactylofusa cucurbita* and *Safirotheca safira* are restricted to the peri-Gondwanan palaeo-province. Likewise, some acritarch and chitinozoan taxa from Baltica and Laurentia are associated with the peri-Gondwanan elements, which suggest the existence of counter-clockwise marine currents which resulted in bringing planktonic organisms (acritarchs and chitinozoans) from lower latitudes (Baltica) to higher latitudes (Northern Gondwana).

### *Chitinozoans*

The following chitinozoan taxa were identified (Plate III- V):

Order Operculifera Eisenack, 1931

Family Desmochitinidae Eisenack, 1931. emend. Paris, 1981

Subfamily Desmochitininae. Paris, 1981

Genus *Calpichitina* Wilson and Hedland, 1964  
*Calpichitina lenticularis* (Bouché, 1965) (Plate IV, 8; Plate V, 3)  
 Genus *Desmochitina* Eisenack, 1931  
*Desmochitina cocca* Eisenack, 1931 (Plate V, 9)  
*Desmochitina minor* Eisenack, 1931 (Plate IV, 12)  
*Desmochitina erinacea* Eisenack, 1931 (Plate IV, 7)  
*Desmochitina juglandiformis* Laufeld, 1967 (Plate IV, 3)  
*Desmochitina nodosa* Eisenack, 1931 (Plate IV, 4)  
 Subfamily Pterochitininae Paris, 1981  
 Genus *Armoricochitina* Paris, 1981  
*Armoricochitina alborzensis* Ghavidel-Syooki and Winchester-Seeto, 2002 (Plate III, 14)  
*Armoricochitina iranica* Ghavidel-Syooki and Winchester-Seeto, 2002 (Plate III, 5)  
*Armoricochitina nigerica* (Bouché, 1965) (Plate III, 2)  
 Subfamily Ancyrochitininae Paris, 1981  
 Genus *Ancyrochitina* Eisenack, 1955  
*Ancyrochitina merga* Jenkins, 1970 (Plate IV, 10, 11)  
 Genus *Angochitina* Eisenack, 1931  
*Angochitina communis* Jenkins, 1967 (Plate III, 11)  
 Genus *Plectochitina* Cramer, 1964  
*Plectochitina cocinna* Achab, 1978 (Plate IV, 1)  
*Plectochitina sylvanica* Jenkins, 1970 (Plate III, 13)  
 Subfamily Belonechitininae Paris, 1981  
 Genus *Hercochitina* Jansonius, 1964  
*Hercochitina crickmayi* Jansonius, 1964 (Plate III, 3, 7)  
 Order Prosomatifera Eisenack, 1972  
 Subfamily Conochitininae Paris, 1981  
 Genus *Euconochitina* Taugourdeau, 1966, emends. Paris et al. 1999  
*Euconochitina moussegoudaensis* Le Herissé, Paris and Steemans, 2013 (Plate III, 8).  
 Genus *Rhabdochitina* Eisenack, 1931  
*Rhabdochitina gracilis* Eisenack, 1962 (Plate IV, 14)  
*Rhabdochitina usitata* Jenkins, 1967 (Plate III, 1)  
 Genus *Euconochitina* Taugourdeau, 1966 emend. Paris. Grahn, Nestor and Lakova, 1999.  
*Euconochitina lepta* (Jenkins, 1970) emend. Paris. Grahn, Nestor and Lakova, 1999 (Plate III, 10; Plate IV, 5; Plate V, 6)  
 Subfamily Cyathochitininae Paris, 1981  
 Genus *Cyathochitina* Eisenack, 1955 emend. Paris, Grahn, Nestor and Lakova, 1999  
*Cyathochitina campanulaeformis* (Eisenack, 1931) 1955b (Plate III, 15, 16; Plate V, 4)  
 Family Lagenochitinidae (Eisenack, 1931) Paris, 1981.  
 Subfamily Lagenochitinidae Eisenack, 1931 emend. Paris, Grahn, Nestor, Lakova, 1999.

Genus *Lagenochitina* Eisenack, 1931  
*Lagenochitina baltica* Eisenack, 1931 (Plate V, 2)  
*Lagenochitina prussica* Eisenack, 1931 (Plate V, 1)  
 Subfamily Tanuchitininae Paris, 1981  
 Genus *Tanuchitina* Jansonius, 1964 emend. Paris, Grahn, Nestor, and Lakova, 1999  
*Tanuchitina elongata* Bouché, 1965 (Plate IV, 16)  
*Tanuchitina ontariensis* Jansonius, 1964 (Plate III, 12; Plate IV, 2, 6)  
*Tanuchitina fistulosa* Taugourdeau and de Jekhowsky, 1960 (Plate III, 4; Plate V, 5)  
 Genus *Hyalochitina* Paris, Grahn, Nestor, and Lakova, 1999  
*Hyalochitina* sp. (Plate V, 8)  
 Order Prosomatifera Eisenack, 1972  
 Subfamily Spinachitininae Paris, 1981  
 Genus *Spinachitina* Schallreuter, 1963. emend. Paris, Grahn, Nestor and Lakova, 1999  
*Spinachitina bulmani* (Jansonius, 1964) (Plate IV, 13)  
*Spinachitina oulebsiri* Paris, Bourahrouh and Le Hérisse, 2000 (Plate IV, 15; Plate V, 7, 8)  
*Spinachitina* sp. (Plate III, 6)

The distribution of the above-mentioned chitinozoan taxa in the study section (Fig. 2) allows recognition of four biozones which are discussed in ascending stratigraphical order as follows:

#### ***Armoricochitina nigerica* Biozone I (40)**

This biozone is marked by the first occurrence of *Armoricochitina nigerica* in sample MG-K and extends through a thickness of 59 m to sample MG8444 (Fig. 2). According to Paris (40, 41) and subsequent studies (4), the *A. nigerica* biozone is a partial-range biozone corresponding to the stratigraphic interval from the first appearance of the eponymous species up to the first appearance of *Ancyrochitina merga*, the index species of the succeeding biozone. The *Armoricochitina nigerica* biozone is correlated to the upper part of the *complanatus* graptolite zone of the British Standard (61), thus corresponding to the Early Katian. Co-occurring chitinozoan taxa in this assemblage are *Desmochitina minor*, *Desmochitina juglandiformis*, *Desmochitina nodosa*, *Desmochitina erinacea*, *Lagenochitina baltica*, *Lagenochitina prussica*, *Armoricochitina iranica*, *Armoricochitina alborzensis*, *Calpichitina lenticularis*, *Euconochitina moussegoudaensis*, *Spinachitina bulmani* and *Rhabdochitina gracilis*. The two species of *Armoricochitina iranica* and *Armoricochitina alborzensis* have been previously recorded in Iran from the Katian of the Northeastern Alborz Mountains, (upper part of the Ghelli Formation (18)). *Calpichitina*

*lenticularis* is a commonly occurring species in the Upper Ordovician stratal sequences of the so called "Northern Gondwana Domain" (40, 41), including North Africa, southwestern Europe, Turkey, Saudi Arabia and Iran. *Spinachitina bulmani* is also a common accessory species of the *A. nigerica* biozone in the North Gondwana Domain (40); it is known to occur from the Sandbian of Scotland and Shropshire (27, 29); the Upper Ordovician of Morocco (13); the Katian of Anticosti, Québec, Canada (1), Norway (24), and Libya (38). *L. baltica* is a well-known species in the Katian both in the Gondwana and the Baltica. So far, this species has been reported in the Katian of Baltica (23); the Lower Middle Ordovician sediments in the Southern Appalachians, the United States (33, 34); Upper Ordovician of Algerian Sahara (42); the Upper Ordovician of Iran (18, 19, 20); the Katian strata of Greenscoe section, Southern Lake District of Britain (55); the Katian of the Vitriival-Bruyère and the Fosses formations, Belgium (56) and the Katian of Southeastern Turkey (44). *Lagenochitina prussica* has been reported from the Molodova Beds (Katian), Podolia; Ukraine, the lower Katian Fjäckå Shale, Dalarna, Sweden; the Lower Katian Vormsi stage, Estonia; the Katian deposits of the Algerian Sahara and the uppermost part of the Bios de Presles Member and lower part of the Faulx les Tomber Member of the Fosses Formation (Katian) of Belgium and the Upper Ordovician Gorgan Schists in southeastern the Caspian Sea (19). *Rhabdochitina gracilis* is recorded for the first time in the Iranian Platform. This species has previously been recorded from the Upper Langevoja to Lower Valaste (uppermost Lower Ordovician to Darriwilian) and the Seby to Lower Dalby limestones (Darriwilian) of Öland, Sweden; the Hunderum (uppermost Floian-lowermost Darriwilian), Dalarna, Sweden and the Aluoja to Kukruse (Upper Darriwilian-Lower Sandbian), Estonia (22). *Euconochitina moussegoudaensis* is a common species in the Abarsaj Formation and it has so far been recorded from basal part of Tanezzuft Formation referred to the latest Hirnantian-basal Rhuddanian in the Moussegouda core hole Northern Chad (31) and the Late Ordovician of the Gorgan Schists, northern Iran (19). *D. juglandiformis* has been recorded from the upper Sandbian-Katian Vitriival-Bruyère Formation and even the basal part of the Katian Fosses Formation in Belgium (56), and the Upper Ordovician of Arabian peninsula (2). Vammeirhaeghe (56) noted that *D. juglandiformis* has not only been recorded from Laurentia, but has also been found in the *Belonechitina robusta* Biozone of Northern Gondwana (only Southern Spain). In Hartfell Score, Scotland (Laurentia), *D. juglandiformis* has been

recorded from the upper part of the graptolite *wilsoni* Biozone to the lower part of the graptolite *clingani* Biozone (58). *Desmochitina nodosa* has been previously recorded from the middle Sandbian of Estonia; the upper Sandbian to lower Katian of Sweden; the Upper Ordovician erratic boulders of Baltica (23) and the Katian Vitriival-Bruyère and the Fosses formations of Belgium (56).

#### ***Ancyrochitina merga* Biozone II (40)**

This biozone has been identified on the basis of the occurrence of the eponymous species between samples MG8444 and MG8451, through a total thickness of 41 m within the Abarsaj Formation (Fig. 2). According to Paris (40) and subsequent studies (4), the *Ancyrochitina merga* Biozone is an interval-range zone between the FAD of *A. merga* and the FAD of *Tanuchitina elongata*, the index species of the succeeding biozone. Arguments concerning the biostratigraphic age of this biozone have been presented in Paris (40) and Bourahrouh et al. (4), supported a Late Katian age. Co-occurring species are *C. lenticularis*, *D. minor*, *D. erinacea*, *D. juglandiformis*, *C. campanulaeformis*, *S. bulmani*, *L. baltica*, *L. prussica*, *A. iranica* and *A. alborzensis*, which range through the present biozone from the underlying *A. nigerica* Biozone (Fig. 2). In addition, three species of *Plectochitina sylvanica*, *P. concinna* and *Euconochitina lepta* make their first inception at the base of the present biozone (sample MG8444). So far, *Plectochitina sylvanica* has been recorded from the Katian of Oklahoma, the United States, Libya, Morocco, Saudi Arabia and Iran. *Plectochitina sylvanica* is a commonly co-occurring species of the *A. merga* Biozone in the Northern Gondwana Domain (2, 4, 18, 40). *Plectochitina concinna* has so far been known from the Katian Vaureal Formation Anticosti Island, Canada (22, 23) and it is recorded from the Abarsaj Formation in Iran for the first time. *Euconochitina lepta* is also a well-known species from the Katian of Oklahoma (Jenkins, 1970), North Africa (39, 42), Saudi Arabia (43), Iran (20, 21)) and Turkey (44). Furthermore, except for acritarch species of *Dactylofusa striata* which disappears at the base of this biozone, the remainder of acritarch taxa of underlying Biozone, consisting of *Multiplicisphaeridium irregulare*, *O. insculptum*, *O. rectangulare*, *A. crassus*, *O. elegantulum*, *B. oligopsakium*, *B. perclarum*, *V. lairdii* group, *N. ancepsipuncta*, *V. trispinosum* group also continues through *Ancyrochitina merga* Biozone. Therefore, both acritarch and chitinozoan taxa of this part of the Formation are assigned to part of time slice 6b of the Katian Stage (Webby et al., 2004).

***Tanuchitina elongata* Biozone III (40)**

This biozone is characterized by the FAD of *Tanuchitina elongata* in sample MG8451 and extends through a thickness of 46 m to sample MG8461 of the Abarsaj Formation (Fig. 2). This biozone corresponds to the partial-range biozone of *T. elongata* (3) from its first occurrence up to the first appearance of *Spinachitina oulebsiri* (61), the index species of succeeding biozone. The species of *T. elongata* is herein regarded as senior synonym of *Tanuchitina bergstromi* (23). It should be noted that the *Tanuchitina elongata* Biozone previously used to be the highest chitinozoan biozone in the North Gondwana Domain (40). Subsequent studies such as Paris et al. (42) on the Upper Ordovician marine glacial sediments in well NI-2 (NE-Algerian Sahara) resulted in a new chitinozoan species of *Spinachitina oulebsiri* from the M' Kratta Formation, suggesting an early Hirnantian age. This biozone is well documented in North Africa (Morocco, Tunisia, Libya, Algeria and Iran (19, 39, 40), the Ra'an Shale Member of the Qasim Formation in Saudi Arabia (37) and Upper Ordovician of the Gorgan Schists, southern the Caspian Sea (19). According to Paris (40), at least the upper part of the Ra'an Shale Member of the Qasim Formation in Saudi Arabia is referred to in the *T. elongata* Biozone which is associated with the *Glyptograptus persculptus* graptolite zone, suggesting part of the Hirnantian Stage (Webby et al., 2004). However, subsequent studies of Paris et al. (42) also suggested the presence of *Spinachitina oulebsiri* Biozone for late Hirnantian age in the uppermost part of the Halevikdere Formation, in Turkey. In this biozone, the associated chitinozoan taxa are *Tanuchitina* sp., *Tanuchitina ontariensis*, *Hercochitina crickmayi* (27) and *Hyalochitina* sp. *Tanuchitina ontariensis* is a characteristic species of the Late Ordovician and it has so far been reported from the Late Ordovician of the Sylvan Shale (Katian) of Oklahoma in the USA (29), Southern Ontario in Canada (27), Saudi Arabia (2), and Turkey (44); the Late Ordovician of Iran (19, 18, 20). Moreover, many acritarch and chitinozoan taxa of preceding biozones enter in this chitinozoan biozone (Fig. 2). This chitinozoan biozone of the North Gondwana Domain is used to define the time slice of 6c for this biozone in the Fazel Abad area (61).

***Spinachitina oulebsiri* Biozone IV (42)**

This chitinozoan biozone has been recognized in the uppermost part of the Abarsaj Formation; it coincides with the occurrence of *Spinachitina oulebsiri* in sample MG8461 and extends to MG8471, through a thickness of 48 m in the study sequence (Fig. 2). This species has been originally established in the Upper Member of the

M' Kratta Formation, northeast Algerian Sahara, Bordj Nili area (Paris et al., 2000a), and was indirectly correlated with the *persculptus* graptolite zone, of latest Hirnantian age (61). Accordingly, the *Oulebsiri* chitinozoan biozone is of particular interest for correlation of latest Ordovician strata and for the recognition of the Ordovician-Silurian boundary. Therefore, this chitinozoan biozone of the North Gondwana Domain is used to define the upper part of time slice of 6c for this biozone in the Fazel Abad area (61).

However, Butcher (5) has recently questioned the taxonomic validity of this species, and hence the usefulness of the associated biozone, demonstrating that it is impossible to find quantitative criteria to clearly distinguish *Spinachitina oulebsiri* (42), from *Spinachitina fragilis*; this latter was then considered by Butcher (5) as senior synonym of the former. According to Paris (42), *S. oulebsiri* could be regarded as an early morphotype stage of the *S. fragilis* lineage, characterized by "the increase of the vesicle's length, by a progressive differentiation of the flexure, and by the development of a crown of spines on the margin while the diameter remains more or less stable" (42, p. 101). Vandenbroucke et al. (2009) also recognized the objective difficulties in differentiating species within the *S. oulebsiri*-*S. fragilis* lineage, especially in moderately preserved material as in the case of the present study. However, Vandenbroucke et al. (55) decided to retain the two species separately, pending more comprehensive analyses. They considered the split between the two morphotypes as being supported by subtle differences (conical vs. cylindrical basal spines, and overall stouter vs. slender chamber appearance in *S. oulebsiri* and *S. fragilis*, respectively). The present material is certainly not adapted to a basis for a taxonomical analysis and revision since both chitinozoan and acritarch taxa of Abarsaj Formation are related to the Late Ordovician whereas the Silurian volcanic materials of Nekarman Formation are barren of palynomorph entities. In addition, some diagnostic chitinozoan species of preceding biozones are still present in this biozone, consisting of *C. lenticularis*, *L. prussica*, *L. baltica*, *E. lepta*, *D. minor* and *E. moussegoudaensis*. Furthermore, most acritarch taxa of preceding biozones disappear at the onset of this chitinozoan biozone and only two acritarch species such as *M. irregulare* and *O. elegantulum* continue throughout this biozone (Fig. 2).

***Integrated acritarch and chitinozoan biostratigraphy***

Despite the fact that recent studies have demonstrated the potential for a refined biozonation that would allow

the recognition of several acritarch biozones at least for the Katian–Hirnantian interval (8, 9, 20, 59), no formal acritarch zonation exists to subdivide the Upper Ordovician. It is only by means of further detailed studies of the Upper Ordovician sedimentary successions worldwide in which independent age evidence is present that progress towards a stable acritarch biozonation can be achieved (58, 59). The present results are to be considered a contribution towards such a goal, and the distribution of the acritarchs are mainly discussed in the context of the chronostratigraphic framework suggested by the chitinozoans, where they are present (that is, in the Upper Ordovician part of the sequence). The vertical distribution of acritarch species highlights two major changes of the palynoflora throughout the study sequence, which in turn permit the identification of two different assemblages. The first conspicuous change is marked by the appearance and disappearance of the Lower Ordovician acritarch species, consisting of *A. angustum*, *S. fragilis*, *M. shintonensis*, *V. africana*, *V. britannica*, *L. simplex*, *L. squama*, *A. grootaerii*, *A. penika* and *A. ubuii* at stratigraphic levels (MG-A to MG-K), coinciding with the base of the Abastu Formation up to the base of the Abarsaj Formation, or the *nigerica* chitinozoan (Fig. 2; Table 1) Biozone as recognized in this study section (Katian; Fig. 2). The second critical palynofloral change is characterized by occurrence of acritarch species including that of *V. setosapellicula*, *M. irregulare*, *O. insculptum*, *O. rectangulare*, *A. crassus*, *O. elegantulum*, *B. oligopsakium*, *B. perclarum*, *V. lairdii*, *N. ancepsipuncta*, *V. trispinosum* group, *G. antiquum*, *S. safira*, *D. cucurbita*, *Tylotopalla* sp., and *Neoveryhachium* sp. cf. *N. carminae* at stratigraphic levels (MG-8433 to MG-8471), corresponding to the base of the Nekarman Formation (the top of the Abarsaj Formation, or the top of the *oulebsiri* Biozone) and it is defined by the extinction of all the taxa. According to the standard Ordovician chitinozoan biozonations (40, 41), there is a hiatus between the Abastu and Abarsaj formations corresponding to *L. destombesi* to *B. robusta* chitinozoan Biozones (Floian-Sandbian). The absence of these chitinozoan biozones affirms that a tectonic activity has happened between the acritarch Assemblage I and Assemblage II, possibly coinciding with the Caledonian Orogeny. In North Africa, the aforementioned acritarch species become extinct at the base of the *oulebsiri* chitinozoan Biozone which is associated with glacial-related sedimentary setting (4, 42). The effects of the well-known Hirnantian glaciation on acritarch Assemblage II is difficult to evaluate due to the presence of a sedimentary hiatus. Detailed

discussions on the global stratigraphic occurrences of the above taxa can be found in references of 58 and 46 and do not need to be repeated here. It is interesting to note that triangular and quadrangular morphotypes of *Veryhachium* (*V. trispinosum* group and *V. lairdii* group) are abundant in the Assemblage II. In previous studies elsewhere, it has been highlighted that a marked change in the relative proportion of abundance of quadrangular vs. triangular *Veryhachium* is observed in coincidence with the onset of glacial related palaeoenvironmental conditions during Hirnantian times, with quadrangular *Veryhachium* largely dominating over triangular morphotypes (4, 42, and 59). Generally, no abrupt extinction is recorded in the fossil record of acritarchs in conjunction with the onset of the Hirnantian glaciation in Gondwana, as has been shown by several studies (58, 59). However, Vecoli (58) and Ghavidel-syooki et al. (20). On the basis of a detailed review on acritarch data across the Ordovician–Silurian transition concluded that an “acritarch turn-over” might be a more appropriate term to describe the significant but gradual changes of the acritarch palynoflora occurring through the end-Ordovician glaciation.

#### ***Palaeobiogeographical implications of palynological assemblages***

Since the paper published by Vavrdová (57), who introduced the concept of palaeolatitudinally-controlled acritarch biogeographical provincialism during Ordovician times, several studies have been published confirming not only the validity of such a concept, but also the successful application of acritarch biogeographic distribution for palaeogeographic reconstructions (16, 46, 50, 59). These models show that biogeographic differentiation of acritarch assemblages started in the Early Ordovician and reached a maximum level in mid-Ordovician (Darriwilian), evidencing a clear distinction between a peri-Gondwanan acritarch “province.” Playford et al., (46: pp. 45 – 46) stated a broad, latitudinally extensive, circumpolar, cold to cool temperate, palaeogeographic belt along the Northern Gondwana border from Argentina through eastern Newfoundland, North Africa, Central and Southern Europe, and Southern Turkey to South China and a Baltican acritarch “province” diffused “primarily in Baltica, including Norway, Sweden, Estonia and Russia, and Poland”). Differentiation of cold-water and warm-water acritarch assemblages has been proposed also for the Tremadoc–Arenig interval (Tremadocian to early Dapingian in terms of modern stratigraphic nomenclature). The “*messaoudensis-trifidum*” assemblage has been defined as a cold-water assemblage in high latitude peri-Gondwana localities



(38). The *Aryballomorpha–Athabascaella–Lua* “warm water” assemblage has been identified in low-latitude localities of Laurentia and China (50). The factors controlling acritarch bioprovincialism are not yet entirely known and evaluated, and even if the palaeolatitudinal gradient plays a role, the effects of oceanic currents (58,59) and continental physiography (50) also have a major influence on the palaeobiogeographical differentiation on ancient oceanic microphytoplankton. So far, evidence for a Late Ordovician acritarch palaeoprovincialism has been considered meager. Insignificant provincialism of acritarch assemblages during Late Ordovician times has been suggested in many previous publications. Molyneux et al. (38) noted that Late Ordovician (Ashgill) acritarch assemblages from Northeastern Libya displayed some similarity to those recorded from coeval sediments in North America. Uutela and Tynni (54) reported that 20% of the Late Ordovician acritarch species of Estonia were common with those known from Baltica and the North America regions. Both the Late Ordovician acritarch assemblages of Molyneux et al. (38; Libya) and Uutela and Tynni (54; Estonia) included significant proportions of previously unrecorded species with unclear biogeographic significance. Le Hérissé (in 38) noted that Late Ordovician microphytoplankton reveal conspicuous similarity at the generic and specific levels throughout the world, indicating insignificant provincialism during this time. Similarly, Playford and Wicander (64: U. S. A.) have stated that undoubted provincialism existed during the Early and Middle Ordovician, but this condition was diminished during the Late Ordovician (Ashgill). More recent papers by Li et al. (32) from the Late Ordovician of China and Iran (19, 21) support little microphytoplankton provincialism during Late Ordovician time. Lack of evidence for a biogeographic differentiation of acritarch assemblages might also result from an insufficient data set and hence a difficulty in the comparison between assemblages from different palaeocontinents (50). Notably, North American Upper Ordovician localities were largely under-investigated for organic-walled microphytoplankton assemblages, compared to North African or Baltic localities. Wicander (50) noted that North American Late Ordovician acritarch studies did not include entire assemblages but only a few selected species; many assemblages were based on one or only a few samples from a single locality and most of the reported occurrences were not from continuous sections. This situation has started to change more recently with the publication of monographs on acritarch assemblages from well-dated sections from North America (63, 64),

including the first detailed study of the rich and diverse acritarch flora from the well-known Upper Ordovician sections of Anticosti Island, Québec, Canada (7). These recent data on Upper Ordovician acritarch assemblages from Laurentian localities and their comparison with Baltican data, allow a new model of acritarch palaeobiogeographical differentiation during the Late Ordovician times (7). According to this model, two phytoplanktonic palaeoprovinces can be distinguished between late Katian and Hirnantian times: a) an eastern Laurentian–Baltican province, characterized by large *Baltisphaeridium*; of “giant” acritarchs such as *Hoegklintia* spp., or *Estiastra* spp.; of large species of the *Goniosphaeridium–Stellechinatum–Polygonium* plexus; as well as by the presence of *Dilatisphaera* species, such as *D. wimani* a peri-Gondwanan province, dominated by netromorph acritarchs (e.g., *D. cucurbita*, *D. striatifera*, *S. safira* and other characteristic forms such as *Tylotopalla* spp. This Late Ordovician microphytoplankton biogeographical differentiation has been tentatively attributed to the blocking of exchange between water masses due to the bathymetric ridge-rise associated with the opening of the Rheic Ocean in conjunction with the sea level drawdown occurring during the end-Ordovician glaciation (7). This model is not in contrast with a general perception of diminishing acritarch palaeobioprovinciality in post-Darriwilian times as noted by many previous authors, but it only introduces the possibility of a newly increased bioprovincialism during latest Ordovician times after the generally observed breakdown in palaeobiogeographical differentiation during the post-Darriwilian (Caradoc–Ashgill). It is noteworthy that many of the typical “Laurentian–Baltican” index taxa do not occur in the present assemblages, with the exception of some large specimens of *Baltisphaeridium* spp. In particular the absence of *Dilatisphaera*, as well as of the “giant” acritarchs *Hoegklintia* and *Estiastra* are noteworthy. The absence of these “giant” acritarchs also reflect ecological, in addition to biogeographical control on the distribution of these species, which are most often found to occur in carbonate platform environments in low to middle palaeolatitudes (e.g., 8, 9). Conversely, the presence and diversity of netromorphic acritarchs (*Dactylofusa*, *Safirotheca*, *Leiofusa* etc.) as well as the occurrence of a morphotype of *Tylotopalla* suggest similarities with “peri-Gondwanan” assemblages. The change in acritarch assemblages mark the boundary between Assemblage I and Assemblage II, and correspond to the base of the *nigerica* chitinozoan Zone. It is also interesting because it coincides with the appearance of many typical taxa which are found in Laurentian and/or Baltican localities

(*B. platynetrella*, *D. hamii* and *N. ancepsipuncta*). This change is thus consistent with the hypothesis of the development of a latest Ordovician biogeographic differentiation of the acritarchs between an Eastern Laurentian–Baltican province and a peri-Gondwanan province, linked to the palaeoclimatic changes leading to the end-Ordovician glaciation (8, 9). The author is aware that some fusiform–netromorphic taxa, which characteristically occur in the Hirnantian peri-Gondwanan assemblages, also occur in pre-Hirnantian, Late Ordovician assemblages from Laurentian localities. However this is not in contradiction with the proposed biogeographical differentiation developing in latest Ordovician (Hirnantian) times following the palaeoenvironmental and palaeoceanographic consequences of the glaciation, and observation that high-latitude, Hirnantian, acritarch assemblages are dominated by netromorphs, in opposition to Laurentian associations that are largely characterized by totally different acritarch morphotypes, as illustrated above (e.g., large acanthomorphs and “giant” acritarchs; see also details in (8, 9). Chitinozoan research during the past twenty years has resulted in well-documented information for three major palaeogeographic provinces: Laurentia, Baltica and North Gondwana (2, 18, 19, 20, 21, 39, 40, 42). In spite of increasing number of studies, fundamental differences have not been revealed in the composition of chitinozoan assemblages between major palaeogeographic domains. So far, five genera (40) appear to be restricted to the North Gondwana realm during the Ordovician when this realm was located in relatively high latitudes (e.g., *Armoricochitina*, *Eremochitina*, *Velatachitina*, *Sagenochitina*, and *Siphonochitina*). Even if many cosmopolitan species are known from both equatorial and circum-polar palaeolatitudes (e.g., *A. symmetrica*, *C. campanulaeformis*, *D. minor*, *L. baltica* and *P. sylvanica*), the biozonations of Achab (1: Laurentia), Paris (40: Gondwana), and Webby et al. (61: Baltic and Gondwana domains) highlight some differences, especially at the species level, between the three major palaeogeographic domains. All of the chitinozoan species found in the Late Ordovician of the Fazel Abad area have been recorded from the North Gondwana Domain (including north Africa: Morocco, Algeria, Tunisia, Libya, and Nigeria; the Middle East: Saudi Arabia, Syria, Jordan, Iran; southwestern Europe: Italy, France, Spain, and Portugal; Czech Republic). In particular, *A. nigerica*, *A. merga*, *T. elongata*, and *S. oulebsiri* have never been recorded outside the North Gondwana Domain (40, 61).

## Results and Discussion

The Ordovician sediments of the Fazel Abad area contain well-preserved and abundant palynomorph entities, consisting of acritarch, chitinozoan, scolecodont and graptolite remains. Two acritarch assemblage and four chitinozoan biozones were established in the Ordovician sediments of this area. The acritarch assemblage zone I occur in the Abastu Formation and suggest a Tremadocian age. The acritarch assemblage II appears in the Abarsaj Formation, indicating a Katian-Hirnantian age. The acritarch taxa from Abarsaj Formation of the Fazel Abad area have broad similarities with Libya, Morocco, Algeria, Saudi Arabia, Portugal, England, the United States and Canada, indicating a cosmopolitan nature for acritarch taxa during the Late Ordovician (except for , those of the Abastu Formation which are only present in the peri-Gondwanan palaeo-province. There is no chitinozoan fauna in the Abastu Formation, but the Abarsaj Formation contains well-known chitinozoan taxa such as *A. nigerica*, *A. merga*, *T. elongata* and *S. oulebsiri*, representing a key affiliation to the North Gondwanan Domain. The presence of acritarch elements of the peri-Gondwanan Palaeo-province in the Lower Ordovician, the Abastu Formation and Gondwanan chitinozoan taxa in the Upper Ordovician sediments of the Kholin-Darreh village in the Fazel Abad area suggests that the Alborz Mountains have been part of the Northern Gondwana Domain during the whole Ordovician. On the other hand, discounting the long ranging chitinozoan species such as *C. campanulaeformis* and *D. minor*, there are 27 other species found in the Abarsaj Formation. Of these, 48% are common in the Gondwana, 28% with Baltica and 24% with Laurentia. This gives a clear indication of close affinity with the Late Ordovician North Gondwana chitinozoan fauna (Fig. 3). Based on palynological data, two major hiatus are present throughout the Lower Palaeozoic sediments of the Fazel Abad area. The first hiatus marks the Lalun/Abastu contact and includes the Middle and Late Cambrian (Furongian) sediments (e.g., the Mila Formation is not present in the study area). The second hiatus occurs at the Abastu/Abarsaj contact and encompasses the Floian, Dapingian, Darriwilian and Sandbian. Likewise, the presence of some chitinozoan and acritarch taxa shared with Baltica and Laurentia suggests the existence of counter-clockwise marine currents which resulted in bringing planktonic organisms (acritarchs and chitinozoans) from lower latitudes (Baltica) to higher latitudes (Northern Gondwana). Moreover, the presence of diverse chitinozoan, acritarch and scolecodont taxa in

the Upper Ordovician strata as well as the Lower Ordovician in the Fazel Abad area suggest a shallow marine environment with cold climatic condition in high-latitude settings for this part of Alborz Mountains. The reworked acritarch taxa from the Tremadocian, Floian, Darriwilian and Sandbian in all chitinozoan biozones of the Abarsaj Formation indicate erosion processes, resulting from local tectonic readjustments, or alternatively marine transgressive events from the Floian to Sandbian upward.

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