Late Devonian (Famennian) to Carboniferous (Mississippian-Pennsylvanian) conodonts from the Anarak section, Central Iran

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Abstract
A relatively complete conodont record from Famennian to the Mississippian/Pennsylvanian boundary was investigated in the Anarak section, Central Iran. The studied interval belongs to the Bahram, Shishtu, Ghaleh and Absheni formations. The Famennian part of the section (Bahram Formation) ranges from the Palmatolepis triangularis Zone into the Bispathodus ultimus Zone. Not all conodont zones could be defined due to the lack of indicative species. Furthermore, it seems likely that a hiatus occurs around the Devonian/Carboniferous (D/C) boundary (most probably from the Siphonodella praesulcata to the ?Siphonodella sulcata–early Siphonodella crenulata conodont zones) based on the lack of stratigraphically important conodonts as well as on sedimentological criteria. The lack of representative siphonodellids and progonathodids at the base of the Mississippian prevents detailed stratigraphic position of the D/C boundary. Lower Carboniferous (Mississippian) rocks are characterized by red nodular limestone which is unique in comparison with other studied sections of the same age in Central Iran. Within the studied section, we could define the Mississippian/Pennsylvanian boundary. The mid-Carboniferous boundary was defined by the occurrence of Declinognathus noduliferus s.l. Conodont biofacies changes (Mississippian genera Gnathodus and Lochriea have been replaced by Pennsylvanian genera Declinognathus and Idiognathodus) are recognized in this section as well.

Keywords Biostratigraphy · Devonian · Carboniferous · Anarak · Central Iran

Introduction
The mid-Palaeozoic, particularly the Devonian/Carboniferous (D/C), transition was a critical interval in Earth’s history which was characterized by dramatic climate and faunal changes, severe anoxic intervals, frequent sea level changes and intensified volcanism which finally led from global greenhouse conditions to icehouse conditions (Caplan et al. 1996; Caplan and Bustin 1999; Streel et al. 2000; Joachimski and Buggisch 2002; Joachimski et al. 2004, 2006; Kaiser et al. 2006, 2011; Buggisch et al. 2008; Caputo et al. 2008; Isaacson et al. 2008; Marynowski et al. 2012; Kumpen et al. 2014a, b; Paschall et al. 2019). The first-order mass extinction at the end of the Devonian (Hangenberg Crisis) caused not only a loss of major fossil groups such as conodonts (the main extinction among conodonts occurred during the global deposition of the Hangenberg Black Shale, see review by Kaiser et al. 2016) but also entire ecosystems such as metazoan reefs. In the aftermath of the Kellwasser Crisis around the Frasnian/Famennian boundary, the reefs were significantly reduced but no reef complex survived the Hangenberg Crisis (e.g. Webb 2002). The D/C transition is characterized by several transgressive/regressive cycles, and widespread ocean anoxia have been recognized along continental margins or epicontinental basins known as the Hangenberg Black Shale.
(HBS) Event. Close to the D/C boundary, a major sea level fall (Hangenberg Sandstone Event, HSS) can be recognized in many sections around the world. This eustatic sea level fall is most probably associated with a glaciation on Gondwana (e.g. Caputo 1985; Isaacsone et al. 1999, 2008; Streel et al. 2000, 2001; Caputo et al. 2008; Brezinski et al. 2008, 2010; Lakin et al. 2016). The Mississippian shows a transition between early Palaeozoic stable warm and greenhouse conditions to more late Palaeozoic oscillating climates, including several major glacial episodes (e.g. Powell 2005, 2007; Kammern and Ausich 2006; Montanez et al. 2007; Mullins and Servais 2008; Heim 2009; Lowry et al. 2014; Sardar Abadi et al. 2017).

Glacial deposits have been reported from the Viséan and Serpukhovian with a maximum extent during the Bashkirian and the Moskovian (Garzanti and Sciuinach 1997; López-Gamundi 1997; López-Gamundi and Martínez 2000). It is believed that the Late Palaeozoic Ice Age (LPIA) is one of the most important ice ages that cover much of the Late Devonian to Permian when the ice waxed and waned across southern Gondwana (Veevers and Powell 1987). The LPIA consisted of several discrete glacial climates with warmer periods of glacial minima. Ice minimum and maximum intervals were reported from low latitudes (e.g. Soreghan and Giles 1999; Bischoff et al. 2009, 2010) as well as from high latitudes (e.g. Caputo et al. 2008; Isbell et al. 2008a, b).

During the Palaeozoic, Iran was part of the northern margin of Gondwana. Marine conditions occurred in Northern and Central Iran from the Middle Devonian to Early Frasnian and persisted into the Early Pennsylvanian (Berberian and King 1981; Husseini 1991; Sharland et al. 2001). A widespread uplift during the latest Carboniferous led to continental environments before the onset of a new marine cycle during the Early Permian. The entire sequence from the Late Devonian, Carboniferous into the Permian deposits of Central Iran is divided into five lithostratigraphic units: the Bahram Formation (Givetian–Famennian), the Shishtu Formation (Tournaisian–Serpukhovian), the Sardar Group (Bashkirian–Moscovian), the Zaladu Formation (Gzhelian–Asselian) and the Jamal Formation (Permian).

The first detailed data on the Upper Devonian to Lower Permian successions in Central and Eastern Iran were obtained during the geological mapping of the Tabas and Kerman areas (Huckriede et al. 1962; Stöcklin et al. 1965; Ruttner and Stöcklin 1966; Ruttner et al. 1968; Stöcklin 1968, 1971; Stepanov 1971; Walliser 1984; Weddige 1984). More recently, numerous publications provided comprehensive stratigraphic and palaeontologic data about this region (Korn et al. 1999; Yazdi 1999; Wendt et al. 2002, 2005; Leven and Gorgij 2009; Leven et al. 2006; Hairapetian et al. 2006; Hashemie et al. 2015). Bahrami et al. (2014) described the first conodont data from the Mississippian/Pennsylvanian boundary interval in Central Iran. The aim of this study is to describe new conodont assemblages from the Late Devonian (Famennian) to the Mississippian/Pennsylvanian boundary of the Anarak section.

**Geological setting**

The Anarak area belongs to the NW part of the Central-East Iranian Microcontinent, which is juxtaposed with the Great...
**Fig. 2** Geological map and location of the investigated section A’—A (modified after Sharkovski et al. 1984)

| TIME | SYMBOL | LITHOLOGY | FORMATION |
|------|--------|-----------|-----------|
| **Cenozoic** | Eolian sand. | **Quartzite**: Eolian sand. | Q<sub>1</sub> Eolian sand. |
| | Middle dash: alluvia-proluvial pebble gravel, sand, conglomerate. | **Plagioclase**: Tuffite, tuff, sandstone, conglomerate, marl, nummulitic limestone, ignimbrite. | Q<sub>2</sub>—Eolian sand. |
| | High dash: alluvia-proluvial pebble gravel and sand, conglomerate, gravelly sandstone. | Weakly cemented boulder conglomerate, coarse-grained sandstone. | PI |
| **Mesozoic** | Conglomerates and red sandstone. | Colored Melange Zone. | K<sub>1</sub> |
| | Dolomitized limestone. | | S |
| **Perm.** | Limestone. **JAMAL Fm.** | Black calcareous quartz sandstone and shale with limestone interbeds. | P<sub>1</sub> |
| **Carb.** | C<sub>1</sub> | **SARDAR Fm.** | |
| **Palaeozoic** | Limestone, sandstone, siltstone, shale. | **SHISHTU Fm.** | D<sub>1</sub>—Limestone, dolomitized limestone, rare marl interlayers. |
| | Dolomite. | **BAHRAM Fm.** | SIBZAR Fm. |
| | Diabase, quartz sandstone. | **PAOEH Fm.** | D<sub>2</sub>—Red and white quartz sandstone, diabase, lenses of quartzite. rarely of dolomitized limestone. |
| | Sandstone, limestone, dolomite, siltstone. | **NIUR Fm.** | S<sub>2</sub>—Sandstone, limestone, dolomite, siltstone. |
| | Violet-red, greenish-grey sandstone, gravelstone, conglomerate, lenses of limestone. | **SHIRGESHT Fm.** | O<sub>2</sub>—Sandstone, limestone, dolomite, siltstone. |
| **L. Pale.** | Lakh marble, Marble, dolomite. | Dolomite. | M<sub>1</sub>—Doshakh metamorphites, epidote-chlorite, carbonate-chlorite schists, phylite, metadiabase, metasandstone, marmorized limestone, marble. |
| **Upper Proterozoic** | | | P<sub>1</sub>—Pol-e Khavand gneiss, schists, gneiss, muscovite granite. |

River, drainage
Major fault
1-29 Dip of bed (Estimated)
Second class road
Third class road
Kavir Block and the Sanandaj–Sirjan Zone, is characterized by a complex tectonic history (Davoudzadeh et al. 1981; Soffel et al. 1996; Korn et al. 1999; Bagheri and Stampfli 2008). The section is composed of a 5000–8000-m-thick series of sedimentary, volcanoclastic and metamorphic rocks (Soffel et al. 1996; Almasian 1997; Korn et al. 1999; Leven et al. 2006; Aghanabati 2010).

The latter ones contain marbles, schists, gneisses and meta-diabases which are unconformably overlain by a series of approximately 1200-m-thick Palaeozoic sediments, ranging stratigraphically from the Ordovician Shirgesht Formation to the Permian Jamal Formation (Lensch and Davoudzadeh 1982; Leven et al. 2006; Hairapetian et al. 2015). Major crustal movements associated with basaltic and ultrabasic volcanism and deposition of preferably shallow-marine deposits led to a complex geology exposed in this area. Several thrust, horst and graben structures and lateral facies changes occur. The entire succession contains some hiatuses due to erosion and/or tectonic uplift.

The section described here (Figs. 1 and 2) is located close to the northern end of the N–S striking mountain range Kuh-e-Bande-Abdol-Hossein which is located southwest of the Kuh-e-Lakh metamorphosed complex, about 34 km southwest of Anarak (sheet 6756 Anarak, 1:100,000; WGS coordinates: base of the section 33° 10′ 44.79″ N, 53° 52′ 23.83″ E; top of the section 33° 10′ 33.78″ N, 53° 52′ 22.90″ E; see Figs. 1 and 2).

The base of the section is composed of 700 m of volcanic and sedimentary deposits of ?Late Cambrian–Late Ordovician age (Hairapetian et al. 2015). These series rests upon the Doshak metamorphic complex (Sharkovsky et al. 1984; Schallreuter et al. 2006; Muttoni et al. 2009). The overlying sedimentary sequence belongs to the carbonate–siliciclastic deposits of the Silurian Niur Formation. Intercalated in this succession are volcanic rocks, such as basalts. Reddish sediments of the Lower to Middle Devonian Padeha Formation with intercalated volcanic rocks at the base cover this succession. The Padeha Formation is commonly overlain by dolostones of the Sibzar Formation which gradually passes into limestones of the Bahram Formation (Bahrami et al. 2014). The Late Devonian (Famennian) Bahram Formation is conformably overlain by the Early Mississippian Shishtu Formation which is composed of red, marly limestones.

Some limestones are rich in fossils and provided an age range from Viséan to late Namurian (Korn et al. 1999). The red nodular limestones are conformably overlain by a cliff-forming, coarse and poorly sorted limestone breccia. The top-most part is composed of Upper Mississippian (Viséan–

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**Table 1** Stratigraphy and formations applied to the Upper Devonian–Permian strata of Central-Eastern Iran, modified after Leven et al. (2006)

| Central and East Iran | Alburz central eastern |
|----------------------|-----------------------|
|                      | Anarak-Yazdi-Tabas    | Kerma-Kalmard |
| Permian              | Asselian              | Khan          | Dorud        |
|                      | Gzhelian               |               |              |
|                      | Kasimovian             |               |              |
| Carboniferous        | Moscovian              |               |              |
|                      | Bashkirian             |               |              |
| Carboniferous        | Serpukhovian           |               |              |
| Mississippian        | Visean                 |               |              |
|                      | Tournasian             |               |              |
| Devonian             | Famennian              |               |              |
|                      | Frasnian               |               |              |
|                      | Givetian               |               |              |
|                      | Sibzar                 |               |              |
|                      | Shishtu                |               |              |
|                      | Huk/Gchal              |               |              |
|                      | Bagher-Abad            |               |              |
|                      | Ghesel - Ghalch        |               |              |
|                      | Mobarak                |               |              |
|                      | Zarand                 |               |              |
|                      | Rahdar                 |               |              |
|                      | Jeirud                 |               |              |
|                      | Khotheyllagh           |               |              |
### Table 2  Conodont element distribution and number of elements of the Anarak section (Devonian part, samples A2–A29)

| Anarak section                           | A2 | A3 | A4 | A5 | A6 | A7 | A8 | A9 | A10 | A11 | A12 | A13 | A14 | A15 | A16 | A17 | A18 | A19 | A20 | A21 | A22 | A23 | A24 | A25 | A26 | A27 | A28 | A29 | Total |
|------------------------------------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Alternognathus regularis regularis       |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 2  |
| Ancyrognathus sinelaminus                | 1  | 1  | 1  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 3  |
| Bispathodus aculeatus aculeatus          |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 1  |
| Bispathodus bispathodus                  |    |    |    |    |    | 1  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 12 | 18 |
| Bispathodus cf. costatus                 |    |    |    |    | 1  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 1  |
| Bispathodus cf. ultimus                  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 1  |
| Bispathodus costatus                     |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 1  |    |    |    |    |    |    |    |    |    | 6  |
| Bispathodus jugosus                      |    |    |    |    |    |    |    |    |    |    |    |    |    | 1  |    |    |    |    |    |    |    |    |    |    |    |    | 3  |
| Bispathodus spinulicostatus              |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 5  |
| Bispathodus stabilis stabilis           |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 14 |
| Bispathodus stabilis vulgaris           |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 5  |
| Bispathodus ultimus                     |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 1  |
| Brannmeila bohlenana                    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 2  |
| Clydagnathus ormiston                   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 2  |
| Icriodus alternatus alternatus          |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 18 |
| Icriodus alternatus helmsi              |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 5  |
| Icriodus cf. cornutus                   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 3  |
| Icriodus cornutus                       |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 3  |
| Icriodus costatus darbyensis            |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 2  |
| Mehlina strigosa                        |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 4  |
| Palmatolepis glabra pectinata           |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 3  |
| Palmatolepis gracilis expansa           |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 3  |
| Palmatolepis gracilis gracilis          |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 2  |
| Palmatolepis gracilis sigmoidealis       |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 4  |
| Palmatolepis minuta loba                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 8  |
| Palmatolepis minuta minuta              |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |10 |
| Palmatolepis perlubata perlubata         |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 2  |
| Palmatolepis perlubata maxima            |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 3  |
| Palmatolepis quadrantinodosalobata       |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 8  |
| Palmatolepis triangularis                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 4  |
| Pelekygnathus inclinatus                 |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 4  |
| Polygnathus aequalis                     |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 5  |
| Anarax section          | A2 | A3 | A4 | A5 | A6 | A7 | A8 | A9 | A10 | A11 | A12 | A13 | A14 | A15 | A16 | A17 | A18 | A19 | A20 | A21 | A22 | A23 | A24 | A25 | A26 | A27 | A28 | A29 | Total |
|-------------------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|-----|
| *Polygnathus aff. subnormalis* | 1  | 1  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 2   |
| *Polygnathus aspelundi*    |    |    |    | 1  | 5  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 6   |
| *Polygnathus brevilaminus* |    |    |    |    |    | 1  | 1  | 2  | 2  | 5  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 10  |
| *Polygnathus cf. alatus*   | 2  | 1  | 1  | 1  | 3  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 8   |
| *Polygnathus cf. politus*  | 4  | 3  | 1  | 3  | 1  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 12  |
| *Polygnathus cf. xylus*    | 5  | 1  | 1  | 2  | 2  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 18  |
| *Polygnathus communis*     |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 1   |
| *Polygnathus collinsoni*   |    |    |    |    |    |    |    |    |    |    |    | 1  | 1  |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 8   |
| *Polygnathus delicatulus*  |    |    |    |    |    |    |    |    |    |    |    | 1  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 3   |
| *Polygnathus granulosus*   |    |    |    |    |    |    |    |    |    |    |    | 3  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 3   |
| *Polygnathus inconcinnus*  |    |    |    |    |    | 1  | 1  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 2   |
| *Polygnathus nodocostatus* | 1  | 1  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 2   |
| *Polygnathus padovanii*    |    |    |    |    |    |    |    |    |    |    |    | 3  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 3   |
| *Polygnathus perplexus*    |    |    |    |    |    |    |    |    |    |    |    | 1  | 1  |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 2   |
| *Polygnathus semicostatus* | 1  | 3  | 5  | 1  | 2  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 12  |
| *Polygnathus tichonovitchi*|    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 1   |
| *Polygnathus triphyllatus* | 2  | 1  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 3   |
| *Polygnathus webbi*        | 1  | 1  | 3  | 6  | 1  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 12  |
| *Pseudopolygnathus primus* |    |    | 1  | 1  | 1  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 3   |
| *Scaphignathus velifer leptus* | 1  | 1  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 2   |
| *Scaphignathus velifer velifer* | 1  | 5  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 6   |
| **Total**                 | 15 | 17 | 8  | 10 | 5  | 1  | 4  | 7  | 4  | 4  | 6  | 9  | 6  | 7  | 8  | 15 | 11 | 10 | 14 | 14 | 18 | 6  | 20  | 2  | 14 | 5  | 7  | 34 | 292 |
Namurian) grey fossiliferous thick-bedded calcareous mudstone (Sharkovski et al. 1984). Leven et al. (2006) studied the Pennsylvanian succession (Sardar Group) of the Anarak section. The Sardar Group (previously Sardar Formation) is divided into two formations: the Ghaleh Formation (formerly “Sardar 1”, early Bashkirian age), which is mainly composed of carbonate, and the siliciclastic or mixed carbonate–siliciclastic Absheni Formation (formerly “Sardar 2”, early Moscovian; see Table 1).

Material and methods

In order to improve and update the biostratigraphy of the Anarak section, fifty-six conodont samples of approximately 4 to 5 kg each were taken from carbonate rock and processed by standard methods (see Jeppsson and Anehus 1995). The process was repeated until samples were dissolved. The washed residues were dried in an oven (~ 40 °C) and later sieved and separated into three different fractions. Conodonts were handpicked utilizing a binocular microscope. Depending on the depositional facies setting, the number of conodonts per sample was highly variable; e.g. in dolostones, no conodonts were found whereas in shallow-water limestones, a good number of species occurred in distinct horizons. Herein, the conodont zonation scheme follows Ziegler and Sandberg (1990), Lane et al. (1999), Kaiser et al. (2009), Hartenfels (2011) and Spalletta et al. (2017). A total number of 373 conodonts were obtained from the residues which led to the identification of 71 species and subspecies within eighteen genera: Alternognathus, Ancyrognathus, Bispathodus, Branmehla, Clydagnathus, Declinognathus, Idiognathus, Gnathodus, Locheria, Icriodus, Mehlina, Palmatolepis, Pelekysgnathus, Polygnathus, Protognathodus, Pseudopolygnathus, Rachistognathus and Scaphignathus (Tables 2 and 3). Overall, the preservation of the conodont elements was good, and several specimens are broken or incomplete as a result of sediment transport. The conodont collection is stored at the Department of Geology (sample numbers: EUIC), University of Isfahan, Islamic Republic of Iran. Repository numbers of the figured specimens are given in the explanations of plates. The colour alteration of conodonts (CAI, Epstein et al. 1977) in the Givetian and Frasnian limestones is CAI 4–4.5 (Shakeri 2017), whereas in the Famennian and Mississippian, the colour gradually changes to lower CAI of 2–2.5.

Lithology

Based on field observations and sedimentological characteristics, the Anarak section was subdivided in five units, which are

| Table 3 | Conodont element distribution and number of elements of the Anarak section (Carboniferous part, samples A30–A53) |
|---------|----------------------------------------------------------------------------------------------------------|
| Anarak section | A30 | A31 | A32 | A33 | A34 | A35 | A36 | A37 | A38 | A39 | A40 | A41 | A42 | A43 | A44 | A45 | A46 | A47 | A48 | A49 | A50 | A51 | A52 | A53 | Total |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Declinognathodus noduliferus | 3 | 3 | 1 | 7 |
| Declinognathodus praenoduliferus | 1 | 1 | 1 | 3 |
| Gnaithodus bilineatus | 1 |
| Gnaithodus cuneiformis | 1 | 1 | 2 | 4 |
| Gnaithodus delicatus | 1 | 1 | 1 | 3 |
| Gnaithodus giryi giryi | 1 | 2 | 2 | 5 |
| Gnaithodus giryi simplex | 1 | 1 | 1 | 3 |
| Gnaithodus pseudosemiglaber | 5 | 7 | 12 |
| Gnaithodus semiglaber | 1 | 1 | 1 | 3 |
| Gnaithodus typicus | 1 | 1 | 1 | 5 |
| Idiognathodus sinuosus | 1 | 1 | 2 |
| Locheria commutata | 1 | 1 |
| Polygnathus inornatus | 2 | 1 | 3 |
| Polygnathus inornatus inornatus | 1 | 1 | 1 | 3 |
| Polygnathus longiposticus | 1 | 1 | 4 |
| Polygnathus parapetus | 1 |
| Protognathodus collinsoni | 1 |
| Rachistognathus minutus minutus | 1 | 1 | 3 | 5 |
| Rachistognathus muricatus | 3 | 1 | 3 | 7 |
| Total | 5 | 6 | 3 | 4 | 4 | 5 | 11 | 9 | 2 | 1 | 5 | 4 | 6 | 4 | 4 | 3 | 2 | 4 | 81 |
summarized from base to top (Figs. 3 and 4). It is not the aim of this paper to provide a detailed sedimentological analysis which will be published elsewhere. The base of the section (package 1, samples A1–A6, thickness 15 m) starts with grey, medium to thick-bedded fossiliferous limestone. This succession is conformably overlain mainly by greyish to white, thin-bedded nodular limestone (package 2, samples A7–A29, thickness 30 m). The portion contains some reddish shale horizons with grade upwards into skeletal limestone. These sediments are overlain by red, nodular limestone which yielded a number of macrofossils, such as gastropods, brachiopods and solitary corals (package 3, samples A30–A48, thickness 68 m). Three meters below the top, a 20-cm-thick marker horizon with goniatites occurs. The next succession (package 4, samples A49–A50, thickness 27 m) is mainly composed of whitish, cliff-forming brecciated limestone and dolostone with rare macro fossils which is overlain by grey, fossiliferous thick-bedded mudstone and limestone (package 5, samples A51–A56, thickness 38 m). Some sedimentological characteristics are shown in Fig. 3.
Fig. 4 Stratigraphic log, samples position, conodont occurrences and biozonation of Anarak section
Conodont succession

Although carbonate samples of 4 to 5 kg per sample were dissolved for biostratigraphic analysis, the overall number of conodont elements is relatively low as it was shown in other shallow-water sections, for instance, by Bahrami et al. (2018, 2019) and Ariuntogos et al. (in press). As a result, we are not able to recognize all of the conodont zones used in the revised Conodont Standard Zonation (see Hartenfels 2011; Spalletta et al. 2017). As it is common practice in high-resolution stratigraphic conodont studies, only Pa elements were identified, as many multielement reconstructions are still doubtful and incomplete. However, studied conodont elements lead to the discrimination of 22 biostratigraphic intervals (Fig. 4).

Palmatolepis winchelli to Ancyrognathus ubiquitus zones (samples A2–A6)

Although the indicative species Palmatolepis winchelli, Palmatolepis bogartensis and Ancyrognathus ubiquitus (Girard et al. 2005) are absent, the upper boundary of this biozone corresponds to the last occurrence of Palmatolepis cf. politus Ovantanova 1969; Palmatolepis webbi Stauffer 1938; and Palmatolepis cf. alatus Huddle 1934 in level A6 in our section. All mentioned species become extinct in the linguiformis Zone (Ziegler and Sandberg 1996, 2000; Ovantanova and Kononova 2001, 2008; Bultynck 2003). Therefore, this assemblage belongs to an Upper Frasian, Upper rhenana-linguiformis interval or more updated global biozones Palmatolepis winchelli to Ancyrognathus ubiquitus. Palmatolepis aequalis and Palmatolepis cf. xylus are the other important associated species. The Frasnian–Famennian boundary of the Anarak section seems to be continuous with no interruptions, no evidence of any disconformity observed in the field which means lithologically the F/F boundary does not show characteristic sediments, such as black limestones or black shales as it is known from many places around the world (see Carmichael et al. 2019), which is a result of overall shallow-water palaeoenvironment. For more detailed conodont biostratigraphic framework and biofacies analysis of the Givetian and Frasian part of the Anarak section (Kuh-e-Bande-Abdol-Hossein), see Bahrami et al. (2019).

Palmatolepis triangularis Zone (samples A7–A9)

Spalletta et al. (2017) proposed the Palmatolepis subperlobata Zone which correlates with the lowest part of the former Lower triangularis Zone. The new base is defined by the first appearance datum (FAD) of Palmatolepis subperlobata. Within the studied section (samples A7–A9), the index conodont Palmatolepis subperlobata was not observed. Thus, the lowermost part of the Famennian according to the new standard zonation (Spalletta et al. 2017) was not proven by conodonts. The base of this following interval was recognized by the entry of Palmatolepis triangularis Sannemann 1955a in level A7. This zone corresponds to the upper part of the former Lower triangularis Zone. The top is defined by the entry of Peleksygnathus inclinatus Thomas 1949 and Ancyrognathus sinelaminus (Branson and Mehl 1934a).
The *Palmatolepis delicatula platys* Zone corresponds exactly to the former Middle *triangularis* Zone of Ziegler and Sandberg 1990. We did not find the zonal name-given conodont species, but the base of this interval (sample A10) was discriminated by the first occurrence of *Pelekosynagnostus inclinatus* Thomas 1949 which ranges from Middle *triangularis* Zone to Upper *praesulcata* Zone (Sandberg and Dreesen 1984; Huang and Gong 2016) and *Anycyrogna thu sinetaminus* Branson and Mehl 1934a which ranges from the Middle *triangularis* Zone into the Uppermost *crepida* Zone (Ziegler and Sandberg 1990). *Palmatolepis perlobata perlobata* Ulrich and Basller 1926 enters in level A12 which is the other important indicator to define the lower limit of this interval. *Icriodus alternatus alternatus* and *Icriodus alternatus helmsi* were the other species recovered in this interval.

**Palmatolepis crepida** Zone (samples A14–A15)

The *Palmatolepis crepida* Zone corresponds to the former Lower *crepida* Zone (Ziegler and Sandberg 1990), and the base can be discriminated by the first appearance of *Palmatolepis minuta loba* Helms 1963 which ranges from the base of the *P. crepida* Zone to *P. rhomboidea* Zone (Spalletta et al. 2017). *Icriodus alternatus helmsi* Sandberg and Dreesen 1984 become extinct at the end of this zone. Other associated species in level A14 are *Icriodus alternatus alternatus* and *Palmatolepis cf. communis communis*.

**Palmatolepis termini** Zone (sample A16)

This interval is equivalent to the former Middle *crepida* Zone (Ziegler and Sandberg 1990). The base is characterized by the entry of *Palmatolepis semicostatus* Branson and Mehl 1934a in level A16, which has its first occurrence within the *Palmatolepis termini* Zone of Spalletta et al. (2017) and extends into the *Bispathodus ultimus* Zone. *Palmatolepis minuta loba*, *Icriodus alternatus alternatus* and *Palmatolepis cf. communis communis* are associated as well.

**Palmatolepis glabra pectinata** to *Palmatolepis rhomboidea* zones (samples A17–A18)

The base is well marked by the first occurrence of *Palmatolepis glabra pectinata* Ziegler, 1962b M1 Sandberg and Ziegler 1973 in level A17 and *Palmatolepis quadrantisnodosalobata* Sannemann, 1955a M1 Sandberg at the base of the next zone. *Polygnathus brevilaminus* and *Polygnathus asplundi asplundi* were also recovered in this zone (Fig. 5).
and Ziegler 1973, and both species have their first occurrence in the *Palmateopsis gracilis* Zone (Spalletta et al. 2017). *Icriodus alternatus alternatus* Branson & Mehl, 1934a, which become extinct at the top of this interval in level A18 (Bultynck 2003; Spalletta et al. 2017), is the other indicator for discriminating the upper boundary of this interval. *Polygnathus cf. communis communis*, *Polygnathus padovanii*, *Polygnathus cf. subnormalis* and *Palmateopsis minuta minuta* are also present.

**Palmateopsis gracilis gracilis** Zone (sample A19)

This interval corresponds to the former *Upper rhomboidea Zone* (Ziegler and Sandberg 1990). The lower limit can be identified by the first entry of *Palmateopsis gracilis gracilis* Branson & Mehl, 1934a and *Polygnathus triphylatus* Helms, 1961, and *Bispathodus stabilis vulgaris* in level A19, the first occurrence of all mentioned species, corresponds to the *Palmateopsis gracilis gracilis* Zone (see Metzger 1994; Klapper and Ziegler 1979; Spalletta et al. 2017). *Polygnathus semicostatus*, *Palmateopsis glabra pectinata*, *Palmateopsis minuta minuta*, *P. subnormalis*, *Melhina strigosa*, *Icriodus cornutus* and *Polygnathus inconcinnus* are the other associated conodonts.

**Palmateopsis marginifera marginifera** Zone (sample A20)

This conodont zone in level A20 is confirmed by the first occurrence of *Palmateopsis perlobata maxima* Müller, 1956, which has its FAD within the lower part of this conodont zone (Spalletta et al. 2017). *Bispathodus stabilis vulgaris*, *Palmateopsis gracilis gracilis*, *Palmateopsis minuta minuta*, *Polygnathus semicostatus* and *Icriodus cornutus* are also present, and *Polygnathus triphylatus* Helms 1961 becomes extinct within the lower part of this conodont zone (Spalletta et al. 2017).

**Scaphignathus velifer velifer** to **Palmateopsis rugosa trachytera** zones (sample A21)

The base of this interval is well defined by the first entry of index species *Scaphignathus velifer velifer* Helms 1959 and *Scaphignathus velifer leptus* Ziegler & Sandberg, 1984, and both have their first occurrences in the *Scaphignathus velifer velifer* Zone (= former *Upper marginifera Zone*). The other associated species are *Polygnathus perplexus*, *Polygnathus granulosus*, *Alternognathus regularis regularis*, *Polygnathus nodocostatus*, *Branmehla bohlenana*, *Bispathodus stabilis vulgaris*, *Palmateopsis perlobata maxima*, *Melhina strigosa* and *Polygnathus semicostatus*.

**Pseudopolynagathus granulosus** Zone (sample A22)

The base of this interval is coincident with the first entry of *Palmateopsis gracilis sigmoidalis* Ziegler, 1962a and *Bispathodus stabilis* (Branson & Mehl, 1934a) [M2], and the top limit can be fully identified by the last occurrence of *Icriodus cornutus* Sannemann, 1955b, *Polygnathus minuta minuta* Branson & Mehl, 1934a and *Scaphignathus velifer velifer* Helms, 1959 in level A22 which all become extinct in the *granulosus Zone* (former *Upper trachytera Zone*) (see Bultynck 2003; Ji and Ziegler 1993; Ziegler and Sandberg 1984; Spalletta et al. 2017). *Bispathodus stabilis vulgaris* and *Melhina strigosa* are also presented.
Polygnathus styriacus to Palmateolpis gracilis manca zones (sample A23)

Sample A23 yielded very few conodonts, and this interval is tentatively assigned between the lower and upper discriminated zones. Scaphignathus velifer leptus Ziegler & Sandberg, 1984 become extinct at the end of this interval in level A23. In fact, Scaphignathus velifer leptus ranges from the lower part of the Scaphignathus velifer leptus Zone to the top of the Palmateolpis gracilis manca Zone (Spalletta et al. 2017). Bispathodus stabilis stabilis, Brannmehla bohlenana and Palmateolpis gracilis sigmoidalis are associated species.

Palmateolpis gracilis expansa Zone (sample A24)

The zone is equivalent to the former Lower expansa Zone. The entry of Bispathodus jugosus (Branson and Mehl 1934a) and Palmateolpis gracilis expansa (Sandberg and Ziegler 1979) in level A24, both range from the P. gracilis expansa into the Bispathodus ultimus zone of Spalletta et al. (2017), defines the base of this interval; associated species are Clydagnathus ormisoti, Bispathodus bispathodus and Bispathodus stabilis stabilis (Fig. 6).

Bispathodus aculeatus aculeatus Zone (sample A25)

This zone corresponds to the former Middle expansa Zone and can be recognized by the first entry of Bispathodus aculeatus aculeatus Branson & Mehl, 1934a in level A25 which ranges from Middle expansa Zone (Ziegler & Sandberg, 1984)–texanus Zone (Lane et al., 1980). Clydagnathus ormisoti Beinert et al., 1971 becomes extinct in this conodont zone.

Bispathodus costatus Zones (sample A26)

The first appearance of Bispathodus costatus Branson, 1934 M1 (Ziegler and Sandberg 1984) is the indicator of the lower boundary of this interval. Bispathodus bispathodus, Bispathodus spinulicostatus, Pseudopolygnathus cf. primus, Polygnathus communis collinsoni, Bispathodus jugosus, Palmateolpis gracilis expansa, Polygnathus perplexus and Bispathodus cf. costatus are also present.

Bispathodus ultimus Zone (samples A27–A29)

This re-defined Bispathodus ultimus Zone is equivalent to the Upper expansa and praesulcata zones and the costatus–kockeli Interregnum of Kaiser et al. (2009). The lower limit of this zone is recognized by the first appearance of Bispathodus ultimus (Bischoff 1957 M1 and M2) which ranges from the Upper expansa Zone into the Middle praesulcata Zone (Ziegler and Sandberg 1984). The assemblage of Bispathodus spinulicostatus, Pseudopolygnathus cf. primus, Bispathodus aculeatus aculeatus, Polygnathus communis collinsoni, Bispathodus costatus, Bispathodus bispathodus and Palmateolpis gracilis expansa was found in this interval.

According to the conodont zonation scheme proposed by Corradini et al. (2016) and Spalletta et al. (2017), the lower boundary is determined by the lower part of the FAD of Protognathodus kockeli, but due to the lack of Protognathodus and only one species of Siphonodella praesulcata in the Anarak section, there was no evidence for discrimination of the latest Famennian, praesulcata, the costatus–kockeli Interregnum (ckI) and kockeli conodont zones.

?Protognathodus kockeli–L. Siphonodella crenulata zones (samples A30–A32)

This interval falls within the first occurrence of red marly nodular limestone at the base of Shishtu Formation. The boundary between the grey limestone of the Bahram Formation and the overlying red nodular limestones of the Shishtu Formation is characterized by a sharp depositional contact. The lack of zonal conodont index species at the base of this interval prevents the identification of the Devonian/Carboniferous boundary. The rare conodont fauna with Protognathodus collinsoni, Polygnathus inornatus, Polygnathus longigosticus and Polygnathus parapetus (Fig. 7), comprised with Siphonodella sulcata–Lower Siphonodella crenulata zones. The lack of biostratigraphic data might be a result of a depositional hiatus which is related to the Hercynian orogeny. Wendt et al. (2005) also reported a discontinuity from the Anarak section around the same level.

Siphonodella isosticha–Upper Siphonodella crenulata to Upper Gnathodus typicus zones (samples A33–A35)

The entry of Gnathodus delicatus, Gnathodus cueniformis, Gnathodus semiglaber and Gnathodus typicus was observed in level 33. Due to the poorness of conodonts in that level, it is difficult to provide a precisely defined conodont zone; thus, only a stratigraphical range can be given.

Scaliognathus anchoralis–Doliognathus latus Zone (samples A36–A37)

The lower limit of this interval is recognized by the first appearance of Gnathodus pseudosemiglaber Thomson & Fellows, 1970 in level A35 which ranges from within the anchoralis–latus Zone through the texanus Zone (Lane et al. 1980; Belka and Korn 1994). The conodont assemblage is quite scarce, and only Gnathodus semiglaber and Gnathodus typicus Hass, 1953 have been recovered in this interval.
Upper *Gnathodus texanus* to *Adetognathus unicornis* zones (samples A38–A45)

The lower boundary of this zone, which is close to the base of the early Viséan, is marked by the FAD of *Locheria commutata* Branson & Mehl, 1941, and the second conodont found in this level is *Gnathodus bilineatus bilineatus* Roundy, 1926. Both taxa were recorded as index species of early Viséan (Meischner and Nemyrovská 1999; Nemyrovská et al. 2006; Sudar et al. 2018).

*Rachistognathus muricatus* Zone (samples A46–A48)

The first appearance of *Rachistognathus muricatus* (Dunn 1966) in level A46 indicates the Rachistognathus muricatus Zone. Conodonts collected from samples A51, A52 and A53 at 135 m from the base of section contained Rachistognathus muricatus Zone. Rachistognathus muricatus Zone conformably lies above the Rachistognathus muricatus Zone. The range of this species is from Upper Mississippian to Lower Pennsylvanian (Krumhardt et al. 1996). *Gnathodus girtyi* girtyi and *Gnathodus girtyi simplex* are the other species which occur in this interval (Fig. 7).

Serpukhovian–Bashkirian (mid-Carboniferous) Boundary

Many conodont specialists indicate that the common early Carboniferous genera *Gnathodus*, *Lochriea* and *Cavusgnathus* become extinct at the end of Serpukhovian, and the first Bashkirian *Declinognathodus* appeared at the mid-Carboniferous boundary between Mississippian and Pennsylvanian (Brenckle et al. 1997; Lane et al. 1999; Nemyrovskaya 1999; Richards and Aretz 2010; Krumhardt et al. 1996). In 1995, International Subcommission on Carboniferous Stratigraphy selected the Arrow Canyon, Nevada (USA), to be the GSSP for the mid-Carboniferous boundary. The first appearances of the index conodont taxa: *Declinognathodus noduliferus* sensu lato, including the subspecies *Declinognathodus noduliferus noduliferus*, *Declinognathodus noduliferus praenoduliferus* Nigmadganov and Nemirovskaya 1992, *Declinognathodus noduliferus* s.l., but in Iranian sections, both species have the same range starting from the *Eumorphoceras–Homoceras* boundary and in the *D. noduliferus* conodont Zone. The last occurrence of *D. noduliferus* s.l. at 135 m above the base indicates the upper boundary of *D. noduliferus* Zone which is conformably overlain by the *Idiognathoides sinuatus–Rachistognathus minutus* Zone. The upper limit also can be identified by the first presence of *Rachistognathus minutus* (Higgins and Bouckaert 1968) in level A51 at the base of next interval.

*Idiognathoides sinuatus–Rachistognathus minutus* Zone (samples A51–A53)

Conodonts collected from samples A51, A52 and A53 at 135 m from the base of section contained Rachistognathus minutus Zone (Higgins and Bouckaert 1968). The range of this species is lower Morrowan (base of *sinuatus–minutus* Zone) in North America (Varker et al. 1991). This interval falls within the first occurrence of thick-bedded micritic limestone which is characterized by a sharp boundary to the lower brecciated limestone. The *I. sinuatus–R. minutus* Zone belongs to the middle Bashkirian and defines the upper boundary of *D. noduliferus* Zone. *Declinognathodus noduliferus* and *Declinognathodus praenoduliferus* are also present in this interval.

Conclusions

Late Palaeozoic Upper Devonian to Lower Carboniferous rocks in Central Iran exhibit a number of different lithologies, which point to a shallow-water shelf setting (Bahrami et al. 2018, 2019; Königshof et al. 2017). Several hiatuses exist due to lateral facies changes and/or synsedimentary vertical movements in the late Palaeozoic which is associated with horst-and-graben structures in different tectonic blocks. The late Palaeozoic (Late Devonian–Permian) deposits of the Anarak section suggest widespread marine conditions. The gradual transition and lithologic similarities between Devonian and Lower Carboniferous (Mississippian) shows that the depositional regime remained virtually unchanged. On the other hand, many sections in Iran exhibit biostratigraphical hiatuses or facies changes, which particularly concern the conodont record (e.g. Königshof et al. in press). However, some section exhibits a rather complete succession, such as the Anarak section. Sediments of this section range from the Middle Devonian and Frasnian (see Bahrami et al. 2019) to the Late Devonian and Mississippian/Pennsylvanian boundary.

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**Compliance with ethical standards**

**Conflict of interest** The authors declare that they have no conflict of interest.

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