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ORIGINAL PAPER

Middle Devonian (Givetian) conodonts from the northern margin of Gondwana (Soh and Natanz regions, north-west Isfahan, Central Iran): biostratigraphy and palaeoenvironmental implications

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Abstract Four sections of mainly Middle Devonian (Givetian) shallow-marine rocks at the northern margin of Gondwana (Central Iran) were investigated with a special focus on the Bahram Formation, as the stratigraphic range of the Bahram Formation is uncertain and still under discussion. Generally, the Bahram Formation is discontinuously underlain by the Lower Devonian Padeha Formation and disconformably overlain by the Permian Jamal Formation. Conodont communities from the four sections in the Soh area (Najhaf and Neqeleh sections) and the Natanz area (Varcamar and North Tar sections) were investigated. The most widely applied conodont standard zonation of the Upper Givetian contain taxa characteristic of deeper shelf facies whereas conodont fauna of the investigated sections mainly show affinities to shallow-marine environments. Shallow-water conodont associations corresponding to the *expansus* Zone and *subterminus* Zone are described from Central Iran for the first time, whereas the vast majority of icriodontid and polygnathid faunas were reported from shallow-marine carbonates around Laurussia (e.g. North America, and Europe). Thirty-six species and subspecies were assigned to five genera (*Ancyrodella*, *Bipennatus*, *Icriodus*, *Polygnathus* and *Pandorinellina*). The sedimentological record is characterised by remarkable lateral facies changes, but in the upper part of the Givetian, a general transgressive trend is obvious due to the dominance of limestones and small biostromes.

Keywords Shallow-water conodont associations · *expansus* Zone · *subterminus* Zone · Microfacies · Bahram Formation · Central Iran

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Introduction

Rocks of Devonian age are widespread in Iran, and the presence of Middle and Upper Devonian rocks in Central Iran has long been established (e.g. Frech 1900; Douvillè 1901, 1904; Stahl 1911). Mid-Palaeozoic rocks in Central Iran generally occur in structurally isolated units and, therefore, correlation between different units is difficult. Djafarian and Brice (1973) documented the first discovery of Famennian brachiopods in Chahriseh- and Zefreh Mountains, close to the studied sections in the Soh and Natanz regions. Conodonts, brachiopods, trilobites and microvertebrate remains were subsequently documented in investigations of the Devonian deposits of the Chah-Riseh and Zefreh sections (Zahedi 1973; Hamedani 1996; Brice et al. 1999; Rohart 1999; Brice and Kebriaei 2000; Mistiaen et al. 2000; Hairapetian et al. 2000; Ghavidel-Syooki 2001; Morzadec et al. 2002; Kebriaei 2003; Gholamalian 2003, 2005, 2007). In the Soh area, Long and Adhamian (2000), Adhamian (2003) and Ghobadipour et al. (2005, 2013) published new biostratigraphic data based on different fossil groups, such as brachiopods, trilobites and conodonts. Studies on regional geology and palaeogeography by Zahedi (1973) provided detailed lithological logs of Palaeozoic to Mesozoic sections. Additional work by Stöcklin

(1974), Davoudzadeh and Schmidt (1982), Soffel and Förster (1984) and Weddige (1984) also contributed to the knowledge on regional geology and palaeogeography, but the first comprehensive overview on stratigraphy, facies and palaeogeography of Northern and Central Iran was published by Wendt et al. (2005). In Central Iran, Devonian deposits occur mainly in the northeast of Isfahan, in the Soh (Najhaf and Neqeleh sections) and Natanz areas (Varcamar and North Tar sections) which are located between the western margin of the Central Iran Microplate and the eastern margin of the Sanandaj-Sirjan Zone as a part of the NW-trending Urumiyeh–Dokhtar volcanic arc (Fig. 1).

We have examined four sections (from N to S: Najhaf, Neqeleh, North Tar, and Varcamar sections) in order to compare the stratigraphic ranges of mainly shallow-water marine conodont associations and to provide a better stratigraphic range of the Bahram Formation. In this paper we provide a generalised lithological description and conodont biostratigraphy for each section; a more detailed sedimentological and geochemical study is forthcoming. This publication is a contribution to IGCP 596—Climate Change and Biodiversity Patterns in the Mid-Paleozoic (Early Devonian to Late Carboniferous).

Geological setting

During the Palaeozoic, the Iran Plate was part of the northern margin of Gondwana (Berberian and King 1981; Scotese 2001). The Central East Iran Microplate (equivalent to the central part of the Iran Plate) was most probably connected to the southern rim of Eurasia during most of the Palaeozoic and Mesozoic (e.g. Soffel and Förster 1984; Weddige 1984). Marine conditions were present in Northern and Central Iran from the Middle Devonian to early Frasnian and persisted into the early Pennsylvanian (Bahrami et al. 2014 and references therein). A widespread uplift in the latest Carboniferous led to continental environments before the onset of a new marine cycle during the Early Permian. Iran is structurally and palaeotectonically divided from north to south and is amalgamated from a number of tectonic blocks (e.g. Soffel et al. 1996; Wendt et al. 2005): There is a northern zone extending from Azerbaijan across the Talesh Range, the Caspian depression into the Kopet Dagh and northwestern Afghanistan. Central Iran comprises western Azerbaijan, the Elburz and Binalud Mountains in the north and various separated Palaeozoic blocks further in the south. The Central East Iran Microplate is bounded by major faults in the northwest, southwest and east which underwent a clockwise rotation since the Late Triassic (Soffel et al. 1996). The Sanandaj-Sirjan Zone stretches from northwest Iran to south Iran. This zone contains a number of Mesozoic and Paleozoic strata, and in Palaeozoic times the Sanandaj-Sirjan Zone was part of the central Iranian shelf (Wendt et al. 2005). The Zagros Mountains in the south contain a few Palaeozoic rocks, which have been deposited on the Precambrian basement of the Arabian Platform.

In the study reported here, we focussed on Palaeozoic strata of the Soh and Natanz areas (Figs. 1, 2) which are part of the Urumiyeh-Dokhtar volcano-plutonic arc extending from Tabriz (Azarbaijan) to Bazman (Sistan-va-Baluchistan) in a NW–SE strike direction. This structure is located at the contact between the Sanandaj-Sirjan Zone and the central Iranian shelf, an area which is 1700 km long and 100 km wide (Fig. 1). The structure runs parallel to the Zagros thrust fault. Volcanism in this area began in the early Late Cretaceous and culminated in the Eocene. The plutonic rocks present in this region are the result of extensive magmatism linked to the Alpine orogeny. The entire area is characterised by tectonic deformation and, consequently, sedimentary sequences exhibit many thrusts and faults. Repetitions of sequences are common.

Lithostratigraphy and facies

We have described four shallow water sections (from N to S: Najhaf, Neqeleh, North Tar and Varcamar sections; Fig. 2) with a special focus on the Bahram Formation. To date, the most comprehensive outcrop-based studies of the Bahram Formation were conducted by Yazdi et al. (2000), Gholamalian (2003, 2005, 2007) and Adhamian (2003). According to these studies, the age of the Bahram Formation in the Isfahan area includes Givetian, Frasnian and discrete Famennian deposits. Yazdi et al. (2000) and Yazdi (2001) described late Famennian conodonts at the top of the Bahram Formation, whereas in other publications the upper boundary of this formation corresponds to Frasnian or Famennian ages (e.g. Yazdi 1999; Yazdi and Turner 2000; Wendt et al. 2005; Gholamalian and Kebriaie 2008; Gholamalian et al. 2009; Bahrami et al. 2011a, b). Conodonts from a Devonian sequence at Kuh-e-Kaftar in the Chah-Riseh area northeast of Isfahan also suggest a late Famennian age, but these have not been assigned to the Bahram Formation (Gholamalian 2003). The Bahram Formation is disconformably overlain by the Permian Jamal Formation but the placing of its base remains controversial. The Bahram Formation is underlain by the Late Devonian Padeha Formation or by the Sibzar Formation which belongs to the Middle Devonian (e.g. Zahedi 1973; Wendt et al. 2005). Brice et al. (2006) dated the base of the formation as Eifelian in the Zefreh area. A Givetian age for the lower boundary in the Soh area was proposed by Adhamian (2003), and an early Frasnian age for the Isfahan area (Chah-Riseh section) was suggested by Gholamalian (2007) and Turner et al. (2002). Gholamalian and Kebriaie (2008) proposed a middle Frasnian age for a section in the Kerman province.

Four sections, including the Neqeleh- and Najhaf sections in the Soh area and the North Tar- and Varcamar sections in the Natanz area, were measured, logged and sampled (Figs. 1, 2).

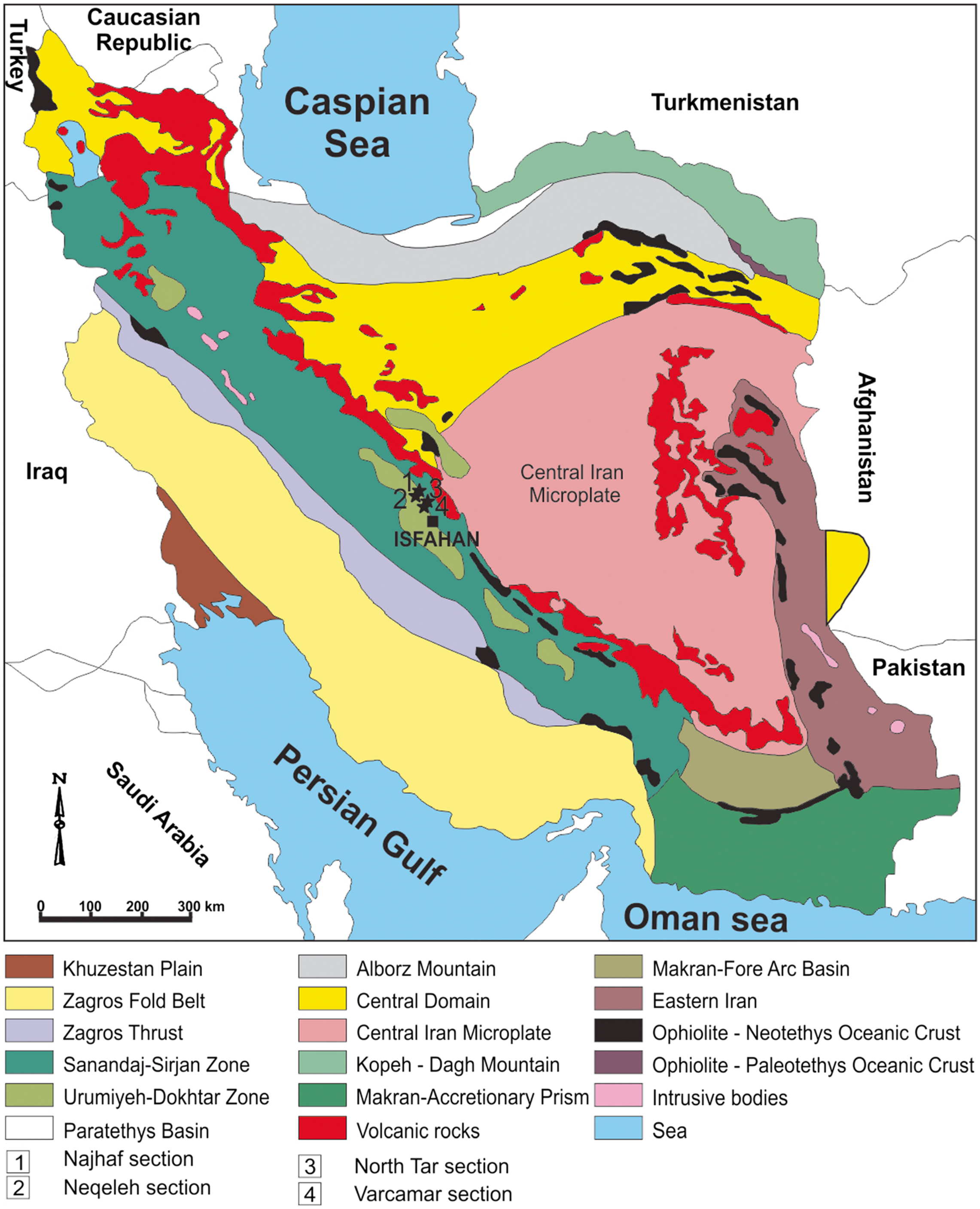


Fig. 1 Structural units of Iran with locations of the studied sections

Generally, all sections exhibit shallow-water sediments characterised by lateral facies changes and rhythmic sedimentation (e.g. calcareous sandstones and limestones). The sedimentological record is described in stratigraphical order from the base to the top, and from the north to the south. The lithological observations and stratigraphic details of each of these four sections are summarised in Figs. 3–6, respectively, and Figs 7 and 8 show representative thin sections, polished slabs and outcrop photographs mainly of the Bahram Formation.

Najhaf section

The Najhaf section (Figs. 2, 3) is located in the Najhaf valley (33°29′31″N, 51°34′55″E), about 110 km northwest of

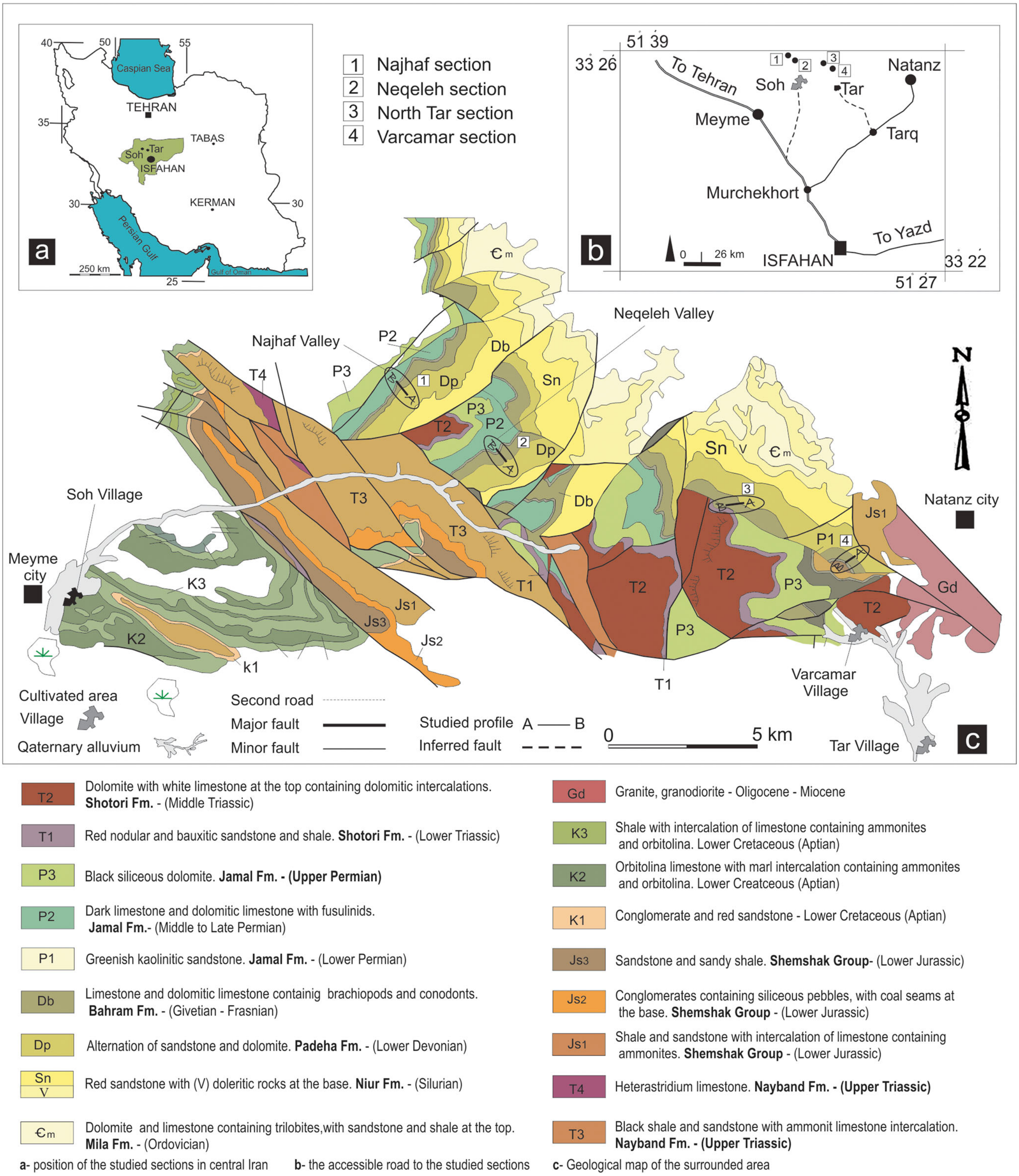


Fig. 2 Position of the studied sections in Central Iran (**a, b**) and (**c**) geological map of area

Isfahan. The section has a thickness of about 120 m. Based on lithological characteristics and field observations, the section can be subdivided as follows:

– The base of the section starts in the Middle Devonian. The contact with older sediments (e.g. the Padeha Formation) is not exposed in this section.

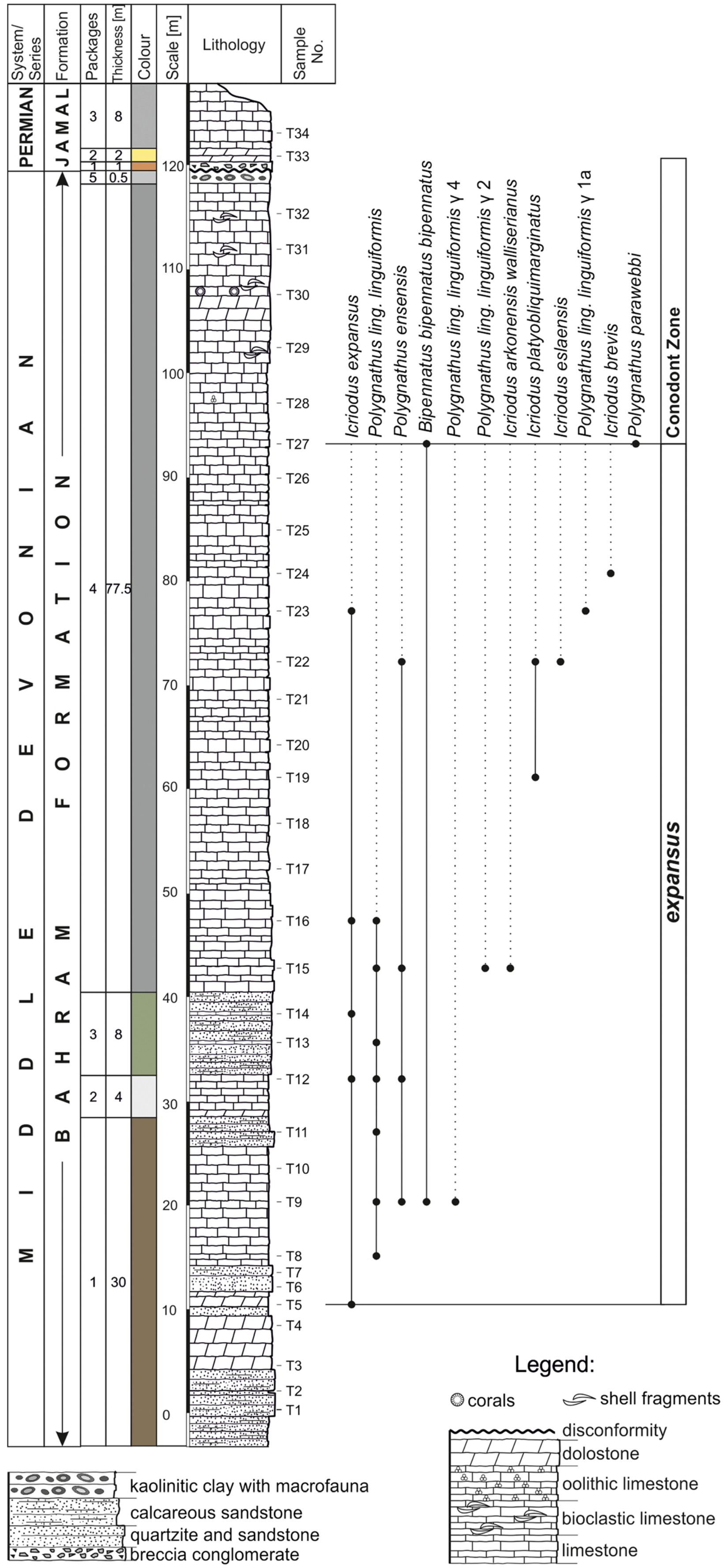
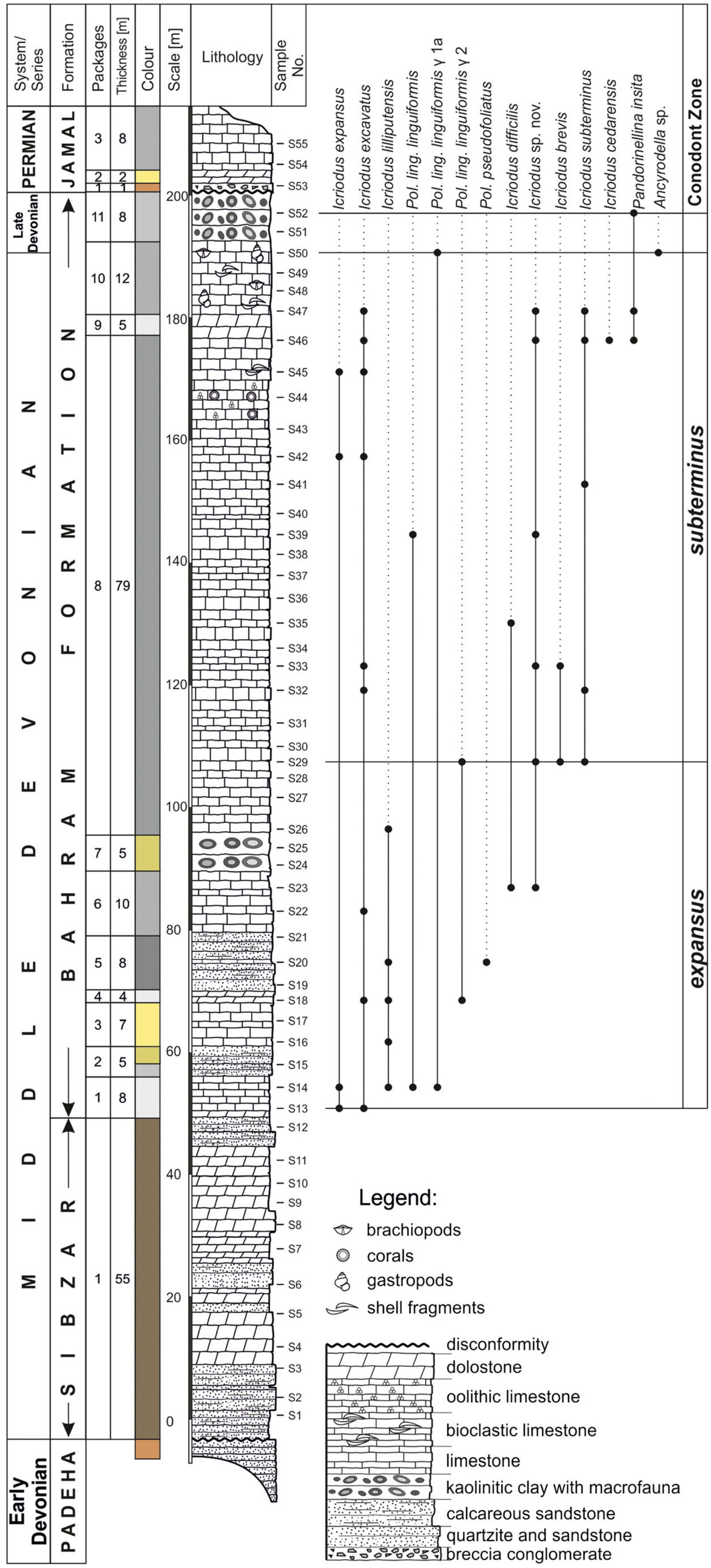


Fig. 3 Detailed lithological column of the Najhaf section and the occurrence of conodonts

Fig. 4 Detailed lithological column of the Neqeleh section and the occurrence of conodonts



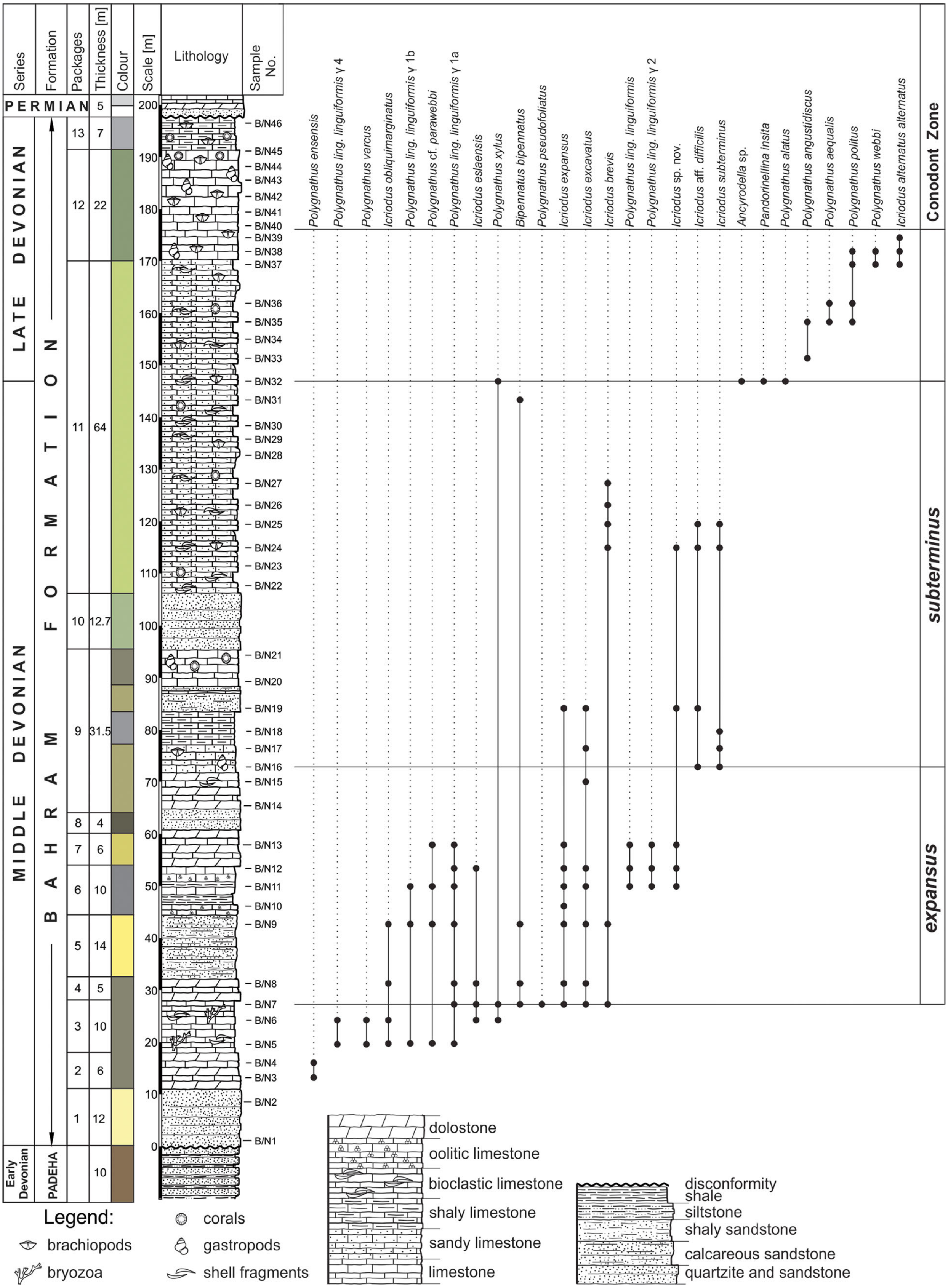


Fig. 5 Detailed lithological column of the North Tar section and the occurrence of conodonts

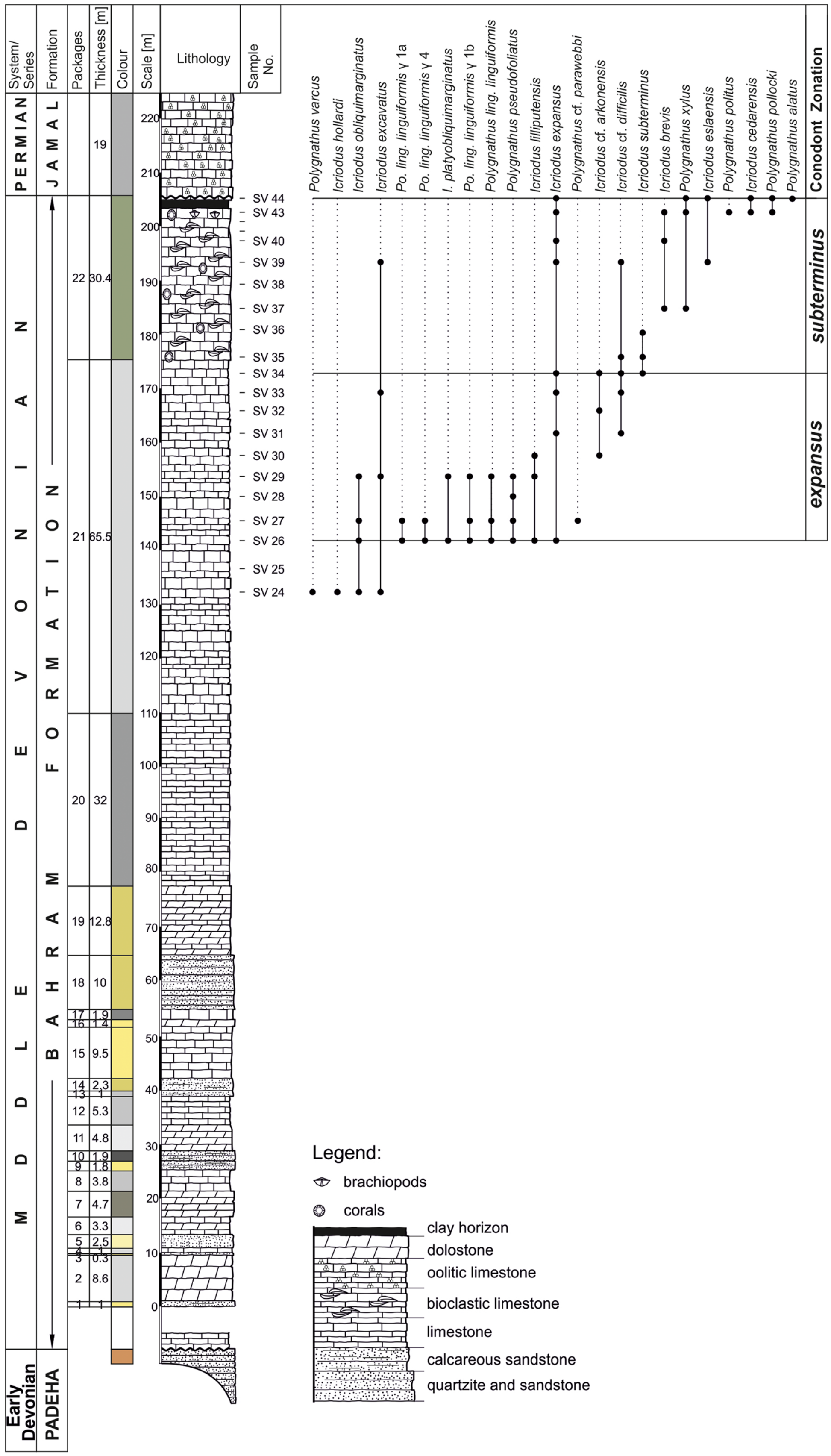


Fig. 6 Detailed lithologic column of the Varcamar section and the occurrence of conodonts

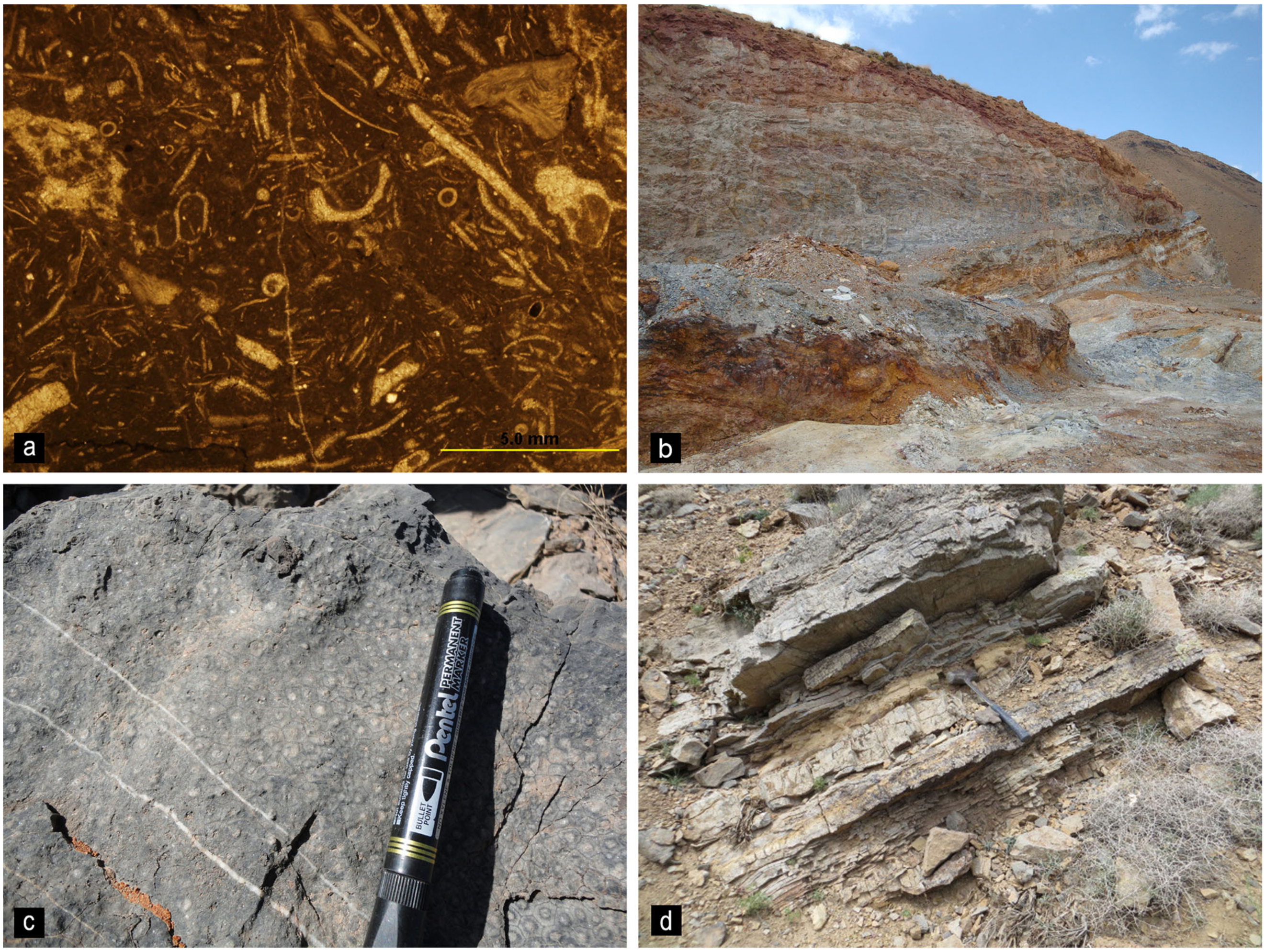


Fig. 7 Lithology and facies of the investigated sections. **a** Lime mudstone to wackestone of the Bahram Formation with abundant fossil remnants, such as brachiopod shells and gastropods (Najhaf section, *expansus* Zone, sample T-18), **b** agillaceous clay to white kaolinite layer at the top of the Bahram Formation (Neqeleh section), **c** coral limestones (biostromes) of the Bahram Formation with *Phillipsastrea* sp. (uppermost part of the North Tar section), **d** dolomites of the Bahram Formation (lower part of the Varcamar section, *hammer* for scale)

– The Bahram Formation in this section starts with an alternation of brown, partly weathered sandstones and thick-bedded dolomites and has a thickness of 40 m (packages 1–3). Thin- to medium-bedded limestones containing rare conodonts are intercalated with these sandstones and dolomites. Greenish, weathered sandstones with limestone intercalations (package 3, Fig. 3) are present in the upper part of this unit.
– The overlying unit has a thickness of 77.5 m (package 4) and is composed of thin- to medium-bedded grey limestones exhibiting diverse biota, such as brachiopods, rare tentaculitids, gastropods, and ostracods among others (Fig. 7a).
– Thin- to medium-bedded kaolinitic, grey argillaceous clay beds (0.5 m) that contain a number of fossils, such as scaphopods, trilobites, brachiopods and plant fossils (package 5), form the topmost package of the Bahram Formation in this section.
– The Bahram Formation is disconformably overlain by breccias, dolomites and dolomitic limestones of the Permian Jamal Formation.

Neqeleh section

The Negeleh section (33°29′34″N, 51°33′63″E) has a thickness of more than 200 m and is subdivided into the following units (Fig. 4):

– The section starts with sandstones regarded as the Lower Devonian Padeha Formation. These rocks are disconformably overlain by alternating cross-bedded sandstones and thick-bedded dolomites. This unit has a thickness of 55 m and belongs to the Middle Devonian Sibzar Formation, which has been

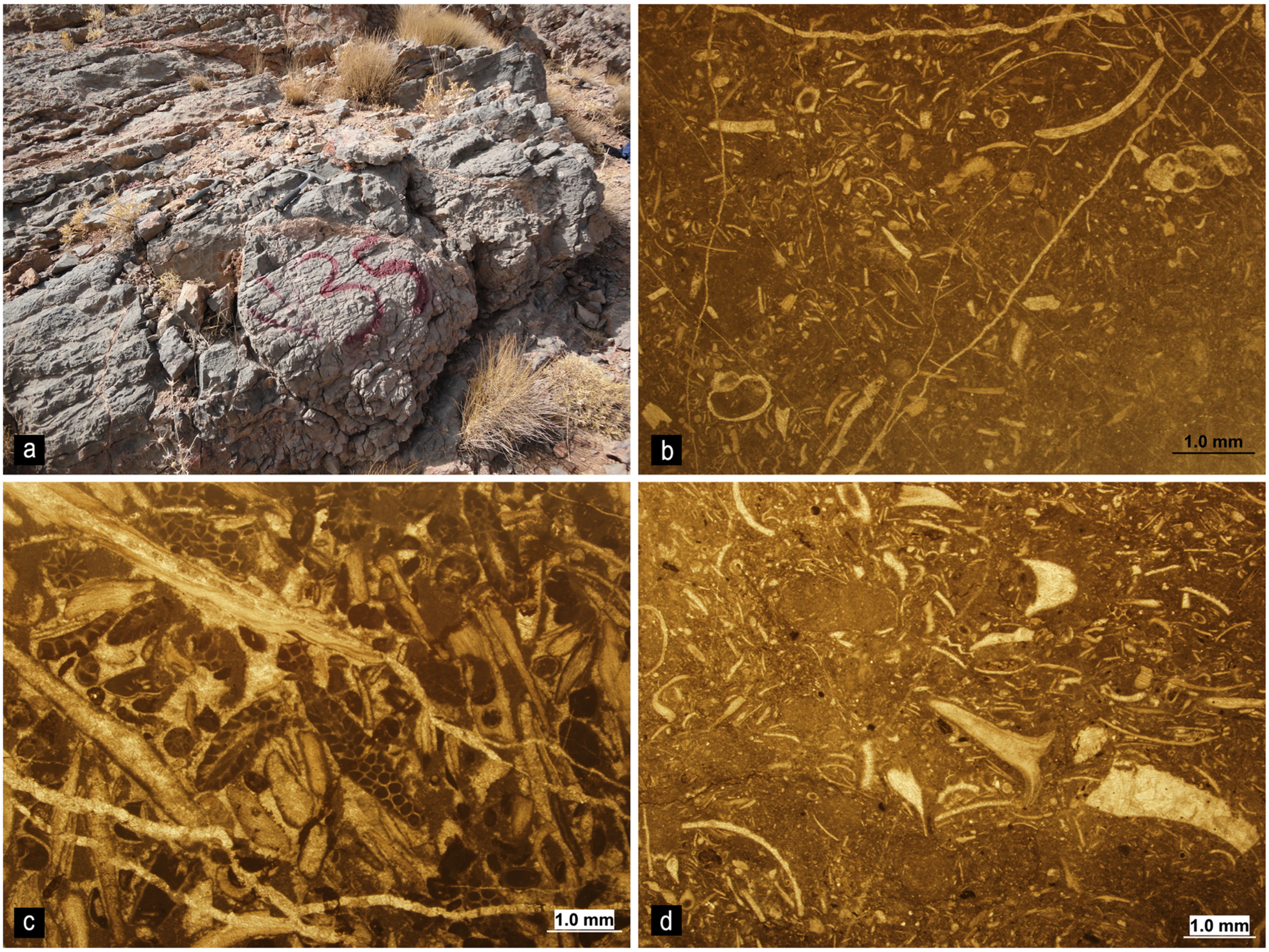


Fig. 8 Lithology and facies of the investigated sections. **a** Reefal limestones of the Bahram Formation (upper part of the Varcamar section, *hammer* for scale), **b** bioclastic wackestone with shell hash and gastropod remains, **c** whole fossil wackestone/floatstone containing mainly brachiopod shells, bryozoans and corals (upper part of the Varcamar section), **d** bioclastic wackestone, strongly burrowed; matrix is composed of a fine-grained pelmicrite (upper part of the Varcamar section)

described in earlier papers by Zahedi (1973) and later by Wendt et al. (2005).

– The Bahram Formation in this section starts at 47 m (packages 1–7) with alternating thin- to medium-bedded coarsely grained sandstones with thin- to medium-bedded limestones (packages 3, 6).
– A kaolinite layer about 90 m from the base of the section may represent a continental interval before the onset of medium- to thick-bedded, fossiliferous limestones which have a thickness of 79 m.
– The limestones are capped by thick-bedded dolomites up to 5 m thick as well as fossiliferous limestones (12 m thick, package 10). Conodont samples of the limestone units yielded a reasonable number of conodont elements. The first occurrence of *Ancyrodella* sp. in this section at the base of package 11 marks the beginning of the Late Devonian (Fig. 4).
– This unit is overlain by argillaceous clay and greenish caliche to white kaolinite which has a thickness of 8 m (Fig. 7b). This level was also described in a section close to our section by Wendt et al. (2005), but in our section these rocks are considerably thicker.
– The Bahram Formation is disconformably overlain by a 1-m-thick breccia followed by dolomites and dolomitic limestones of the Permian Jamal Formation, representing the onset of Middle Permian platform sedimentation (Wendt et al. 2005).

North Tar section

The North Tar section is located west of Natanz city (Figs. 1, 2; 33°27′56″N; 51°41′ 29″E). The Bahram Formation has a

Table 1 Taxa identified in the Varcamar section (Natanz area, Iran)

Taxa	SV24	SV26	SV27	SV28	SV29	SV30	SV31	SV32	SV33	SV34	SV35	SV36	SV37	SV39	SV40	SV43	SV44	Total
Icriodus cf. *arkonensis*						8		2										13
Icriodus brevis													3		2	4		9
Icriodus cedarensis																3	2	5
Icriodus cf. *difficilis*							3		6	2	2			1				14
Icriodus eslaensis														2			3	5
Icriodus excavatus	2				7				2					3				14
Icriodus expansus		1					3		2	8				2	6	12	9	43
Icriodus hollardi	2																	2
Icriodus lilliputensis		1			1													3
Icriodus obliquimarginatus	2	2	3		1													8
Icriodus platyobliquimarginatus		3			2													5
Icriodus subterminus										1	2	1						4
Polygnathus alatus																	2	2
Polygnathus politus																2		2
Polygnathus pollocki																2	3	5
Polygnathus ling. linguiformis		5	3		2													10
Polygnathus ling. linguiformis γ*1a*		3	2															5
Polygnathus ling. linguiformis γ *1b*		3	1		3													7
Polygnathus ling. linguiformis γ 4		1	2															3
Polygnathus cf. *parawebbi*			1															1
Polygnathus pseudofoliatus		2	1	1	1													5
Polygnathus varcus	3																	3
Polygnathus xylus													4			3	1	8
Unassigned elements	10	2	3	8	5	1	5	2	2	23	2	1	2	3	30	16	5	120
TOTAL	19	23	16	9	22	10	11	4	12	37	6	2	9	11	38	42	25	296

Table 2 Taxa identified in the North Tar section (Natanz area, Iran)

Taxa	B/ N3	B/ N4	B/ N5	B/ N6	B/ N7	B/ N8	B/ N9	B/ N10	B/ N11	B/ N12	B/ N13	B/ N15	B/ N16	B/ N17	B/ N18	B/ N19	B/ N24	B/ N25	B/ N26	B/ N27	B/ N31	B/ N32	B/ N33	B/ N35	B/ N36	B/ N37	B/ N38	B/ N39	Total
Ancyrodella sp.																						1							1
Bipennatus bipennatus					1	2	1														1								5
Icriodus alt. alternatus																										1	1	1	3
Icriodus brevis					1		2										2	3	2	1									11
Icriodus aff. *difficilis*													1			3	4	7											15
Icriodus eslaensis				1	2	2				1																			6
Icriodus expansus					3	3	5	2	7	4	2					3													29
Icriodus excavatus					2	2	1		1	1		3		1		1													12
Icriodus obliquimarginatus			1	1		1	1																						4
Icriodus subterminus													2	1	5		1	3											12
Icrioudus sp. nov.									5	7	2					8	18												40
Pandorinellina insita																						1							1
Polygnathus aequalis																								1	1				2
Polygnathus alatus																						4							4
Polygnathus angustidiscus																							1	1					2
Polygnathus ensensis	2	2																											4
Polygnathus ling. linguifromis									2	2	1																		5
Polygnathus ling. linguifromis γ *1a*			2		1	2	1		2	1	1																		10
Polygnathus ling. linguifromis γ *1b*			1				2		3																				6
Polygnathus ling. linguifromis γ*2*									1	1	1																		3
Polygnathus ling. linguifromis γ4			2	3																									5
Polygnathus cf. *parawebbi*			2				1		1		2																		6
Polygnathus politus																								1	2	1	1		5
Polygnathus pseudofoliatus					1																								1
Polygnathus varcus			2	2																									4
Polygnathus webbi																										1	1		2
Polygnathus xylus				2	1																	1							4
unassigned elements		8			1	5	3	1	8	15	1	1	19	4	1	9	8										9	1	94
TOTAL	2	10	10	9	13	17	17	3	30	32	10	4	22	6	6	24	33	13	2	1	1	7	1	3	3	3	12	2	296

Table 3 Taxa identified in the Neqeleh section (Soh area, Iran)

Taxa	S13	S14	S16	S18	S20	S22	S23	S26	S29	S32	S33	S35	S39	S41	S42	S45	S46	S47	S50	S52	Total
Ancyrodella sp.																			2		2
Icriodus brevis									3		2										5
Icriodus cedarensis																	3				3
Icriodus difficilis							7					6									13
Icriodus excavatus	3			2		3				3	6				2	1	7	9			36
Icriodus expansus	2	5													3	4					14
Icriodus sp. nov.							8		4		1		1				3	2			19
Icriodus subterminus									2	2				1			1	2			8
Icriodus lilliutensis		1	1	3	2			1													8
Pandorinellina insita																	2	1		1	4
Polygnathus ling. linguiformis γ1a		1																	5		6
Polygnathus ling. linguiformis γ2				3					2												5
Polygnathus ling. linguiformis		2											2								4
Polygnathus pseudofoliatus					2																2
unassigned elements	13	56		34	6	5	8	7	8	29	1	7	19	22	4	9		2	11	3	244
TOTAL	18	65	1	42	10	8	23	8	19	34	10	13	22	23	9	14	16	16	18	4	373

thickness of about 202 m and can basically be subdivided into a lower part (mainly siliciclastic sediments) and an upper part (more calcareous units; Fig. 5). The lower 105 m (packages 1–10) contains an alternating sequence of cross-bedded sandstones and dolomites with intercalated limestones, whereas the upper 93 m (packages 11–13) are composed of medium- to thick-bedded limestones and reefal limestones (Fig. 7c).

– The base of the section contains brownish, bedded sandstones of the Early Devonian Padeha Formation.
– The Padeha Formation is disconformably overlain by sediments of the Bahram Formation which are composed of thin-bedded, grey limestones at the base, followed by alternating grey limestones and dolomites (packages 1–3).
– This unit is overlain by a 5-m-thick grey to brown dolomite (package 4 in Fig. 5).

Table 4 Taxa identified in the Najhaf section (Soh area, Iran)

Taxa	T5	T8	T9	T11	T12	T13	T14	T15	T16	T17	T19	T22	T23	T24	T27	Total
Bipennatus bipennatus bipennatus			1												2	3
Icriodus arkonensis walliserianus								1								1
Icriodus brevis														1		1
Icriodus eslaensis												3				3
Icriodus expansus	3				2		1		6				2			14
Icriodus platyobliquimarginatus											2	3				5
Polygnathus ensensis			1		1			2				1				5
Polygnathus ling. linguiformis		2	1	2	4	2		21	1							33
Polygnathus ling. linguiformis γ 1a																3
Polygnathus ling. linguiformis γ4			1													1
Polygnathus ling. linguiformis γ2								2								2
Polygnathus parawebbi															1	1
unassigned elements	2	1		3	3	1		2		7	1			1	7	28
TOTAL	5	3	4	5	10	3	1	28	7	7	3	7	5	2	10	100

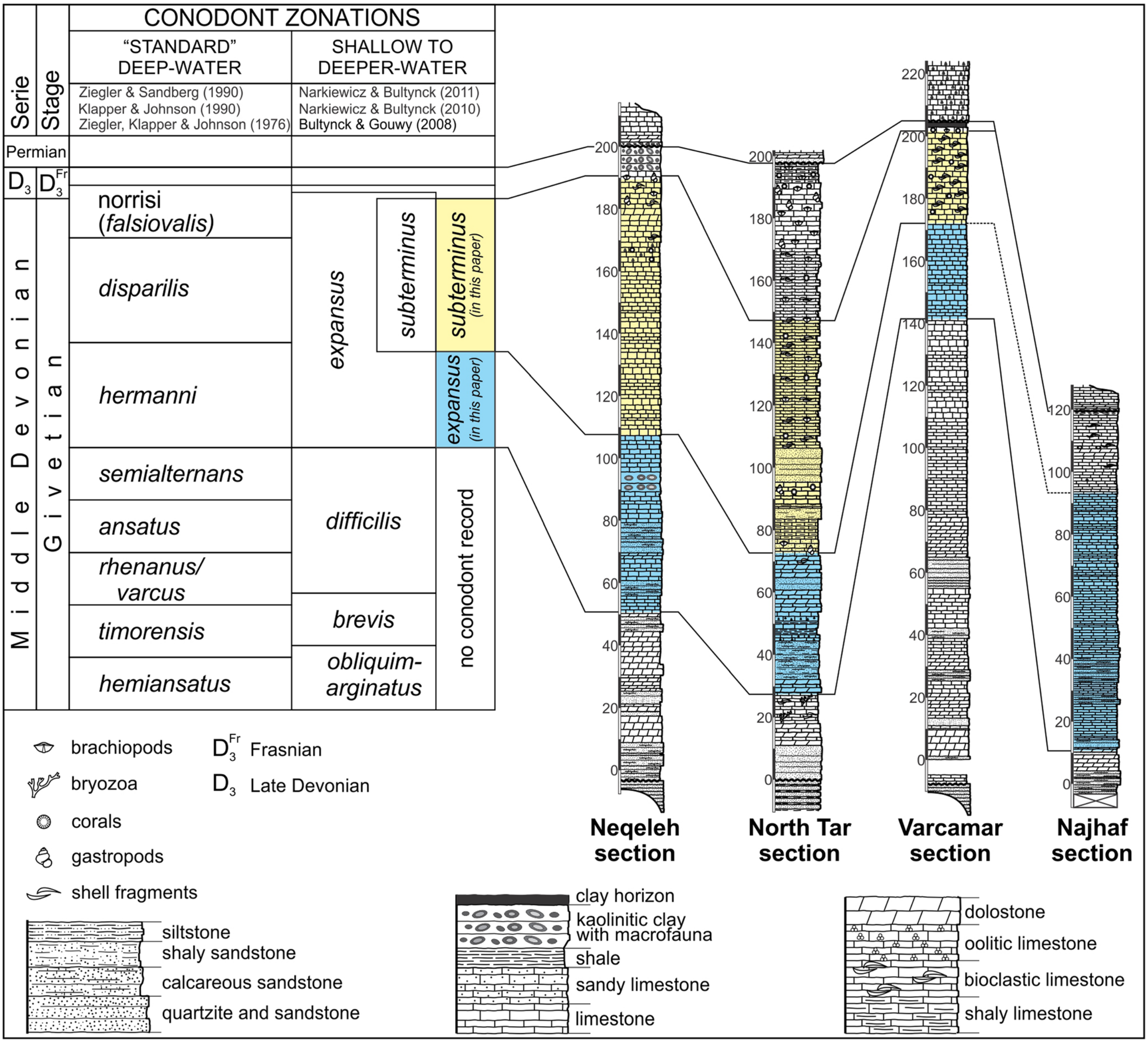


Fig. 9 Lithological and biostratigraphical correlation of the investigated sections. The different colours mark the occurrence of shallow-water conodonts in the sections (for explanations, see text)

- The overlying sediments are composed of thin-bedded sandstones with shale intercalations and alternating oolitic limestones and shales (packages 5, 6).
- The overlying dolomite is covered by thin-bedded yellowish sandstones, followed by a 31.5-m-thick alternating sequence of dolomites, sandy limestones and sandstones (package 9).
- This unit is covered by a fine-grained sandstone which exhibits cross-stratification (package 10).
- The overlying 64-m-thick unit is composed of grey, medium-bedded limestones rich in microfauna, such as conodonts and ostracodes (package 11). The conodont fauna in this section indicates that the Bahram Formation also includes rocks of Frasnian age.
- The next interval (package 12) starts with very fossiliferous, thick-bedded partly reefal limestones passing into shaley limestones at the top of the Bahram Formation.
- The Bahram Formation is disconformably overlain by alternating of white sandstones, dolomites and fossiliferous limestones which belong to the Permian Jamal Formation.

Varcamar section

The Varcamar section is located close to the North Tar section near Varcamar village (33°27′24″N; 51° 42′16″E), and the measured profile has a thickness of 205 m (Fig. 6). The

Bahram Formation of the Varcamar section can be subdivided into three lithologic units. The lower unit primarily consists of alternating sandstones and dolomites (packages 1–19, 76.9 m thick) and is capped by thin-bedded, fossiliferous carbonates (package 20, 21–97.5 m thick). The upper part is mainly composed of thick-bedded limestones with some fossiliferous horizons, particularly brachiopods (package 22, 30.4 m thick).

- The base of the stratigraphic column contains sandstones of the Early Devonian Padeha Formation which is disconformably overlain by limestones followed by a hiatus.
- The measured section of the Bahram Formation contains alternating beds of sandstones, dolomites and limestones of various thicknesses up to package 17 (Fig. 6) and contains poorly preserved fossils.
- The next unit is composed of a cross-stratified, thin-bedded sandstone which is covered by dolomites and thin-bedded limestones (Figs. 7d, 8a).
- The next unit (32 m thick) is composed of thin-bedded limestones and contains rare brachiopod and gastropod remnants (Fig. 8b).
- The middle to upper part of the Bahram Formation in this section is composed of medium-bedded limestones grading to oolitic limestones. This unit is fossiliferous and contains brachiopods, ostracods and conodonts (package 21). The upper part of the Bahram Formation in this section has a thickness of 30.4 m (package 22) and is composed of thick-bedded limestones. These limestones are rich in fossils, such as microvertebrate remains, brachiopods, gastropods, ostracodes and conodonts. Occasionally small biostromes composed of stromatoporoids and corals are present (Fig. 8c). In the upper part of this section, strongly bioturbated sediments are common (Fig. 8d).
- A clay horizon we did not find in the other sections at the top of the Bahram Formation represents the youngest part.
- The top of the Formation is identified by an erosional unconformity and is overlain by oolitic, fossiliferous limestones of the Jamal Formation.

Methods

A total of 179 samples (3–4 kg each) were collected from the studied sections in northwest Isfahan. All samples were processed following the standard technique for conodont extraction (see Jeppsson and Anehus 1995), and 79 samples yielded conodonts: 14 samples from the Najhaf section, 20 samples from the Neqeleh section, 17 samples from the Varcamar section, and 28 samples from the North Tar section. Approximately 1065 conodont elements were collected, but these exhibit low species diversity. The state of preservation of the conodonts is generally excellent in all sections even if the conodonts show high conodont alteration values (CAI) of CAI 4.5 and CAI 5. All specimens described here (including thin sections and polished slabs) are stored in the Department of Geology (sample identification code: EUIC), University of Isfahan, I.R. Iran. Repository numbers of the figured specimens can be obtained from the plate captions.

Biostratigraphy

In the four studied sections (Neqeleh, Najhaf, North Tar, Varcamar) we identified 36 species and subspecies belonging to five genera, namely, *Ancyrodella*, *Bipennatus*, *Icriodus*, *Polygnathus* and *Pandorinellina* (Tables 1–4). The depositional facies setting is characterised by marginal marine and open marine environments and exhibits a diverse conodont fauna dominated by the shallow-water genera *Icriodus* and *Polygnathus*. *Pandorinellina* species are scarce in all sampled horizons; therefore, icriodids and polygnathids were used to identify the zonal boundaries. A shallow-water conodont fauna is dominant and characterised by the lack of important zonal index taxa of the widely applied conodont standard zonation (see Klapper and Ziegler 1979; Clausen et al. 1993). Thus, we chose to follow an alternative shallow-marine conodont zonation for Givetian (Narkiewicz and Bultynck 2007, 2010; Bultynck and Gouwy 2008; Narkiewicz 2011). The boundary between Givetian and Frasnian is defined by the first appearance of *Ancyrodella* in two sections, i.e. the North Tar and Neqeleh sections. Based on the general lack of index taxa, the biostratigraphic analysis also takes into account the total stratigraphic ranges of all taxa identified in each sample. Givetian conodont communities investigated in Central Iran correspond to the *expansus* Zone and *subterminus* Zone.

expansus Zone

According to Narkiewicz and Bultynck (2010), the lower boundary of the *expansus* Zone is defined by the first appearance of *Icriodus expansus*, and the upper boundary corresponds to the base of the *Icriodus symmetricus* Zone, as defined by Sandberg and Dreesen (1984).

Icriodus expansus is not regarded as a typical shallow-water species, and thus the boundary between the *expansus* Zone and the *symmetricus* Zone is less facies controlled, as discussed by Narkiewicz and Bultynck (2010).

Najhaf section

The lower boundary of the *expansus* Zone is defined with the first occurrence of *I. expansus* at 10 m from the base of the section in sample T5 and corresponds closely to the base of the Upper Givetian *hermanni* Zone. The lack of index conodonts does not allow the upper boundary of *expansus* Zone in Najhaf section to be fixed.

The following conodont association of *Icriodus excavatus*, *Polygnathus ensensis*, *Icriodus platyobliquimarginatus*, *I. arkonensis walliserianus*, *Polygnathus parawebbi*, *Icriodus eslaensis*, *Polygnathus linguiformis linguiformis* γ, *Icriodus brevis* and *Bipenathus bipennatus bipennatus* has concurrent ranges in this stratigraphical interval and justifies the classification of sediments between T5 and T27 in the Najhaf section as Upper Givetian.

Neqeleh section

The lower boundary of the *expansus* Zone in the Neqeleh section corresponds to sample S13 (about 50 m from the base of the section at the lowermost part of the Bahram Formation in package 1, just above the Sibzar Formation where *Icriodus expansus* was found) (Fig. 4). The upper boundary of the *expansus* Zone is determined by the first appearance of *Icriodus subterminus* at 120 m from the base in sample S29. This interval is composed of medium- to thick-bedded grey to yellow limestones which are rich in conodonts. The conodont assemblage in this interval contains *Icriodus excavatus*, *I. lilliputensis*, *Polygnathus linguiformis linguiformis* γ and *P. pseudofoliatus*, and this interval is assigned as Upper Devonian. This interval is covered by a conodont fauna which can be attributed to the *subterminus* Zone.

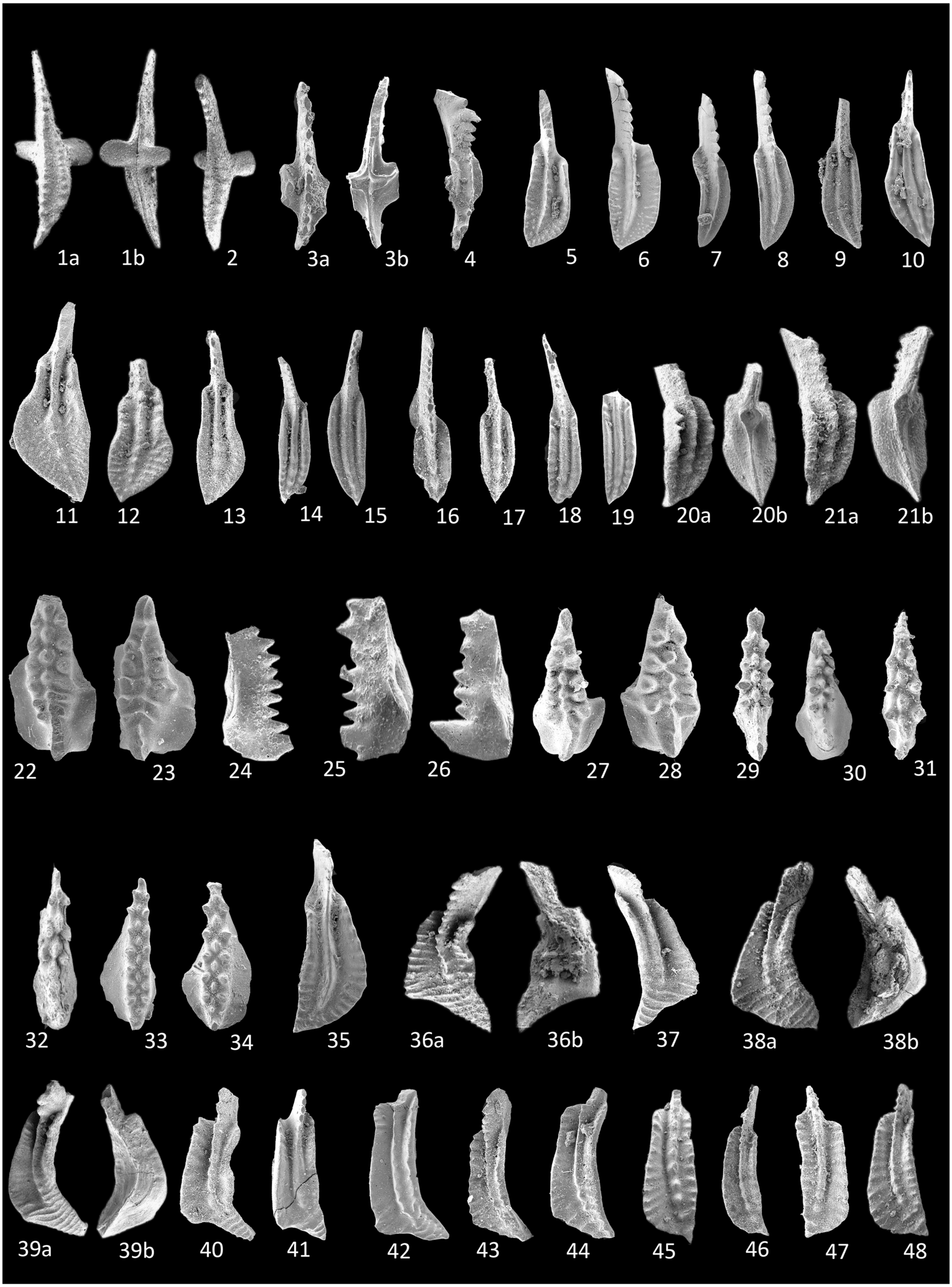
North Tar section

The lower boundary of the *expansus* Zone in the North Tar section occurs in package 3 at 28 m from the base of the section in sample BN7. The sediments related to this zone are 45 m thick and consist of thin-bedded sandstones with shale intercalations and alternating oolitic limestones, grey limestones, dolomites and shales. The following species have been sampled in the *expansus* Zone: *Icriodus expansus*, *I. excavatus*, *I. eslaensis*, *I. brevis*, *I. obliquimarginatus*, *Polygnathus* cf. *parawebbi*, *P. linguiformis linguiformis* γ, *P. xylus*, *P. pseudofoliatus*, *P. parawebbi*, *P. varcus* and *Bipennathus bipennatus*

Varcamar section

In the Varcamar section conodonts have been found only in the upper part of the section in package 21 which marks the beginning of the *expansus* Zone by the first occurrence of *Icriodus expansus* (sample SV26). The upper part of the section is about 33 m thick and is composed of medium-bedded limestones and oolitic limestones. A few conodonts have been found below sample SV26, such as *Polygnathus varcus*, *I. excavatus, I. obliquimarginatus* and *I. hollardi* which are found in sample S24 at 140 m above the base of the section. In

Fig. 10 Conodonts from the sampled sections in Iran. *1*, *2 Bipennatus bipennatus* Bischof and Ziegler, 1957, alpha morph Bultynck, 1987: *1* upper (*1a*) and lower (*1b*) views of EUIC 5705, Najhaf section, sample T9, *2* upper view of EUIC 5706, Najhaf section, sample T27. *3 Ancyrodella* sp.: upper (*3a*) and lower (*3b*) views of EUIC 373C, North Tar section, sample B/N32. *4 Polygnathus angustidiscus* Youngquist, 1947: upper view of EUIC 372C, North Tar section, sample B/N35. *5*, *6 Polygnathus aequalis* Klapper and Lane, 1985: *5* upper view of EUIC 376C, North Tar section, sample B/N36, *6* upper view of EUIC 377C, North Tar section, sample B/N35. *7*, *8 Polygnathus politus* Ovnatanova, 1969: *7* upper view of EUIC 366C, North Tar section, sample B/N38, *8* upper view of EUIC 368C, North Tar section, sample B/N36. *9*, *10 Polygnathus alatus* Huddle, 1934: *9* upper view of EUIC 10256, Varcamar section, sample SV44, *10* upper view of EUIC 370C, North Tar section, sample B/N32. *11–13 Polygnathus pseudofoliatus* Wittekindt, 1966: *11* upper view of EUIC 10266, Varcamar section, sample SV28, *12*) upper view of EUIC 10268, Varcamar section, sample SV29, *13* upper view of EUIC 5673, Neqeleh section, sample S20. *14*, *15 Polygnathus pollocki* Druce, 1976: *14* upper view of EUIC 10260,Varcamar section, sample SV43, *15* upper view of EUIC 10263, Varcamar section, sample SV43. *16 Polygnathus varcus* Stauffer, 1940: upper view of EUIC 10255, Varcamar section, sample SV24. *17–19 Polygnathus xylus* Stauffer, 1940: *17* upper view of EUIC 371C, North Tar section, sample B/N32, *18* upper view of EUIC 378C, North Tar section, sample B/N6, *19* upper view of EUIC 379C, North Tar section, sample B/N7. *20*, *21 Polygnathus ensensis* Ziegler, Klapper and Johnson, 1976: *20* upper oblique (*20a*) and lower (*20b*) views of EUIC 5704, Najhaf section,sample T12, *21*) upper oblique (*21a*) and lower (*21b*) views of EUIC 5705, Najhaf section, sample T12. *22*, *23 Icriodus hollardi* Walliser and Bultynck, 2011: *22* upper view of EUIC 10301, Varcamar section, sample SV24, *23* upper view of EUIC 10302, Varcamar section, sample SV24. *24–26 Pandorinellina insita* Stauffer, 1940: *24* lateral view of EUIC 5679, Neqeleh section, sample S52, *25* lateral view of EUIC 5680, Neqeleh section, sample S47, *26* lateral view of EUIC 5681, Neqeleh section, sample S46. *27*, *28 Icriodus platyobliquimarginatus* Bultynck, 1987: *27* upper view of EUIC 10290, Varcamar section, sample SV26, *28* upper view of EUIC 10303, Varcamar section, sample SV29. *29–32 Icriodus obliquimarginatus* Bischoff and Ziegler, 1957, β morphotype: *29* upper view of EUIC 10291, Varcamar section, sample SV26, *30* upper view of EUIC 10292, Varcamar section, sample SV29, *31* upper view of EUIC 455C, North Tar section, sample B/N6, *32* upper view of EUIC 456C, North Tar section, sample B/N6. *33*, *34 Icriodus alternatus alternatus* Branson and Mehl, 1934: *33* upper view of EUIC 420C, North Tar section, sample B/N37, *34* upper view of EUIC 422C, North Tar section, sample B/N39. *35 Polygnathus webbi* Stauffer, 1938: upper view of EUIC 423C, North Tar section, sample B/N37. *36*, *37 Polygnathus linguiformis linguiformis* Hinde, 1879: *36* upper (*36a*) and lower (*36b*) views of EUIC 5683, Najhaf section, sample T15, *37* upper view of EUIC 10279, Varcamar setion, sample SV26. *38*, *39 Polygnathus linguiformis linguiformis* Hinde, 1879: *38* Upper (*38a*) and lower (*38b*) views of EUIC 5684, Najhaf section, sample T23, *39* upper (*39a*) and lower (*39b*) views of EUIC 5667, Neqeleh section, sample S14. *40–42 Polygnathus linguiformis linguiformis* Hinde, 1879, γ 1*b* morphoptype: *40* upper view of EUIC 10278, Varcamar section, sample SV27, *41* upper view of EUIC 353C, North Tar section, sample B/N5, *42* upper view of EUIC 355C, North Tar section, sample B/N11. *43*, *44 Polygnathus* cf. *parawebbi* Chatterton, 1974: *43* upper view of EUIC 10273, Varcamar section, sample SV27, *44* upper view of EUIC 347C, North Tar section, sample B/N5. *45–47 Polygnathus linguiformis linguiformis* Hinde, 1879, γ 4 morphoptype: *45* upper view of EUIC 5691, Najhaf section, sample T9, *46* upper view of EUIC 10275, Varcamar section, sample SV26, *47* upper view of EUIC 349C, North Tar section, sample B/N5. *48 Polygnathus linguiformis linguiformis* Hinde, 1879: upper view of EUIC 5690, Najhaf section, sample T8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the *expansus* Zone the conodont fauna is composed of *I. expansus*, *I. lilliputensis*, *I. obliquimarginatus*, *I. platyobliquimarginatus*, *I. excavatus*, *I. arkonensis*, *I.* cf *difficilis*, *Polygnathus linguiformis linguiformis*, *P. pseudofoliatus* and *P.* cf *parawebbi* (Fig. 6).

subterminus Zone

Narkiewicz and Bultynck (2010) defined the lower boundary of the *subterminus* Zone by the first occurrence of *Icriodus subterminus* and the upper boundary by the first occurrence of *Ancyrodella pristina* and/or most of the early morphotypes of *Ancyrodella rotundiloba* (sensu Klapper 1985) and/or *Ancyrodella binodosa*. As we were not able to distinguish between the lower and upper "*subterminus*" fauna in our sampled sections, the undivided *subterminus* Zone is reported herein, corresponding to the uppermost part of the *hermanni* Zone to the lower *falsiovalis* Zone of the Standard Conodont Zone (see fig. 10 in Narkiewicz and Bultynck 2010).

Neqeleh section

The lower boundary of the *subterminus* Zone is defined by the first appearance of *Icriodus subterminus,* in sample S29 at 114 m from the base of the section in package 8 (Fig. 4). The *subterminus* Zone in Neqeleh section comprises about 87 m of thin-bedded grey to yellow limestone rich in conodonts, microvertebrate remains and crinoid stems (packages 8, 9, 10). *Icriodus subterminus* was found together with *I. subterminus*, *I. brevis*, *I. expansus*, *I. excavatus*, *I. difficilis*, *I. cedarensis*, I. sp. nov., *Polygnathus linguiformis linguiformis* and—rarely—*Pandorinellina insita*. This association confirms a late Givetian age. The boundary Givetian/Frasnian is fixed at 190 m from the base by the appearance of *Ancyrodella* sp. in sample S50 (Fig. 4).

North Tar section

The lower boundary of the zone is defined by the first appearance of *Icriodus subterminus* at 73 m above the base of the section in sample BN16. The Neqeleh and North Tar sections are the most interesting sections sampled because they exhibit a reasonable number of conodont species, including those of Frasnian age (Fig. 5). The *subterminus* Zone in this section is mainly composed of thin- and medium-bedded limestones that are rich in bioclasts. The boundary between the Middle and Late Devonian occurs at sample BN32 with the entry of *Ancyrodella* sp.

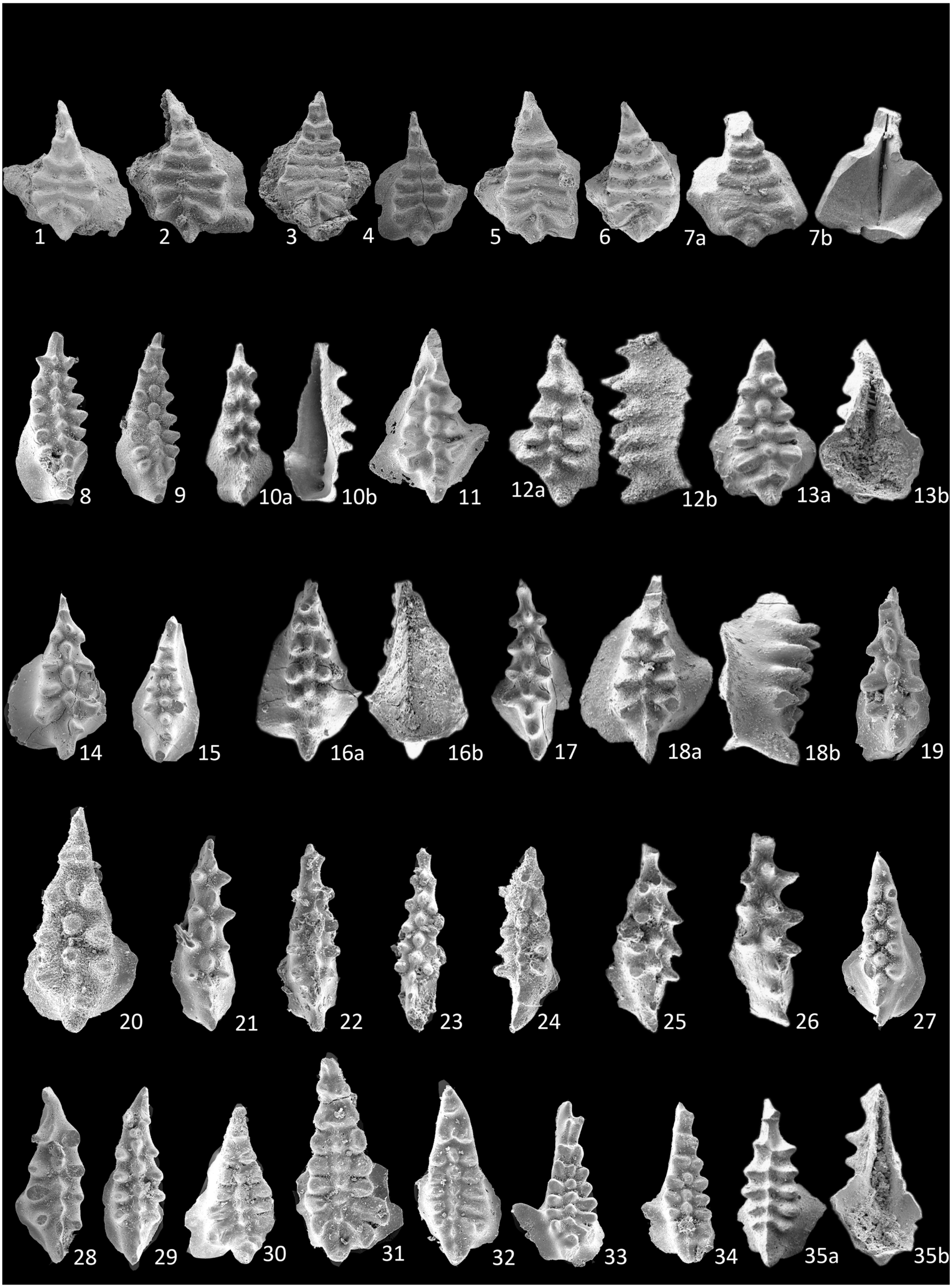
Varcamar section

The lower boundary of the *subterminus* Zone in the Varcamar section occurs at 174 m from the base of the section in sample SV34 (package 21). The Givetian *subterminus* Zone is disconformably overlain by the Permian Jamal Formation (Fig. 6). The conodont association of the *subterminus* Zone in the Varcamar section was obtained from grey, thick-bedded limestones that are rich in microvertebrate remains and other fossils. The conodont association contains the following taxa: *Icriodus subterminus*, *I. brevis*, *I. expansus*, *I. excavatus*, *I.* cf. *arkonensis*, *I. difficilis*, *I. eslaensis*, *I. cedarensis*, *Polygnathus xylus*, *P. pollocki*, *P. politus* and *P. linguiformis.* Upper Devonian sediments are missing in the Varcamar section.

Fig. 11 Conodonts from the sampled sections in Iran. *1–7 Icriodus* sp. nov.: *1* upper view of EUIC 410C, North Tar section, sample B/N24, *2* upper view of EUIC 411C, North Tar section, sample B/N19, *3* upper view of EUIC 412C, North Tar section, sample B/N11, *4* upper view of EUIC 413C, North Tar section, sample B/N12, *5* upper view of EUIC 414C, North Tar section, sample B/N13, *6* upper view of EUIC 415C, North Tar section, sample B/N13, *7* upper (*7a*) and lower (*7b*) views of EUIC 5617, Neqeleh section, sample S29. *8*, *9 Icriodus expansus* Branson and Mehl, 1938: *8* upper view of EUIC 10293, Varcamar section, sample SV44, *9* upper view of EUIC 10319, Varcamar section, sample SV44. *10 Icriodus eslaensis* Van Adrichem Boogaert, 1967: upper (*10a*) and oblique lateral (*10b*) views of EUIC 5604, Najhaf section, sample T22. *11–13 Icriodus excavatus* Weddige, 1984: *11* upper view of EUIC 394C, North Tar section, sample B/N17, *12* upper (*12a*) and lateral (*12b*) views of EUIC 5624, Neqeleh section, sample S18, *13* upper (*13a*) and lower (*13b*) views of EUIC 5629, Neqeleh section, sample S42. *14–18 Icriodus subterminus* Youngquist, 1947: *14* upper view of EUIC 393C, North Tar section, sample B/N17, *15* upper view of EUIC 395C, North Tar section, sample B/N18, *16* upper (*16a*) and lower (*16b*) views of EUIC 5607, Neqeleh section, sample S46, *17* upper view of EUIC 5638, Neqeleh section, sample S46, *18* upper (*18a*) and lateral (*18b*) views of EUIC 5621, Neqeleh section, sample S32. *19*, *20 Icriodus lilliputensis* Bultynck, 1987: *19* upper view of EUIC 10304, Varcamar section, sample SV29, *20* upper view of EUIC 10305, Varcamar section, sample SV26. *21–26 Icriodus brevis* Stauffer, 1940: *21* upper view of EUIC 424C, North Tar section, sample B/N7, *22* upper view of EUIC 406C, North Tar section, sample B/N25, *23* upper view of EUIC 409C, North Tar section, sample B/N9, *24* upper view of EUIC 408C, North Tar section, sample B/N7, *25* upper view of EUIC 5604, Neqeleh section, sample S29, *26* upper view of EUIC 5605, Neqeleh section, sample S33. *27–29 Icriodus cedarensis* Narkiewicz and Bultynck, 2010: *27* upper view of EUIC 10314, Varcamar section, sample SV44, *28* upper view of EUIC 10321, Varcamar section, sample SV43, *29* upper view of EUIC 10322, Varcamar section, sample SV44. *30–32 Icriodus* cf. *arkonensis* Stauffer, 1938: *30* upper view of EUIC 10326, Varcamar section, sample SV32, *31* upper view of EUIC 10327, Varcamar section, sample SV34, *32* upper view of EUIC 10328, Varcamar section, sample SV34. *33*, *34 Icriodus* cf. *difficilis* Ziegler and Klapper, 1976: *33* upper view of EUIC 10332, Varcamar section, sample SV33, *34* upper view of EUIC 10333, Varcamar section, sample SV31. *35 Icriodus arkonensis walliserianus* Weddige, 1988: upper (*35a*) and lower (*35b*) views of EUIC 5659, Najhaf section, sample T15

Discussion and concluding remarks

Our study provides new data from northern Gondwana from four sections (Neqeleh, Najhaf, North Tar, Varcamar) in Central Iran. These sections are of Middle and Late Devonian age and record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the deposition of a mixed carbonate-siliciclastic ramp, as expressed by the Bahram Formation. In the investigated area, the Bahram Formation is discontinuously underlain by the Middle Devonian Sibzar Formation or the Lower Devonian Padeha Formation and discontinuously overlain by the Permian Jamal Formation. The variable and sometimes cyclic lithology of the sections may exhibit several transgression–regression (T–R) cycles which may coincide with other T–R cycles during the Middle Devonian elsewhere (although more detailed sedimentological work is necessary to allow direct correlations). The entire area shows remarkable lateral facies changes (e.g. detrital limestones that grades laterally into small coral/stromatoporoid biostromes) which are due to the neritic facies setting. A general deepening trend in the studied sections is obvious, as evidenced by the increasing sedimentation of carbonates and the occurrence of reefal limestones to the top of the sections. This study does not provide answers to all of our questions, thus necessitating more detailed sedimentology and facies analysis. For example, the Sibzar Formation has been described in the Neqeleh section only (see also Wendt et al. 2005), but this formation has not been defined in the other sections even if the strata are similar, such as at the base of the Varcamar section. Further studies on the geochemistry of the sections are necessary to determine whether known Middle Devonian events are likewise traceable in shallow sections such as those described herein. Widespread black shale deposits, particularly in deeper water facies settings, are common during the Middle Devonian (especially in the late Givetian) and may be associated with episodes of sea-level highstands and the expansion of dysoxic environments to anoxic ones (van Geldern et al. 2006; Elrick et al. 2009; Joachimski et al. 2009). Such hypoxic intervals appear to have a global expression and may coincide with several extinctions, immigrations and accelerated speciation (Brett et al. 2011). Such events also occur in shallow water realms, but to date they have not been investigated in detail. In contrast to pelagic facies settings, neritic successions generally do not exhibit characteristic lithofacies, such as black shales (e.g. Carmichael et al. 2014; Königshof et al. 2015). In shallow-water realms, events may also be associated with accelerated faunal speciation. In Upper Givetian sediments in shallow-marine facies settings conodont faunas are often dominated by Icriodontids. The presence of specialised icriodid and polygnathid faunas which flourished in shallow-water shelves (Weddige and Ziegler 1976) and which have been described from shelf carbonates in the USA, Canada and Europe (e.g. Brice et al. 1979; Racki 1992; Norris and Uyeno 1998; Sobstel 2003; Day and Whalen 2005; Uyeno and Wendte 2005; Narkiewicz and Bultynck 2010) confirms our results.

The fluctuation between marginal marine and more open marine sediments of the investigated sections led to discontinuous conodont succession. The biostratigraphic interpretation of the Givetian conodont fauna in the investigated sections required the application of an alternative conodont zonation for neritic facies setting that is well known from Givetian shallow-water carbonate platform deposits in North America and elsewhere. The stratigraphic range of the Bahram Formation in the four sections corresponds mainly to the Givetian and comprises shallow-water conodont associations corresponding to the *expansa* Zone to the *subterminus* Zone (Fig. 9). Conodont elements exhibit low species diversity, and 36 species and subspecies were assigned to five genera: *Ancyrodella*, *Bipennatus*, *Icriodus*, *Polygnathus* and *Pandorinellina* (Figs. 10, 11).

Because of the dominance of shallow-water sediments, the generally low number of conodont elements, the scarcity or absence of zonally diagnostic taxa and the irregular vertical distributions of some taxa, the Givetian Standard Conodont Zonation was not readily applicable and, therefore, an alternative shallow marine conodont zonation for Givetian was used (Narkiewicz and Bultynck 2007, 2010; Bultynck and Gouwy 2008; Narkiewicz 2011). The *expansus* Zone was used despite the consensus that *Icriodus expansus* is not a characteristic shallow-water species (see also Narkiewicz and Bultynck 2010), but this species is very frequent in our samples. Furthermore, the *expansus* Zone has a longer stratigraphic range in comparison to the *subterminus* Zone (Fig. 9). The base of the *expansus* Zone corresponds closely to the base of the Upper Givetian *hermanni* Zone (Narkiewicz and Bultynck 2010). In our section, no deep-water index conodonts for the base of the *hermanni* Zone, such as *Schmidtognathodus hermanni*, *Schm. pietzneri* or the entry of *Ozarkodina semialternans*, *Polygnathus dubius*, *P. limitaris* (see, for example, Aboussalam and Becker 2001) were found. Very often *Icriodus excavatus* co-occurs with *I. expansus*, but both species are not typical shallow-water species.

The lower boundary of the *expansus* Zone is defined with the first occurrence of *I. expansus* at 10 m from the base of the Najhaf section in sample T5. The lack of index conodonts do not allow the upper boundary of the *expansus* Zone in the Najhaf section to be fixed. The *subterminus* Zone was recognised in three sections, except the Najhaf section.

Pandorinellina insita is not very frequent in all sections. According to Narkiewicz and Bultynck (2010), *Pandorinellina insita* is common where *I. subterminus* is rare or absent. These authors assume that the "*insita*" fauna is an isochronous lateral biofacies of a "*subterminus*" fauna. Our results in studied Iranian sections confirm this observation. In one of two sections (in the Neqeleh section) containing *Pandorinellina insita*, *Icriodus subterminus* was also found (Figs. 4, 5).

In the Neqeleh section and in the North Tar section the stratigraphic range of the Bahram Formation reaches the Late Devonian. The boundary was defined in the two sections by the first occurrence of *Ancyrodella* sp.. In the North Tar section a number of conodonts have been found in the Late Devonian, but the stratigraphic range has not yet been determined. There might also be the presence of a hiatus, which has not yet been recognised in the field. The youngest part of the Late Devonian obviously belongs to the Late *rhenana* Zone which is defined by the entry of *Icriodus alternatus alternatus* (Branson and Mehl 1934), which first occurs at or just after the start of the Late *rhenana* Zone (Ziegler and Sandberg 1990). On the other hand, no Palmatolepid conodonts are present in the sample. According to sedimentological, facies and faunal data, the Bahram Formation was deposited in a shallow subtidal environment. The conodont fauna represents a nearshore polygnathid–icriodondid biofacies. The Bahram Formation most probably belongs to an inverval in the investigated area extending from the *expansus* Zone to the Late *rhenana* Zone. We provide here a more detailed stratigraphic range for the Middle Devonian part of the Bahram Formation in shallow-water facies in Central Iran and part of the Late Devonian. Our results will serve as baseline data for further sedimentological and geochemical studies in a shallow subtidal environment in Central Iran.

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