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Silurian stratigraphy of Central Iran – an update

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ABSTRACT:

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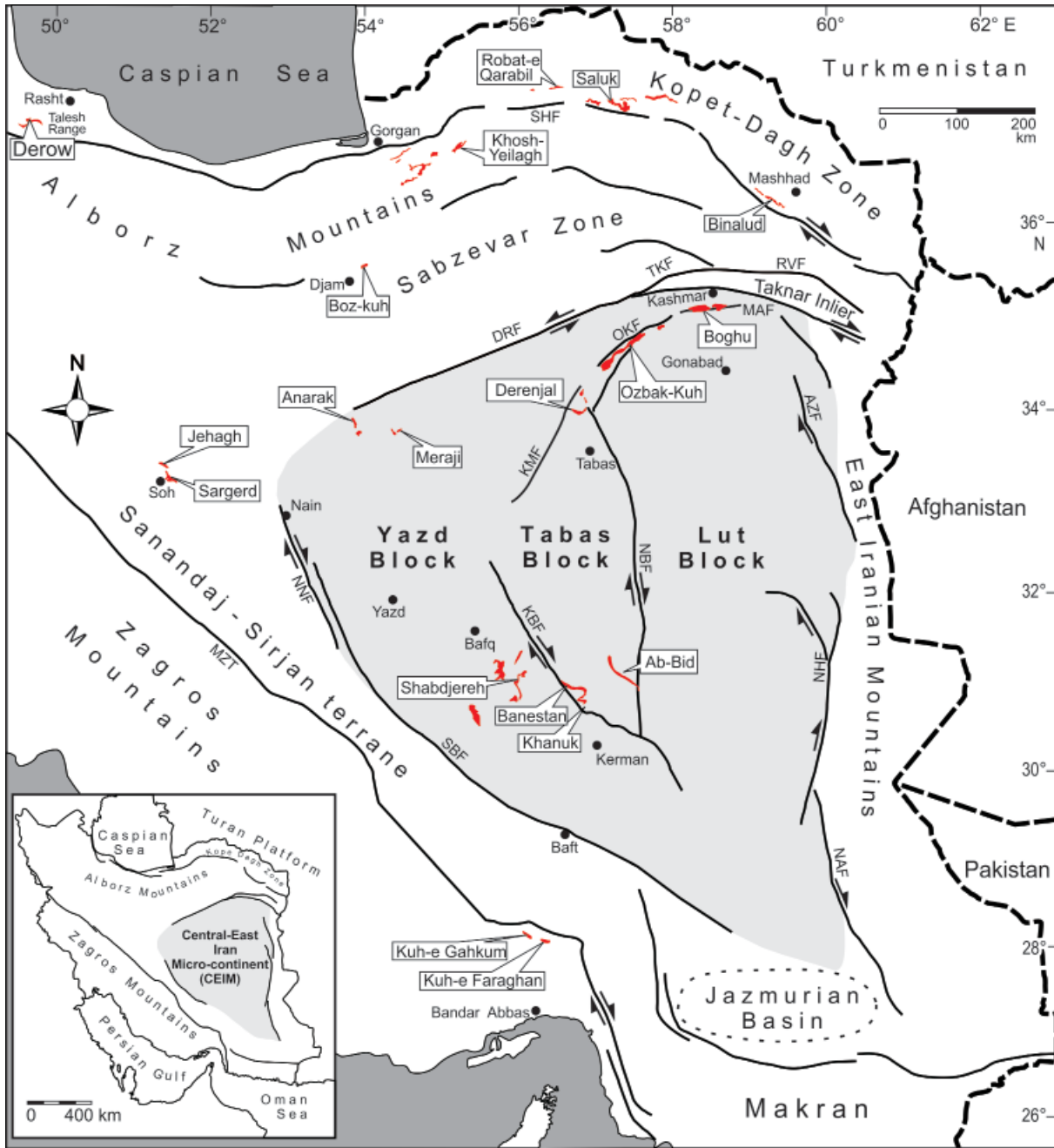
The Silurian biostratigraphy, lithostratigraphy, and facies of Central Iran including the Kashmar (Boghu Mountains), Tabas (Derenjal Mountains, Ozbak-Kuh), Anarak (Pol-e Khavand) and Kerman regions is reviewed and updated. The current state of knowledge of the Silurian in the Zagros Basin, Alborz, Kopet-Dagh and Talysh regions, as well as in a few areas scattered across the Sabzevar Zone, and the Sanandaj-Sirjan terranes is also reviewed. Silurian volcanism in various parts of Iran is briefly discussed. The end of the Ordovician coincided with a widespread regression across Iran synchronous with the Hirnantian glaciation, and only in the Zagros Basin is there a continuous Ordovician–Silurian transition represented by graptolitic black shales of the Sarchahan Formation. In the Central-East Iranian Platform marine sedimentation re-commenced in the early to mid Aeronian. By the Sheinwoodian, carbonate platform depositional environments were established along its north-eastern margin. In other parts of Iran (e.g., Kopet-Dagh and the Sabzevar Zone), siliciclastic sedimentation continued probably into the late Silurian. The Silurian conodont and brachiopod biostratigraphy of Central Iran is significantly updated facilitating a precise correlation with the Standard Global Chronostratigraphic Scale, as well as with key Silurian sections in other parts of Iran. The Silurian lithostratigraphy is considerably revised and two new lithostratigraphical units, namely the Boghu and Dahaneh-Kalut formations, are introduced.

Key words: Iran; Silurian; Biostratigraphy; Lithostratigraphy; Sedimentology; Correlation.

INTRODUCTION

The presence of Silurian deposits in Central Iran was established more than half a century ago (Flügel 1962; Huckriede *et al.* 1962). However, little progress had subsequently been made in Silurian research until the past decade, when a number of pub-

lications considerably increased our knowledge of Iranian Silurian litho- and biostratigraphy. This has significantly changed our general understanding of Silurian geology in Iran, whereas reviews published more than ten years ago have become increasingly outdated. The main objective of this paper is to outline in detail the Silurian successions and associated



Text-fig. 1. Simplified tectonic maps of Iran showing the location of Silurian outcrops (marked with red colour; small exposures are exaggerated) discussed in the paper (base map modified mainly from Ramezani and Tucker 2003 and Hairapetian *et al.* 2012); structural data compiled from various sources, e.g., Berberian and King (1981), Lindenberg *et al.* (1984) and Alavi (1991). Abbreviations: AZF – Abiz Fault; DRF – Doruneh Fault; KBF – Kuhbanan Fault; KMF – Kalmard Fault; MAF – Mehdiabad Fault; MZT – Main Zagros Thrust; NAF – Nostratabad Fault; NBF – Nayband Fault; NHF – Nehbandan Fault; NNF – Nain Fault; OKF – Ozbak Kuh Fault; RVF – Rivash Fault; SBF – Shahre-Babak Fault; SHF – Syahkuh Fault; TKF – Taknar Fault

faunas of the Central-East Iranian Platform, which is the major Silurian domain in Iran (Text-fig. 1). During the early Palaeozoic, this region is considered to have been situated within temperate latitudes on

the margins of the Gondwana Supercontinent (e.g., Golonka 2012; Torsvik and Cocks 2013). While its precise position in relation to the other Gondwana terranes cannot be defined with any degree of confi-

dence at present, recently documented early Silurian faunas from Central Iran suggest closest links with Afghanistan and the north-east Iranian Kopet-Dagh Range (Hairapetian *et al.* 2012; Popov *et al.* 2014). In the south-west, the Central-East Iranian Platform is bounded by the Sanandaj-Sirjan terrane and the Main Zagros Thrust Zone. The existing Silurian record of the Sanandaj-Sirjan terrane is very poor with the only documented Silurian deposits within the region cropping out in the Jehagh Anticline and Sargerd Mountain Ranges, in the vicinity of Soh village (Text-fig. 1). Silurian deposits are widespread along the north-eastern margin of the Arabian Platform on the opposite side of the Main Zagros Thrust Zone, where they are represented mainly by black graptolitic shales assigned to the Sarchahan Formation of Iran (Ghavidel-Syooki *et al.* 2011a). These black shales can be found in the subsurface through the Zagros Mountains and are the major hydrocarbon source rock for the Dalan and Kangan reservoirs (Saber *et al.* 2016). The Silurian sedimentology and biostratigraphy of the Zagros Basin has been outlined in some detail by Ghavidel-Syooki *et al.* (2011a) and Saber *et al.* (2016). The Alborz Mountains are often considered part of Central Iran in a broad sense, but most probably represent an isolated microplate in the early Palaeozoic (Popov *et al.* 2016). Here the Silurian is represented by volcanic rocks of the Soltan-Maidan Formation.

The only other Silurian outcrops in Iran are in the Boz-Kuh area (Sabzevar Zone) and in the Talesh Range, west of Rasht (Text-fig. 1). While the presence of the Silurian rocks in these regions was established more than 40 years ago (Alavi-Naini 1972; Clark *et al.* 1975), present knowledge of their litho- and biostratigraphy remains very general and their tectonic position in relation to other early Palaeozoic terranes uncertain. They probably had no close relation to the Alborz Microplate.

The material illustrated and/or discussed below is deposited in the National Museum of Wales, Cardiff, UK (NMW), in the Department of Earth Science, Natural History Museum, London, UK (NHMUK PM X), and in the Department of Geology, Azad University, Esfahan, Iran (AEU).

PREVIOUS WORK

Although the presence of Silurian sedimentary rocks was reported well over half a century ago from several regions in Iran, very few details of lithofacies, stratigraphy and faunal distribution have been pub-

lished since then. The first reports of the Silurian deposits from Iran were published by Flügel (1962), who documented their presence in the Ozbak-Kuh Region, and by Huckriede *et al.* (1962), who reported the presence of fossiliferous limestones and dolomites in the vicinity of Shabdjereh, Deh-Ali and Yazdan-Abad to the north-west of Kerman. They considered these deposits as Ordovician to Silurian based on occurrences of corals, brachiopods (including rhynchonellids and “*Platystrophia*”, probably *Stegocornu*), bryozoans and tentaculites.

The Palaeozoic geology of the Derenjal Mountains, including the Shirgesht area, north of Tabas (north-eastern Central Iran) was described in more detail by Ruttner *et al.* (1968). They defined the Silurian to Lower Devonian formations of the Gushkamar Group and considered the Niur Formation in the Derenjal Mountains as the lower unit of that group. They also provided comprehensive lists of brachiopods and corals found in Silurian deposits across the region.

Probably the first assessment of the Silurian stratigraphy of Iran was given by Berry and Boucot (1972) in their Special Paper dedicated to the correlation of the Silurian rocks of SE Asia and the Near East. They gave a brief review of the Silurian strata of the Kerman Region, at Shirgesht (Tabas Region) and Kuh-e-Gahkum, north of Bandar-Abbas. Illustrations of some Silurian fossils from Iran, including brachiopods, which were mostly incorrectly identified, can be also found in Kalantari (1981). Nine Silurian brachiopod taxa originally derived from the Niur Formation of Shirgesht and from Kuh-e-Gahkum in the south-eastern Zagros Range were identified. Wolfart (1981) gave the first general review of the Silurian stratigraphy of Iran. He suggested that the Silurian sedimentary successions are restricted to the north-eastern, east-central and south-eastern parts of Iran bordered from the east by the Lut Block and by possible Silurian highs to the south and north-west. The review publication by Wensink (1991) outlined the general stratigraphy of the northern and central regions of Iran. All of these publications are significantly outdated and do not represent the current state of knowledge based on recent work by Iranian researchers.

The subdivision of the Silurian System into series and stages in Iran remained problematical until recently and the boundaries of the major internationally recognised chronostratigraphic units were not established in the region due to a shortage of precise and systematic palaeontological and biostratigraphic studies. The most recent systematic review

of the Silurian stratigraphy of Iran was published by Stocklin and Setudehnia (1991). They listed several brachiopods and corals from the Niur Formation exposed at Ozbak-Kuh and Shirgesht in the Tabas Region.

Hamedi *et al.* (1997) questioned previous preliminary fossil identifications used to show evidence of Silurian sedimentary units in Iran, suggesting that they were often out of date and not always reliable. The only exception was Cocks (1979a), who reported a rich silicified brachiopod fauna from the Kopet-Dagh Range (north-eastern Iran), and introduced the Qarabil Formation for the Silurian deposits exposed in the region. Wendt *et al.* (2002, 2005) briefly discussed the facies patterns and the palaeogeography of the Silurian of Iran. However, the lithostratigraphic, lithofacies and palaeogeographic data they presented are now considered outdated.

In recent years, significant progress has been made in the study of the Silurian sedimentary sequences of the Zagros Basin and Central Iran (Tabas and Kashmar regions) where abundant graptolites, ostracodes, rugose corals, palynomorphs (including acritarchs and chitinozoans) and sporadic fish remains were documented in a number of recent publications (for summary see Ghavidel-Syooki 2001; Hairapetian *et al.* 2008, 2011). The Silurian brachiopods and conodonts of Central Iran are currently under extensive study and are partly published (Hairapetian *et al.* 2012; Männik *et al.* 2013, 2015; Popov and Cocks 2013; Popov *et al.* 2015a). These works have expanded our knowledge of the Silurian geology, stratigraphy and palaeontology of Central Iran and the Kopet-Dagh Region.

The lithostratigraphical subdivision of the Silurian system in Iran is very poorly constrained and requires revision. The Niur Formation defined by Ruttner *et al.* (1968) was the first formal lithostratigraphical unit introduced to cover the Silurian sedimentary rocks of Central Iran. Currently the term Niur Formation is applied to a wide range of Silurian sedimentary rocks cropping out all over Iran except for the Zagros Basin. The most extensive work has been done by the authors in the Tabas, Kashmar and Kerman regions, all within the Central-East Iranian Microplate, where the Silurian deposits are well exposed. However, the type section of the Niur Formation situated in the Ozbak-Kuh area in the vicinity of Niur village has not been restudied since the work of Ruttner *et al.* (1968) and a detailed description of the type section of the unit has not been produced. As a result and despite the extensive use of the formation name, the stratigraphic range and boundaries of the Niur Formation

in the type section remain formally undefined. Wendt *et al.* (2002, p. 131) pointed out that the Ozbak-Kuh area is highly tectonized and represents a mosaic of small slices and blocks so that it is impossible to observe the stratigraphical relationships between the lithostratigraphical units established here. It is difficult to use them for geological mapping and they need to be restudied and redefined. The type section of the Niur Formation at Ozbak-Kuh is considered to be faulted in its lower part and is composed mainly of carbonates (Ruttner *et al.* 1968). However, contrary to the original description of the section in the Derenjal Mountains by Ruttner *et al.* (1968), the lower contact of the Niur Formation, i.e. its contact with the Lower to Middle Ordovician deposits of the Shirgesht Formation, is also faulted (Bruton *et al.* 2004; Ghobadi Pour *et al.* 2006).

The use of the term Niur Formation has become almost synonymous with the Silurian System in Iran, and this has made it difficult to apply to geological mapping (see also Wendt *et al.* 2002). We suggest that the easiest solution is to raise this lithostratigraphical unit to the rank of group, which unites all documented Silurian successions within the Tabas Block. However, such defined “Niur Group” becomes then a junior synonym of the Gushkamar Group, which was established earlier (by page priority) in Ruttner *et al.* (1968) and this should be formally applied.

OUTLINE OF REGIONAL STRATIGRAPHY

Kashmar Region

Extensive outcrops of Silurian deposits are known south and south-west of the town of Kashmar in north-eastern Central Iran. The best Silurian succession in the whole area documented up to date is located on the southern slope of the Boghu Mountains, c. 25 km south-west of Kashmar (Text-fig. 1). It was first described in some detail by Ghavidel-Syooki (2003) who assigned acritarchs from the Silurian part of the succession to the local Acritarch Assemblage Zone 7, which is dated as Llandovery to Wenlock. A detailed stratigraphical column and faunal logs for the Silurian succession in the Boghu Mountains were later published by Hairapetian *et al.* (2012). The Silurian deposits assigned here to the Boghu Formation are underlain by the upper Katkoyeh Formation of Upper Ordovician siliciclastic rocks. There is controversy over the position of the base of the Silurian in the area. The lower part of the exposed section comprises green siltstone/shale beds intercalated with beds of

bioclastic limestone rich in tentaculitids and beds of sandstone. This interval was previously assigned to the Niur Formation and indicated on the geological map of the Kashmar area as lowermost Llandovery based on conodont faunas (Taheri and Shamanian 2001, sheet 1:100 000). However, the occurrence of *Icriodella* aff. *superba* Rhodes, 1953 in association with *Amorphognathus* cf. *ordovicicus* (Branson and Mehl, 1933) within this interval (Text-fig. 2, units UK1 and UK2, samples K5–K10), clearly indicates a Late Ordovician (Katian) age.

The lower boundary of the Boghu Formation is placed at the base of the first limestone bed (Text-fig. 2, Unit B1), in which the conodont *Walliserodus* cf. *curvatus* (Branson and Branson, 1947) first appears in the section. According to Armstrong (1996) this conodont, characteristic of the Rhuddanian and Aeronian, already appears in the uppermost Ordovician, in the *Metabolograptus persculptus* Graptolite Biozone (GB). The lower boundary of Unit B1 was provisionally considered as the base of the Silurian in the Boghu succession (Hairapetian *et al.* 2012) because it is separated from the last occurrence of the Upper Ordovician conodont *Amorphognathus* cf. *ordovicicus* by a barren interval of about 107 m.

Boghu Formation

(*Silurian, Aeronian to lower Sheinwoodian*)

Type section: Boghu Mountains, 25 km SW of Kashmar town. Coordinates of base of section: N 34°04' 6.2"; E 58°15'48.8", altitude 1222 m.

Distribution: Exposed in the northern part of Central-East Iran, in particular in the Ozbak-Kuh, Boghu and Derenjal mountains, and in the Anarak Region.

Lower boundary: In its type section the Boghu Formation rests unconformably on Upper Ordovician, probably Katian deposits (Text-fig. 3). Here, the lower boundary of the formation corresponds to the base of the carbonate succession. In the Anarak Region, the lowermost part of the Boghu Formation is represented by shales overlying Upper Ordovician sandstones (Unit 6) of the Chahgonbad Formation. In the Derenjal Mountains the lower contact of the Boghu Formation is faulted (Bruton *et al.* 2004; Ghobadi Pour *et al.* 2006).

Upper boundary: In the type section of the Boghu Formation, there is a faulted upper contact. Ghavidel-Syooki (2003, fig. 2) stated that in the northern part

of the Boghu Mountains it is conformably overlain by a thick unit of limestones assignable to the Dahaneh-Kolud Formation. However, our extensive field work has been unable to show this due to numerous tectonic faults and related displacement of limestone units in the upper part of the Boghu Formation. In the Derenjal Mountains the Boghu Formation is overlain conformably by the Dahaneh-Kalut Formation.

Subdivision: The type section of the Boghu Formation is 540.6 m thick and consists of 14 informal units (Text-figs 2–5) in ascending order as follows (mainly after Hairapetian *et al.* 2012):

Unit B1. About 25 m. Reddish brown bioclastic limestone with abundant crinoid ossicles.

Unit B2. About 20 m. Thin- to medium-bedded limestone with interbeds of argillite.

Unit B3. About 19.7 m. Green siltstone with thin interbeds of sandstone and limestone. Three subunits include: (a) 4.5 m, green siltstone; (b) 12.7 m, green siltstone with thin interbeds of sandstone and limestone; (c) 2.5 m, green siltstone with elongated lenses of limestone.

Unit B4. About 15 m. Bioclastic limestone with thin interbeds of siltstone and argillite. Two lithological subunits were recognised: (a) 4.2 m, intercalations of bioclastic limestone and argillite; (b) 10.8 m, thick-bedded limestone (in the lower part) and alternation of red echinoderm and cephalopod limestone, and siltstone (in the upper part).

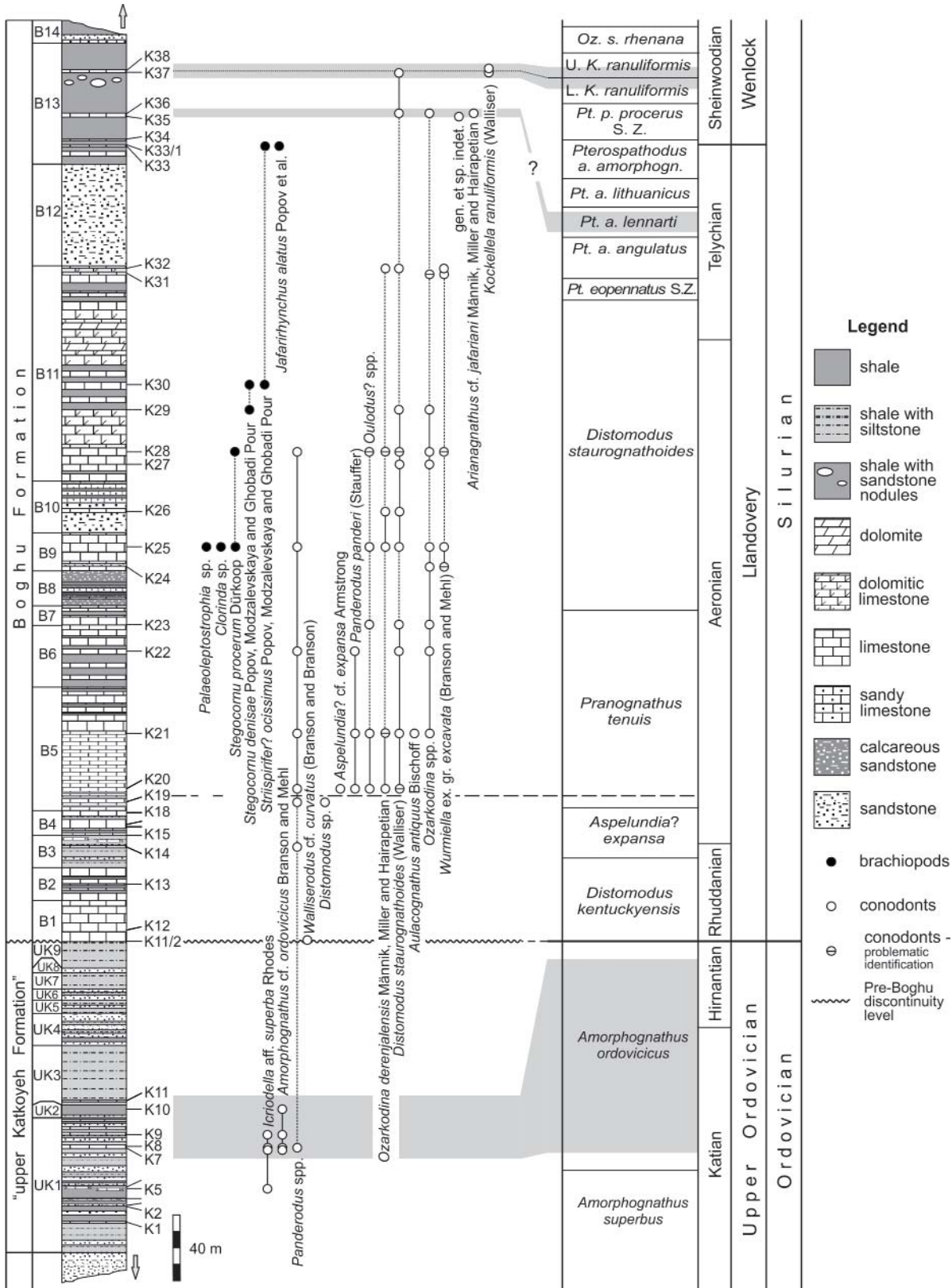
Unit B5. About 75.1 m. Thin-bedded yellow to grey limestone with rare interbeds of argillaceous limestone and argillite. The interval is subdivided into two subunits: (a) 48.4 m, thin-bedded yellow to grey limestone with brachiopods, corals and nautiloids; (b) 26.7 m, thin-bedded yellow to grey limestone with interbeds of argillite.

Unit B6. About 37.8 m. Green argillite interbedded with brachiopod limestone.

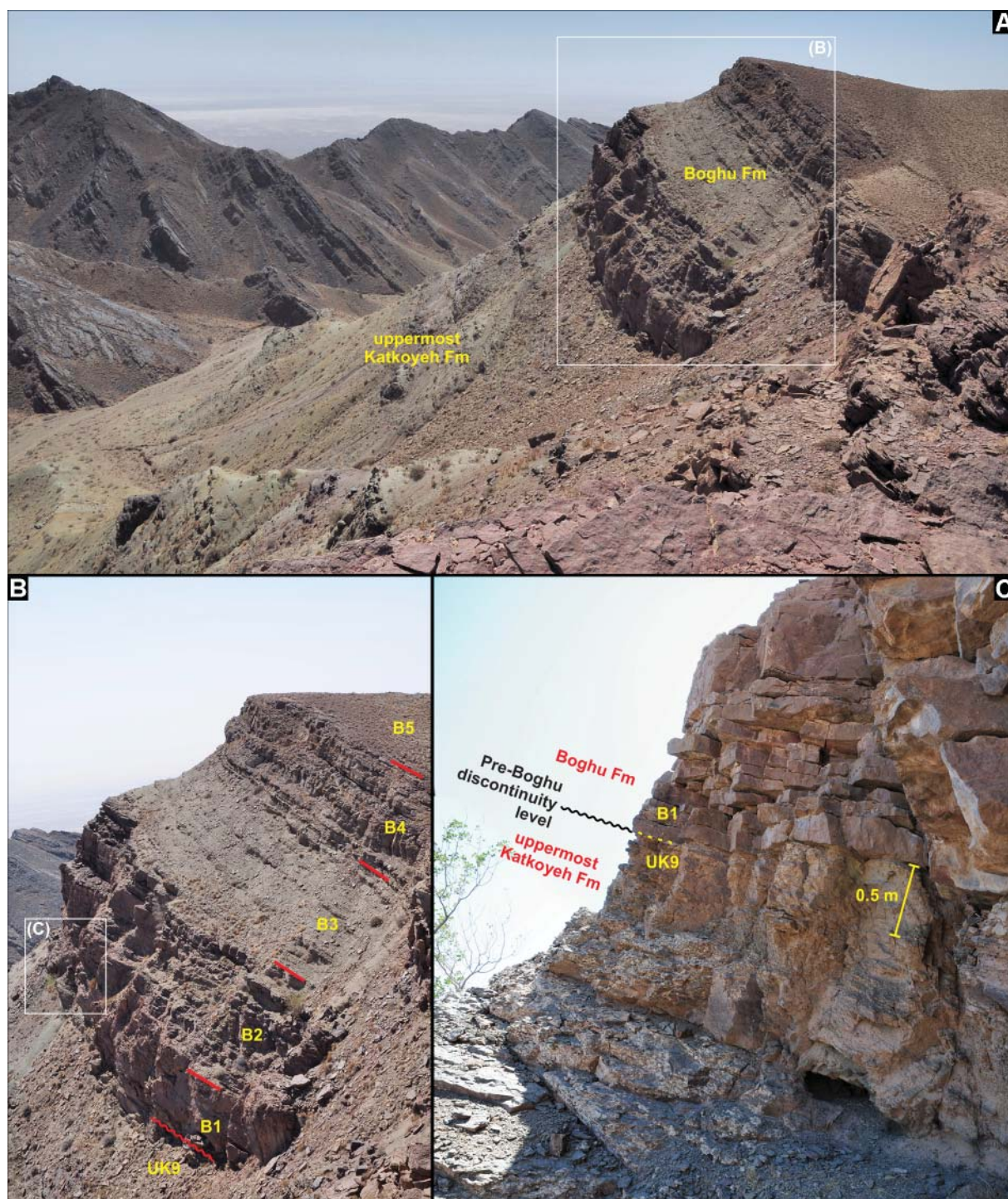
Unit B7. About 11.8 m. Limestone with interbeds of argillite.

Unit B8. About 21.3 m. Alternation of calcareous sandstone, thin-bedded dolomitic limestone and argillite. Detailed lithological subunits are: (a) 2.3 m sandstone; (b) 6.3 m calcareous sandstone and thin-bedded limestone; (c) 12.7 m calcareous sandstone, argillite and sandy limestone with brachiopods.

Unit B9. About 22.9 m. Limestone with corals, brachiopods, nautiloids and tentaculites, and sandstone. Three subunits were described: (a) 4.2 m, limestone with brachiopods and orthoconic cephalopods; (b) 1.1 m, sandstone with thin interbeds of limestone yielding large colonies of favositid tabulate corals

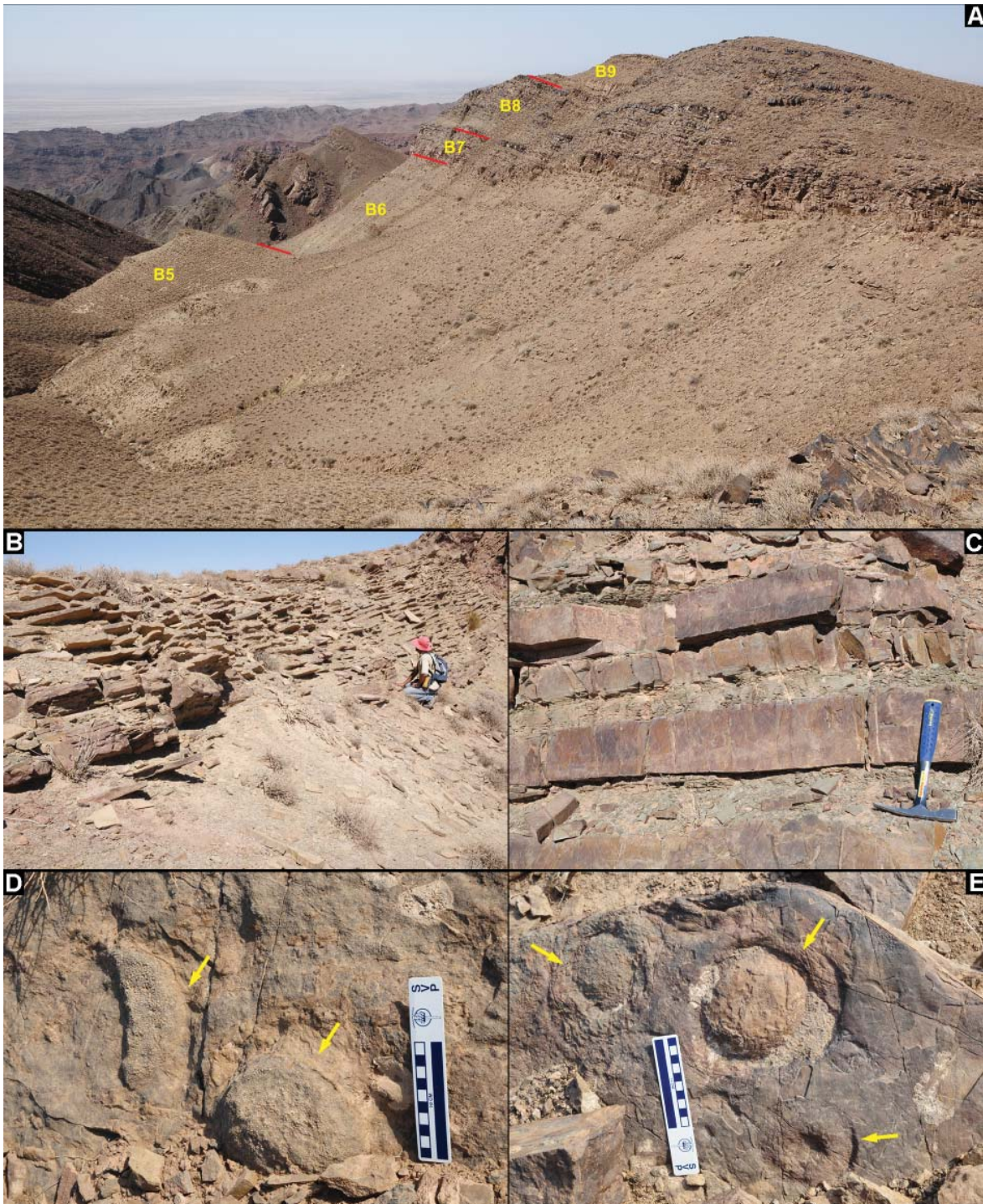


Text-fig. 2. Boghu Mountains section. From left to right: formations; described units; lithological log (arrows below and above the log indicate that the section continues in both directions); locations and numbers of samples; distribution of taxa; conodont biozones (after Cramer *et al.* →



Text-fig. 3. Field photographs of the Upper Ordovician and Silurian (Llandovery) exposures in the Boghu Mountains. A – Southwesterly view of the uppermost part of the outcrop showing the uppermost Ordovician–lowermost Silurian interval; B – Ordovician–Silurian boundary (= boundary between units UK9 and B1) and lower part of the Boghu Formation (units B1–B5); C – Close-up view of the Ordovician–Silurian boundary (marked by a discontinuity surface between units UK9 and B1). Distinct facies change occurs at the system boundary

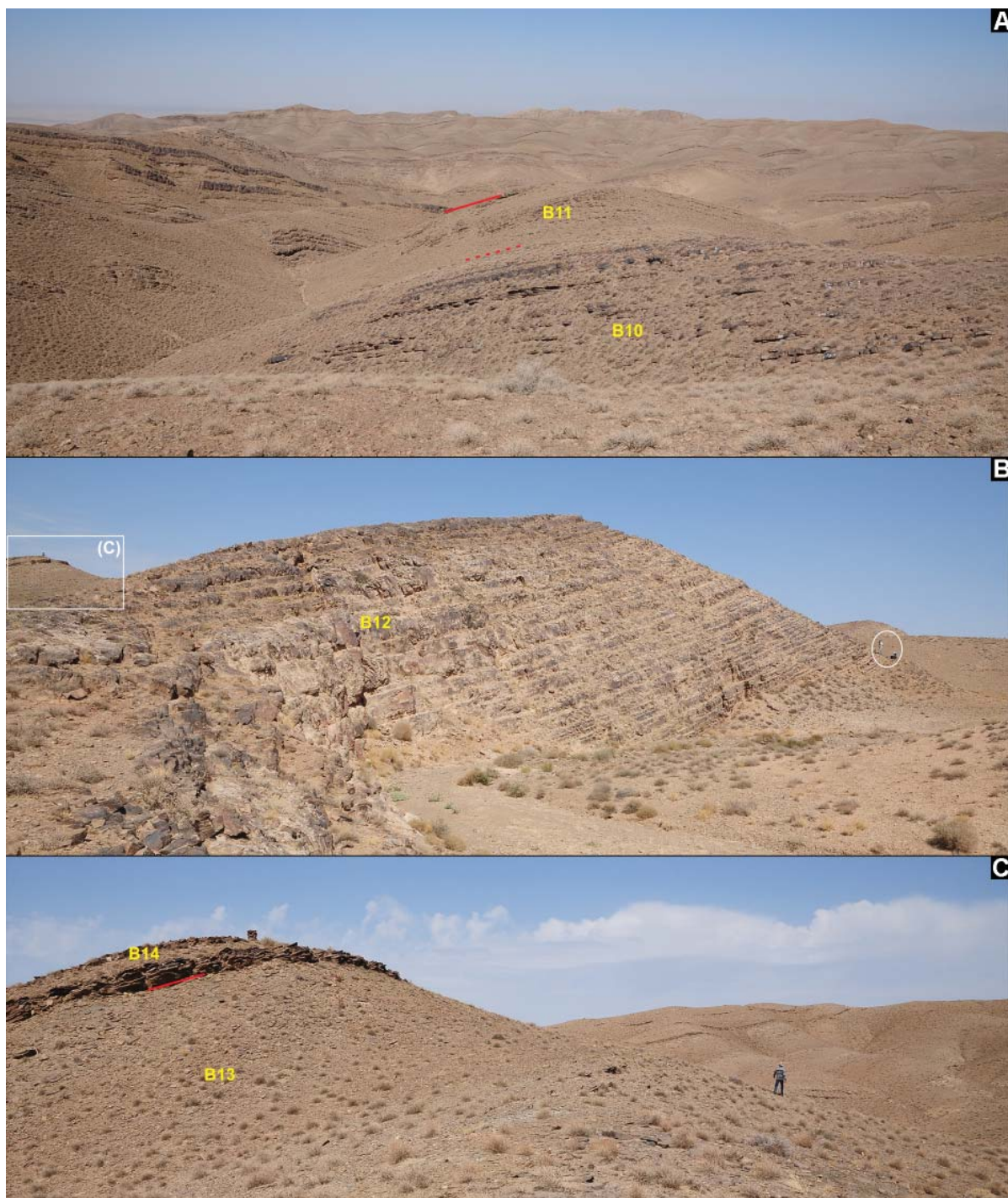
2011) and general stratigraphy (Stage, Series, System). Grey boxes in the column of conodont biozonation indicate biozones (or parts of) that were recognised in the studied section. Abbreviations: *Pt.* – *Pterospathodus*; *a.* – *amorphognathoides*; *p.* – *pennatus*; *K.* – *Kockelella*; *Oz.* – *Ozarkodina*; *s.* – *sagitta*; *o.* – *ortus*; S.Z. – Superzone



Text-fig. 4. Field photographs of the middle part of the Boghu Formation in the Boghu Mountains. A – Westerly view of the Boghu Formation, units B5–B9; B – Alternation of thin-bedded limestone and argillite in the lower part of Unit B5; C – Alternation of dark brown sandstone and greyish-green argillite in Unit B8; D-E – Large favositid tabulate corals (indicated with arrows) in units B9 (0.6 m above K24/3) and B11 (1.9 m below sample K27)

(up to 20 cm in diameter); (c) 17.6 m, limestone with large colonies of favositid tabulate corals, brachiopods and tentaculites.

Unit B10. About 31.3 m. Alternation of sandstone, shale and limestone. Five subunits were identified: (a) 12.3 m, sandstone; (b) 2.5 m, bioclastic limestone



Text-fig. 5. Field photographs of the Boghu Formation in the Boghu Mountains. A – General view of units B10 and B11; B – Sandstones in Unit B12; C – Units B13 and B14. People for scale are c. 1.8 m tall

with interbeds of argillite; (c) 3.4 m, brown sandstone; (d) 11.9 m, sandy limestone with interbeds rich in brachiopods and of argillite; (e) 1.2 m, sandstone.

Unit B11. 131.7 m. Alternation of limestone and argillite with rare interbeds of sandstone. Nine sub-

units were recognised: (a) 10.25 m, limestone and argillite with large colonies of favositid tabulate corals (up to 20 cm in diameter); (b) 12.2 m, limestone with brachiopods; (c) 0.9 m, sandstone; (d) 21 m, dolomitic limestone with brachiopods; (e) 27.1 m, argillite and

limestone with brachiopods; (f) 33.5 m, dolomitic limestone and dolostone; (g) 23.1 m, bioclastic limestone and argillite; (h) 2.2 m, dolomitic limestone with brachiopods; (I) 1.5 m, bioclastic limestone.

Unit B12. About 61.8 m. Grey to white cross-bedded sandstone with interbeds of argillite and siltstone.

Unit B13. About 73.7 m. Alternation of shale and limestone with brachiopods and trilobites at some levels.

Unit B14. About 5.25 m. Sandy limestone and sandstone.

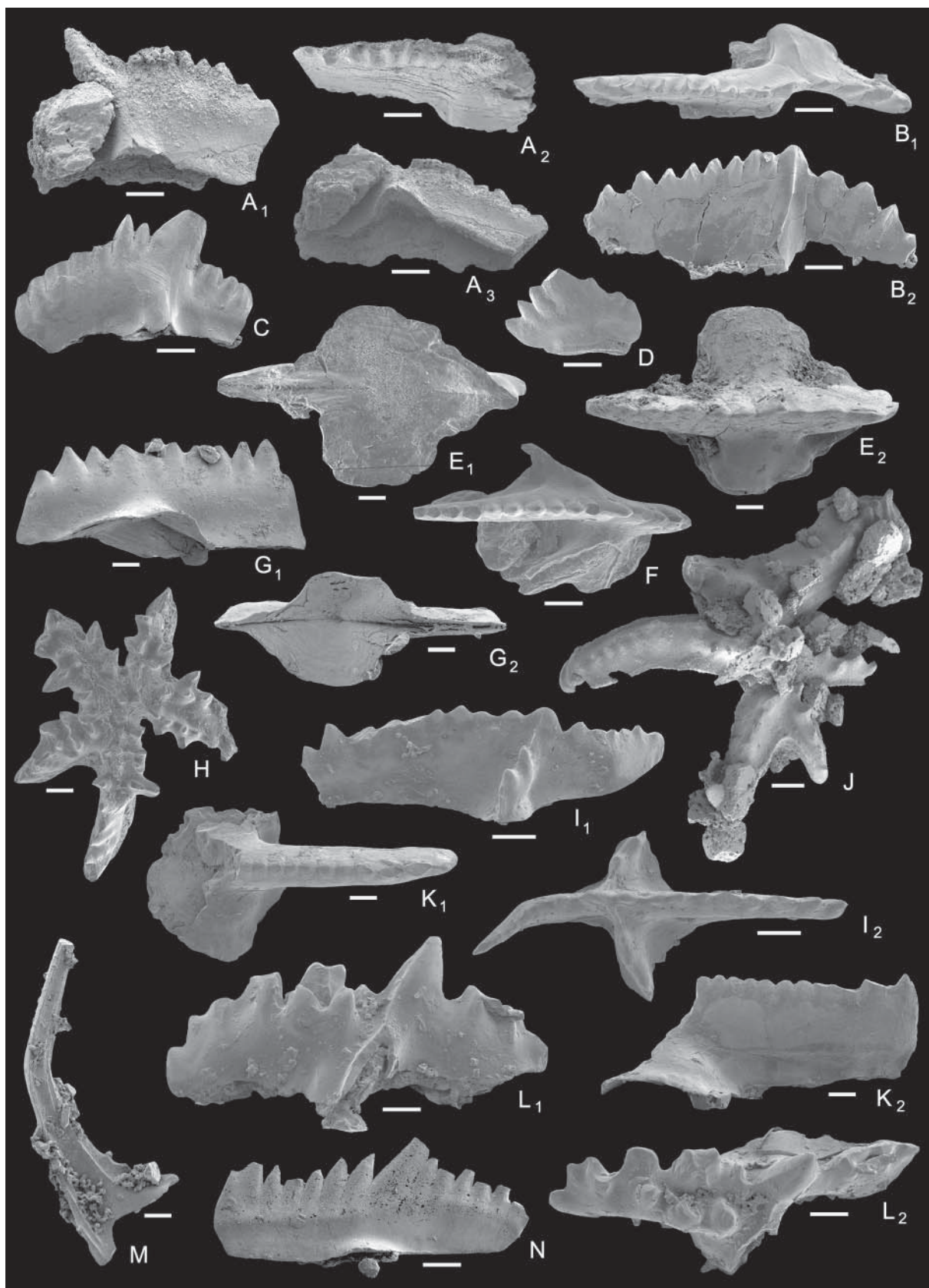
Biostratigraphy and age: The conodont *Distomodus staurognothoides* (Walliser, 1964) in sample K21 and possibly also in K20 (Text-fig. 2, Unit B5; Text-fig. 6H) suggests that this level is not older than the Aeronian: in the Baltic *Distomodus staurognothoides* probably appears in the upper *Demirastrites triangulatus* GB but is definitely present in the *Demirastrites simulans* GB (Loydell et al. 2010). *Aulacognathus antiquus* Bischoff, 1986 in sample K21 (Text-figs 2 and 6I) indicates an even younger middle Aeronian age for the sample. In New South Wales, Australia, *Aulacognathus antiquus* occurs in the upper Aeronian *Stimulograptus sedgwickii* or lower Telychian *Spirograptus turriculatus* GBs (Bischoff 1986). However, graptolites of these biozones have not been recorded from the Quarry Creek Limestone, which yielded the conodonts and, thus, there is no evidence to support this biostratigraphic assignment. Recent data from Estonia demonstrates that *Aulacognathus antiquus* is already present in the *Pribylograptus leptotheca* GB (Männik et al. 2016). Hence, based on conodonts, sample K21 comes from a level not older than the middle Aeronian *Pribylograptus leptotheca* GB.

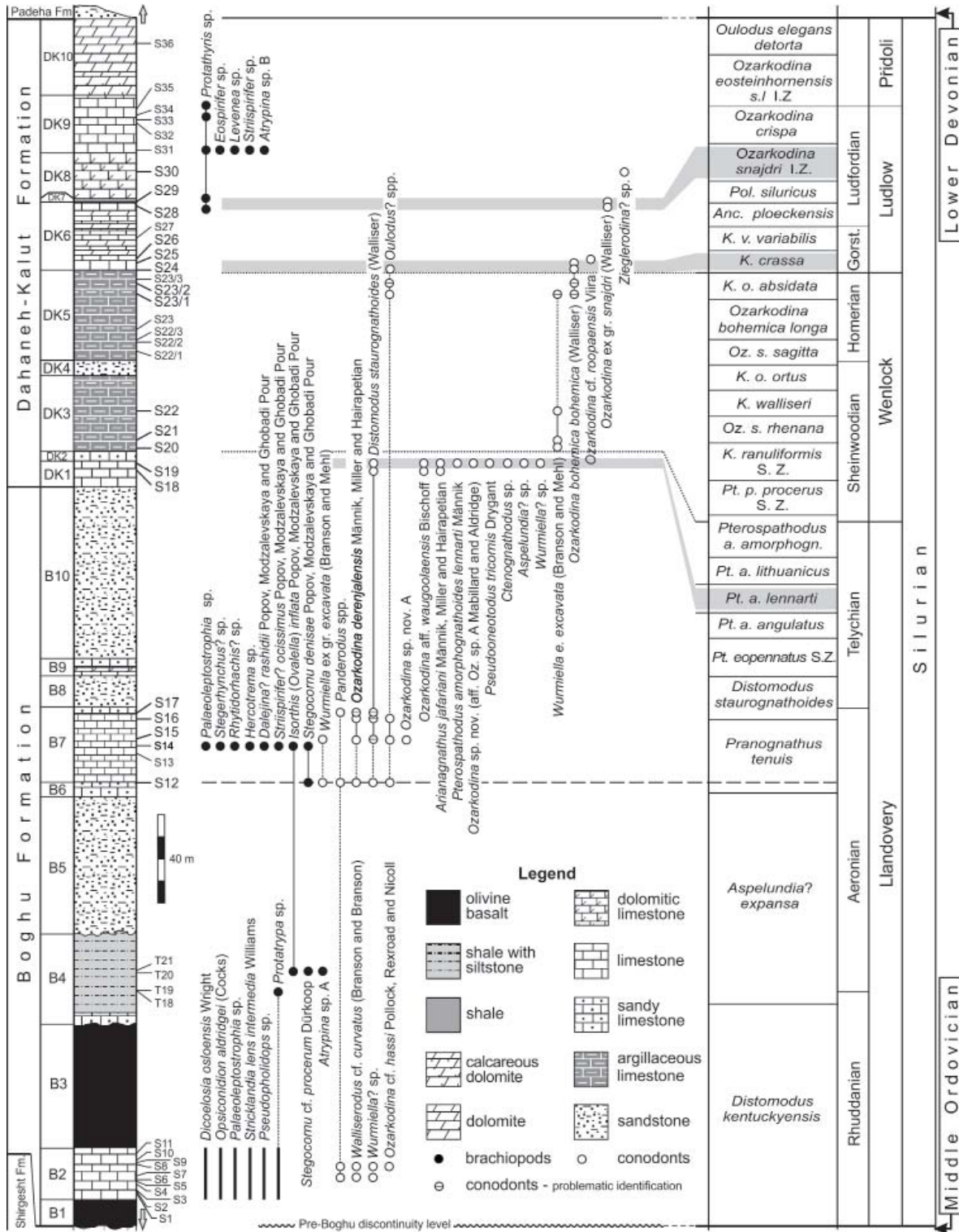
In sample K36 a single specimen of *Arianagnathus* (identified as *A. cf. jafariani* Männik, Miller and Hairapetian, 2015; Text-fig. 2, Unit B13; Text-fig. 6A) was found. Based on the data from the Derenjäl Mountains (Männik et al. 2013, fig. 3; Text-fig. 7) beds with *Arianagnathus jafariani* correspond to the *Pterospathodus celloni* Conodont Superzone and are of middle Telychian age.

Distomodus staurognothoides ranges up to Unit B13. The uppermost specimen in the section comes from sample K37 (Text-figs 2 and 5), where it occurs with *Kockelella ranuliformis* (Walliser, 1964). In the next sample studied (K38) only *Kockelella ranuliformis* (Text-fig. 6K) was found. It is probable that both samples were collected from the boundary interval between the Lower and Upper *Kockelella ranuliformis* CBs, K37 just below and K38 just above it, and both are of early Sheinwoodian age.

The brachiopod fauna is represented by three succeeding low diversity rhynchonellide associations (Hairapetian et al. 2012; Popov et al. 2015a), which occur in the middle to upper part of the Boghu Formation (Text-fig. 2; units B9–B13). The lowermost association is dominated by *Stegocornu procerum* Dürkoop, 1970. This species first appears in Unit B9 (Text-fig. 2; sample K25), where it occurs with *Clorinda* sp. and *Palaeoleptostrophia* sp. [= *Mesoleptostrophia* (*Mesoleptostrophia*) sp. of Hairapetian et al. 2012] and ranges up into Unit B11 (Text-fig. 2; sample K28), where it forms a monotaxic association. Higher in that unit (samples K29, 30), *Stegocornu procerum* is replaced by *Stegocornu denisae* Popov, Modzalevskaya and Ghobadi Pour in Hairapetian et al., 2012. This replacement occurs in the upper part of the *Distomodus staurognothoides* CB. *Stegocornu denisae* has a very narrow strati-

Text-fig. 6. Selected conodonts from the Boghu and Derenjäl sections. **A** – *Arianagnathus cf. jafariani* Männik, Miller and Hairapetian, 2015; sinistral Pa element, inner lateral (A₁), upper (A₂) and oblique lower (A₃) views, Boghu section, sample K36, Boghu Formation, NHMUK PM X 3687; **B** – *Arianagnathus jafariani* Männik, Miller and Hairapetian, 2015; dextral Pa element, upper (B₁) and inner lateral (B₂) views, Derenjäl section, sample S19, Dahaneh-Kalut Formation, NHMUK PM X 3603; **C, D, F** – *Pterospathodus amorphognathoides lennarti* Männik, 1998; **C** – sinistral Pb₁ element, outer lateral view, NHMUK PM X 3599; **D** – dextral Pb₂ element, outer lateral view, NHMUK PM X 3597; **F** – dextral Pa element, upper view; all specimens from Derenjäl section, sample S19, Dahaneh-Kalut Formation, NHMUK PM X 3598; **E** – *Ozarkodina ex gr. snajdri* (Walliser, 1964), dextral Pa element, lower (E₁) and upper (E₂) views, Derenjäl section, sample S28, Dahaneh-Kalut Formation, NHMUK PM X 3268; **G** – *Ozarkodina bohémica bohémica* (Walliser, 1964), dextral(?) Pa element, lateral (G₁) and lower (G₂) views, Derenjäl section, sample S24, Dahaneh-Kalut Formation, NHMUK PM X 3273; **H** – *Distomodus staurognothoides* (Walliser, 1964), dextral Pa element, upper view, Derenjäl section, sample S12, Boghu Formation, NHMUK PM X 3275; **I** – *Aulacognathus antiquus* Bischoff, 1986, dextral Pa element, lateral (I₁) and upper (I₂) views, Boghu section, sample K21, Boghu Formation, NHMUK PM X 3615; **J** – *Amorphognathus cf. ordovicicus* (Branson and Mehl, 1933), dextral Pa element, upper view, Boghu section, sample K8, “upper Katkoyeh Formation”, NHMUK PM X 3688; **K** – *Kockelella ranuliformis* (Walliser, 1964), sinistral(?) Pa element, upper (K₁) and lateral (K₂) views, Boghu section, sample K38, Boghu Formation, NHMUK PM X 3622; **L** – *Icriodella aff. superba* Rhodes, 1953, sinistral Pa element, outer lateral (L₁) and upper (L₂) views, Boghu section, sample K9, “upper Katkoyeh Formation”, NHMUK PM X 3606; **M** – *Walliserodus cf. curvatus* (Branson and Branson, 1947), dyscritiform element, lateral view, Boghu section, sample K11/2, Boghu Formation, NHMUK PM X 3689; **N** – *Ozarkodina derenjälensis* Männik, Miller and Hairapetian, 2015, Pa element, lateral view, Boghu section, sample K25, Boghu Formation, NHMUK PM X 3690. Scale bars represent 0.1 mm





Text-fig. 7. Dahaneh-Kalut section in the Derenj Mountains. From left to right: formations; described units; lithological log (arrows below and above the log indicate that the section continues in both directions); locations and numbers of samples; distribution of taxa; conodont biozones (after Cramer *et al.* 2011) and general stratigraphy (Stage, Series, System). Grey boxes in the column of conodont biozonation indicate zones (or their parts) that were recognised in the studied section. Abbreviations: *Pt.* – *Pterospathodus*; *a.* – *amorphognathoides*; *p.* – *pennatus*; *K.* – *Kockelella*; *Oz.* – *Ozarkodina*; *s.* – *sagitta*; *o.* – *ortus*; *v.* – *variabilis*; *Anc.* – *Ancoradella*; *Pol.* – *Polygnathoides*; S.Z. – Superzone; I.Z. – Interval Zone; Gorst. – Gorstian

graphical range, which probably coincides with this conodont biozone (Text-fig. 2). We suggest that the occurrence of this brachiopod species in Iran is an important biostratigraphical marker showing a latest Aeronian age.

The third brachiopod association occurs in Unit B13 (Text-fig. 2; sample K33/1). It includes only the rhynchonellide *Jafarirhynchus alatus* Popov, Hairapetian, Ghobadi Pour and Modzalevskaya, 2015 as the dominant species and the spiriferide *Striispirifer? ocissimus* Popov, Modzalevskaya and Ghobadi Pour in Hairapetian *et al.*, 2012. Based on the conodont distribution through the section, a Telychian age is suggested for this association.

Depositional environments and lithofacies: The Boghu Formation was deposited in a shallow shelf environment varying from shoreface zone to shallow offshore shelf, characteristic of Benthic Assemblage Zones (BA) 2–3 (after Boucot 1975). In the middle to upper part of the formation there is a proliferation of rhynchonellide biofacies characterized by low to medium diversity rhynchonellide associations dominated by *Stegocornu* (Text-fig. 8D) in the middle to upper Aeronian part of the succession and by *Jafarirhynchus* (Text-fig. 8B) in the Telychian (Hairapetian *et al.* 2012; Popov *et al.* 2015a). In the Derenjal Mountains the lower part of the Boghu Formation contains bioherms of tabulate corals.

Derenjal Mountains

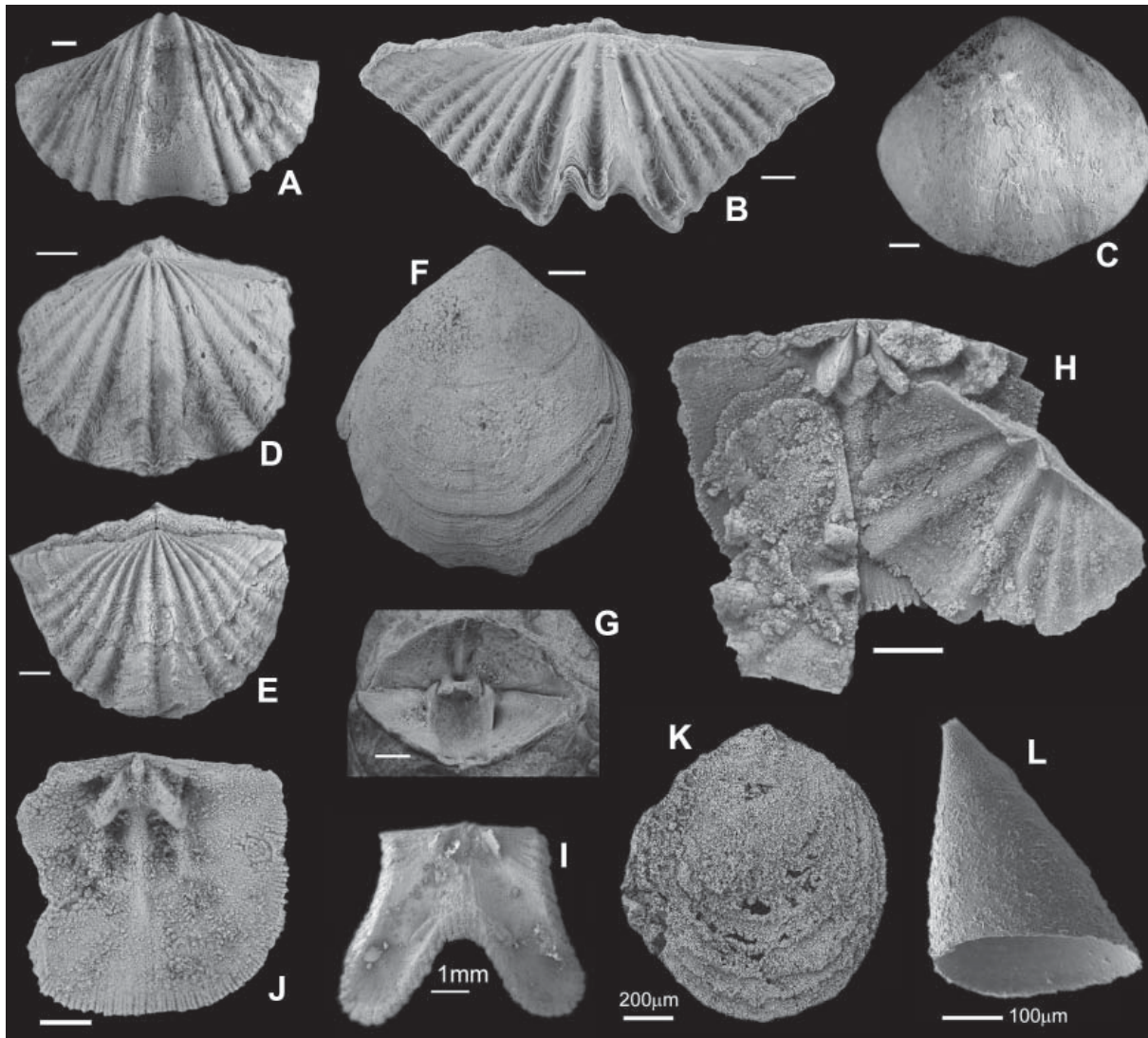
The area is located in north-eastern Central Iran about 65 km north-west of Tabas (Text-fig. 1; see also Ruttner *et al.* 1968; Hairapetian *et al.* 2008). The Silurian deposits crop out relatively widely in the southern and eastern parts of the Derenjal Mountains, on the flanks of a large anticline. The best section in the area is situated c. 1.4 km east of the Dahaneh-Kalut valley and 8.3 km north-north-east from the Shirgesht railway station. The profile is composed of outcrops located across three major hills named A, B and C by Hairapetian *et al.* (2008).

The Silurian succession in the area was first documented in detail by Ruttner *et al.* (1968). Later, the contact between the Ordovician and Silurian was found by Bruton *et al.* (2004) to be faulted. For a long time the rugose and tabulate corals, and stromatoporoids described by Flügel (1969), Flügel and Saleh (1970) and Hubmann (1991) were the only Silurian fossils monographically documented from the area. Recently, rich Silurian faunas, including brachiopods, ostracodes and thelodont fishes, have

been discovered and published by Hairapetian *et al.* (2008, 2011, 2012) from the section. The distribution of Llandovery to Ludlow conodonts (Männik *et al.* 2013) indicates that the Derenjal Mountains show the most complete Silurian sedimentary succession so far documented in Iran. The Silurian deposits in the area were previously assigned entirely to the Niur Formation but are now subdivided in ascending order into the Boghu and Dahaneh-Kalut formations.

The Boghu Formation, the lower part of the Silurian succession in the Derenjal Mountains, is a heterolithic unit with a total thickness up to 286 m (Text-fig. 7). It comprises (in ascending order; Männik *et al.* 2013): (1) up to 12.8 m of olivine basalt; (2) up to 23.5 m of limestone, mainly of bioclastic packstone and grainstone; (3) 56.4 m of altered, dark green olivine basalt; (4) c. 43 m of siltstone intercalating with silty argillite; (5) c. 63 m of white, cross-laminated quartz arenite; (6) up to 6.7 m of brown thin-bedded sandy limestone; (7) up to 33.8 m of grey to brown, medium- to thin-bedded bioclastic packstone and grainstone with interbeds rich in brachiopod shells; (8) up to 14.2 m of white medium- to thin-bedded allochemic sandstone; (9) 7.8 m of brown limestone intercalating with dolomitic limestone; (10) up to 77.7 m of allochemic sandstone. In the described transect the Boghu Formation is overlain conformably by the Dahaneh-Kalut Formation.

The lowermost unit of the Boghu Formation in the Derenjal Mountains contains a few conodonts, notably *Ozarkodina cf. hassi* (Pollock, Rexroad and Nicoll, 1970), *Walliserodus cf. curvatus*, *Wurmiella?* sp. and *Panderodus* sp. identified by P. Männik. This assemblage of conodonts has a stratigraphic range from the lower Rhuddanian to the middle Aeronian. The occurrence of the brachiopods *Stricklandia lens intermedia* Williams, 1951 and *Dicoelosia osloensis* Wright, 1968 (Text-fig. 7) also suggest an early Aeronian age. In Baltoscandia and Britain they have a stratigraphic range from the late Rhuddanian *Coronograptus cyphus* GB up to the mid Aeronian *Lituigraptus convolutus* GB (Wright 1968; Barlii 1986; Cocks 2008; Rubel 2011). The list of brachiopod genera from Unit B2 includes *Coolinia*, *Dolerorthis*, *Eospirigerina*, *Isorthis*, *Leptaena*, *Meifodia*, *Stricklandia*, *Stegorhynchus*, *Palaeoleptostrophia*, *Protatrypa* and *Triplesia*. The occurrence of the acrotretide *Opsiconidion aldridgei* (Cocks, 1979b) is remarkable, because it is one of the earliest Silurian records of the Order Acrotretida (Text-fig. 8L). A Lazarus taxon is the craniopside *Pseudopholidops* (Text-fig. 8K). Previously, the last documented occurrence of this genus was in the Hirnantian (Popov *et al.* 2013).



Text-fig. 8. Selected brachiopod taxa from the Silurian of the Boghu and Derenjal Mountains. **A** – *Striispirifer? ocissimus* Popov, Modzalevskaya and Ghobadi Pour in Hairapetian *et al.*, 2012, NMW 2011.11G.359, ventral view of a pair of conjoined valves, sample K-30, Unit 30 in Text-fig. 2 (Hairapetian *et al.* 2012, fig. 11A); **B** – *Jafarirhynchus alatus* Popov, Hairapetian, Ghobadi Pour and Modzalevskaya, 2015, AEU1502, dorsal view of a pair of conjoined valves, sample K33/1, Unit B13 in Text-fig. 2 (Popov *et al.* 2015a, fig. 3C₁); **C** – *Clorinda* sp., NMW 2011.11G.1, ventral view of a pair of conjoined valves, sample K25, Unit 18 in Text-fig. 2 (Hairapetian *et al.* 2012, fig. 6N); **D** – *Stegocornu procerum* Dürkoop, 1970, NMW 2011.11G.213, dorsal view of a pair of conjoined valves, sample K25, Unit 18 in Text-fig. 2 (Hairapetian *et al.*, 2012, fig. 7D); **E** – *Stegocornu denisae* Popov, Modzalevskaya and Ghobadi Pour in Hairapetian *et al.*, 2012, NMW 2011.11G.269, dorsal view of a pair of conjoined valves, sample S14, Unit 7 in Text-fig. 8 (Hairapetian *et al.* 2012, fig. 7J); **F** – *Protathyris* sp., AEU825, ventral view of a pair of conjoined valves, sample K28/29, Unit 20 in Text-fig. 8; **G** – *Protathyris* sp., AEU826, view on cardinalia of a pair of conjoined valves, sample K31+3 m, Unit 20 in Text-fig. 8; **H** – AEU827, cluster of two dorsal valves of *Striispirifer* sp. and one dorsal valve of *Levenea* sp. showing interiors, sample S31, Unit 20 in Text-fig. 8; **I** – *Levenea* sp., AEU827, dorsal valve interior, sample S31, Unit 20 in Text-fig. 8; **J** – *Dicoelosia osloensis* Wright, 1968, AEU828, dorsal valve interior, Unit 2 in Text-fig. 8; **K** – *Pseudopholidops*, AEU829, ventral valve exterior, Unit 2 in Text-fig. 8; **L** – *Opsiconidion aldridgei* (Cocks, 1979b), NHMUK PI BC 64277, ventral valve exterior, side view, Unit 2 in Text-fig. 8. Scale bars represent 2 mm except where indicated

However, new data from Iran clearly demonstrate that it had survived into the Silurian. In spite of a significant number of newly evolved brachiopod genera, there is no sign of endemism in the fauna; many of them acquired almost global distribution in the late

Rhuddanian to Aeronian low latitude faunas (Popov *et al.* 2014; Rong and Cocks 2014). There is a significant proportion of extinction survivors (Cocks and Rong 2008; Popov *et al.* 2014). Bioclasts in the rock are mainly fragments of tiny fenestrate bryozoans,

represented by at least six genera, which are currently under study.

A notable feature of this locality is the presence of coral build-ups, represented by bioherms up to 3 m across. This is one of the earliest records of metazoan organic build-ups in the Silurian and probably the earliest Silurian record of reef-building activity in temperate latitudes. Tabulate corals are represented by the favositids *Palaeofavosites* sp. and *Mesofavosites* sp., the halysitids (Text-fig. 9E) *Catenipora obliqua* (Fischer-Benzon, 1871), *Catenipora* cf. *louisvillensis* (Stumm, 1964), *Catenipora khorasanensis* Hubmann, 1991, *Catenipora micropora* (Whitfield, 1882), *Catenipora* cf. *jarviki* Stasińska, 1967, *Catenipora gotlandica* (Yabe, 1915), *Halysites labyrinthicus* (Goldfuss, 1826) and *Eocatenipora nicholsoni* (Kiær, 1930) (Hubmann 1991; localities 64/AR/101, 5.2.43, 66/HF/96). Rugose corals are represented by *Grewingkia alternata* Flügel and Saleh, 1970, *Paliphyllum* (*Paliphyllum*) *oblongaecystosum* Flügel and Saleh, 1970, *Schlotheimophyllum* sp., *Streptelasma ruttneri* Flügel and Saleh, 1970 and *Tryplasma* sp. (Flügel and Saleh 1970; localities 64/AR/101, 5.2.43, 66/HF/96).

The ostracod fauna of the lower part of the Boghu Formation comprises 14 taxa, including *Steusloffina cuneata* (Steusloff, 1895), *Bairdiocypris attenuatus* Melnikova and Michailova, 1999 and species of *Dicranella*, *Aechmina*, *Lomatopisthia*, *Punctaparchites* and *Elliptocypris* transitional from the Late Ordovician, which co-occur with typical Silurian species, such as *Pachydomella wolfei* Copeland, 1974, *Punctobeecherella punctata* Copeland, 1974, *Arcuaria? triangulata* Neckaya, 1958 and *Ovornina* (Hairapetian *et al.* 2011). Other components of the fauna include micromorphic trilobites and rostroconch molluscs, which are currently under study.

There are two fossiliferous horizons in Unit B4, which overlies the second bed of basalt volcanics. The lower fossiliferous horizon (Text-fig. 7; samples T-18, T-19) contains a single atrypide brachiopod species, *Protatrypa* sp., while the upper fossiliferous horizon (Text-fig. 7; samples T-20, T-21) contains *Atrypina* sp. A, *Isorthis* (*Ovalella*) *inflata* Popov, Modzalevskaya and Ghobadi Pour in Hairapetian *et al.*, 2012 and *Stegocornu* cf. *procerum*, suggesting a closer link to the brachiopod assemblages from the overlying units. The rugose coral *Streptelasma shirgeshtensis* Flügel and Saleh, 1970, was probably sampled from the same unit (Flügel and Saleh 1970, fig. 8, sample a3).

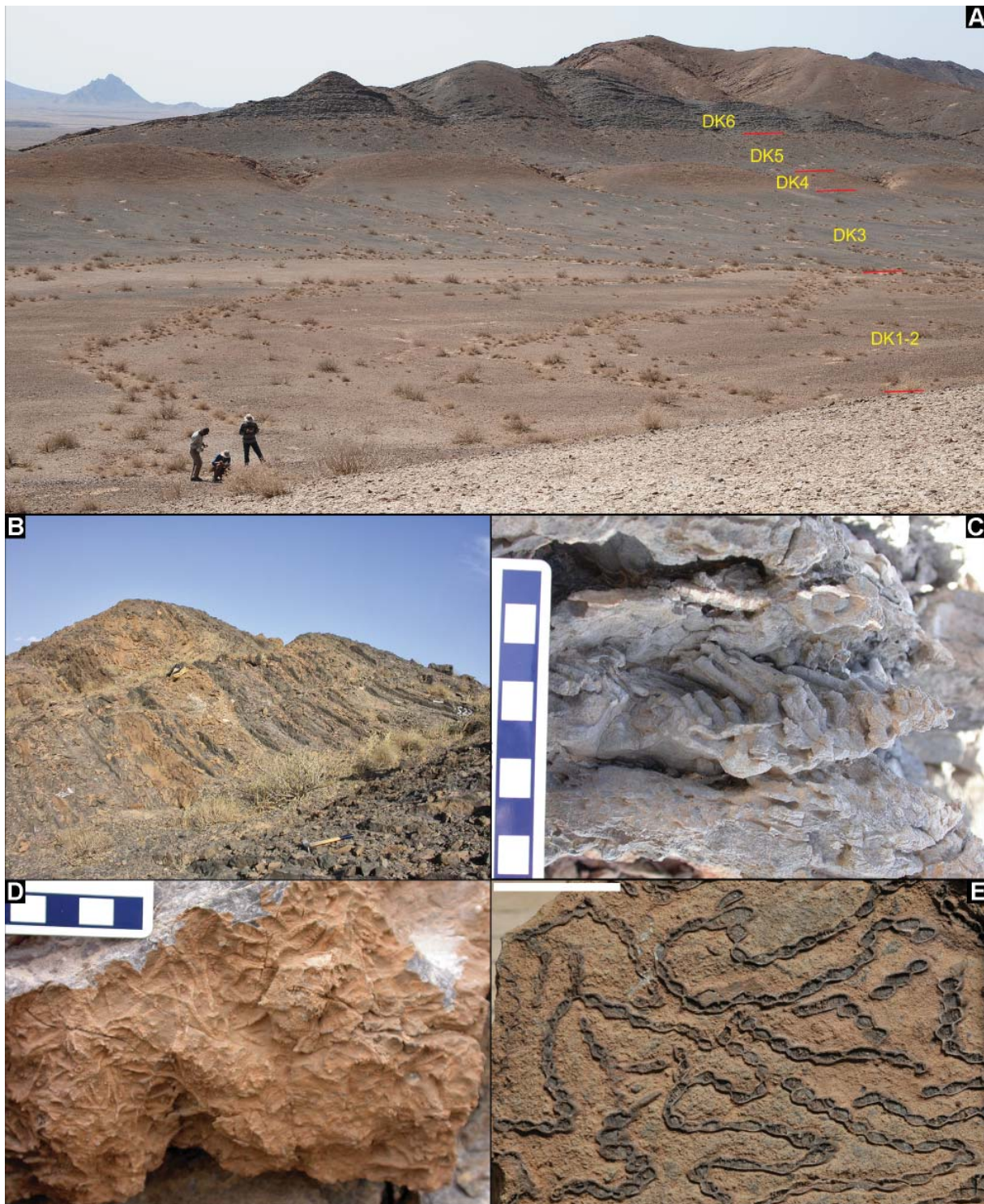
The conodonts in this part of the succession occur in the basal part of Unit B7 (Text-fig. 7, sample S12). They include *D. staurognathoides*, which indicates that these strata are not older than the early Aeronian

(see above). Associated macrofauna are mainly represented by abundant brachiopods which form characteristic shell beds. In the lower part of the unit the shell beds contain exclusively disarticulated valves of the rhynchonellide *Stegocornu denisae* (Hairapetian *et al.* 2012, fig. 9). The middle part of the unit (Text-fig. 7, sample S14) is the main source of the rich brachiopod fauna described by Hairapetian *et al.* (2012), which includes also *Dalejina? rashidii* Popov, Modzalevskaya and Ghobadi Pour in Hairapetian *et al.*, 2012, *Hercotrema* sp., *Isorthis* (*Ovalella*) *inflata*, *Palaeoleptostrophia* sp., *Rhytidorhachis? sp.*, and *Striispirifer? ocissimus*. The assemblage of rugose corals reported by Flügel and Saleh (1970, sample 64/AR/212) is probably derived from the same unit and includes *Schlotheimophyllum patelloides* Flügel and Saleh, 1970, *Paliphyllum* (*Paliphyllum*) *oblongaecystosum*, *Tenuiphyllum spinosum* Flügel and Saleh, 1970, *Streptelasma ruttneri*, and *Streptelasma* cf. *sibirica* (Nikolayeva in Nikiforova, 1955). The uppermost 100 m of the Boghu Formation in the Derenjal Mountains are barren; nevertheless, the occurrence of mid-Telychian conodonts characteristic of the *Pterospathodus amorphognathoides lennarti* Conodont Subzone just above its upper boundary, in Unit DK1, suggests that the Boghu Formation is confined entirely to the Llandovery (Aeronian to middle Telychian).

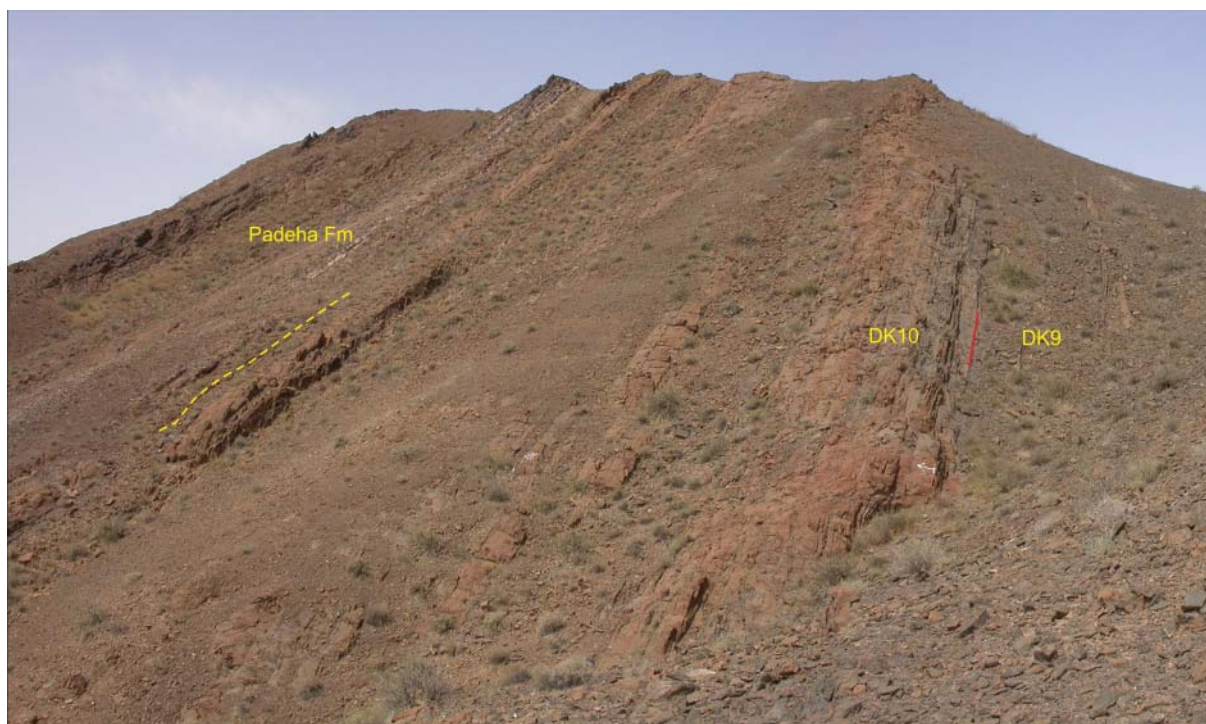
The upper part of the Silurian succession in the Derenjal Mountains comprises mainly shallow water carbonates assigned here to the newly erected Dahaneh-Kalut Formation. The late Telychian age of the lower part of the Dahaneh-Kalut Formation in the type section is well supported by the occurrence of conodonts of the *Pterospathodus amorphognathoides lennarti* Conodont Subzone; the occurrence of the conodont *Ozarkodina* ex gr. *snajdri* (Walliser, 1964) (Text-figs 6E and 7) indicates a late Ludlow age for the upper part of the formation. The uppermost part of the Dahaneh-Kalut Formation, c. 82 m thick, does not contain conodonts, while a low diversity athyrid-dominated brachiopod fauna with *Protathyris* from units DK9–10 does not exclude a Pridoli age at least for part of that interval. A detailed description of the type section of the Dahaneh-Kalut Formation is presented below.

Dahaneh-Kalut Formation (Silurian, middle Telychian to Pridoli?)

Type section: Southern part of Derenjal Mountains, c. 1.4 km east of the Dahaneh-Kalut valley and about 8 km NNE of the Shirgesht railway station.



Text-fig. 9. Field photographs of the section in the Derenjal Mountains. A – Lower part of the Dahaneh-Kalut Formation (middle Telychian–lower Ludfordian, units DK1–DK6), southerly view; B – Grey limestones and dolostones in Unit DK6, hammer for scale is 35 cm; C – Floatstone with colonial rugose corals (Dahaneh-Kalut Formation, Unit DK6), scale represents 8 cm; D – Floatstone with numerous fragments of bryozoan colonies (Dahaneh-Kalut Formation, Unit DK6), scale represents 4 cm; E – Halysitid coral floatstone with specimens of *Catenipora* (Boghu Formation, Unit B2, sample S1). Scale-bar represents 2 cm



Text-fig. 10. Field photograph from the Derenjal Mountains showing the boundary between limestones and dolostones (Unit DK10) of the Dahaneh-Kalut Formation (Silurian) and the siliciclastic Padeha Formation (Lower Devonian). The position of the quartzarenite bed at the base of the Padeha Formation is accentuated by a yellow dashed line. Field of view is c. 60 m across

Distribution: Presently the unit is only known in north-eastern Central Iran in the Derenjal and Ozbak-Kuh Mountains.

Lower boundary: In the type section, the Dahaneh-Kalut Formation rests conformably on the Boghu Formation. Its lower boundary corresponds to the base of the continuous carbonate succession. In the Ozbak-Kuh Mountains the lower contact of the Dahaneh-Kalut Formation is not known and is possibly not exposed.

Upper boundary: In the type area the Dahaneh-Kalut Formation is overlain conformably by the Lower Devonian Padeha Formation (Text-figs 7 and 10). The boundary is placed at the top of the last sandy dolostone bed.

Subdivision: The type section of the Dahaneh-Kalut Formation, total thickness 212.4 m, is subdivided into ten informal units (Text-figs 7, 9, 10), in ascending order (mainly after Hairapetian *et al.* 2012):

Unit DK1. 11.7 m. Grey bioclastic limestone (mudstone, wackestone and grainstone) with brachiopod shell beds and rugose corals, and with a characteristic 15 cm thick bed of yellow limestone at the top.

Unit DK2. 4.4 m. Brown to red sandy limestone.

Unit DK3. Up to 34.2 m. Dark-grey argillaceous bioclastic limestone (wackestone and packstone).

Unit DK4. About 7 m. Brown sandstone and calcareous sandstone.

Unit DK5. Up to 40.8 m. Bedded argillaceous bioclastic limestone (mudstone, wackestone, packstone and grainstone) with brachiopod shell beds and rugose corals.

Unit DK6. Up to 31 m. Grey, bedded bioclastic packstone with interbeds rich in brachiopod shell beds and with rare beds of dolostone.

Unit DK7. 1.5 m. Grey to yellow marlstone with brachiopods.

Unit DK8. Up to 20.5 m. Grey dolomitic limestone (bioclastic packstone).

Unit DK9. Up to 26.2 m. Bioclastic limestone with brachiopod shell beds and echinoderm beds.

Unit DK10. Up to 35.1 m. Brown calcareous dolostone and sandy dolostone with a brachiopod shell bed at the base of the unit.

Biostratigraphy and age: Conodonts of the *Pteropathodus amorphognathoides lennarti* Conodont Subzone in Unit DK1 (Text-fig. 7) suggest that the lowermost part of the Dahaneh-Kalut Formation in the

Derenjal Mountains is still within the middle to upper part of the Telychian Stage. The lower boundary of the Ludlow Series is located close to the base of Unit DK6. Here *Ozarkodina bohemica bohemica* (Walliser, 1964) (Text-fig. 6G), suggesting the *Kockelella crassa* CB was found. The uppermost part of the same unit contains *Ozarkodina* ex gr. *snajdri*, a taxon characteristic of the upper Ludlow (Text-fig. 7; Männik *et al.* 2013). The unit contains an abundant, but low diversity brachiopod fauna dominated by *Protathyris* sp. (Text-fig. 8F, G), and the rugose coral *Oyalophyllum* (*Goronoruga*) sp. (Flügel and Saleh 1970, locality 64/AR/110). An abundant but low diversity fauna from the upper part of the Dahaneh-Kalut Formation includes the brachiopods *Eospirifer* sp., *Atrypina* sp. B, *Levenea* sp. (Text-fig. 8H), *Protathyris* sp. (Text-fig. 8F, G) and *Striispirifer* sp. (Text-fig. 8I), and the rugose coral *Cystiphyllum* (*Holmophyllum*) *pauciseptatum* (Flügel and Saleh, 1970) from locality 66/HF/90. While the most probable age of the fauna is Silurian, the position of the Silurian–Devonian boundary cannot be located in the section. Tentatively this boundary is placed in the top of the Dahaneh-Kalut Formation (Text-fig. 10). The position of the boundary between the Ludlow and Pridoli stages in the Derenjal section also remains undefined.

Depositional environments and lithofacies: Limestones of the Dahaneh-Kalut Formation in the Derenjal Mountains were deposited mainly on a restricted shelf within a carbonate platform depositional environment. Concentrations of articulated shells representing a single athyridide or occasionally rhynchonellide species, which were formed within their original habitat, are characteristic. Storm-generated shell beds, mostly formed by disarticulated spiriferide valves are more common in the upper part of the Dahaneh-Kalut Formation suggesting a more turbulent environment.

Ozbak-Kuh

The Ozbak-Kuh area is situated on the north-eastern prolongation of the Derenjal Mountains (Text-fig. 1). Type sections of several Silurian and Devonian formations are located in the area, including those of the Gushkamar and Ozbak-Kuh groups. It is also considered as the type area of the Niur Formation, despite the fact that the Silurian succession of Ozbak-Kuh has never been described in detail and was only briefly outlined by Ruttner *et al.* (1968) and Flügel and Saleh (1970). These authors suggested that the Silurian is 446 m thick, comprising a unit of bar-

ren dolostone (c. 110 m) and an overlying bioclastic and coral limestone with subsidiary units of argillite. The lower boundary of the Silurian succession in Ozbak-Kuh is faulted, but it is conformably overlain by the Lower to Middle Devonian Padeha Formation (Ruttner *et al.* 1968).

According to Flügel (1962) and Flügel and Saleh (1970), a rich fauna of tabulate and rugose corals was sampled from five fossiliferous horizons and could be assigned to two “faunal zones”. The lower “faunal zone” is characterized by a rich assemblage of tabulate and rugose corals. The assemblage was mainly described by Flügel (1962); its precise stratigraphical position remains undefined. It includes the rugose corals *Cystiphyllum* (*Cystiphyllum*) *siluriense* Lonsdale, 1839, *Cystiphyllum* (*Holmophyllum*) *holmi* Wedekind, 1927, *Cystiphyllum*? *paucicystosum* Flügel, 1962, *Dinophyllum*? sp., *Entelophyllum*? *obrutschewi* (Soshkina in Nikiforova, 1955), *Spongophyllum sugiyamai* Yabe and Egtjchi, 1945, *Thecia swinderniana* (Goldfuss, 1826), *Tryplasma lonsdalei* Ethebidge, 1890, and the tabulate corals *Coenites*? cf. *declivis* Weissermel, 1939, *Favosites favosus* (Goldfuss, 1826), *Favosites hisingeri* Milne-Edwards and Haime, 1851, *Mesofavosites obliquus* Sokolov, 1952, *Palaeofavosites alveolaris karinuensis* Sokolov, 1951, *Palaeofavosites schmidti borealis* Sokolov, 1951, *Palaeofavosites paulus* Sokolov, 1951, *Palaeofavosites forbesiformis* Sokolov, 1952, *Staphylopora*? sp., *Striatopora peetzi* Dubatolov, 1956, *Syringopora schmidti* Tschernychev, 1937, *Halysites catenularius* (Linnaeus, 1767), *Halyolites labyrinthicus*, *Heliolites daintreei* Nicholson and Etheridge, 1879, *Heliolites decipiens* (McCoy, 1850), *Heliolites porosus maior* Weissermel, 1939, *Heliolites* cf. *relictus* Stumm, 1954 and *Propora conferta* Milne-Edwards and Haime, 1851. According to Flügel (1962) the fauna is late Llandovery to Wenlock in age.

The “upper faunal zone” of Flügel and Saleh (1970, fig. 5, samples b3–b5) is characterized by rugose corals, including *Gyalophyllum* (*Gyalophyllum*) *niurense* Flügel and Saleh, 1970, *Holacanthia* sp., *Loyolophyllum praesepimentosum* Flügel and Saleh, 1970, *Microconoplasma*? *coniseriata coniseriata* Flügel and Saleh, 1970, *Phaulactis* sp., *Spongophylloides* (*Spongophylloides*) *mirabilis* Sytova, 1968, and *Strombodes* (*Kyphophyllum*) *conicum* Wedekind, 1927, suggesting a Ludlow age.

Weddige (1984, p. 186) listed and interpreted as latest Silurian (Pridoli) the conodonts *Pandorinellina steinhornensis eosteinhornensis* (Walliser, 1964), *Plectospathodus extensus* Rhodes, 1953 (the only illustrated species), *Trichonodella excavata* (Branson

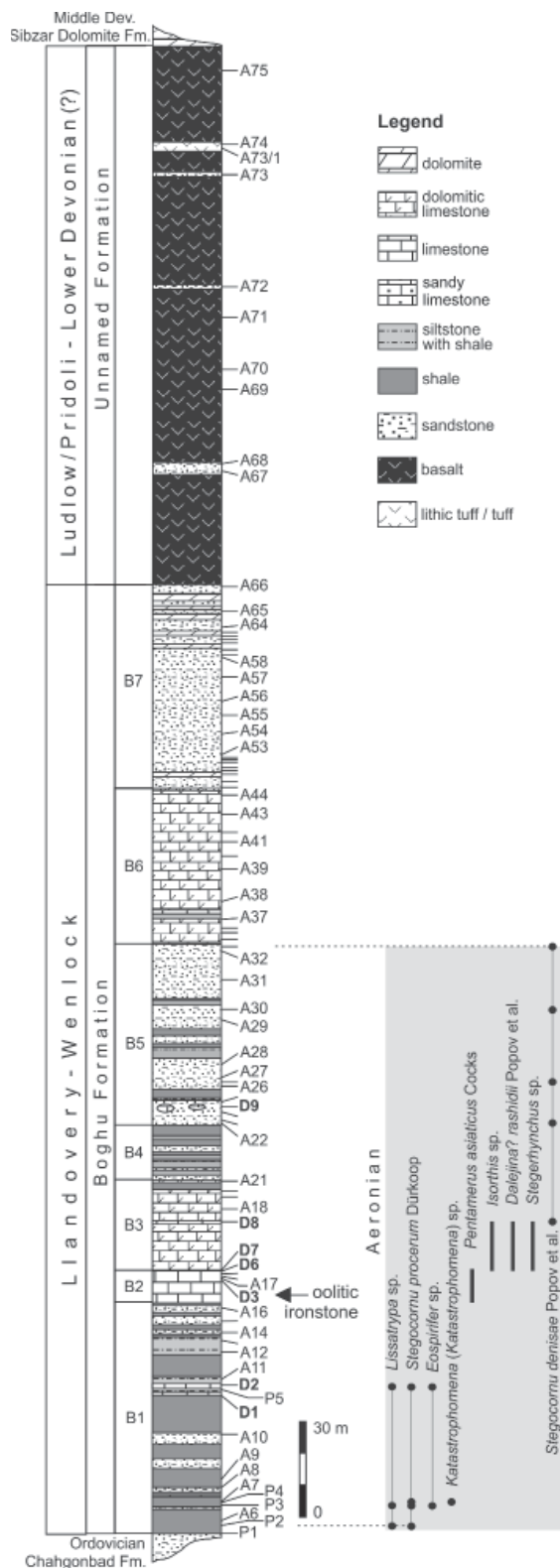
and Mehl, 1933), *Hindeodella* sp., *Prioniodus* sp. and *Ozarkodina* sp. from the Huk section, located to the north-east of Ozbak-Kuh village. The identifications cannot be checked without restudy of the collection. It is most probable that the conodont identified as *Pandorinellina steinhornensis eosteinhornensis* is synonymous with *Ozarkodina eosteinhornensis* (Walliser, 1964), recognised from the Pridoli in various parts of the world.

As suggested by Ruttner *et al.* (1968), the lower, heterolithic part of the Silurian succession in the Derenjil Mountains, which is assigned herein to the Boghu Formation, is completely missing in the Ozbak-Kuh succession, while the upper part shows a similar lithology and fauna. We suggest that it is almost certain that the Llandovery part of the Silurian succession is almost completely missing in the Ozbak-Kuh section and the Silurian deposits exposed here are assigned to the Dahaneh-Kalut Formation.

Anarak Region

The Silurian deposits in the vicinity of Anarak were first discovered by Russian geologists during geological mapping activities for 1:100,000 map sheets of the Geological Survey of Iran (Sharkovski *et al.* 1984). In their lithostratigraphical scheme of the Ordovician and Silurian successions, they adopted the formal units established earlier by Ruttner *et al.* (1968) for the adjacent Tabas Block in eastern Central Iran. Consequently, the Silurian rocks in the Anarak area were assigned to the Niur Formation (Sharkovski *et al.* 1984).

Recent studies by Hairapetian *et al.* (2015) and Popov *et al.* (2015b) revealed that the lower Palaeozoic succession of the Anarak Region differs significantly from those in the other parts of Iran. In particular, it was confirmed that the presumably Furongian to Lower Ordovician Polekhavand Formation introduced in these papers has a sharp unconformable boundary with the underlying Doshakh metamorphic complex presumably of Cambrian age. The Polekhavand Formation, which contains a significant proportion of volcanic rocks, was deposited mainly in a terrestrial environment. The area was flooded by a shallow sea only in Darriwilian time. The Middle to Upper Ordovician part of the succession has been assigned to the Chahgonbad Formation, which rests unconformably on the Polekhavand Formation and contains a bed of oolitic ironstones in its basal part. The Darriwilian to Katian age of the unit is based on brachiopod and trilobite faunas (Popov *et al.* 2015b).



Text-fig. 11. Uppermost Ordovician to Middle Devonian succession in the Anarak Region. From left to right: series; formations; described units; lithological log; locations and samples; distribution of brachiopods

The Silurian deposits of the Anarak area, assigned to the Boghu Formation herein, represent a heterolithic succession, which consists mainly of dark-grey fine clastic sediments with a distinct content of kerogenous material in the lower part, limestones with shell beds in the middle part, and siliciclastic rocks with subsidiary limestone beds in the upper part. The middle to late Aeronian age of the formation is suggested by the occurrence of the brachiopods *Stegocornu procerum*, *Stegocornu denisae* and *Pentamerus asiaticus* Cocks, 1979a, as is discussed below in more detail, while the upper 60 m of the formation are barren and may be of a younger age (Text-fig. 11). A characteristic horizon of oolitic ironstones in the lower part of the formation (Unit B2, Text-fig. 11) is unknown in other Silurian sections in Central Iran. The documented successions in general show distinct similarities to the Llandovery succession in the Derenjal Mountains. However, in the Anarak area the lowermost part of the Boghu Formation comprises siliciclastic rocks, whereas in the Derenjal section it consists of limestones and the lower boundary of the Boghu Formation coincides there with a nonconformity at the contact with the underlying basalt lavas.

The succession of the Boghu Formation in the Anarak area can be subdivided into seven informal units (Text-figs 11 and 12) in ascending order as follows:

Unit B1. 75 m. It can be subdivided into six subunits: (a) 6 m, dark grey shale with a few brachiopod shell beds; (b) 39.5 m, dark grey argillite, with intercalations of sandstone; (c) 6 m, green siltstone with a few limestone beds rich in brachiopods and bryozoans; (d) 8.3 m, alternating grey argillite and green calcareous siltstone; (e) 4.3 m, green siltstone; (f) 10.9 m, intercalation of argillite and sandstone, sandstone beds dominating in the upper part. Lower 6 m of olive and grey argillite overlain by 39.5 m of strongly weathered, dark grey argillite with rare interbeds of fine-grained sandstone. Shell beds, each 0.2 m thick, in the lower part of the unit (Text-fig. 11, samples P2–4) contain the brachiopods *Eospirifer* sp., *Katastrophomena (Katastrophomena)* sp., *Lissatrypa* sp., and *Stegocornu procerum*. The shell beds in the middle part of the unit (Text-fig. 11, samples D1 and D2) contain the brachiopods *Eospirifer*

sp., *Lissatrypa* sp., and *Stegocornu procerum*. The bryozoans listed by Sharkovski *et al.* (1984) as *Nicholsonella* aff. *vaupeliformis* Modzalevskaya in Nikiforova, 1955 and *Hallopora* sp. are probably derived from this level.

Unit B2. 10.1 m. Yellowish-grey and dark-grey limestone with numerous shell beds formed by accumulations of disarticulated broken valves of *Pentamerus asiaticus* (Text-fig. 13D), a few bryozoan fragments, tabulate and rugose corals (Text-fig. 11, sample D7), and several interbeds of calcareous oolitic ironstones. The tabulate corals derived from this unit were listed by Sharkovski *et al.* (1984) as *Favosites gotlandicus* Lamarck, 1816.

Unit B3. 29.7 m. Yellow bedded limestone and dolomitic limestone with brachiopod shell beds, the upper 7.7 m consisting mainly of dolomitic limestone with argillite interbeds. The shell beds contain numerous silicified brachiopod shells and rugose corals. The brachiopod assemblage includes *Dalejina? rashidii* (Text-fig. 13A), *Isorthis* sp., *Stegerhynchus* sp. (Text-fig. 13B, C), and *Stegocornu denisae*.

Unit B4. 17.2 m. Alternation of green micaceous siltstone, sandstone and argillite.

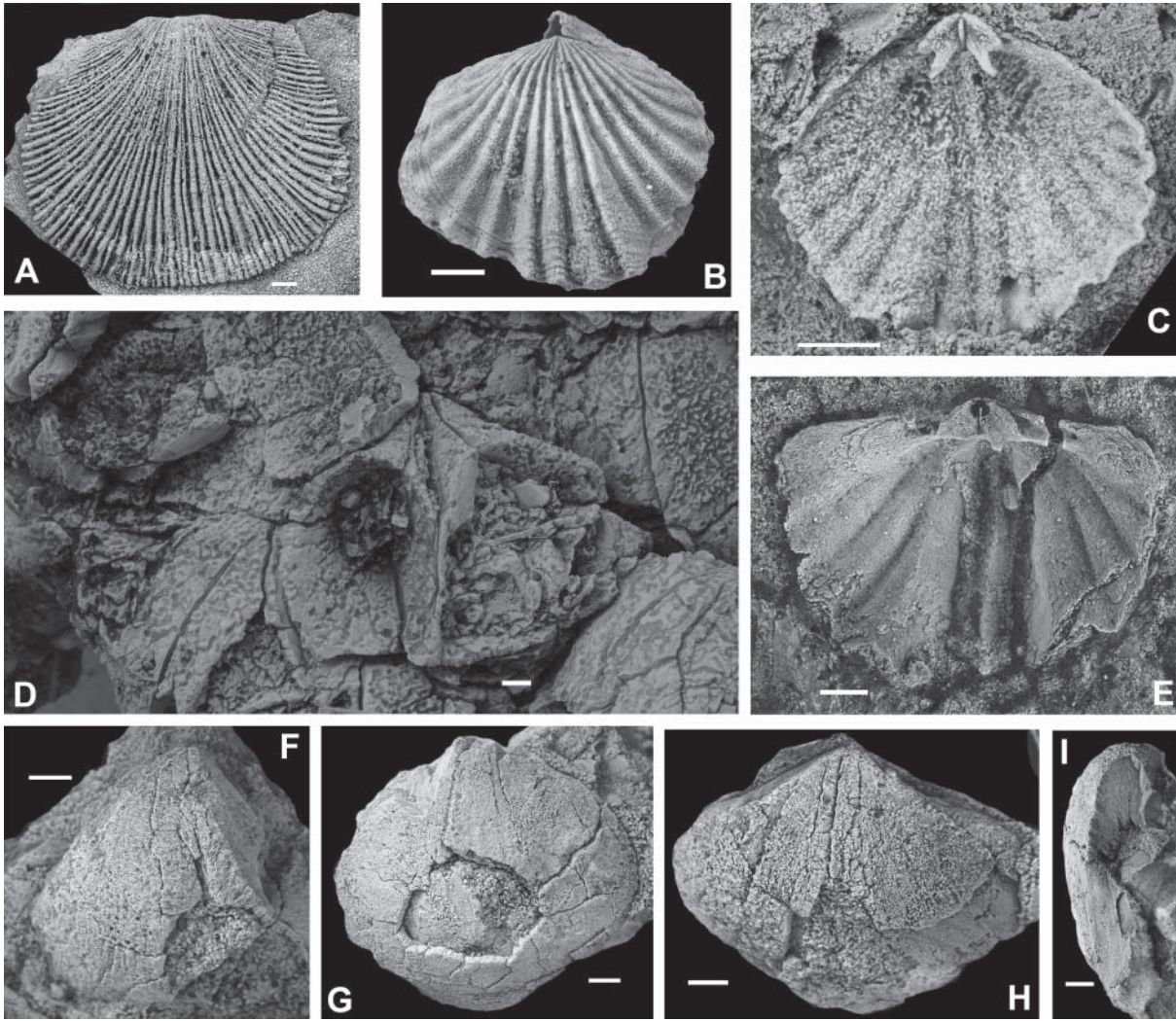
Unit B5. 59.6 m. Alternation of sandstone, siltstone and argillite with subsidiary limestone beds at the base and at the top. Six subunits can be recognised: (a) 7.1 m, laminated sandstone with limestone lenses; (b) 1.7 m, sandstone and siltstone intercalations; (c) 2.7 m, green, micaceous argillite; (d) 4.6 m, cross-bedded sandstone and siltstone; (e) 25.7 m, intercalation of sandstone, siltstone and argillite with decalcified brachiopod shells in the upper part; (f) 17.8 m, sandstone with decalcified brachiopod shells. Disarticulated and mostly broken valves of *Stegocornu denisae* occasionally present at the top of the unit (Text-fig. 11, samples A30, A32; Text-fig. 13E).

Unit B6. 49.5 m. Dark grey and brownish grey dolomitic limestone and siltstone with very poorly preserved brachiopods. Three subunits include: (a) 8.2 m, dolomitic limestone; (b) 1.6 m, purple siltstone; (c) 39.7 m, dolomitic limestone.

Unit B7. 60.5 m. Purple and white, cross-bedded medium- to coarse-grained sandstone with a bed of yellow dolostone at 3.7–4.9 m from the base, and sandstone and dolostone intercalations in the upper 18 m.

Text-fig. 12. Field photographs from the Anarak Region. A – Northeasterly view of the section showing exposure of the Boghu Formation (B) and an unnamed unit of volcanic rocks above it (V); B – Easterly view of the Ordovician–Silurian boundary (marked by red dashed line) interval in the Anarak section showing sharp transition from the Katian siliciclastic rocks of the Chahgonbad Formation to the Llandovery argillites and siltstones of the Boghu Formation (Unit B1); C – General view of Unit B3 consisting of yellowish-grey limestones and calcareous oolitic ironstones (marked by arrow); D – Close-up view of Unit B3: calcareous oolitic ironstones with numerous disarticulated and fragmented valves of *Pentamerus asiaticus* Cocks, 1979a; E – Close-up view of the volcanic rocks in the upper part of the Pol-e Khavand section





Text-fig. 13. Selected brachiopod taxa from the Silurian Boghu Formation in the Pol-e Khavand area. **A** – *Dalejina? rashidii* Popov, Modzalevskaya and Ghobadi Pour in Hairapetian *et al.*, 2012, NMW 2012.7G109, ventral valve exterior, Unit 3 in Text-fig. 11; **B**, **C** – *Stegerhynchus* sp., NMW 2012.7G.360, dorsal view of a pair of conjoined valves, dorsal valve interior, Unit 3 in Text-fig. 11; **D** – *Pentamerus asiaticus* Cocks, 1979a, NMW 2012.7G.361, ventral valve interior on the surface of a shell bed, Unit 2 in Text-fig. 11; **E** – *Stegocornu denisae* Popov, Modzalevskaya and Ghobadi Pour in Hairapetian *et al.*, 2012, NMW 2012.7G.121, dorsal valve interior, sample A-30, Unit B5 in Text-fig. 11; **F-I** – *Pentamerus* cf. *asiaticus* Cocks, 1979a from the shell bed 12 m above the stratigraphic contact between volcanic rocks and sandstones of Silurian deposits in the Jehagh section, Soh area; **F-H** – NMW 2012.7G.362, 363, ventral valve exteriors; **G** – NMW 2012.7G.364, dorsal valve exterior; **I** – NMW 2012.7G.365, side view of broken ventral valve showing spondylium and long median septum. Scale bars represent 2 mm

Palynomorph samples taken from the argillites in the lower part of the Silurian succession and conodont samples from the overlying limestone intervals were barren. Nevertheless, a rich brachiopod fauna recovered from units B1–B3 and B5 provides a good basis for biostratigraphic correlation with sections from other regions within Central Iran and elsewhere. The lowest fossiliferous horizon (Text-fig. 11, sample P2) at c. 2.5 m above the base of Unit B1 contains the brachiopods *Lissatrypa* sp. and *Stegocornu procerum*, which are typical of post-extinction recovery faunas

in Iran (Hairapetian *et al.* 2012; Popov *et al.* 2014). These two taxa are also the most common brachiopods in Unit B2.

In the Saluk Mountains of Kopet-Dagh, *Stegocornu procerum* appears in the lower part of the Qarabil Formation, above black argillites with graptolites characteristic of the lower Aeronian *Demirastrites triangulatus* GB (Evans *et al.* 2015). Thus the base of the Boghu Formation in the Anarak section is probably not older than the mid Aeronian. The upper 70 m of the underlying Chahgonbad

Formation is barren, while the uppermost fossiliferous horizons contain the endemic Katian brachiopod species *Hindella prima* Popov, Holmer and Baars in Popov *et al.*, 2015 and *Hibernodonta lakhalensis* Popov, Holmer and Baars in Popov *et al.*, 2015. There is no palaeontological evidence for the Hirnantian and Rhuddanian in the succession, while the Aeronian deposits rest with sharp contact on the underlying sandstones of the Chahgonbad Formation suggesting a disconformity and a probable hiatus.

Pentamerus asiaticus from the overlying Unit B2 (Text-fig. 11, samples D4–D7) is known also from the upper part of the Qarabil Formation in the Kuh-e Saluk Mountains, while *Stegocornu denisae*, which is derived from Unit B5 (Text-fig. 11, samples A30, A32; Text-fig. 13E), is widespread in the Aeronian of the Kashmar and Tabas regions, where it occurs together with conodonts characteristic of the Aeronian to lowermost Telychian *Distomodus staurognathoides* CB (Hairapetian *et al.* 2012; Männik *et al.* 2013).

The lower part of the Boghu Formation in the Anarak area is mainly a siliciclastic succession comprising green to dark grey argillites, siltstones and fine-grained sandstones (Text-fig. 12B). In spite of the dark colour of sedimentary rocks in the lower part of the Silurian succession, there is no sign of oxygen starvation near the sediment-water interface. Brachiopods recovered from this interval (Text-fig. 11, samples P2–P4, D1, D2) are commonly represented by articulated shells, suggesting that they are mostly preserved within their original habitat. The rhynchonellide *Stegocornu* and the atrypide *Lissatrypa* are the most common genera in the assemblage. According to Hairapetian *et al.* (2012), *Stegocornu* is a core taxon in the shallow-water rhynchonellide biofacies (*Stegocornu* Brachiopod Association) characteristic of Benthic Assemblage Zone 2 (BA2), which was widespread during the mid to late Aeronian in Central Iran, as well as in neighbouring Afghanistan and Kopet-Dagh. As a result, the organic matter, which gives a dark-grey colour to the rocks, is probably allochthonous. Unit B2 contains several beds of oolitic ironstone and shell beds formed by the disarticulated valves of *Pentamerus asiaticus* (Text-fig. 12C, D). As Ziegler *et al.* (1968) indicated, the *Pentamerus* dominated biofacies is characteristic of shallow shelf offshore regions periodically affected by (seasonal) storms (Benthic Assemblage Zone 3). However, shell beds in Unit B2 most probably formed outside the original habitat of *Pentamerus asiaticus* and result from strong storm events.

Unit B3 was probably deposited offshore, slightly below the seasonal storm wave base. It contains a moderately diverse brachiopod assemblage without

any dominant taxa. Brachiopods are often preserved as articulated shells and probably were not displaced significantly from their original habitat. There are also abundant rugose corals, a few small colonies of tabulate corals (mainly favositids), and echinoderm ossicles. The monotaxic brachiopod association with *Stegocornu denisae* from Unit B5 belongs to the rhynchonellide biofacies of Benthic Assemblage Zone 2 characteristic of a shallow marine nearshore environment.

Kerman Region

In southern Central Iran, Silurian outcrops assigned by Hamedí (1995) and Hamedí *et al.* (1997) to the Shabdjereh Formation are relatively widespread between the city of Kerman and the town of Bafq on both sides of the Kuhbanan Fault separating the Tabas and Yazd blocks (Text-fig. 1). The Shabdjereh Formation represents an up to 1000 m thick heterolithic succession of siliciclastic fluvial deposits in the lower part and several intercalating shallow marine carbonate and siliciclastic units in its middle and upper part. The age constraints for the Silurian deposits in the Kerman Region are very poor. The brachiopod fauna was described by Brice (1999) based on a small collection sampled by Lapparent in 1973 from a small Silurian outcrop now assigned to the Shabdjereh Formation, in the vicinity of Khanuk village. No description of the section or stratigraphical logs were provided and the reported geographical coordinates do not point to a viable exposure. Nevertheless, the section is probably located somewhere south-east of Khanuk village, east of the Kuhbanan Fault. Reassessment of the brachiopod identifications given by Brice (1999) suggests that the assemblage includes *Stegocornu denisae* (= *Stegocornu* aff. *procerum*), a new species of *Iranospirifer* (*Hedeinopsis* spp.), and *Striispirifer* (= *Nikiforovaena*? sp.), although precise taxonomical affiliation of two other taxa assigned to *Howellella* and *Rhynchotrema* is questionable. Brice (1999) tentatively dated the fauna as Wenlock. However, the occurrence of *Stegocornu denisae* is strong evidence for a late Aeronian age. A small brachiopod collection sampled in the vicinity of Shabdjereh, probably from the type section is housed in the CNIGR Museum, St Petersburg. It contains the mid to late Aeronian *Stegocornu procerum* and *S. denisae*, but no stratigraphical logs enabling the identification of the precise position of the fossiliferous horizons was provided. Specimens of *Jafarirhynchus alatus* sampled somewhere in the Kerman Region and erroneously identified as "*Platystrophia*" are displayed in the mu-

seum of the Iranian Geological Survey in Tehran, but no detailed collection site information is available. These specimens are the only evidence that part of the Shabdjereh Formation is Telychian in age.

Niko *et al.* (1999) reported on the occurrence of the orthoconic cephalopods, including *Armenoceras banestanense* Niko, Kakuva, Watanabe and Matsumoto, 1999, *Armenoceras* sp., *Elrodoceras* sp. and *Huroniella iranica* Niko, Kakuva, Watanabe and Matsumoto, 1999 in the upper part of the Silurian succession in Banestan. They also included a stratigraphical column showing the position of the fossiliferous horizons. According to their assessment, the age of the cephalopod fauna could be from late Llandovery to early Wenlock, the youngest age for the Shabdjereh Formation published to date. Hamed *et al.* (1997) briefly noted that conodonts identified by R.J. Aldridge suggest a Llandovery to Pridoli age for the succession in the vicinity of Kerman but no faunal lists were provided to support that statement.

According to Hamed (1995), the type section of the Shabdjereh Formation is located c. 6 km north-west of Shabdjereh village, to the west of the Kuhbanan Fault. Here Silurian deposits rest unconformably on the Ordovician Katkoyeh Formation and are unconformably overlain by the Lower Devonian Padeha Formation. The Silurian succession can be subdivided into 12 informal units as follows:

Unit 1. 83.3 m of dark-red siliciclastic rocks representing several cycles of stream channel and floodplain deposits.

Unit 2. 63.9 m of intercalating sandstone, argillite, gypsiferous argillaceous limestone, limestone and dolostone.

Unit 3. 3 m of white quartz arenite with bidirectional cross bedding.

Unit 4. 214.2 m of dark, thin-bedded limestone, argillaceous limestone with salt pseudomorphs and calcareous sandstone.

Unit 5. 76.3 m of stromatolitic dolomite, calcareous sandstone and sandstone with a bed of conglomerate with sandy matrix at the base.

Unit 6. 85.5 m of limestone, dolostone, argillaceous limestone and calcareous sandstone with salt pseudomorphs.

Unit 7. 137 m of cross-bedded sandstone intercalating with argillite and a few thin interbeds of limestone.

Unit 8. 107.1 m of intercalating argillite, argillaceous limestone, thin-bedded limestone, dolostone and calcareous sandstone with a bed of matrix-supported conglomerate less than 1 m thick at the base of the unit.

Unit 9. 30.7 m of cross-bedded sandstone and argillite intercalations with a few beds of dolostone.

Unit 11. 32.1 m of several cycles of dark-red sandstone and argillite couplets representing the transition from supratidal to floodplain deposits.

Unit 12. 63.6 m of green argillite and sandstone intercalations with several thin beds of calcareous limestone.

Unit 13. 44 m of bedded yellow to grey dolostone.

The total thickness of the Shabdjereh Formation in its type section is 869 m.

Boz-Kuh

Alavi-Naini (1972) documented an isolated Silurian outcrop area in the Sabzevar Zone, in the Boz-Kuh area, c. 25 km north-east of the town of Djam, Semnan Province, and reported a thickness of c. 591 m assigned to the Bozkuh Formation. The succession comprises mainly siliciclastic rocks with beds of bioclastic limestone in its lower part and basalt to trachyandesite volcanic rocks in the middle part. The Silurian age of the formation is based on the occurrence of brachiopods and favositid tabulate corals in the lower part of the succession, but no further details were presented. Based on this limited information neither age nor palaeogeographical position of the area in relation to other Iranian terranes can be convincingly defined at present.

Talesh Mountains

Further north-west of Boz-Kuh, small Silurian outcrops were documented by Clark *et al.* (1975) in the Talesh Range, west of Rasht (SW of the Caspian Sea) between Aliyan Rud, Tatavrud and Rude-Qurubars (Masuleh), east of Tatavrud village. The Silurian deposits in the area are represented by thick-bedded red cephalopod limestone about 40 m thick ("unit 3" of Clark *et al.* 1975). Here the Silurian rocks rest paraconformably on Ordovician bioclastic limestones rich in trilobites of Katian age (Clark *et al.* 1975). The trilobites were described by Karim (2009). The Silurian (Telychian to middle Ludlow) age of the cephalopod limestone is supported by conodonts, collected from the lower and middle parts of "unit 3" in the Derow section (Hamdi 1975).

A condensed Upper Ordovician to Silurian carbonate succession in the Tatavrud area has no analogies in other parts of Iran. Therefore it is likely that the lower Palaeozoic rocks in the Talesh Range belong to an exotic terrane. Moreover, the Ordovician trilobite fauna described by Karim (2009) shows similarity to

that known from the Turkestan-Altai Region of the Tien Shan and Chu-Ili terrane in South Kazakhstan. At present the Silurian succession and fauna of the Talesh Range is poorly known so further discussion of the biogeographic position of the terrane and its affinity to other parts of Iran is problematical.

Soh Region

The only known Silurian deposits in the Sanandaj-Sirjan terrane (Text-fig. 1) were documented by Zahedi (1973) in the Jehagh Anticline and Sargerd Mountains, north and east of Soh village. According to Zahedi (1973), the Silurian rocks, subdivided into 13 informal units, rest unconformably on the presumably Cambrian–Lower Ordovician deposits of the “Mila Formation”. However, neither the age nor the lithostratigraphic affiliation of the underlying sedimentary succession can be confirmed at present.

At the base of the studied Silurian succession there is an unnamed unit of basal volcanic rocks up to 100 m thick, representing flood basalts. It includes several syndimentary packages, in places up to 50 m thick. The Silurian sedimentary succession starts with 210 m of medium to thick cross-bedded red ferruginous quartzitic sandstone. There are a few lens-like shell beds up to 15 cm thick (Text-fig. 14A–E) in the lower 15 m of the siliciclastic succession (within “unit 3” of Zahedi 1973). The shell beds represent accumulations of broken valves of *Pentamerus* cf. *asiaticus* suggesting a late Aeronian age (Text-figs 13F–I and 14D). The “*débris de brachiopodes*” reported from the grey limestone bed of “unit 9” by Zahedi (1973), appears to be poorly preserved and consists of unidentifiable bivalve shells.

IGNEOUS ROCKS

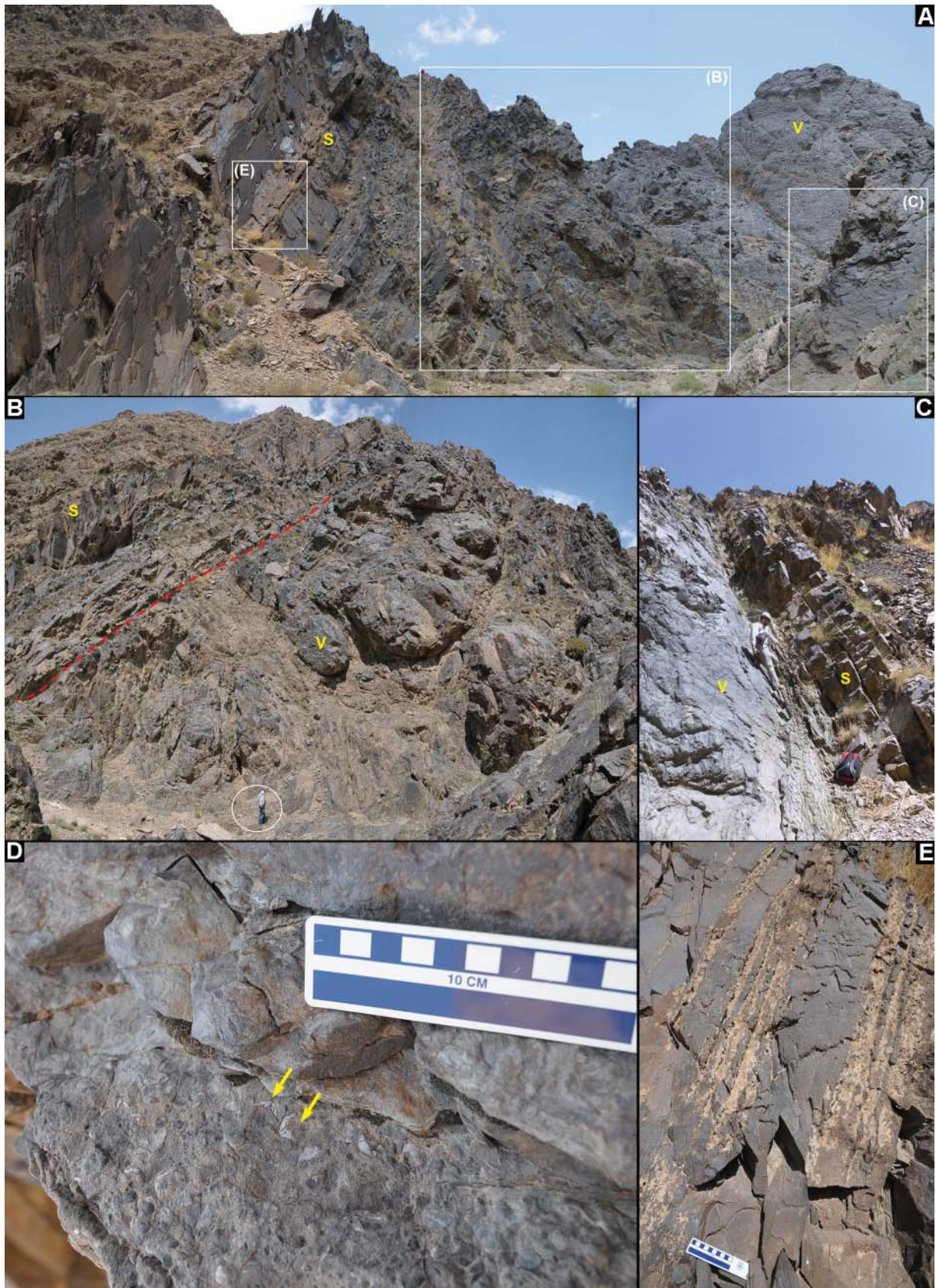
The documented record of Silurian volcanism in Central Iran is very poor and probably incomplete. There are two units of olivine basalt in the lowermost part of the Silurian succession in the Derenjaj Mountains (Text-fig. 7). They are usually described as sills (Wendt *et al.* 2005, p. 78). However, Ruttner *et al.* (1968) suggested that they were produced by lava flows and, so, are probably intracontinental rift-related flood basalts. Lack of detailed data on the petrology and geochemistry of these rocks does not permit discussion of their palaeotectonic settings. It is interesting to note the presence of a horizon of oolitic ironstones, which occurs in the Anarak section approximately at the same level as the second unit of

basalts in the Derenjaj Mountains. This correlation is supported by the occurrence of *Stegocornu procerum* above these units in both sections. Following the model of oolitic ironstone formation proposed by Sturesson *et al.* (1999) where hydrolysis and dissolution of volcanic glass in ashes provides the iron for the ooids, it is probable that reworked volcanic ash was the major source of iron for the ironstones in the Anarak section.

The Boghu Formation in the Anarak Region is overlain by c. 168 m of intercalations of basalt lava and lithic tuff. Basalts, together with the uppermost siliciclastic unit of the described Silurian succession (Text-figs 11 and 12A, E) were provisionally assigned by Sharkovski *et al.* (1984) to the Lower Devonian Padeha Formation. As there is good evidence for the Llandovery age for most of the Silurian succession, this implies a considerable period of non-deposition and erosion. Nevertheless, any significant hiatus at the base of Unit B7 in the Anarak section (Text-fig. 11) is unlikely, because its contact with the underlying heterolithic Unit B6 is conformable and transitional. Therefore, a late Silurian age for these basalts is quite plausible. Based on geochemical studies, they were recently referred to intracontinental tholeiitic/transitional basalts (Torabi and Hashemi 2010).

Similar large exposures of Silurian volcanic rocks, c. 50 m thick, consisting of flows and pillow-like structures of basalt lava, were recorded in the Jehagh Anticline and Sargerd Mountain Range in the Soh area (Zahedi 1973; Ayati *et al.* 2011). As mentioned above, these are overlain by sandstone units of late Aeronian age (lower part of the siliciclastic succession) suggesting that the volcanic event may have occurred in the Aeronian at the latest.

The eastern Alborz Region represents the major Silurian volcanic province in Iran. Here, the Silurian is represented by an up to 700 m thick succession of trachybasalt to trachyandesite volcanic rocks (including tuffs) of the Soltan-Maidan Formation. The suggested Silurian age of the unit is mostly based on its lithostratigraphical position. In the Khosh-Yeilagh area it rests on Ordovician deposits dated by palynomorphs to the Hirnantian *Spinachitina oulebsiri* Chitinozoan Biozone (Ghavidel-Syooki *et al.* 2011b). It is overlain by deposits assigned tentatively to the Lower Devonian Padeha Formation (Wendt *et al.* 2005; Ghavidel-Syooki *et al.* 2011b). Recently, a $^{206}\text{Pb}/^{238}\text{U}$ zircon age of 434.4 ± 6.4 Ma was obtained for granitic pebbles in conglomerates from the lower part of the Soltan-Maidan Formation (Ghavidel-Syooki *et al.* 2011b) implying that the age of the volcanic rocks is probably younger than the



Llandovery. As the overlying Devonian deposits are faunally barren, a Silurian age for the whole unit is still possible. There are no granitic plutons of Silurian age yet reported from Alborz or from elsewhere in Iran (Ghavidel-Syooki *et al.* 2011b).

It is possible that the Soltan-Maidan volcanic suite formed at approximately the same time as basalts at the top of the Silurian succession in the Anarak area. At present, lack of evidence hampers any suggestion about a possible relationship between these two volcanic events.

A link between the Soltan-Maidan volcanic rocks and flood basalt volcanism in the lower Palaeozoic succession of the Kopet-Dagh Region suggested by Wendt *et al.* (2005) is highly problematical: in Kopet-Dagh (Saluk Mountains) mafic volcanism has been reported from the Furongian (upper Cambrian) *Eoconodontus notchpeakensis* CB (Jahangir *et al.* 2015). Volcanism continued through the Ordovician and, based on the occurrence of oolitic ironstones in the upper part of the lower Aeronian graptolitic shales (*Demirastrites triangulatus* GB) in the Saluk Mountains (Evans *et al.* 2015), probably continued into the early Silurian.

BIOSTRATIGRAPHY AND CORRELATION

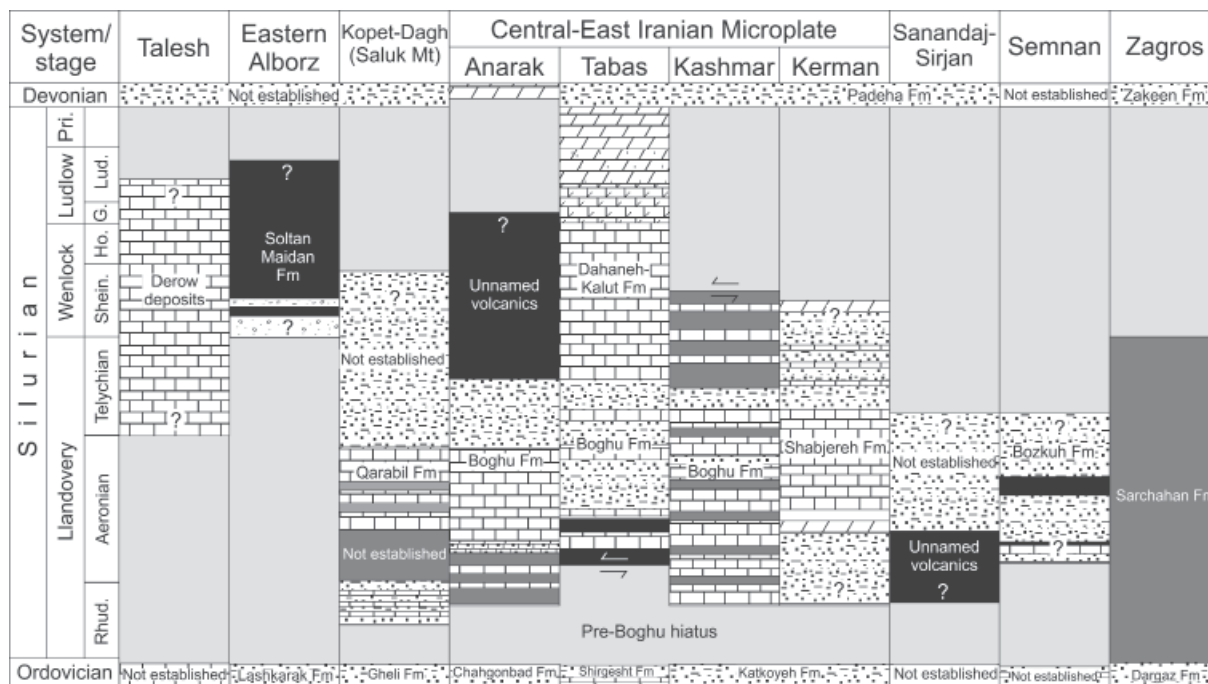
Available data about the Silurian successions from various parts of the Central-East Iranian Microplate (Hamedī 1995; Hairapetian *et al.* 2011; Männik *et al.* 2013; Popov *et al.* 2015a) suggest a widespread unconformity at the base of the Silurian in the region (Text-fig. 15). In the Derenjal and Boghu mountains, the oldest Silurian deposits dated by conodonts are Aeronian (Männik *et al.* 2013). In the Kerman Region, the Upper Ordovician part of the Katkoyeh Formation is overlain by the Shabdjereh Formation. The lower part of the Shabdjereh Formation consists of deposits characteristic of alluvial systems suggesting subaerial exposure and widespread erosion during the latest Ordovician–earliest Silurian. A marine transgression probably commenced sometime in the mid Aeronian. This is indicated by the occurrence of *Stegocornu procerum* (Hairapetian *et al.* 2012).

A distinct lineage of endemic rhynchonellide brachiopods can be seen in the Llandovery of the Central Iran region: *Stegocornu procerum*→*Stegocornu denisae*→*Jafarirhynchus alatus*. The two species of *Stegocornu* succeed one another in the upper Aeronian strata (within the upper part of the *Distomodus staurognathoides* CB) and *Jafarirhynchus alatus* occurs in the Telychian (Hairapetian *et al.* 2012; Popov *et al.* 2015a). This lineage has also been recognised in Kopet-Dagh and Afghanistan. All of these species can be used for high resolution biostratigraphy and correlation of middle and upper Llandovery deposits within Central Iran and adjacent regions.

At present, deposits of Wenlock to Ludlow age are known only from the regions located along the northern margin of the Central-East Iranian Microplate. They are represented by the carbonate succession of the Dahaneh-Kalut Formation, which is dated by conodonts (Männik *et al.* 2013) and brachiopods. It is possible that the Dahaneh-Kalut section extends into the Pridoli but no age-diagnostic taxa have yet been recovered.

Outside Central Iran, Silurian deposits are relatively well documented in the Zagros Basin and in the Iranian Kopet-Dagh. In the Zagros Basin, the Silurian is represented by black graptolitic shales and overlying siliciclastic deposits of the Sarchahan Formation. Both are relatively widespread in the subsurface, but are exposed only in two small areas c. 100 km north of Bandar-Abbas, namely the Kuh-e Faraghan and Kuh-e Ghakum areas (Text-fig. 1). Kuh-e Faraghan is the only place in Iran where a continuous transition from the Ordovician to the Silurian is documented in the lowermost part of the Sarchahan Formation (Ghavidel-Syooki *et al.* 2011a). Biostratigraphy based on graptolites (Rickards *et al.* 2000; Ghavidel-Syooki *et al.* 2011a) and palynomorphs (Ghavidel-Syooki and Khosravi 1995; Ghavidel-Syooki 2000; Ghavidel-Syooki and Winchester-Seeto 2004; Ghavidel-Syooki *et al.* 2011a) suggests a Rhuddanian to Telychian age for the main part of the Silurian succession in the Zagros Basin. Rare brachiopods recently described and illustrated from the Sarchahan Formation include the lingulide *Paterula* sp. and spiriferide *Iranospirifer* sp. (Ghavidel-Syooki *et al.* 2015). The latter genus is endemic and occurs also in the Aeronian of Kopet-

- ← Text-fig. 14. Field photographs of the Jehagh section in the vicinity of Soh village. A – Lower part of the Jehagh section, north-westerly view: exposure of an unnamed formation of volcanic rocks (V) unconformably overlain by mid to late Aeronian siliciclastic rocks (S) – those in white squares are detailed in the following photographs; B – Lava flows with interbedded packages and overlying beds of sandstone (S) (person for scale), westerly view of the exposure; C – Easterly view of the stratigraphic contact between volcanic rocks (V) and sandstone (S) (person for scale); D – Close-up view of a shell bed formed by accumulation of disarticulated valves of *Pentamerus* cf. *asiaticus* Cocks, 1979a; E – Close-up view of the sandstone beds intercalating with thin layers of calcareous sandstone in the lower part of the section



Text-fig. 15. General correlation of the Silurian formations in Iran based on all available data. For lithological explanations see Text-fig. 7. Lithologies within formations are generalized. Abbreviations: G. – Gorstian; Ho. – Homerian; Lud. – Ludfordian; Pri. – Pridoli; Rhud. – Rhuddanian; Shein. – Sheinwoodian

Dagh (Popov and Cocks 2013) and in the Kerman Region (Brice 1999).

The extensive occurrence of black graptolitic shales in the Zagros Basin, which occupied the outer margin of the Arabian sector of Gondwana through the Palaeozoic, is in sharp contrast with the Silurian successions documented elsewhere in Iran. Available data suggest also that the onset of the black shale deposition was diachronous across the Zagros Basin. At Kuh-e-Faraghan the base of the Sarchahan Formation is dated as the late Hirnantian *Metabolograptus persculptus* Graptolite Biozone (GB), while at Kuh-e-Gahkum the lowermost part of the formation contains graptolites of the early Aeronian *Demirastrites triangulatus* GB (Ghavidel-Syooki et al. 2011a). At Kuh-e-Faraghan there is a cryptic hiatus corresponding to the middle and upper Rhuddanian at the base of the *Demirastrites triangulatus* GB (Suyarkova, personal communication 2012; Saberi et al. 2016; Text-fig. 12) and evidence for significant local scouring, which could have been produced by the direct action of ice abrasion, melt-water, or a combination of both (Ghavidel-Syooki et al. 2011a). A prominent fan-shaped clastic wedge of amalgamated conglomerate sheets at Kuh-e-Gahkum was possibly deposited within a tunnel-channel shoulder (Ghavidel-Syooki et al. 2015).

This may indicate that the Hirnantian satellite ice sheet was present in the Zagros area.

Unlike in the Zagros Basin, a widespread hiatus occurs at the Ordovician–Silurian boundary in the Central-East Iranian Microplate. Here, Hirnantian and most of Rhuddanian strata are missing, and shallow marine deposition only commenced sometime in the Aeronian when heterolithic siliciclastic and carbonate deposits yielding intervals with abundant brachiopod shells and small metazoan build-ups started to form.

The Silurian of Kopet-Dagh has been widely studied (Ghavidel-Syooki 1996; Ghavidel-Syooki and Vecoli 2007; Popov and Cocks 2013; Evans et al. 2015). However, there are still unresolved questions, for example the Ordovician–Silurian boundary in that succession has not been defined. It is most probably within a thick siliciclastic succession separating the unnamed unit of Upper Ordovician flood basalts from the unit of graptolitic black shales with a few beds of oolitic ironstone, and with the graptolites of the lower Aeronian *Demirastrites triangulatus* GB in the upper part. In the Saluk Mountains, the unit of graptolitic black shales is up to 90 m thick (Evans et al. 2015). The middle part of the Silurian succession comprises mainly limestones with subsidiary beds of siltstone and argillite. These limestones have been

assigned by Cocks (1979a) to the Qarabil Limestone Formation, which has its type section in the vicinity of Robat-e Qarabil. However, no detailed description of the Silurian succession in the area has been published and the best documented Silurian section is situated c. 60 km south-east in the Saluk Mountains (Evans *et al.* 2015). The Qarabil Formation is characterized by a diverse fauna of brachiopods and orthoconic cephalopods (Cocks 1979a; Popov and Cocks 2013; Evans *et al.* 2015). The occurrence of *Stegocornu procerum* and *Pentamerus asiaticus* suggests a mid to late Aeronian age for the formation. The upper part of the Silurian succession in Kopet-Dagh is barren of fossils. It comprises up to 250 m of intercalated sandstones and siltstones with desiccation cracks indicating numerous subaerial exposure surfaces. Based on sporadically occurring cryptospores these strata have been provisionally dated as Wenlock (Ghavidel-Syooki and Vecoli 2007, p. 175). In the Saluk Mountains Silurian siliciclastic rocks are unconformably overlain by Devonian siliciclastic deposits.

CONCLUSIONS

1. Silurian successions from five major outcrop areas within the Central-East Iranian Microplate, including the Kashmar (Boghu Mountains), Tabas (Derenjal Mountains, Ozbak Kuh Mountains), Anarak, and Kerman regions have been assessed and characterized in detail. A brief review of the current state of knowledge of Silurian deposits across Iran is given.

2. The Silurian conodont succession in Central Iran is not complete and contains significant gaps. However, it is possible to correlate the Silurian deposits of Central Iran with the Standard Global Chronostratigraphic Scale quite precisely. Using a local endemic brachiopod succession (based on *Stegocornu* and *Jafarirhynchus*) a relatively high resolution regional correlation of the Aeronian and Telychian can be achieved.

3. There is a significant hiatus at the Ordovician–Silurian boundary and strata of Hirnantian–Rhuddanian age are missing in Central Iran. The oldest biostratigraphically dated Silurian deposits on the northern margin (in recent coordinates) of the Central-East Iranian Microplate are early to middle Aeronian. In the Kerman Region, middle Aeronian shallow marine sedimentary rocks overlie terrestrial deposits representing alluvial systems (Hamedi 1995) that show evidence of subaerial exposure and erosion.

4. Carbonate sedimentation on the northern margin of the Central-East Iranian Microplate com-

menced in the Aeronian (Boghu Formation). It was interrupted in the Telychian when siliciclastic sedimentation started to dominate. In the early Wenlock (Sheinwoodian) a carbonate platform (Daheneh-Kolud Formation) was established in the region located along the north-eastern margin of the Central-East Iranian Plate (Derenjal Mountains, Ozbah-Kuh). Here, the platform existed until the Ludlow whereas in the other regions [including Kopet-Dagh, the Sanandaj-Sirjan terrane and Sabzevar Zone (Boz-Kuh and Soh areas)] siliciclastic sedimentation continued during and after the Wenlock. In the Kerman Region the lower part of the heterolithic Shabdjareh Formation formed in a non-marine environment, but during formation of its middle and upper parts shallow marine deposition dominated (Hamedi 1995). Although the middle part of the Silurian succession in the Kerman Region has been dated as Aeronian to Telychian, no detailed faunal logs are available at present.

5. Widespread distribution of black graptolitic shales (Sarchahan Formation, “hot” shales) is characteristic of the Llandovery of the Arabian sector of Gondwana (including the Zagros Region; Ghavidel-Syooki *et al.* 2011a; Saberi *et al.* 2016). However, there is no record of black shale formation across the Central-East Iranian Microplate. There are reports of Aeronian black graptolitic shales from Kopet-Dagh (Evans *et al.* 2015), but Rhuddanian strata in that succession are represented mainly by siliciclastic deposits with rare interbeds of bioclastic limestone, which accumulated in a shallow marine, well aerated environment. Although the most likely palaeogeographical position of Central Iran covers temperate latitudes, close to or at the Gondwanan margin, a position in front of the Arabian sector of Gondwana as indicated by Late Ordovician and Silurian palaeogeographical reconstructions (e.g., Torsvik and Cocks 2009, figs 4 and 5) is questionable.

6. Proliferation of the endemic Aeronian *Stegocornu* brachiopod fauna, which occurs in Central Iran, Afghanistan and the Kopet-Dagh regions, suggests that these regions were in close proximity at that time (Hairapetian *et al.* 2012).

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