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The Frasnian-Famennian boundary in the Southern Urals

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On the western slope of the Southern Urals, a continuous conodont zone sequence within different facies of the Frasnian-Famennian (F-F) boundary beds is documented. In all the sections the boundary between both stages runs within lithologically uniform successions and can be determined only by a sharp faunal change. In brachiopod facies, it is placed within brachiopod shell beds and relates to the base of the Barma Beds, i.e., the level marked by a simultaneous appearance of the index brachiopod species *Pugnoides*(?) *markovskii* and the zonal conodont species *Palmatolepis triangularis*. In goniatite facies, the F-F boundary can be traced by the disappearance of diverse Frasnian conodonts and goniatites of the genus *Manticoceras*, coupled with the first occurrence of the conodont *Pa. triangularis*; the sequence shows also the well-known icriodid blooms in the earliest Famennian. Finds of Famennian goniatites (representatives of the genus *Cheiloceras*) are confined to the *crepida* zones. In the sections of the West-Zilair, where the F-F boundary passage consists of siliceous-terrigenous deposits, the boundary can be established only by a change in conodont assemblages. In all the sections under investigation the F-F boundary level shows a drastic faunal change that corresponds to the global Kellwasser Event.

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INTRODUCTION

The paper is devoted to the Frasnian-Famennian (F-F) boundary in sections representing different facies at the western slope of the Southern Urals. The authors have long worked on this topic (Abramova, 1992; Guidebook..., 1995; Abramova, 1999; Abramova and Artyushkova, 1999, 2002; Yakupov *et al*., 2002). Investigations began after the internationally accepted stage boundary at the base of the Early *triangularis* Zone was established by the Subcomission on Devonian Stratigraphy during the Calgary International Symposium on the Devonian System, Canada, 1987. In spite of long discussions the principal argument for this position (down from the 1983 Middle *triangularis* Zone) was that it was the earliest, widely recognized marker, following the event (Dineley, 1988); this global event corresponds to one of the largest mass extinctions in the Phanerozoic (F-F boundary or Kellwasser Event; see Walliser, 1996).

In recent years many publications from different regions have appeared on this problem (Kuz'min *et al*., 1998; Yudina *et al*., 2002). Thus, some additional data obtained lately in the Southern Urals (Rzhonsnitskaya *et al*., 1998; Veimarn *et al.*, 2002), and revision of the available faunal collections has stimulated a review of this problem.

BRIEF HISTORICAL REVIEW

A general framework for the modern biostratigraphy of Devonian deposits in the Southern Urals, in which local stratigraphical units were established by brachiopods or goniatites, was developed in the early 1930s. Nalivkin (1926) was the first to put forward a stratigraphical scheme for Devonian deposits of the USSR developed in different facies. He identified two types of Famennian limestone facies in the Southern Urals sections. The first one was a goniatite facies, and the second included brachiopod limestones with a very rich and diversified fauna of dominant *Productus* ex. gr. *subaculeatus* Murchison, *Productus* ex. gr. *praelongus* Sowerby, *Spirifer* cf. *archiaci* Murchison, *Rhynchonella* (*Pugnax*) *triaequalis* Gosselet and many others. The characteristic feature is abundance of *Productus* and *Pugnax*, paired with absence of *Pentamerus* and *Atrypa* (Nalivkin, 1926, p. 85). These limestones, named by him "Barmian", lie upon Frasnian deposits with goniatites of the genus *Manticoceras* and the brachiopods *Hypothyridina cuboides* Sowerby or *Theodossia*

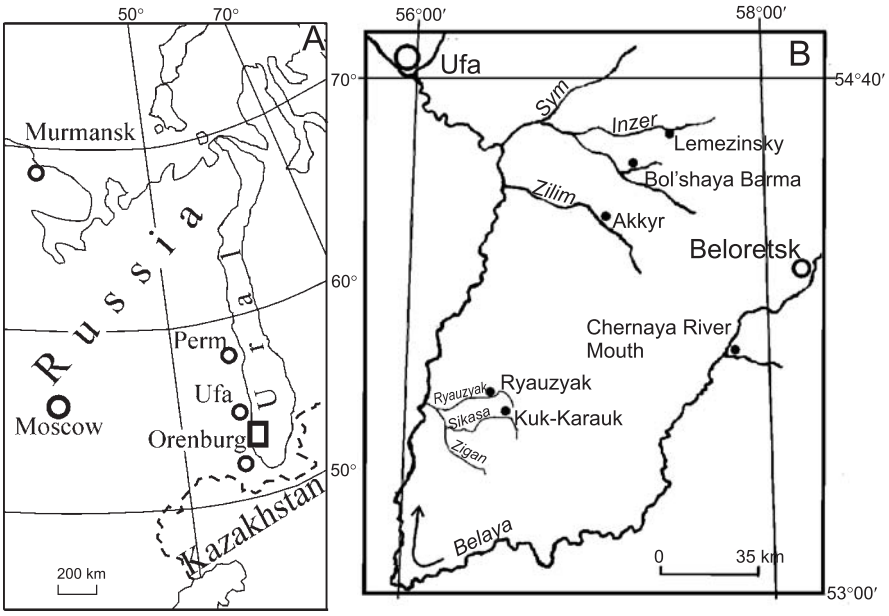

Fig. 1. A — the location of the studied area in Russia; B — the location of the sections

katavensis Nalivkin. Thus, there was originally no doubt about the Famennian age of the deposits with *Pugnoides triaequalis* = *Rhynchonella* (*Pugnax*) *triaequalis* Gosselet according to Nalivkin. Later on, Markovsky (1948), proceeding from his research of Upper Devonian sections along the Sikaza and Ryauzyak rivers, concluded that the Frasnian-Famennian boundary should be drawn in the upper part of the limestones with *Pugnoides triaequalis*. As was pointed out by Rozman (1962), however, Markovsky's *Pugnoides triaequalis*, widespread within the Barma strata at the western slope of the South Urals, does not correspond to the species from Ardennes described by Gosselet. Yudina (1997) revised brachiopods collected by Abramova in the Southern Urals and described this form as a new species, *Pugnoides*(?) *markovskii* Yudina.

The argument used by Markovsky to establish the F-F boundary at the top of Barma Beds, and not at their base, was a considerable number of brachiopod species from the underlying Askynian deposits, which occurred in a specific Barmian assemblage. Markovsky's (1948) view concerning the Frasnian age of the Barmian limestones was adopted in all subsequent schemes of the Devonian stratigraphy of the Urals (1951, 1968, 1980). The term the "Barma Beds" (= beds with *Pugnoides triaequalis*) as well as the "Askyn" unit was proposed by Domrachev (1952). Up to now, many geologists have considered the Barmian limestones as a facies variety of the Askyn Horizon.

The Stratigraphical Charts of the Urals (Stratigraficheskie skhemy..., 1980, 1993) place the Askyn Horizon (*Crickites expectatus* and *Theodossia anossofi* biozones) and the Makarovo Horizon (*Cheiloceras, Zilimia polonica–Cyrtospirifer archiaci* biozones) in the F-F boundary interval on the western slope. Although the Barma Beds are shown to be in the upper Askyn Horizon, the last chart (1993) correlated them with the lowermost Famennian. In goniatite facies the deposits with *Crickites* are analogous in age to the Askyn Horizon.

In the sections where the typical macrofaunal assemblages of the Barma Beds are absent, the F-F boundary was established by the extinction of Askynian brachiopods or the goniatite *Crickites*, and also by the first occurrence of the Famennian brachiopods *Cyrtospirifer archiaci* Murchison or goniatites of the genus *Cheiloceras*. As representatives of this macrofauna occur very rarely, the F-F boundary was a matter of convention. Its recognition was also complicated because of frequent breaks in succession. Therefore, conodonts appeared to be of primary importance in solving the problem of hiatuses at the boundary interval.

The results of our research on conodont faunas, carried out in the 1980–90s for a number of different facies sections of the Southern Urals (Fig. 1), made it possible to specify the position of the F-F boundary and to correlate it with the standard conodont scale of Ziegler and Sandberg (1990).

RESEARCH PROCEDURE

Six selected sections: Bol'shaya Barma, Akkyr, Kuk-Karauk, Ryauzyak, Lemezinsky, Chernaya River Mouth (Fig. 1) were measured and sampled for all kinds of fauna, with special emphasis on conodonts and brachiopods. The most detailed, layer-by-layer sampling was made for the key Barma Beds, with each sampled layer between 0.04 to 0.1 m thick. Conodont samples weighed from 0.4 to 1 kg, and conodont frequency varies from rare to abundant.

STUDIED SECTIONS AND FACIES TYPES

In the Southern Urals localities, where the F-F boundary is clearly documented as regards the succession of conodont faunas, the sections can be attributed to four facies types.

The first type, the most widely distributed and best studied, is represented by shallow-shelf facies marked by a wide range of brachiopod biofacies (Askyn facies *sensu* Domrachev, 1952). It includes sections of the Askyn, Zilim, Zigan, Belaya

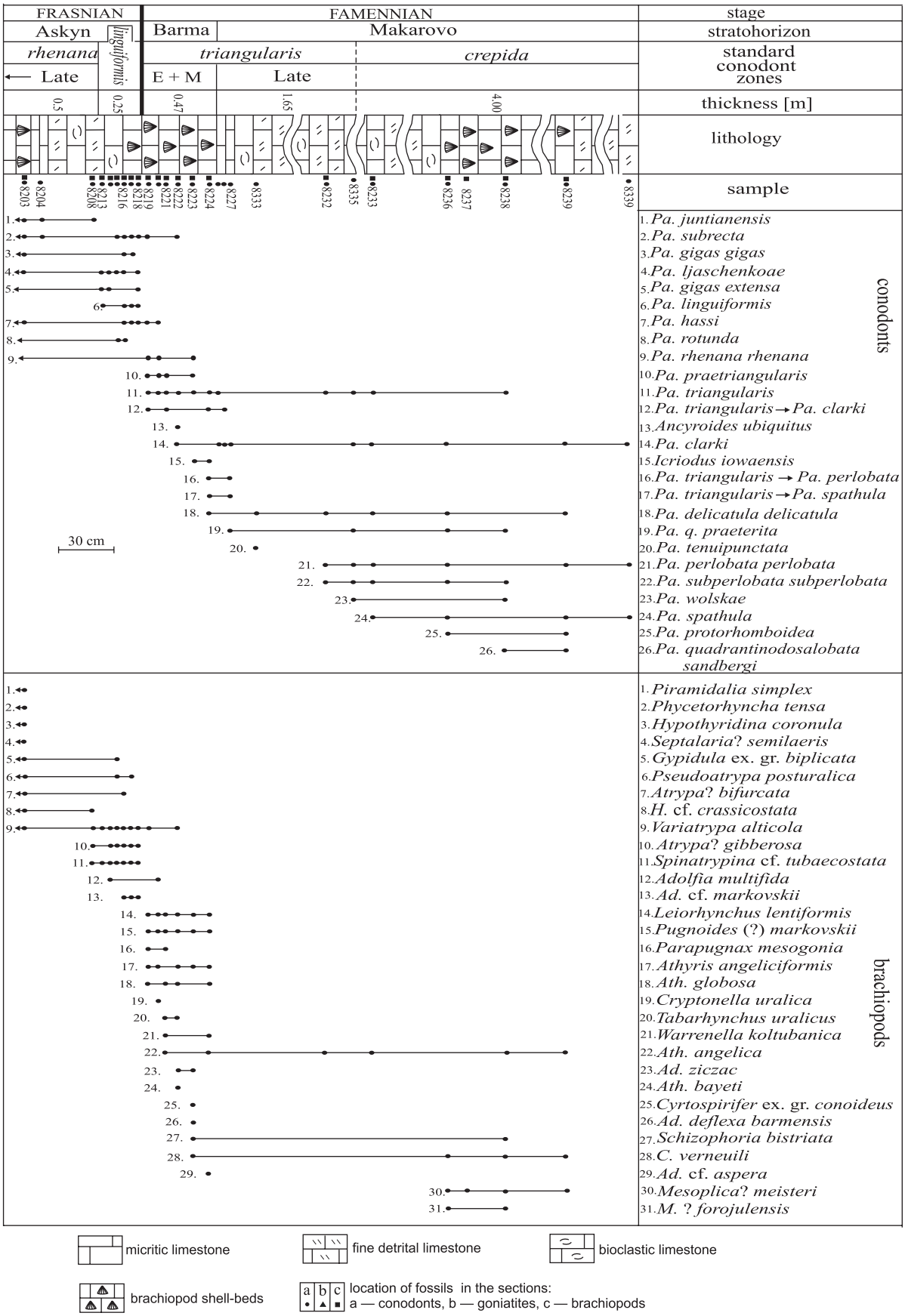

Fig. 2. Conodont and brachiopod distribution in the Frasnian-Famennian boundary beds in the Bol'shaya Barma section

An. — *Ancyrodella*, *Anc.* — *Ancyrognathus, Pa.* — *Palmatolepis, P.* — *Polygnathus*, *Ad.* — *Adolfia*, *Ath.* — *Athyris*, *H.* — *Hypothyridina*, *C.* — *Cyrtospirifer*, *M.* — *Mesoplica*, *Ma.* — *Manticoceras*, E — Early, M — Middle

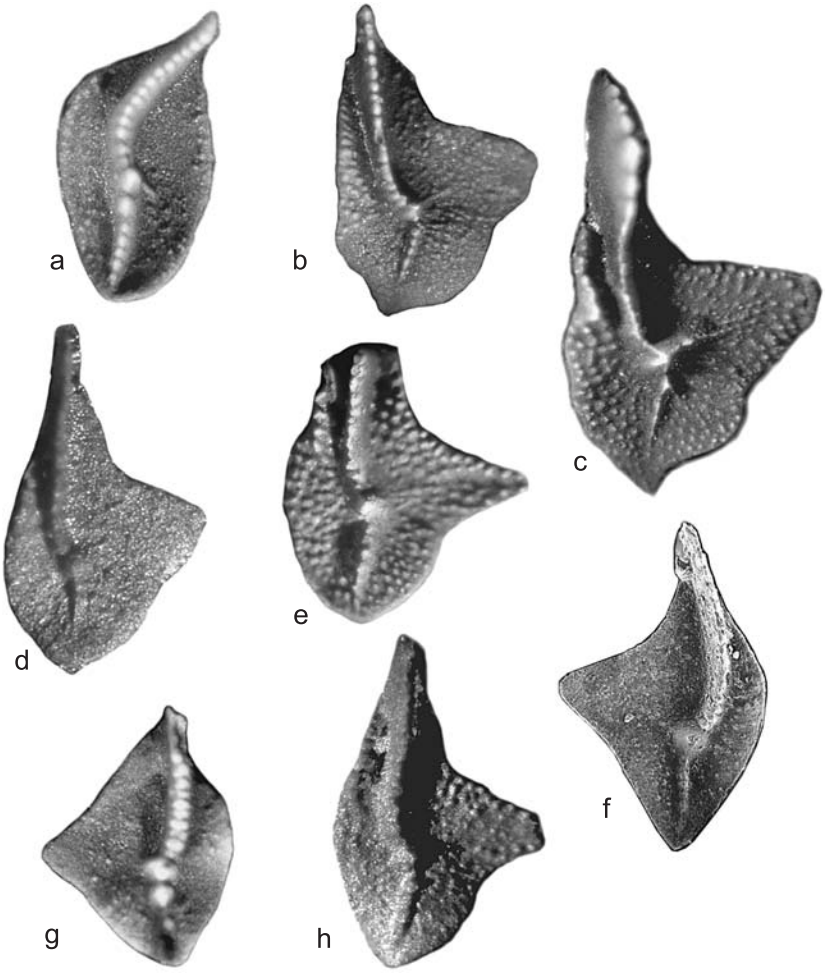

Fig. 3. Frasnian conodonts from the Bol'shaya Barma, Ryauzyak and Lemezinsky sections

a — *Palmatolepis linguiformis* Müller, Lemezinsky section, *Crickites* Beds, *linguiformis* Zone, 162/20, sample 7198, x 40; **b** — *Pa. hassi* Müller and Müller, Lemezinsky section, *Crickites* Beds, *linguiformis* Zone, 162/21, sample 7198, x 30; **c** — *Pa. ljaschenkoae* Ovnatanova, Bol'shaya Barma section, Askyn Horizon, *linguiformis* Zone, 162/22, sample 8218, x 40; **d** — *Pa.* cf. *amplificata* Klapper and Foster, Ryauzyak section, Askyn Horizon, Late *rhenana* Zone, 162/12, sample 6430, x 25; **e** — *Pa. amplificata* Klapper and Foster, Lemezinsky section, *Crickites* Beds, *linguiformis* Zone, 162/23, sample 7198, x 25; **f** — *Palmatolepis* cf. *Pa. delicatula* Branson and Mehl (*sensu* Ziegler and Sandberg, 1990), Ryauzyak section, Askyn Horizon, *linguiformis* Zone, 162/24, sample 6433, x 35; **g** — *Pa. hassi* Müller and Müller, Ryauzyak section, Askyn Horizon, Late *rhenana* Zone, 162/13, sample 6431; x 25; **h** — *Pa. praetriangularis* Ziegler and Sandberg, Bol'shaya Barma section, Barma Horizon, Early-Middle *triangularis* Zone, 162/27, sample 8220, SEM, x 50

River basins (the latter river being taken in the latitudinal direction). In the present paper the Bol'shaya Barma, Akkyr and Kuk-Karauk sections are referred to this facies (Fig. 1). The second facies variety, termed here the Ryauzyak-type, is intermediate between brachiopod and goniatite biofacies and consists of thin and relatively deep-marine sediments. The third facies type, the Inzer facies, was distinguished by Domrachev (1952). It includes F-F boundary deposits developed in deeper-shelf goniatite biofacies, and is represented by the most complete and best exposed Lemezinsky Section.

The fourth facies type includes sections of the West Zilair zone. They characterize a transitional zone between shelf and bathyal facies, in which carbonate-terrigenous rocks are replaced by the flysch-like greywacke of the Zilair Formation (Yakupov *et al*., 2002; Veimarn *et al*., 2002). The Ilyukhina Glade and Chernaya River Mouth sections at the Belaya River are good exposures of the F-F boundary beds developed as the West Zilair type.

ASKYN-TYPE FACIES

Characteristic features this facies type are brachiopod shell-beds, with layers and lenses of different thickness, occurring in the F-F boundary interval. The Barma Beds are recognized only by the onset of the index species *Pugnoides*(?) *markovskii* Yudina = *Pugnoides triaequalis* Markovsky (non Gosselet), *Tabarhynchus uralicus* Yudina (= *Camarotoechia neapolitana* Whidborne), *Cyrtospirifer markovskii* Nalivkin, and *Athyris globosa* Roemer.

The type section of the Barma Beds is situated on the right bank of the Bol'shaya Barma River (the right tributary of the Askyn River), 1.3 km upstream of its mouth (Fig. 1). On the lower part of the slope, the outcrop reveals limestones at least 10 m thick. Their lower part consists of light grey, thick-bedded limestones with brachiopod, crinoid, and conodont faunas of the Askyn Horizon. Conodonts indicate that this 5 or 6 m-thick interval corresponds to the Late *rhenana* Zone (Fig. 2).

Above these deposits there is a brachiopod coquina bed 0.72 m thick. Two brachiopod and conodont assemblages are clearly distinguishable in this interval. The lower part (0.25 m thick) contains brachiopods restricted to the Askyn Horizon, and conodonts characteristic of the *linguiformis* Zone. The overlying 0.47 m interval is noted for the first appearance of brachiopods diagnostic of the Barma Beds: *Pugnoides*(?) *markovskii* Yudina, *Tabarhynchus uralicus* Yudina, *Athyris globosa* Roemer, and many other species occurring only in the Famennian stage (Fig. 2). The first *Palmatolepis triangularis* specimens are also found here. A peculiarity of brachiopod shelly accumulations in this succession is that its assemblage combines both Barmian- and Askynian-type species; the species typical of Frasnian faunas, such as *Variatrypa alticola* (Frech), *Adolfia multifida* (Scupin), *Cryptonella uralica* Nalivkin and *Warrenella koltubanica* Nalivkin constitute 30% of the collection. The same is true for conodont associations, where rare representatives of the Frasnian species *Ancyrodella* cf. *curvata, Palmatolepis gigas extensa, Pa. hassi, Pa. jamieae,*

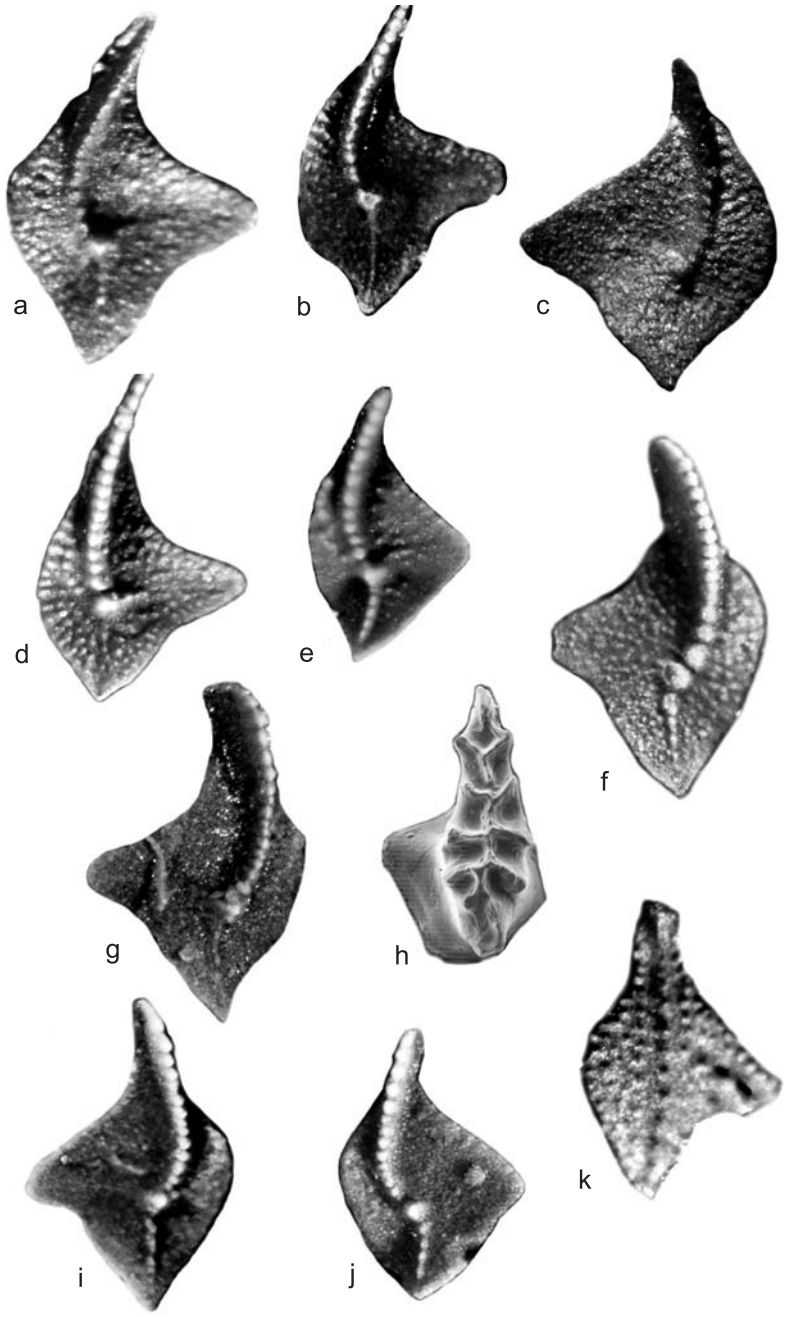

Fig. 4. Early Famennian conodonts from the Bol'shaya Barma, Ryauzyak and Lemezinsky sections

a — *Palmatolepis triangularis* Sannemann, Bol'shaya Barma section, Barma Horizon, Early-Middle *triangularis* Zone, 162/28, sample 8224, x 60; **b** — *Pa. triangularis* Sannemann *Pa. perlobata perlobata* Ulrich and Bassler, Bol'shaya Barma section, Makarovo Horizon, Late *triangularis* Zone, 162/36, sample 8232, SEM, x 40; **c** — *Pa. triangularis* Sannemann, Bol'shaya Barma section, Makarovo Horizon, Late *triangularis* Zone, 162/37, sample 8232, x 40; **d** — *Pa. spathula* Schülke, Lemezinsky section, *Cheiloceras* Beds, Early *crepida* Zone, 162/38, sample 7191, x 50; **e** — *Pa. delicatula delicatula* Branson and Mehl, Bol'shaya Barma section, Makarovo Horizon, Late *triangularis* Zone, 162/39, sample 8328, x 60; **f** — *Pa. triangularis* Sannemann, Bol'shaya Barma section, Makarovo Horizon, Late *triangularis* Zone, 162/40, sample 8232, x 50; **g** — *Pa. praetriangularis* Ziegler and Sandberg, Bol'shaya Barma section, Barma Horizon, Early-Middle *triangularis* Zone, 162/29, sample 8223, x 60; **h** — *Icriodus iowaensis* Youngquist and Peterson, Ryauzyak section, Barma Horizon, Early-Middle *triangularis* Zone, 162/25, sample 6437, SEM, x 40; **i** — *Pa. subperlobata* Branson and Mehl, Ryauzyak section, Barma Horizon, Early-Middle *triangularis* Zone, 162/31, sample 6440, x 60; **j** — *Pa. delicatula delicatula* Branson and Mehl, Bol'shaya Barma section, Makarovo Horizon, Late *triangularis* Zone, 162/41, sample 8328, x 65; **k** — *Ancyroides ubiquitus* Sandberg, Ziegler and Dreesen, Akkyr section, Barma Horizon, Early-Middle *triangularis* Zone, 162/26, sample 7122c, x 50

Pa. praetriangularis, Pa. rhenana rhenana, Pa. subrecta are found together with *Pa. triangularis* (Fig. 3). It is possible, however, that the Frasnian-type species owe their occurrence in this succession (Schülke, 1995) either to favourable facies conditions or to local small-scale submarine erosion of the underlying deposits. It is known that some typical Frasnian conodont species may have survived the F-F extinction (Schülke, 1995; Racki *et al*., 2002) but we have no sufficient data to establish this fact more firmly. The section described is exceptional among those studied in displaying mixed Frasnian and Famennian conodont and especially brachiopod faunas within the Barma Beds.

Besides the index species of the *triangularis* zones, the conodont assemblage typical of the Barma Beds includes *Pa. delicatula delicatula, Pa. praetriangularis, Pa. triangularis→Pa. clarki* and *Pa. triangularis→Pa. spathula* and *Pa. triangularis→Pa. perlobata* (Figs. 4 and 5). Element frequency is low, and the platform elements occur as single specimens. Conodonts from the Barmian limestones characterise the undivided Early and Middle *triangularis* zones.

The lithology of the overlying Makarovo Horizon is very different. The basal part consists of thin-platy pale grey micritic limestones without macrofauna. Their conodont assemblage is typical of the Late *triangularis* Zone. The succession is overlain by brownish-grey thick-layered limestones containing rare brachiopods and conodonts of the same age. The section is capped with a brownish-grey shell bed with abundant Famennian brachiopods: *Mesoplica*? *meisteri* (Peetz) and *M.*? ex. gr. *forojulensis* (Frech). Conodonts typical of the *crepida* zones appear in the middle part of the bed.

The Akkyr section**,** situated on the right bank of the Zilim River, near the mouth of the Bol'shaya Kinderlya, is noted for a maximum thickness of the Barma Beds (1.4 m; see Fig. 6). They are represented by thick-bedded brachiopod limestones, dolomitized in places, and pale grey, grey or brownish-grey in colour. The Barma Beds rest upon limestones in which brachiopod coquinas occur at different stratigraphical levels and which form lens-shaped accumulations of various thicknesses. From these deposits Rzhonsnitskaya and Markowskii (in:

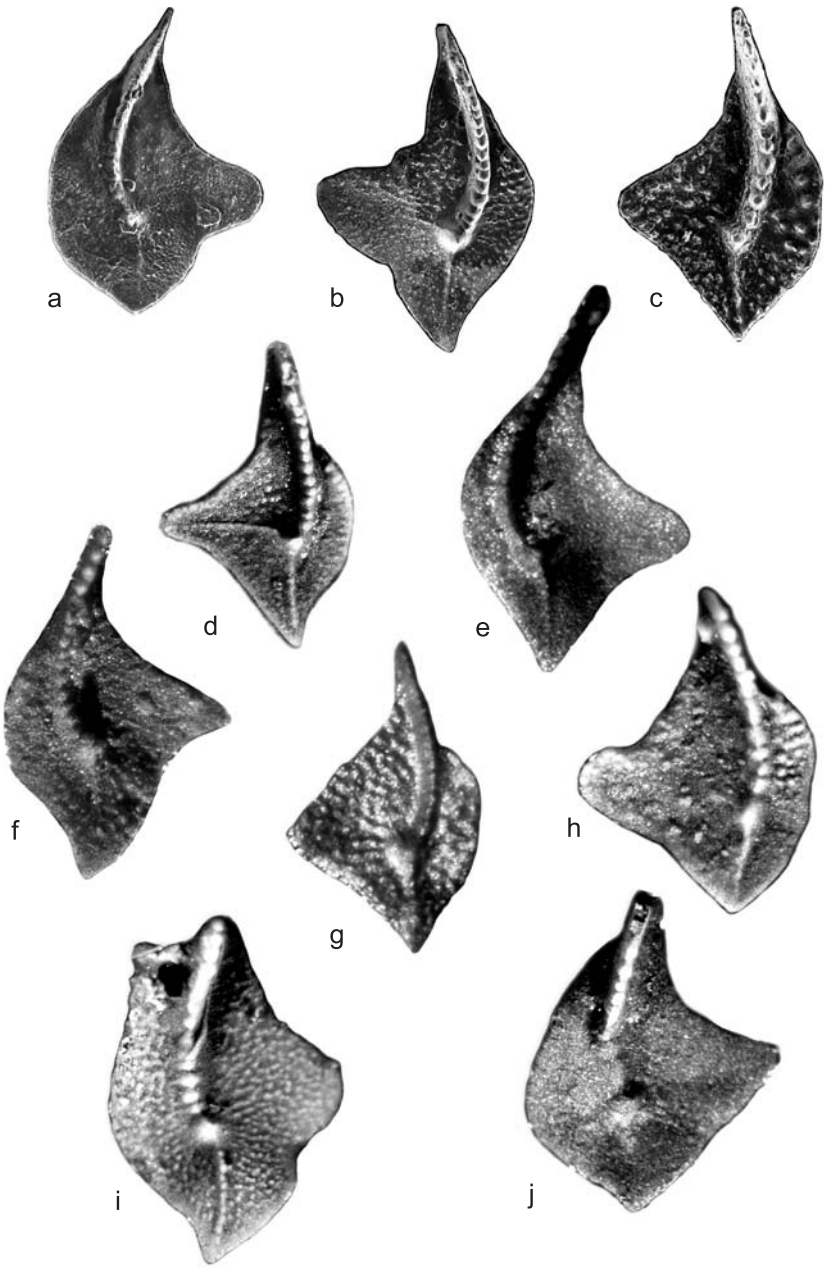

Fig. 5. Early Famennian conodonts from the Bol'shaya Barma, Ryauzyak and Lemezinsky sections

a — *Palmatolepis wolskae* Ovnatanova, Bol'shaya Barma section, Makarovo Horizon, *crepida* zones, 162/45, sample 8238, SEM, x 35; **b** — *Pa. quadrantinodosalobata praeterita* Schülke, Lemezinsky section, *Cheiloceras* Beds, Early *crepida* Zone, 162/42, sample 7191, SEM, x 30; **c** — *Pa. triangularis* Sannemann, Bol'shaya Barma section, Barma Horizon, Early-Middle *triangularis* Zone, 162/33, sample 8220, SEM, x 50; **d** — *Pa. triangularis* Sannemann, Ryauzyak section, Barma Horizon, Early-Middle *triangularis* Zone, 162/34, sample 6437, x 35; **e** — *Pa. subperlobata* Branson and Mehl, Lemezinsky section, *Cheiloceras* Beds, Early *crepida* Zone, 162/43, sample 7191, x 40; **f** — *Pa. triangularis* Sannemann *Pa. perlobata perlobata* Ulrich and Bassler, Bol'shaya Barma section, Barma Horizon, Early-Middle *triangularis* Zone, 162/35, sample 8224, x 40; **g** — *Pa.* aff. *protorhomboidea* Sandberg and Ziegler, Bol'shaya Barma section, Makarovo Horizon, *crepida* zones, 162/46, sample 8233, x 50; **h** — *Pa. quadrantinodosalobata* Sannemann, Lemezinsky section, *Cheiloceras* Beds, Early *crepida* Zone, 162/44, sample 7191, x 40; **i** — *Pa. perlobata perlobata* Ulrich and Bassler, Ryauzyak section, Makarovo Horizon, *crepida* zones, 162/47, sample 6445, x 30; **j** — *Pa.* aff. *circularis* Szulczewski, Ryauzyak section, Makarovo Horizon, *crepida* zones, 162/48, sample 6445, x 35

Rzhonsnitskaya *et al*., 1998) identified some atrypid species abundant in the Askyn Horizon of this region: *Pseudoatrypa* ex. gr. *devoniana* (Webster), *Costatrypa*(?) *posturalica* (Markovskii), *Gibberosatrypa gibberosa* (Markovskii), *Spinatrypa planosulcata* Webster, *Spinatrypina* (*Exatrypa?*) *bifurcata* (Markovskii) and *Desquamatia* (*Desquamatia*) *alticoloformis* Rzhonsnitskaya. The *linguiformis* Zone has been determined in the upper Askynian deposits (Abramova, 1999). Its thickness measures 0.43 m. Within this interval the taxonomic diversity of conodonts decreases but element frequency may reach hundreds per kilogram of rock. No Askynian-type brachiopods are found in the Barma Beds unlike in the Bol'shaya Barma section. In the Akkyr section, the Barma Beds are recognized only by a brachiopod assemblage within the lithologically homogeneous shelly unit. The assemblage includes all the Barmian index species (Abramova, 1999). *Palmatolepis triangularis* and *Pa. delicatula clarki*, characteristic of the Early-Middle *triangularis* zones, as well as various species of *Icriodus* and *Polygnathus*, appear in the section from the very base of the Barma Beds. The overlying 0.8 m of the section, composed of coquina, are characterized by an assemblage including *Palmatolepis subperlobata, Pa. triangularis Pa. spathula, Pa. triangularis Pa. clarki*. The occurrence of these species is also restricted to the Middle *triangularis* Zone.

Above the Barma Beds the fauna becomes different. In addition to conodont species appearing in the Late *triangularis* Zone, it comprises *Palmatolepis quadrantinodosalobata sandbergi* and *Pa. perlobata schindewolfi*, known from the *crepida* zones. Such a succession of conodont faunas suggests the absence of deposits of the Late *triangularis* zone in this section. The brachiopods *Plicatifera mugodjarica* Nachimson, *Cyrtospirifer tschernyschevi* Khalfin, *C.* ex. gr. *archiaci* Murchison, *C.* ex. gr. *pamiricus* Reed, *C.* ex. gr. *calcaratus* Sowerby and *Mucrospirifer posterus* Hall are characteristic of the Makarovo Horizon.

A similar pattern is seen in the section at the Sikaza River, here named the Kuk-Karauk section after the neighbouring farm (Figs. 7 and 8). Askynian brachiopod shell-beds, much as in the Akkyr section, are overlain by the Barma and Makarovo horizons, distinguished only by their faunal content. The thickness of the *linguiformis* Zone is relatively large in this section

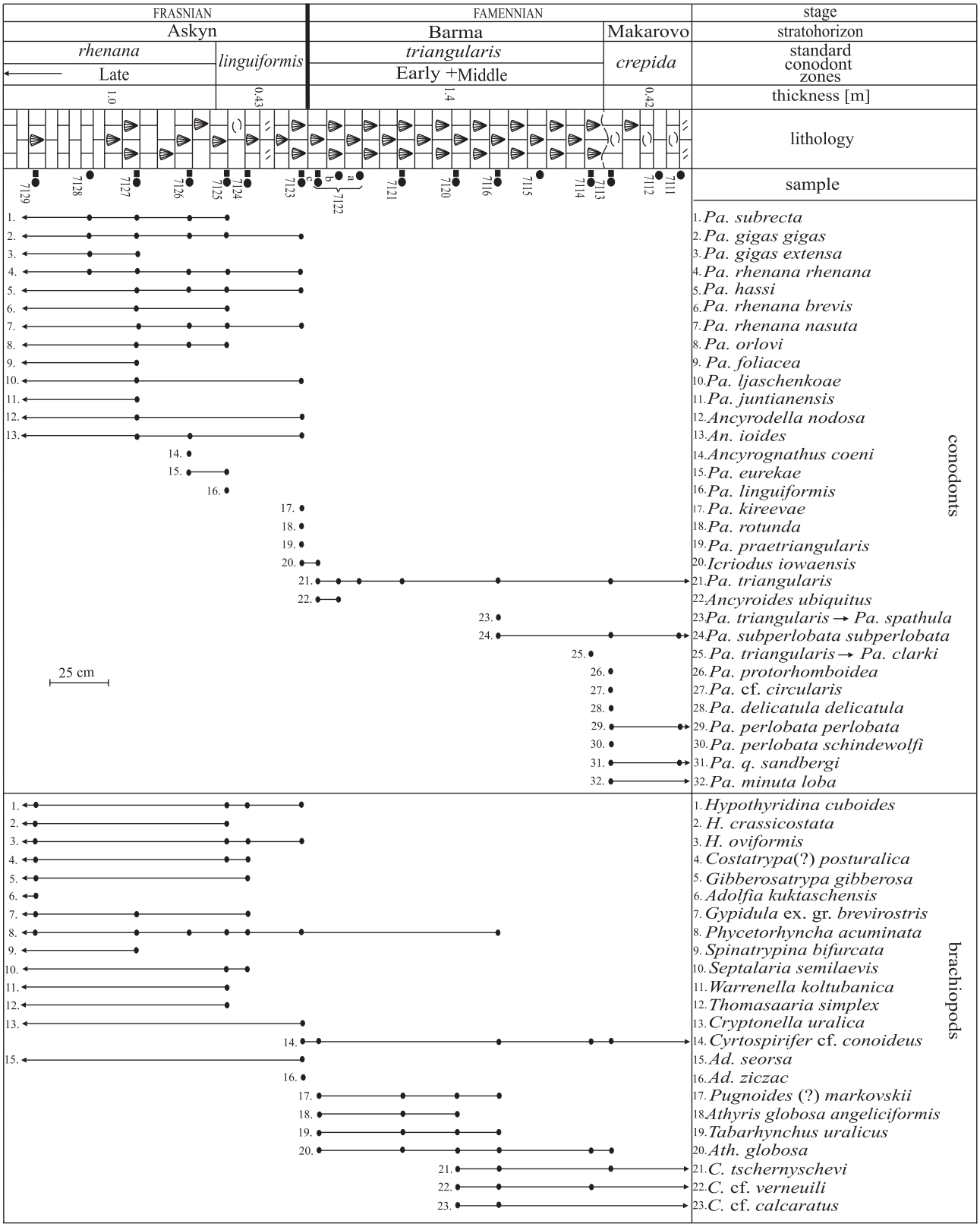

Fig. 6. Conodont and brachiopod distribution in the Frasnian-Famennian boundary beds in the Akkyr section

For explanations see Figure 2

and totals 4.0 m. The Barma Beds are 0.6 m thick, and representatives of the genus *Icriodus* and rare *Palmatolepis* are found within the lowest 0.15 m. Identifiable specimens of *Palmatolepis triangularis* are met 0.15 m above the base. An assemblage typical of the Late *triangularis* Zone is found above the Barma Beds within 0.4 m interval. Thus, it can be assumed that the Barma Beds, as in the above described sections, correspond to the Early-Middle *triangularis* zones, and the ab-

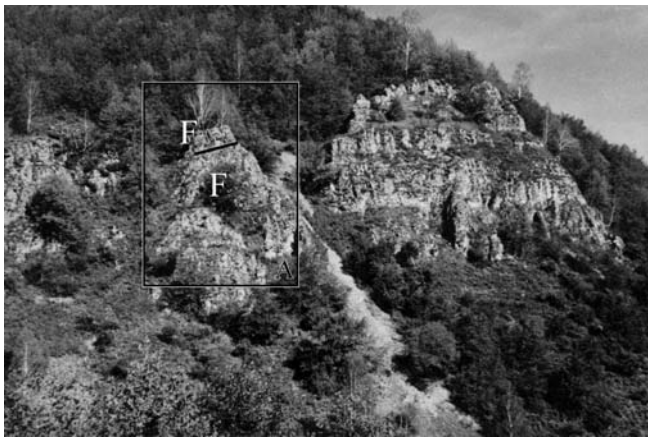

Fig. 7. Exposure of Upper Devonian deposits in the Kuk-Karauk section

A — portion of the section including the Frasnian-Famennian boundary

sence of typical conodont zonal assemblages is either due to insufficient data or, perhaps, in particular more shallow-water icriodid biofacies; this is the worldwide F-F phenomenon (Sandberg *et al*., 1988*b*; Schülke, 1995; Yudina *et al*., 2002; Racki *et al*., 2002, and our data below).

In summary, the Barma Beds are characterized by distinct assemblages of brachiopods and conodonts. All of the sections under study contain also other fossil groups, especially crinoids, but these have not yet been studied. The simultaneous appearance of *Pa. triangularis* and Barmian-type brachiopods *Pugnoides*(?) *markovskii* Yudina, *Tabarhynchus uralicus* Yudina, *Athyris globosa* Roemer, is noted in all the localities. In many sections, however, the undoubted Barmian association includes also Askynian-type species. However, the majority of genera of the Askynian assemblage became extinct at this level. By the beginning of the Barmian times, the rich and diversified conodont assemblage is drastically reduced. Together with the appearance of Barmian brachiopod species, we find *Pa. triangularis, Pa. delicatula delicatula* and *Pa. delicatula clarki,* characteristic of the Famennian stage. This is unambiguous evidence of the Famennian age of the Barma Beds.

Analysis of brachiopods by Yudina (1997) and Rzhonsnitskaya *et al*. (1998) from the F-F boundary interval in the Askyn-type sections, shows that the most significant changes in assemblages occur at the base of the Barma Beds. At this level, one can notice the extinction of the genera *Gypidula, Hypothyridina, Theodossia, Pseudoatrypa, Spinatrypa, Warrenella* and *Thomasaaria* that form main constituents of the fauna of the Askyn Horizon. Only representatives of *Schizophoria, Cyrtospirifer* and *Athyris* pass into the Barma Beds. The most typical species of the Barma Beds are *Pugnoides*(?) *markovskii* Yudina, *Tabarhynchus uralicus* Yudina, *Cyrtospirifer markovskii* Nalivkin and *Athyris globosa* Roemer. Changes that take place at the boundary between the Barma Beds and Makarovo Horizon are less important than those found lower in the sequence; they occur mainly at the species level. Such a distinct replacement of benthic and pelagic communities is a regional ecological response to global geological events, resulting in the F-F boundary mass extinction (Rzhonsnitskaya *et al*., 1998).

RYAUZYAK-TYPE FACIES

The unique character of the Ryauzyak-type facies consists in the fact that although it has all the features of a relatively deeper marine goniatite biofacies, it nevertheless contains brachiopod shelly accumulations. Thus, it is very important for correlation purposes (Fig. 14). The Ryauzyak section, a reference Upper Devonian exposure of this facies type, is situated on the right bank of the Ryauzyak River, 5 km upstream of the village of Sargaevo (Fig. 1). The section is characterized by a reduced thickness of the Frasnian deposits. Thus, the thickness of the Askyn Horizon here is only 2.2 m, brachiopod shell beds occuring solely within the F-F boundary interval.

All standard Frasnian conodont zones have been established in the thoroughly sampled succession, beginning with the *transitans* zones (Abramova, 1999). Brachiopod limestones, with a total thickness of 0.6 m, provide conodonts of the *linguiformis* Zone that includes the upper Askyn Horizon (0.15 m thick) and the Barma Beds (0.45 m). Brachiopod shell-beds, divided into two brachiopod assemblages, have been clearly established by Markovsky (1936, unpub.). Besides the reduced thickness in this section, the *linguiformis* Zone is characterized by a low-diversity conodont assemblage (Figs. 9 and 10). The zonal index species was found only in the lowermost shell bed. In the *linguiformis* Zone, brachiopods are represented by an impoverished Askynian-type assemblage (only 6 species).

The succeeding Barmian brachiopod association contains exclusively Famennian species. At the very base of the Barma Beds, conodonts are represented by ramiform elements and also by fragments of *Icriodus* and *Polygnathus*. Within the overlying 0.16 m (samples 6437–6439) the conodont assemblage includes, in addition to *Palmatolepis triangularis*, all other species diagnostic for the Early *triangularis* Zone (Fig. 4). In the Southern Urals, this is the only section with such a high conodont diversity in the post-extinction level. The collected samples, in particular sample 6437, contain assemblages dominated by the genera *Icriodus* and *Polygnathus*. The same biofacies turnover is known worldwide in the earliest Famennian (Sandberg *et al*., 1988). For example, by the end of the Early *triangularis* Zone, the conodont assemblages in West European sections show a large proportion of icriodids (~35%; Schülke, 1995).

The overlying limestones do not contain any brachiopods, whilst numerous conodonts characterize the *crepida* zones. The Late *triangularis* Zone is not established in this section.

INZER-TYPE FACIES

Sections of this type are represented by relatively deeper shelf facies marked by goniatite biofacies. Their distribution is limited to the Inzer and the Mendym River basins. In this facies, the *Crickites* Beds are age-equivalents of the Askyn Horizon, as shown by Domrachev (1952). In the type section of the Askyn Horizon on the Karan'yurt River, he found *Ńrickites* co-occurring with the Askynian-type brachiopod assemblage. Such a correlation was confirmed by conodonts, and the *Crickites* (=Askyn) Beds are recently considered to correspond to the Late *rhenana-linguiformis* zones (Abramova, 1999). The *Crickites*

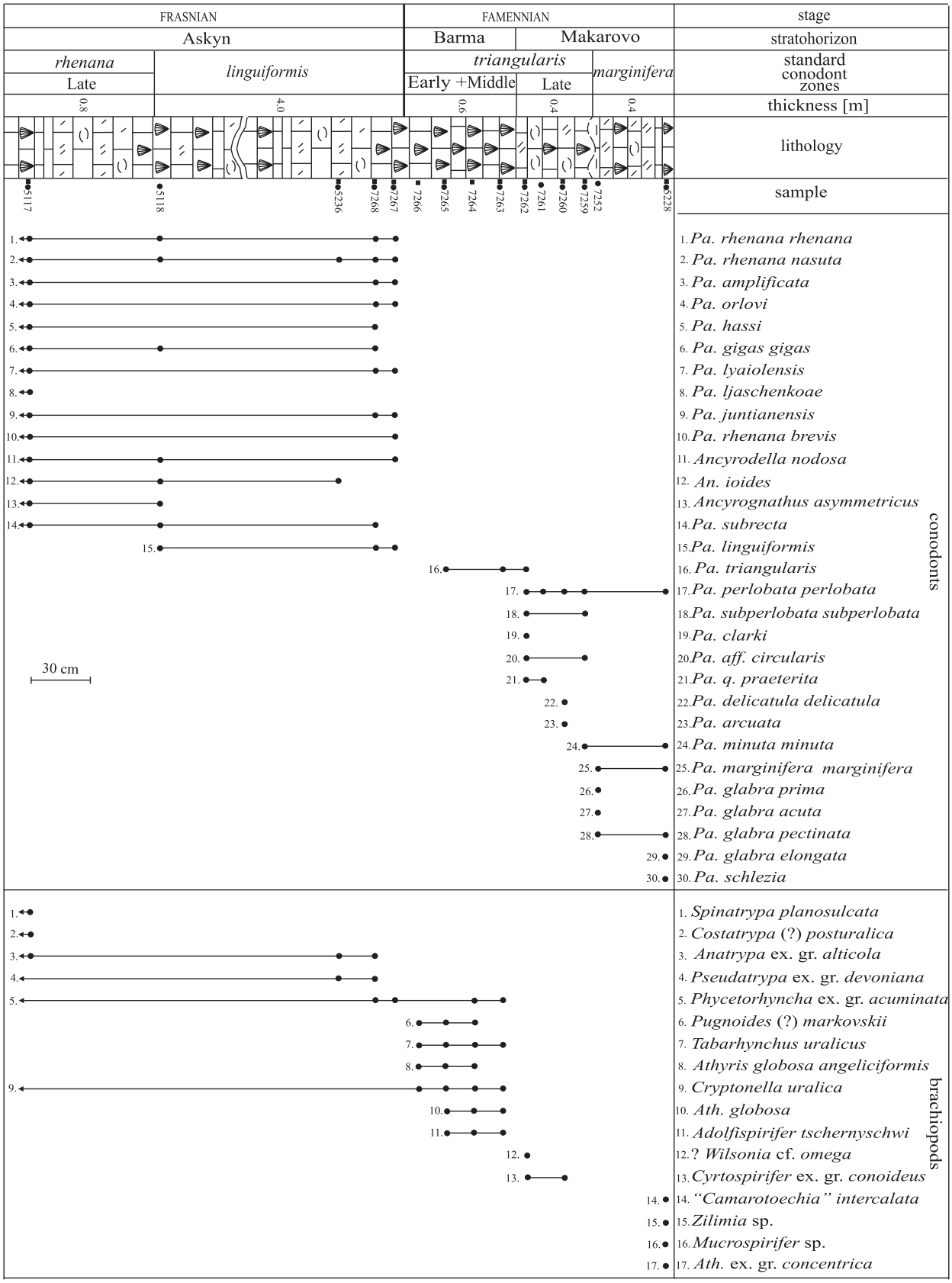

Fig. 8. Conodont and brachiopod distribution in the Frasnian-Famennian boundary beds in the Kuk-Karauk section

For explanations see Figure 2

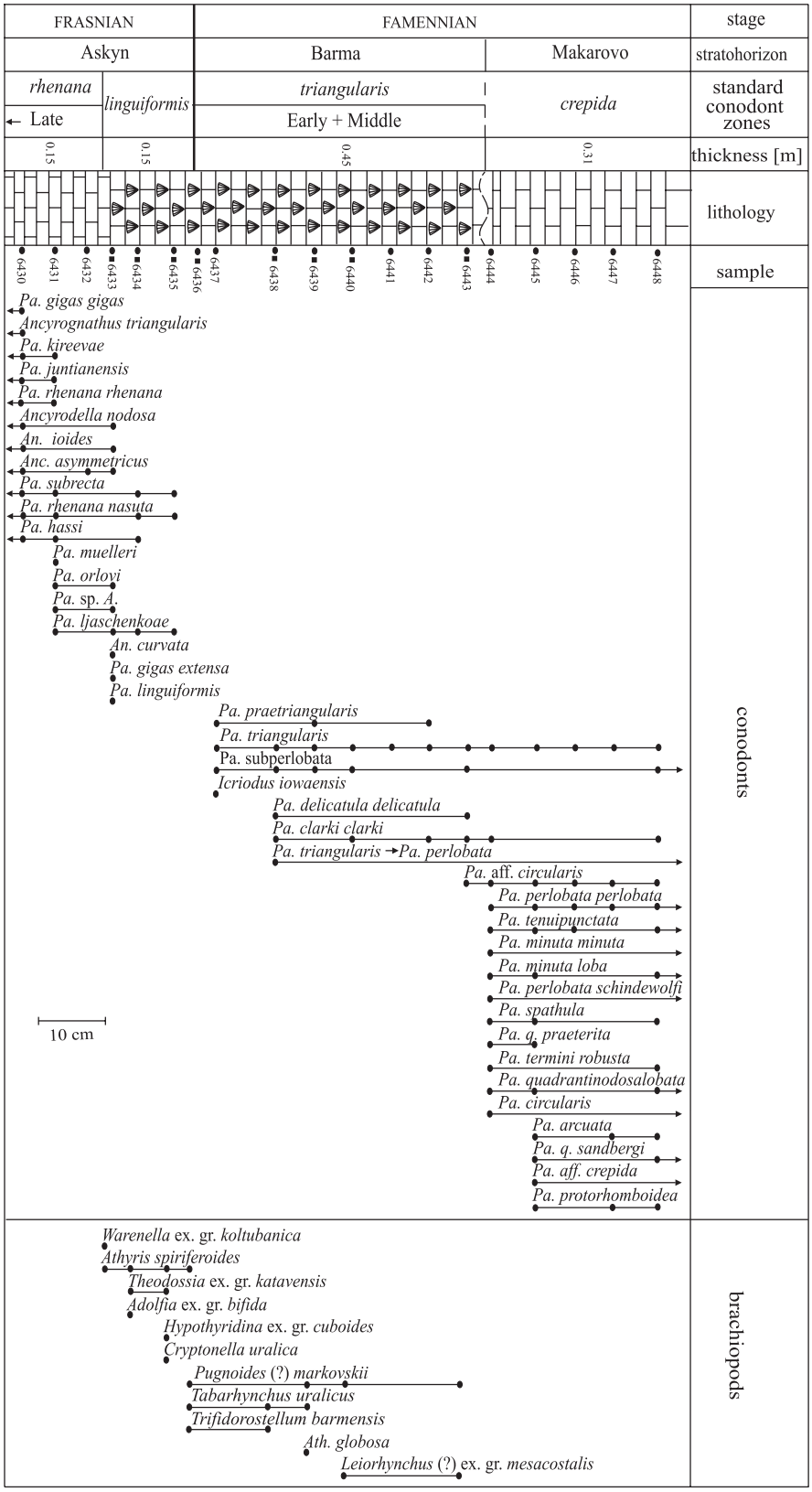

Fig. 9. Conodont and brachiopod distribution in the Frasnian-Famennian boundary beds in the Ryauzyak section

For explanations see Figure 2

Beds consist mainly of pelagic deeper marine thin-bedded micritic, commonly bituminous grey and dark grey limestones.

The Lemezinsky section is a well-known Upper Devonian locality of this facies type. The section is situated on the left slope of the Inzer River valley, opposite the former village of Lemezinsky (Fig. 1). The *linguiformis* Zone corresponds to a 0.47 m thick carbonate sequence, and numerous conodonts were found in each layer of the succession (Figs. 3, 10 and 11). The upper interval (0.14 m) of the *linguiformis* Zone consists of black thin-bedded bituminous limestone, particularly rich in diverse faunas: conodonts, goniatites, orthoceratids, pelecypods, brachiopods, ichthyofauna and less numerous ostracods. Goniatites of the genus *Crickites* have not been found but *Tornoceras* sp., *Manticoceras* cf. *layolense* Bogosl., *M.* cf. *eliseevi* Bogosl., *M. intermedium* Sandb., *M. adorfense* Wdkd., *M. drevermanni* Wdkd. are common in the underlying Mendym Horizon (Fig. 11). This interval may well be equivalent to the Kelwasser Horizon.

The overlying Famennian deposits display variable composition. In their basal part they are represented by a set of thin-platy interbedded brownish-grey, grey and dark grey, locally dolomitized, commonly silicified micritic limestones, and fine-grained friable sandstones, siltstones and greenish-grey clays (0.98 m thick). Individual layers are 0.01 to 0.05 m thick. The lower part (0.31 m) of this succession contains conodonts typical of the undivided Early-Middle *triangularis* zones. Along with *Palmatolepis*, the assemblage includes representatives of the genera *Polygnathus, Icriodus* and ramiform elements. The overlying layers (1.02 m) contain conodonts indicative of the *crepida* zones (Fig. 5). The Late *triangularis* Zone, as in the Akkyr and Ryauzyak sections, has not been recognized.

In summary, conodont assemblages in all the layers are characterized by a great species diversity and abundance. In addition to conodonts, the section reveals two levels with goniatites. These are late Frasnian representatives of the genus *Manticoceras* from the *linguiformis* Zone and early Famennian species of the genus *Cheiloceras* from the *crepida* zones. The Lemezinsky section perfectly records a severe extinction of the rich conodont fauna at the F-F boundary, while goniatites, undergo similar changes.

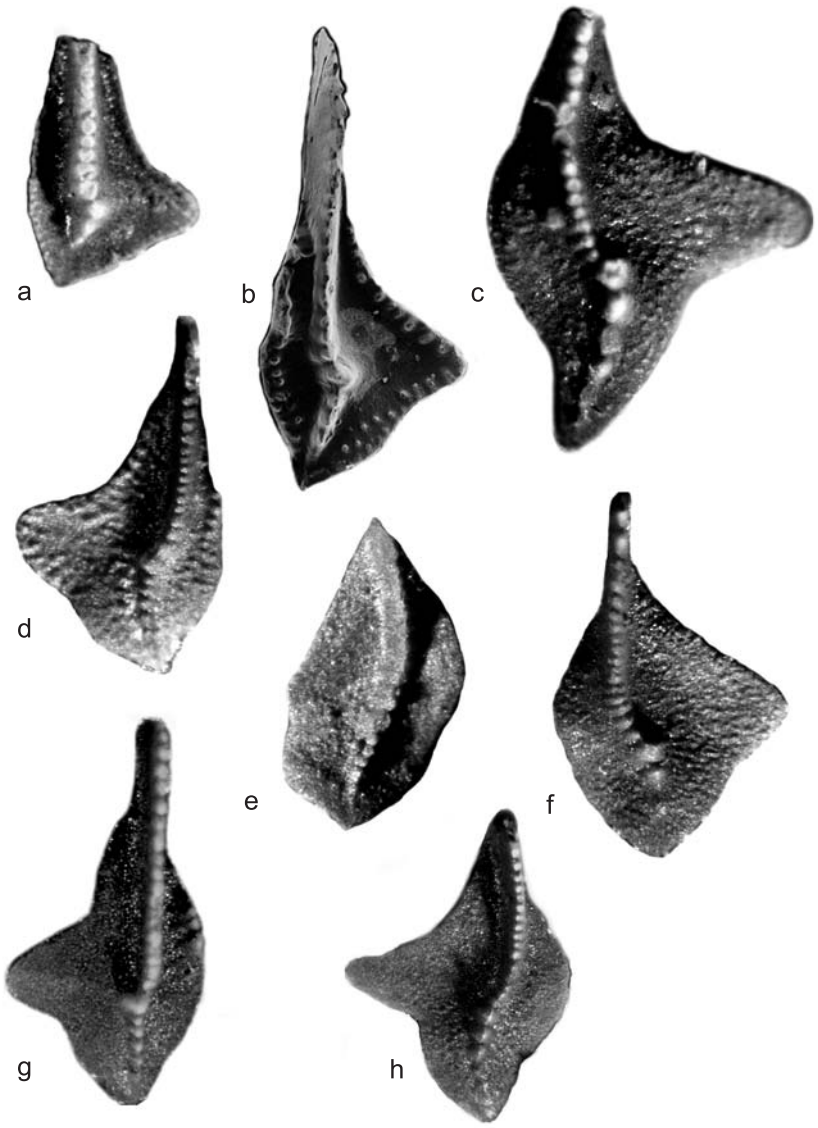

Fig. 10. Frasnian conodonts from the Ryauzyak and Lemezinsky sections

a — *Palmatolepis juntianensis* Han, Ryauzyak section, Askyn Horizon, Late *rhenana* Zone, 162/10, sample 6431, x 30; **b** — *Pa. gigas extensa* Ziegler and Sandberg, Ryauzyak section, Askyn Horizon, *linguiformis* Zone, 162/17, sample 6433, SEM, x 35; **c** — *Pa. rhenana rhenana* Bischoff, Ryauzyak section, Askyn Horizon, Late *rhenana* Zone, 162/11, sample 6430, x 30; **d** — *Pa. subrecta* Miller and Youngquist, Lemezinsky section, *Crickites* Beds, *linguiformis* Zone, 162/14, sample 7197, x 30; **e** — *Pa. linguiformis* Müller, Lemezinsky section, *Crickites* Beds, *linguiformis* Zone, 162/16, sample 7198, x 35; **f** — *Pa. lyaiolensis* Khrustcheva and Kuz'min, Lemezinsky section, *Crickites* Beds, *linguiformis* Zone, 162/15, sample 7198, x 30; **g** — *Pa. sp.* Lemezinsky section, *Crickites* Beds, *linguiformis* Zone, 162/18, sample 7197, x 20; **h** — *Pa. rhenana nasuta* Müller, Lemezinsky section, *Crickites* Beds, *linguiformis* Zone, 162/19, sample 7198, x 20

WEST ZILAIR-TYPE FACIES

A distinctly different type of the F-F succession occurs in the upper (meridional) Belaya River on the western flank of the Zilair Megasynclinorium. It is represented by relatively deep marine deposits consisting of siliceous-terrigenous rocks. The continuous Frasnian-Famennian boundary interval documented by conodonts, has been studied in three sections: Kagarmanovo, Ilyukhina Glade and Chernaya River Mouth (Yakupov *et al*., 2002). In each of them, the boundary interval is represented by thin-platy siliceous-terrigenous shales and siliceous siltstones deformed as complex folds; their total thickness does not exceed 20 m (Fig. 12). The underlying deposits consist of grey medium-bedded goniatite limestones (2–3 m thick), with a conodont assemblage typical of the *linguiformis* Zone. The assemblage is distinctive for common representatives of the genus *Ancyrodella* (about 20%), in contrast to the other Urals sections at this level. At the contact between limestones and the siliceous-terrigenous member, a 0.1 m-thick layer of greenish-grey ferruginous siliceous-carbonate shale occurs, capped by a layer of platy cherts. The base of the unit is distinguished by silicified limestones and carbonate nodules with conodonts typical of the *linguiformis* Zone. Specimens of *Pa. triangularis* were found in the upper portion of the succession, and a conodont assemblage typical of the Late *triangularis* Zone is present at its top. We consider this member to be transitional between the carbonate Belaya Formation and the flysch-like Zilair Formation. The overlying deposits consist of grey-green rhythmically interbedded polymictic sandstones, siltstones, and clayey shales.

The left bank of the Belaya River, 0.5 km upstream of the mouth of the Chernaya River, exposes only the upper portion of the transitional F-F unit (8–8.5 m thick). The section consists of siliceous siltstones and clayey shales with rare thin (1–2 cm) interbeds of calcareous siltstones (Fig. 13). The thickness of siliceous siltstone intercalations is reduced upwards, while clayey shales become thicker. In the lower 6.0–6.5 m, at several levels, we found a rich conodont assemblage diagnostic of the *linguiformis* Zone whereas early Famennian conodonts typical of the Early-Middle *triangularis* zones occur in the upper part (2 m thick). The uppermost layers show conodonts of the Late *triangularis* Zone. It dates the base of the overlying flysch-like Zilair Formation.

In summary, in this type of section the F-F boundary is situated within a lithologically monotonous succession of siliceous-clayey-carbonate rocks.

CONCLUSIONS AND FINAL REMARKS

1. Upper Devonian sections of the Southern Urals exhibit the complete sequence of standard conodont zones as defined by Ziegler and Sandberg (1990). In continuous sections, the Frasnian-Famennian boundary runs within the lithologically uniform succession and can be established only by faunal

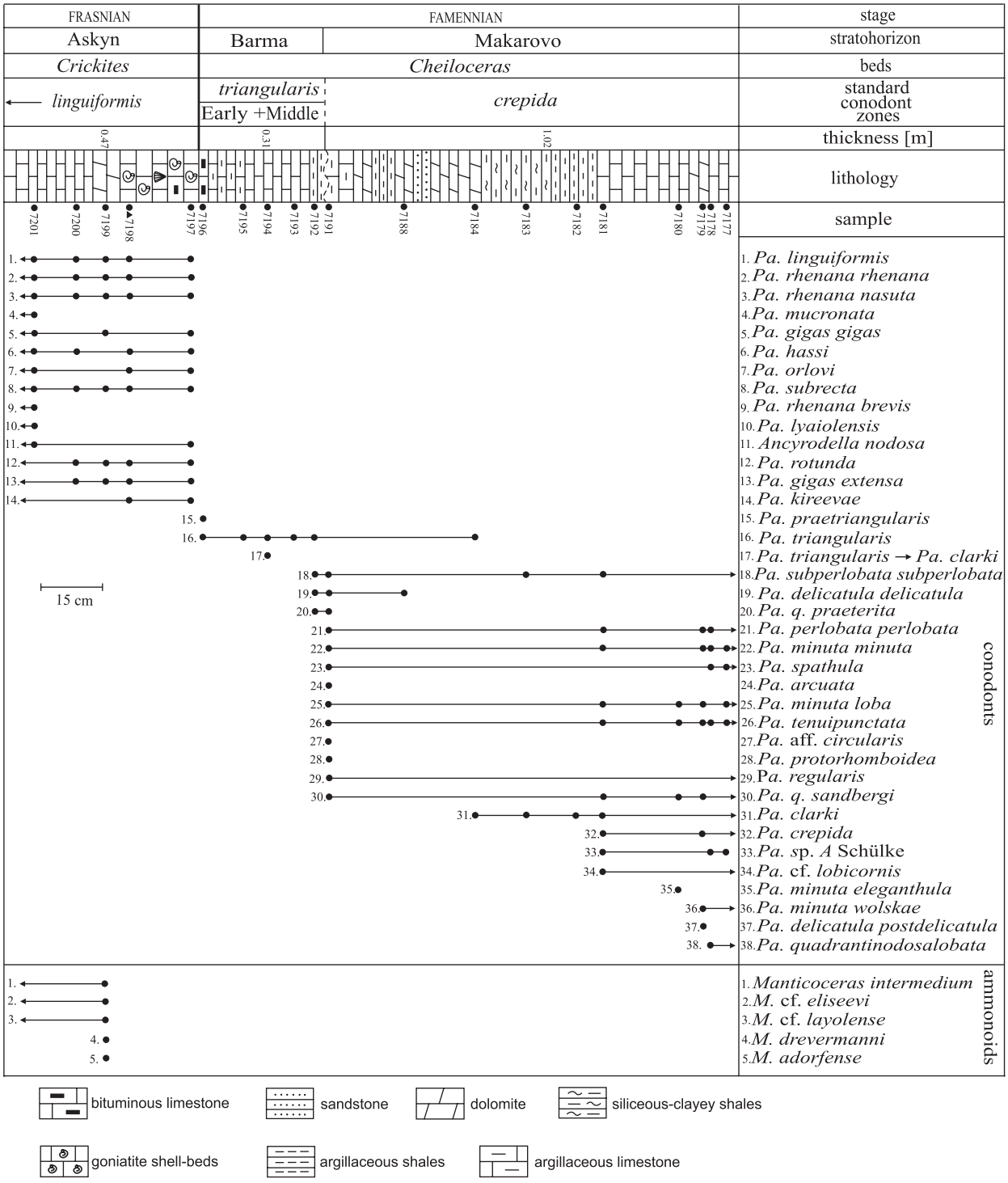

Fig. 11. Conodont and goniatite distribution in the Frasnian-Famennian boundary beds in the Lemezinsky section

For explanations see Figure 2

changes (Fig. 14). For the Askyn type of section, this boundary is drawn at the base of the Barma Beds (Abramova, 1999). It is precisely the level where a dramatic shift in brachiopod and conodont assemblages occurs. The bulk of the Barma Beds (= beds with *Pugnoides*(?) *markovskii* Yudina) corresponds to the undivided Early-Middle *triangularis* Zone of the Famennian age. The Makarovo Horizon is assigned to the Late *triangularis* Zone. As the Barma Beds occupy a definite stratigraphical interval below the Makarovo Horizon and are clearly of Famennian age we here propose that they should be defined as a new independent biostratigraphical horizon within the Famennian Stage in the Urals.

2. The Frasnian-Famennian boundary beds in the Southern Urals distinctly record the global biotic Kelwasser Event, manifested in the mass extinction of many different faunal groups (see summary in Walliser, 1996). Southern Urals sections are noted

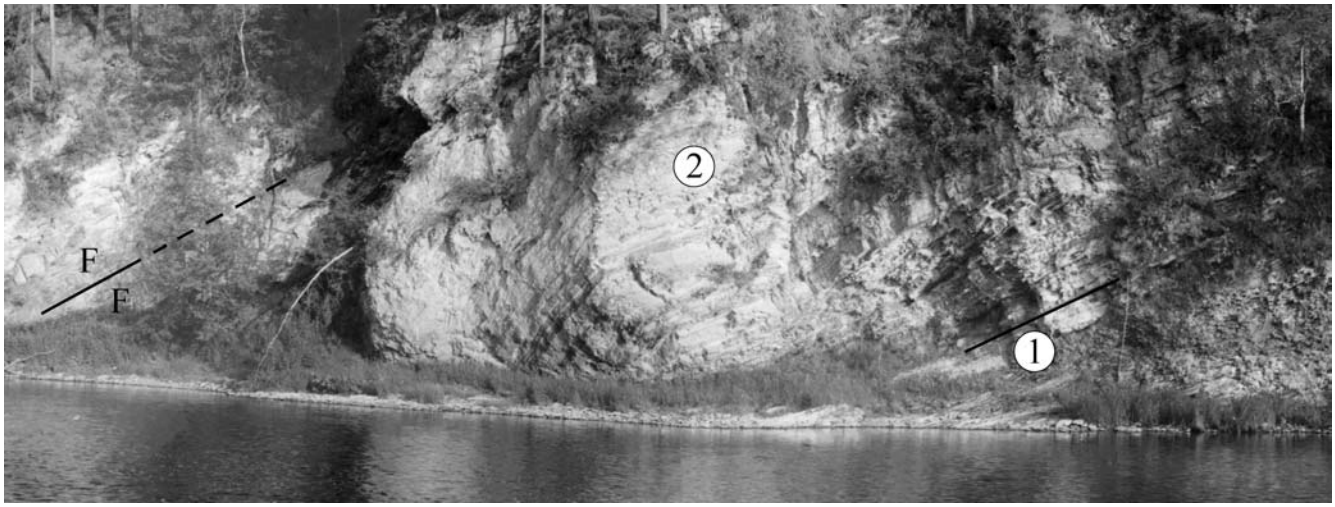

Fig. 12. Exposure of the Frasnian-Famennian deposits representative of the West-Zilair type

The Ilyukhina Glade section: 1 — goniatite limestones with a conodont assemblage of the *linguiformis* Zone; 2 — thinly platy siliceous-terrigenous shales and siliceous siltstones

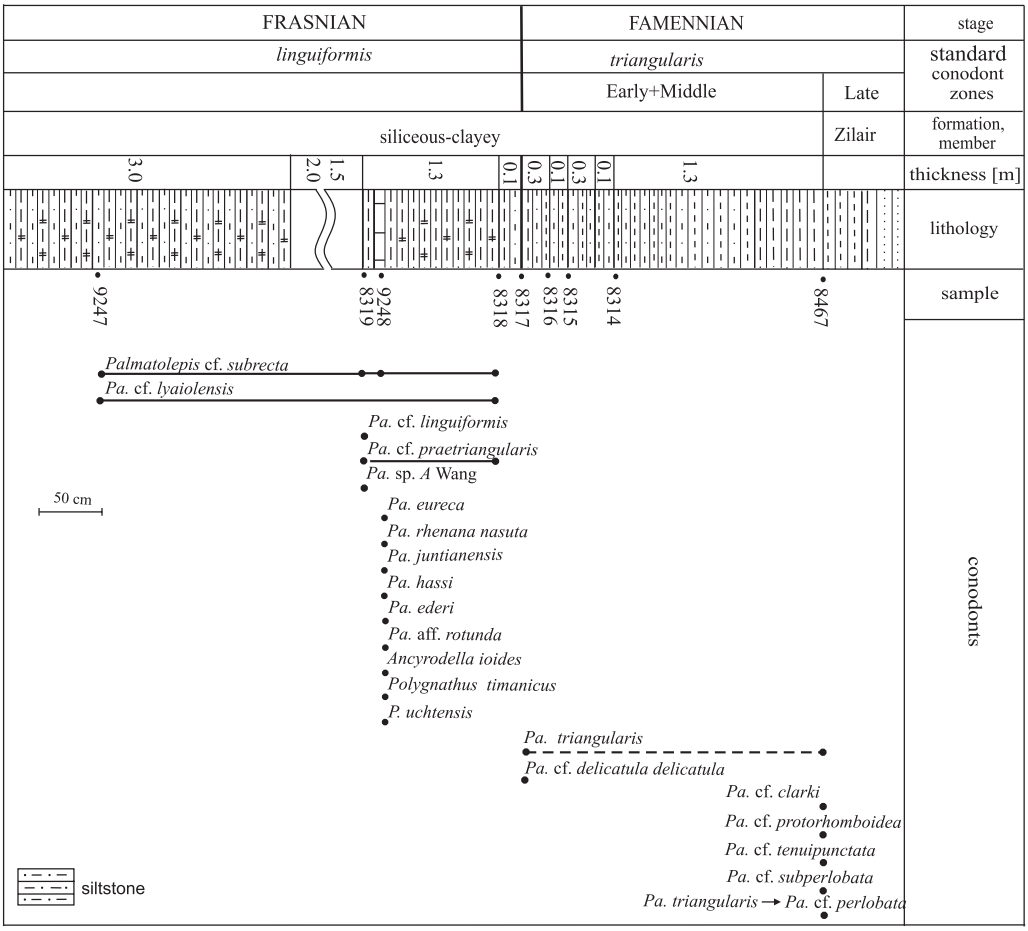

Fig. 13. Conodont distribution in the Frasnian-Famennian boundary beds in the Chernaya River Mouth section

For other explanations see Figures 2 and 11

for a fundamental rearrangement in the biota, especially brachiopod faunas, at the boundary between the *linguiformis* and *triangularis* conodont zones. The sequence exhibits also the well-known icriodid blooms in the earliest Famennian. There is also sedimentological evidence for a diversity of events ranging over the *linguiformis* and Early-Middle *triangularis* zones:

— formation of brachiopod coquinas (Askyn- and Ryauzyak-type sections);

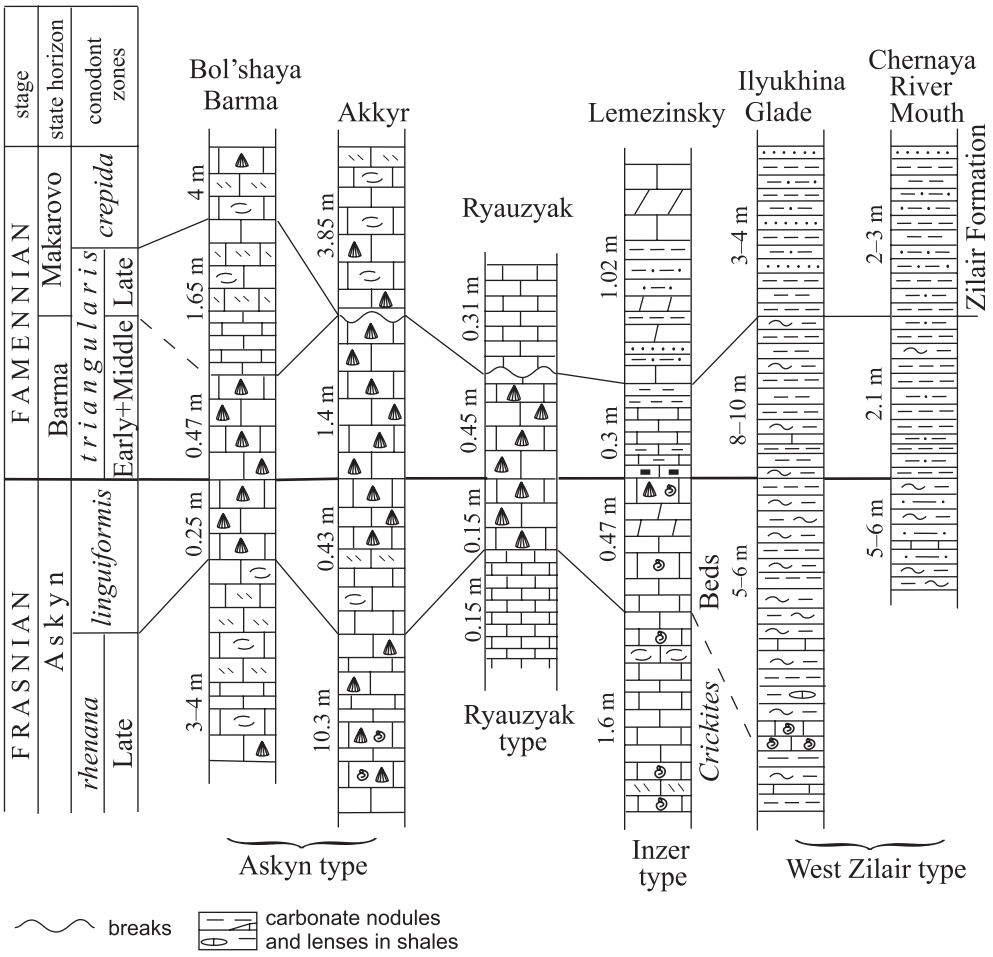

Fig. 14. Correlation of different facies sections of the Frasnian-Famennian boundary deposits in the Southern Urals

The vertical scale is arbitrary (but compare thicknesses of the units in metres given on the left side of each column); for explanations see Figures 2, 11 and 13

— deposition of black bituminous limestone very rich in goniatite and brachiopod shells (Inzer-type section);

— stratigraphic breaks of various duration (all facies types);

— deposition from turbidity currents (Zilair type facies).

3. Sharing other researchers' views (Johnson *et al*., 1985; Johnson and Sandberg, 1988; Sandberg *et al*., 1988*b*; House *et al*., 2000) we think that a sharp decrease in taxonomic diversity and the extinction of many high-rank taxa (for example, the brachiopod orders Atrypida and Pentamerida) was possibly linked with an eustatic fall in sea level, beginning in the *linguiformis* Zone and having its maximum by the Early *triangularis* Zone. It was precisely the time interval when stable and prolonged pelagic sedimentation occurring in the Southern Ural Ocean (siliceous-clayey Mukasovo Formation) gave way to the active manifestation of arc volcanism (basalts of the Bugodak Series) accompanied by the formation of sedimentary olistostromes and turbidites (Biyagoda Formation; Veimarn *et al*., 1998; 2002; Maslov *et al*., 1999; Maslov and Artyushkova, 2000, 2002). As many authors have also emphasized in recent years, mass extinctions are likely due to a combination of endogenic, exogenic, and extraterrestrial factors having a complex interaction (e.g., Racki, 1998; Veimarn *et al*., 1998; Koren., 2000; Yudina *et al*., 2002).

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