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Recent progress in the bio- and chronostratigraphic understanding of the upper Frasnian (Upper Devonian) sedimentary sequences in Armenia

Keywords: Paleontology, biostratigraphy, chronostratigraphy, Gondwana, Paleozoic, Lesser Caucasus.

Introduction. The Late Devonian time interval bears a particular significance for the evolution of marine ecosystems, since the diversity of the marine biosphere was affected profoundly by two major mass extinction events: the Kellwasser and Hangenberg extinction events [1]. More specifically, around 372 million years (Myr) ago, at the boundary between the Frasnian and Famennian (F–F) stages, one of the most severe biological crises in Earth's history occurred. This event had a devastating impact on reef building organisms and led to major diversity losses in other typical Paleozoic lineages, both benthic and nektonic. Although the ultimate cause of this disaster remains debated, the most widely accepted scenario involves widespread oceanic anoxia, likely triggered by climate warming caused by massive volcanic activity [1].

In the southern part of Central Armenia (Vayots Dzor and Ararat Regions, Fig. 1a) ca. 1,500 m-thick Middle Devonian–lower Carboniferous sedimentary sequences crop out [2]. These sequences accumulated in a rather shallow-water depositional marine environment, under a tropical/subtropical climate; they record the earliest depositional history of Paleozoic sequences in the area and represent the beginning of a rather rapid subsidence of the Gondwanan northern margin, as at the time, Armenia was part of the northern margin of the mega-continent Gondwana, facing the Paleotethys Ocean (Fig. 1b). This part of Gondwana was later individualized as the South Armenian Block, following its northward migration and opening of Neotethys Ocean further to the South [3, 4]. Understanding the regional dimension of changes in Late Devonian marine paleobiodiversity is of great importance, especially for the F–F transitional interval; this kind of insights rely on detailed taxonomic and stratigraphic data. Following a brief overview of the previous bio-chronostratigraphic evidence for the F–F transitional interval in Armenia and Nakhichevan, we will present a synthesis of recent results achieved over the past two years within the framework of the GREATPAL project ("Deciphering the Global vs Regional record of Environmental chAnges in The PALeozoic mountains of Armenia") and discuss their implications.

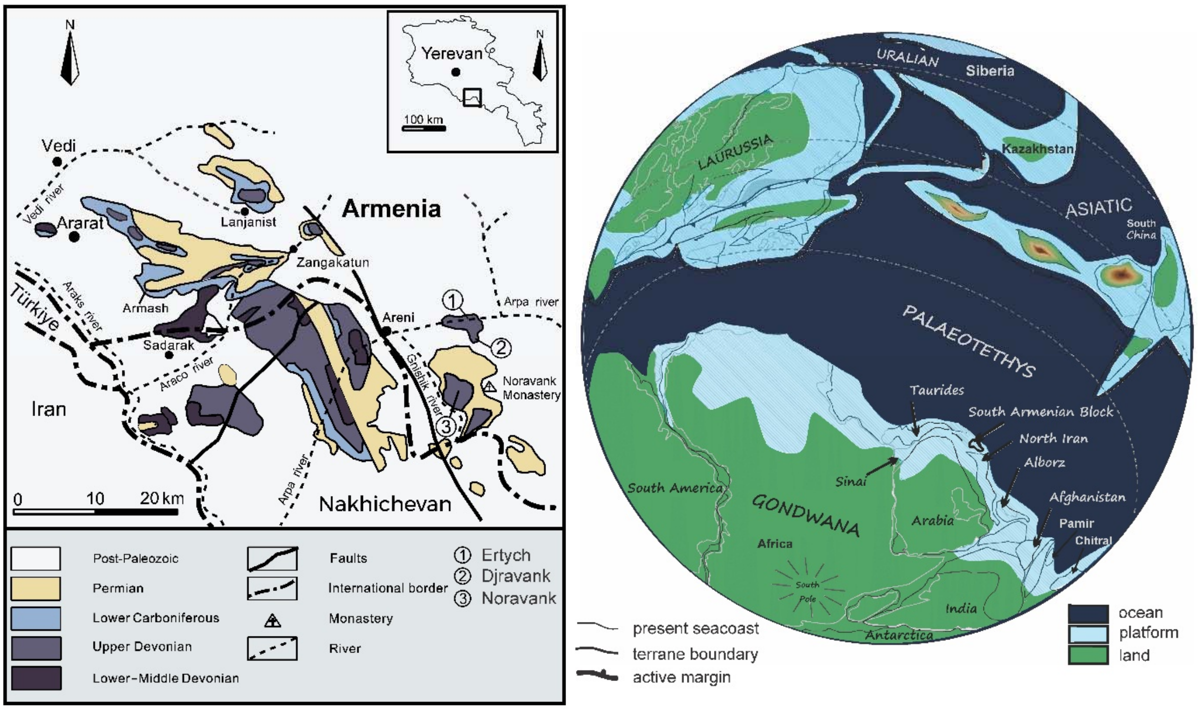
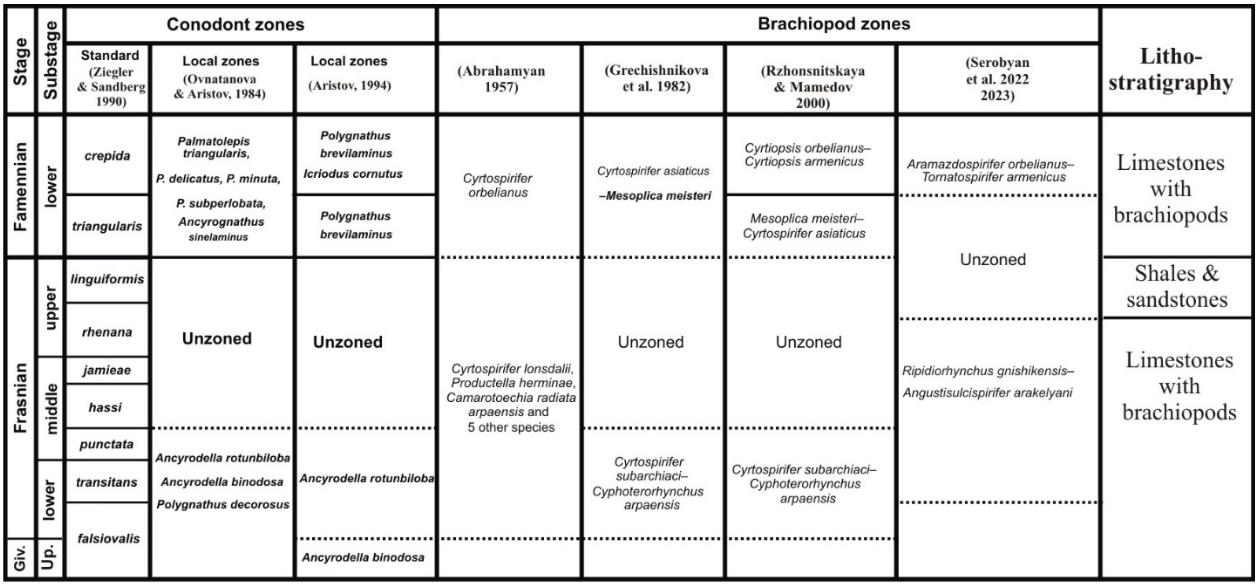


Figure 1. A) Geological map of the sequences in Central Armenia and Nakhichevan, including the location of the two studied sections; B) Late Devonian paleogeographic map including the position of the South Armenian Block in the northern margin of Gondwana (after [10], modified).

Previous studies. The F–F sequences are exposed mainly below the monastery of Noravank and around the locality Ertych, two sites that are about 12 km apart (Fig. 1a). The sedimentary sequences of these localities display two distinct brachiopod bearing limestone intervals intercalated by a 50–70 m-thick terrigenous sequence that is dominated by shales at its lower part, which are overlain in their turn by an over 30 m-thick sequence of mature sandstones (Figs. 2, 3).

Brachiopods were the main fossils used in the initial biostratigraphic subdivisions of Upper Devonian sequences in the Lesser Caucasus. Abrahamyan [5] developed a continuous biostratigraphic scheme characterized by taxon-range and assemblage biozones (Fig. 2). Other brachiopod specialists applied her zonal scheme in Nakhichevan, while improving and complementing it for some intervals [6]. Others [7], in addition to updating their brachiopod zonal scheme, also correlated it with the conodont biozonation established by [8] in Nakhichevan, although a long unzoned interval remained between the lower Frasnian part and the base of the Famennian (see Fig. 2). The brachiopods of both the lower and upper limestone intervals were recently revised by Serobyan [9, 10], who also revised the Frasnian and lower Famennian brachiopod biozones in Armenia; thus, the lower limestone interval is assiged to the *Ripidiorhynchus gnishikensis–Angustisulcispirifer arakelyani* zone, characterized importantly by the species *A. arakelyani* (Pl. 1, figs. 3–4). This limestone interval also includes representatives of the order Atrypida (i.e. *Spinatrypa* sp., Pl. 1, figs. 1-2), for which we know that they went extinct at the end of the Frasnian. Conodont evidence presented in [10], clearly confirms their Frasnian age, ranging from the *transitans* Zone (latest early Frasnian) to the upper *rhenana* Zone (late Frasnian). The upper limestones are assigned to the *Aramazdospirifer orbelianus–Tornatospirifer armenicus* brachiopod assemblage Zone, characterized by the presence of species *A. orbelianus* (Pl. 1, figs. 3–4) and *T. armenicus* (Pl., figs. 5–6); these limestones are considered as early Famennian in age [11].



Stage	Substage	Conodont zones			Brachiopod zones				Litho-stratigraphy
		Standard (Ziegler & Sandberg 1990)	Local zones (Ovnatanova & Aristov, 1984)	Local zones (Aristov, 1994)	(Abrahamyan 1957)	(Grechishnikova et al. 1982)	(Rzhonsnitskaya & Mamedov 2000)	(Serobyan et al. 2022 2023)	
Famennian	lower	*crepida*	***Palmatolepis triangularis,*** ***P. delicatus, P. minuta,*** ***P. subperlobata,*** ***Ancyrognathus sinelaminus***	***Polygnathus brevilaminus*** ***Icriodus cornutus***	*Cyrtospirifer orbelianus*	*Cyrtospirifer asiaticus* ***–Mesoplica meisteri***	*Cyrtiopsis orbelianus–Cyrtiopsis armenicus*	*Aramazdospirifer orbelianus–Tornatospirifer armenicus*	Limestones with brachiopods
		triangularis		***Polygnathus brevilaminus***			*Mesoplica meisteri–Cyrtospirifer asiaticus*	Unzoned	
Frasnian	upper	*linguiformis*	**Unzoned**	**Unzoned**	*Cyrtospirifer lonsdalii, Productella herminae, Camarotoechia radiata arpaensis* and 5 other species	Unzoned	Unzoned		Shales & sandstones
		rhenana						*Ripidiorhynchus gnishikensis–Angustisulcispirifer arakelyani*	Limestones with brachiopods
	middle	*jamieae*							
		hassi							
		punctata	***Ancyrodella rotunbiloba*** ***Ancyrodella binodosa*** ***Polygnathus decorosus***	***Ancyrodella rotunbiloba***		*Cyrtospirifer subarchiaci–Cyphoterorhynchus arpaensis*	*Cyrtospirifer subarchiaci–Cyphoterorhynchus arpaensis*		
	lower	*transitans*							
		falsiovalis							
Giv.	Up.			***Ancyrodella binodosa***					

Figure 2. Bio-chronostratigraphic framework of the Frasnian–lower Famennian sedimentary sequences in the Lesser Caucasus, including correlation with the different brachiopod and conodont biozones established in the region and their correlation with the standard conodont zones. Abbreviations: Giv., Givetian; up., upper (after [10], modified).

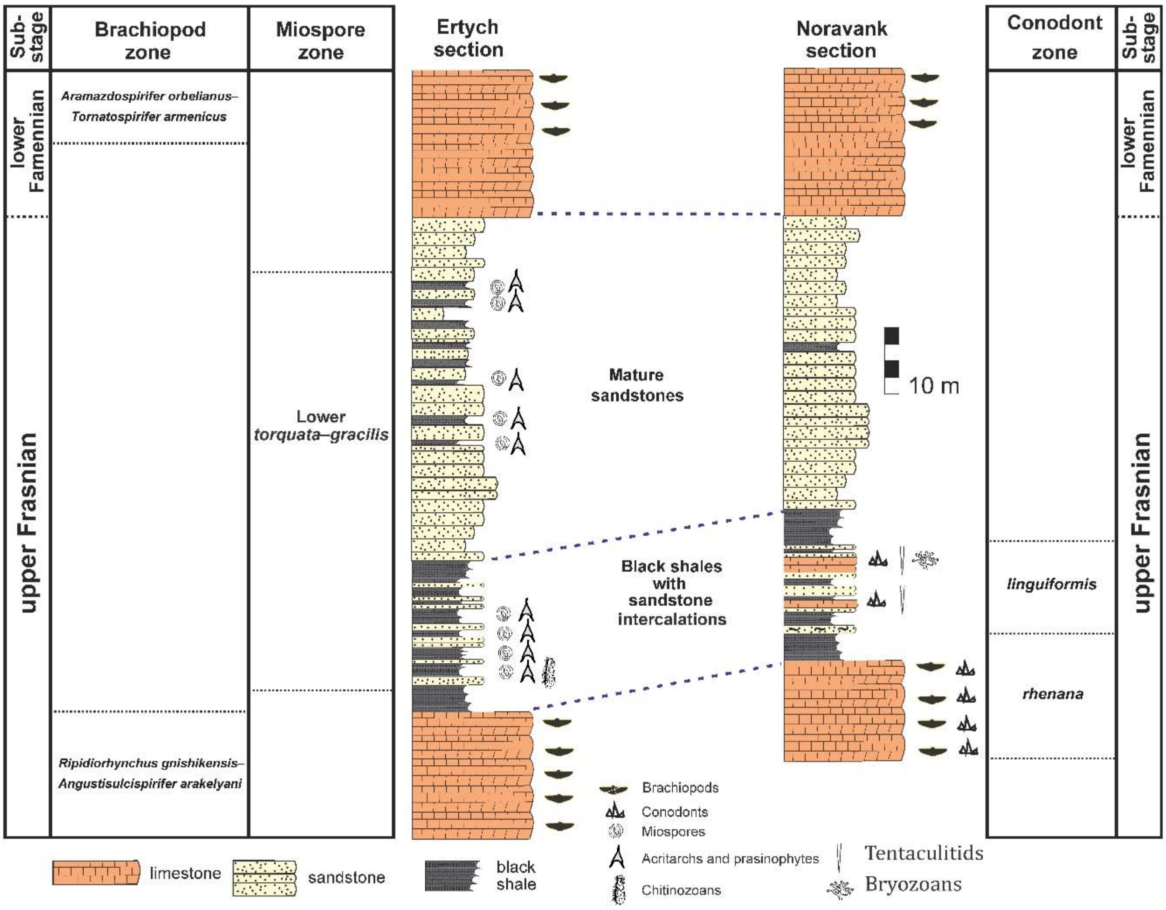


Fig. 3. Litho-, bio-, chronostratigraphic correlations of the Ertych and Noravank sections, synthesizing all the currently existing fossil data.

Recent achievements. The first biostratigraphic constraint for the terrigenous interval emerged unexpectedly, following palynological preparations of shales from the Ertych section that revealed a diverse assemblage of miospores, acritarchs, and chitinozoans. Indeed, a rather well preserved and diverse miospore assemblage (Pl. 1, figs. 15–17) was observed and documented recently throughout this interval [12]. The presence of the miospore species *Teichertospora torquata* (Pl. 1, fig. 15) is noteworthy, as it allows to correlate this interval with the *torquata–gracilis* miospore biozone of [13], which has been correlated with the late Frasnian–early Famennian time interval. In addition, the presence of *Acinosporites lindlarensis* (Pl. 1, fig. 16) is extremely important, as its parent plant is known to be *Leclerquia*, a small Devonian lycophyte. A recent global synthesis of the stratigraphic and biogeographic distribution of both *A. lindlarensis* and *Leclerquia* establishes the disappearance of both of them at the end of the Frasnian [14]. Consequently, the entire terrigenous sequence corresponds to the lower part of the *torquata–gracilis* biozone and can be correlated with the late Frasnian. Therefore, the F–F boundary is tentatively placed between the siliciclastic interval and the upper limestones (Fig. 3).

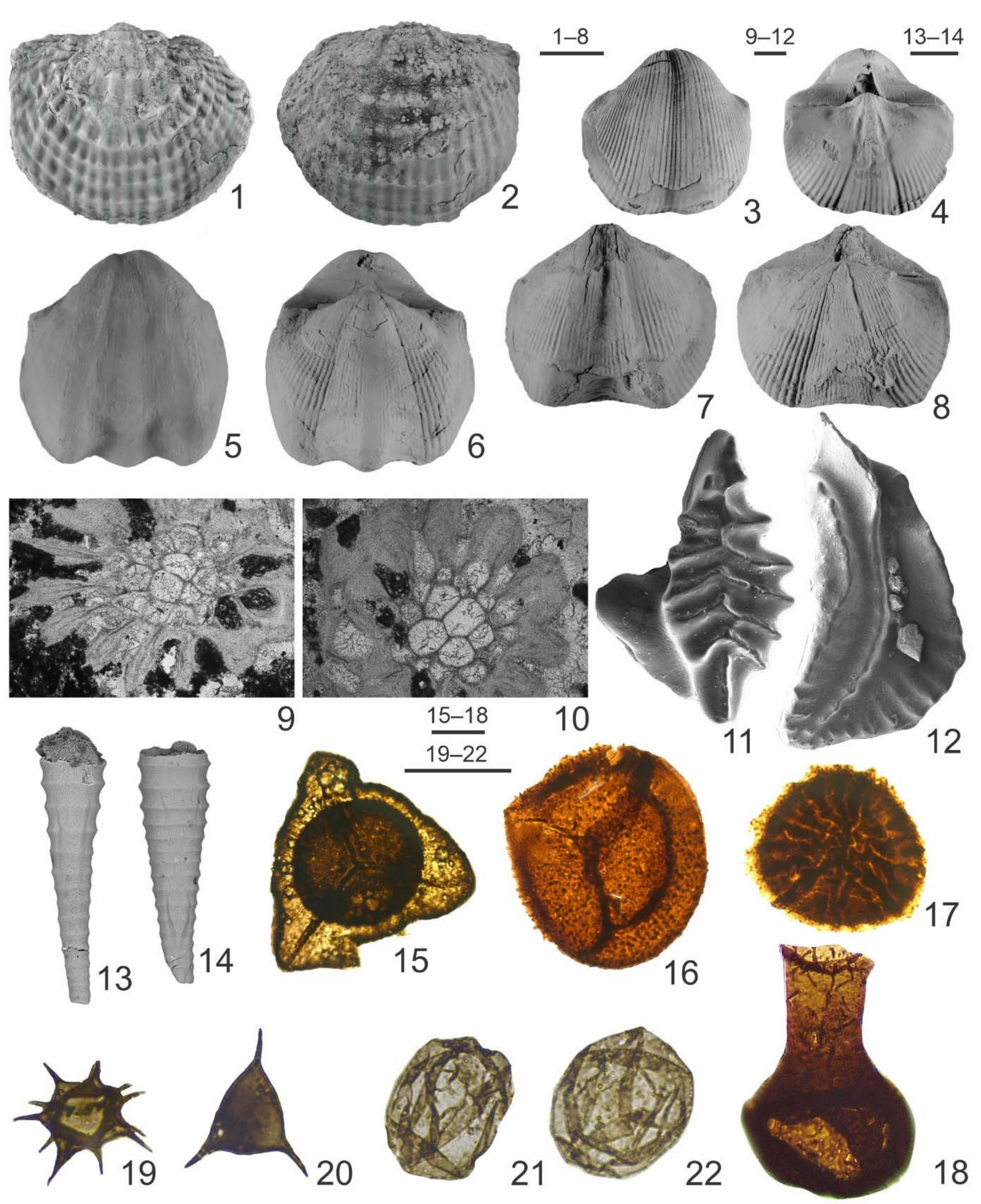


Plate 1. Upper Frasnian and lower Famennian fossils from Central Armenia. **1–2.** *Spinatrypa* sp., almost complete specimen in ventral (**1**) and dorsal (**2**) views; IGSNASRAGM 3937/PS 3043, Ertych section, upper Frasnian. **3–4.** *Angustisulcispirifer arakelyani* Serobyan et al., partly exfoliated specimen in ventral (**3**) and dorsal (**4**) views; IGSNASRAGM 3972/AR

3078, Ertych section, upper Frasnian. **5–6.** *Aramazdospirifer orbelianus* (Abich), neotype, almost complete specimen in ventral (**5**) and dorsal (**6**) views; IGSNASRAGM 3897/AB97/48, Noravank section. **7–8.** *Tornatospirifer armenicus* (Abrahamyan), neotype, partly exfoliated specimen in ventral (**7**) and dorsal (**8**) views; IGSNASRAGM 3981/PS 3087, Shamamidzor section. **9.** *Bigeyella indigena* (Morozova and Weiss in Morozova et al.), oblique thin section; Nv17/9h, upper Frasnian. **10.** *Euthyrhombopora tenuis* Ernst et al., branch transverse section; Nv17/9v, upper Frasnian. **11.** *Icriodus iowaensis iowaensis* Youngquist and Peterson; IGS-C23, sample Nv23/2, upper Frasnian. **12.** *Polygnathus webbi* Stauffer; IGS-C5, sample Nv23/2, upper Frasnian. **13–14.** Tentaculitidae gen. et sp. indet., specimen in ventral (**13**) and dorsal (**14**) views; sample Nv19/134, Noravank section, lower Famennian. **15.** *Teichertospora torquata* (Higgs) McGregor and Playford; sample Er18/P13, Q68/2, lower Famennian. **16.** *Acinosporites lindlarensis* Riegel; sample Er18/P7, G14/4, lower Famennian. **17.** *Kraeuselisporites ollii* McGregor and Camfield; sample Er18/P2, X11/2, lower Famennian. **18.** *Angochitina mourai* Lange; sample Er18/P2, D50, lower Famennian. **19**. *Micrhystridium stellatum* Deflandre; sample Er17/12/3, T51, lower Famennian. **20.** *Gorgonisphaeridium cf. ohioense*; sample Er17/7/1, K71/3, lower Famennian. **21–22.** *Leiosphaeridia* sp.; sample Er17/5/3 (**21**), B58/4 and sample Er17/5/2 (**22**), Y61/1, lower Famennian. **Scale bars** = 10 mm (**1–8**), 100 µm (**9–12**), 200 µm (**13–14**), 20 µm (**15–22**).

The presence of representatives of marine phytoplankton, such as acritarchs (Pl. 1, figs. 19–22) and prasinophytes [14], but also of chitinozoans (Pl. 1, fig. 18), in the same palynological samples studied by [12] for miospores, attest for the marine depositional environment of this terrigenous sequence, in which the spores were transported. The late Frasnian–early Famennian time interval is also suggested by the phytoplankton record present in the same samples, 'with a closer affinity' to the late Frasnian [15].

Recently, a number of important fossil data were also obtained from the Noravank section. Two cryptostome bryozoan species, *Bigeyella indigena* (Pl. 1, fig. 9) and *Euthyrhombopora tenuis* (Pl. 1, fig. 10), were discovered and documented by [16] from a limestone bed intercalated in the lower shaly interval of the terrigenous sequence; their presence suggests a Frasnian age for this bed based on comparison with the bryozoan record known from Iran [17]. Some other limestone beds within the same interval yielded tentaculitids (Pl. 1, figs. 13–14) with uniquely preserved phosphatized soft tissues and muscle bars, which allowed [18] to clarify the phylogenetic affinities of this mysterious Paleozoic fossil group. Interestingly, the authors consider these limestone beds bearing the significance of typical Konservat-Lagerstätte, meaning sedimentary deposits of an exceptional taphonomy, which allowed the preservation of soft tissues.

Even more recently, conodonts were found and documented from the lower part of the Noravank section [19]; the ones found in the lower limestone interval assigned to the *Ripidiorhynchus gnishikensis–Angustisulcispirifer arakelyani* brachiopod Zone allow to precise their assignement to the upper Frasnian *rhenana* conodont Zone (*sensu lato*). More importantly, some other conodonts obtained from thin limestone beds intercalated in the shaly interval allow their assignment to the uppermost Frasnian *linguiformis* conodont Zone (Fig. 3). This important dating is thanks to the co-occurrence of species *Icriodus iowaensis iowaensis* (Pl. 1, fig. 11) and *Polygnathus webbi* (Pl. 1, fig. 12).

Discussion. Previous biostratigraphic efforts encountered two main problems. Brachiopods, used in Armenia and Nakhichevan since the 1960s, are only encountered in the limestone intervals and still only in particular horizons [9, 10], while the F–F sections in Armenia (and Nackichevan) contain a ca. 50–70 m thick interval of siliciclastic (terrigenous) sediments, which were left unzoned because of the absence of brachiopods. Another difficulty encountered in the biostratigraphic subdivisions of these sequences is the shallow water depositional environment of their accumulation. As a consequence, even the carbonate facies that deliver so far conodonts, do not include the index *Palmatolepis* species, which are present in deeper water environments. However, all these difficulties that are inherent to the nature of the sedimentary record in Armenia for the F–F transitional interval are now about to be overridden by palynology and the discovery of rare conodont-bearing limestone beds intercalated in the terrigenous sequence.

Moreover, in an effort to date precisely the late Frasnian mass extinction events (known as Lower and Upper Kellwasser events), important progress has been achieved by [20] in dating precisely, with orbitochronology, the upper Frasnian standard conodont zones and the F–F boundary. Thus, according to their results the duration of the *linguiformis* conodont Zone is evaluated at 240 ka. Given that the shaly interval is now correlated with the *linguiformis* Zone and the F–F boundary is tentatively placed at the sedimentary switch between sandstones and upper limestones, it is very likely that the entire terrigenous sequence was accumulated during 240 ka (or less). Consequently, all our recent results obtained from this terrigenous sequence allow to document the fossilized components of both marine and terrestrial ecosystems that existed during this time slice (latest Frasnian), in the northern edge of the megacontinent Gondwana.

Future challenges still concern the establishment of the record of the Kellwasser events in Armenia. The most recent biostratigraphic constraints from the lower shales that are part of the terrigenous interval are promising in this respect, as they allow to individualize the conodont zone (the *linguiformis* Zone) during which the Upper Kellwasser event took place [1, 20]. In this respect, the taphonomic inferences made by [18] are particularly interesting, as they consider that the sea floor on which were preserved the soft tissues of tentaculitids were likely anoxic, hampering thus the presence of scavengers and facilitating the preservation of soft body elements.

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Recent progress in the bio- and chronostratigraphic understanding of the upper Frasnian (Upper Devonian) sedimentary sequences in Armenia

Abstract

Recently obtained biostratigraphic results in terrigenous sequences (shales and sandstones) intercalated between brachiopod-bearing limestones constitute an important breakthrough in our understanding of the chronostratigraphic framework of the Frasnian–Famennian transitional interval. More precisely, miospores obtained from the Ertych section constrain the entire terrigenous sequence to the late Frasnian, while acritarchs, prasinophytes and chitinozoans found in the same samples establish that their accumulation took place in marine environments. Conodonts extracted from the Noravank section establish that the lower part of the terrigenous interval, dominated by shales, was accumulated during the *linguiformis* conodont zone. Taking into account the combined chronostratigraphic evidence in the two sections, it may be inferred that the terrigenous sequence accumulated in less than 240 thousand years. Our results establish, for the first time, a relatively precise time framework to describe and reconstruct marine and terrestrial paleoecosystems that existed in the northern edge of the megacontinent Gondwana.

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Հայաստանի վերին Ֆրանի (վերին դևոն) նստվածքային հաջորդականությունների կենսա- և ժամանակաշերտագրական ըմբռնման վերջին ձեռքբերումները

Բրախիոպոդներ պարունակող կրաքարերի միջև ընկած տերիգեն նստվածքային հաջորդականությունների (թերթաքարեր և ավազաքարեր) վերաբերյալ վերջերս ստացված կենսաշերտագրական տվյալները կարևոր առաջընթաց են Ֆրան–Ֆամեն անցումային միջակայքի ժամանակաշերտագրական կառուցվածքի ըմբռնման գործում: Մասնավորապես, Էրտիչի կտրվածքից ստացված միոսպորները թույլ են տալիս սահմանափակել ամբողջ տերիգեն հաջորդականության տարիքը ուշ Ֆրանով: Միևնույն ժամանակ, այս նույն նմուշներում հայտնաբերված

ակրիտարխները, պրազինոֆիտները և խիտինոզոաները հաստատում են դրանց նստվածքակուտակումը ծովային միջավայրում: Նորավանքի կտրվածքի կոնոդոնտները ցույց են տալիս, որ տերիգենային միջակայքի ստորին հատվածը, որը հիմնականում ներկայացված է թերթաքարերով, կուտակվել է *linguiformis* կոնոդոնտային զոնային համապատասխանող ժամանակում: Հաշվի առնելով երկու կտրվածքներից ստացված ժամանակաշերտագրական տվյալների ամբողջությունը, կարելի է եզրակացնել, որ տերիգեն հաջորդականության ձևավորումը տեղի է ունեցել ոչ ավել, քան 240 հազար տարվա ընթացքում: Ստացված արդյունքները հնարավորություն են տալիս առաջին անգամ սահմանել համեմատաբար ճշգրիտ ժամանակային շրջանակներ Գոնդվանա գերմայրցամաքի հյուսիսային եզրին գոյություն ունեցած ծովային և ցամաքային պալեոէկոհամակարգերի նկարագրության և վերակառուցման համար:

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