Ordovician of North Iran: New lithostratigraphy, palaeogeography and biogeographical links with South China and the Mediterranean peri-Gondwana margin

Mansoureh Ghobadi Pour, Leonid E. Popov, J. Javier Álvaro, Arash Amini, Vachik Hairapetian & Hadi Jahangir

The Ordovician litho- and biostratigraphic framework of Alborz, Kopet-Dagh and the East-Central Iranian blocks is outlined and significantly updated, and a broad summary of the current state of knowledge of the Ordovician deposits and faunas across Iran is documented. Four tectono-stratigraphical units (including the Alestan, Damghan, Saluk and Talesh domains) are distinguished in northern Iran. They differ considerably from one another in their lithology, facies, fossil record and completeness of their sedimentary record. A comprehensive revision of the Ordovician stratigraphy in the eastern Alborz and the Kopet-Dagh regions leads to the definition of the (i) Simeh-Kuh Formation (new), (ii) the Qumes Formation (new) and its subdivision into the Gerd-Kuh (new) and Raziabad (new) members, (iii) the Lashkarak Formation and its subdivision into the Cheshmeh-Ali (new) and Hajiabad (new) members, (iv) the Abarsaj Formation (formalised) in the Alestan Domain, (v) the Qyzlar (new) and Pelmis formations in the Saluk Domain, and (vi) the Tatavrud Formation (new) in the Talesh Domain. The Ordovician strata of the eastern Alborz and Kopet-Dagh Mountains comprise a rifting volcanism emplaced within an active horst-and-graben palaeotopography. Despite the strong Ordovician biogeographical affinities with South China and, to a lesser extent, with Mediterranean peri-Gondwana, zircon populations analysed from Cambro–Ordovician sandstones in the area point to the Arabian-Nubian Shield of the western Arabian Peninsula and northeastern Africa as the principal continental sources. Consequently, an open oceanic communication between the Mediterranean and the northern (Alborz) margins of Gondwana and the southern margin of South China favoured the establishment of strong biogeographical affinities between these mid-latitude basins. • Key words: Ordovician, lithostratigraphy, biostratigraphy, paleobiogeography, Iran, Gondwana.

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The presence of Ordovician fossils in the Alborz Mountains was established in 1934, when Bobek collected trilobites at Alam-Kuh (Fig. 1), which were subsequently identified by Dietrich (1937). They were only documented in more detail thirty years later, when Gansser & Huber (1962) introduced the fossiliferous Lashkarak Formation, named after its homonymous mountain. Davies *et al*. (1972) and Clark *et al*. (1975) also reported the presence of Ordovician fossiliferous strata in the Talesh Mountains, southwest of Rasht city (Fig. 1). Their Late Ordovician age was supported by a rich trilobite fauna subsequently described by Karim (2009).

There was little progress in Ordovician studies for the next forty years. The information on the Ordovician and the stratigraphical ranges of the fossil content in the Alborz Mountains by Stöcklin & Setudehnia (1991), Hamedi *et al*. (1997) and Bruton *et al*. (2004) was imprecise. Significant confusion arose after re-definition of

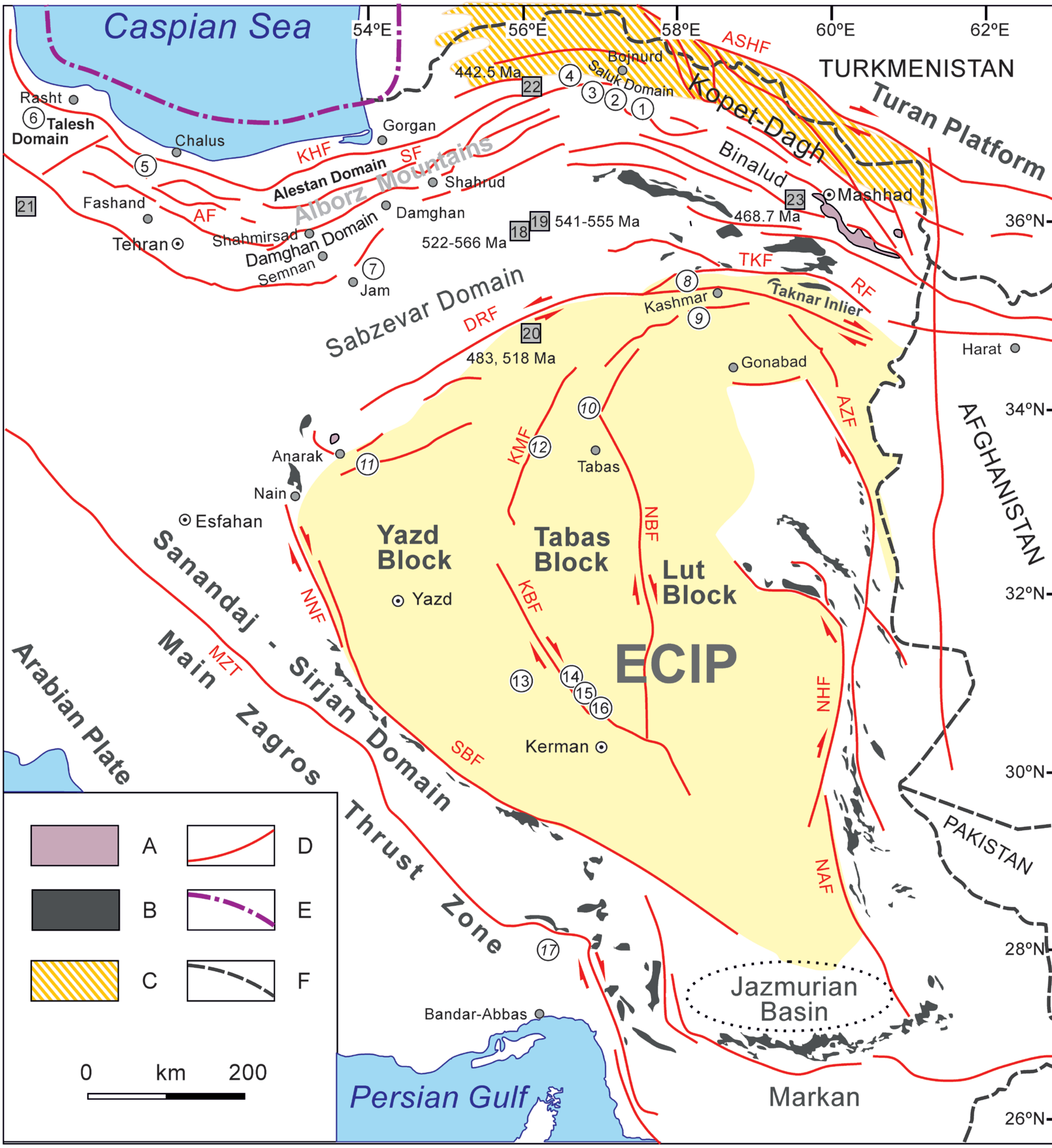


Figure 1. Simplified tectonic map of Iran (modified from Ramezani & Tucker 2003; Hairapetian *et al*. 2012, 2017; Álvaro *et al*. 2022) showing the geographical setting of the Ordovician outcrop areas discussed in the paper, including: 1–2 – Saluk Mountains; 1 – Pelmis Pass and Kalat valley; 2 – Ghelli; 3 – Navia Inlier; 4 – Robat-e Qarabil Inlier; 5 – Alam-Kuh; 6 – Tatavrud Inlier in Talesh Mountains; 7 – Boz-Kuh Mountains west of Djam; 8 – Taknar Inlier; 9 – Boghu Mountains; 10 – Derenjal Mountains; 11 – Pol-e wKhavand Inlier, southeast of Anarak; 12 – Kalmard area west of Tabas; 13–16 – Kerman Region; 13 – Shaabjereh area; 14 – Banestan area; 15–16 – Gatkuiyeh area; 17– Faraghan Mountains, Zagros Ranges; 18 – Torud-Biarjmand metamorphic complex; 19 – Delbar metamorphic–igneous complex; 20 – Aierkan granites; 21 – Sarv-e Jahan granites; 22 – Dasht area; 23 – Buzhan and Rud valleys in the Binalud Mountains. Abbreviations: ECIP – East-Central Iranian Plate; AF – Astaneh Fault; ASHF – Ashghabad Fault; AZF – Abiz Fault; DRF – Doruneh Fault; KBF – Kuhbanan Fault; KHF – Khazar Fault; KMF – Kalmard Fault; MZT – Main Zagros Thrust; NAF – Nostratabad Fault; NBF – Nayband Fault; NHF – Nehbandan Fault; NNF – Nain Fault; RF – Rivash Fault; SBF – Shahre-Babak Fault; SF – Shahrud Fault; TKF – Taknar Fault. Legend: A – Palaeozoic ophiolites; B – Mesozoic ophiolites; C – Kopet-Dagh orogen; D – major faults; E – present-day outer boundary of the oceanic crust in the South Caspian Basin; F – state borders.

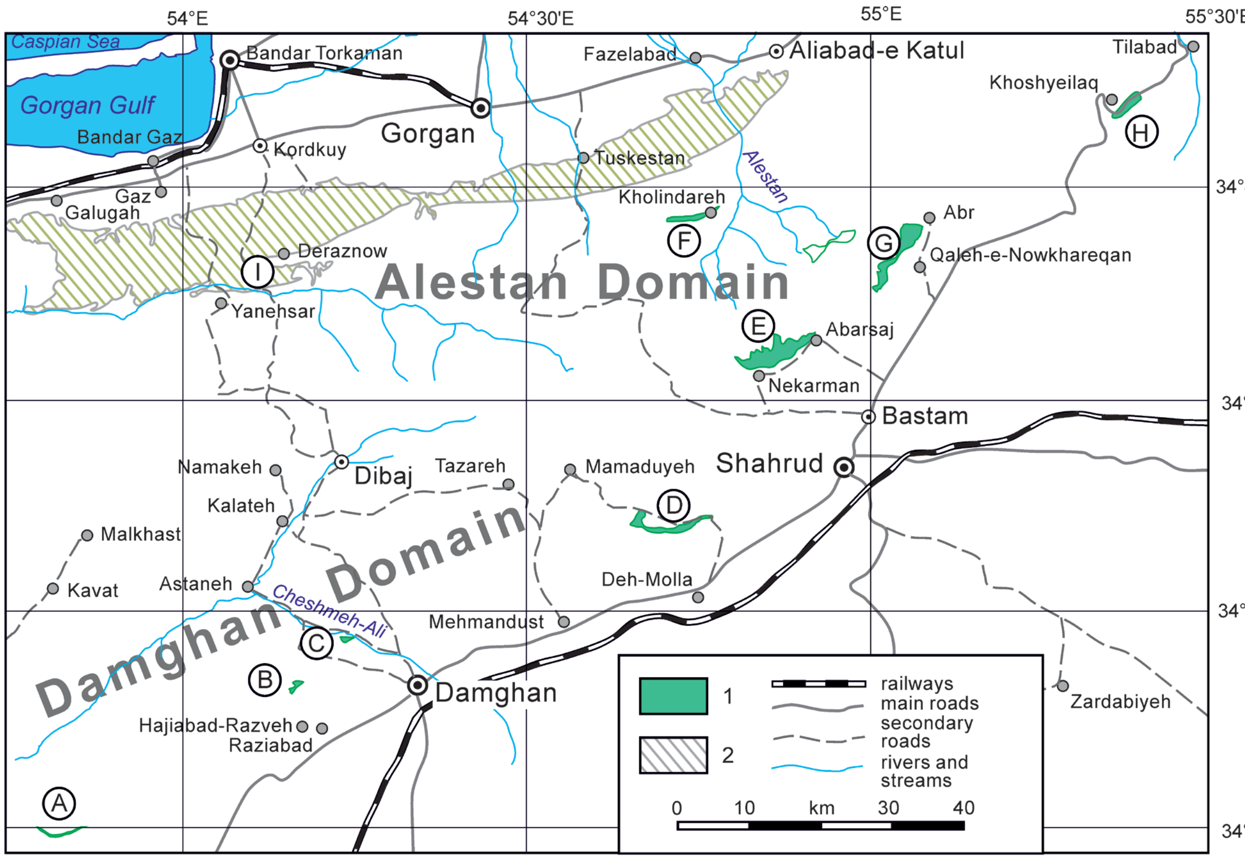


Figure 2. Simplified geographical map of eastern Alborz Region. • 1 – Ordovician strata, including: A – Mila-Kuh Inlier; B – Gerd-Kuh Inlier; C – Simeh-Kuh Inlier; D – Deh-Molla Inlier; E – Shahvar Mountains including Avesta river valley; F – Kholin-Darreh; G – Siaheh Mountains including Cheshmeh-Seyed valley; H – Khoshyeilaq Inlier. • 2 – outcrop area of the 'Gorgan Schists' including: I – vicinity of Radkan.

the Lashkarak Formation by Glaus (1965), and a report by Müller (1973) focused on the occurrence of Early Ordovician conodonts (now latest Furongian; see Jahangir *et al*. 2016) in the Mila Formation. Since then, both units were often considered as partly overlapping and potentially synonymous (*e.g.* Stöcklin & Setudehnia 1991).

The last fifteen years have witnessed significant progress in stratigraphical knowledge of the Ordovician across the Alborz Mountains (Fig. 2). Based on a detailed biostratigraphical study of the Ordovician succession at Deh-Molla, west of Shahrud city, Ghavidel-Syooki (2006) developed a palynomorph zonation for these deposits. He also convincingly demonstrated the presence of Middle and Upper Ordovician strata in the area, which were assigned to the Ghelli Formation, previously introduced in the Kopet-Dagh Region (Afshar-Harb 1979, Ahmadzadeh-Heravi 1983). Ghavidel-Syooki (2006) also recognised the existence of a considerable gap interrupting the Ordovician succession and marking the base of the Darriwilian at the Deh-Molla section (Fig. 3). It was later demonstrated that the Ordovician has wider exposures in the southern foothills of eastern Alborz (Ghobadi Pour 2006, Ghobadi Pour *et al*. 2015b), in particular, to the northwest of Damghan city (Simeh-Kuh and Gerd-Kuh inliers), where they were originally mapped as Devonian on geological maps by the Geological Survey of Iran (*e.g.* Alavi & Salehi-Rad 1975, Shahrabi 1991).

Significant stratigraphical changes occur in Ordovician strata cropping out to the north of the Shahrud and Astaneh fault systems (SF and AF in Fig. 1). Together they form an important regional neotectonic shear zone (Hollingsworth *et al*. 2008). There, the thickness of the Ordovician increases considerably and comprises almost exclusively siliciclastic deposits with a few interbeds of basalt lava flows. Unlike the southern sections, the dominant Late Ordovician age of these strata was exclusively constrained by palynomorphs. Unfortunately, there is no consistency in the lithostratigraphical subdivision of the Ordovician units across that region. Depending on the fossil content, they were assigned to the Abastu, Abarsaj, Ghelli and Lashkarak formations. Northwards, Ordovician deposits, known as the 'Gorgan Schists', are strongly affected by low grade metamorphism. Their Late Ordovician age was

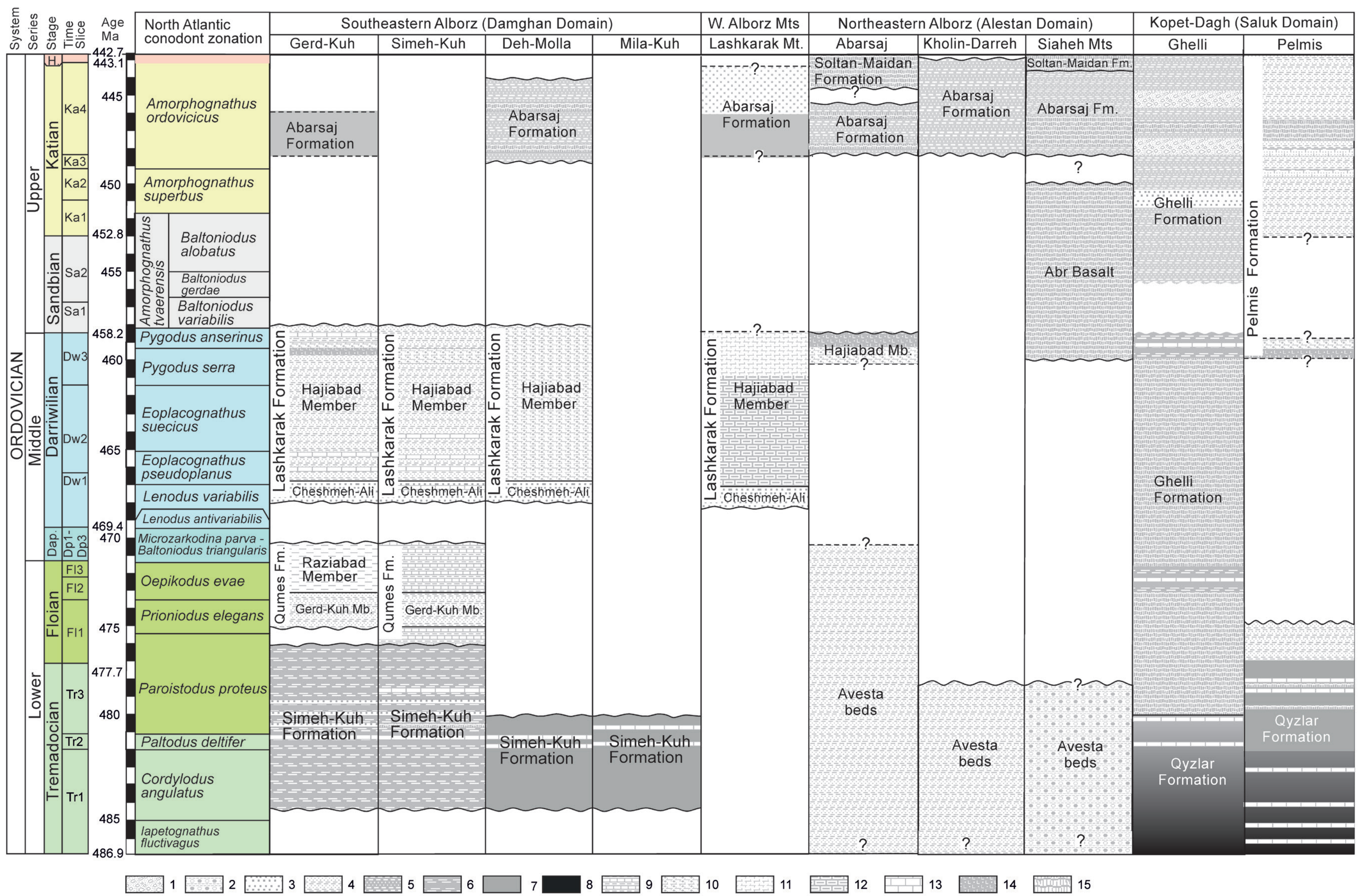


Figure 3. General correlation of Ordovician lithostratigraphical units in northern Iran, including Alborz Mountains and Saluk Mountains. Lithologies within formations are generalised. Lithologies: 1 – diamictites/olistostrome horizons; 2 – conglomerate and siltstone intercalations; 3 – sandstones; 4 – sandstones and siltstones; 5 – sandstone, siltstone and argillite intercalations; 6 – siltstones and argillites; 7 – green and light grey argillites; 8 – black shales; 9 – limestone and argillite intercalations; 10 – oolitic ironstones; 11 – calcareous argillites and siltstones; 12 – argillaceous limestones; 13 – limestones; 14 – tuffs; 15 – basalt volcanic rocks. International Chronostratigraphical Scale and conodont biozonation are mainly after Cooper *et al.* (2012) with emendations.

confirmed by the occurrence of diagnostic acritarchs and chitinozoans (Ghavidel-Syooki 2008).

Another important sector that includes widespread Ordovician exposures is the South Kopet-Dagh Region (Figs 1, 3). An almost complete succession of Lower Palaeozoic strata, presumably ranging from Miaolingian (former “middle Cambrian”) to Silurian, was discovered in the Saluk Mountains by Afshar-Harb (1979). He subdivided the Lower Palaeozoic rocks into the Mila, Lashkarak, Ghelli and Niur formations. Later, Ahmadzadeh-Heravi (1983) reported the occurrence of conodonts and brachiopods that identified the ages of these formations and confirmed the presence of the Upper Ordovician in this part of Iran. Blourchi & Mehr Parto (1987) mapped the Kopet-Dagh Region at the 1:250,000 scale. They subdivided the Lower Palaeozoic rocks into the Mila, Lashkarak and Niur formations. Another map made by Jafarian & Taheri (1994), at the 1:100,000 scale, included further stratigraphical refinements, but no evidence of Silurian sediments. They also subdivided the mapped area into the Binalud (southern part) and Kopet-Dagh (northern part) structural domains. The Binalud Domain was considered by the cited authors as the eastern structural prolongation of the Alborz Mountains. The Ordovician biostratigraphy of the Kopet-Dagh Region is based mostly on palynomorphs (Ghavidel-Syooki 2001, 2017a, b; Ghavidel-Syooki & Winchester-Seeto 2002). Conodont biostratigraphy across the Cambrian–Ordovician transition was discussed in some detail by Jahangir *et al*. (2015). Available information on Ordovician fossil groups occurring in the region (*e.g.* brachiopods, trilobites and molluscs) is still incomplete.

The main purpose of this work is to offer the first updated synthesis of the Ordovician litho- and biostratigraphical framework of northern Iran, especially of the eastern Alborz (*sensu lato*) Mountains, including the South Kopet-Dagh Region, with references to other parts of Iran (Figs 1, 2). The Ordovician deposits reported from the Boz-Kuh Mountains, to the west of Djam town (Alavi-Naini 1972), located close to the northern margin of the Sabzevar Domain, and the Taknar Inlier (Müller & Walter 1984), along the northern margin of the East-Central Iranian Plate (ECIP, Fig. 1), are still inadequately known and are not considered in detail below. In some study areas, there are striking differences between our field observations and the geological maps produced by the Geological Survey of Iran, as well as published geological interpretations based on these maps, which require appropriate reference and discussion. Some palaeobiogeographical comparisons with South China and the Mediterranean peri-Gondwana margin are added to constrain previous studies focused on detrital zircon provenances (*e.g.* Horton *et al*. 2008, Shafaii Moghadam *et al*. 2017).

Material and methods

The Lower Palaeozoic successions of the eastern Alborz and South Kopet-Dagh regions have been the subject of intensive research based on extensive palaeontological, biostratigraphical and sedimentological studies in the field during the last decade. A detailed trilobite-based biostratigraphical subdivision of the Tremadocian was proposed by Ghobadi Pour (2006) and Ghobadi Pour *et al*. (2015b) (Fig. 16), which has been subsequently constrained by a conodont-based biostratigraphy established for the Furongian and Lower Ordovician (Jahangir *et al*. 2015, 2016) and, to a lesser degree, for the Middle Ordovician. These data make possible a precise correlation of the Ordovician strata from the Alborz Mountains with the global chronostratigraphical standard.

Some microfossils used in this study (*e.g*. linguliform brachiopods, conodonts, ostracods and foraminiferans) were extracted from carbonate rocks dissolved in dilute (10–15%), buffered acetic acid using a standard technique at the Department of Natural Sciences, National Museum of Wales and the Department of Geology, Golestan University.

Updated Ordovician lithostratigraphy of Alborz and Kopet-Dagh

In spite of significant progress in palaeontological and biostratigraphical studies, the current lithostratigraphical framework applied to the Ordovician of Iran is seriously outdated. There are essentially no designated lithostratigraphical units with well-defined boundary stratotypes. The age, chronostratigraphical range and geographical distribution of the units (*e.g*. Lashkarak, Ghelli and Shirgesht formations) have been dramatically fluctuating in successive reports. Therefore the main objective of this section is the validation and proper definition of lithostratigraphical units, presently used and newly designated for northern Iran, to meet the recommendations of the International Stratigraphic Guide (Salvador 1994). The revised lithostratigraphical framework adopted in the paper is illustrated in Figures 3 and 4.

Eastern Alborz Mountains

This section defines and formalises some Ordovician units of the eastern Alborz Mountains, which include (i) the Sime-Kuh Formation (new), (ii) the Qumes Formation (new) and its subdivisions into the Gerd-Kuh (new) and Raziabad (new) members, (iii) the Lashkarak Formation (formalised) and its subdivisions into the Cheshmeh-Ali (new) and Hajiabad (new) members, and (iv) the Abarsaj Formation (formalised).

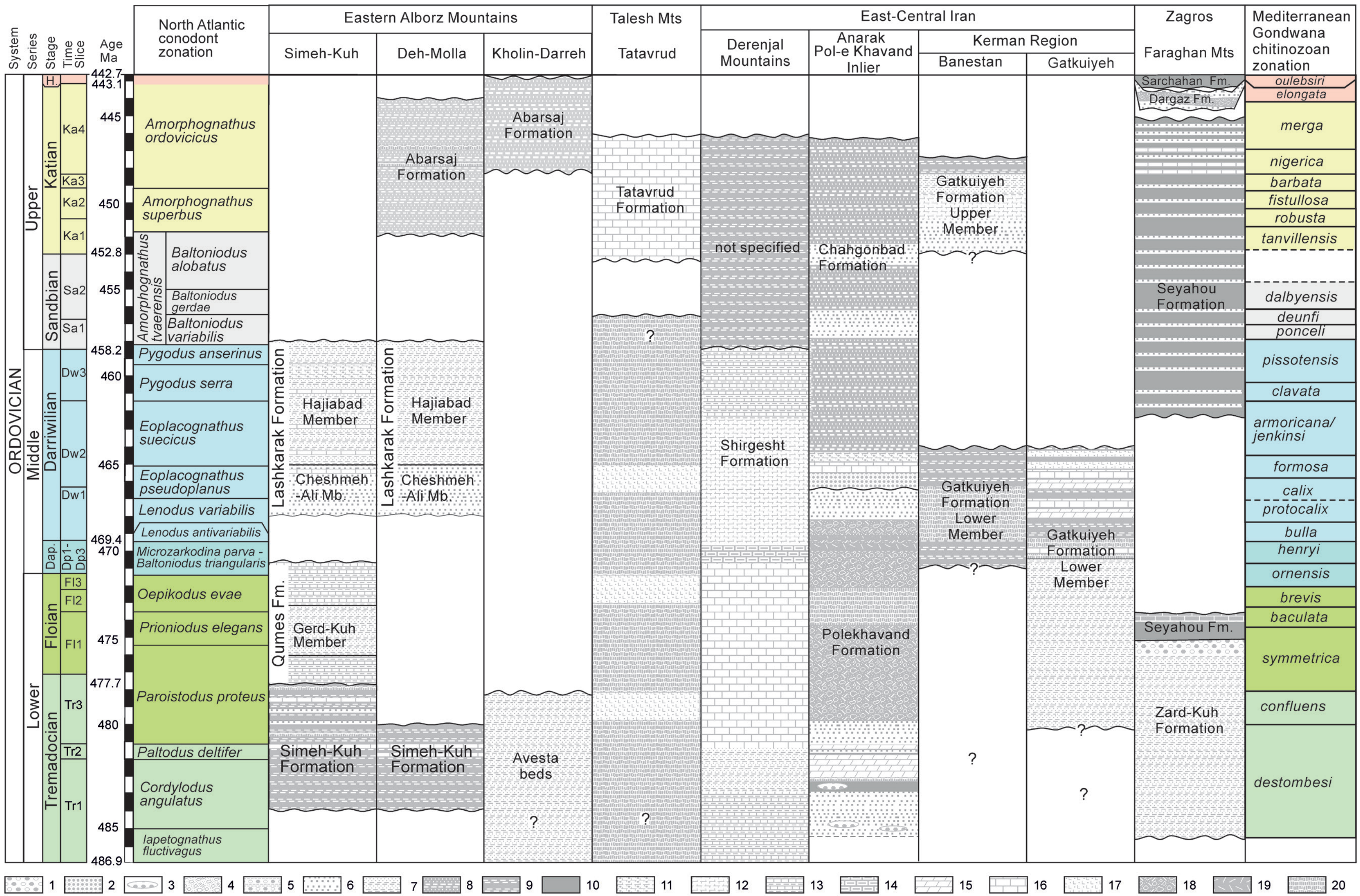


Figure 4. General correlation of Ordovician lithostratigraphical units across Iran; lithologies within formations are generalised. Lithologies: 1 – conglomerates; 2 – microconglomerates; 3 – conglomerate lenses; 4 – diamictites/olistostrome horizons; 5 – conglomerate and siltstone intercalations; 6 – sandstones; 7 – sandstones and siltstones; 8 – sandstone, siltstone and shale alternations; 9 – siltstones and argillites; 10 – shales; 11 – oolitic ironstones; 12 – calcareous argillites and siltstones; 13 – limestone and argillite interbeds; 14 – argillaceous limestones; 15 – dolomites; 16 – limestones; 17 – basic tuffs; 18 – rhyolite agglomerate tuffs; 19 – rhyolite tuffs, 20 – basalt volcanic rocks. Global geochronological scale and conodont biozonation are mainly after Cooper *et al*. (2012) with emendations, chitinozoan biozonation for Mediterranean peri-Gondwana is after Paris (1990).

Simeh-Kuh Formation
[new]

Derivation of name. – The name refers to the Simeh-Kuh section, northwest of Damghan city, where the most extensive and complete exposure of the unit is documented.

Stratotype. – Natural exposure in the Simeh-Kuh Inlier, 13 km northwest of Damghan city (Figs 2, 3, 5A, 6); geographical coordinates for the base level of the section are 36° 12′ 40.2″ N, 54° 13′ 40.3″ E, the altitude is 1361 m above sea level. The updated sedimentary succession of the type section (Figs 5, 6) is presented in the Appendix 1.

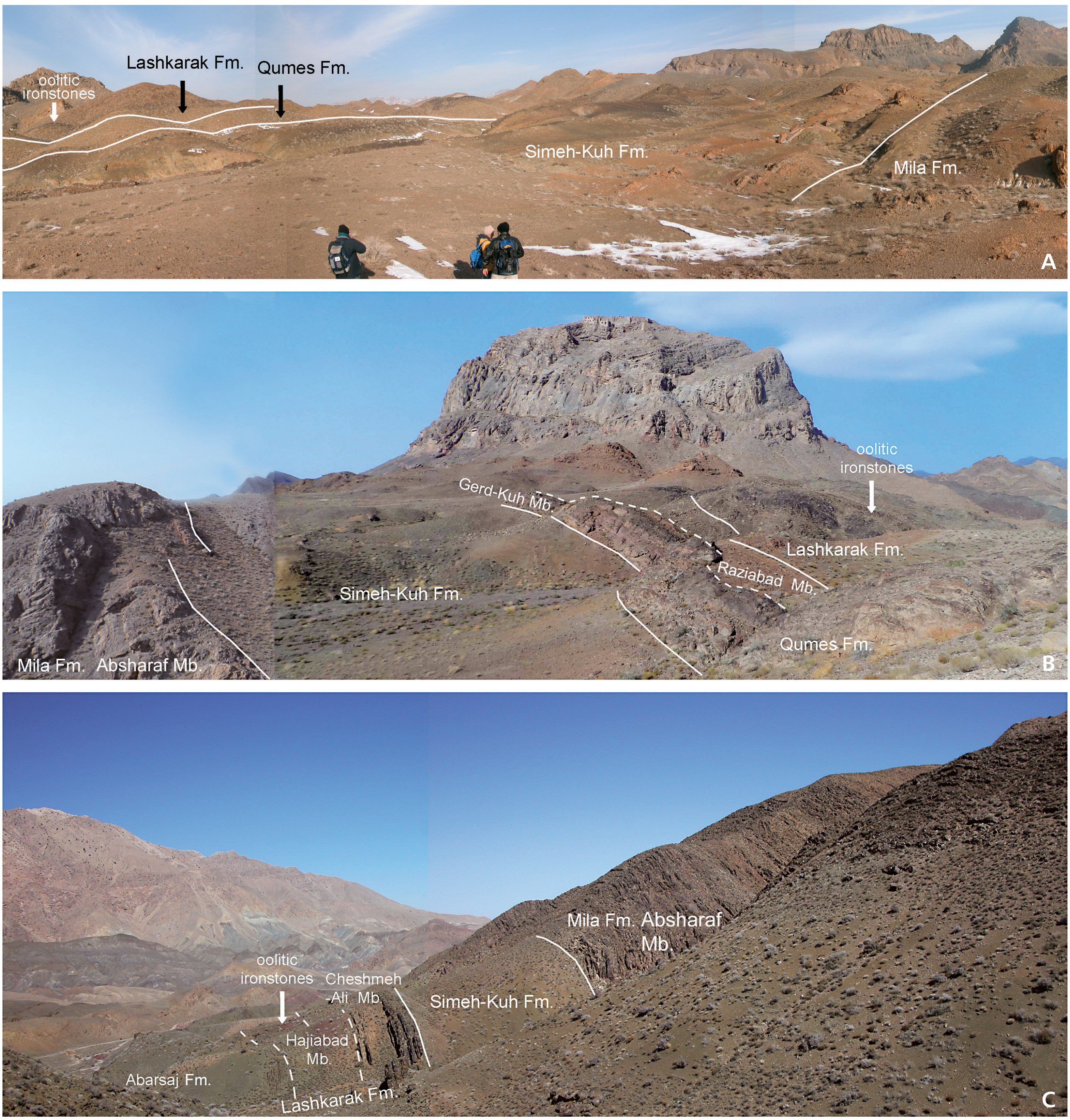


Figure 5. A – general northward view of the Ordovician outcrops at Simeh-Kuh, the type area for Simeh-Kuh and Qumes Formations, showing major lithostratigraphic units and their boundaries. B – general northwardly view of the uppermost Cambrian and Ordovician outcrops at Gerd-Kuh, the type area for the Gerd-Kuh and Raziabad members, showing major lithostratigraphic units and their boundaries. C – eastward view of the Cambrian (Furongian) to Ordovician succession at Deh-Molla showing major lithostratigraphic units and their boundaries.

Lithology. – The Simeh-Kuh Formation comprises predominantly grey to dark grey, laminated shales without traces of bioturbation that include a few bioclastic limestone interbeds, not exceeding 0.2–0.3 m in thickness. Thin beds of fine-grained sandstone, with wavy and hummocky bedding, usually not exceeding 0.1 m but occasionally up to 0.4 m, occur in the lower part of the formation at the stratotype. Up to three interbeds of fine- to medium-grained sandstone and impure limestone with abundant brachiopod coquinas, varying from 1 to 3 m in thickness, occur in the middle part of the formation (*Paltodus deltifer* to lower *Drepanoistodus proteus* zones) in the most complete sections at Simeh-Kuh and Gerd-Kuh sections.

In the Simeh-Kuh section, two strongly weathered diabase sills occur in the uppermost part of the formation. The intrusion seems related to the Late Devonian volcanism widely developed in the adjacent Gerd-Kuh Inlier.

Boundaries. – The Simeh-Kuh Formation unconformably overlies the uppermost Furongian Absharaf Member ("*Cruziana* Sandstones" or Member 5) of the Cambrian (Miaolingian–Furongian) Mila Formation (Álvaro *et al*. 2022). The top is highly diachronous; in the most complete Simeh-Kuh section, it is conformably overlain by the Qumes Formation, whereas in the Mila-Kuh section it is unconformably overlain by the Upper Devonian Geirud Formation.

Distribution and age. – The Simeh-Kuh Formation is exposed discontinuously over 110 km between Mila-Kuh and Shahrud city in the eastern Alborz (Fig. 2). Probably, it is also present in the western Alborz where argillites with graptolites, identified as *Tetragraptus* and *Didymograptus* (Stöcklin 1972), have been reported.

The Tremadocian–early Floian age of the lower part of the formation is confirmed by the common preservation of trilobites belonging to the *Asaphellus inflatus–Dactylocephalus* to *Asaphellus fecundus–Taihungshania miqueli* zones (Ghobadi Pour *et al*. 2015b, Ghobadi Pour 2019), graptolites *Hunnegraptus*? sp. (Rushton *et al*. 2021) and conodonts from the *Paltodus deltifer* and *Paroistodus proteus* zones (Jahangir *et al*. 2015). The uppermost part of the formation at Simeh-Kuh contains the graptolites *Baltograptus geometricus* (Törnquist, 1901) associated with the lower Floian *Cymatograptus protobalticus* Zone of Baltoscandian Basin (Egenhoff & Maletz 2007, Rushton *et al*. 2021).

The maximum thickness of the formation is 133.2 m at Simeh-Kuh. It decreases down to 60 m at Mila-Kuh to the west (Kebria-ee Zadeh *et al*. 2015) and to 58 m at Deh-Molla to the east (Ghobadi Pour *et al*. 2011b, Ghobadi Pour 2019), where only the Tremadocian part of the formation, up to the *Psilocephalina lubrica–Asaphopsis elhameae* trilobite Zone, is preserved. The presence of Ordovician deposits in the western flank of the 'Deh-Molla Syncline' was depicted on the 1:250,000 geological map by Shahrabi (1991) and the 1:100,000 scale geological map of the Shahrud district produced by the Geological Survey of Iran. However, this has not been confirmed by our field observations.

Depositional environments. – As stated above, the Simeh-Kuh Formation unconformably overlies the Absharaf Member of the Mila Formation. The gap involved at the Mila/Sime-Kuh contact includes part of the Tremadocian. Return to marine conditions in eastern Alborz is highlighted by a significant drowning event (Ghobadi Pour *et al*. 2015b), which was probably contemporaneous with Miller's (1984) transgressive phase of the Black Mountain Eustatic Event. As a result, the latest Furongian shoal complexes (Absharaf Member = '*Cruziana* sandstones' of Mila Member 5) were onlapped by a condensed succession with laminated siltstones and claystones, which continued with minor interruptions until the early Floian (Fig. 7A), with occasional thin layers of fine-grained sandstones in the lower part. A few bioclastic limestone beds (Fig. 7B) in the middle and upper parts of the Sime-Kuh Formation probably represent proximal tempestites.

The trilobite fauna yielded by the Simeh-Kuh Formation mainly belongs to the nileid and raphiophorid biofacies (Ghobadi Pour 2006, Ghobadi Pour *et al*. 2007a), although the *Asaphellus inflatus–Dactylocephalus* trilobite Association, including the olenide *Chungkingaspis sinensis* (Sheng, 1958), proliferated in the lower part of the formation (Ghobadi Pour 2019). According to Ghobadi Pour *et al*. (2015b), this association is probably vicariant with the Early Ordovician olenid – *Asaphellus* biofacies from the Cordillera Oriental, Argentina, described by Balseiro *et al*. (2011). The sediments of the Simeh-Kuh Formation predominantly represent upper offshore environments somewhat below seasonal storm wave base (Ghobadi Pour *et al*. 2015b). The lack of bioturbation, the olenid occurrences in the lower part, and the graptolites in the upper part of the formation suggest episodic dysaerobic conditions on the sediment/seawater interface.

Calm conditions were interrupted episodically by the input of coarser sediments resulting in the record of up to four sandstone interbeds, *c*. 1–3 m thick. The lowermost unit, traceable along the Simeh-Kuh and Gerd-Kuh areas, is barren. The two upper interbeds consist of medium- to coarse-grained sandstones and impure limestones with horizontal, low-angle cross-laminae and hummocky cross-stratification, which include extensive brachiopod shell beds formed mostly by dense bioaccumulations of relatively well-preserved, disarticulated brachiopod valves of *Protambonites hooshangi* Popov *et al*., 2009a and *Tarfaya jafariani* Popov *et al*., 2009a. These calcareous sandstone interbeds represent both proximal tem-

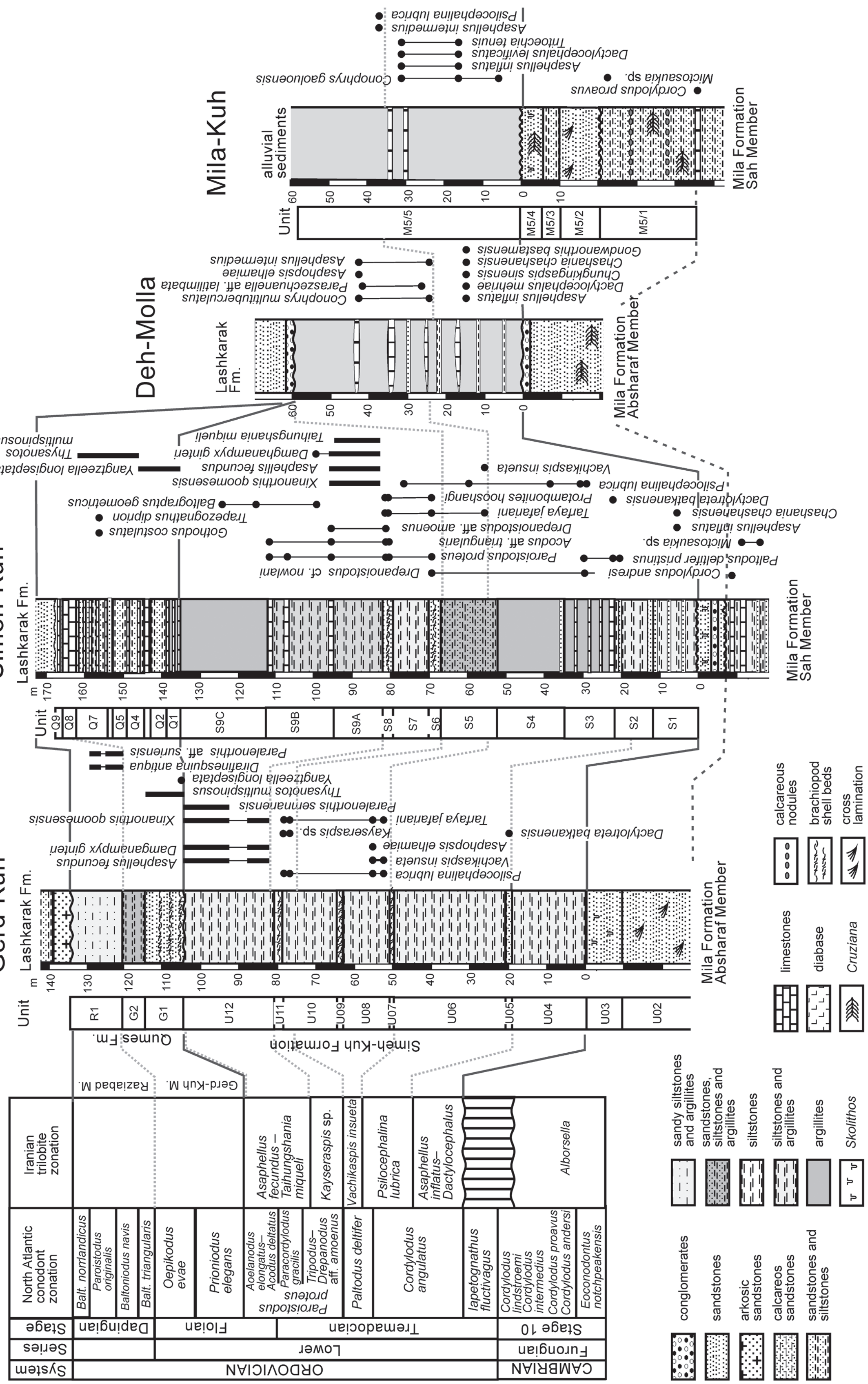


Figure 6. Stratigraphical columns of main Ordovician (Tremadocian to Dapingian) sections of Simeh-Kuh and Qumes formations at southern foothills of eastern Alborz Mountains, showing stratigraphical distribution of selected trilobite, conodont, and brachiopods species. Individual units for Gerd-Kuh Formation at Gerd-Kuh section are after Popov & Cocks (2017). Individual units for Simeh-Kuh section are as in Appendix 1 and Appendix 2.

pestites and partly eroded shoal complexes. These event interbeds occur within the stratigraphical interval of the *Psilocephalina lubrica* to *Kayseraspis* trilobite zones and the *Paltodus deltifer* to lower *Drepanoistodus proteus* conodont zones (Figs 6, 7C; Simeh-Kuh section).

Remarks. – The lower part of the Simeh-Kuh Formation exposed at Mila-Kuh served originally to define the upper shale unit of the Mila Formation Member 5 (Stöcklin *et al*. 1964). Since then, the Cambrian *vs*. Ordovician age of the upper part of the Mila Formation has been a regular matter of debate (Kushan 1973, Müller 1973, Peng *et al*. 1999, Bruton *et al*. 2004), until the discovery of Tremadocian trilobites and brachiopods from the uppermost argillite unit of Member 5 at Mila-Kuh that was convincingly demonstrated by Kebria-ee Zadeh *et al*. (2015). In some publications (*e.g.* Ghavidel-Syooki 2006; Ghobadi Pour 2006; Ghobadi Pour *et al*. 2006, 2007b; Popov *et al*. 2008, 2009a), the Tremadocian succession in the southern foothills of eastern Alborz was erroneously assigned to the Lashkarak Formation. A log of the lower and middle part of the succession was illustrated by Jahangir *et al*. (2016: units L3–L11), but referred to an “unnamed formation”.

Qumes Formation
[new]

Derivation of name. – The name refers to the ancient Qumes Province, where the type section of the unit is located.

Stratotype. – Natural exposure in Simeh-Kuh Inlier, 13 km northwest of Damghan city (Figs 2, 5a, 6; units Q1–Q9). Geographical coordinates for the base of the section are 36° 12′ 49.8″ N, 54° 13′ 30.6″ E, and altitude 1406 m. There, the formation conformably overlies the graptolite-bearing shales of the Simeh-Kuh Formation (Figs 3, 5–6). The base of the unit is placed at the first bioclastic limestone bed (Fig. 7D). The sedimentary succession of the stratotype (Figs 5A, 6) is detailed in the Appendix 2.

Members. – The Qumes Formation is subdivided into the Gerd-Kuh and Raziabad members.

Lithology. – The formation is heterolithic with significant lateral facies changes at relatively short distances. At the Gerd-Kuh Inlier, it comprises exclusively siliciclastic deposits punctuated by some brachiopod shell beds, whereas at Simeh-Kuh, carbonates mostly represented by bioclastic limestones and bioaccumulations are relatively abundant (Figs 3; 6; 7D, F; 8C, D).

Boundaries. – The Qumes Formation commonly rests conformably on the Tremadocian – lower Floian Simeh-Kuh Formation, *e.g.* in the Simeh-Kuh Inlier.

Distribution and age. – The Qumes Formation occurs throughout the Gerd-Kuh and Simeh-Kuh inliers, northwest of Damghan city. Its maximum thickness is 31.6 m at Simeh-Kuh and 27.7 m at Gerd-Kuh. The Floian to Dapingian age of the unit is based on the occurrence of conodonts characteristic of the *Prioniodus elegans*–*Baltoniodus navis* zones (Figs 6, 9), as well as of linguliform and rhynchonelliform brachiopods (Popov *et al*. 2008, Ghobadi Pour *et al*. 2011a, Popov & Cocks 2017).

Depositional environments. – The Qumes Formation was deposited in palaeobathymetries ranging from upper offshore to proximal shoreface settings. Sandy strata with subsidiary brachiopod shell beds and siltstones of the Gerd-Kuh Member predominantly represent remnants of Floian shoal complexes, while condensed temperate-water carbonates (Fig. 7F) in the lower and upper parts of the Qumes Formation, by analogy with similar Floian to Dapingian successions of east Baltica and probably South China, are considered as proximal tempestites deposited in a storm-dominated platform varying from lower shoreface to upper offshore settings. Individual bioclastic limestone beds, 2–10 cm thick, were probably storm-induced events, which interrupted a background deposition characterized by offshore shales (Dronov 1998, 1999). The condensed succession of the fine clastic Raziabad Member was contemporaneous with the upper carbonate unit of the Qumes Formation, which contains numerous brachiopod shells embedded in the sediment that probably represent autochthonous benthic communities preserved in life position.

Remarks. – The Qumes Formation is the only Ordovician lithostratigraphical unit within the Alborz Mountains with episodic accumulation of temperate-water shelly carbonates. While the linguliform brachiopods from this unit are relatively well known (Popov *et al*. 2008), the rhynchonelliform brachiopods are best known from the Raziabad Member (Popov & Cocks 2017). Complete shells of *Martellia* and *Yangtzeella* are relatively common in the lower carbonate interbeds of the Qumes Formation at the Simeh-Kuh section suggesting an analogy with the Benthic Assemblage 3 of the *Yangtzeella pooli*–*Nereidella typa* Association from the Dapingian Dawan Formation of South China (Zhan *et al*. 2007), a characteristic biofacies for upper offshore environments.

Gerd-Kuh Member
[new]

Derivation of name. – The name refers to the Gerd-Kuh Inlier, northwest of Damghan, where the stratotype is located.

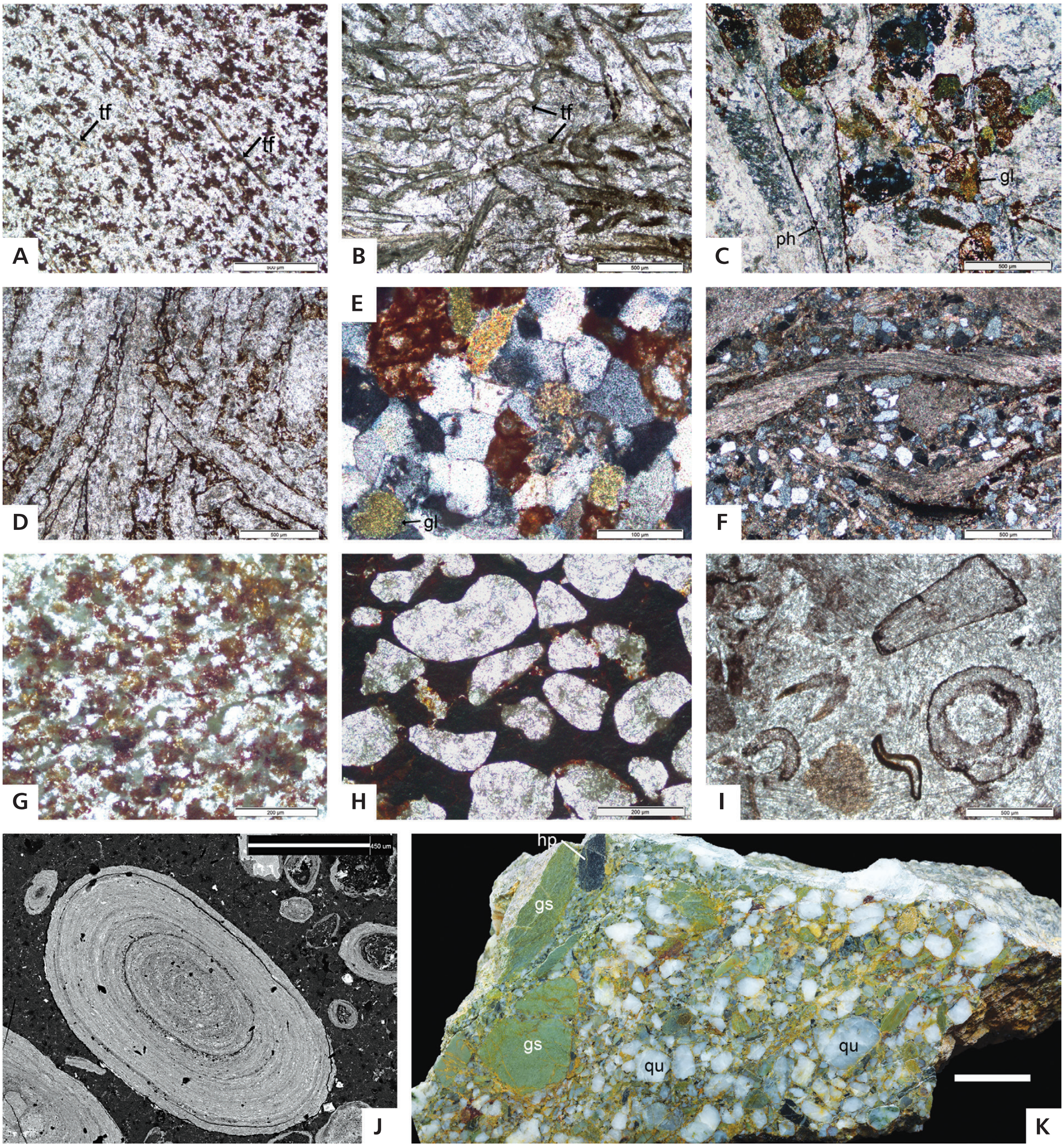


Figure 7. A – plane-polarised light photomicrograph of siltstone with numerous phosphatic grains and trilobite fragments (tf), Simeh-Kuh Formation, unit S1, 6.51–6.68 m from the base (Fig. 6) at Simeh-Kuh. • B – plane-polarised light photomicrograph of bioclastic limestone with numerous trilobite fragments (tf) from the Simeh-Kuh Formation, unit S2, upper limestone bed (Fig. 6) at Simeh-Kuh. • C – plane-polarised light photomicrograph of impure bioclastic limestone with glauconitic grains (gl) and phosphatic veneer (ph) on bioclast surface from the Simeh-Kuh Formation, unit S6, uppermost 0.05 m (Fig. 6) at Simeh-Kuh. • D – plane-polarised light photomicrograph of brachiopod shell bed from lower carbonate unit of the Qumes Formation, unit Q1 (Fig. 6) at Simeh-Kuh. • E – plane-polarised light photomicrograph of mature, fine-grained quartzose sandstone with glauconite from the Gerd-Kuh Member, unit Q2 (3.2 m above the base of the unit) at Simeh-Kuh. • F – plane-polarised light photomicrograph of bioclastic, sandy glauconitic limestone from the Qumes Formation, unit Q8 (1.80–1.88 m above the base of the unit) at Simeh-Kuh. • G – plane-polarised light photomicrograph of siltstone with iron oxide and chloritic cements from the Raziabad Member at Gerd-Kuh. • H – plane-polarised light photomicrograph of supermature, coarse grained quartzose sandstone with iron oxide cement from the Gerd-Kuh Member, upper part of unit 13 (Fig. 6). • I – plane-polarised light photomicrograph of echinoderm limestone from the Tatavrud Formation at Tatavrud. • J – SEM photomicrograph of chamosite ooids from oolitic ironstone bed of the Hajiabad Member (unit L22) at Simeh-Kuh showing well preserved fine lamination. • K – polished surface of conglomerate bed at the base of the Polekhavand Formation with reworked green schist matrix. Abbreviations: gl – glauconitic grains; gs – green schist clast; hp – high preasure metamorphic rock clast; ph – phosphatic veneer; qu – quartz clast; tr – trilobite fragments. Scale bars: 500 μm (A–D, I); 100 μm (E); 200 μm (G, H); 450 μm (J); 2 cm (K).

Stratotype. – Natural exposure along the eastern side of an unnamed dry creek confined to the southeastern slope of Gerd-Kuh (Figs 5B, 6; units G1–G2). The geographical coordinates are 36° 09′ 49″ N, 54° 09′ 51″ E. The description of the stratigraphical interval was detailed in Popov & Cocks (2017: p. 3, fig. 2; units U13–14).

Lithology. – The Gerd-Kuh Member is siliciclastic and comprises bedded quartzose to subarkosic sandstones (Fig. 7H) with horizontal and low angle cross-laminae, and subsidiary siltstones. Infrequent presence of glauconite grains is characteristic (Fig. 7E). Rhynchonelliform brachiopod shell beds, 0.05–0.30 m thick, occur sporadically. The presence of broken obolid shells is characteristic, as well as occasional bioaccumulations rich in well-preserved disarticulated valves of the large obolid *Thysanotos multispinulosus* Popov *et al*., 2008 forming shell pavements on bedding surfaces (Fig. 8B).

Boundaries. – In the type section, the unconformably Simeh-Kuh/Gerd-Kuh contact is marked by a sharp, uneven surface encrusted with hematite and, locally, capped by a breccia bed about 0.05 m thick. At Simeh-Kuh, the base of the member is apparently conformable, placed on the top of a limestone bed named unit Q3 (Fig. 6). The Gerd-Kuh Member is conformably overlain by the Raziabad Member (Fig. 8A).

Distribution and age. – The Gerd-Kuh Member is restricted to the Gerd-Kuh (up to 16 m thick) and Simeh-Kuh (up to 18 m thick) inliers, northwest of Damghan city. Its Floian age is supported by the occurrence of the brachiopods *Leptembolon* sp., *Thysanotos multispinulosus* Popov *et al*., 2008, *Martellia* sp., *Yangtzeella longiseptata* Ghobadi Pour *et al*., 2011c and conodonts of the *Prioniodus elegans* and *Oepikodus evae* zones (Fig. 6; Tab. 1) (Popov *et al*. 2008, Ghobadi Pour *et al*. 2011c).

Depositional environments. – The Gerd-Kuh Member was deposited on a shallow shelf, probably varying from coastal-plain to shoreface and upper offshore settings. Episodes of high energy are supported by disarticulation and broken preservation of linguliform and rhynchonelliform brachiopod shells. The outer walls

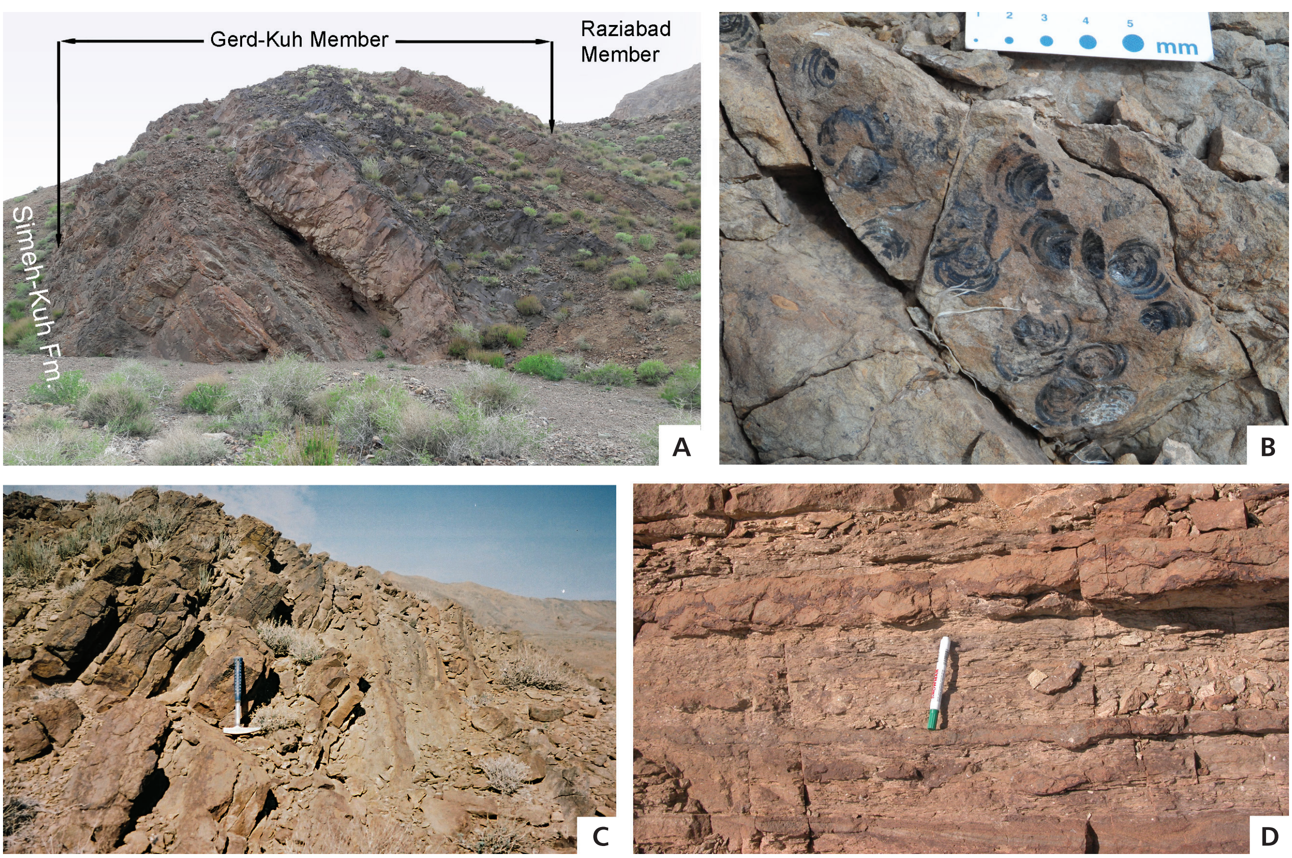


Figure 8. A – westerly view of the exposure of the Gerd-Kuh member at Gerd-Kuh. • B – shell pavement on the sandstone bedding surface formed by bioaccumulations of well-preserved disarticulated valves of the large obolid *Thysanotos multispinulosus* Popov *et al*., 2008, Gerd-Kuh Member at Simeh-Kuh. • C, D – bedded limestones of unit Q8 in the upper part of the Qumes Formation; C – general view of exposure; D – close up view showing limestone and argillite intercalations.

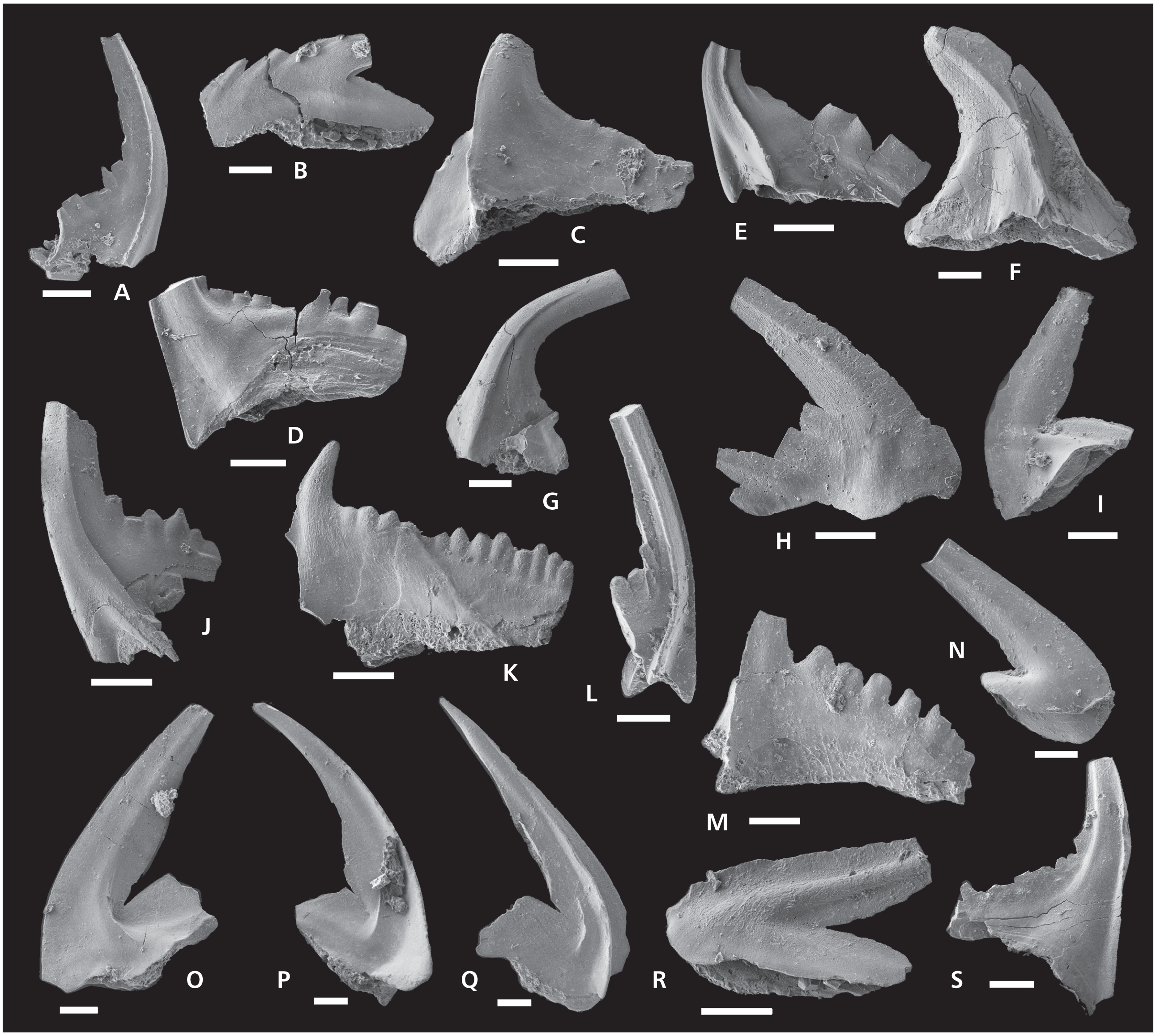


Figure 9. Selected conodont elements characteristic of *Prioniodus elegans* to *Oepikodus evae* zones from the Qumes Formation, Simeh-Kuh section, eastern Alborz Mountains, Northern Iran. Scale bars are 0.1 mm. • A, J, L – *Gothodus* cf. *costulatus* (Lindström, 1955); A – M element, sample SK-3/4; J – Sc element, sample SK-3/14; L – Sb element, sample SK-3/15. • B – *Bergstroemognathus extensus* (Graves & Ellison, 1941), P element, sample SK-3/4. • C, M, S – *Baltoniodus* aff. *triangularis* (Lindström, 1955); C – Pa element, sample SK-3/14; M – Pa element, sample SK-3/15; S – S element, sample SK-3/19. • D, F, G, J – *Gothodus costulatus* Lindström, 1955; D – S element, SK-3/12; F – M element, sample SK-3/12; G – M element, sample SK-3/13; J – Sc element, sample SK-3/14. • E – *Trapezognathus diprion* (Lindström, 1955), Pb element, sample SK-3/13. • H, I – *Periodon flabellum* (Lindström, 1955); H – Pa element, sample SK-3/12; I – M element, sample SK-3/13. • N – *Drepanoistodus contractus* (Lindström, 1955), S element, sample SK-3/15. • O–Q – *Oistodus lanceolatus* Pander, 1856, S elements, sample SK-3/19. • R – *Drepanoistodus forceps* (Lindström, 1955), M element, sample SK-3/19.

of some *Thysanotos multispinulosus* shells, relatively abundant, exhibit a characteristic microornament of alternating semicylindroid and hemispherical pits; this pattern is explained as the result of periodic dehydration of the periostracum due to subaerial exposure *in vivo* at a time of low tides (Artyushkov *et al*. 2000, Popov *et al*. 2008: fig. 6i–k). Characteristic bioaccumulations of disarticulated valves of *Thysanotos multispinulosus* were probably covered on a beach by sediment during storm events. According to observations on recent lingulides living within sandy shoals, their valves disintegrate in a matter of weeks due to mechanical abrasion, hydrolysis and bacterial disintegration of the organic components that form the shell (Emig 1997). The rhynchonelliform brachiopod shell beds from the upper part of the Gerd-Kuh Member likely represent event concentrations formed at lower shoreface to upper offshore settings.

Raziabad Member
[new]

Derivation of name. – The name refers to Raziabad village, situated at the proximity of the Gerd-Kuh Inlier, northwest of Damghan city, where the type section of the unit is located.

Stratotype. – Natural exposure at the southeastern foothills of Gerd-Kuh (Figs 5B, 6; unit R1). Geographical coordinates for the base of the member are 36° 09′ 48″ N, 54° 09′ 49″ E. The description of the stratotype is detailed in Popov & Cocks (2017: p. 3, fig. 2; unit U15).

Lithology. – The unit mainly consists of homogeneous, bedded greenish-grey sandy siltstones with iron oxide and chloritic cements (Fig. 7G), up to 11.8 m thick. Brachiopod shell pavements are relatively common on bedding surfaces.

Distribution and age. – The member is restricted to the Gerd-Kuh Inlier, northwest of Damghan city. The unit contains a low diversity of rhynchonelliform brachiopods (Popov & Cocks 2017), represented mostly by endemic taxa (e.g. *Dirafinesquina*, *Leptastichidia*? and *Martellia*) characteristic of the Middle Ordovician. Its late Floian to Dapingian age is based on conodonts representative of the *Oepikodus evae* to *Baltoniodus navis* zones (Figs 6, 9), and the stratigraphical position between the Gerd-Kuh Member (containing Floian brachiopods and conodonts) and the Lashkarak Formation (bearing a distinctive Darriwilian fossil record at the base; Ghobadi Pour *et al*. 2011a, Popov *et al*. 2016, Ghobadi Pour 2019). The occurrence of *Paralenorthis* cf. *suriensis* Benedetto, 2003, provisionally assigned to the species, which was originally described from the upper member of the Suri Formation (*Oepikodus evae* Zone, latest Floian Stage) in the Famatina Range of northwest of Argentina, may indicate a Floian age at least for the lower part of the unit. The member has a conformable contact with the underlying sandstones of the Gerd-Kuh Member and is unconformably overlain by the Lashkarak Formation.

Depositional environments. – The shaly sediments of the Raziabad Member were deposited in a quiet, well-oxygenated environment, probably slightly below the seasonal storm wave base (Popov & Cocks 2017). Brachiopod shells are common in the unit, while trilobites and echinoderms are extremely rare. They are preserved mainly as disarticulated valves without traces of significant abrasion and cracking. Disarticulated brachiopod valve concentrations on bedding surfaces reflect condensation levels.

Remarks. – The Raziabad Member is a lateral equivalent of the upper carbonate units Q8 and Q9 of the Qumes Formation at Simeh-Kuh (Fig. 6). It differs from the Qumes Formation in lacking carbonates, probably as a result of its palaeogeographically distal position from the major source of bioclastic material.

Lashkarak Formation
[formalised by Gansser & Huber 1962; emended by Ghobadi Pour *et al*. 2011b]

Stratotype. – A natural outcrop at Alam-Kuh (36° 20′ 07″ N, 50° 58′ 52″ E), Takht-e Soleyman Massif, Lashkarak Mountains, western Alborz Mountains, northwest of Tehran (Figs 1, 10), described by Gansser & Huber (1962); see also discussion by Ghobadi Pour *et al*. (2011a).

Notes on the formation name. – Both ‘Lashkarak’ and ‘Lashkerak’ toponymies are in use and both are applicable. However, we select the former because the latter spelling is based on a local dialect.

Members. – The Lashkarak Formation includes the Cheshmeh-Ali and Hajiabad members.

Lithology. – The Lashkarak Formation is mainly siliciclastic and contains thin interbeds of bioclastic limestones in the lower part and a distinctive oolitic ironstone bed in the middle or upper part.

Boundaries. – The base of the Lashkarak Formation is sharp, unconformable with various Ordovician units in eastern Alborz (Fig. 10). In the type area, northwest of Tehran, it rests on an unnamed, presumably Furongian unit of quartzose sandstones. The top of the Lashkarak Formation is overlain disconformably by the Abarsaj Formation.

Distribution and age. – In western Alborz, the Lashkarak Formation is exposed between Alam-Kuh and the Chalus road, and also probably to the northwest of Fashand (Fig. 1). Farther east, it crops out on the southern foothills of eastern Alborz between Gerd-Kuh and Siaheh Mountains, east of the road connecting Shahrud and Azadshahr cities (Fig. 2). The Darriwilian age of the lower part of the Lashkarak Formation (Cheshmeh-Ali Member) is constrained by conodonts (Nestell *et al*. 2016), trilobites and brachiopods (Ghobadi Pour *et al*. 2011a), while the upper part (Hajiabad Member) contains Darriwilian brachiopods and trilobites (Ghobadi Pour *et al*. 2011a, Popov *et al*. 2016, Kebria-ee Zadeh *et al.* 2017, Ghobadi Pour 2019). The thickness of the Lashkarak Formation at the type section is about 35 m, at Gerd Kuh and Simeh-Kuh it approaches 100 m, while at Deh-Molla it is up to 34 m.

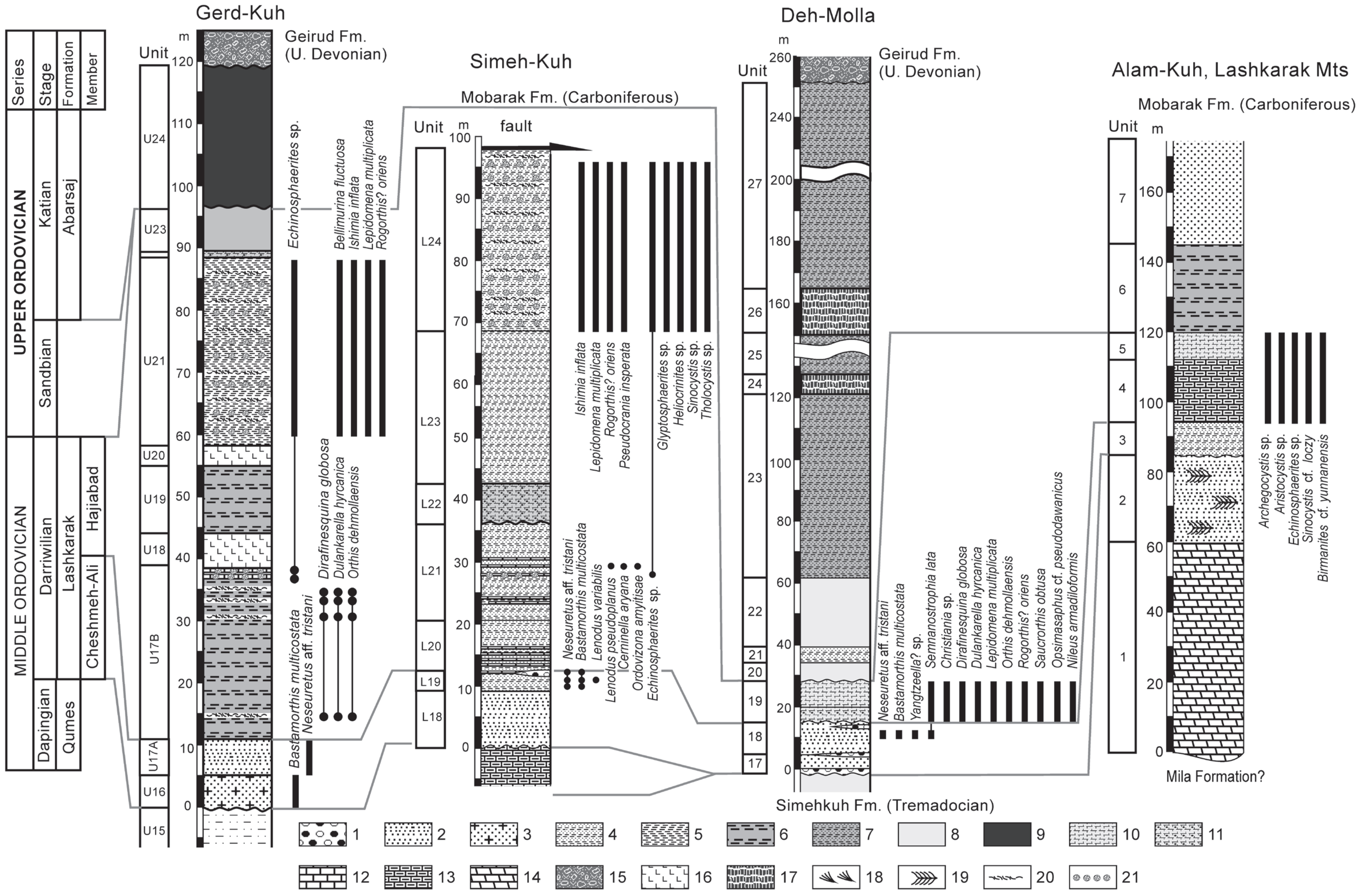


Figure 10. Stratigraphical logs of main Ordovician (Darriwilian to Hirnantian) sections of the Lashkarak and Abarsaj formations at the eastern Alborz Mountains and stratigraphical log of its type section of the Lashkarak Formation at Alam-Kuh showing stratigraphical distribution of selected trilobite, ostracod, conodont, brachiopod and echinoderm species. Lithologies: 1 – conglomerates; 2 – sandstones; 3 – arkosic sandstones; 4 – sandstone/shale interbeds; 5 – siltstones and argillites; 6 – siltstones; 7 – sandstone, siltstone and argillite intercalations; 8 – green and light grey argillites; 9 – black shales; 10 – calcareous siltstones and argillites; 11 – oolitic ironstones; 12 – limestones; 13 – argillaceous limestones; 14 – dolomites; 15 – agglomerate tuffs; 16 – diabase sills; 17 – basalt and basalt volcanics; 18 – cross lamination; 19 – *Cruziana* trace fossils; 20 – brachiopod shell beds; 21 – echinoderm thecae accumulations.

Depositional environments. – The deposition of the Lashkarak Formation commenced in the early Darriwilian onlapping a previous unconformity (gap), probably related to rifting uplift and tilting throughout a horst and graben palaeotopography (Álvaro *et al*. 2022). Quartzose to subarkosic sandstones and associated shell beds of the Cheshmeh-Ali Member, at the lowermost part of the unit, represent shoal complexes, while the succeeding fine siliciclastic deposits of the Hajiabad Member include characteristic echinoderm shell and oolitic ironstone beds developed across the shoreface-offshore transition.

Remarks. – For a long time, the Lashkarak Formation was considered a Lower Ordovician unit, representing, at least partly, a stratigraphical equivalent of Member 5 of the Mila Formation. Ghobadi Pour *et al*.'s (2011b) revision of the Darriwilian stratigraphy in eastern Alborz demonstrated that the Lashkarak Formation, as originally designated by Gansser & Huber (1962), could not be earlier than Darriwilian, while the early Tremadocian age of the uppermost part of the Mila Member 5 (Absharaf Member after Álvaro *et al.* 2022), originally suggested by Stöcklin *et al*. (1964), was convincingly demonstrated by Kebria-ee Zadeh *et al*. (2015).

Bayet-Goll & Neto de Carvalho (2017) have recently provided a detailed sedimentological description of some Lower Palaeozoic sediments in the Shahmirzad area assigned to the Lashkarak Formation. However, no biostratigraphical evidence of an Ordovician age for the described sedimentary rocks was presented. There are no Ordovician deposits preserved in the Shahmirzad area and there is no Lashkarak Formation exposed according to our field observations. The siliciclastic succession described in the cited publication may belong to the stratigraphical equivalent of the upper part of the Sah Member (Mila Member 4), as defined in the type area at Mila Kuh (Álvaro *et al*. 2022).

Cheshmeh-Ali Member

[new]

Derivation of name. – The name refers to the Cheshmeh-Ali river, east of the Simeh-Kuh area where the type section of the unit is located.

Stratotype. – Natural exposure at Simeh-Kuh, 13 km northwest of Damghan city (Figs 2, 10). A detailed updated log of the succession was illustrated by Ghobadi Pour *et al*. (2011b: units L18–L19). The geographical coordinates for the base of the member are 36° 12′ 47.6″ N, 54° 13′ 25″ E, at 1429 m altitude above the sea level.

Lithology. – The unit comprises brown, fine- to medium-grained, arkosic sandstones with horizontal and cross stratification. They include poorly preserved disarticulated and often decalcified brachiopod valves forming several thin shell beds in the lower part, and fine-grained sandstone and siltstone interbeds in the upper part. The presence of impure bioclastic limestone interbeds, up to 0.25 m thick and rich in disarticulated valves of *Bastamorthis multicostata* Ghobadi Pour *et al*., 2011b, is characteristic in the upper part of the unit. Lenticular channels of polymictic pebbly conglomerates with sandy matrix, 0.25–1.0 m thick, occur sporadically in the lower and middle parts of the member, and are most characteristic for the Deh-Molla area.

Boundaries. – The base of the member is sharp, unconformably overlying both the Simeh-Kuh Formation in the Deh-Molla area, and the Qumes Formation to the northwest of Damghan city. The upper contact with the Hajiabad Member is transitional in the Gerd-Kuh and Simeh-Kuh inliers.

Distribution and age. – The Cheshmeh-Ali Member is exposed discontinuously along the southern foothills of the eastern Alborz Mountains, between Gerd-Kuh and Shahrud. The thickness of the unit is up to 9.8 m at Gerd-Kuh, 21.2 m at Simeh-Kuh and 17.3 m at Deh-Molla (Fig. 10). Its age is based on the occurrence of conodonts belonging to the lower Darriwilian *Lenodus variabilis* Zone at Simeh-Kuh (Nestell *et al*. 2016) and the trilobite *Neseuretus* aff. *tristani* (Brongniart, 1817) *in* Desmarest (1817) (Ghobadi Pour *et al*. 2007b, 2011b; Ghobadi Pour 2019). The low-diversity rhynchonelliform brachiopods described by Ghobadi Pour *et al*. (2011b) from this member are mostly endemic to the area.

Depositional environments. – The Cheshmeh-Ali Member represents a remnant of shoal complexes. The proliferation of the *Neseuretus* trilobite Association may suggest a considerable early Darriwilian cooling in the region (Fortey & Morris 1982, Ghobadi Pour *et al*. 2007b, Ghobadi Pour 2019).

Hajiabad Member

[new]

Derivation of name. – The name refers to Hajiabad-Razi village, situated at the proximity of the Gerd-Kuh Inlier, northwest of Damghan, where the type section of the unit is located.

Stratotype. – The stratotype is situated on the eastern foothills of Gerd-Kuh (Figs 2, 10). A detailed updated log of the succession was illustrated by Popov & Cocks (2017: pp. 3–5, fig. 2, units 17B–23). The geographical coordinates for the base of the section are 36° 9′ 50″ N, 54° 9′ 49″ E.

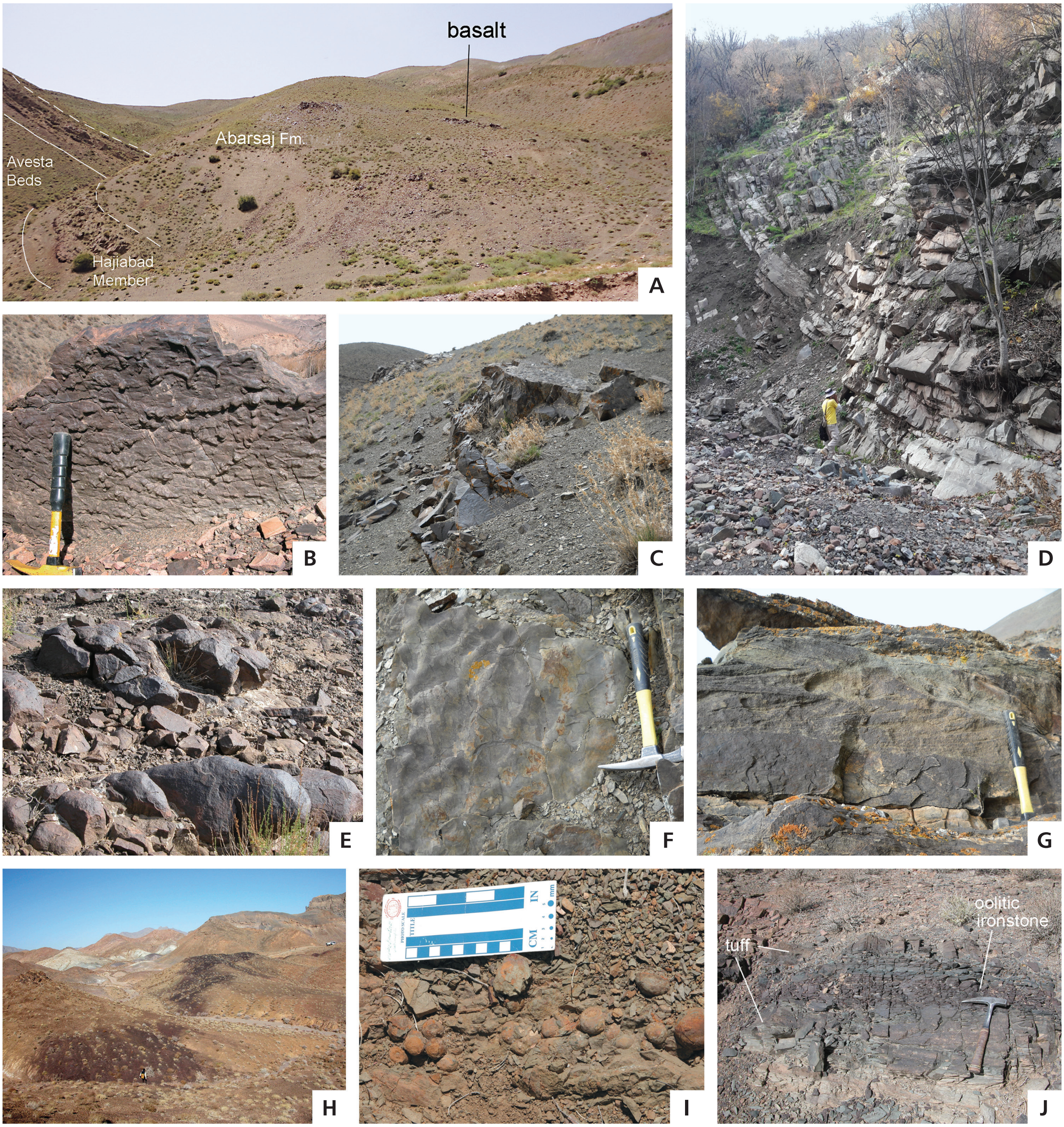


Figure 11. A – westerly view of the exposure of the Hajiabad Member (Lashkarak Formation) and the Abarsaj Formation on the west side of the Avesta river valley. • B – trace fossils on the sandstone bedding surface, Abarsaj Formation at Deh-Molla. • C – unit of basalts in the middle part of the Abarsaj Formation exposed on the west side of the Avesta river valley. • D – exposure of siliciclastic turbidites of the Abarsaj Formation at Kholin-Darreh. • E – pillow basalts in the middle part of the Abarsaj Formation at Deh-Molla. • F – wave-formed ripple marks on the sandstone bedding surface, Avesta Beds, west side of the Avesta river. • G – sandstones with bidirectional cross lamination, Avesta Beds, west side of the Avesta river. • H – exposure of oolitic ironstones of the Hajiabad Member (unit L22) at Simeh-Kuh. • I – bed of *Echinosphaerites* limestone in the Hajiabad Member (upper part of unit 17B) at Gerd-Kuh. • J – a bed of oolitic ironstone sandwiched between two layers of tuff (unit 22) at Gerd-Kuh.

Lithology. – This heterolithic unit comprises mainly siltstones intercalated with subsidiary fine-grained sandstones and a few decimetre-scale beds of argillaceous and bioclastic limestones (Fig. 10). A characteristic feature of the Hajiabad Member is the presence of an oolitic ironstone bed, up to 7 m thick at Simeh-Kuh, and locally mined as a source of iron (Fig. 11H). At Gerd-Kuh, a bed of oolitic ironstone, about 0.10 m thick, is sandwiched between two tuff layers, 0.35 m and 0.15 m thick respectively (Fig. 11J), but no other tuffs occur eastwards. Only in the Abarsaj area, 16 km north of Shahrud, the oolitic ironstone bed, about 1.2 m thick, is overlain by a 2 m thick layer of greenish tuffs (Fig. 11A). The ooids show well-preserved fine concentric laminae, mostly composed of chamosite (Fig. 7J). Only at Deh-Molla a significant proportion of ooids is made of goethite and hematite. Cores of ooids are bioclasts, fragments of ooids, quartz and occasional feldspar grains. The matrix varies from highly argillaceous to calcareous argillite. Clay minerals are represented by montmorillonite and illite. In addition to ooids the fraction > 20 μm is dominated by bioclasts, mostly fragments of brachiopod shells and echinoderm ossicles, although the fraction < 20 μm is dominated by quartz and feldspar (orthoclase), also includes zircon, anatase, occasional fluorapatite and rutile. Glauconitic peloids are recorded only at the Abarsaj section.

Boundaries. – The Cheshmeh–Ali/Hajiabad contact is conformable at the sections northwest of Damghan city and paraconformable at the Deh-Molla and probably Abarsaj areas. The upper contact with the Abarsaj Formation is disconformable. At Simeh-Kuh, the upper contact is faulted.

Distribution. – The Hajiabad Member is invariably present in all exposed sections of the Lashkarak Formation studied between Gerd-Kuh and Abarsaj. Its maximum thickness is 89.2 m at Gerd-Kuh and decreases down to 16.6 m at Deh-Molla.

Depositional environments. – The sediments of the Hajiabad Member were deposited in lower shoreface to upper offshore environments. Distinct bioaccumulations and centimetre-scale *Echinosphaerites* beds, characterized by complete echinoderm thecae, are traceable across the area northwest of Damghan city (Fig. 11I). They are associated with a significant proportion of brachiopods preserved as articulated shells (Popov *et al*. 2016) suggesting calm substrates below fair wave base. Oolitic ironstones most probably developed under wave influence, in high-energy shoreface-dominant environments (Sturesson *et al*. 1999). The ironstone bed at Deh-Molla is characterised by a calcareous-argillaceous matrix, while the brachiopod shells often occur articulated and complete echinoderm thecae are common. An oolitic ironstone bed at Simeh-Kuh, 6 m thick (Fig. 11N), is probably the remnant of a progradational shoreface-to-upper offshore bar. A close association of oolitic ironstones with basic volcanic tuffs at Gerd-Kuh, Deh-Molla and Abarsaj, the ubiquitous presence of zircons, which often occur as angular (so reworked) crystals, and iron silicates suggest that strongly reworked volcanic ash falls were the original source of iron for the ooids, which is in agreement with the model of the volcanic origin of some oolitic ironstones proposed by Sturesson *et al*. (2000).

Remarks. – Oolitic ironstones of the Hajiabad Member are time-specific upper Darriwilian lithofacies, which can be traced widely across northern Iran (Alborz, Kopet-Dagh) and the Anarak Region of Central Iran (Popov *et al*. 2015).

Abarsaj Formation
[formalised]

Stratotype. – The natural exposure is on both sides of the Avesta river valley west of Abarsaj village in the Shahvar Mountains (Figs 2; 11A, C). The geographical coordinates for the base of the section are 36° 33′ 54″ N, 54° 52′ 13″ E. The Upper Ordovician deposits, allegedly more than 460 m thick exposed in the area, were briefly characterised by Ghavidel-Syooki & Khandabi (2013), who assigned them to the Ghelli Formation.

Lithology. – The Abarsaj Formation comprises alternating fine-grained sandstones and olive-green to dark grey shales (Fig. 11D) that episodically exhibit abundant ichnofossils on the bedding planes (Fig. 11B). Occasional units of basalts occur interbedded in the middle and upper part of the member (Fig. 11C, E).

Boundaries. – The base of the Abarsaj Formation at the type section is marked by a sandstone bed (about 3 m thick), which overlies a tuff (2 m thick) that subsequently overlies the Hajiabad oolitic ironstone bed (Fig. 11A). The base of the Abarsaj Formation coincides with a major flooding surface and it is probably paraconformable, because the Acritarch Assemblage VIII of Ghavidel-Syooki & Khandabi (2013) from a fossiliferous sample collected *c*. 20 m above the Abarsaj Formation base, contains *Baltisphaeridium longispinosum* (Eisenack, 1931), *Multiplicisphaeridium bifurcatum* Staplin, Jansonius & Pocock, 1965 and *Multiplicisphaeridium irregulare* Staplin, Jansonius & Pocock, 1965. According to Vecoli & Le Herissé (2004), this assemblage makes its first appearance throughout the Mediterranean margin of Gondwana in the *Euconochitina tanvillensis* chitinozoan Zone (earliest Katian). The same is apparently true for the base of the Abarsaj Formation in the Deh-Molla area (Ghavidel-Syooki 2006). In the vicinity of Kholin-Darreh village, the Abarsaj Formation unconformably overlies a Lower Ordovician siliciclastic unit, sometimes informally named the Abastu Beds (= Avesta Beds), while the age of the lowermost part of the member is not later than the *Armoricochitina nigerica* chitinozoan Zone (Ghavidel-

Syooki 2017a). The top of the Abarsaj Formation is unconformable and also diachronous with either the Silurian Soltan-Maidan Formation (Fig. 18G) or the Upper Devonian Geirud Formation.

Distribution and age. – In eastern Alborz, the Abarsaj Formation is best preserved north of the Shahrud Fault (Figs 2–3). South of the fault, the most complete section of the Abarsaj Formation is documented at Deh-Molla where it exceeds 210 m in thickness. At the Gerd-Kuh Inlier, the Abarsaj Formation is represented by dark grey argillites, 25 m thick, unconformably overlain by the tuff agglomerates of the Upper Devonian Geirud Formation. At the Lashkarak section in Alam-Kuh, two uppermost units represented by *c*. 25 m of grey, silty argillites and *c*. 30 m of sandstones can be provisionally assigned to the Abarsaj Formation; however, they are barren and their Ordovician age cannot be confirmed with certainty. The Katian age of the Abarsaj Formation at the type section is confirmed by acritarchs, and by the occurrence of chitinozoans from the *Ancyrochitina merga* Zone in the uppermost part of the member (Ghavidel-Syooki & Khandabi 2013). At Kholin-Darreh, the topmost beds of the Abarsaj Formation contain Hirnantian chitinozoans characteristic of the *Tanuchitina elongata* and *Spinachitina oulebsiri* zones (Ghavidel-Syooki 2017a).

Depositional environments. – Deposition of the Abarsaj Formation occurred in a basinal environment at a time of general drowning in the eastern Alborz area during Katian–Hirnantian times, resulting in increased rates of accommodation space and higher influx of fine siliciclastic sediments (Álvaro *et al*. 2022, Fig. 17). Occasional basalt and basalt lava flows, intebedded in the Abarsaj Formation, represent the prelude of an extensive late Katian–Silurian rifting volcanism (Soltan-Maidan Formation) in the eastern Alborz (Derakhshi & Ghasemi 2015; Derakhshi *et al*. 2017, 2022; Álvaro *et al*. 2022).

Remarks. – The Abarsaj Formation was first named as a formation on the 1:250,000 map sheet of Gorgan (Shahrabi 1991) and later in an abstract (Shahrabi 1992) focused on the upper part of the Ordovician succession exposed in the Shahvar and Siaheh Mountains, north and northwest of Shahrud (Fig. 2). However, the unit was never formalised and subsequently not formally applied to the Upper Ordovician of the Alborz Mountains. These sediments were usually assigned to the Ghelli Formation (Ghavidel-Syooki 2006, Ghavidel-Syooki *et al*. 2011). Recently, Ghavidel-Syooki (2017a) assigned an Upper Ordovician succession of 194 m in the vicinity of Kholin-Darreh village to the Abarsaj Formation, and proposed the Shahvar Mountains (E in Fig. 2) as the type area for the unit.

Avesta Beds [= Abastu Beds]

[Abastu Formation in Shahrabi (1991, 1992), Ghavidel-Syooki (2017a)]

Remarks. – The "Abastu Formation" was originally established by Shahrabi (1991, 1992), but the designation was informal and the spelling incorrect. The name was probably derived from the Avesta river. According to the original description, it included a carbonate unit at the base of the section exposed at the headwaters of the Avesta river gorge (E in Fig. 2) and the overlying siliciclastic unit of intercalating quartzose sandstones and shales with glauconite and obolid brachiopod fragments, *c*. 65 m thick. Unlike the Simeh-Kuh Formation, sandstone units often exhibit bidirectional cross lamination (Fig. 11G) and fair weather wave ripple marks (Fig. 11F), suggesting deposition in a tidally influenced, shoreface environment.

Our field observations confirmed that the limestone unit, exposed in the anticline core of the Shahvar Mountains, contains Furongian trilobites, while the siliciclastic unit on its northern flank contains Tremadocian acritarchs (Ghavidel-Syooki & Khandabi 2013). The limestone unit is provisionally assigned here to Member 4 of the Mila Formation. The Cambrian–Ordovician boundary is placed somewhere within the siliciclastic unit, but its precise position cannot yet be defined. Nevertheless, the term can be used provisionally as the Avesta Beds, in application to the siliciclastic units at the base of the Ordovician succession in northeastern Alborz, including the areas north of the Shahrud Fault (Fig. 3). In particular, a similar siliciclastic unit with Tremadocian acritarchs appears in the Ordovican of Kholin-Darreh, where it was recognised as the "Abastu Formation" (Ghavidel-Syooki 2017a).

The "Abastu Formation" appears in the Furongian–Upper Ordovician succession of the Abarsaj area illustrated by Bogolepova *et al*. (2014: fig. 2). However, the lithology shown in that publication, *e.g*. more than 100 m-thick carbonates including stromatolitic limestones with a basaltic bed at the base, is absent in the area (Ghavidel-Syooki & Khandabi 2013; and our field observations). Moreover, there is no comparable Lower to Middle Ordovician section presently known in the entire Alborz Mountains. While the Darriwilian age of the cephalopods described in Bogolepova *et al*. (2014) is likely, the whereabouts of the source area remain uncertain.

Talesh Mountains

In northwest Iran, the Talesh Mountains contain some Ordovician exposures, west of Rasht, in a small area between Aliyan-Rud, Tatavrud, Kolur and Rude-Qurubars

(Masuleh), east of Tatavrud village (Fig. 1). The Ordovician succession of the Talesh Mountains was firstly documented by Clark *et al*. (1975), while a rich Late Ordovician trilobite fauna was subsequently monographed by Karim (2009). Based on previous publications and personal field observations, the Upper Ordovician deposits of the Talesh Mountains are here assigned to the newly designated Tatavrud Formation.

Tatavrud Formation
[new]

Derivation of name. – The name refers to the Tatavrud village situated close to the type section.

Stratotype. – Natural exposure on the eastern side of Tatavrud valley, southeast of the homonymous village. The geographical coordinates are 37° 15′ N, 49° 11′ E.

Lithology. – The Tatavrud Formation represents a condensed succession of reddish bedded bioclastic limestones.

Distribution and age. – The Tatavrud Formation has a restricted distribution in Masuleh, Kolur valley and the Talesh Mountains, 35 km southwest of Bandar-e Anzali along the Caspian Sea coastline (Fig. 2). It is 40 m thick in the best documented section southeast of Tatavrud village. The age of the formation, based on conodonts and trilobites, is most probably Katian; however, a late Sandbian age cannot be excluded for its lower part (Fig. 4). The age of the unit is supported by the occurrence of a rich trilobite fauna including 19 genera, such as *Amphoriops*, *Birmanites*, *Cyclopyge*, *Dicranopeltis*, *Eccoptochile*, *Geragnostus*, *Illaenus*, *Lichas*?, *Metopolichas*, *Mezzaluna*, *Nileus*, *Ovalocephalus*, *Panderia*, *Panarchaeogonus*, *Parisoceraurus*, *Phorocephala*, *Symphysops*, *Sphaerexochus* and *Trinodus* (Karim 2009). There is a reported occurrence of *Ovalocephalus* cf. *tetrasulcatus* (Kielan, 1960), a biostratigraphically significant trilobite taxon (Zhou *et al*. 2009), together with *Phorocephala* cf. *ulugtana* (Petrunina, 1975) *in* Repina *et al*. (1975), *Panderia* cf. *curta* Petrunina, 1975 *in* Repina *et al*. (1975) and *Birmanites* cf. *asiaticus* Petrunina, 1975 *in* Repina *et al*. (1975) (provisionally assigned to the species described by Petrunina *in* Repina *et al*. 1975), from the Upper Ordovician of the *Kielanella–Tretaspis* beds (Katian) at the Turkestan-Alai Region. A small conodont fauna recovered from the Tatavrud Formation (Männik personal communication 2018) includes *Drepanoistodus*? sp. and *Scabbardella* cf. *altipes* (Henningsmoen, 1948) (Fig. 12A–F).

Boundaries. – In the type section, the reddish bioclastic limestones of the Tatavrud Formation rest unconformably on an unspecified unit of spilitic volcanic rocks, which are underlain by barren reddish arkosic sandstones. No reliable evidence to date the underlying units is presently available. The Tatavrud Formation is succeeded by Silurian cephalopod-bearing limestones showing evidence of reworked weathered material from the underlying unit, and being patchily conglomeratic at the base (Clark *et al*. 1975). Therefore, the Ordovician–Silurian boundary is considered here as a paraconformable surface.

Depositional environments. – Bedded, bioclastic (packstone to grainstone) limestones of the Tatavrud Formation are rich in disarticulated trilobite sclerites, as well as brachiopod and cephalopod shells and abundant echinoderm and bryozoan fragments. They were probably deposited in lower shoreface to upper offshore environments, somewhat below fair weather wave base. However, due to extensive vegetation and the patchy character of the outcrops, it is difficult to observe lateral facies changes in the Upper Ordovician carbonates through the area.

Remarks. – Clark *et al*. (1975) reported the presence of cephalopods, identified by Kobayashi as *Cycloseras* sp. and *Michelinoceras* sp. and of brachiopods identified by Cocks as *Leptaena* sp., *Ptychoglyptus* sp. and *Sowerbyella* sp. All these identifications require updating.

Kopet-Dagh Region

The Ordovician deposits of the South Kopet-Dagh Region are exposed discontinuously south and southwest of Bojnurd city in the Saluk Mountains, in the Navia Inlier and in the vicinity of Rabat-e Qarabil village (Fig. 1). They are best documented at the Kalat river valley, along the road connecting Bojnurd city to Esfarayen town and north of Ghelli village. The Ordovician deposits in the South Kopet-Dagh Region have been commonly assigned to the Ghelli Formation (*e.g.* Ghavidel-Syooki 2001, 2017b, c). Recent observations on the Ordovician geology of the Saluk Mountains clearly point to a significant palaeogeographical differentiation of the area. In particular, the Lower–Middle Ordovician of the western part of the Saluk Mountains comprises a volcano-sedimentary succession, unlike the eastern part of the area, where the volcanic rocks interfinger with a thick succession of fine siliciclastic rocks with subsidiary limestones, and a few units of basalt volcanic rocks and tuffs. Therefore, the Ghelli Formation can be recognised only in the western part of the Saluk Mountains. The Ordovician strata in other parts of the South Kopet-Dagh Region are assigned to the newly designated Qyzlar and Pelmis formations.

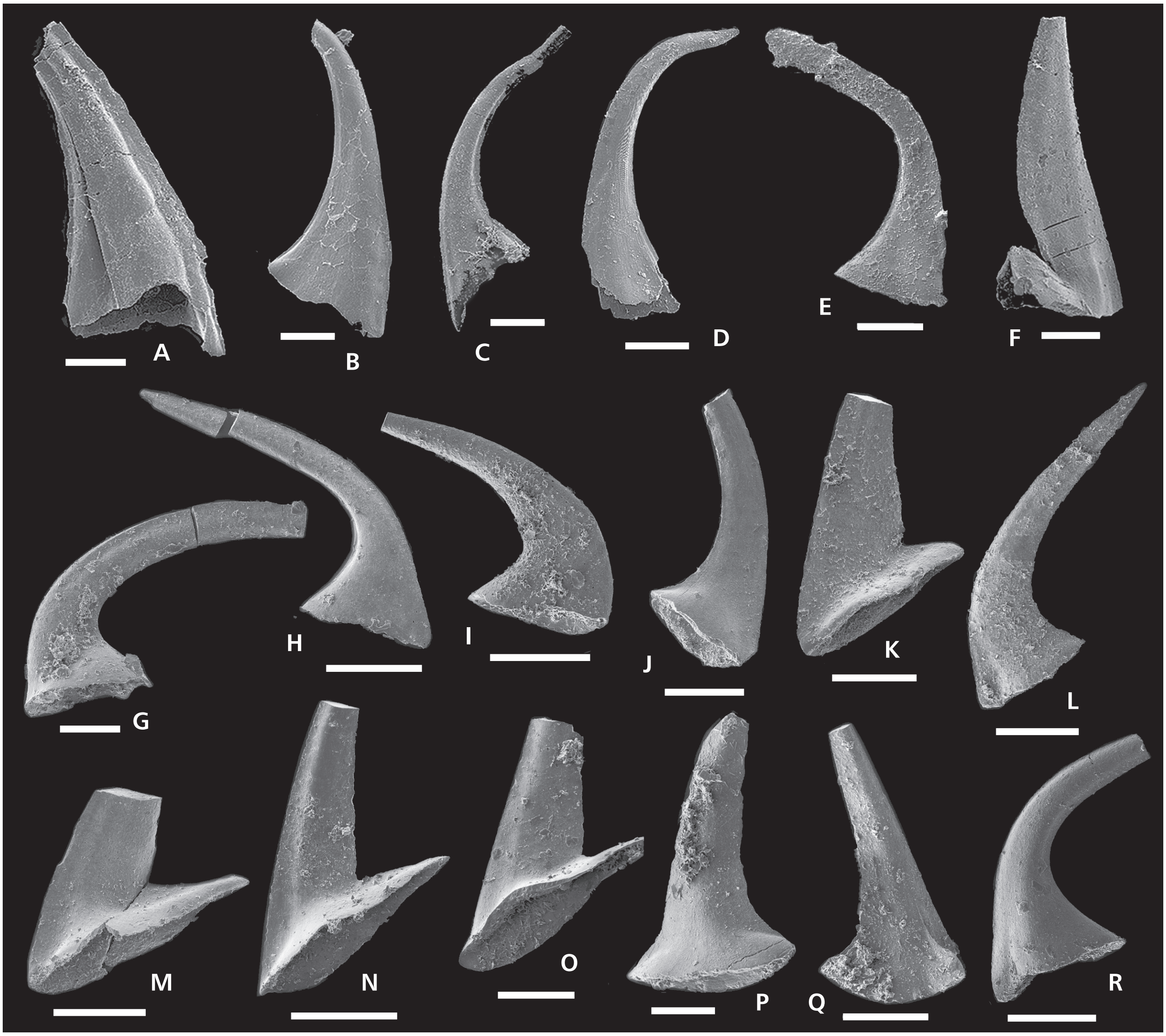


Figure 12. Selected conodont elements from the Tatavrud and Ghelli sections. • A–E – *Scabbardella* cf. *altipes* (Henningsmoen, 1948); A – S element, outer lateral view, sample T-1; B – S element, lateral view, sample T-1; C – S element, lateral view, sample T-1; D – S element, lateral view, sample T-2; E – S element, lateral view, sample T-3. • F – *Drepanoistodus*? sp., M element, posterior lateral view, sample T-1. A–F – Tatavrud Formation, type section, western Alborz, Northern Iran. • G–J – *Drepanoistodus basiovalis* (Sergeeva, 1963), S elements; G – inner lateral view, sample Q-1; H – outer lateral view, sample Q-1; I – inner lateral view, sample Q-2; J – inner lateral view, sample Q-2. • K, L – *Paltodus deltifer pristinus* Viira, 1970, sample Q-1; K – M element, inner lateral view; L – S element, outer lateral view. • M–O – *Paltodus deltifer deltifer* Lindström, 1955, M elements, inner lateral views, sample Q-1. • P–R – *Drepanodus arcuatus* Pander, 1856, sample Q-2; P, Q – Sp elements, inner lateral views; R – Sa element, outer lateral view. G–R – Qyzlar Formation, Ghelli section, Saluk Mountains. Scale bars: 0.2 mm (A–F, H–O, Q–R); 0.1 mm (G, P).

Ghelli Formation

[= Qelli Formation in Ahmadzadeh-Heravi 1983, Afshar-Harb 1979, Ghavidel-Syooki 2017c]

Stratotype. – A natural exposure is along the Ghelli river valley on the southern slopes of the Saluk Mountains. The base of the section is located *c*. 1.5 km upstream of Ghelli village. Geographical coordinates are 56° 55′ 51.80″ E, 37° 11′ 39.82″ N. The latest updated stratigraphical log of the section was given by Ghavidel-Syooki (2017c).

Lithology. – In the type area, the Ghelli Formation is subdivided into three informal members. The lower member is a volcano-sedimentary succession, *c*. 260 m thick, with 20 m of tuff agglomerates succeeded by basaltic volcanic rocks with subsidiary units of argillites, limestones and sandstones, 0.5–20 m thick. The middle member consists of a brownish-red, argillaceous cephalopod limestone, 2 m thick, succeeded by 370 m of graded greenish-grey sandstones and shales, rich in trace fossils, and overlain by *c*. 40 m of sandstones. The upper member, *c*. 410 m thick, comprises an intercalation of sandstones and shales with a few limestone interbeds. According to Ghavidel-Syooki (2017c), there are also two diamictite interbeds and a basaltic unit in the upper part (Fig. 13F).

Distribution and age. – The Ghelli Formation is currently widely applied to a wide spectrum of siliciclastic Middle–Upper Ordovician deposits across northern Iran; however, they invariably have no extensive volcanic unit at the base and diamictites in the upper part, which makes the Ghelli Formation unique to the eastern part of the Saluk Mountains. Some conodonts characteristic of the *Paltodus deltifer* Zone yielded by limestone beds from the topmost part of the Qyzlar Formation in the Ghelli section (Figs 12G–R, 13E) suggest that the age of the lower Ghelli member cannot be earlier than Late Tremadocian. A bed of red cephalopod limestone capping the basalts (Fig. 18F) probably represents a stratigraphical equivalent of the Darriwilian oolitic ironstone and cephalopod limestone beds that mark the base of the Pelmis Formation, exposed at the Kalat valley 40 km east (Evans *et al*. 2021). Siliciclastic rocks of the middle and upper members of the Ghelli Formation show a continuous succession of the chitinozoan *Tanuchitina fistolusa* to *Spinachitina oulebsiri* zones, suggesting a Katian to Hirnantian age. It may suggest also a cryptic disconformity corresponding to the Sandbian Stage on the top of the cephalopod limestone bed (Fig. 3).

Boundaries. – In the type area, the base of the Ghelli Formation, underlying a distinct unit of tuff aglomerates, is conformable with the Qyzlar Formation (Fig. 13E). The top is unconformable with Silurian (presumably Rhuddanian) deposits provisionally assigned to the Qarabil Formation (Hairapetian *et al*. 2017).

Depositional environments. – The lower member of the Ghelli Formation formed in a significant part by submarine basalt lava flows, probably related to rifting conditions. The two upper units were deposited in offshore environments below seasonal storm wave base, which locally recorded the onset of basaltic volcanic rocks.

Ghavidel-Syooki (2017c) argued that two diamictite beds from the upper member of the Ghelli Formation are glacially derived; however, such a sedimentological assignation requires further study. Their interpretation as turbiditic olistostromes and slope-related deposits looks more likely.

Remarks. – Bayet-Goll & Neto de Carvalho (2016) provided a detailed description of the Upper Ordovician lithostratigraphy assigned to the middle member of the Ghelli Formation at Navia, *c*. 27 km northwest Ghelli. The Lower Palaeozoic rocks exposed there occupy a tectonic window at the base of a major thrust sheet. Unlike the type section, at Navia, it consists of heterolithic siliciclastic rocks rich in ichnofossils deposited in a shallow marine, turbulent, tide-influenced deltaic environment. Therefore it is re-assigned here to the Pelmis Formation. Shafaii Moghadam *et al*. (2017) reported the presence of andesitic volcanic rocks in the lower member of the Ghelli Formation, but they are neither supported by chemical analyses nor petrographic studies. Our field observations do not confirm the presence of andesites within the unit; although volcanic rocks of the Soltan-Maidan Formation in the Alestan Domain are represented exclusively by slightly alkaline basalts according to Derakhshi & Ghasemi (2015) and Derakhshi *et al*. (2017). The report on the occurrence of andesites in the Ghelli Formation is considered here as tentative, and should be resolved with geochemical analyses.

Qyzlar Formation
[new]

Derivation of name. – The new name refers to the Qyzlar valley crossing the type section near its base.

Stratotype. – Natural exposure is on the eastern side of the Kalat valley (Figs 1, 13A, 14) at the eastern part of the Saluk Mountains along the road connecting Bojnurd to Esfarayen, *c*. 39 km south of Bojnurd city. Geographical coordinates of the type section base are 37° 13′ 42″ N, 57° 23′ 19″ E, altitude 1620 m. A detailed stratigraphic log is described in the Appendix 3.

Lithology. – The Qyzlar Formation is mainly siliciclastic and dominated by black to dark-grey laminated kerogenous argillites in the lower part and laminated grey to olive-green argillite and siltstone intercalations in the upper part, with a few decimetre-scale brachiopod shell beds and basaltic volcanic interbeds. A calcareous sandstone containing abundant brachiopod coquinas, 20 m thick, occurs in the upper part of the formation at the type section.

Distribution and age. – The Qyzlar Formation is presently known from the Saluk Mountains. The early Tremadocian age of its basal part is supported by the occurrence of planktonic graptolites assigned to *Rhabdinopora* cf. *flabelliformis* (Eichwald, 1840) (Rushton *et al*. 2021) in the upper part of *Cordylodus lindstromi* Zone; as well as conodonts belonging to the *Cordylodus angulatus* and *Paltodus deltifer* zones upwards. There are also sporadic occurrences of Tremadocian trilobites, such as *Asaphellus inflatus* and *Conophrys* cf. *gaoluoensis* in the lower and middle part of the formation (Fig. 14). The Floian–Dapingian age of the upper part of the Qyzlar Formation is

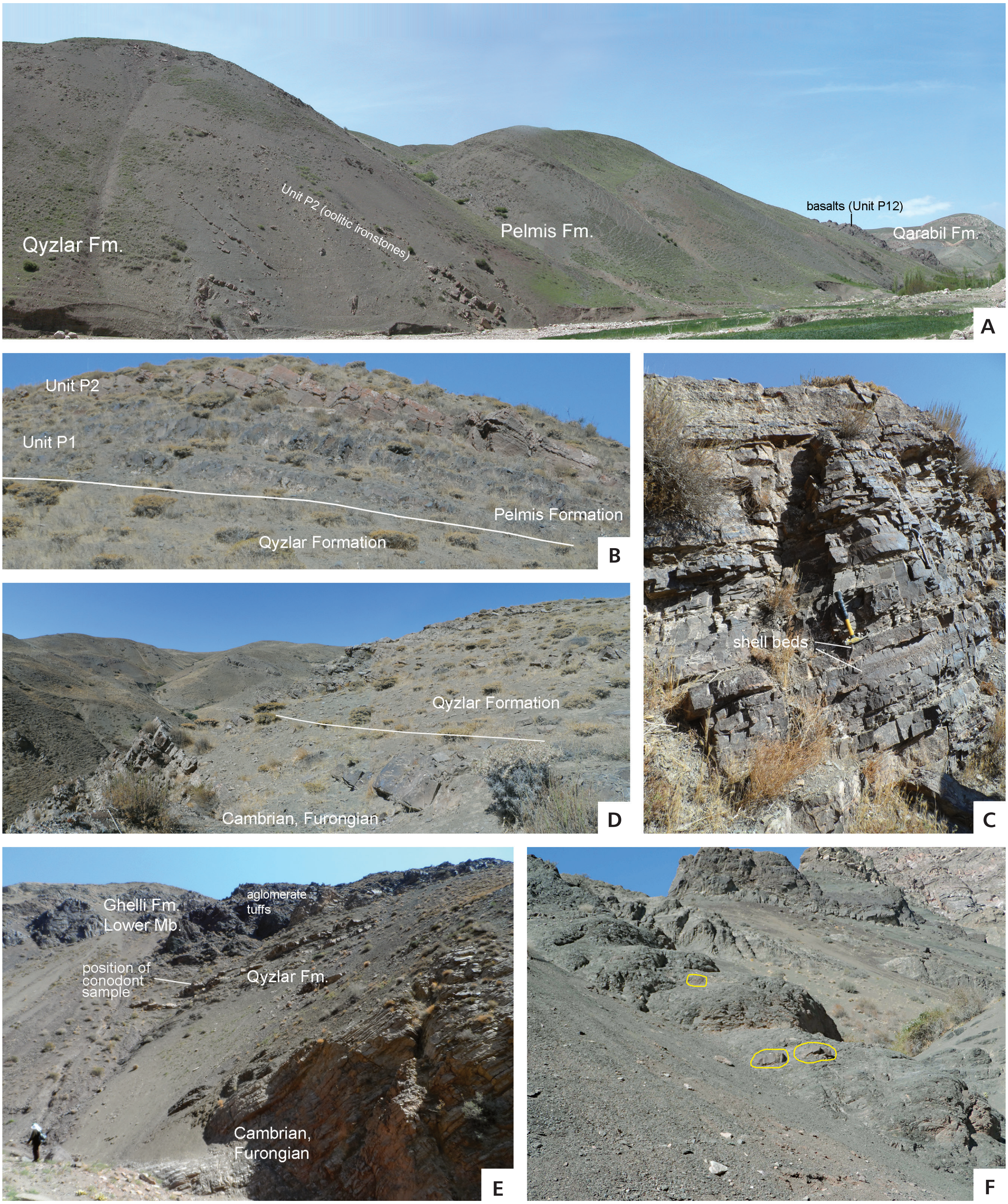
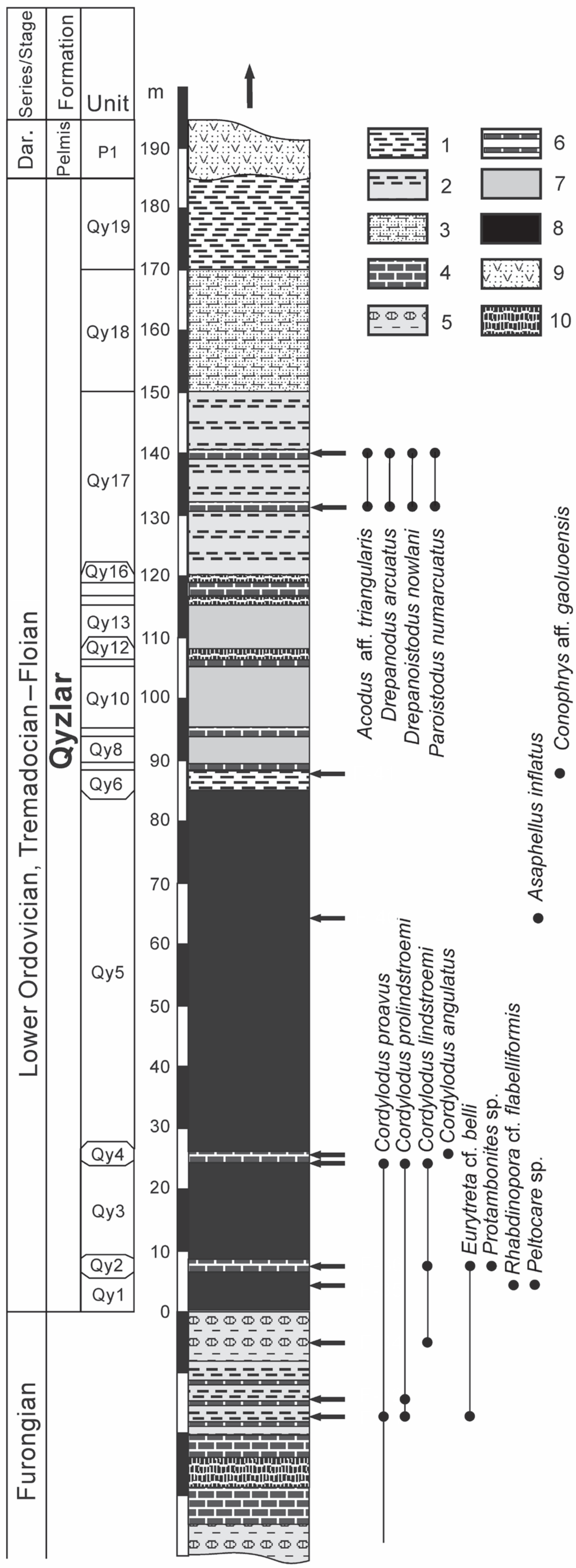


Figure 13. A – westerly view of the Qyzlar and Pelmis formations in the type section on the west side of the Kalat river, Saluk Mountains. • B – northerly view of the transition between the Qyzlar and Pelmis formations on the west side of the Kalat river, Saluk Mountains, showing a bed of tuff at the base of the Pelmis Formation (unit P1) succeeded by a bed of oolitic ironstone with cephalopods (unit P2). • C – brachiopod and bivalve mollusc shell beds in sandstones at the middle part of the Pelmis Formation (Fig. 15, unit P8) on the west side of the Kalat river, Saluk Mountains. • D – southerly view of the exposure of the Qyzlar Formation and lower (volcanic) member of the Ghelli Formation, showing position of the sample with conodonts of *Paltodus deltifer* Zone, at the area north of Ghelli village, Saluk Mountains. • E – easterly view of the exposure of the Ghelli Formation upper member at the type area north of the Ghelli village showing olistoliths associated with siliciclastic turbidite succession.



based on the occurrence of acritarchs characteristic of the local Acritarch Assemblage Zone 3 of Ghavidel-Syooki (2001). The brachiopods are abundant in the uppermost part of the formation, which require further study.

Boundaries. – In the type section, the Qyzlar Formation rests conformably on unnamed Furongian heterolitic rocks that comprise siltstones and argillites, often interrupted by calcareous nodules, intercalating with bedded bioclastic and argillaceous nodular limestones (Fig. 13D). The base of the formation is placed at the occurrence of black shales. Calcareous nodules disappear completely above the contact, while bioclastic limestone beds significantly reduce in number and comprise almost exclusively disarticulated brachiopod shells (Fig. 13D), unlike the limestone beds of the underlying units, which show abundant disarticulated trilobite sclerites on bedding surfaces. The upper contact is diachronous: in the eastern part of the Saluk Mountains, the Qyzlar Formation is placed at the base of an basaltic tuff bed, which underlies an oolitic ironstone bed, both assigned to the Pelmis Formation (Fig. 13B); in the western part of the Saluk Mountains, the unit is unconformably overlain by an agglomerate tuff of the Ghelli Formation (lower member) (Fig. 13E). The mid Tremadocian age of the upper part of the Qyzlar Formation at the Ghelli section is supported by the occurrence of conodonts characteristic of the *Paltodus deltifer* Zone (Fig. 12G–R).

Depositional environments. – Deposition of the Qyzlar Formation commenced at a time of rifting-enhanced subsidence leading to the onset of lower offshore conditions, and its base probably coincides with a drowning surface. Interbedded brachiopod shell beds probably represent proximal tempestites. Black shale deposition through the *Cordylodus lindstromi–Cordylodus angulatus* zones suggests widespread dysaerobic conditions at the water/sediment interface. Nevertheless, the occurrence of the trilobites *Peltocare* sp., *Conophrys* aff. *gaoluoensis* and *Asaphellus inflatus* indicates intervention of repetitive oxygenised episodes. There is progressive shallowing in the upper part of the formation which terminates with some of calcareous sandstones rich in brachiopod coquinas that reflect episodes of upper offshore settings.

Remarks. – The Qyzlar Formation is partially contem-

Figure 14. Stratigraphical log of Qyzlar Formation at Pelmis, eastern Saluk Mountains, showing distribution of selected conodont, trilobite, brachiopod and graptolite taxa. Lithologies: 1 – siltstones; 2 – argillites with subsidiary siltstone beds; 3 – calcareous sandstones; 4 – limestones; 5 – argillites and siltstones with limestone nodules; 6 – bioclastic limestone beds; 7 – argillites; 8 – black shales; 9 – tuffs; 10 – basalt volcanic rocks.

poraneous with the Simeh-Kuh Fomation of eastern Alborz, but these two units were deposited under different tectonic regimes and show important differences. The Qyzlar Formation was formed at the time of ongoing rifting in conditions related to high supplies of siliciclastic sediment. The lower part of the unit is characterised by deposition of graptolite-bearing black shales, which are not characteristic of the Simeh-Kuh Formation. They are gradually replaced upsection by coarser siliciclastic sediments displaying a distinct progradational pattern. The Simeh-Kuh Formation is a condensed unit formed under low siliciclastic supply, and neither distinct progradational nor retrogradational trends are recognisable (Ghobadi Pour *et al*. 2015b). Graptolite-bearing argillites appear only in the uppermost part of the Simeh-Kuh Formation.

Pelmis Formation
[formalised by Evans *et al*. 2021]

Stratotype. – Natural exposure is on the east side of the Kalat river valley at the eastern part of the Saluk Mountains along the road connecting Bojnurd to Esfarayen, *c*. 38 km south of Bojnurd city (Figs 1, 15). The geographical coordinates of type section base are 37° 13′ 49″ N, 57° 23′ 3″ E. A detailed stratigraphic log was described in Evans *et al*. (2021).

Lithology. – The Pelmis Formation comprises heterolitic siliciclastic strata ranging from coarse-grained sandstones to siltstones displaying horizontal and low-angle cross laminae, and occasional shell beds (Fig. 13C) in the lower to middle part, and moderately burrowed shales with fine-grained sandstone interbeds in the upper part, separated by a 40–200 m thick unit of basaltic volcanic rocks.

Distribution and age. – Outside the type area in the eastern Saluk Mountains, the Pelmis Formation is exposed as a tectonic window at the base of a major thrust sheet in the Navia Inlier, northeast of Nabiya village, where it was originally assigned to the Ghelli Formation by Bayet-Goll & Neto de Carvalho (2016), and north of Robat-e Qarabil village (Ghavidel-Syooki & Borji 2018).

The age of the lower part of the Pelmis Formation is supported by preservation of a moderately rich orthoconic cephalopod association (Evans *et al*. 2021), although the occurrence of the brachiopod *Christiania* sp. and the

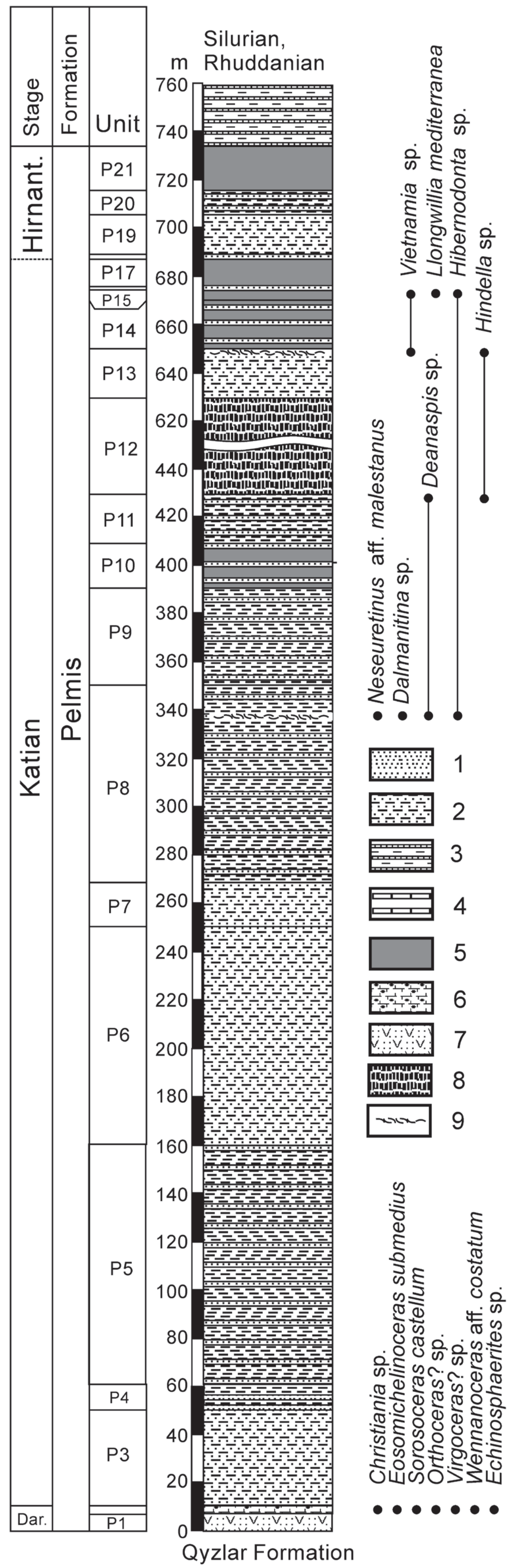


Figure 15. Stratigraphical logs of the Pelmis Formation at Pelmis, eastern Saluk Mountains, showing distribution of selected trilobite, brachiopod, cephalopod and echinoderm taxa (after Evans *et al*. 2021, modified). Lithologies: 1 – sandstones; 2 – sandstone and siltstone intercalations; 3 – siltstone and limestone intercalations; 4 – beds of bioclastic limestones; 5 – grey argillites; 6 – oolitic ironstones; 7 – tuffs; 8 – basalt volcanic rocks; 9 – brachiopod shell beds.

rhombiferan echinoderm *Echinosphaerites* sp. in oolitic ironstones at the type section suggests that its age is not earlier than Darriwilian. The Pelmis Formation contains a complete succession of chitinozoan zones from the mid–Katian *Armoricochitina nigerica* Zone to the late Hirnantian *Spinachitina oulebsiri* Zone (Ghavidel-Syooki 2017b, Ghavidel-Syooki & Borji 2018). The Katian age of the upper part of the formation is also supported by sporadic occurrences of the brachiopods *Hibernodonta* sp., *Hindella* sp., *Longvillia mediterranea* Havlíček, 1981 and the trilobite *Vietnamia* sp. (Fig. 15). Cryptospores are abundant in the palynomorph samples through the Upper Ordovician succession at the type section (Ghavidel-Syooki 2017b), suggesting that sedimentation occurred in relative proximity to the land.

Boundaries. – The lower contact of the Pelmis Formation at the type section is disconformable with a bed of tuff at the base, which is overlain by the bed of oolitic ironstone rich in orthoconic cephalopods (Fig. 13B). In the type section it has a disconformable contact with the Silurian (Llandovery) Qarabil Formation.

Depositional environments. – The Pelmis Formation was deposited in shallow marine environments, mainly shoreface grading into upper offshore within the *Ancyrochitina merga* Zone at the Pelmis section. Depth increase was probably due to tectonically induced subsidence prior to a major episode of basaltic extrusive volcanism.

The middle part of the Pelmis Formation in the Navia Inlier was interpreted by Bayet-Goll & Neto de Carvalho (2016) as a tide-influenced deltaic siliciclastic succession with facies association characteristic of lower distributary channels, delta front and prodelta. It contains abundant trace fossils belonging to the *Cruziana* and *Skolithos* ichnofacies.

Remarks. – The Ordovician deposits belonging to the Pelmis Formation were previously considered as part of the Ghelli Formation (Bayet-Goll & Neto de Carvalho 2016, Ghavidel-Syooki 2017b, Ghavidel-Syooki & Borji 2018).

Recenly, Derakhshi *et al*. (2022, fig. 22) suggested that the basalt unit exposed in the middle part of the Pelmis (= Ghelli) Formation is Darriwilian to early Katian age. However, this age is not supported by the chitinozoan distribution documented by Ghavidel Syooki (2017b, fig. 2), which suggests that the siliciclastic deposits underlying and overlying this volcanic unit contains chitinozoans from the *Ancyrochitina merga* Zone, including the eponymous species. These volcanic rocks do not represent an equivalent of the lower volcanic member of the Ghelli Formation which is underlain by the Qyzlar Formation, containing conodonts of the *Paltodus deltifer* Zone in the upper part, and overlain by the cephalopod limestone bed of a possible Darriwilian age (Evans *et al*. 2021). The second basalt volcanic unit from the upper 'mélange' member of the Ghelli Formation is latest Katian to Hirnantian in age (Ghavidel Syooki 2017c).

Chronostratigraphy and correlation

There is significant progress in the study of the Early and Middle Ordovician fossil record in the eastern Alborz Mountains, which allows us to propose a detailed trilobite- and conodont-based bio- and chronostratigraphical subdivision and correlation for this time span (Figs 3, 4). Palynomorphs and especially chitinozoans are instrumental for biostratigraphical dating and correlation of the Upper Ordovician (Fig. 4). Other biostratigraphically informative groups include graptolites, brachiopods, ostracods, gastropods and echinoderms (Tabs 1–5).

Conodonts

A conodont-based biostratigraphy was recently summarised for northern Iran by Jahangir *et al.* (2015, 2016). Although discontinuous, a reliable conodont biostratigraphical succession from the Furongian *Proconodontus muelleri* Zone to the Darriwilian *Lenodus pseudoplanus* Zone is documented for eastern Alborz (Figs 6, 10; Tab. 1), allowing a relatively precise correlation of the above-reported stratigraphical framework with the International Chronostratigraphical Scale (Figs 3, 4; Tab. 1). The stratigraphical record contains gaps constrained at the lower Tremadocian and upper Dapingian, whereas the Darriwilian succession is incomplete due to the episodic occurrence of condensed carbonate interbeds. The Saluk Mountains in the Kopet-Dagh Region display an almost continuous succession of conodont zones, ranging from the *Proconodontus tenuiserratus* Zone to the *Paltodus deltifer* Zone through the lower part of the Qyzlar Formation (Fig. 14). In the absence of the biostratigraphically indicative species *Iapetognathus fluctivagus* (*sensu* Miller *et al*. 2014), the Cambrian–Ordovician boundary is tentatively placed below the first appearance of the early *Rhabdinopora* species assigned to *Rhabdinopora* cf. *flabelliformis* (Eichwald, 1840) (Jahangir *et al*. 2015, Rushton *et al.* 2021); in addition, the latest Furongian *Cordylodus andresi* Zone recorded from eastern Alborz was not documented in Kopet-Dagh. Another succession of conodont zones across the Cambrian–Ordovician boundary interval was reported by Ghaderi *et al*. (2008) from the lower part of the Shirgesht Formation in the Derenjal Mountains, Central Iran.

Table 1. Stratigraphical and geographical distribution of Tremadocian–Darriwilian conodont species in the Simeh-Kuh, Qumes and Lashkarak formations of eastern Alborz and Qyzlar Formation of Kopet-Dagh.

Formations	Qyzlar Fm.			Simeh-Kuh		Qumis			Lashkarak		Localities			
	Cordylodus lindstromi	*Cordylodus angulatus*	*Paltodus deltifer*	*Paltodus deltifer*	*Drepanoistodus proteus*	*Prioniodus elegans*	*Oepikodus evae*	*Baltoniodus navis*	*Lenodus variabilis*	*Lenodus pseudoplanus*	Simeh-Kuh	Deh-Molla	Ghelli	Pelmis
Cordilodus lindstromi	+													+
Cordilodus proavus	+													+
Cordylodus prolindstrmi	+													+
Cordylodus angulatus		+											+	+
Drepanodus arcuatus				+	+					+	+			+
Drepanoistodus basiovalis				+									+	
Drepanoistodus nowlani				cf.	cf.						cf.	cf.		
Monocostodus sp.				+							+	+		
Paltodus deltifer pristinus			+	+							+	+	+	
Paltodus deltifer deltifer			+	+	+							+	+	
Paltodus quinqucostatus				+								+		
Paroistodus numarcuatus				+								+		
Rossodus beimadaonsis				cf.								cf.		
Variabiloconus variabilis				cf.								cf.		
Acodus triangularis					cf.						cf.			+
Cornuodus sp.					+						+			
Drepanoistodus amoenus					aff.						aff.			
Kallidontus sp.					+						+			
Oneotodus variabilis					+						+			
Paltodus subaequalis					+						+			
Paroistodus proteus					+						+			
Scandodus furnishi					cf.							cf.		
Triangulodus tarapintinensis					cf.						cf.			
Baltoniodus triangularis							aff.							
B. navis								+			+			
Bergstromeognathus exstensus							+				+			
Drepanoistodus contractus							+				+			
D. forceps							+				+			
Gothodus costulatus							+	+			+			
Oistodus lanceolatus							+	+			+			
Periodon flabellum							+				+			
Trapezognathus diprion							+				+			
Trapezognathus sp.							+				+			
Trapezognathus quadrangulum								+			+			
Baltoniodus norrlandicus									cf.	cf.	cf.			
Lenodus pseudoplanus										+	+			
Lenodus variabilis									+		+			
Microzarkodina hagetiana									+		+			
Periodon aculeatus									cf.		cf.			
Scalpellodus gracilis										+	+			
Venoistodus balticus										cf.	cf.			

There are only a few reports on conodont occurrences in other parts of Iran. According to Müller & Walter (1984), a late Tremadocian conodont assemblage, including *Acodus deltatus* Lindström, 1955, *Drepanodus arcuatus* Pander, 1856, *Drepanoistodus inconstans* (Lindström, 1955), *Drepanoistodus* cf. *forceps* (Lindström, 1955) and *Paroistodus* cf. *proteus* (Lindström, 1955), occurs in the Taknar Inlier in an unnamed formation of black and grey shales intercalated with sandstones and black limestones in the upper part.

Late Ordovician conodonts are presently known only from the Talesh Mountains, where a small late Sandbian–Katian conodont assemblage including *Drepanoistodus*? sp. and *Scabbardella* cf. *altipes* (Henningsmoen, 1948) was identified by Peep Männik (personal communication 2018) in samples collected from the Tatavrud Formation (Fig. 12A–F). In the southeastern part of Central Iran (Kerman Region), several isolated occurrences of Early–Middle Ordovician conodonts were reported from the Gatkuiyeh Formation. In particular, a small conodont association of late Tremadocian age (*Serratognathus bilobatus* Zone of North China), including *Bergstroemognathus hubeiensis* An *et al.*, 1981, *Juanognathus variabilis* (Serpagli, 1974), *Drepanoistodus* spp. and *Baltoniodus* sp. was recovered from the lower part of the formation in the vicinity of Gatkuiyeh and Khoda-Afarin villages (Zhen *et al.* 2001). In the upper part of the Gatkuiyeh Formation, exposed 5 km northwest of the Shaabjereh village (Fig. 1), another conodont-bearing level contains *Erraticodon* cf. *balticus* Dzik, 1978, *Scolopodus* aff. *princeps* Bagnoli & Stouge, 1997 and *Eoplacognathus*? sp., suggesting an early Darriwilian age (Percival *et al.* 2009). Hamedi *et al.* (1997) reported the occurrence of the Katian conodont *Icriodella* cf. *superba* Rhodes, 1953 in the upper member of the Gatkuiyeh Formation at the Gezueh Gorge (Fig. 1). *Icriodella* aff. *superba* associated with *Amorphognathus* cf. *ordovicicus* (Branson & Mehl, 1933) were reported from the Ordovician deposits provisionally assigned by Hairapetian *et al.* (2017) to the Gatkuiyeh Formation in the Boghu Mountains, *c.* 25 km southwest of Kashmar city (Fig. 1). These are only two records on the occurrence of Katian conodonts in Central Iran.

In the Zagros Ranges, a phosphoritic bed marking the top of the lower member of the Seyahou Formation contains the early representatives of the *Baltoniodus* phylogenetic lineage identified as *Baltoniodus* aff. *triangularis* Lindström, 1955 (Ghavidel-Syooki *et al.* 2014). These conodonts are probably conspecific with *Baltoniodus* sp. from the lower member of the Rann Formation at Ras Al Khaimah (Fig. 16), United Arab Emirates (Fortey *et al.* 2011), and points to a latest Floian age. In South China, the earliest yet unnamed species of *Baltoniodus* occurs already in the late Floian *Oepikodus evae* Zone (Wang *et al.* 2005, 2009).

Trilobites and ostracods

Trilobites are probably the most important group, complementary to conodonts, for the biostratigraphical subdivision of the fine siliciclastic Lower Ordovician deposits in northern Iran. A regional trilobite-based zonal scale developed by Ghobadi Pour (2006, 2019) and Ghobadi Pour *et al.* (2015b) includes the *Asaphellus inflatus–Dactylocephalus*, *Psilocephalina lubrica*, *Vachikaspis insueta*, *Kayseraspis* sp. and *Asaphellus fecundus–Taihungshania miqueli* zones (Fig. 6, Tab. 2). There is no co-occurrence of trilobites characteristic of the *Asaphellus inflatus–Dactylocephalus* Zone with conodonts in the Alborz Region; however, the first occurrence of *Asaphellus inflatus* is documented in Kopet-Dagh within the *Cordylodus angulatus* Zone (Jahangir *et al.* 2015). This co-occurrence suggests the onset of a considerable hiatus at the base of the Ordovician in the Alborz Mountains. Trilobites of the *Psilocephalina lubrica* and *Vachikaspis insueta* zones usually occur in association with conodonts of the *Paltodus deltifer* Zone (*sensu lato*), whereas the *Kayseraspis* sp. and *Asaphellus fecundu–Taihungshania miqueli* zones correlate with the lower part of the *Drepanoistodus proteus* Zone (Jahangir *et al.* 2016). The upper part of the *Asaphellus fecundus–Taihungshania miqueli* Zone is Floian in age, as constrained by the co-occurrence with the conodont *Acodus* cf. *kechikaensis* Pyle & Barnes, 2002 and the graptolites *Baltograptus*? cf. *sinicus* Lee & Chen, 1962 and *Baltograptus* cf. *kunmingensis* (Ni, 1979) *in* Mu *et al.* (1979) (Rushton *et al.* 2021). The trilobite-based biostratigraphical succession of the Alborz Region shows strong similarities with that documented in South China (for a discussion, see Ghobadi Pour *et al.* 2015b). *Taihungshania miqueli* (Bergeron, 1894) is a biostratigraphically significant species which makes a slightly diachronous appearance across the Mediterranean margin of NW Gondwana. It is presently known from the lower Floian of the Montagne Noire, France (Bergeron 1894, Courtessole *et al.* 1985), the Seydişehir Formation of the eastern Taurus Mountains in central Turkey (Dean & Monod 1990), and the lower member of the Rann Formation (Fig. 16) in United Arab Emirates (Fortey *et al.* 2011).

Ostracods are locally abundant in the middle and upper parts of the Tremadocian Simeh-Kuh Formation (Figs 3, 4; Tab. 2). They are mostly decalcified which makes their taxonomical identification difficult. The only exceptions are the silicified carapaces of *Nanopsis pairidaeza* Ghobadi Pour *et al.* 2011b that co-occur with conodonts of the *Paltodus deltifer* Zone at Deh-Molla (Tab. 2).

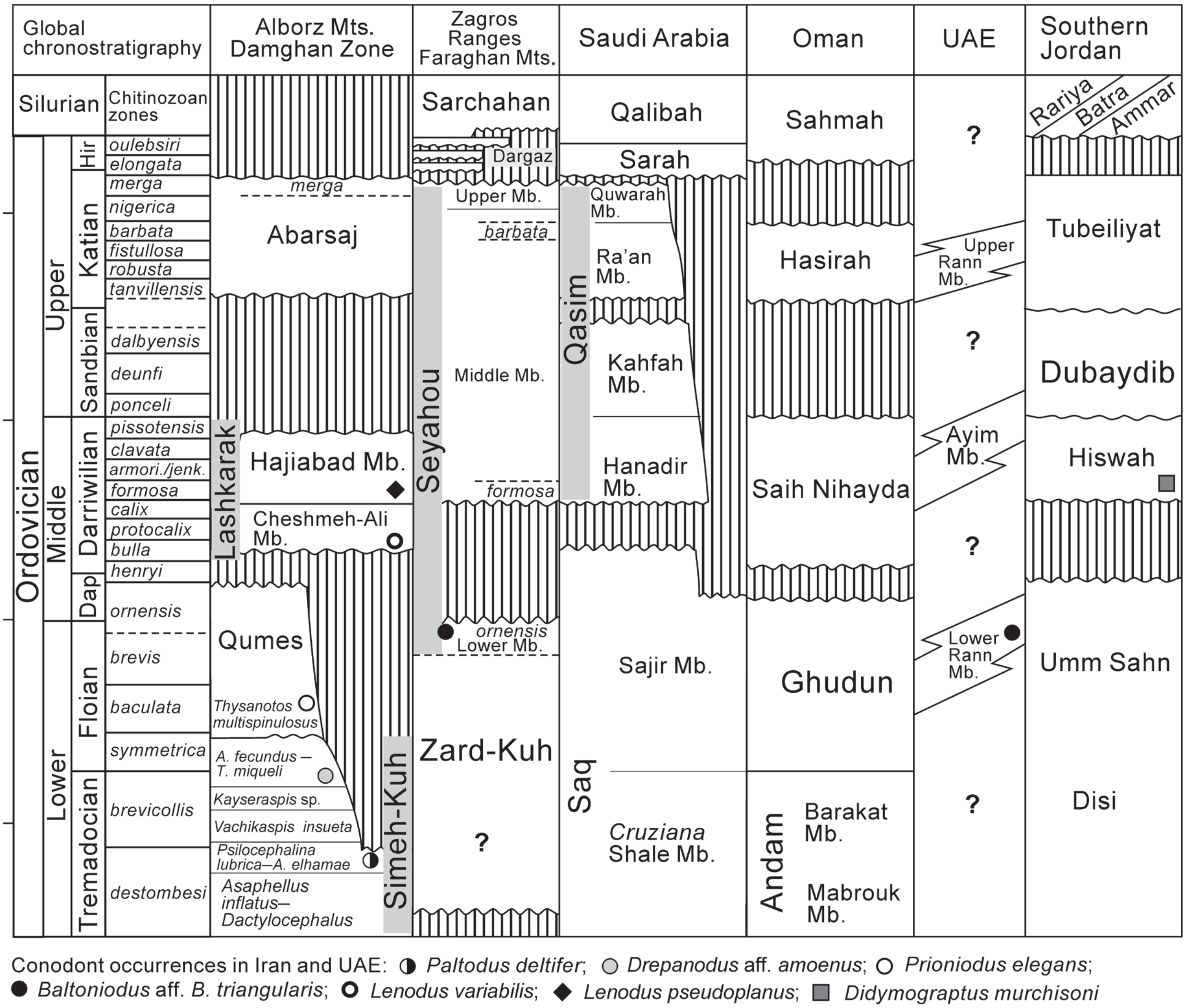


Figure 16. Ordovician chrono- and lithostratigraphic chart of the Damghan Domain, eastern Alborz with successions of Arabian segment of Gondwana, based on Ghavidel-Syooki *et al*. (2014) and references herein, showing occurrences of selected biostratigraphically indicative species of conodonts, brachiopod, graptolite and trilobites. Abbreviations: *A.* – *Asaphellus*; *T.* – *Taihungshania*; Mb. – Member; Mts – Mountains; UAE – United Arab Emirates.

Dapingian trilobites are almost unknown from Alborz. The only species yet documented from the upper part of the Qumes Formation is *Ningkianites* sp., which represents a genus otherwise known only from the Dapingian to Darriwilian of South China (Ghobadi Pour *et al*. 2007b). In other parts of Iran, Dapingian and early Darriwilian trilobites are known from the middle part of the Shirgesht Formation in the Derenjal Mountains (Pillet 1973, Bruton *et al*. 2004, Ghobadi Pour & Turvey 2009). The trilobites include the low diversity *Pseudocalymene* – asaphide association dominated by leiostegiids, including endemic species of *Pseudocalymene*, *Liomegalaspides* and *Nileus*, but also *Illaenus sinensis* Yabe, 1920 *in* Yabe & Hayasaka (1920), which was originally described from the upper part of the Dawan Formation (upper Dapingian to lower Darriwilian) in South China.

An almost monotaxic trilobite association, with *Neseuretus* aff. *tristani* (Brongniart, 1817) *in* Desmarest (1817) as dominant species, is characteristic of shoal complexes from the Cheshmeh-Ali Member of the Lashkarak Formation (Fig. 3, Tab. 3). The assemblage includes conodonts of the *Lenodus variabilis* Zone, the foraminifera *Psammosphaera rugosa* Eisenack, 1954 and the brachiopods *Bastamorthis multicostata* Ghobadi Pour *et al*., 2011a, *Martellia*? sp., *Semnanostrophia lata* Ghobadi Pour *et al*., 2011a, *Yangtzeella* sp. and *Biernatia* aff. *rossica* (Gorjansky, 1969).

A trilobite association from the Hajiabad Member of the Lashkarak Formation (Fig. 3, Tab. 3) includes *Amphoriops* sp., *Illaenus* sp., *Neseuretinus birmanicus* (Reed, 1906), *Nileus armadilloformis* Lu, 1957 and *Opsimasaphus* cf. *pseudodawanicus* (Lu, 1975). The two latter taxa occur

Table 2. Stratigraphical and geographical distribution of Tremadocian–Dapingian trilobite, ostracod, brachiopod, cephalopod and graptolite species in the Simeh-Kuh and Qumes formations of eastern Alborz and Qyzlar Formation of Kopet-Dagh.

Formations	Simeh-Kuh					Qumis				Eastern Alborz				Qyz.
Biozones/Members	*Asaphellus inflatus–Dactylocephalus*	*Psilocephalina lubrica*	*Vachikaspis insueta*	*Kayseraspis* sp.	*Asaphellus fecundus–T. miquelli*	Lower part (Floian, unspecified)	Upper part (Dapingian, unspecified)	Gerd-Kuh Member	Raziabad Member	Mila-Kuh	Gerd-Kuh	Simeh-Kuh	Deh-Molla	Pelmis (Kopet-Dagh)
TRILOBITA														
Asaphellus inflatus	+									+		+		+
Chashania chashanensis	+									cf.		+	+	
Conophrys gaoluoensis	+									+				
Conophrys pentagonalis	cf.													cf.
Conophrys simehensis	+	+										+	+	
Chungkingaspis sinensis	+									cf.		+	+	
Dactylocephalus levificatus	+									+				
Dactylocephalus mehriae	+											+	+	
Geragnostus yangtzeensis	cf.									cf.			cf.	
G. sidenbladhi jafari	+	+										+		
Apatokephalus sp. 1		+										+		
Asaphellus intermedius		+								+			+	
Asaphopsis elhamae		+									+	+	+	
Conophrys multituberculatus		+											+	
Kayseraspis ghavideli		+										+		
Orometopus sp.		+								+				
Parapilekia? sp.		+										+		
Paraszechusnella latilimbata													aff.	
Peltocare sp.	+													+
Presbynileus? *biroonii*		+										+	+	
Psilocephalina lubrica		+	+	+						+	+	+		
Vachikaspis insueta			+								+	+		
Kayseraspis sp.				+							+	+		
Apatokephalus sp.2					+							+		
Asaphopsis? sp.					+							+		
Euloma sp.					+							+		
Damghanampyx ginteri					+						+	+		
Geragnostella lycaonica					+							+		
Taihungshania miqueli					+						+	+		
Ningkianites sp.						+						+		
OSTRACODA														
Euprimitiid sp.						+						+		
BRADORIIDA														
Bradoriid sp.						+						+		

Table 2. Continued.

Formations	Simeh-Kuh					Qumis				Eastern Alborz				Qyz.
Biozones/Members	*Asaphellus inflatus–Dactylocephalus*	*Psilocephalina lubrica*	*Vachikaspis insueta*	*Kayseraspis* sp.	*Asaphellus fecundus–T. miquelli*	Lower part (Floian, unspecified)	Upper part (Dapingian, unspecified)	Gerd-Kuh Member	Raziabad Member	Mila-Kuh	Gerd-Kuh	Simeh-Kuh	Deh-Molla	Pelmis (Kopet-Dagh)
LINGULIFORMEA														
Acanthambonia sp.							+							+
Acrotreta maior							cf.					cf.		
Aipyotreta conferta							+					+		
Biernatia rossica							aff.					aff.		cf.
Eosiphonotreta sp.						+	+					+		
Numericoma sp.							+					+		
Ottenbyella sp.						+						+		
Paterula sp.							+					+		
Rowellella sp. 2							+					+		
Wahwahlingula? sp. 2							+					+		
BIVALVIA														
Glyptarca sp.					+	+						+		
Pensarnia laeviformis						aff.						aff.		
CEPHALOPODA														
Bactroceras sp.					+			+				+	+	
Eosomichelinoceras huananense													+	
Sorosoceras castellum													+	
Orthoceras? sp.													+	
Virgoceras? sp.													+	+
Wennanoceras aff. *costatum*													+	
GRAPTOLITHINA													+	
Acrograptus sp.														
Baltograptus geometricus						+						+		
Baltograptus kunmingensis						+						+		
Hunnegraptus? sp.						cf.						cf.		
Tetragraptus? sp.					+							+		

in the Darriwilian of South China (Ghobadi Pour 2019), while *Neseuretinus birmanicus* was originally described from the Naungkangyi Group of northern Shan States, Myanmar (Sibumasu terrane), where it occurs associated with brachiopods of the *Saucrorthis* Association (Cocks & Zhan 1998). *Neseuretinus birmanicus* is also known from the middle part of the Shirgesht Formation in the Derenjal Mountains of Central Iran, where it co-occurs with the trilobites *Birmanites* sp., *Deanaspis* sp., *Liomegalaspides* (= *Megalaspides*) *winsnesi* (Bruton, 2004) *in* Bruton *et al.* (2004), *Ovalocephalus kanlingensis* (Zhang, 1981), *Radnoria* sp. and *Thaleops* (*Amphoriops*) sp. (Ghobadi Pour & Popov 2009, Ghobadi Pour & Turvey 2009). Another component of the fauna from the Shirgesht Formation is a moderately rich ostracod assemblage, which includes *Aechmina*?, *Cerninella*,

Table 3. Stratigraphical and geographical distribution of Darriwilian–Katian trilobite, ostracod, brachiopod, gastropod, cephalopod echinoderm and foraminifer species in the Lashkarak and Tatavrud formations of Alborz and Pelmis Formation of Kopet-Dagh.

Stage/region	Darriwilian		Katian		Alborz Mountains						
Formation/locality	Cheshmeh-Ali Mb.	Hajiabad Mb. Lashkarak	Tatavrud Formation	Pelmis Formation	Gerd-Kuh	Simeh-Kuh	Deh-Molla	Abarsaj	Lashkarak	Talesh Mountains	Pelmis, Saluk Mts. (Kopet-Dagh)
TRILOBITA											
Gog sp.	+						+				
Neseuretus tristani	aff.				aff.	aff.	aff.				
Illaenus sinensis	?								+		
Symphysurus subquadratus	cf.								cf.		
Amphoriops sp.		+				+	+				
Birmanites yunnanensis		cf.							cf.		
Illaenus sp. 1		+				+					
Neseuretinus birmanicus		+				+					
Nilleus armadiloformi		+					+				
Opsimasaphus pseudodawanicus		cf.				cf.	cf.				
Birmanites asiaticus			cf.							cf.	
Cyclopyge binodosa			cf.							cf.	
Cyphoniscus socialis			cf.							cf.	
Dicranopeltis polytoma			cf.							cf.	
Eccoptochile sp.			+							+	
Failleana? sp.			+							+	
Illaenus sp. 2			+							+	
Lichas? sp.			+							+	
Metopolichas sp.			+							+	
Mezzaluna tatavrudensis			+							+	
Ovalocephalus tetrasulcatus			cf.							cf.	
Panarchaeogonus sp.			+							+	
Panderia curta			cf.							cf.	
Paratiresias alborzensis			+							+	
Parisoceraurus sp.			+							+	
Phorocephala ulugtana			cf.							cf.	
Sphaerexochus fibrisulcatus			cf.							cf.	
Symphysops sp.			+							+	
Trinodus tardus			cf.							cf.	
Deanaspis sp.				+							+
Neseuretinus malestanus				aff.							aff.
Vietnamia sp.				+							+
OSTRACODA											
Cerninella aryana		+				+					
Ordovizona amyitisae		+				+					
Pariconchoprimitia sp.		+				+					

Table 3. Continued.

Stage/region	Darriwilian		Katian				Alborz Mountains				
Formation/locality	Cheshmeh-Ali Mb.	Hajiabad Mb. Lashkarak	Tatavrud Formation	Pelmis Formation	Gerd-Kuh	Simeh-Kuh	Deh-Molla	Abarsaj	Lashkarak	Talesh Mountains	Pelmis, Saluk Mts. (Kopet-Dagh)
RHYNCHONELLIFORMEA											
Anisopleurella antiqua		+					+				
Bastamorthis multicostata	+					+	+				
Bellimurina fluctuosa		+			+		+				
Calyptolepta? sp.		+			+		+				
Christiania sp.		+		+			+				+
Dirafinesquina globosa		+			+		+	+			
Dulankarella hyrcanica		+			+	+	+				
Eoporambonites sp.		+			+	+					
Ishimia inflata		+			+	+	+				
Lepidomena multiplicata		+			+	+	+				
Leptastichidia sp.		+					+				
Martellia? sp.	+					+					
Orthis dehmollaensis		+			+	+	+	+			
Phragmorthis shahrudensis		+					+				
Porambonites sp.		+					+				
Rogorthis? *oriens*		+			+	+	+				
Saucrorthis obtusa		+					+				
Semnanostrophia lata	+						+				
Simehorthis fascicostellata		+			+	+	+				
Vellamo? sp.		+			+	+					
Yangtzeella? sp.	+					+	+				
CRANIIFORMEA											
Pseudocrania insperata		+				+					
LINGULIFORMEA											
Biernatia rossica	aff.					aff.					
Eoconulus cryptomyus		aff.				aff.					
Schizocrania sp.		+				+					
Thysanotos sp.		+				+					
GASTROPODA											
Lesueurilla prima		+					+				
Psammosphaera rugosa	+	+				+					
Sorosphaera darriwiliensis		+				+					
Sorosphaera iranensis		+				+					
Sorosphaera? *tricella*		aff.				aff.					

Table 3. Continued.

Stage/region	Darriwilian		Katian				Alborz Mountains				
Formation/locality	Cheshmeh-Ali Mb.	Hajiabad Mb. Lashkarak	Tatavrud Formation	Pelmis Formation	Gerd-Kuh	Simeh-Kuh	Deh-Molla	Abarsaj	Lashkarak	Talesh Mountains	Pelmis, Saluk Mts. (Kopet-Dagh)
CEPHALOPODA											
Cycloceras sp.			?							?	
Endoceras sp.		?							?		
Eosomichelinoceras sp.		?						?			
Michelinoceras sp.		?	?						?	?	
Protocyclendoceras sp.		+				+					
Proterovaginoceras incognitum		?						?			
Sactorthoceras sp.		?						?			
Virgoceras sp.		+					+				
ECHINODERMATA											
Archegocystis? sp.		+							+		
Aristocystis sp.		+							+		
Echinosphaerites sp.		+			+	+	+		+		
Glyptosphaerites sp.		+				+					
Heliocrinites sp.		+			+	+					
Sinocystis loczy		cf.							cf.		
Sinocystis sp.		+			+	+					
Tholocystis sp.		+				+			?		
FORAMENIFERA											
Amphitremoida simehkuhensis		+				+					
Amphitremoida longa		aff.				aff.					
Damghanites lashkarakensis		+				+					
Psammosphaera rugosa	+	+				+					
Sorosphaera darriwiliensis		+				+					
Sorosphaera iranensis		+				+					
Sorosphaera? *tricella*		aff.				aff.					

Longiscula, *Ogmoopsis*, *Ordovizona*, *Pullvillites*, *Rectella* and *Vogdesella* (Ghobadi Pour *et al*. 2006). Among them, *Aechmina*? cf. *ventadorni* Vannier, 1986 is probably conspecific with a taxon known in western France (Vannier 1986, Vannier *et al*. 1989) from the uppermost Darriwilian (*Hustedograptus teretiusculus* graptolite Zone equivalent). Two other species, including *Cerninella aryana* Williams *et al*., 2006 *in* Ghobadi Pour *et al*. (2006) and *Ordovizona amyitisae* Williams *et al*., 2006 *in* Ghobadi Pour *et al*. (2006), are also known in the eastern Alborz from the Hajiabad Member (Fig. 3, Tab. 3), where they co-occur with the echinoderm *Echinosphaerites* sp. and conodonts of the *Lenodus pseudoplanus* Zone (Ghobadi Pour *et al*. 2007a, b; Nestell *et al*. 2016).

Late Ordovician trilobites are known in northern Iran from the Talesh Mountains (Figs 1, 4; Tab. 3), where they occur in both the Tatavrud Formation (Karim 2009), and the upper part of the Pelmis Formation from the South Kopet-Dagh Region (Saluk Mountains). According to Karim (2009), who gave a detailed discussion of the age and biogeographical affinities of the trilobite assemblage from the Talesh Mountains, it shows the closest similarity with the late Sandbian–early Katian trilobite fauna of Turkestan and Alai Ranges (Alai terrane) documented by

Petrunina (in Repina *et al*. 1975), and with the Katian (Late Ordovician) fauna of northeastern Central Kazakhsatan (Selety terrane) described by Apollonov (1974). The occurrence of *Ovalocephalus* cf. *tetrasulcatus* (Kielan, 1960) probably supports a Katian age for the Iranian fauna. A trilobite assemblage of similar age, probably Katian, was reported from the Taknar Inlier (Fig. 1) by Müller & Walter (1984). It includes *Amphytrion* sp., *Cyclopyge* sp., *Illaenus* sp., *Ovalocephalus* cf. *tetrasulcatus*, *Stenopareia* sp., *Telephina* sp. and *Trinodus tardus* Barrande, 1846 sampled from a black limestone in the vicinity of Dahan-Qaleh. It probably represents a trilobite association living on the outer shelf and shares no common genera with the shallow-marine Katian trilobite associations presently known from other parts of Iran, except the Talesh Mountains.

The trilobite fauna from the Pelmis Formation in the Saluk Mountains (Figs 1, 15; Tab. 3) includes only four taxa, *Dalmanitina* sp., *Deanaspis* sp., *Neseuretinus* aff. *malestanus* (Wolfart, 1970) and *Vietnamia* sp., which are only known from preliminary identifications. Specimens of *Vietnamia* sp. are probably not conspecific with *Vietnamia* cf. *teichmulleri* (Hamman & Leone, 1997) described from the Chahgonbad Formation in the Pol-e Khavand Inlier on northwestern Central Iran (Popov *et al*. 2015), and are only indicative of the Late Ordovician age of the formation, while *Neseuretinus* aff. *malestanus* may be conspecific with the specimens described and illustrated by Ghobadi Pour *et al*. (2015a) from the middle part of the Seyahou Formation. The latter are associated with species of *Dalmanitina* (*Dalmanitina*), *Deanaspis*, *Iberocoryphe* and *Sardoites*, within the interval dated as the upper part of the *Acanthochitina barbata* chitinozoan Zone and the lower part of the *Armoricochitina nigerica* chitinozoan Zone (Ghobadi Pour *et al*. 2015a).

Brachiopods

While there is no brachiopod-based formal biostratigraphical scheme yet developed for the Ordovician of Iran, there are several distinctive faunal associations and a number of biostratigraphically indicative taxa that can be applied for the age discrimination and correlation of the local lithostratigraphical units in northern Iran.

The earliest Tremadocian brachiopods from Alborz (Tab. 4) include the endemic polytoechioid species *Tritoechia tenuis* Kebria-ee Zadeh *et al*., 2015 and *Gondwanorthis bastamensis*, which was originally assigned to *Nanorthis* (Ghobadi Pour *et al*. 2011a). Both species occur in the lowermost part of the Simeh-Kuh Formation (*Asaphellus inflatus*–*Dactylocephalus* trilobite Zone). The only other *Gondwanorthis* species yet known is *G. claderensis* (Benedetto, 2007) from the lower Tremadocian (*Cordylodus angulatus* conodont Zone) of Cordillera Oriental, northwest Argentina.

The middle Tremadocian *Psilocephalina lubrica* trilobite Zone is characterised by the proliferation of distinctive micromorphic linguliform brachiopods (Tab. 4) including *Acrotreta dissimilis* (Biernat, 1973), *Akmolina minor* (Biernat, 1973), *Diencobolus* sp., *Dactylotreta batkanensis* Popov & Holmer, 1994, *Elliptoglossa* sp., *Eoconulus* sp., *Eurytreta ahmadii* Ghobadi Pour *et al*., 2011a, and *Wahwahlingula kharbashi* Ghobadi Pour *et al*., 2011a. This brachiopod assemblage shares close similarities with a contemporaneous brachiopod association belonging to the *Paltodus deltifer pristinus* conodont Zone known from Tremadocian chalcedonites of the Holy Cross Mountains in Poland (Biernat 1973, Holmer & Biernat 2002). In particular, *Acrotreta dissimilis* and *Akmolina minor* are shared species. Tremadocian occurrences of *Diencobolus* are otherwise known from the Holy Cross Mountains, while Tremadocian occurrences of *Eoconulus* in eastern Alborz and the Holy Cross Mountains are the earliest occurrence for the genus (Ghobadi Pour *et al*. 2011a).

The orthid brachiopod *Tarfaya jafariani* Popov *et al*., 2009a is abundant in the middle part of the Simeh-Kuh Formation (*Vachikaspis insueta* and *Kayseraspis* sp. zones; Tab. 4). While the species is endemic to Alborz, the genus *Tarfaya* has a narrow stratigraphical range, restricted to the upper part of the Tremadocian to lower Floian (time slices Tr2–Fl1). It is relatively widespread along the Gondwana margins, being documented from Anti-Atlas (Morocco), eastern Alborz (northern Iran), Tasmania and Central Andean Basin (Argentina), as documented by Benedetto & Muñoz (2017). In the upper part of its stratigraphical range, *Tarfaya* forms shell beds comprising the polytoechioid *Protambonites hooshangi* Popov *et al*., 2009a. *Protambonites* is widespread in the Tremadocian of other parts of Iran. In particular, the taxon forms shell beds in the lower part of the Qyzlar Formation in the Saluk Mountains at Kopet-Dagh, and in the Shirgesht Formation of the Derenjal Mountains in Central Iran (Bassett *et al*. 1999, 2002: fig. 3e, f). In both cases, it co-occurs with conodonts of the *Cordylodus angulatus* Zone (Figs 3, 4). Outside Iran, *Protambonites* occurs in the Tremadocian to early Floian of the Uralian margin of Baltica (Kidryas and Akbulaksai formations), Bohemia (Trenice Formation) and Spain (Havlíček 1977, Villas *et al*. 1995, Popov *et al*. 2001) being characteristic for high-to-temperate latitudes.

A different brachiopod association, including only endemic species like *Polytoechia hecatompylensis* Popov *et al*., 2009a, *Paralenorthis semnanensis* Popov *et al*., 2009a, *Ranorthis cheshmehaliana* Popov *et al*., 2009a and *Xinanorthis qoomesensis* Popov *et al*., 2009a, co-occurs with trilobites of the succeeding *Asaphellus fecundus*–

Table 4. Stratigraphical and geographical distribution of Tremadocian–Dapingian brachiopod species in the Simeh-Kuh and Qumes formations of eastern Alborz and Qyzlar Formation of Kopet-Dagh.

Formations	Simeh-Kuh Formation					Qumes Formation				Eastern Alborz				Qz.
Biozones/Members	*Asaphellus inflatus–Dactylocephalus*	*Psilocephalina lubrica*	*Vachikaspis insueta*	*Kayseraspis* sp.	*Asaphellus fecundus–T. miquelli*	Lower part (Floian, unspecified)	Upper part (Dapingian, unspecified)	Gerd-Kuh Member	Raziabad Member	Mila-Kuh	Gerd-Kuh	Simeh-Kuh	Deh-Molla	Pelmis (Kopet-Dagh)
RHYNCHONELLIFORMEA														
Gondwanorthis bastamensis													+	
Protambonites sp.	+													+
Tritoechia tenuis	+									+				
Tritoechia sp.		+											+	
Tarfaya jafariani			+	+							+	+		
Protambonites hooshangi			+	+							+	+		
Paralenorthis semnanensis					+						+	+		
Polytoechia hecatompylensis					+						+	+		
Ranorthis cheshmehaliana					+							+		
Xinanorthis qoomesensis					+						+	+		
Paralenorthis sp.						+						+		
Yangtzeella longiseptata						+		+			+	+		
Martellia sp. 1								+			+	+		
Yichangorthis sp.								+			+			
Dirafinesquina antiqua														
Eoporambonites raziabadensis														
Leptastichidia? sp.														
Martellia chabdjerehensis								aff.			aff.			
Paralenorthis suriensis								cf.			cf.			
Zhanorthis gerdkuhensis														
LINGULIFORMEA														
Eurytreta belli	+													cf.
Siphonobolus sp.	+													+
Acrotreta dissimilis		+											+	
Akmolina minor		+											+	
Diencobolus sp.		+											+	
Dactylotreta batkanensis		+								+	+	+		
Elliptoglossa sp.		+											+	
Eoconulus sp. 1		+											+	
Eurytreta ahmadii		+											+	
Wahwahlingula kharbashi		+										cf.	+	
Lingulella sp.			+								+			
Rowellella? sp. 1				+								+		

Table 4. Continued.

Formations	Simeh-Kuh Formation					Qumes Formation				Eastern Alborz				Qz.
Biozones/Members	*Asaphellus inflatus–Dactylocephalus*	*Psilocephalina lubrica*	*Vachikaspis insueta*	*Kayseraspis* sp.	*Asaphellus fecundus–T. miquelli*	Lower part (Floian, unspecified)	Upper part (Dapingian, unspecified)	Gerd-Kuh Member	Raziabad Member	Mila-Kuh	Gerd-Kuh	Simeh-Kuh	Deh-Molla	Pelmis (Kopet-Dagh)
LINGULIFORMEA														
Broeggeria? sp.					+							+		
Eosiphonotreta sp.					+							+		
Ghavidelia damghanensis					+							+		
Orbithele sp.					+							+		
Ottenbyella sp.						+						+		
Leptembolon sp.								+				+		
Thysanotos multispinosus								+			+	+		
Eosiphonotreta sp.						+	+					+		
Ottenbyella sp.						+						+		
Acanthambonia sp.							+							
Acrotreta maior							cf.					cf.		
Aipyotreta conferta							+					+		
Biernatia rossica							aff.					aff.		
Numericoma sp.							+					+		
Paterula sp.							+					+		
Rowellella sp. 2							+					+		
Wahwahlingula? sp. 2							+					+		

Taihungshania miqueli Zone (Tab. 2). According to Popov *et al*. (2009a), these brachiopod shells preserved outside their original habitat and were transported offshore by strong storms. The genus *Xinanorthis* is known outside Alborz only in South China.

The Floian brachiopods in eastern Alborz are inadequately known. Among the rhynchonelliforms, only *Yangtzeella longiseptata* Ghobadi Pour *et al*., 2011b, which is the most abundant in the lower part of the Qumes Formation, is formally described, while shells of *Martellia* and *Yichangorthis*, which can be found in shell beds from the upper part of the Gerd-Kuh Member, still require further study (Tab. 4). All three genera are known from the Floian to Darriwilian of South China, but only *Yichangorthis* is confined to the Floian Stage (Rong *et al*. 2017). In contrast, linguliforms, represented by *Thysanotos multispinulosus* Popov *et al*. 2008 and *Leptembolon* sp. (Tab. 4), belong to the distinctive *Thysanotos–Leptembolon* Association (Popov *et al*. 2008), which spread widely during late Tremadocian–Floian times along the margins of Baltica (North Estonia, Holy Cross Mountains in Poland and South Urals) and also occurs in Perunica (Bohemia), which was within the Mediterranean margin of Gondwana at that time (Popov & Holmer 1994; Mergl 1997, 2002; Bednarczyk 1999). The proliferation of the *Thysanotos–Leptembolon* fauna closely coincided with significant environmental changes recorded in Baltoscandia and Alborz, related to the development of a temperate-water (mid-latitude) carbonate production and the proliferation of benthic communities characteristic of the so-called Palaeozoic Evolutionary Fauna (Bassett *et al*. 2002).

The Dapingian brachiopod fauna of Alborz includes a micromorphic linguliform brachiopod association, which occurs in the uppermost carbonate unit of the Qumes Formation at Simeh-Kuh, together with conodonts of the *Baltoniodus navis* Zone, including the eponymous taxon (Popov *et al*. 2008). At Gerd-Kuh, these limestones are laterally replaced by the fine siliciclastic deposits of the Raziabad Member (Figs 3, 6), which contain the so-called *Dirafinesquina* Brachiopod Association (Popov & Cocks 2017). The abundance of the strophomenoid *Dirafinesquina antiqua* Popov & Cocks, 2017, which is the earliest yet documented representative of the Family Rafinesquinidae, is a highly unusual feature. Otherwise, strophomenids of similar age are known only from South and North China (Zhan *et al*. 2013), but there are no rafinesquinids. Other taxa, such as *Eoporambonites raziabadensis* Popov & Cocks, 2017, *Zhanorthis gerdkuhensis* Popov & Cocks, 2017, *Leptastichidia*? sp., *Martellia* aff. *chabdjerehensis* Percival *et al*., 2009, are local endemics or biostratigraphically uninformative, except *Paralenorthis* cf. *suriensis* Benedetto, 2003. The latter is probably conspecific with shells from the uppermost Floian (*Oepikodus evae* Zone) of the Famatina Range in northwest Argentina. A micromorphic linguliform brachiopod assemblage includes species of *Acanthambonia*, *Acrotreta*, *Alichovia*, *Aipyotreta*, *Biernatia*, *Eosiphonotreta*, *Numericoma*, *Paterula* and *Rowellella* (Tab. 4). Most of them were described in open nomenclature, have therefore limited biostratigraphical value, and share a clear biogeographical signature with mid-latitude peri-Gondwana (Avalonia, Bohemia) and subsidiary affinities with South China (Popov *et al*. 2013).

An early Darriwilian (*Lenodus variabilis* conodont Zone) brachiopod fauna was documented by Ghobadi Pour *et al*. (2011c) from the Cheshmeh-Ali Member of the Lashkarak Formation (Figs 3, 10); it is confined to the *Neseuretus* biofacies, characteristic of nearshore shoal complexes. This association includes only four taxa (Tab. 4), two of them, *Bastamorthis multicostata* Ghobadi Pour *et al*., 2011c and *Semnanostrophia lata* Ghobadi Pour *et al*., 2011c, are local endemics, while two other ones, *Martellia*? sp. and *Yangtzeella*? sp., are common in the Floian to Darriwilian of South China. A brachiopod fauna of similar age (*Lenodus variabilis* conodont Zone) is known also from the Gatkuiyeh Formation of the Kerman Region in southern Central Iran. It contains only four taxa, including *Leptellina*? sp., *Martellia shabdjerensis* Percival *et al*., 2009, *Paralenorthis* sp. and an indeterminate strophomenoid that may belong to *Semnanostrophia* (Percival *et al*. 2009).

The mid to late Darriwilian (*Lenodus pseudoplanus* conodont Zone) is characterised in eastern Alborz by the proliferation of the *Saucrorthis* Fauna, known from the Hajiabad Member (Fig. 10), but it is yet unknown from other parts of Iran. The brachiopod assemblage from the lower part of the Chahgonbad Formation (Fig. 4) at the Pol-e Khavand Inlier, south-west of Anarak town in Central Iran, has a similar age but only the genus *Phragmorthis* is common (Popov *et al*. 2015). Another genus that also occurs in the Darriwilian of the eastern Alborz is *Yangtzeella*. It is a distinct component of the *Saucrorthis* Fauna in South China, but it is absent in the Hajiabad Member. The *Saucrorthis* Fauna, exclusively Darriwilian in age, is confined geographically to South China and the Sibumasu terrane. The latter was fringing the Gondwana margin at that time, although the *Saucrorthis* Fauna made a delayed appearance in Alborz by comparison to South China. Detailed discussions of the Iranian *Saucrorthis* Fauna were made by Popov *et al*. (2016). Somewhat unusual is the occurrence in the Hajiabad Member (late Darriwilian) of such genera as *Orthis*, *Pseudocrania* and *Porambonites* (*sensu stricto*), which are otherwise considered as typically Baltoscandian (Bassett *et al*. 2013, Popov *et al*. 2016).

Late Ordovician brachiopods are known in North Iran from the Tatavrud Formation (Figs 1, 4) in the Talesh Mountains (Clark *et al*. 1975), and from the Pelmis Formation (Fig. 3) at the Kopet-Dagh Region, but these records are only based on preliminary identifications. In Central Iran, a small Katian brachiopod fauna includes only three taxa, *Hibernodonta lakhensis* Popov *et al*., 2015, *Hindella prima* Popov *et al*., 2015 and *Rostricellula* cf. *ambigena* (Barrande, 1847), which is known from the upper part of the Chahgonbad Formation (Popov *et al*. 2015) in the Anarak area (Fig. 4). Bassett *et al*. (1999) reported the occurrence of *Cryptothyrella*? (= *Hindella*), *Drabovia*, *Rhynchotrema* and *Rostricellula* in the Gatkuiyeh Formation at the vicinity of Zarand town, Kerman Region (Fig. 1). The Katian age of these brachiopods is well established, but the fauna requires further study. A moderately diverse mid Katian (*Acanthochitina barbata*–*Armoricochitina nigerica* chitinozoan zones) brachiopod fauna was documented by Ghavidel-Syooki *et al*. (2015b) from the Seyahou Formation in the Faraghan Mountains of the Zagros Ranges, southern Iran (Figs 1, 4). This fauna shows strong similarities with contemporaneous faunas of the western Mediterranean region, such as Spain, France, Sardinia, the Carnic Alps and Bohemia.

Graptolites

The first record of Early Ordovician graptolites in Alborz was discovered more than half a century ago (Ruttner *et al*. 1968: p. 39, Stöcklin 1972). Alavi-Naini *et al*. (1982) also reported the occurrence of graptolites in the Ordovician of the Takab area, Zanjan region, western Alborz. Since then, graptolites have received little attention despite their potential biostratigraphical significance. Nevertheless, in the eastern Alborz they are relatively abundant in the upper part of the Simeh-Kuh Formation (Rushton *et al*. 2021). Among them, *Hunnegraptus*? sp. and *Tetragraptus*? sp. (strongly recalling *Tetragraptus longus* Lindholm, 1991), occur in the lower part of the *Asaphellus fecundus–Taihungshania miqueli* trilobite Zone (Tab. 2). *Baltograptus geometricus* (Törnquist, 1901) is the most abundant species in the succeeding upper part of the shale unit (Fig. 6). It is common in the *Cymatograptus protobalticus* graptolite Zone of Baltoscandia (Egenhoff & Maletz 2007) and first appears close to the base of *Prioniodus elegans* conodont Zone (Maletz *et al*. 1996: figs 4, 5). *Baltograptus* cf. *kunmingensis* (Ni, 1979) *in* Mu *et al*. (1979), which occurs up sequence in the Simeh-Kuh Formation (Tab. 2), is probably conspecific with early Floian species from South China. In the Saluk Mountains (Kopet-Dagh), the early planktonic graptolites assigned to *Rhabdinopora* cf. *flabelliformis* (Eichwald, 1840) have been reported from the upper part of *Cordylodus lindstromi* Zone (Jahangir *et al*. 2015, Rushton *et al*. 2021) in the lower part of the Qyzlar Formation (Figs 3, 14). This is the only continuous succession through the Cambrian–Ordovician boundary interval in Iran, where the position of the Ordovician base can be constrained with some degree of precision.

In Central Iran, a moderately rich early Darriwilian graptolite fauna was described by Rickards *et al*. (1994, 2001) from the Gatkuiyeh Formation. It includes numerous dendroid taxa, such as *Callograptus huckriedei* Rickards *et al*., 2001, *Dictyonema bitubulata* Rickards *et al*. 2001, *Dendrograptus* cf. *flexuosus* Hall, 1865, *Acanthograptus divergens* Skevington, 1963 and *Thallograptus*? *succulentus* Ruedemann, 1904, the tuboid graptolite *Galeograptus* sp., the graptoloids *Aulograptus*? sp., *Didymograptus incertus* Perner, 1895, *Undulograptus formosus* (Mu & Lee, 1958) and *Yutagraptus* cf. *mantuanus* Riva, 1994, co-occurring with the rhabdopleurids *Rhabdopleura* aff. *primaevus* (Kozłowski, 1967) and *Kystodendron*? sp., and the hydrozoan coelenterate *Palaeotuba* sp.

Late Ordovician graptolites are known in Iran only from the Faraghan Mountains, located at the southeastern part of the Zagros Ranges. In particular, Rickards *et al*. (2000) reported the occurrence of *Orthograptus amplexicaulis abbreviatus* Elles & Wood, 1907 in the Seyahou Formation (middle Katian) and *Normalograptus persculptus* (Elles & Wood, 1907) in the lowermost Sarchahan Formation (Hirnantian). Subsequently, Ghavidel-Syooki *et al*. (2011) provided more detailed data on the Hirnantian graptolite fauna from the Sarchahan Formation with *Normalograptus ajjeri* (Legrand, 1977), as a dominant species.

Palynomorphs

Among palynomorphs, the chitinozoans are especially useful for the detailed biostratigraphical subdivision and correlation of the Upper Ordovician in northern Iran and especially in the eastern Alborz Mountains. In general, they share strong affinities with the chitinozoans of the Mediterranean margin of Gondwana, and therefore a zonal scheme developed for that region (Paris 1990) can be applied (Fig. 16). In Kopet-Dagh Region, an almost continuous succession from the mid Katian *Tanuchitina fistulosa* Zone to the Hirnantian *Spinachitina oulebsiri* Zone was reported by Ghavidel-Syooki (2017c) for the type section of the Ghelli Formation, north of Ghelli village in the Saluk Mountains (Figs 1, 3; Tab. 5). In the eastern Alborz, the most complete Katian–Hirnantian biostratigraphical succession from the *Belonechitina robusta* to the *Spinachitina oulebsiri* zones was documented by Ghavidel-Syooki (2008) for the 'Gorgan Schists' at the vicinity of Radkan village (Fig. 2, Tab. 5); however, the presence of the *Tanuchitina fistulosa* Zone was not confirmed. Data on chitinozoans also demonstrated a Katian age for the base of the Abarsaj Formation, in the Kholin-Darreh and Khoshyeilaq not older than the *Armoricochitina nigerica* Zone (Ghavidel-Syooki *et al*. 2011, Ghavidel-Syooki 2017a), although the late Hirnantian age of the uppermost part of the unit was confirmed in both cases. In the absence of chitinozoans, the Katian age for the lower part of the Abarsaj Formation in its type section and in Deh-Molla area was confirmed by acritarchs (Ghavidel-Syooki 2006, Ghavidel-Syooki & Khandabi 2013), as discussed above. These data clearly demonstrate the existence of a considerable hiatus in the Ordovician succession of the eastern Alborz Mountains that includes the entire Sandbian. Also the acritarch data point to a Tremadocian age for the unnamed siliciclastic unit (Avesta Beds; Figs 3, 4) underlying the Abarsaj Formation, north of the Shahrud Fault (Ghavidel-Syooki 2017a), suggesting even a wider gap in the Ordovician succession of the Alestan Domain, on the northern part of eastern Alborz (Figs 2, 3).

In addition, rich cryptospore and trilete spore assemblages have been recently documented from the Katian–Hirnantian of the Saluk Mountains in Kopet-Dagh (Ghavidel-Syooki 2017b). While a formal biozonal scheme has not yet been proposed, three succeeding cryptospore assemblages were recognised in the aforementioned deposits assigned to the Pelmis Formation, two of them corresponding to the *Armoricochitina nigerica* Zone and the third one to the late Katian *Ancyrochitina merga* Zone plus Hirnantian. A total of 26 cryptospore species were recognised plus two trilete taxa, including *Ambitisporites avitus* Hoffmeister *sensu* Steemans *et al*., 1996 and *Retusotriletes* sp. According to Ghavidel-Syooki (2017b),

Table 5. Stratigraphical and geographical distribution of Katian–Hirnantian chitinozoan species in the eastern Alborz and Kopet-Dagh.

Stage/Region	Katian					Hirn.		Eastern Alborz						Kopet-Dagh		
Chitinozoan biozone/ locality	*Belonechitina robusta* Zone	*Tanuchitina fistulosa* Zone	*Acanthochitina barbata* Zone	*Armoricochitina nigerica* Zone	*Ancyrochitina merga* Zone	*Tanuchitina elongata* Zone	*Spinachitina oulebsiri* Zone	Abarsaj	Cheshmeh-Seyed	Kholin-Darreh	Khoshyeilagh	Radkan	Ghelli	Pelmis	Rabat-e Qarabil
CHITINOZOA															
Belonechitina micracantha	+											+			
Belonechitina robusta	+											+			
Belonechitina wesenbergensis	+	+	+	+	+							+	+		
Calpichitina lenticularis		+	+	+	+	+	+			+	+	+	+	+	
Conochitina chidea	+											+			
Cyathochitina campanulaeformis	+	+	+	+	+					+		+	+		
Euconochitina communis	+											+			
Pistillachitina pistillifrons	+	+	+	+								+	+		
Rhabdochitina usitata	+			+						+		+			
Cyathochitina latipatagium		+	+	+	+							+	+		
Desmochitina minor		+	+	+	+	+		+		+	+		+		
Desmochitina mortoni		+	+	+	+								+		
Desmochitina typica		+	+	+	+	+	+						+		
Sphaerochitina sp.		+	+	+	+								+		
Spinachitina ourneidaensis		cf.	cf.	cf.	cf.								cf.		
Tanuchitina fistulosa		+	+	+	+								+		
Acanthochitina barbata			+	+	+				+				+	+	
Acanthochitina latebrosa			+	+	+								+		
Angochitina communis			+	+								+	+	+	
Armoricochitina iranica			+	+	+	+				+	+		+		
Armoricochitina persianense			+	+	+								+		
Desmochitina piriformis												+			
Euconochitina lepta			+	+	+								+	+	
Fungochitina actonica			+	+	+								+		
Fungochitina spinifera			+	+	+								+		
Hyalochitina jajarmensis			+	+	+								+		
Lagenochitina baltica			+	+	+	+	+		+	+		+	+		
Spinachitina bulmani			+	+	+					+	+	+	+		
Armoricochitina alborzensis				+	+	+				+					
Armoricochitina nigerica				+	+	+	+	+	+	+	+	+	+	+	
Desmochitina cocca				+						+		+			
Desmochitina juglandiformis				+	+					+					
Ancyrochitina merga					+			+	+	+		+	+	+	
Cyathochitina campanulaeformis					+	+	+			+					
Desmochitina juglandiformis					cf.								cf.		
Desmochitina nodosa					+	+	+			+		+			
Desmochitina ernacea					+	+				+					

Table 5. Continued.

Stage/Region	Katian					Hirn.		Eastern Alborz					Kopet-Dagh		
Chitinozoan biozone/ locality	*Belonechitina robusta* Zone	*Tanuchitina fistulosa* Zone	*Acanthochitina barbata* Zone	*Armoricochitina nigerica* Zone	*Ancyrochitina merga* Zone	*Tanuchitina elongata* Zone	*Spinachitina oulebsiri* Zone	Abarsaj	Cheshmeh-Seyed	Kholin-Darreh	Khoshyeilagh	Radkan	Ghelli	Pelmis	Rabat-e Qarabil
Euconochitina lepta					+	+	+			+		+			
Hyalochitina hyalophrys					+								+		
Lagenochitina prussica					+	+	+		+	+		+			
Plectochitina cocinna					+					+					
Plectochitina sylvanica					+					+		+			
Euconochitina communis				+					+						
Euconochitina lepta					+	+			+				+		
Kalochitina multispinata				?					+						
Rhabdochitina gracilis					+	+				+		+			
Conochitina rotundata						+	+						+		
Hercochitina crickmayi						+				+		+			
Pistillachitina comma						+	+					+	+		
Tanuchitina alborzensis						+							+		
Tanuchitina elongata						+				+		+	+	+	
Tanuchitina ontariensis						+						+			
Spinachitina oulebsiri							+			+		+	+	+	
Belonechitina kordkuyensis							+					+			
Belonechitina tenuicomata							+						+		
Cyathochitina caputoi							+						+	+	
Euconochitina moussegoudaensis							+					+		+	
Hercochitina spinetum					cf.		cf.				cf.		cf.		
Spinachitina iranense							+						+		
Spinachitina aidaensis							+					+			
Tanuchitina anticostiensis							+						+		

some cryptospores significantly outnumber other palynomorph remains (*e.g.* acritarchs and chitinozoans) in residues from the Upper Ordovician deposits, here assigned to the Pelmis Formation in the Saluk Mountains. The cryptospores preserved in shallow marine (shoreface) deposits were likely brought from the land nearby.

Echinoderms

The Early Ordovician echinoderms from eastern Alborz are poorly known. To date, the only taxon identified is the rhombiferan *Macrocystella* sp., which occasionally occurs as disarticulated plates in the *Asaphellus inflatus*–*Dactylocephalus* Zone at Deh-Molla. A significant proliferation of echinoderms is evident in mid Darriwilian times. It starts with the broad development of distinct echinoderm ossicle beds comprising densely packed thecae of *Echinosphaerites* sp. These bioaccumulations are laterally traceable through the middle part of the Hajiabad Member (Lashkarak Formation) across the Gerd-Kuh and Simeh-Kuh areas, (Figs 2, 3). Conodonts found in the limestone beds about that level suggest their inclusion in the *Lenodus pseudoplanus* Zone (Nestell *et al*. 2016). Remarkably, about that time, *Echinosphaerites* invaded the Baltoscandian Basin, where it became ubiquitous in the upper part of the Kunda and Aseri regional stages. A diverse echinoderm fauna was documented by Lefebvre *et al*. (2005) from the Hajiabad Member at Simeh-Kuh. It includes fistuliporate (*Echinosphaerites* sp. and *Heliocrinites* sp.) and dichoporite (unidentified hemicosmitids and glyptocystitids), rhombiferans, aristocystitides (*Sinocystis* sp.) and sphaeronitides (*Glyptosphaerites* sp. and *Tholocystis* sp.) (Fig. 10, Tab. 3). A diverse echinoderm assemblage, including *Archegocystis*? sp., *Aristocystis* sp., *Echinosphaerites* and *Sinocystis*, was reported by Gansser & Huber (1962) and Glaus (1965) from the Lashkarak Formation, exposed in the eponymous mountain (Figs 1, 3). In addition *Echinosphaerites* sp. also occurs at the base of the Pelmis Formation. As pointed out by Lefebvre *et al*. (2005), *Codiacystis* may belong or be closely related to *Tholocystis*, but this cannot be confirmed without the re-study of original specimens. According to the authors, the presence of aristocystids suggests close biogeographical links of the Darriwilian echinoderm fauna from Alborz with contemporaneous Ordovician faunas of the Mediterranean peri-Gondwana, South China and Sibumasu, which is also supported by biogeographical analyses of trilobites and brachiopods.

There are few reports of Late Ordovician echinoderm occurrences in Iran, and all of them are located outside the Alborz Mountains. *Pleurocystites* sp. and unidentified rhombiferans are the only fossils yet reported (Alavi-Naini 1972) from the Upper Ordovician of the Djam Inlier (Fig. 1). A small echinoderm association is documented from the Upper Ordovician part of the Seyahou Formation (*Armoricochitina nigerica* Zone, Katian) (Fig. 4) in the southeast of Zagros Ranges (Ghavidel-Syooki *et al*. 2015a). The assemblage includes the cosmopolitan crinoid *Ristnacrinus*, a crinoid of uncertain affinity assigned to *Rosulicrinus rosulus* Stukalina, 1980, which is known only from disarticulated columnals and otherwise occurs in the middle Katian (Akkol Beds) of the Chu-Ili terrane at southern Kazakhstan (Stukalina, 1980), and enigmatic *Sumsaricystis radiatus* Stukalina, 1978, also known exclusively from dissociated columnals. The later taxon is quite common in the middle Katian Obikalon Beds of the Zerafshan Range in southern Uzbekistan (Stukalina, 1978).

Molluscs

Molluscs are represented in the Early–Middle Ordovician of eastern Alborz by bivalves, gastropods and cephalopods, but they remain a minor component of the fossil record. Only cephalopods show significant proliferation across Iran in mid to late Darriwilian times. Their inadequate preservation precludes their identification, which is only to generic level. The earliest yet documented cephalopod from Iran is *Bactroceras* sp. from the Simeh-Kuh Formation (*Asaphellus fecundus–Taihungshania miqueli* Zone) (Tab. 2) of Simeh-Kuh in eastern Alborz. This is one of the earliest occurrences of the genus, approximately contemporaneous with that of Montagne Noire, France (Kröger & Evans 2011, Evans *et al*. 2013). Darriwilian cephalopods are also rare in eastern Alborz, where they are represented by only two genera, *Protocyclendoceras* and *Virgoceras*, which occur in the Hajiabad Member of the Lashkarak Formation (Tab. 3). *Eosomichelinoceras* sp., *Proterovaginoceras incognitum*? and *Sactorthoceras* sp. allegedly occur in the Darriwilian (probably Hajiabad Member) of the Abarsaj section (Bogolepova *et al*. 2014), but the provided geological and locality data are doubtful.

Cephalopods are rather common in the oolitic ironstone bed that marks the base of the Pelmis Formation in the eastern Saluk Mountains (Evans *et al.* 2021). The moderately rich Darriwilian assemblage includes *Eosomichelinoceras huananense* Chen, 1974, *Sorosoceras castellum* Evans, 2021 *in* Evans *et al*. (2021), *Orthoceras*? sp., *Virgoceras*? sp., *Wennanoceras* aff. *costatum* Chen, 1976.

Rich cephalopod faunas were documented from the Darriwilian of Central Iran, in particular, from the lower part of the Chahgonbad Formation in the Anarak Region (Popov *et al*. 2015) and the middle part of the Shirgesht Formation in the Derenjal Mountains (Evans *et al*. 2013). Late Ordovician cephalopods are known from the upper Gatkuiyeh Formation (Katian) of the Kerman Region, where they are represented by the single species *Sactorthoceras banestanensis* Evans, 2006 *in* Dastanpour *et al*. (2006), and from the Seyahou Formation (*Acanthochitina barbata* and *Armoricochitina nigerica* zones, Katian) of the Faraghan Mountains in the southeastern Zagros Ranges (Fig. 1), where the occurrence of *Geisonocerina dargazense* Evans, 2015 *in* Ghavidel-Syooki *et al*. (2015a), *Isorthoceras* cf. *bisignatum* (Barrande, 1870) and *Sactorthoceras*? sp. were documented by Ghavidel-Syooki *et al*. (2015a).

Bivalves made their first appearance in northern Iran in the late Tremadocian. A small assemblage, including *Glyptarca* sp. and *Pensarnia* aff. *laeviformis* Cope, 1996, was recently discovered in the upper Simeh-Kuh Formation (*Asaphellus fecundus–Taihungshania miqueli* Zone, Tremadocian) of Simeh-Kuh in eastern Alborz (Fig. 2, Tab. 4). It is among the oldest Ordovician bivalve faunas (Cope & Ghobadi Pour 2020) so far known. These bivalves show close affinities with the Floian (lower Arenig Series) bivalve fauna of Avalonia described by Cope (1996), but is much less diverse. Mid Ordovician bivalves are as yet unknown from Iran, while Late Ordovician (Katian) bivalves are relatively common in Kopet-Dagh, Central Iran and the southern Zagros Ranges, though they are in need of revision.

Gastropods are almost unknown in the Ordovician of northern Iran. The only species yet discovered is *Lesueurilla prima* Barrande, 1903 *in* Perner (1903), which occurs in association with the *Saucrorthis* brachiopod fauna, in the Hajiabad Member (middle to upper Darriwilian) of Deh-Molla in eastern Alborz. The same species is also known from the middle part of the Shirgesht Formation (Darriwilian) in the Derenjal Mountains, eastern Central Iran (Ebbestad *et al*. 2016), where it occurs associated with *Sinuites* sp. and the trilobite *Neseuretinus birmanicus*. *Lesueurilla prima* has a relatively wide stratigraphical range, although it is mainly confined geographically to the cold-water faunas of the Mediterranean margin of Gondwana (Horný 1997, Ebbestad *et al*. 2016). The only other gastropod fauna yet known from Iran was described by Ebbestad *et al*. (2008) from the Katian Gatkuiyeh Formation of the Kerman Region in eastern Central Iran. It includes seven species with *Tritonophon peeli* Horný, 1997 as dominant taxon, and also shows clear biogeographical links with the Mediterranean Gondwana cold-water faunas.

Foraminifera

Agglutinated benthic foraminifers are relatively common in the Ordovician, but usually remain overlooked. In the Darriwilian of Alborz they firstly appear in the Cheshmeh-Ali Member, where specimens of *Psammosphaera rugosa* Eisenack,1954 were recovered from brachiopod shell beds together with conodonts of the *Lenodus variabilis* Zone (Nestell *et al*. 2016) (Fig. 3, Tab. 3). A more diverse assemblage was recovered from a limestone bed of the Hajiabad Member at Simeh-Kuh, where they co-occur with abundant ostracods (Fig. 3, Tab. 3). The fauna includes *Amphitremoida simehkuhensis* Nestell & Ghobadi Pour, 2016 *in* Nestell *et al*. (2016), *A*. aff. *longa* Nestell & Tolmacheva, 2004, *Damghanites lashkarakensis* Nestell & Ghobadi Pour, 2016 *in* Nestell *et al*. (2016), *Psammosphaera rugosa* Eisenack, 1954, *Sorosphaera iranensis* Nestell & Ghobadi Pour, 2016 *in* Nestell *et al*. (2016), *S. darriwiliensis* Nestell & Ghobadi Pour, 2016 *in* Nestell *et al*. (2016), and *S*.? aff. *tricella* Moreman, 1930. Apart from other occurrences in South China, there are no other reports on Ordovician foraminifers in peri-Gondwana. Therefore, it is not surprising that most of the listed taxa are endemic to eastern Alborz.

Ordovician igneous and metamorphic rocks

Volcanic rocks of Alborz and Kopet-Dagh

The first signs of volcanism in the eastern Alborz Mountains are Darriwilian in age, and represented by tuff beds deposited in the middle and upper part of the Hajiabad Member in Gerd-Kuh and Abarsaj. These occur in close association with oolitic ironstone beds, which are traceable farther east towards Simeh-Kuh and Deh-Molla (Fig. 3). There are diabase sills within the Lower–Middle Ordovician deposits at Gerd-Kuh and Simeh-Kuh, and seem to be related to the Late Devonian volcanism of the area (Álvaro *et al*. 2022).

Basalts of Katian age are common in the Abarsaj Formation. They have been studied in the Shahvar and Siaheh mountains, north of Bastam town, and in the Deh-Molla area, all in vicinity of Shahrud city (Ghasemi & Kazemi 2013). These volcanic units are amygdaloidal trachybasalt submarine lava flows. They also contain xenoliths of sandstone and siltstone probably derived from the underlying Abarsaj Formation. Ghasemi & Kazemi (2013) considered these basalts as a product of rift-related intraplate volcanism. There are also sills and dykes of micro-gabbro rocks, which were linked to the extensive Silurian volcanism in the area by the same authors.

Volcanic rocks of the overlying Soltan-Maidan Formation vary from basalt to basalt with transitional to alkaline natures (Derakhshi & Ghasemi 2015). While the age of the thick, predominantly volcanic Soltan-Maidan Formation is often considered as presumably Silurian, there is a clear evidence for extensive Late Ordovician (Katian–Hirnantian) basalt volcanic episodes in eastern Alborz (Derakhshi 2014; Derakhshi & Ghasemi 2015; Derakhshi *et al*. 2017, 2022). In particular, a 1300 m thick succession of basalts exposed along the Cheshmeh-Seyed valley, Siaheh Mountains (Figs 2, 17) is subdivided into two parts by a ~ 220 m interval including two sedimentrary units (Derakhshi *et al*. 2017: fig. 2, c1, c2). Both sedimentary units are rich in Late Ordovician acritarchs and chitinozoans, including *Acanthochitina barbata* Eisenack, 1931, *Ancyrochitina merga* Jenkins, 1970, *Armoricochitina nigerica* Bouché, 1965, *Euconochitina communis* Taugourdeau, 1961, *Euconochitina lepta* (Jenkins, 1970), *Kalochitina multispinata* (Jansonius, 1964), *Lagenochitina baltica* Eisenack, 1931 and *Lagenochitina prussica* Eisenack, 1931. While no precise ranges of chitinozoan species were reported from the Cheshmeh-Seyed valley section by Derakhshi (2014), it is important to note that *E. communis* do not overlap stratigraphically with *A. merga* in the Mediterranean chitinozoan biostratigraphical chart. Therefore it is probable that *E. communis* is most probably derived from the sedimentary unit ‘C1’, while *A. merga* is possibly confined to the sedimentary unit ‘C2’ (Fig. 17). There is no distinct Hirnantian chitinozoan taxa in the provided list, suggesting a late Katian age for the sedimentary units ‘C1’ and ‘C2’. Nevertheless, *Ancyrochitina merga* ranges up to the lower part of the *Spinachitina oulebsiri* Zone. This volcano-sedimentary interval represents a stratigraphical equivalent of the Abarsaj Formation from the Khoshyeilaq and Kholin-Darreh sections (Figs 3, 17) and therefore here it is assigned to the same formation. This implies that over 830 m of basalts below unit C1 in Cheshmeh-Seyed have early Katian and older ages. Álvaro *et al*. (2022) named them provisionally the 'Abr Basalts' after the Abr village situated at the southern foothills of the Siaheh Mountains (Fig. 2). Accordingly, the extensive basaltic volcanism occurred at the time of the widespread Sandbian–early Katian hiatus documented in numerous sections across the Damghan and Alestan domains (Fig. 3).

In the vicinity of Khoshyeilaq village, the Abarsaj Formation (as defined above) is underlain by a barren unit of brown, pebbly conglomerates and purple argillites of uncertain age, resting on pillow basalts, *c*. 120 m thick. As well as the lower part of the Abarsaj Formation containing chitinozoans characteristic of the *Armoricochitina nigerica* Zone, including the eponymous species (Ghavidel-Syooki *et al*. 2011), this volcanic unit can be correlated with the lowermost basalt bed of the Abarsaj Formation at the Abarsaj section in the Avesta valley (Fig. 17). Pillow lava basalts separated by thin sandstone and siltstone interbeds form another basaltic unit with distinctive columnar jointing (Fig. 18E) that erupted under subaerial conditions (Derakhshi & Ghasemi 2015). The age constraint of the 'Abr Basalts' is poor; nevertheless, they are definitely the oldest volcanic rocks documented from the Ordovican succession of the Alestan Domain (Fig. 2). The widespread Sandbian hiatus in the sedimentary successions across eastern Alborz suggests that subaerial basaltic eruptions might have occurred at that time. Also these basalts can be considered as a source of the tuffs reported from the Hajiabad Member of the Lashkarak Formation.

The basaltic lavas of the Ghelli Formation, in the eastern Saluk Mountains, are considered slightly older equivalents of the Soltan-Maidan basalts, and suggest that the Early Palaeozoic rifting magmatism started earlier in the Kopet-Dagh Region. In this region, the earliest records of mafic extrusive volcanism are evident since the Tremadocian. In particular, the Tremadocian–lower Floian Qyzlar Formation exposed on the western side of the Kalat river valley, in the eastern part of the Saluk Mountains, contains basaltic rocks (Figs 2, 14).

In the western Saluk Mountains, three units of basaltic volcanic rocks are recognized, exceeding 200 m in the type section and some places up to 600 m in thickness in the lower member of the Ghelli Formation (Fig. 13E). While attribution of these basaltic eruptions to the intraplate rift-related volcanism is likely, their detailed geochemistry remains unknown. However, the early Darriwilian basalts (468.7 ± 0.3 Ma) documented by Derakhshi *et al*. (2022) from the eastern Binalud Mountains, in the vicinity of Neyshabur city (Fig. 1), show geochemical characteristic closely similar to those of the Soltan-Maidan basalts (Derakhshi *et al*. 2022: figs 20, 21). The basic tuffs and overlying oolitic ironstone bed, which are documented at the base of the Pelmis Formation at the Kalat section (Figs 13B, 15), are considered Darriwilian in age.

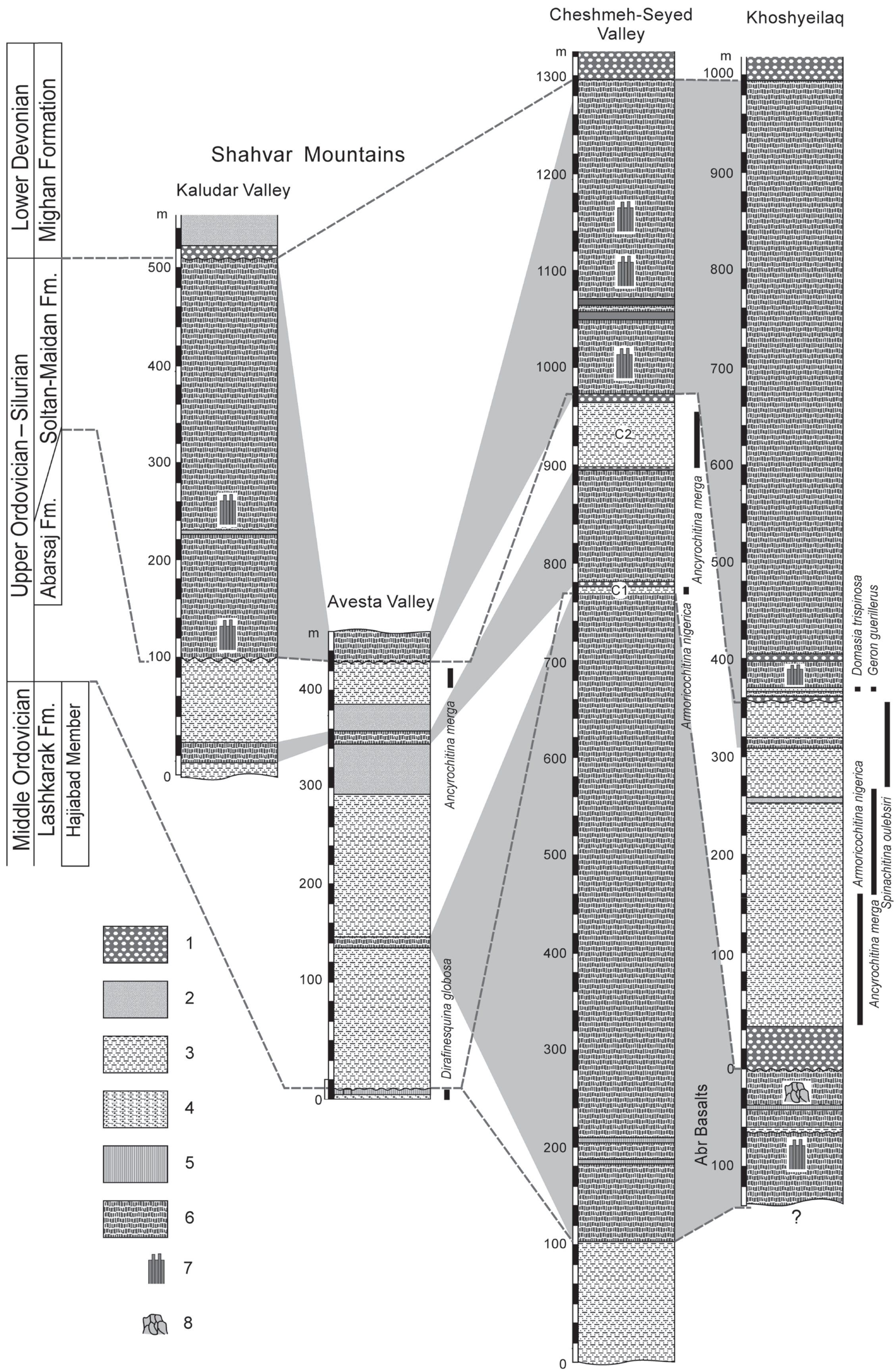
A *c*. 40–200 m thick unit of basaltic rocks is characteristic for the middle part of the Pelmis Formation (*Ancyrochitina merga* Zone, Katian) (Figs 13A, 15). This unit is not synchronous with the basalt unit from the Ghelli Formation upper 'mélange' member of the Ghelli section (Fig. 1), which is likely of Hirnantian age (Ghavidel- Syooki 2017c). Also the so-called 'Dasht basalts' cropping out west of the Dasht village (Fig. 1) has a younger, Llandovery age (442.5 ± 2.5 Ma), as reported by Derakhshi *et al*. (2022). A similar stratigraphical position can be inferred for the basalt unit that marks the base of the Silurian in the Rabat-e Qarabil section (Ghaderi *et al.* 2018) (Fig. 1).

In the Talesh Mountains, the Upper Ordovician Tatavrud Formation is underlain by a succession of spilitic volcanic rocks, tuffs and tuffaceous sandstones, *c*. 100–140 m thick (Clark *et al*. 1975). The Ordovician age of this volcanic unit has not been sufficiently proved and requires further study.

'Gorgan Schists'

The 'Gorgan Schists' represent a metamorphic complex exposed along the northern foothills of the Alborz Mountains, about 105 km, between Galugah at the west and Aliabad-e Katul town at the east (Fig. 2). The name was introduced by Gannser (1951) for a suite of phyllites, sericite-chlorite schists, quartzites and metabasalts. The 'Gorgan Schists' are unconformably overlain by the Upper Triassic–Jurassic Shemshak Formation, which contains pebbles reworked from the underlying metamorphic rocks forming a basal conglomerate lag (Berberian *et al*. 1973). The age of the 'Gorgan Schists' was uncertain for some time (for details, see Ghavidel-Syooki 2008, Ghasemi *et al*. 2015), but now there are sufficient arguments to support a Katian–Hirnantian age (*Belonechitina robusta–Tanuchitina elongata* chitinozoan zones) for the metasedimentary rocks (Fig. 18H), and a Hirnantian age (*Tanuchitina elongata–Spinachitina oulebsiri* chitinozoan zones) for the overlying metabasalts (Ghavidel-Syooki 2008).

Figure 17. Simplified stratigraphical logs showing Ordovician and Silurian succession including the Abarsaj and Soltan-Maidan formations at southern part of the Alestan Domain and stratigraphical ranges of selected biostratigrapnically indicative species of acritarchs, chitinozoans and brachiopods (mainly after Ghavidel-Syooki *et al.* 2011; Ghavidel-Syooki & Khandabi 2013; Derakhshi & Ghasemi 2015; Derakhshi *et al*. 2017, 2022 with modifications). Lithologies: 1 – conglomerates; 2 – sandstones; 3 – sandstone and siltstone intercalations; 4 – oolitic ironstones; 5 – tuffs; 6 – basalt volcanic rocks; 7 – columnar jointing; 8 – pillow basalts.


Lower Devonian
Mighan Formation
Upper Ordovician–Silurian
Soltan-Maidan Fm.
Abarsaj Fm.
Middle Ordovician
Lashkarak Fm.
Hajiabad Member
Shahvar Mountains
Kaludar Valley
Avesta Valley
Cheshmeh-Seyed Valley
Khoshyeilaq
Ancyrochitina merga
Dirafinesquina globosa
Armoricochitina nigerica
Abr Basalts
Domasia trispinosa
Geron guerillerus
Spinachitina oulebsiri
C1
C2
1
2
3
4
5
6
7
8

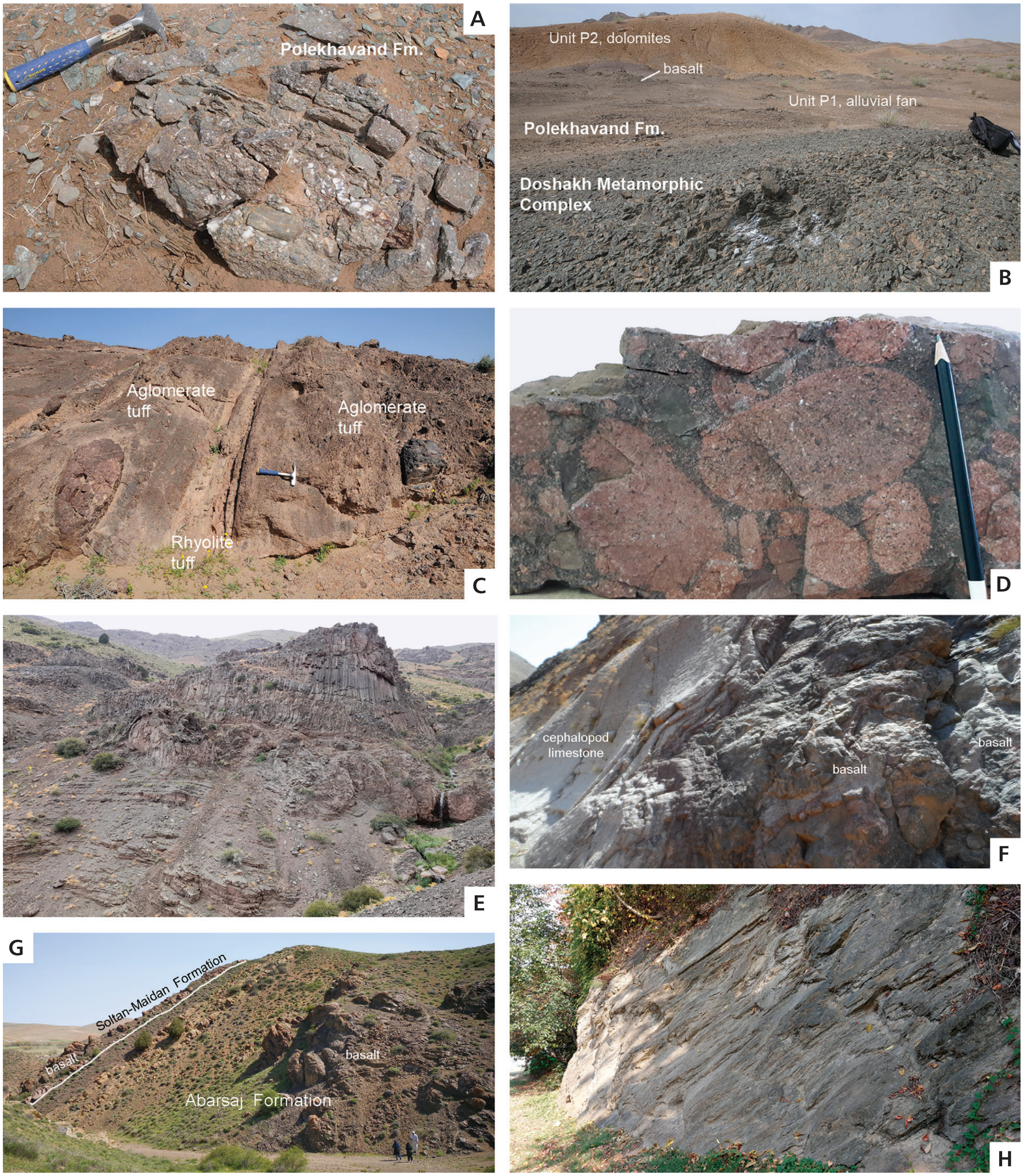


Figure 18. A – close up view of basal conglomeratic lens of the lower part of the Polekhavand Formation, probably resulted from channel-fill deposits. • B – southerly view of the unconformable boundary between green schists of the Doshakh metamorphic complex and basal part of the Polekhavand Formation, southeast of Anarak. • C – westerly view of the rhyolite and agglomerate tuffs exposure (Polekhavand Formation unit 4) at Polekhavand Inlier, southeast of Anarak. • D – plagiogranite xenoliths in basalts of the Soltan-Maidan Formation from the west side of the road connecting Shahrud and Azadshahr, south west of the Khoshyeilaq village. • E – northern view of the exposure north of the Nekarman village showing the upper part of the Abarsaj Formation and overlying basalts of the Soltan-Maidan Formation with well-developed columnar joints. F – north-western view of exposure showing a cephalopod limestone bed at the base of the Ghelli Formation middle member and underlying basalts of the lower member at north of the Ghelli village, Saluk Mountains. • G – natural exposure of the Ordovician–Silurian boundary beds in the vicinity of Khoshyeilaq. The siliciclastic rocks of the uppermost Abarsaj Formation between two basaltic units contain Hirnantian chitinozoans of the *Spinachitina oulebsiri* Zone (Ghavidel-Syooki *et al*. 2011: fig. 2). The shale bed within basalts of the overlying Soltan-Maidan Formation contains Silurian palynomorphs. • H – natural exposure of the 'Gorgan Schists' metasedimentary rocks at Nahar-Khoran, southern outskirts of the city of Gorgan.

The age of metamorphism is considered now as mid–late Triassic (Ghasemi *et al*. 2015). Remarkably, the stratigraphical relationship between the metasedimentary and metavolcanic units within the 'Gorgan Schists' is opposite to that reported by Stöklin & Setudehnia (1991). Ghasemi *et al*. (2015) pointed out a strong similarity in the age, petrology, magmatic sources and geochemistry between the metavolcanic rocks of the 'Gorgan Schists' and the basaltic rocks from the upper part of the Upper Ordovician deposits, assignable to the Abarsaj Formation, and to the volcanic rocks of the Soltan-Maidan Formation. Therefore, it is likely that the protoliths of the 'Gorgan Schists' were fine siliciclastic and basaltic rocks of the Abarsaj Formation and basalts of the Soltan-Maidan Formation (Álvaro *et al*. 2022). Another important point which should be considered is a close association of the Upper Ordovician Abarsaj Formation and the Soltan-Maidan basalts of Late Ordovician to Silurian age (Derakhshi *et al*. 2017) in the north of the Shahrud Thrust Fault. A thick unit of metavolcanic rocks, reported by Ghavidel-Syooki (2008) at the top of the 'Gorgan Schists', and dated as Hirnantian, may represent a metamorphosed counterpart of the Soltan-Maidan volcanic rocks. Recent published evidence by Derakhshi *et al*. (2017, 2022) clearly suggests that extensive basalt extrusive volcanism occurred, at least in part, synchronously throughout these areas of eastern Alborz. A report by Hubber (*in* Stöklin & Setudehnia 1991) focused on a possible occurrence of tentaculites in quartzites associated with the 'Gorgan Schists' would suggest a Silurian age for some rocks incorporated into the metamorphic complex.

Volcano-sedimentary succession at Pol-e Khavand Inlier and Airekan granites

The Palaeozoic margin of the East-Central Iranian Plate was significantly destroyed by arc-continent collision, which occurred in the Late Triassic (Bagheri & Stampfli 2008). Yet it can be observed in Pol-e Khavand and Taknar inliers (Müller & Walter 1984, Hairapetian *et al*. 2015). The Lower Palaeozoic succession at Pol-e Khavand (33° 10′ N, 53° 53′ E), southwest of Anarak (Figs 1, 19), includes the volcano-sedimentary Polekhavand and siliciclastic Chahgonbad formations. Detailed characterisation of both lithostratigraphical units was given by Hairapetian *et al*. (2015) and Popov *et al*. (2015).

The lower part of the Polekhavand Formation comprises alluvial fan (sandstones, gritstones and polymict conglomerates) deposits topped by an amygdaloidal basalt member (Figs 18A, B; 20, unit 1). The middle and upper parts of the formation consists of more than 110 m of felsic tuffs and mass flow deposits (Figs 18C, 20, unit 4), probably deposited on the slope of a volcanic build-up.

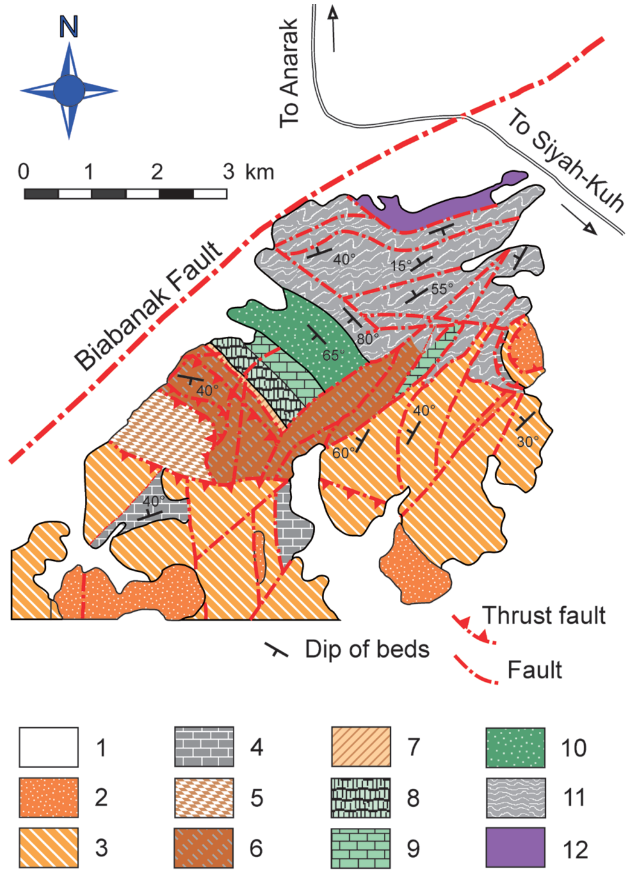


Figure 19. Simplified geological map (slightly modified after Sharkovski *et al*. 1984) of the Pol-e Khavand area southeast of Anarak. Legend: 1 – Pliocene–Holocene sediments, unspecified; 2 – Permian–Triassic (dolomite), unspecified; 3 – Permian, Jamal Formation; 4 – upper Carboniferous–lower Permian Anarak and Sardar groups; 5 – Upper Devonian–lower Carboniferous, Shishtu Formation; 6 – Middle–Upper Devonian, Bahram Formation; 7 – Middle Devonian, Sibzar Formation; 8 – Silurian–Lower Devonian?, unspecified; 9 – Silurian (Llandovery), Boghu Formation; 10 – Cambrian (Furongian)?–Upper Ordovician, Polekhavand and Chahgonbad formations; 11 – Doshakh metamorphic unit; 12 – ultramafic rocks, unspecified.

The acidic volcanism at the Pol-e Khavand Inlier points to the former existence of a pre–Darriwilian continental active margin along the northern boundary (recent coordinates) of the East-Central Iranian Plate facing the Sabzevar tectonic Domain (Fig. 1); however, in the absence of biostratigraphical or geochronological dating, the age of the volcanism remains an unresolved issue. The Polekhavand Formation rests non-conformably on the green schists of the Doshakh metamorphic unit, which is considered by Bagheri & Stampfli (2008) as a remnant of the Triassic accretionary wedge; however, the Triassic age of the unit looks questionable, because green schists and quartz clasts derived from it are redeposited as basal conglomeratic lenses of the Polekhavand Formation (Figs 7K, 18A), probably resulted from channel-fill deposits.

The clasts of high pressure metamorphic rocks occur also occasionally in these conglomerates. The Doshakh metamorphic rocks belong to the heterogeneous Anarak Metamorphic Complex (Bagheri & Stampfli 2008, Buchs *et al*. 2013). According to the cited researchers, there are two other metamorphic events recorded in the area, dated as Late Devonian–early Carboniferous and Late Triassic, but their effect on the Ordovician rocks at Pol-e Khavand is negligible. Therefore, the metamorphism and subsequent exhumation of the Doshakh metamorphic unit occurred in pre–Darriwilian times.

The Anarak Metamorphic Complex includes a carbonate unit informally named the Lakh Marbles. Bagheri & Stampfli (2008) inferred that the unit represents a remnant of the Permian reefal build-up grown on a volcanic seamount. They reported the occurrence of frame-building fossils (*e.g*. corals, bryozoans), but no taxonomic identifications were provided, and they dismissed earlier reports (Sharkovski *et al*. 1984) focused on the occurrence of early Cambrian archaeocyathids as being unsupported by actual evidence. Yet description of the Lakh Marbles succession with locality data and photographs of 'archaeocyathids' assigned to *Coscinocyathus* sp. and *Dictocyathus* sp. (Mel'nikov *et al*. 1986: fig. 4). Kruse & Zhuravlev (2008) revised the presumed 'archaeocyathids' from the Lakh Marbles, presently housed in the Palaeontological Institute of Moscow, and concluded that they represent naturally extracted specimens of the desmosponge *Rankenella* associated with eocrinoid oscicles. In the eastern Alborz, *Rankenella* occurs as an important reef-builder in the Mila Formation Member 3 (Cambrian, Paibian–Jiangshanian) (Kruse & Zhuravlev 2008).

The occurrence of *Rankenella* leaves no doubt about the Cambrian (Miaolingian to early Furongian) age of the unit. The minimum age of the metamorphism that transformed protoliths to metamorphic rocks, subsequently incorporated as pebbles into the Anarak Complex, would be Furongian. Consequently, the age of the Polekhavand Formation overlapping the Doshakh metamorphic unit is probably within the range from the Furongian to Middle Ordovician.

The Airekan Complex of peraluminous S-type granites is exposed on the northern margin of the East-Central Iranian Plate, *c*. 140 km northeast of Anarak (Fig. 1C). According to Shirdashtzadeh *et al*. (2018), the crystallization age of this granite is 483 ± 2.9 Ma, hence they may represent an Early Ordovician (Tremadocian) arc-related magmatic episode approximately synchronous with the rhyolite extrusive volcanism at Pol-e Khavand (Hairapetian *et al*. 2015). The Airkan granites were affected also by a high grade metamorphic event that took place in Mid Devonian times (382.6 Ma). It is not synchronous with the metamorphic age (326.50 ± 1.79 Ma)

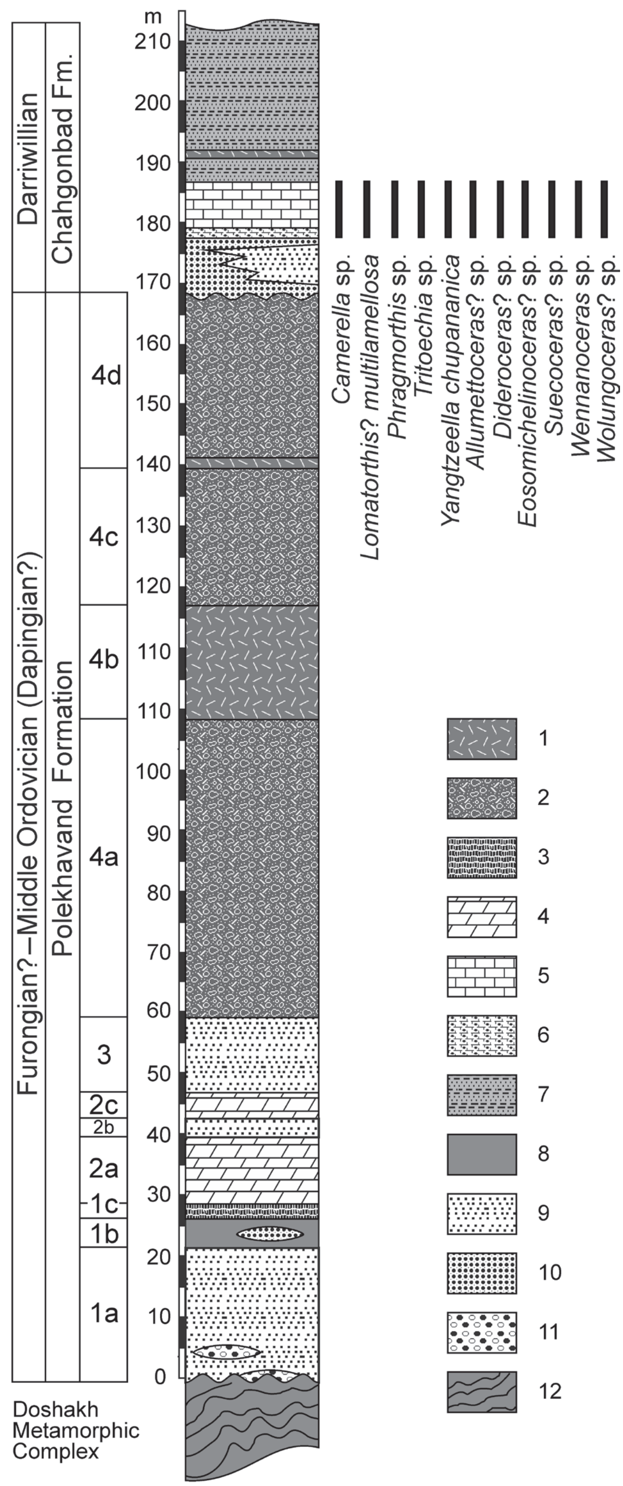


Figure 20. Stratigraphical column of the Polekhavand and lower part of the Chahgonbad Formation exposed at the Pol-e Khavand area, showing lithostratigraphical subdivision, position of fossil locality, and stratigraphical distribution of brachiopods and cephalopods. Legend: 1 – tuff; 2 – rhyolitic agglomerate; 3 – basalt; 4 – dolomite; 5 – limestone; 6 – oolitic ironstone; 7 – alteration of argillite, siltstone and sandstone; 8 – argillite; 9 – sandstone; 10 – microconglomerate; 11 – conglomerate; 12 – folded schist.

of the Morghab unit, which overthrusts the Doshakh metamorphic rocks in the Pol-e Khavand area (Bagheri & Stampfli 2008). Similar ages (*c*. 387 Ma) were obtained by Bagheri (Buchs *et al*. 2013: p. 268) for two gabbroid samples derived from the ultramaphic rocks of the Nakhlak area; however, they were considered as part of the accretionary wedge developed along the Alborz active margin at Late Devonian–Triassic times (Bagheri & Stampfli 2008) and therefore would have no relationship with the East-Central Iranian Plate.

Tectono-stratigraphical domains

The analysis of the Ordovician successions documented from the Alborz Mountains allows distinction of four distinct tectono-stratigraphical units, which display different Ordovician lithologies, facies and varying stratigraphical completeness of sedimentary record, position of major unconformities, duration of hiatuses and characters and timing of extrusive volcanism. The tectono-stratigraphical units are named below: (i) Damghan Domain, typified by the Mila-Kuh, Gerd-Kuh, Simeh-Kuh and Deh-Molla sections (Figs 2–4, 10); (ii) Alestan Domain, typified by the Abarsaj, Kholin-Darreh and Khoshyeilaq sections (Figs 2, 3); (iii) Saluk Domain of the south Kope-Dagh Region, typified by sections in the Saluk Mountains, south of Bojnurd city (Figs 1, 3, 14, 15); and (iv) Talesh Domain, confined to the small Tatavrud Inlier, west of Rasht city in the Talesh Mountains (Figs 1, 4). The limited number of Ordovician inliers scattered across the Alborz and Kopet-Dagh mountains precludes tracing the lateral continuity of lithofacies changes.

Damghan Domain

The Damghan Domain lies along the southern foothills of the eastern Alborz Mountains (Fig. 2). The base of the Ordovician in the Damghan Domain is marked by a widespread unconformity. The trilobite-based correlation with South China suggests that the lowermost Ordovician rocks in the eastern Alborz are not earlier than the *Asaphellus inflatus–Dactylocephalus* Zone of the South Chinese trilobite-based chronostratigraphic succession or the *Cordylodus angulatus* Zone of the North Atlantic biozonal scheme (Ghobadi Pour *et al*. 2015b). The Tremadocian–early Floian times were characterised by the accumulation of the condensed, fine siliciclastic sediments of the Simeh-Kuh Formation. Wide extension of the nileid and raphiophorid biofacies suggests depositional environments ranging from the upper offshore to the offshore-basinal transition. It seems likely that the Tremadocian–Dapingian depositional successions were mainly controlled by eustatic sea level fluctuations but, since late Dapingian or early Darriwilian times, they were also increasingly affected by tectonically induced events. After the Darriwilian, the Damghan Domain was located along the shoulders of a rift axis developed along the adjacent Alestan Domain.

The most complete successions of the Simeh-Kuh and Gerd-Kuh inliers, in the vicinity of Damghan city, contain up to three 12–30 m thick shallowing-upward cycles of, from bottom to top, shales with impure limestone interbeds capped by medium- to coarse-grained sandstones exhibiting low angle and hummocky cross-lamination grading upwards into trough cross stratification. Extensive brachiopod shell beds developed from the *Paltodus deltifer* Zone to the *Drepanoistodus* aff. *amoenus* Subzone (*Paroistodus proteus* Zone). The top of these cycles may represent remnants of reworked shoal complexes. Sharp, erosive surfaces marking the top of the units may indicate intervals of non-deposition, probably at the time of maximum progradation, subsequently followed by sharp flooding.

The Floian–Dapingian interval is preserved only in the central Damghan Domain (Gerd-Kuh and Simeh-Kuh inliers), where they are represented by the uppermost Simeh-Kuh and Qumes formations. In the western and eastern parts of the domain, sediments were probably removed due to late Dapingian–early Darriwilian rifting episodes of uplift and subsequent erosion, leaving a considerable gap in the stratigraphic record (Figs 3, 6). The Floian–Dapingian strata are condensed, hardly exceeding 30 m in thickness and strongly variable laterally in facies composition, with numerous brachiopod shell beds and local development of temperate-water shelly carbonates. In the most complete sections from the Simeh-Kuh Inlier, the lowermost Floian deposits exhibit a distinct progradational pattern changing upsequence from graptolite-bearing argillites through limestone beds intercalating with silty to sandy interbeds towards the top. This part of the succession is absent in the Gerd-Kuh Inlier, where the unconformity that marks the base of Qumes Formation is overlain by a breccia lag rich in ironstone crust. The base of the Gerd-Kuh Member coincides with a maximum regressive surface. The succeeding part of the Qumes Formation shows a retrogradational trend from shoreface (mainly arenaceous Gerd-Kuh Member) to upper offshore (fine siliciclastic Raziabad Member at Gerd-Kuh and upper carbonate units at Simeh-Kuh) settings, interrupted by a significant hiatus traceable regionally and marking the base of the Lashkarak Formation. The amplitude of the gap is strongly variable, increasing eastwards and westwards of the Damghan area (Figs 3, 6, 10).

The Darriwilian succession of the Lashkarak Formation exhibits a retrogradational trend, starting with the establishment of shoal complexes (the sandstone-dominated Cheshmeh-Ali Member), dated by conodonts as early Darriwilian (Dw2, *Lenodus variabilis* Zone). Brachiopod shell beds mainly comprise disarticulated valves of the orthid *Bastamorthis multicostata* and trilobites of the *Neseuretus* biofacies. The succeeding Hajiabad Member comprises siltstones and subsidiary sandstones with extensive echinoderm and brachiopod shell beds in the upper part, mainly representing upper offshore environments. Rare limestone interbeds from the lower part of the unit contain conodonts of the *Lenodus pseudoplanus* Zone. A flooding surface probably coincides with an echinoderm limestone bed containing abundant complete thecae of rhombiferan *Echinosphaerites*, just below the first documented occurrence of *Lenodus pseudoplanus* at the Simeh-Kuh section (Fig 10). It represents a distinct marker level traceable throughout exposures of the Lashkarak Formation in the Damghan area (Fig. 11I). The retrogradational pattern of the Darriwilian succession is interrupted by a sharp shallowing episode marked, in the Simeh-Kuh section, by a 7 m thick oolitic ironstone bed representing a reworked ironstone shoal (Fig. 11H). The second retrogradational sequence is abruptly interrupted by another unconformity.

Upper Ordovician deposits are absent over the most of the Damghan Domain, probably due to post–Ordovician erosion. They only partially preserved outcrops in the Gerd-Kuh Inlier and the best documented from the Deh-Molla area, which are assigned to the Abarsaj Formation. The unit is dominated by fine siliciclastic rocks deposited during the Katian in offshore substrates. The occurrence of acritarchs, including *Baltisphaeridium longispinosum*, *Multiplicisphaeridium bifurcatum* and *Multiplicisphaeridium irregulare* from the Acritarch Assemblage Zone V of Ghavidel-Syooki (2006), from the base of the Abarsaj Formation at Deh-Molla, suggest a Katian age for the unit, but correlation with any chitinozoan zonal scheme is constrained by the long stratigraphical ranges of these fossils. There is no evidence of Hirnantian deposits at Deh-Molla or elsewhere within the Damghan Domain.

The Darriwilian shows the first indirect signs of extrusive volcanic activity in the region, marked by occasional tuff beds from the upper part of the Hajiabad Member at Gerd-Kuh and Abarsaj. Two basaltic units also occur in the Abarsaj Formation at Deh-Molla. They reflect the early signs of rifting volcanism implying a primary tectonic control in the accommodation space, which resulted in the record of a widespread unconformity and its related hiatus at the base of Darriwilian. This geodynamic scenario significantly increased the accommodation space and related subsidence in the Katian preceding a major volcanic event in the neighbouring Alestan Domain, which started in the late Katian–Hirnantian and continued into the Silurian (Derakhshi *et al*. 2017).

Alestan Domain

The Alestan Domain is situated on the central and northern parts of eastern Alborz, including the area of distribution of the 'Gorgan Schists' (Fig. 2). Its southern boundary can be broadly associated with the Shahrud Fault System, which represents an important regional neotectonic shearing zone (Hollingsworth *et al*. 2008).

Unlike the Damghan Domain, the Ordovician succession in the Alestan Domain is rather incomplete and mainly comprises the siliciclastic deposits of the Abarsaj Formation, up to 460 m thick, (Fig. 3). The Katian to Hirnantian age of the unit (*Armoricochitina nigerica–Spinachitina oulebsiri* zones) is confirmed by chitinozoans (Ghavidel-Syooki 2017a); however, data obtained by Ghavidel-Syooki (2008) from the Radkan transect in 'Gorgan Schists' and acritarch dating from the Abarsaj section (Avesta valley) in the Shahvar Mountains (Ghavidel-Syooki & Khandabi 2013) suggest that the base of the Abarsaj Formation is diachronous and, in places, may range to the *Econochitina tanvillensis* chitinozoan Zone (lower Katian). In the Shahvar Mountains, the Abarsaj Formation rests unconformably on the oolitic ironstones and tuffs of the Hajiabad Member. The latter unit is mainly characteristic of the Damghan Domain and is absent in other sections of the Alestan Domain, where an extensive hiatus commonly comprises a Floian to the lower Katian gap (Fig. 3). Another feature of the Alestan Domain is a close association of the Abarsaj and Soltan-Maidan formations.

During the Furongian–Dapingian, the Alestan Domain was seemingly a low land, occasionally flooded by the shallow sea (such as in the Tremadocian). Strong starvation in the neighbouring Damghan Domain suggests that the area became an extensive peneplain. From late Dapingian to early Darriwilian times, the Alestan Domain was an uplifted area, which experienced denudation in the Darriwilian–Sandbian, probably affecting other uplifted and tilted shoulders throughout the eastern Alborz rift. The first signs of volcanism in the area are basic tuffs from the Hajiabad Member (late Darriwilian), followed by subaerial extrusive volcanism (Abr Basalts). A general subsidence, which occured in Katian times, can be also linked to the extensive rift-related extrusive volcanism that continued into the Silurian (Derakhshi *et al*. 2017, 2022).

Saluk Domain

The Ordovician succession of the Saluk Domain (Fig. 1) exhibits continuous sedimentation through the Cambrian–Ordovician transition, unlike other parts of northern Iran. Sedimentation was mostly tectonically controlled and the whole sector experienced short-term episodes of subsidence during the Early–Middle Ordovician. It was synchronous with the major phase of basaltic extrusive volcanism. The resulting available accommodation space was mainly filled with heterolithic siliciclastic sediments by the beginning of the Silurian. In the Saluk Domain, the Ordovician mainly exhibits a progradational character interrupted by sharp pulsations of increased subsidence in the late Katian (*Ancyrochitina merga* Zone) preceding a second major episode of extrusive basaltic volcanic activity.

The south Kopet-Dagh Region is often considered as the eastern prolongation of Alborz (Bayet-Goll & Neto de Carvalho 2016, Ghavidel-Syooki 2017b, c). Both regions show Early Palaeozoic faunal signatures shared with the mid-latitude margins of Gondwana, yet characters of Cambrian–Silurian sedimentary succession show remarkable differences. In South Kopet-Dagh, extensive rifting volcanism associated with sharp increases in accommodation space occurred close to the Cambrian–Ordovician boundary, and was reactivated throughout the Early–Middle Ordovician. It resulted in the deposition of a thick siliciclastic-dominant Ordovician succession (Ghavidel-Syooki 2017c). In contrast, the Lower–Middle Ordovician deposits in Alborz are condensed, with local development of temperate-water shelly carbonates. Tectonically induced uplift-tilting and related development of a horst-and-graben palaeotopography occurred in the eastern Alborz in two pulses, late Dapingian–early Darriwilian and Sandbian in age, while a gradual subsidence within the Alestan Domain is evident through Katian–Hirnantian times. The Katian–Silurian in eastern Alborz was a time of extensive rifting volcanism (Derakhshi *et al*. 2017), while, in Kopet-Dagh, there is a Llandovery–Wenlock shallow-marine sedimentary succession with no traces of extrusive volcanism, except a few oolitic ironstone beds in the lower Aeronian, probably reflecting ash falls from remote volcanic eruptions (Hairapetian *et al*. 2017), which may be linked to the Dasht basalts (Derakhshi *et al*. 2022). Therefore, the Alborz and South Kopet-Dagh regions are suggested as two different peri-Gondwana tectono-stratigraphical units with distinctive palaeogeographical features.

Talesh Domain

The Talesh Domain comprises a small inlier bearing Lower Palaeozoic rocks at Kolur, Masuleh and the Tatavrud river Basin, Talesh Mountains (Fig. 1), here referred as the Tatavrud Formation (Fig. 4). The Upper Ordovician condensed carbonate-dominant succession of the Talesh Range has no analogies with other parts of Iran, and there is virtually no carbonates of that age elsewhere in the Alborz Region, where the Upper Ordovician is represented by the thick siliciclastic succession of the Abarsaj Formation. Also, except the trilobite *Amphoriops*, *Birmanites*, *Geragnostus* and *Ovalocephalus* listed from this domain (Karim 2009), other genera have never been reported elsewhere from Iran except *Ovalocephalus* cf. *tetrasulcatus* (Kielan, 1960) and *Trinodus tardus*, reported by Müller & Walter (1984) from the Upper Ordovician of the Taknar Inlier, south of Mashhad city (Fig. 1). A detailed biogeographical analysis of the trilobite association from the Tatavrud Formation (Karim 2009) recognised close affinities with the contemporaneous faunas of tropical peri-Gondwana and, in particular, to the faunas of Alai, Selety and Chi-Ili terranes, as well as the North China continent. Therefore, the lithological and biogeographical features of the Talesh Region seem unrelated to the neighbouring domains reported above. As pointed out by Wendt *et al*. (2005), the black limestones with abundant conodonts of unspecified Early Devonian age reported from Talesh have no close analogies elsewhere in Iran. As a result, the Talesh Domain would have been distinctly separated from Alborz and other parts of Iran through the Early Palaeozoic, and biogeographically related to the Kazakh cluster of microplates and island arcs.

Palaeogeographical implications

It is generally acknowledged that the area of present-day Iran comprises several first order fault-bounded tectono-stratigraphical units (Fig. 1) with different Early Palaeozoic geological histories (Wendt *et al*. 2005, Hairapetian *et al*. 2017). The preservation of two major oceanic sutures, attributed to the closure of the Palaeotethys and Neotethys, suggests that for some time the tectono-stratigraphical units described above were separated by either considerable oceans or narrow channels (*e.g.* Stampfli & Borel 2002; Golonka 2007, 2012; Torsvik & Cocks 2017). Three of the Iranian first-order tectono-stratigraphical units, including (i) East-Central Iranian Plate, (ii) Alborz plus South Kopet-Dagh regions at North Iran and (iii) Main Zagros Thrust Zone, preserve complete and rather well-documented Cambrian to Silurian strata. At present, only the palaeogeographical position of the areas located southwest of the Main Zagros Thrust, situated along the margins of the Arabian Plate, can be established with certainty. During the Ordovician, they were integral parts of the Arabian segment of Gondwana due to the strong fossil and sedimentary links with the Ordovician successions of the adjacent Arabian Peninsula (Ghavidel-Syooki *et al*. 2011, 2014) (Fig. 22). The Zagros Ranges are separated from the East-Central Iranian Plate by the Sanandaj-Sirjan Domain (Fig. 1), which has a very poor Lower Palaeozoic sedimentary record. The latter most probably represents a tectono-stratigraphical puzzle incorporated into the post-Palaeozoic accretionary complex, formed along the active margin of the East-Central Iranian Plate and therefore excluded from further discussion. While the Neotethys suture, confined within the Main Zagros Thrust, can be defined with certainty, the position of the Palaeotethys suture in Iran is elusive. The most common assumption is that it should be broadly placed along the margins of the South Caspian Basin (*e.g*. Gaetani *et al*. 2009, Muttoni *et al*. 2009, Shafaii Moghadam & Stern 2014, Derakhshi *et al*. 2022), which has a modified oceanic-type basement dated to *c*. 200 Ma and associated with a relic back-arc basin (Golonka 2007, Kaz'min & Verzhbitskii 2011). Probably, the main and only reason for that is the development of the low grade metamorphic 'Gorgan Schists' along the northern margins of eastern Alborz. An alternative view suggests that the Palaeotethys suture should be located along the northern margin of the East-Central Iranian Plate (see Golonka 2007). There is no evidence for Palaeozoic and Mesozoic subduction-related complexes and ophiolites between Alborz and South Caspian.

As discussed above, available petrological, geochemical and litho- and biostratigraphic data (*e.g.* Ghavidel-Syooki 2008, Ghasemi *et al*. 2015) clearly suggest that the 'Gorgan Schists' protolith includes Ordovician and Silurian rocks assignable to the Abarsaj and Soltan-Maidan formations. The age of metamorphism is broadly reported as Mid–Late Triassic (Ghasemi *et al*. 2015), which probably developed in an extensional back-arc setting at the initial stages of the Caspian Basin generation. The southern Lower Palaeozoic boundary of the Alborz is not preserved, having been strongly affected by subsequent tectonic events. Nevertheless, characters of the Ordovician sedimentation along the southern foothills of the eastern Alborz Mountains suggest that it was located in relative proximity to the continental margin.

The Lower Palaeozoic northern Iranian domains are separated from the Lower Palaeozoic core of the East-Central Iran by the 250 km-wide Sabzevar Domain (Fig. 1), which is also known as the Great Kavir Block (Bagheri & Stampfli 2008). The Lower Palaeozoic (Cambrian–Silurian) rock exposures within this domain were documented by Alavi-Naini (1972) in the Boz-Kuh Mountains, west of Jam town (Fig. 1); however, they are still incompletely known to make more detailed comments. There is also the Chah Jam-Biarjmand and Delbar metamorphic-igneous complexes (Balaghi *et al*. 2014, Shafaii Moghadam *et al*. 2015a) exposed at the Sabzevar Domain northern part, southeast of the town of Shahrud. Crystallisation ages for the granitoids of the Chah Jam-Biarjmand Complex (538 ± 5 and 522 ± 4 Ma) and leucogranites associated with Delbar Complex (541 ± 4.7 – 547 ± 11 Ma) suggest late Ediacaran to Terreneuvian ages. Orthogneisses form the Delbar Complex have broadly similar $^{238}U/^{206}Pb$ ages (530–548 Ma), while the paragneisses contain abundant zircon dated on average as 552 Ma, but also fractions with ages as old as 609–620 Ma, 1732 Ma and 2457 Ma. This spectrum closely resembles zircon ages obtained from the Cambrian Lalun, Barut and Mila formations of Alborz (Horton *et al*. 2008) suggesting similar sources. Both metamorphic complexes are related to the same metamorphic event which was, probably, linked to a volcanic arc that existed south (recent geographical coordinates) of Alborz/Kopet-Dagh in late Ediacaran–earliest Cambrian times. These data can be taken as evidence for the evolution of a pre-Cambrian continental crust along the southern margin of Alborz/Kopet-Dagh in the northern Sabzevar Domain.

The Devonian, Permian and Upper Cretaceous–Pliocene ophiolitic mélange complexes developed in the vicinity of Mashhad city are rather characteristic of the eastern termination of the Sabzevar Domain (*e.g*. Bagheri & Stampfli 2008: fig. 1, Muttoni *et al*. 2009: fig. 1, Zanchetta *et al.* 2013, Shafaii Moghadam & Stern 2014, Shafaii Moghadam *et al*. 2015b). The presence of Palaeozoic metamorphic rocks assigned to the Anarak Metamorphic Complex and poorly dated serpentinites (Fig. 1) is documented along the boundary with the East-Central Iranian Plate (Bageri & Stampfli 2008, Buchs *et al*. 2013). The Upper Devonian–Carboniferous Godar-e-Siah Complex includes metamorphosed volcano-sedimentary successions interpreted as a remnant of the 'Eurasian active margin' (Bageri & Stampfli (2008). These data can be taken as clear indicators of the oceanic separation between Alborz (including South Kopet-Dagh) and the East-Central Iranian Plate at these times.

Biogeographical constraints

After excluding the Talesh Domain, which most probably represents an exotic terrane, the remaining Lower Palaeozoic first-order tectono-stratigraphical units, including Alborz, South Kopet-Dagh, East-Central Iranian Plate and Zagros Basin, show distinct Gondwanan palaeobiogeographical signatures in the Ordovician. On the existing palaeogeographical reconstructions, their relative position is almost identical to that observed nowadays (*e.g*. Stampfli & Borel 2002, Torsvik & Cocks 2017). It implies that the Iranian terranes seemingly rifted, drifted and again assembled in almost the same geometrical arrangement revealing a perfect example of 'strange attractors' *sensu* Meert (2014). Such a coincidental scenario may suggest that views on the tectonic evolution of the Palaeozoic Iranian terranes and tectono-stratigraphical units are distinctly biased. Their relative position to each other and to the margins of Gondwana requires justification.

The Lower Palaeozoic core of the East-Central Iranian Plate was most likely attached to the margins of the Arabian margin of Gondwana (Torsvik & Cocks 2017: p. 61). The most striking evidence for that is the complete absence of black shales across the Ordovician–Silurian boundary interval. Instead, there is a significant hiatus that precludes the identification of Hirnantian–Rhuddanian marine sediments in Central Iran (Hairapetian *et al*. 2017), which points to Hirnantian glaciogenic incision close to a source area. A biogeographical affinity with the Mediterranean margin of Gondwana is already present during the Tremadocian (Álvaro *et al*. 2007), but becomes more evident for the Late Ordovician (Bassett *et al*. 1999, Ghavidel-Syooki 2003, Popov *et al*. 2015), while the biogeographical signatures of the mid Ordovician faunas are mixed, showing a significant proportion of the brachiopod and trilobite genera shared with contemporaneous faunas of South China, *e.g*. brachiopods *Martellia*, *Yangtzeella* and trilobites *Birmanites*, *Liomegalaspides* and *Pseudocalymene* (Ghobadi Pour & Turvey 2009). Two biogeographically significant trilobite genera, *Neseuretinus* and *Ovalocephalus,* made their earlier appearance in East-Central Iran, where they are known from the late Darriwilian (Ghobadi Pour & Popov 2009), while their record throughout Mediterranean peri-Gondwana is confined to the Katian. The only published palaeomagnetic record for the Ordovician of Iran (32° S ± 4) was obtained by Muttoni *et al*. (2009) from the lowermost part of the Chahgonbad Formation at the Pol-e Khavand Inlier, located on the northern margin of the Yazd block (Fig. 1). The reported Late Ordovician age of the sample was based on ostracod identifications by Schallreuter *et al*. (2006); however, the sampled unit also contains the brachiopod genera *Tritoechia* and *Yangtzeella*, which strongly supports a mid Ordovician age for these strata (Hairapetian *et al*. 2015, Popov *et al*. 2015).

The Early–mid Ordovician benthic faunal assemblages, especially trilobites and brachiopods, indicate very close links of the Alborz faunas with those contemporaneous from South China. The trilobite biostratigraphical succession is almost identical for Alborz and South China (Ghobadi Pour *et al*. 2015b). There is also a number of common genera, e.g. *Chashania*, *Chungkingaspis*, *Dactylocephalus*, *Ningkianites*, *Psilocephalina*, *Xinanorthis* and species like *Asaphellus inflatus*, *Chashania chashanensis*, *Conophrys gaoluoensis*, *Chungkingaspis sinensis*, *Nileus armadiloformis*, *Opsimasaphus* cf. *pseudodawanicus* and *Psilocephalina lubrica*, which are unknown outside these regions. Thus, Early–Middle Ordovician faunal links favour a strong biogeographical connection of Alborz with the South China palaeocontinent. The Ordovician faunas of the Saluk Domain are still poorly known; nevertheless, Early Ordovician links to South China are also evident.

Zircon data

The Neoproterozoic crystalline basement with zircon ages not exceeding 650 Ma, is inferred for the East-Central Iranian Plate and Alborz (*e.g.* Hassanzadeh *et al*. 2008, Honarmand *et al*. 2016: p. 294, Shirdashtzadeh *et al*. 2018). The pre-Cimmerian stratigraphical succession of Alborz includes a discontinuous Neoproterozoic–Middle Triassic succession deposited mainly along a rifting to passive margin affected by the terminal Ediacaran glaciation (Etemad-Saeed *et al*. 2016), opening of the Paleotethys Ocean during Early Palaeozoic times, and, indirectly, by the opening of the Neotethys Ocean later in the Palaeozoic (Stampfli *et al*. 1991, Torsvik & Cocks 2017).

The proximity of the Arabian sector of Gondwana, East-Central Iranian Plate and Alborz blocks during the Cambrian–Ordovician has long been a matter of prolonged discussion due to differing interpretations based on palaeobiogeographical *vs*. zircon provenance studies. Uranium–lead zircon ages and Hf isotopic compositions of detrital zircon grains sampled from the Ediacaran to Cambrian sedimentary rocks are derived mostly from central and western Alborz. The U–Pb zircon ages from the Ediacaran Bayandor and Kahar formations show unimodal distributions (Fig. 21J, K) mainly within the age range from 550 to 1100 Ma (*c*. 80%), with a major peak at 550–600 Ma and occasional secondary peaks within the range from 800 to 1100 Ma (Horton *et al*. 2008, Etemad-Saeed *et al*. 2015, Honarmand *et al*. 2016, Shafaii Moghadam *et al*. 2020). There is also minor, but persistent Palaeoproterozoic and Archaean zircon grains. Uranium–lead ages obtained from detrital zircons in Ediacaran–Cambrian sandstones from Israel, Jordan (*e.g*. for the Cambrian Amudei-Shelomo, Salib, Shehoret and Timna formations) and possibly Egypt (Kröner *et al*. 1990, Wilde & Youssef 2002, Avigad *et al*. 2003, Kolodner *et al*. 2006), reflect common sedimentary sources from the Arabian-Nubian Shield of the western Arabian Peninsula and northeastern Africa (Fig. 21H, I). Consequently, there is a general opinion that the East African orogen and, in particular, the Arabian-Nubian Shield, was the most significant source for the Pan-African zircon populations from Alborz (*e.g.* Horton *et al*. 2008). It implies a broad expansion of the late Ediacaran to Early Palaeozoic siliciclastic depositional systems across the Arabian margin of Gondwana towards Central Iran and Alborz.

Uranium–lead zircon ages and Hf isotopic compositions in detrital zircon from the Cambrian deposits (Barut, Zaigun, Lalun and Mila formations) from western Alborz (Horton *et al*. 2008, Honarmand *et al*. 2016), Lower Ordovician (Ghelli Formation) of the Saluk Domain and the Lower Devonian of the Saluk and Alestan domains have yielded major age populations at ~ 2.5 Ga, ~ 0.8–0.6 Ga

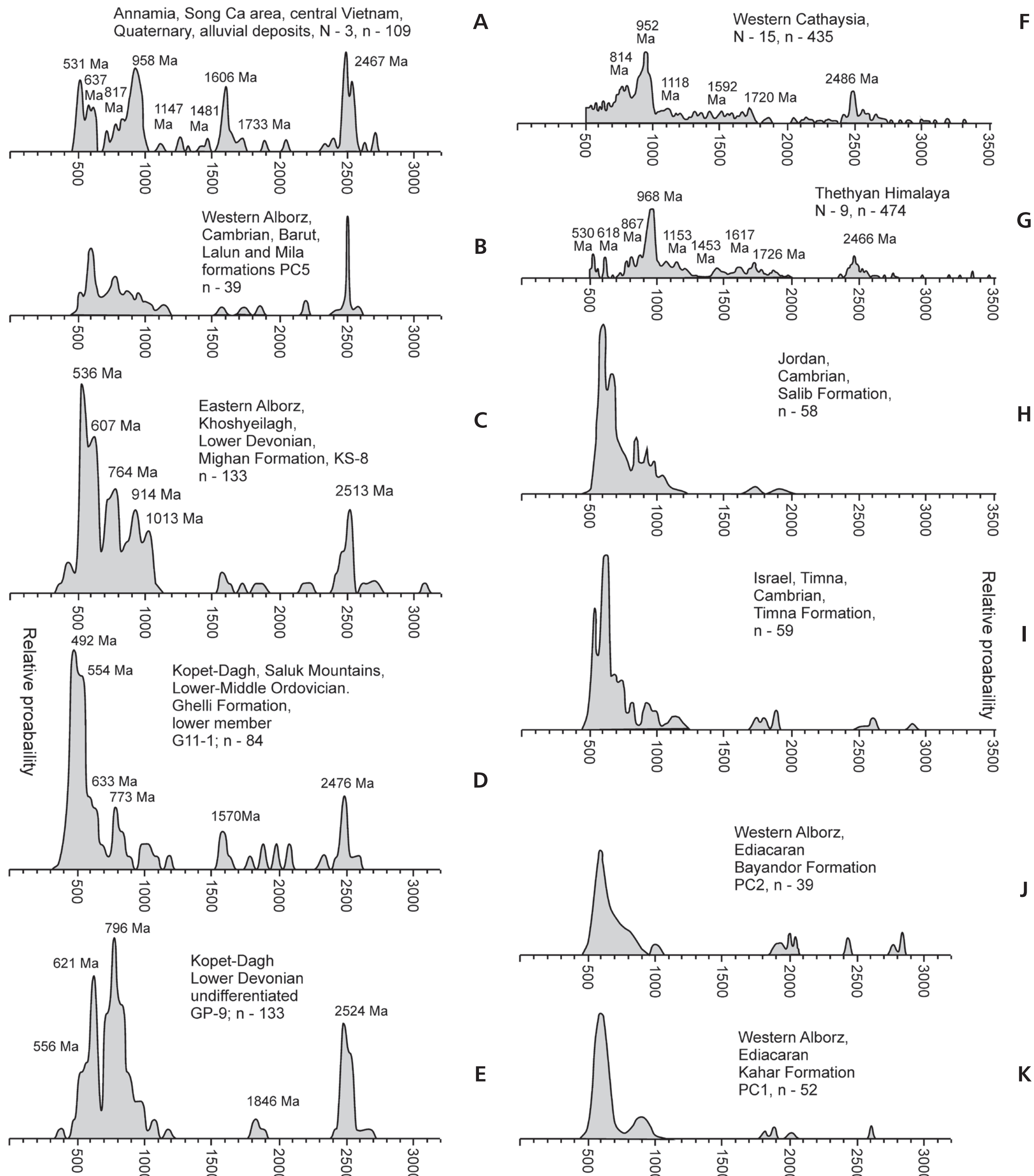


Figure 21. Relative age probability distributions for zircon U–Pb ages from Iranian and selected Gondwanan terranes. • A – Annamia, Song Ca area of central Vietnam, Quaternary, alluvial deposits (Usuki *et al*. 2013). • B – western Alborz, Barut, Lalun and Mila formations (Cambrian) (Horton *et. al*. 2008). • C – eastern Alborz, vicinity of Khoshyeilaq village, Alestan Domain, Mighan Formation (Lower Devonian) (Shafaii Moghadam *et al*. 2017). • D – Kopet-Dagh Region, vicinity of Shirooyeh village, Saluk Domain, Ghelli Formation, (lower member) Lower–Middle Ordovician (Shafaii Moghadam *et al*. 2017). • E – Kopet-Dagh Region, Saluk Mountains near Pelmis Pass, Saluk Domain, Lower Devonian, undifferentiated (Shafaii Moghadam *et al*. 2017). • F – western Cathaysia, late Neoproterozoic metasediments and river sediments (Usuki *et al*. 2013 and references therein). • G – Tethyan Himalaya, lower Permian, Ordovician, Cambrian and Neoproterozoic sedimentary rocks (Usuki *et al*. 2013 and references therein). • H – Jordan, El Quweira, Salib Formation (Cambrian) (Kolodner *et al*. 2006). • I – Israel, Timna, Timna Formation (Unnamed Cambrian Stage 4 – Miaolingian) (Kolodner *et al*. 2006). • J – western Alborz, Bayandor Formation (Ediacaran–Terreneuvian) (Horton *et. al*. 2008). • K – western Alborz, Kahar Formation (Ediacaran) (Horton *et. al*. 2008).

(with peaks at *c*. 750–800 and 600–630 Ma) and ~ 0.55–0.4 Ga (with peaks at 492 and 555 Ma for the Saluk Domain and 434 and 536 Ma for the Alestan Domain), as well as a minor broad peak at ~1.0 Ga (Horton *et al*. 2008, Shafaii Moghadam *et al*. 2017). Distinct general similarity of the zircon age spectra from these units (Fig. 21B–E) suggest a close geographical proximity of the Alestan and Saluk domains through the Early Palaeozoic and provide important information on the character and evolution of the source areas.

The major peaks are Neoproterozoic in age (*c*. 750–800 and 600–630 Ma), the latter being derived from the unroofing of late-stage granitic rocks from the Arabian-Nubian Shield (Ali *et al*. 2010, Avigad *et al*. 2015, Morag *et al*. 2011), as supported by positive εHf (t) values; the negative ones suggest derivation from an older, probably reworked crust from the Saharan Metacraton (Abdelsalam *et al*. 2002). Nevertheless, sedimentological studies (Etemad-Saeed *et al*. 2015, Shafaii Moghadam *et al*. 2020) have established that the Ediacaran Bayandor and Kahar formations comprise immature sediments, and identified the intermediate-felsic igneous and, in less degree, metamorphic rocks from proximal arc settings as the most likely source area for the Ediacaran zircon populations. They also suggested that the significance of the local zircon sources for the Ediacaran–Fortunian sedimentary rocks in western Alborz is considerably underestimated. However, the terminal Ediacaran glaciation recently recognised at Alborz (Etemad-Saeed *et al*. 2016) implies significant isostatic vertical movements, and related glacial and postglacial erosion probably resulting in the exhumation of crystalline basement.

The Cambrian arenites (*e.g.* Zaigun Formation) include a large proportion of strongly reworked or long-transported sand grains (Honarmand *et al*. 2016). It was assumed that detrital zircons with negative εHf (t) values give 2.2–1.7 Ga model ages, suggesting the influence of a reworked Palaeoproterozoic crust, probably, involving either the West African Craton (Linnemann *et al*. 2014) or the poorly studied Saharan Metacraton.

There is a steady increase in proportion of late Cryogenian–Stenian (750–1100 Ma) zircon populations at Alborz and Kopet-Dagh from the Ediacaran to Early Devonian (Fig. 21B–D). A similar trend can be observed in zircon spectra from the Arabian margin of Gondwana (Kolodner *et. al*. 2006: fig. 4), which is explained by unroofing of the older continental crust within the Arabian-Nubian Shield (*e.g*. Horton *et. al*. 2008). In particular, major pre-Ediacaran detrital zircon populations (with a major peak at ~ 773 Ma in the Devonian Mighan Formation at Kopet-Dagh) look consistent with derivation from other calc-alkaline volcanic episodes, probably sourced in eastern Arabia (Stern & Johnson 2010). It is also suggested that detrital zircon populations with minor peaks at 1019 Ma might be sourced from the Sinai basement (Be'eri-Shlevin *et al*. 2009), which also occur as detrital zircons in Libya and Jordan (Meinhold *et al*. 2013). While the Arabian-Nubian Shield can be considered as a probable original source of these zircon populations in the region, significant rift-related differentiated movements, which occurred in the region in mid Ordovician–Silurian times, suggest that the presence of these zircon populations is due to reworking from older local sources.

Sizeable Neoproterozoic 0.9–1.1 Ma age populations of similar magnitude can be seen in zircon spectra from the Floian–Dapingian Umm Sahn Formation (peaks at 0.974 and 1.017 Ma) of Jordan (Kolodner *et al*. 2006: fig. 5) and Lower Devonian Mighan Formation (peaks at 0.914 and 1.013 Ma) of eastern Alborz (Fig. 21C). No crust of this age is yet known from the Arabian-Nubian Shield, and appearance of zircon population in Israel and Jordan was assigned (Kolodner *et al*. 2006) to Cryogenian glacial transport from East Africa, because the shape of these grains is inconsistent with long distance transport by fluvial systems. This explanation, however, can be hardly applied to Alborz, which was affected by an Ediacaran glaciation (Etemad-Saeed *et al*. 2016). Zircon populations of that age are most characteristic of the Indian margin of Gondwana (Zhu *et al*. 2011, Usuki *et al*. 2013), which can also be considered as possible alternative source.

Another important detrital zircon population in Alborz peaks at 2.5 Ga. Its source is somewhat enigmatic. It could have been sourced either from the Saharan Metacraton (Abdelsalam *et al*. 2002), the Afghanistan or Tarim blocks (Long *et al*. 2010, Ma *et al*. 2012, Faryad *et al*. 2016). These Neoarchaean to Siderian zircon populations form a prominent spike easily recognisable in all samples from Alborz and Kopet-Dagh (Fig. 21B–E) from Cambrian to Lower Devonian strata (Horton *et al*. 2008, Honarmand *et al*. 2016, Shafaii Moghadam *et al*. 2017). Similar Neoarchaean zircon populations persistently occur in Cambrian–Ordovician rock samples from the Arabian sector of Gondwana (Fig. 21; Kolodner *et al*. 2006, Horton *et al*. 2008); however, their concentrations are invariably low and do not approach the magnitudes documented for the Cambrian–Lower Devonian samples from Alborz and Kopet-Dagh. Also, Neoarchaean zircon enrichment during long-distant transportation from the Saharan Metacraton or Central Africa towards Alborz/Kopet-Dagh looks a highly unlikely scenario, and it is not further considered. Tarim was a separate microcontinent through the Early Palaeozoic (Torsvik & Cocks 2017) and therefore cannot represent a source for Neoarchaean zircons in the Cambrian–Lower Ordovician sedimentary rocks of Alborz and Kopet-Dagh. A persistent input of Neoarchaean to Siderian zircons, which constitute a sizeable fraction in the samples for almost 130 Ma, may suggest the presence of an exhumed basement of that age relatively close to the area of sedimentation. The Annamia terrane has not been considered previously, and may represent a part of the puzzle (Fig. 22). In Early Palaeozoic plate tectonic reconstructions (Cocks & Torsvik 2013, Torsvik & Cocks 2017), Annamia and South China are combined into a single continental block located at southern mid-latitudes in close proximity to the Gondwana margin: Annamia is placed opposite the Central Iranian and Afghan terranes, and the Cathaysian margin of South China is facing Qiantang and Himalaya (Fig. 22B). Usuki *et al*. (2013) suggested that Annamia was connected to the Indian margin of Gondwana due to distinct similarities of the Precambrian zircon spectra with those from Qiangtang and Tethyan Himalaya (Fig. 21A, G), which probably shared a common source provenance (Fig. 22A). There is also a difference: while the contribution of Pan-African zircons (500–650 Ma) in Tethyan Himalaya is relatively minor (Zhu *et al*. 2011), they represent in western Qiangtang (Zhu *et al*. 2011: fig. 2f) and especially in Annamia (Fig. 21A) a sizeable fraction, suggesting a proximal source, which could be the Arabian sector of Gondwana or/and Iranian terranes. While there is no report of the presence of a Siderian–Neoarchaean basement in Annamia, zircon populations of that age form a prominent peak (2467 Ma) in samples obtained by Usuki *et al*. (2013: fig. 5), comparable in magnitude with those from the Cambrian–Lower Devonian of Alborz and Kopet-Dagh (Fig. 21B–D; 2476–2525 Ma). Zircon spectra of that age form distinct peaks in analyses made in Tethyan Himalaya and western Cathaysia (Fig. 21F, G); however, the Neoarchaean continental crust (Cavinh Complex; 2.5–2.8 Ga) is documented from western Cathaysia north of the Song Ma suture (Lan *et al*. 2001).

Samples from the Lower Devonian Mighan Formation of the Alestan Domain in east Alborz (Fig. 21B; Shafaii Moghadam *et al*. 2017: fig. 7e, f) contain rich Llandovery zircon populations peaked at 435 Ma. There are no exhumed Silurian plutonic rocks yet documented here and elsewhere in Iran (Ghavidel-Syooki *et al*. 2011, Harapetian *et al*. 2017). The possible source of the Silurian zircons in the Mighan Formation are reworked xenolites of A-type granites in basalts of the Soltan-Maidan Formation (Fig. 18D), which developed within the area and occurs unconformably underlying the Devonian unit (Wendt *et al*. 2005). Remarkably, the zircon ages of 441 Ma (Silurian, late Rhuddanian–early Aeronian) obtained from the reworked Soltan-Maidan granitic xenolites in the lower part of the Mighan Formation at Khoshyeilaq may indicate the crystallisation age of the source volcanic rock (Omrani, personal communication 2019).

Data on the provenance of the Ordovician rocks within North Iran are presently available from only two samples from the lower and middle part of the Ghelli Formation at the Saluk Domain (Shafaii Moghadam *et al*. 2017). The lower sample (G11-1) was taken from immature arkosic sandstone with volcanic clasts sandwiched between basaltic lava flows. It contains rich Furongian to early Tremadocian zircon population peaked at 492 Ma. Another sample (G11-3) derived from similar arkoses, probably on the top of the volcanic unit yielded a peak at 457 Ma (early Sandbian). In the absence of exhumed Ordovician plutons in south Kopet-Dagh, the most likely possibility of zircon sources, by analogy with the Soltan-Maidan Formation, are reworked granitic xenoliths brought to the surface by basalt extrusive volcanics. The observed zircon ages give a possible duration of the major episode of basalt extrusive volcanism in the Saluk Domain.

There are distinct late Ediacaran–Cambrian Series 2 zircon populations in samples from the Lower Palaeozoic sedimentary rocks in Alborz. In the Lower Devonian of the Alestan and Saluk domains, they comprise sizeable populations peaked at 536 and 511 Ma (Shafaii Moghadam *et al*. 2017). While the local origin of these zircon populations was recognised in the cited publication, it was not supported by additional evidence or discussion. Yet crustal terranes built of infra-Cambrian metamorphic rocks and granites assigned to the Torud–Biarjmand and Delbar metamorphic-igneous complexes are exposed nearby in the northern part of the Sabzevar Domain (Fig. 1). According to Balaghi *et al*. (2014), the crystallization ages of leucogranites from the Delbar Complex are within the range 541–547 Ma, while the detrital zircons from the mica-schists have yielded youngest deposition ages for the protolith (*c*. 549–551 Ma). In the adjacent Torud-Biarjmand Complex, the granites intruding Ediacaran granitic gneisses (561.3 ± 4.7 Ma) have Terreneuvian crystallisation ages (522.3 ± 4.2 and 537.7 ± 4.7 Ma) (Shafaii Moghadam *et al*. 2016). Authors of both publications suggested that these magmatic episodes and associated metamorphic events were linked to continental arc settings.

Late Ediacaran continental arc-related granitic plutonism and related metamorphic events are documented by Hassanzadeh *et al*. (2008) also in the southern vicinity of Zanjan along the norther margin of the Sanandaj–Sirjan Domain, in particular, for the Sarv-e Jahan granitic Complex (544 ± 29 Ma) (Fig. 1) and the Moghanlou granitic orthogneiss (548 ± 27 Ma). The youngest detrital zircon populations from quartzose sandstones of the Zaigun Formation in the same area are *c*. 520 Ma (Honarmand *et al*. 2016). While being discontinuous, the evidence of volcanic arc-related magmatism suggests that crustal growth along the southern margin of Alborz and Kopet-Dagh terranes continued until the end of Terreneuvian times and, probably, up to Cambrian Epoch 4.

While sediments transported by fluvial systems were probably an important source for Pan-African zircon populations in the Ediacaran–early Cambrian of Alborz

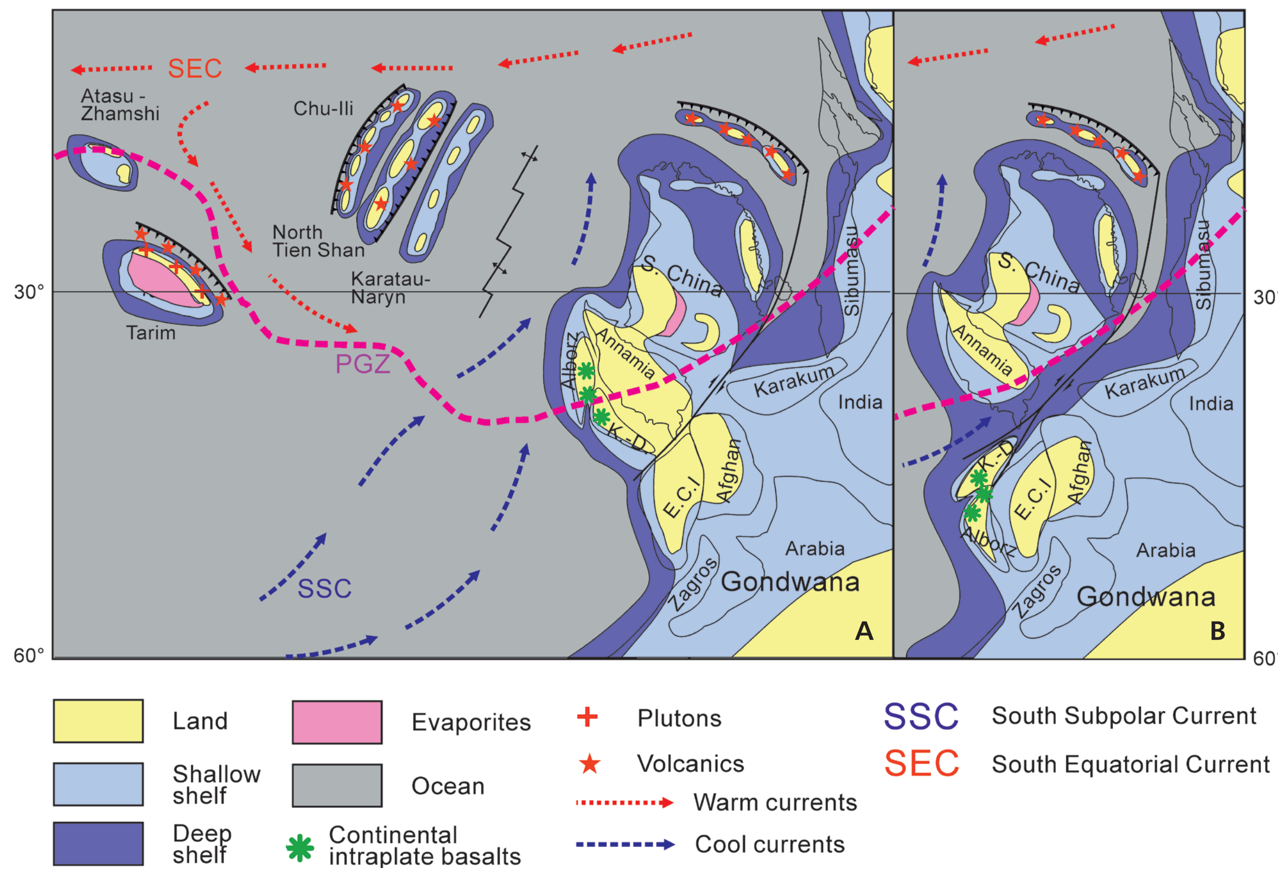


Figure 22. Two alternative reconstructions for the late Darriwilian–Sandbian time showing position of the Iranian terranes, South China and Annamia in relation to each other and Gondwana margin: A – South China–Annamia plate with attached Alborz and Kopet-Dagh terranes and a transform boundary with mainland Gondwana (after Usuki *et al*. 2013 with major modifications); B – traditional reconstruction with Alborz and Kopet-Dagh terranes attached to the East-Central Iranian Plate, while the combined South China–Annamia continent is separated from the Gondwana margin by a narrow oceanic channel (mainly after Torsvik & Cocks 2017, with emendations).

and Kopet-Dagh, input from different localized sources including supply from nearby terranes and reworking of older basement rocks was steadily increasing with time. The provenance of the Furongian–Ordovician sedimentary rocks from Alborz and Kopet-Dagh is of great importance to understand the evolution of the source areas, but existing information is sparse and insufficient.

Discussion

It is widely acknowledged that the formation of the continental crust in the Zagros, Central Iranian blocks and Alborz largely reflects an Ediacaran–early Cambrian continental arc which formed on 'North' Gondwana, followed by rifting conditions, although precise timing for these events is still controversial (Garfunkel 2004, Abbo *et al*. 2015). Remarkably, the early Cambrian crustal growth occurred along the southern margin of the Alborz and Kopet-Dagh terranes, which call into question the direction of subduction inferred in some plate tectonic reconstructions (*e.g*. Shafaii Moghadam & Stern 2014, Shirdashtzadeh *et al*. 2018).

At the same time, the Terreneuvian–Cambrian Stage 4 siliciclastic units (*e.g*. Bayandor, Barut, Zaigun and Lalun formations) show predominantly Pan-African zircon age signatures with age probability spectra strongly recalling those from the siliciclastic rocks (*e.g*. Amudei, Salib and Timna formations) of a similar age from the northwestern part of the Arabian Peninsula. This is taken as support for the former existence of an enormous early Cambrian clastic wedge covering the whole Arabian sector of Gondwana and Iranian terranes (Horton *et al*. 2008).

It looks highly probable that remnants of the Ediacaran to Terreneuvian volcanic arc traceable along the northern margin of the Sebzavar Domain were parts of the same continental arc system, while the Alborz and Kopet-Dagh terranes were integrated into the margins of the Gondwana supercontinent for a significant part of the Early Palaeozoic (Fig. 22A). However, the recent position of Alborz and Kopet-Dagh in relation to the northern margins of the Central-Iranian Plate and Arabian sector of Gondwana are secondary, and this may imply oroclinal bending. According to the Ordovician–Devonian palaeogeographical reconstructions by Cocks & Torsvik (2013) and Torsvik & Cocks (2017), South China was amalgamated with Annamia, located in temperate southern latitudes, and drifted northwards along the western Gondwana margin. In the Early–mid Ordovician, the Annamia segment was facing the northern Arabian margin of Gondwana, probably with East-Central Iran being separated by a narrow oceanic channel (Fig. 22B) or, alternatively, separated by a system of strike-slip faults (Usuki 2013: fig. 6). Usuki (2013) also tentatively placed Annamia attached to Gondwana during a considerable part of the Early Palaeozoic (Fig. 22A). The Kopet-Dagh and Alborz domains were also probably located in close proximity to the western margin of Annamia, as suggested by the above-reported re-interpretation of the zircon spectra obtained by Shafaii Moghadam *et al*. (2017) from the Ordovician and Devonian rocks of Alborz and Koppet-Dagh (Fig. 21). In that case, the East-Central Iranian Plate might represent a natural route for the fluvial systems that transported clastic material from the Arabian-Nubian Shield to the Gondwana margins including the Kopet-Dagh and Alborz domains. Also, Afghanistan and the East-Central Iranian Plate probably constituted a single geodynamic unit through most of the Phanerozoic, but the provenance of the Early Palaeozoic sedimentary rocks from the Cental-East Iranian Plate is yet inadequately known.

From a biogeographical point of view, the Cambrian–Ordovician trilobites of the Kopet-Dagh and Alborz domains as well as the East-Central Iranian Plate share affinities with South China and Mediterranean peri-Gondwana, occupying an intermediate position between East and West Gondwana (Cocks & Fortey 1988, Peng *et al*. 1999, Ghobadi Pour 2006, Ghobadi Pour *et al*. 2007a, Popov *et al*. 2009a, b). No significant biogeographical differences between Cambrian trilobites of these three units were established after using parsimony analysis of endemicity (Álvaro e*t al*. 2013).

While the closest biogeographical connection of Alborz to South China looks well established, there were several episodes linked to environmental changes, when biogeographical links with the Mediterranean margin of Gondwana became more evident. In particular, the proliferation of the brachiopod *Protambonites*, which form brachiopod accumulations in the middle part of the Simeh-Kuh Formation, is probably coincident with successive sea-level falls near the boundary of the *Paltodus deltifer* and *Paroistodus proteus* conodont zones. The genus is otherwise characteristic of the Mediterranean peri-Gondwana and the Uralian margin of Baltica (Popov *et al*. 2009b). The trilobite *Taihungshania miqueli* is known outside Iran from the lower Floian of Montagne Noire (southern France), Oman (Fig. 16) and the Turkish Taurids (Ghobadi Pour *et al*. 2007a, Fortey *et al*. 2011). Also the bivalve mollusc *Glyptarca* occurs outside Iran in the Floian of South Wales (Cope & Ghobadi Pour 2020). Both taxa probably dispersed from Alborz, where they already thrived in the latest Tremadocian–early Floian. The proliferation of the *Thysanotos*–*Leptembolon* Association was linked to the onset of temperate carbonate sedimentation in eastern Alborz, as discussed above. Finally, the development of the cold-water *Neseuretus* biofacies in the early Darriwilian (*Lenodus variabilis* conodont Zone), also known from the Darriwilian of the Arabian margin of Gondwana, may be linked to a cooler climate (Ghobadi Pour *et al*. 2006, Ghobadi Pour 2019). While the Late Ordovician fauna of Kopet-Dagh is still inadequately known, yet it shows apparent links to the East-Central Iranian Plate and Mediterranean Gondwana, accentuated by the occurrence of some key trilobite taxa, such as *Deanaspis*, *Vietnamia* and *Neseuretinus* and brachiopod *Hindella*.

These Ordovician biogeographical changes are most probably due to shifts of the climatic belt with a general tendency to global cooling at the end of the Ordovician. In particular, the mid to late Katian proliferation of low diversity benthic faunas rich in the brachiopod *Hindella* and trilobite *Vietnamia* both in Kopet-Dagh Domain and in East-Central Iran may reflect the influence of cooler climate trends. No signs of significant faunal immigration and increasing rates of carbonate production related to the Katian Boda Event have yet been documented from Iranian terranes, probably due to widespread hiatuses close to the Ordovician–Silurian boundary in shallow marine successions (Fig. 4).

In the Silurian (Aeronian), South Kopet-Dagh, East-Central Iran and Afghanistan were the areas of proliferation of the rhynchonellide dominated, shallow marine *Stegocornu* brachiopod Association, which was endemic to these regions (Hairapetian *et al*. 2012, 2017). It was one of the first indicators of growing faunal endemism at the time of cosmopolitan post-extinction recovery brachiopod faunas, which can be considered as clear evidence of close geographical proximity of South Kopet-Dagh, East-Central Iran and Afghanistan at the beginning of the Silurian (and probably still earlier). It is also likely that they drifted alongside Gondwana at least until the end of Llandovery, while an early proliferation of spiriferides, which occurred in Aeronian (Popov & Cocks 2013), suggests proximity to South China – the centre of spiriferide dispersal at the beginning of the Silurian (Zhan *et al*. 2012). This reflects also that the northward drift of the South China palaeocontinent in relation to the Gondwana margin reported by Cocks & Torsvik (2013) was somewhat overestimated for the Ordovician and may occur only from Silurian (post-Llandovery) times. A significant problem is the insufficient sedimentary record for the Wenlock–Ludlow in South China and for the post-Llandovery Silurian–Early Devonian in Alborz and Kopet-Dagh.

The Alestan and Saluk domains represent fragments of a common rift framework. The rift axis is directed obliquely to the existing terrane boundaries. The Damghan Domain was situated on its southern shoulder. The northern rift shoulder is probably preserved at the northern part of the Saluk Domain; however, it was cut off in Alborz, during the time of formation of the South Caspian back-arc Basin sometimes in the Mesozoic (Zonenshain & Le Pichon 1986, Brunet *et al*. 2003, Golonka 2007, Kaz'min & Verzhbitskii 2011). According to Derakhshi & Ghasemi (2015) and Derakhshi *et al*. (2017, 2022), the Soltan-Maidan basalts exhibit oceanic island basalt-like (OIB) geochemical affinities, while a partially melted enriched mantle of type 1 (EM1) was considered as a possible magmatic source. In the Alestan Domain, a general Sandbian uplift preceded the major rifting phase related to extensive alkaline basalt volcanism and subsidence in the mid to late Katian. Therefore, the Alborz rift may represent a plume-related active rift with initial doming (Şengör & Natal'in 2001, Merle 2011). The Saluk and Alestan domains show diachronous, long-lived alkaline magmatism about *c*. 30–45 Ma (Álvaro *et al*. 2022). As was shown on the palaeogeographical reconstructions by Torsvik & Cocks (2017: fig. 6.1), Annamia was about that time crossing the southern boundary of the Tuzo Plume Generating Zone. If we accept Derakhshi *et al*.'s (2017) assumption that the major rifting event in Alborz probably occurred sometimes in the Devonian, it could be nearly isochronous to the separation of South China from Annamia (Cocks & Torsvik 2013, Torsvik & Cocks 2017).

Rift-related Ordovician–Devonian magmatism is known also from the margins of the East-Central Iranian Plate, nowadays facing the present Sabzevar and Sanandaj–Sirjan domains (for details see Hairapetian *et al*. 2017, Vesali *et al*. 2020 and references therein). Its duration is not well defined, but with a reference to a specific location (Kerman Region, Pole-Khavand, Shirgesht *etc.*), it looks considerably shorter than that of the Alborz. There is no evidence of uplift events, and the thickness of the basalt/volcanic units does not usually exceed 150 m. According to Vesali *et al*. (2020), they display OIB-like geochemical features, suggesting that these volcanic rocks are plume-related. Also, a possible magmatic source of the Jalal Abad alkaline maphic intrusions associated with rift related volcanism show isotopic signatures suggesting HIMU–EM2-like mantle source, which support a mantle plume origin, but they differ markedly from the isotopic signatures of the Soltan-Maidan alkaline basalts (Vesali *et al*. 2020: fig. 10). Therefore, it is likely that the alkaline basalt volcanism from the East-Central Iranian Plate probably occurred under passive rift conditions, and its magmatic source was probably different from that of the Soltan-Maidan basalts. While the first signs of the alkaline basalt volcanism in the East-Central Iran were evident in the Middle Ordovician (Gatkuiyeh Formation, Kerman Region), the major volcanic events occurred in the Silurian (post-Aeronian) to Lower Devonian. As demonstrated by Fitton (2007), OIB-like basalts often occur in oceanic and continental settings without distinct links to active mantle plumes; therefore in the shortage of detailed data on geological setting and geochemistry for a significant number of the Lower to Middle Palaeozoic volcano-sedimentary units from the East-Central Iranian Plate, their association with mantle plume activity still requires verification.

The significance of the Alborz and other Iranian rifts as remnants of the 'Palaeotethys' opening is questionable, unless more evidence is presented. Conventionally, the opening of Palaeotethys is attributed to the detachment of a cluster of the so-called 'Hunnic' terranes or 'Hunnic Continent' from the Gondwana margins. The eastern cluster of 'Hunnic' terranes usually includes Tarim, Greater Caucasus and the Karakum-Turan terranes (Stamplfli & Borel 2002). The two latter are sometimes considered as a single block (*e.g*. Torsvik & Cocks 2017). A significant problem is that the eastern 'Hunnic' terrane cluster neither existed in the Early to Mid Palaeozoic, nor was attached to the Gondwana margin in front of the Iranian terrains. The Tarim microplate was discussed in some details by Cocks & Torsvik (2013), who concluded that Tarim was not attached to Gondwana or any other Early Palaeozoic continent (Fig. 22A) by the Furongian, and probably much earlier, whereas the Mid to Late Ordovician faunas show closer affinities with the Kazakh cluster of terranes and South China. The Precambrian zircon spectra for Tarim (Rojas-Agramonte *et al*. 2011) are markedly different from those of Alborz and Kopet-Dagh. Although, as demonstrated by Natal'in & Şengör (2005), the Karakum-Turan block represents an amalgamation of ancient volcanic arcs and accretionary wedges, which can be considered as remnants of a single 'Silk Road Arc'. The oldest Palaeozoic rocks reported from the Karakum-Turan block are Devonian. Shafaii Moghadam *et al*. (2017), based on zircon data from the Saluk Domain, suggested that rifting of the 'Hunnic' terranes, associated with the 'Palaeotethys' opening, had already occurred in the Furongian to Ordovician; however, this looks hypothetical. Instead, the opening of the eastern branch of the Palaeotethys, can probably be assigned to oceanic separation of the combined South China plus Annamia block, which occurred presumably along a formerly transform border sometimes in the Early–Middle Devonian (Cocks & Torsvik, 2013: p. 69). According to the latter authors, the strike-slip movement is evident from the Cambrian, based on the few available palaeomagnetic data from South China (Yang *et al*. 2004, Torsvik & Cocks 2009: tab. 1). Keeping in mind a 135° post-Triassic counterclockwise rotation of the East-Central Iranian Plate, it is possible that rift-related alkaline basalt volcanism along the plate margins occurred in the pull-apart basins formed along a major strike-slip fault system (*e.g.* Merle 2011 and references herein).

Derakhshi *et al*. (2017) assumed that the major rifting event in Alborz occurred some time in the Devonian, somewhat close in time to the detachment of the combined South China–Annamia continent, which was later followed by the Annamian drift (Cocks & Torsvik 2013, Torsvik & Cocks 2017). Horton *et al*. (2008) reported a significant supply of first-cycle igneous zircon detritus aged 390–280 Ma in the Geirud (Upper Devonian) and Dorud (Permian) formations, which suggests an active continental margin as continental source. It is consistent with data presented by Bagheri & Stampfli (2008: pp. 127, 128) on the volcano-sedimentary Godar-e-Siah Complex resting on the ophiolitic mélange, which they considered as remnants of the Upper Devonian–Carboniferous 'Euroasian' active margin and the Late Devonian–early Carboniferous metamorphic event recorded in the Jandaq metamorphic belt; both exposed along the south margin of the Sabzevar Domain in the Anarak and Kabudan areas. Therefore, by the Late Devonian, the Alborz and Kopet-Dagh terranes were already drifting from Gondwana.

Conclusions

(1) The biostratigraphical subdivision and correlation of Ordovician deposits from various parts of Iran and beyond have been considerably improved due to significant progress in the study of the conodonts, palynomorphs, trilobites and brachiopods accomplished during the last decade. The precise setting of the base and top of the Ordovician and the correlation of the Iranian stratigraphical units with the standard stages of the International Chronostratigraphical Scale is better constrained.

(2) Analysis of the stratigraphical succession and fundamental revision of the Ordovician litho- and biostratigraphy of the eastern Alborz Ranges and the Kopet-Dagh Region has led to the distinction of four tectono-stratigraphic units (including the Alestan, Damghan, Saluk and Talesh domains), which differ considerably in their lithological, facies, fossil record and completeness of the sedimentary record.

(3) Geochemical and biostratigraphical evidence suggests that protoliths of the 'Gorgan Schists' metamorphic rock complex derived from the Lower Palaeozoic volcano-sedimentary rocks of the Alestan Domain. They were affected by low grade metamorphism during the mid–late Triassic, which probably developed in the extensional Cordilleran-type back-arc environment at the initial stages of the Caspian Basin generation. They cannot be used as evidence for the setting of the major Palaeotethys suture.

(4) The Middle–Late Ordovician sedimentary succession of eastern Alborz and Kopet-Dagh was deposited on an unstable horst-and-graben rifting palaeotopography affected by episodic mafic extrusive volcanism. This Ordovician rifting magmatism post-dated an Ediacaran to early Cambrian arc-related magmatism, and was followed by rifting and drifting during Devonian times.

(5) Changes in biogeographical affinities of the benthic faunas from the Iranian blocks, located within mid palaeolatitudes through the Ordovician, are most probably due to shifts of climatic belt boundaries with a general trend to global cooling at the end of the Ordovician.

(6) Despite the strong Ordovician biogeographical affinities with South China, and less important with the Mediterranean peri-Gondwana, zircon populations analysed from Cambrian–Ordovician sandstones across northern Iran reflect common sediment sources from the Arabian-Nubian Shield of the western Arabian Peninsula and northeastern Africa. However, the persistence of a sizeable fraction of Neoarchaean–Siderian zircon for almost 130 m.y. may suggest the neighbouring presence of exhumed basement blocks of that age.

(7) The condensed Upper Ordovician carbonate sedimentation, differing from other parts of Iran, and distinct faunal links together with contemporaneous trilobite faunas of Alai and Kazakh terrane assemblages, suggest that the Talesh Domain was part of an exotic terrane only attached to North Iran in latter times.

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Appendix 1. Stratigraphical log of Simeh-Kuh Formation stratotype.

Unit S1. – Grey to dark-grey argillites and siltstones, total 11.8 m thick, with subsidiary centimetre-scale beds of fine-grained silty sandstones at 5.82–5.90 m, 6.20–6.35 m, 6.51–6.68 m, 7.82–7.90 m, 7.95–8.0 m and 8.20–8.30 m. Stratigraphical interval at 9.0–9.4 m above the base of the unit contains trilobites (Fig. 6), mostly preserved as decalcified, isolated sclerites (Ghobadi Pour 2006; sample A-1/3), including *Asaphellus inflatus* Lu, 1962, *Chashania chashanensis* Lu & Shu, 1977 *in* Zhou *et al*. (1977), *Chungkingaspis sinensis* (Sheng, 1958), *Conophrys simehensis* (Ghobadi Pour, 2006), *Dactylocephalus mehriae* Ghobadi Pour, 2006 and *Geragnostus* cf. *yangtzeensis* Lu, 1975.

Unit S2. – Argillites and argillaceous siltstones as background deposit, total 9.5 m thick, with several sandstone and silty sandstone beds as follows: (a) 0.7 m of bedded silty sandstones; (b) 0.8 m of brownish-grey bedded sandstones with lenticular bedding, trough cross-bedding and a lens-like bed of microconglomerates at the base with medium-sorted, well-rounded pebbles; (c) 1.6 m of fine-grained silty sandstones (individual layers varying from 2 to 10 cm thick) intercalated with subsidiary beds of greenish-grey argillites with trace fossils on the bedding surfaces; (d) 5.9 m of dark-grey, laminated argillites and argillaceous siltstones.

Unit S3. – Dark-grey silty argillites, total 13.84 m thick, with four beds of dark-grey (brown on the weathered surface) limestones at 0–0.6 m, 3.5–3.7 m, 4.6–4.7 m and 12.0–12.1 m from the base of the unit. Three upper limestone beds contain conodonts of the *Paltodus deltifer* Zone documented by Jahangir *et al*. (2016; samples SK4/19, SK4/20 and SK4/23). A bed of yellowish-brown calcareous sandstones with a few brachiopod shells of *Dactylotreta batkanensis* Popov & Holmer, 1994 occurs at 3.7–4.7 m from the base of the unit and another bed of massive, yellowish-grey, fine-grained sandstones is documented at 8.30–8.85 m from the base of the unit. The uppermost bed of limestones rich in trilobite sclerites, mostly of *Psilocephalina lubrica* Hsü, 1948, and also contains the micromorphic linguliform brachiopods *Dactylotreta batkanensis* and *Eurytreta* sp. (Jahangir *et al.* 2016). The overlying argillites at the top of the unit are rich in disarticulated trilobite sclerites. The assemblage includes *Apatokephalus* sp., *Conophrys simehensis*, *Geragnostus sidenbladhi jafari*, *Kayseraspis ghavideli* Ghobadi Pour, 2006, *Psilocephalina lubrica* and *Presbynileus*? *biroonii* Ghobadi Pour, 2006 (Ghobadi Pour 2006; sample B-3/1).

Unit S4. – Laminated silty argillites, up to 17.6 m thick, with a characteristic 0.1 m thick bed of sandstone with reverse grading at the base. Interval at 1.0–1.23 m from the base of the unit contains abundant disarticulated trilobite sclerites including including *Apatokephalus* sp., *Conophrys simehensis*, *Geragnostus sidenbladhi jafari*, *Kayseraspis ghavideli* Ghobadi Pour, 2006, *Psilocephalina lubrica* and *Presbynileus*? *biroonii* Ghobadi Pour, 2006 (Ghobadi Pour 2006; sample B-3/2).

Unit S5. – Grey to greenish-grey siltstones intercalated with argillaceous siltstones and sandy siltstones, total 16.8 m thick. The stratigraphical interval from 6.5 to 7.4 m above the base of the unit contains the abundant trilobites *Vachikaspis insueta* Ghobadi Pour, 2006 and brachiopods *Tarfaya jafariani* Popov *et al*., 2009a (Ghobadi Pour 2006; Popov *et al*. 2009a; sample B-4), another fossiliferous interval at 10.24–10.50 m from the base of the unit contains the trilobites *Kayseraspis* sp. and *Psilocephalina lubrica*.

Unit S6. – Fine- to medium-grained parallel- and cross-bedded sandstones with channels filled by bioclastic limestones, and intercalating brachiopod shell beds, total 2.33 m thick. The shell beds comprise disarticulated valves of the brachiopods *Protambonites hooshangi* Popov *et al*., 2009a and *Tarfaya jafariani* (Popov *et al*. 2009a; sample C.1/A). Conodonts *Drepanodus arcuatus* Pander, 1856, *Drepanoistodus* cf. *nowlani* Ji & Barnes, 1994, *Paroistodus numarcuatus* Lindström, 1955 and *Paroistodus proteus* Lindström, 1955 were recovered by Jahangir *et al*. (2016; sample SK4/29) at 2.25–2.30 m above the base of the unit.

Unit S7. – Dark-grey argillaceous siltstones, total 8.92 m thick, with trilobites *Kayseraspis* sp. and *Psilocephalina lubrica*.

Unit S8. – Cross-bedded and parallel-bedded, medium- to fine-grained sandstones and impure limestones with abundant brachiopod coquinas, total 2.86 m thick. A bed of pebbly conglomerates is present at 0.7–0.8 m below the top of the unit. The brachiopods are represented by *Protambonites hooshangi* and *Tarfaya jafariani* (Popov *et al*. 2009a; sample B0). Three conodont samples (SK4/31, SK4/32 and SK4/33) taken respectively at 1.0 m, 1.3 m from the base and from upper 0.1 m at the top of the unit by Jahangir *et al*. (2016) contain the conodonts of the *Paroistodus proteus* Zone. In addition, occurrence of *Drepanoistodus* aff. *amoenus* (Lindström, 1955) identified by Oliver Lehnert (University of Erlangen) was reported by Popov *et al*. (2008).

Unit S9. – Dark-grey, laminated, silty argillite, total 52.85 m thick, as background deposit with subsidiary millimetre-scale layers of siltstones and a few limestone beds at the middle part. It can be subdivided into four sub-units as follows:

Sub-unit A: It comprises 13.65 m of dark-grey silty argillites with the abundant trilobites *Asaphellus fecundus* Ghobadi Pour *et al*., 2007a, *Damghanampyx ginteri* Ghobadi Pour *et al*., 2007a, *Taihungshania miqueli* (Bergeron, 1894), brachiopods *Paralenorthis semnanensis* Popov *et al*., 2009a, *Polytoechia hecatompylensis* Popov *et al*., 2009a, *Ranorthis cheshmehaliana* Popov *et al*., 2009a, *Xinanorthis qoomesensis* Popov *et al*., 2009a, and graptolites *Hunnegraptus*? sp. and *Tetragraptus*? sp. (Ghobadi Pour *et al*. 2007a, Popov *et al*. 2009a, Rushton *et al*. 2021).

Sub-unit B: Dark-grey, laminated silty argillites with occasional millimetre-scale siltstone interbeds and three bioclastic limestone beds at 0–0.6 m, 10.24–10.34 m from the base and at the upper 0.1 m at the top of the sub-unit, total 16.7 m thick. The lowermost limestone bed is rich in brachiopod coquinas, mainly disarticulated shells of the rhynchonelliforms *Paralenorthis semnanensis*, *Polytoechia hecatompylensis*, *Ranorthis cheshmehaliana* and *Xinanorthis qoomesensis* and micromorphic linguliform brachiopods, including *Eosiphonotreta* sp., *Ghavidelia damghanensis* Popov *et al*., 2008, *Orbithele* sp. and *Wahwahlingula?* sp. (Popov *et al*. 2008, 2009a; sample 'Tc'). Two lowermost limestone beds within the sub-unit contain the conodonts *Acodus* sp. cf. *A. triangularis* (Ding, 1993) *in* Wang (1993), *Drepanodus arcuatus*, and *Paroistodus proteus* (Jahangir *et al*. 2016; samples SK4/34, 35), while the uppermost limestone bed in addition to the listed taxa yields *Acodus* cf. *kechikaensis* Pyle & Barnes, 2002, *Cornuodus* sp., *Paltodus subaequalis* Pander, 1856 and *Triangulodus* cf. *larapintinensis* Crespin, 1943. Argillites at 0–0.5 m above the lowermost limestone bed contain trilobites *Asaphellus fecundus*, *Apatokephalus* sp., *Damghanampyx ginteri*, *Euloma* sp., and *Geragnostus* (*Geragnostella*) *lycaonicus* Dean, 1971 (Ghobadi Pour 2006; sample C-2/1), and a few graptolites *Acrograptus* sp. (Rushton *et al*. 2021). Another graptolite-bearing level is present at 3.3 m above the top of the lowermost limestone bed. It contains *Baltograptus geometricus* (Törnquist, 1901) and *Acrograptus* sp., which occur in association with the trilobites *Asaphellus* sp. and *Geragnostus* (*Geragnostella*) *lycaonicus*, the brachiopod *Paralenorthis* sp. and the bivalve *Glyptarca* sp. (Cope & Ghobadi Pour, 2020) (Rushton *et al*. 2021; sample C-2/2).

Sub-unit C: Light- to dark-grey argillites and silty argillites, about 22.5 m thick with several fossiliferous horizons containing graptolites. Interval from 0 to 0.5 m above contact with diabase sill intruded within the lowermost part of the sub-unit, contains monotaxic association, including *Baltograptus geometricus* (Rushton *et al*. 2021; sample C-3/0). Another fossiliferous horizon taken at 3.3 m from the contact with the diabase sill contains *Baltograptus* cf. *sinensis* (Lee & Chen, 1962), which occurs in association with the trilobite *Asaphellus* sp., the brachiopod *Paralenorthis* sp. and the bivalve *Glyptarca* sp. (Rushton *et al*. 2021; sample C-3/2). The next fossiliferous level *c*. 1 m above the previous one contains *Baltograptus* cf. *kunmingensis* (Ni, 1979) *in* Mu *et al*. (1979) and a few *Baltograptus* aff. *geometricus* (Rushton *et al*. 2021; sample C-3/2A). Two uppermost graptolite-bearing horizons at 11.6 m and 11.2 m below the top of the Simeh-Kuh Formation contain *Baltograptus geometricus* and *Baltograptus* aff. *geometricus* (Rushton *et al*. 2021; samples SK-3/2B1 and SK-3/2B2).

Appendix 2. Stratigraphical log of Qumes Formation stratotype.

The type section of Qumes Formation is a natural exposure located in the Simeh-Kuh Inlier, 13 km northwest of Damghan city. Geographical coordinates for the base of the section are 36° 12′ 49.8″ N, 54° 13′ 30.6″ E, and altitude 1406 m. The stratigraphical succession in ascending order is as follows:

Unit Q1. – Alternation of bioclastic limestones and greenish-grey argillites, 3.63 m thick, comprising: (a) 0.3 m of greenish-brown bioclastic limestones with a brachiopod shell bed, up to 5 cm thick at the base; (b) 0.47 m of greenish-grey argillites with a brachiopod shell bed about 1 cm thick located at 0.38 m above the base; (c) 0.13 m of brownish-grey bioclastic limestones representing a brachiopod shell bed with uneven, erosive surface at the base; (d) 0.03–0.06 m lenticular bed of greenish-grey argillites; (e) 0.56 m fine- to medium-grained, quartzose to subarkozic calcareous sandstones with uneven, erosive surface at the base; (f) 0.26 m of dark-grey bioclastic limestones; (g) 0.1 m of greenish-grey argillites with a lenticular bed of argillaceous limestones 1–4 cm thick in the mid part; (h) 0.95 m of bedded brownish-grey bioclastic limestones with individual beds 1–6 cm thick and up to 0.15 m thick brachiopod shell bed at the top.

Unit Q2. – Fine-grained sandstones and siltstones, total 3.85 m thick with five brachiopod shell beds at 1.1–1.2 m, 17–2.2 m, 2.5–2.6 m, 3.4–3.42 m and 3.6–3.8 m from the base.

Unit Q3. – Brown bioclastic limestones, total 0.65 m thick.

Unit Q4. – Brownish-grey, medium to fine grained quartzose sandstones with glauconite and sandy siltstone intercalations in proportion approximately 60%–40% and rhynchonelliform brachiopod shell beds at 0.74–0.98 m and at upper 0.3 m of the unit, total 4.56 m thick.

Unit Q5. – Brownish-grey to grey, fine grained sandstones and sandy siltstones (individual beds 0.1–0.2 m thick) interbeds, total 3.77 m thick.

Unit Q6. – Greyish-brown, fine-grained, subarkosic sandstones with intraclasts, total 0.74 m thick.

Unit Q7. – Sandstones and siltstones intercalations with proportion of siltstones significantly increasing towards the top of the unit, total 8.76 m thick. Five beds of bioclastic limestone are present in the upper part of the unit at 4.90–4.95 m, 5.20–5.25 m, 6.20–6.24 m, 6.88–6.93 m and 7.82–7.85 m.

Unit Q8. – Bedded bioclastic limestones, total 3.48 m thick. Individual limestone beds vary in thickness 2–10 cm, with uneven hardground surfaces on the top, separated by the thin lenticular layers of siltstones and silty argillites 1–3 cm thick.

Unit Q9. – Fine-grained sandstones with lenses and lenticular beds of limestone, total 2.13 m thick.

Units Q4–Q7 are assigned to the Gerd-Kuh Member.

Appendix 3. Stratigraphical log of Qyzlar Formation stratotype.

The type section of Qyzlar Formation is located on the east side of the Kalat valley in the eastern part of the Saluk Mountains along the road connecting Bojnurd to Esfarayen, *c*. 39 km south of Bojnurd city. Geographical coordinates of the type section base are 37° 13′ 42″ N, 57° 23′ 19″ E, altitude 1620 m. The stratigraphical succession in ascending order looks as follows:

Unit Qy1. – Laminated black argillites about 6.8 m thick, with graptolites and a few trilobites including *Peltocare* sp. (Fig. 14).

Unit Qy2. – Dark-grey argillites with two brachiopod shell beds at the base (0.7 m thick) and at the top (0.3 m thick), total 2.4 m thick. Contains brachiopods *Eurytreta* cf. *belli* (Davidson, 1868), *Protambonites* sp. and conodonts *Cordylodus lindstromi* Druce & Jones, 1971 (Jahangir *et al*. 2015; sample F-36, taken from the top of the unit) (Fig. 14).

Unit Qy3. – Black to dark-grey laminated argillites up to 17 m thick.

Unit Qy4. – Brachiopod shell beds with silicified, disarticulated valves of *Protambonites* sp. intercalating with dark-grey argillites, about 1.7–2.0 m thick, with conodonts *Cordylodus prolindstromi* Nicoll, 1991, *Cordylodus proavus* Müller, 1959, *Cordylodus lindstromi* and *Cordylodus angulatus* Pander, 1856 (Fig. 14).

Unit Qy5. – Dark-grey laminated argillites up to 61 m thick, with sporadic occurrences of the trilobite *Asaphellus inflatus* (Fig. 14).

Unit Qy6. – Olive-grey laminated siltstones with argillite intercalations, up to 3.3 m thick. The upper part of the unit contains the trilobites *Conophrys* aff. *gaoluoensis* Zhou, 1977 *in* Zhou *et al*. (1977) (Fig. 14).

Unit Qy7. – Grey, bedded bioclastic limestones with abundant brachiopod coquinas, up to 0.9 m thick.

Unit Qy8. – Olive-grey to grey argillites, up to 4 m thick.

Unit Qy9. – Strongly weathered, bedded, bioclastic limestones, up to 1.7 m thick.

Unit Qy10. – Grey to olive-grey argillites with a few thin, lenticular limestone beds, total up to 9.6 m thick.

Unit Qy11. – Grey (brownish-grey on the weathered surface), bioclastic limestones up to 0.7 m thick.

Unit Qy12. – A bed of basalt volcanic rocks about 1.5 m thick.

Unit Qy13. – Grey, laminated argillites up to 6 m thick.

Unit Qy14. – A bed of basalt volcanic rocks, c. 1.0–1.1 m thick.

Unit Qy15. – A bed of limestone up to 1.70 m thick.

Unit Qy16. – A bed of basalt volcanic rocks up to 1.4 m thick.

Unit Qy17. – Olive-green argillites and siltstones with two beds of bioclastic limestones at 11 m from the base and 10 m from the top, total up to 30 m thick.

*Unit Qy1*8. – Dark-grey, fine-grained, calcareous sandstones with abundant brachiopod coquinas, total up to 20 m thick.

Unit Qy19. – Greenish-grey siltstones up to 15 m thick.

Appendix 4. Stratigraphical log of Polekhavand Formation stratotype.

Unit 1. – Greenish-grey fine-grained sandstones, with conglomerate lenses and a bed of amygdaloidal basalts at the top of unit, total up to 28.5 m thick. Detailed lithological sub-units are: (a) greenish-grey, well sorted, fine-grained sandstones total 21 m thick, with lenses of polymict conglomerates (clasts represented by milky quartz, green metamorphic shale and intrusive rocks); (b) argillites with lenses of mircroconglomerates, total 5.3 m; (c) amygdaloidal basalts, up to 2.2 m thick.

Unit 2. – Yellowish-brown to blue dolomites and sandstones, up to 17.3 m thick. Detailed lithological sub-units are: (a) dolomite, up to 12.7 m thick; (b) medium- to coarse-grained sandstones, about 2 m thick; (c) dolomites with lenses of cherts, up to 2.6 m thick.

Unit 3. – Sandstones, total 15.7 m. Detailed lithological sub-units are: (a) violet, poorly sorted sandstones, up to 8.7 m thick; (c) fine-grained sandstones, up to 7 m thick.

Unit 4. – Laterally variable succession of the agglomerates and lithic tuffs, total 178.9 m thick, which can be subdivided into several sub-units in the measured transect, as discussed below:

Sub-unit 4a: Purplish-brown, poorly sorted agglomerate tuffs intercalated with beds of lithic tuffs and tuffs, *c*. 117.8 m thick. Rhyolite lithic clasts (up to 90 cm in size) within the agglomerate tuffs are predominant. Intercalated within the agglomerates are several distinct horizons of fine-grained lithic tuff and tuffaceous material, all pink to red in colour. Several sub-units can be determined based on size of pyroclasts, separated by tuff horizons probably representing a multiple rhyolite flows produced by collapsing and fragmentation of growing rhyolite domes (or flows). Each flow horizon represents one explosive event, in small extent which can be interbedded with pyroclastic deposits (tuffs and tuffites). Laterally there are a few small packages of red jaspers of commercial-grade quality which also suggests that they are derived from a hot rhyolite flow by hot water leaching and re-precipitating in cool cavities commonly found in the outer margins of the flow. Detailed lithological sub-units are: (a) agglomerate tuffs with clasts of rhyolite volcanic rocks and sedimentary rocks derived from underlying deposits, up to 49.5 m thick.

Sub-unit 4b: Pink, thin-bedded fine-grained lithic tuffs, up to 19.5 m thick.

Sub-unit 4c: Agglomerate tuffs with a thin bed of tuffs in the uppermost part of the unit, total 24.8 m thick with a thin bed of tuff *c*. 0.1 m thick at 2.3 m below the top of the unit.

Sub-unit 4d: Rhyolitic agglomerate tuffs with a few thin beds of lithic tuffs in the middle and upper part, total up to 17.1 m thick, as follows: (a) red thin-bedded rhyolitic tuffs up to 1.8 m thick; (b) fining upwards agglomerate tuffs with clasts of rhyolite volcanic rocks strongly variable in sizes, up to 5.8 m thick; (c), a bed of lithic tuff about 0.35 m thick; (d) a bed of rhyolitic tuffs, about 0.9 m thick; (e) a bed of tuffs about 0.3 m thick; (f) agglomerate tuffs up to 7.2 m thick.