FOSSILS AND STRATA

An international monograph series of palaeontology and stratigraphy

Number 66 • August 2021

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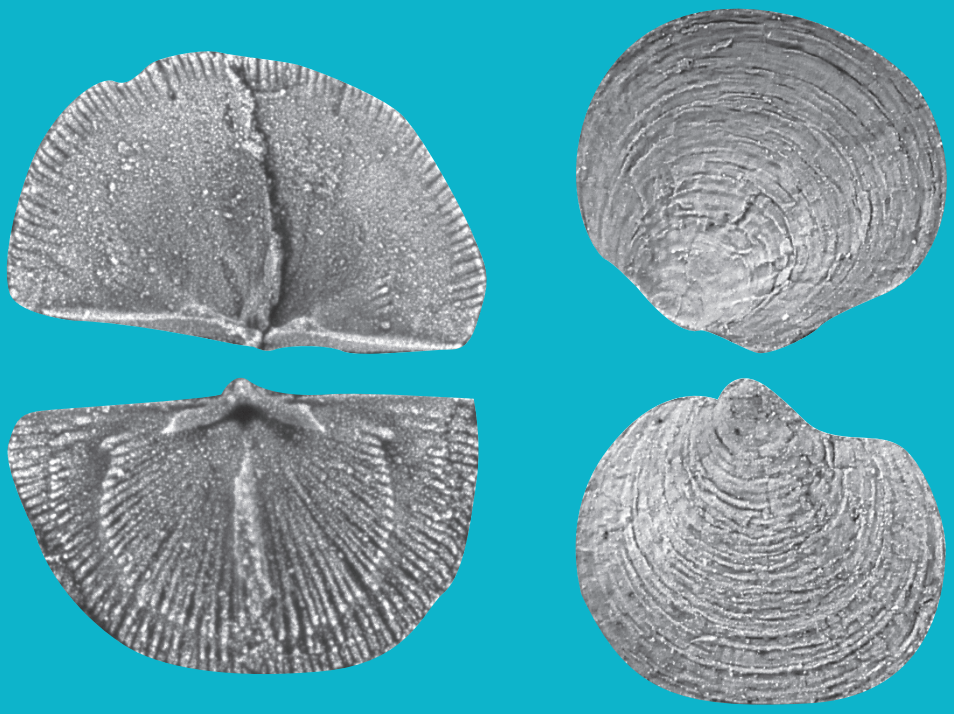

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Acknowledgements

Financial support for the publication of this issue of Fossils and Strata was provided by the Lethaia Foundation

DOI 10.1002/9781119782377

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FOSSILS AND STRATA

THE LETHAIA FOUNDATION

Popov, L.E. & Cocks, L.R.M. 2021: A mid-Ordovician brachiopod evolutionary hotspot in southern Kazakhstan. *Fossils and Strata*,

Chu-Ili, now in Kazakhstan, was a substantial independent equatorial microcontinental terrane in Ordovician times, with a small Precambrian core fringed by several island arcs. Its mid-Ordovician (late Darriwilian to early Katian) faunas were a major evolutionary hotspot within an equatorial archipelago at a period when Palaeozoic sea levels and temperatures were at their highest. As well as reviewing the previously described brachiopods from elsewhere in Chu-Ili, the mid-Ordovician brachiopods of the West Balkhash Region, which outcrops west of Lake Balkhash within Chu-Ili, are newly described here, mainly from the Berkutsyur and Baigara formations. Many represent the earliest occurrence of their lineages, notably the oldest member of the Order Atrypida. More than twelve brachiopod associations are defined, many for the first time and together hosting 73 genera and over 91 species. The new family Kellerellidae is erected within the superfamily Lissatrypoidea. New genera are *Aploobolus* (Obolidae), *Doughlatomena* (Rafinesquinidae), and *Altynorthis*, *Lictorthis*, and *Baitalorthis* (all Plectorthidae), *Baitalorhynchus* (Sphenotretidae), *Lydirhyncha* (Ancistrorhynchidae) and *Costistriispira* (Kellerellidae). Eleven new species, including *Aploobolus*? *tenuis*, *Doughlatomena splendens*, *Bimuria karatalensis*, *Apatomorpha akbakaiensis*, *Lepidomena betpakdalenis*, *Sonculina baigarensis*, *Altynorthis betpakdalensis*, *Altynorthis vinogradovae*, *Phaceloorthis*? *corrugata*, *Batailorhyncha rectimarginata* and *Costistriispira proavia*, and one new subspecies *Sowerbyella* (*Sowerbyella*) *verecunda baigarensis* are also erected. The global palaeogeographical affinities of all the Chu-Ili brachiopod faunas are discussed, as well as Chu-Ili's place within the peri-Gondwanan archipelago. Newly named stratigraphical units are the Berkutsyur (Darriwilian to early Sandbian) and overlying Kopkurgan (Sandbian to Katian) formations within West Balkhash, and the Tastau (Darriwilian) and Takyrsu (Darriwilian to early Sandbian) formations within the northern Betpak-Dala desert. □ *Brachiopoda, Evolutionary hot spot, Kazakhstan, Ordovician.*

Leonid E. Popov [leonid.popov@museumwales.ac.uk], Department of Geology, National Museum of Wales, Cathays Park Cardiff CF10 3NP, UK; L. Robin M. Cocks [r.cocks@nhm.ac.uk], Department of Earth Sciences, The Natural History Museum, Cromwell Road London SW7 5BD, UK; *manuscript received on 23/04/2020; manuscript accepted on 3/07/2020.*

Introduction

During the mid-Ordovician, sea levels and temperatures were at their highest in the whole Palaeozoic, and second highest only to the mid-Cretaceous in the entire Phanerozoic, as known from many papers, reviewed by Torsvik & Cocks (2017). In those mid-Ordovician times (late Darriwilian to early Katian), the Chu-Ili Terrane formed part of an archipelago which straddled the Equator, comparably to the East Indies today (Popov & Cocks 2017). Some Middle and Late Ordovician brachiopods from several sectors of the Chu-Ili Terrane have been described, but not from the West Balkhash Region which are thus monographed here. The brachiopods described in previous works from the Chu-Ili Terrane include the Anderken Formation (Sandbian) (Popov *et al.* 2002), the Dulankara Formation (early Katian) (Popov *et al.* 2000; Popov & Cocks 2006), and the Uzunbulak Formation (Darriwilian) (Nikitina *et al.* 2006). Our aim here is to complete the task for the Middle Ordovician of the entire terrane so as to get a clear picture of its biological and geological significance. We also define more than 12 associations dominated by brachiopods, some previously unrecognised. The freshly described faunas came mostly from the newly defined Berkutsyur and Kopkurgan formations, which outcrop south-west of Lake Balkhash in central Kazakhstan (Fig. 1) as well as from the Baigara Formation together with the new Tastau and Takyrsu formations exposed between the Karatal River and Baigara Mountain in the inhospitable southern Betpak-Dala desert, where access is particularly difficult.

Our conclusion is that Chu-Ili hosted one of the most rapidly-evolving brachiopod faunas in the world in those times, and fully justifies identification as a 'hotspot'. The terrane is thus of cosmopolitan

DOI 10.1002/9781119782377

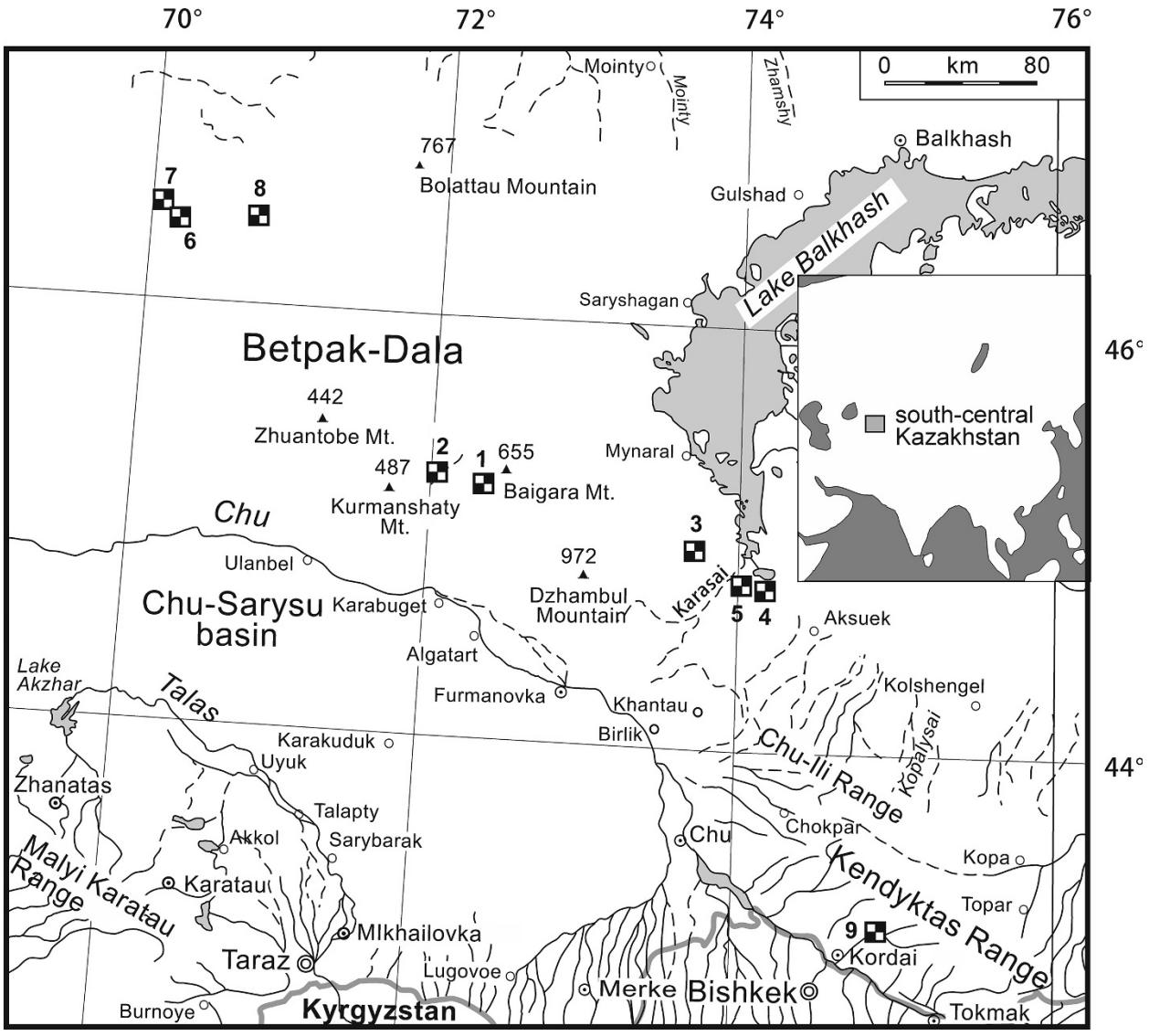

Fig. 1. Generalised map of the West Balkhash Region and eastern Betpak-Dala desert showing the position of the studied areas. Inset, location of south-central Kazakhstan within Asia. Brachiopod localities: 1, area 6 km south west of Baigara Mountain; 2, River Karatal; 3, area 15 km west of Chimpek Bay (Locality 388); 4, area 4 km south-west of Lake Alakol; 5, area 7 km south-west of Lake Alakol; 6, Golubaya Gryada (localities 562, 563); 7, Karakan Ridge (Locality 154); 8, Ergenekty Mountains (Locality 1501); 9, Talapty site.

importance, and played a key role in the Great Ordovician Biodiversification Event (Webby *et al.* 2004). The justification for that conclusion is within the 'Implications for biodiversity' section below.

Geological setting and key sections

The Chu-Ili Terrane was one of about twenty independent microcontinents and island arcs whose remnants are now preserved in the very large country of Kazakhstan, whose Ordovician rocks were reviewed by Nikitin (1972, 1973), as well as in its adjacent countries of Central Asia, notably Kyrgyzstan, Uzbekistan, and the north-western part of China including Tarim. In Lower Palaeozoic times they were independent terrane units not far from the vast continent of Gondwana to its north-west (Popov & Cocks 2017; Torsvik & Cocks 2017) and are together known as the 'Kazakh terranes'. Chu-Ili itself is made up of a Proterozoic core with 2.8 Ga zircons and an Early to Late Ordovician accretionary wedge which was caused by the progressive nearing of the adjacent Mynaral - South Dzhungaria Terrane to its north. Chu-Ili and North Tien Shan merged in mid-Silurian time (Popov & Cocks 2017), well after the rocks described in this paper were deposited. However, despite differing statements by some authors

(Degtyarev & Ryazantsev 2007; Bazhenov *et al.* 2012; Wilhem *et al.* 2012), it was not until the Early Devonian that the much larger continent of Kazakhstania, which included Chu-Ili and North Tien Shan as well as several other terranes, became an entity.

South Betpak-Dala

The Ordovician stratigraphy of the southern Betpak-Dala desert between Baigara Mountain at the south-east and the Karatal River at the north-east, all situated on the north-western prolongation of the Chu-Ili Terrane (Fig. 1), was summarised by Esenov *et al.* (1971) and Nikitin *et al.* (1980). The area is on the south-eastern (modern orientation) margin of the Chu-Ili terrane facing the Zhalair-Naiman Fault Zone, which is the Silurian suture (Popov *et al.* 2009). The Ordovician succession in the area is, in ascending order: (1) a thick succession of graded siliciclastic rocks with subsidiary units of fine rhyolitic tuffs and a few horizons of phosphoritic conglomerates assigned to the Karatal Formation (Floian to early Darriwilian) with an estimated thickness up to 2000 m and whose stratigraphical relationship with the underlying units remains unknown; (2) the Baigara Formation (late Darriwilian to early Sandbian), a transgressive succession of polymict conglomerates, intercalated brownish-red and greenish-grey sandstones and siltstones with lingulides, succeeded by intercalating units of siltstones, argillites and nodular limestones with abundant dasyclad algae; (3) a succession of graded siliciclastic rocks with occasional graptolites over 1000 m thick; (4) the Anderken Formation (Sandbian) of mainly sandstones and siltstones with a few units of polymict conglomerates and bioclastic limestones, 1000–1500 m thick; and (5) the Dulankara Formation (Katian) of polymict conglomerates, sandstones, siltstones, and limestones up to 1600 m thick (Popov & Cocks 2006). Most of the fossil lists in previous publications are based on preliminary identifications, and the existing monographic record is poor. The Floian to Darriwilian graptolites from the Karatal Formation are known from Tsai (1974, 1976), and conodonts from a single locality in that unit were made known by Tolmacheva (2014). A few brachiopod species from the Baigara Formation were published by Nikiforova & Popov (1981), Popov *et al.* (2001), and Bassett *et al.* (2013), but many more are described in the present paper, while the brachiopod fauna from the Anderken Formation was documented by Popov (1980*a*, 1980*b*, 1985), and Popov *et al.* (2002). The rich brachiopod faunas in the Baigara Formation described here were first discovered by T. B. Rukavishnikova in 1952, and were sampled by D. T. Tsai, L. E. Popov and I. F. Nikitin in 1974.

Area 6 km south-west of Baigara Mountain

This is the type area for the Baigara Formation (Figs 1–3). That unit rests with a slight angular unconformity on the graded siliciclastic rocks of the Karatal Formation and contains Darriwilian graptolites in its upper part (Tsai 1976).

The sedimentary succession in ascending order is as follows:

Unit B1. – Polymict conglomerates succeeded upsection by gritstones and intercalated green and brownish red sandstones and siltstones up to 60 m thick with abundant lingulide fragments including *Ectenoglossa* sp. in the upper part.

Unit B2. – Green, fine-grained sandstones, 50 m.

Unit B3. – Intercalated fine-grained calcareous sandstones, calcareous limestones (rhynchonellide shell beds) and siltstones, 22 m thick, with bivalves, trilobite fragments, and abundant brachiopods of the *Ancistrorhyncha* Association (Locality 1020).

Unit B4. – Green, laminated fine-grained sandstones and siltstones, 6 m.

Unit B5. – Bedded light-grey silty limestones with a 9 m silty sandstone in the lower part with abundant brachiopods of the *Scaphorthis–Strophomena* Association (Localities 1021, 765e).

Unit B6. – Green, laminated siltstones, 4 m, above which is an unexposed interval of about 40 m.

Unit B7. – Greenish-grey slightly argillaceous limestones, 4 m thick, with abundant dasyclad algae and brachiopods of the *Altynorthis* Association, with bryozoans, rare trilobites, and cephalopods (Locality 1022).

Unit B8. – Grey nodular limestones with abundant dasyclad algae and bryozoans, 60 m thick, with brachiopods of the *Altynorthis* Association and cephalopods (Locality 1023).

Unit B9. – Green siltstones with thin layers of limestones and limestone nodules, 67 m.

Unit B10. – Grey and greenish grey graded sandstones and siltstones up to 630 m thick, with rare graptolites including *Climacograptus* sp., *Dicellograptus* sp. and *Leptograptus* sp. (Fig. 2; localities 24 and 26).

In the studied transect the Baigara Formation is overlain conformably by the Anderken Formation.

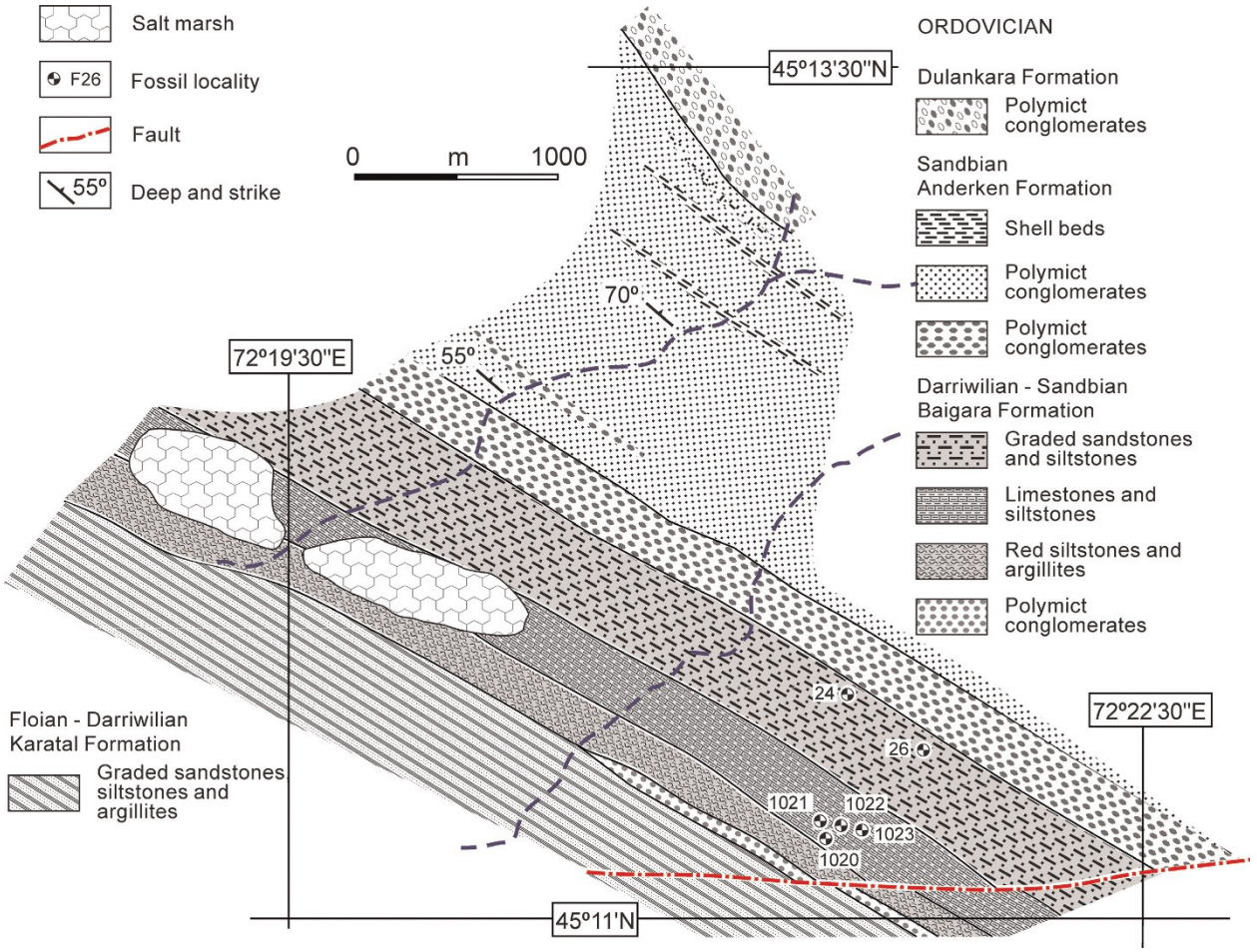

Fig. 2. Schematic geological map of the outcrop area of the Baigara Formation 6 km south-west of Baigara Mountain (Fig. 1, locality 1) showing the positions of the numbered brachiopod localities.

Area on the west side of the Karatal River

This is about 20 km north-west of the Baigara section (Figs 1, 3, 4). D. T. Tsai, L. E. Popov and I. F. Nikitin mapped and measured the section in 1974, which is about 1 km north-east from the River Karatal, where the Baigara Formation rests with minor angular unconformity on graded siliciclastic rocks of the Karatal Formation. The succession in ascending order is as follows:

Unit K1. – Poorly sorted, polymict, brown-grey conglomerates with a sandy matrix, 17 m.

Unit K2. – Intercalations of green and brownish-red sandstones, siltstones, and argillites, with lenses and thin beds of conglomerates in the lower part, 85 m.

Unit K3. – Greenish-grey to brownish-grey siltstones with beds of nodular limestone in the lower part and sandstone in the upper part, total 103 m thick. Limestone beds (Locality 1025) with the *Altynorthis* Association.

Unit K4. – Intercalations of greenish-grey fine-grained sandstones and siltstones with nodules and lenses of a dark-grey, argillaceous limestone, 90 m. Sandstones (Locality 1026) and limestones (Locality 1026b) with abundant *Bimuria-Grammoplecia* brachiopod Association. This unit also occurs on the east side of the River Karatal, at the isolated Locality 1028, 1.4 km south-east from Locality 1026 (Fig. 4).

Unit K5. – Graded greenish-grey and dark-grey sandstones and siltstones up to 1000 m thick. Siltstones in the lowermost part contain the *Bimuria-Grammoplecia* Association (Locality 1026a).

The transition from the Baigara to the Anderken Formation is on the east side of the Karatal River about 2 km west of Sorbulak Spring (Fig. 4, localities 1024, 1024a–c, 1027, and 1027a). Brachiopods of the *Ectenoglossa* and *Tesikella* associations were documented by Popov (1980b, 1985) and Popov *et al.* (2002), and include *Ectenoglossa sorbulakensis*, *Christiania egregia*, *Eodalmanella extera*, *Phragmorthis*

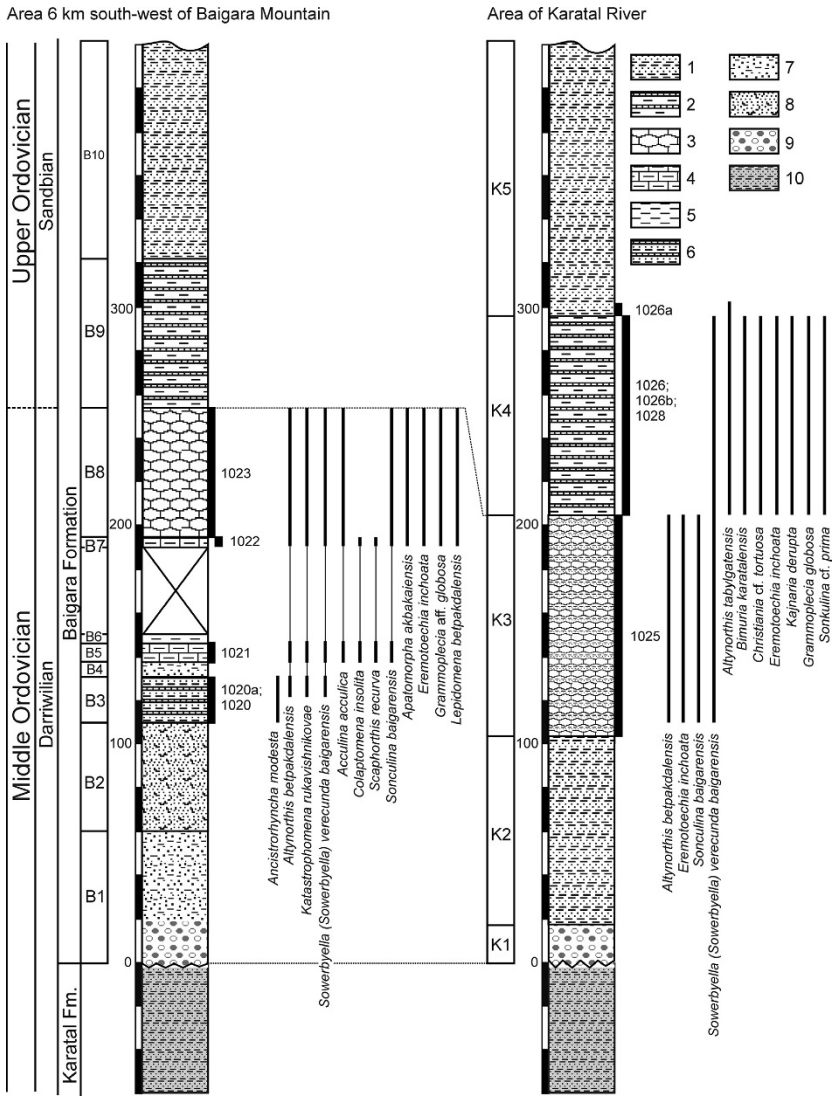

Fig. 3. Schematic stratigraphical sections of the Baigara Formation in the area 6 km south-west of Baigara Mountain and in the area of Karatal River (Fig. 1, localities 1 and 2) showing sample horizons and stratigraphical ranges of selected brachiopod species. Geographical position of the sections and fossil localities are shown on Figs 1, 2, and 4. Lithologies: Baigara Formation (upper Darriwilian – Lower Sandbian): 1, graded sandstones and siltstones; 2, intercalations of siltstones and thin limestone beds; 3, nodular limestones; 4, silty limestones; 5, siltstones; 6, sandstone and siltstone intercalations with brachiopod shell beds; 7, sandstones and siltstones; 8, sandstones with obolid coquinas; 9, polymict conglomerates. Karatal Formation (Floian – Darriwilian): 10, graded sandstones and siltstones.

conciliata, and *Sowerbyella (S.) rukavishnikovae*. The position of the Middle to Upper Ordovician boundary within the Baigara Formation cannot be defined precisely, but *Altynorthis tabylgatensis* and *Sonculina prima* in association with graptolites of the *Nemagraptus gracilis* Biozone in the Tabylgaty Formation in the neighbouring North Tien Shan Terrane (Misius 1986), and *Christiania* cf. *C. tortuosa*, *Grammoplecia globosa*, and *Kajnaria derupta* in units of Sandbian age elsewhere in Kazakhstan, together indicate that Unit K4 in the Karatal section is probably Sandbian.

North Betpak-Dala

Brachiopods from the Middle to Upper Ordovician of North Betpak-Dala are variably known. A rich Darriwilian linguliform brachiopod fauna was described by Nazarov & Popov (1980) from the Karakan Limestone in a barren, unpopulated area informally called the Karakan Ridge (Locality 7 on Fig. 1). Nikitina (1989) described a rhynchonelliform brachiopod fauna from the same locality in her unpublished Ph.D. thesis; and the early Katian rhynchonelliform brachiopods of the *Kellerella* Association from the mud-mound at Sartan-Manai were

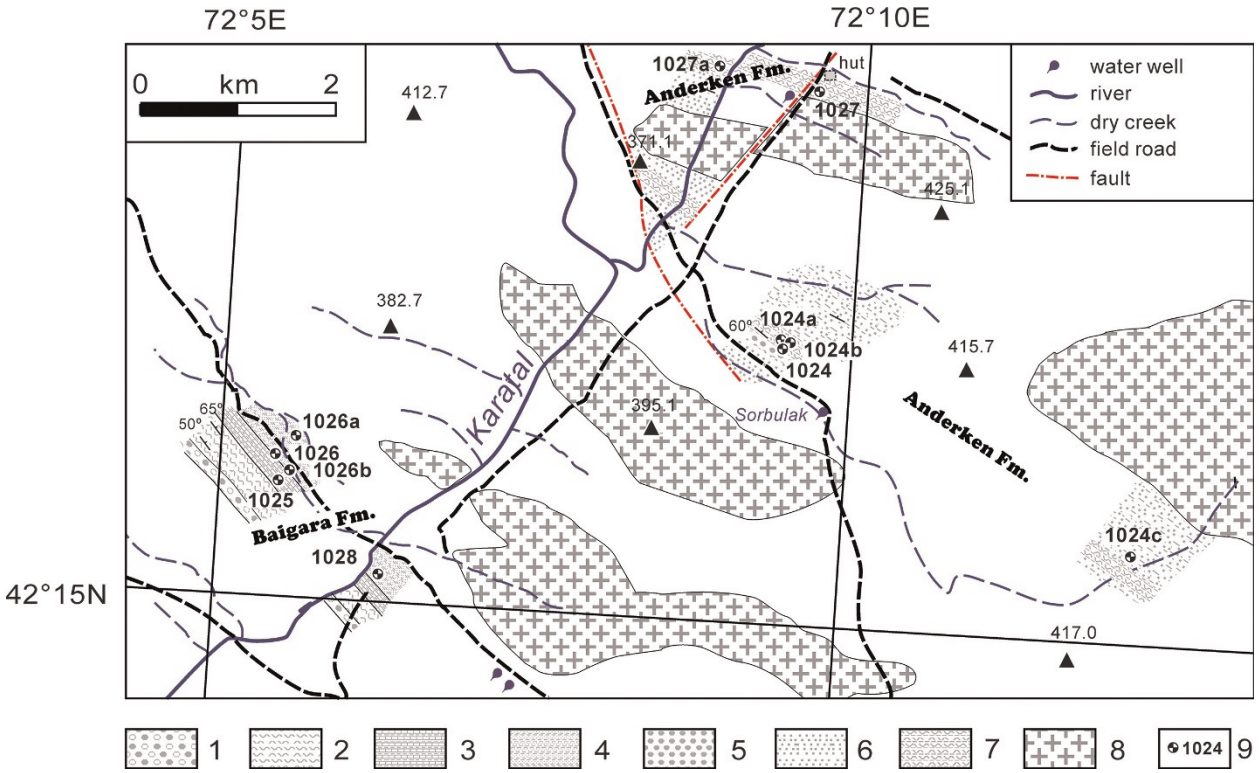

Fig. 4. Schematic map of the outcrop area of the Baigara and Anderken formations at Karatal River basin and in the vicinity of Sorbulak well, south Betpak-Dala (Fig. 1, locality 2) showing positions of brachiopod localities. Baigara Formation (upper Darriwilian – lower Sandbian): 1, polymict conglomerates; 2, green and brownish red sandstones, siltstones, and argillites; 3, nodular limestone and siltstone intercalations; 4, graded sandstones and siltstones. Anderken Formation (Sandbian); 5, polymict conglomerates; 6, sandstones; 7, green and brownish siltstones with argillite intercalations; 8, granitic intrusives.

documented by Nikitin & Popov (1996) and Nikitin *et al.* (1996).

The complex geology of the area was discussed by Keller & Lisogor (1954), Nikitin (1972), Nikitin *et al.* (1980), Nikitina *et al.* (2006), and Ghobadi Pour *et al.* (2009), but is still not yet fully understood. The area was initially surveyed by L. E. Popov in 1973 and 1974 and again between 1986 and 2004 with the late E. V. Alperovich and E. A. Vinogradova. The lithostratigraphy (Kushaky, Savid, Algabas, and Kuyandy formations) previously applied to the Ordovician in the region was imported from the distant Sarysu-Teniz Region by Nikitin *et al.* (1980), Nikitin (1991), and Nikitina *et al.* (2008), but that region is within the North Tien Shan Microcontinent on the opposite side of a Silurian suture (Popov *et al.* 2009; Popov & Cocks 2017) and thus its terminology cannot sensibly be used in the Chu-Ili Terrane. Vinogradova (*in* Ghobadi Pour *et al.* 2009) found that andesite-basalt volcanic rocks assigned to the Savid Formation in the Golubaya Gryada area (Locality 6 on Fig. 1) represent a chain of exhumed intrusive subvolcanic bodies of younger Palaeozoic age which have no relation to the exposed Upper Ordovician stratigraphical succession as was suggested in some previous publications.

Thus the only existing Ordovician lithostratigraphical name which can correctly be applied in the Betpak-Dala area is the Karakan Formation, whose type area was described by Nikitina *et al.* (2008) and which is a sedimentary succession of bioclastic limestones rich in brachiopods and trilobites, microbial build-ups, and oligomict sandstones, all underlain, overlain, and intercalating with laminated siltstones, black siliceous argillites and cherts with Darriwilian graptolites of the isograptid biofacies. Paragenetic association of the carbonate lithofacies deposited at the environments of inner to mid shelf with distal turbidites and hemipelagites deposited on the continental slope and representing lithofacies of the outer fan and fan fringe is an improbable scenario. We therefore conclude that the carbonate bodies (often referred as the Karakan Limestone) are allochthonous and represent parts of a large slump complex transported by turbidites down the continental slope. The presumed basal units of the Karakan Formation, which include ophiolitoclastic breccias and

sandstones, are parts of a serpentinite melange, which includes limestones. Shear lenses of serpentinites and ophiolitic breccias also occur in the limestones and are seen in cores (Nikitina *et al.* 2008), all suggesting that the emplacement of ultramafic volcanic rocks and serpentinites occurred after the Mid Ordovician. Thus, the limestones and fine siliciclastic matrix used by Nikitina *et al.* (2008) as evidence for a Darriwilian age of these heterogenous units must be ignored. Lithologically similar carbonates with comparable faunas preserved as olistoliths also occur in the upper part of the Darriwilian Uzunbulak Formation at Kopalysai, southern Chu-Ili (Nikitina *et al.* 2006). The original sources of these carbonates in both cases might possibly be a collapsed carbonate platform, but such deposits are unknown *in situ* within the region.

Since the lithostratigraphical units designated for the Ordovician of the Baikanur Region are inapplicable, they are replaced here by the new Tastau Formation (Floian to Darriwilian) and Takyrsu Formation (Darriwilian to Sandbian). A further problem is the proper characterisation of the Upper Ordovician (Katian) deposits assigned to the Kuyandy Formation by Nikitin *et al.* (1980) and Nikitin (1991), which remain inadequately known. We conclude that the term 'Karakan Limestone' should be confined to the allochthonous carbonate unit preserved as olistoliths and olistoplacks within the upper part of the Tastau Formation. Yet another dilemma is that the Upper Ordovician Kuyandy Formation of the Baikanur Region is homonymous with the later-named Cambrian (Furongian) Kuyandy Formation of the Boshchekul Region, and the latter name should therefore be replaced in due course.

There is another unnamed upper Ordovician formation exposed on the opposite side of the Chu-Ili Terrane in the Ergenekty Mountains (Fig. 1; site 8) which is 600 m of intercalating sandstones and siltstones with a faulted lower boundary. The upper boundary of the unit is disconformable, with an approximately 350 m unit of brown polymict conglomerates with subsidiary beds of sandstones and siltstones, occasionally with dense raindrop impressions on bedding surfaces in the upper part. The late Ordovician (early to mid Katian) age of the lower unit is confirmed by the brachiopods at Locality 1501 near the Ergibulak well which include *Bokotorthis kasachstanica*, *Qilianotryma* cf. *Q. suspectum*, *Shlyginia* cf. *S. extraordinaria*, and *Sowerbyella (S.) ampla* which are all common in the Otar and Degeres beds of the Dulankara Formation in the southern Chu-Ili Range (Popov *et al.* 1999, 2000; Popov & Cocks 2006).

Tastau Formation (New)

Derivation of name. – The name is derived from Tastau Hill in the type area.

Stratotype. – The type section is the natural exposure cropping out along the ridge informally named by Keller & Lisogor (1954) as Golubaya Gryada (Blue Ridge), north-east of Tastau Hill at 46°26′18″N, 70°23′3″E, altitude 451 m (Fig. 2). It is a remote area in the northern part of the Betpak-Dala Desert (Fig. 1, Locality 6) about 250 km west of Lake Balkhash and 48 km north-east of the Betpak-Dala weather station, which is the closest settlement.

Definition of boundaries. – The lower boundary of the Tastau Formation is poorly defined, but is apparently faulted against serpentinites associated with unspecified Lower Palaeozoic mafic and ultramafic rocks. Keller & Lisogor (1954) and Nikitin *et al.* (1980) reported a thick unit below, the 'Kusheky' Formation of intercalating quartzose and polymict sandstones and siltstones with graptolites of the *Paratetragraptus approximatus* Biozone, including the eponymous species in its uppermost part. Those beds are assigned here to the Lower Member of the Tastau Formation. The upper boundary of the Tastau Formation is faulted in the type area, and previously reported stratigraphical contacts with a so-called 'Savid' Formation are not confirmed by our field observations. However, 15 km south-east, a preliminary visit appeared to show that the Tastau Formation has conformable stratigraphical contact with the late Darriwilian to Sandbian Takyrsu Formation, but that requires confirmation.

Description. – At the type area the Ordovician rocks form a steep monocline dipping at 80° north-east. The Tastau Formation can be divided into three members in ascending order: the Lower Member, mainly graded, light grey, arkosic and quartzose sandstones and subsidiary siltstones, with thickness over 500 m; the Middle Member of bluish-grey to black, graded fine-grained arkosic and quartzose sandstones, siltstones, laminated siliceous siltstones, argillites, and radiolarian cherts, up to 320 m thick; and the Upper Member, which in the type area consists of *c.* 120 m grey to brownish-red argillites and up to 50 m of yellowish grey siliceous argillite and siltstone intercalations. Further west, the Upper Member includes in its lower part an olistostrome complex with large olistoliths and olistoplacks of shallow marine carbonates known as the Karakan Limestone whose thickness increases up to 250 m

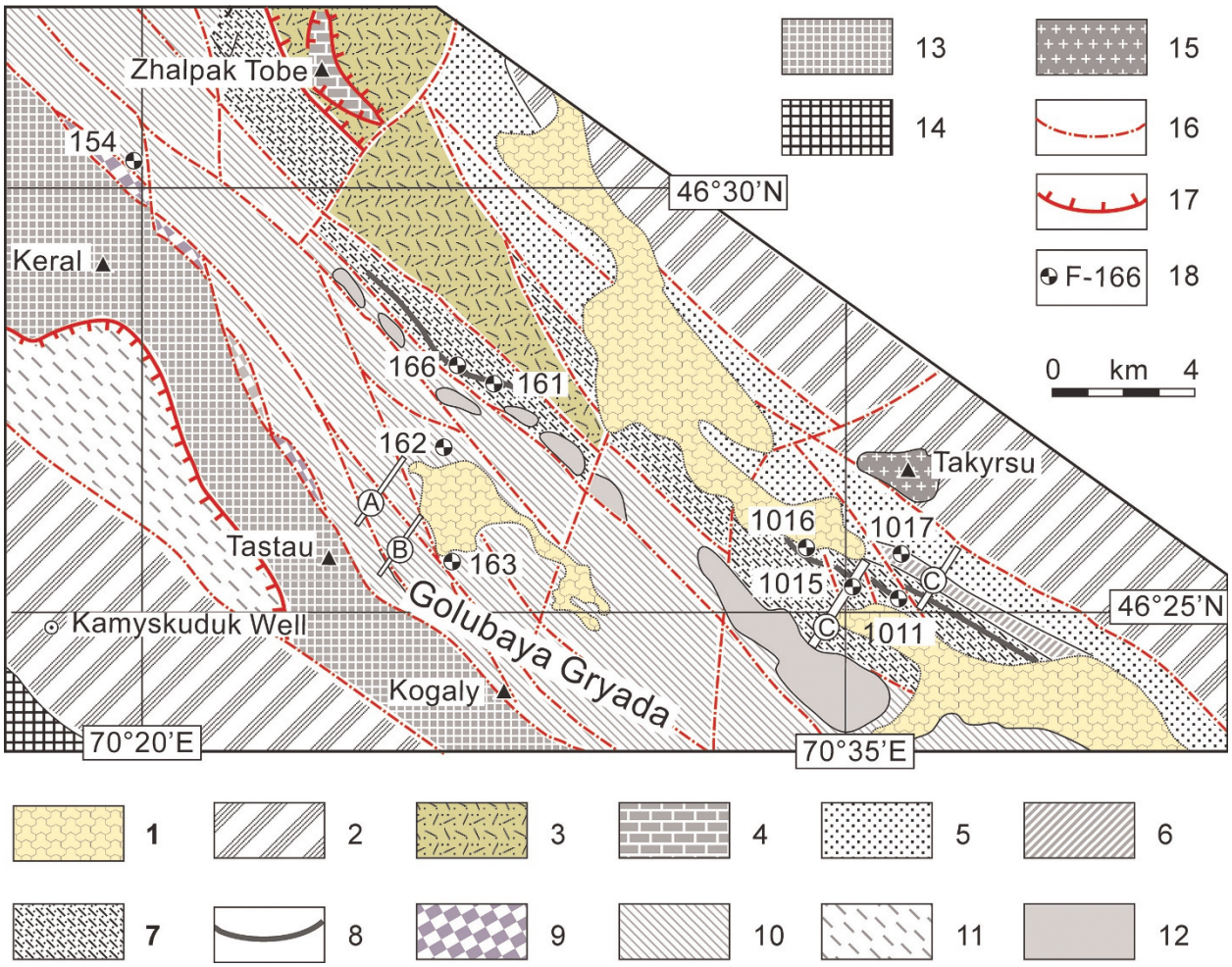

Fig. 5. Schematic geological map of north Betpak-Dala (Fig. 1, localities 6 and 7), showing position of the type sections of newly designated lithostratigraphical units and fossil localities (modified from Ghobadi Pour *et al.*, 2009). Lithologies: 1, salt marshes; 2, Devonian (unspecified); 3, Silurian? volcanic rocks and tuffs; 4, Upper Ordovician limestones (unspecified); 5–8, Takyrsu Formation (late Darriwilian to Sandbian): 5, intercalating sandstones and siltstones, horizons of limestones and conglomerates; 6, graded sandstones and siltstones; 7, intercalating sandstones and siltstones, horizons of tuffs, limestones and conglomerates; 8, marker limestone beds; 9, Karakan Limestone (Darriwilian olistostrome complex); 10, Tastau Formation of graded siltstones, sandstones, siliceous argillites and radiolarian cherts; 11–13, unspecified Lower Palaeozoic rocks: 11, siliciclastic rocks; 12, subvolcanic diabase intrusions; 13, ultramafic rocks and serpentinites; 14, Precambrian; 15, Devonian granites; 16, faults; 17, thrust faults; 18, fossil localities. A-B, type area of the Tastau Formation: A, position of section described by Dubinina *et al.* (1996); B, position of section described by Nikitina *et al.* (2008) and Tolmacheva (2014). C, type section of the Takyrsu Formation.

(Dubinina *et al.* 1996; Nikitina *et al.* 2006; Tolmacheva 2014).

The Tastau Formation crops out more or less continuously in the northern Betpak-Dala desert for about 50 km north-east of the Zhalair Naiman Fault Zone, south-east of the Zhidely dry river. Further south-east it is apparently replaced by the Karatal Formation, which is mainly graded sandstones and siltstones with subsidiary thin layers of tuffs. By comparison with the latter unit, the volcanic tuffs in the Tastau Formation are relatively minor, while the proportion of radiolarian cherts and siliceous argillites (representing background deposits) is considerably greater. The Middle Member contains graptolites characteristic of the *Pendeograptus fruticosus*, *Didymograptus protobifidus*, and *Isograptus maximodivergens* biozones, and conodonts of the *Oepikodus evae* and local *Periodon flabellum/Periodon macrodentatus* biozones (Dubinina *et al.* 1996; Tolmacheva 2014), indicating a late Floian to early Darriwilian age. The Upper Member contains conodonts of the local *Paroistodus horridus* Biozone in its lowermost part (Nikitina *et al.* 2008) and graptolites of the local *Paraglossograptus tentaculatus* and *Pseudoclimacograptus romanovskyi* biozones, indicating a Darriwilian age. Other fossils reported from the Upper Member include the trilobite *Pricyclopyge* sp. and the brachiopods *Akadyria simplex*, *Broeggeria* cf.