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**Lower to Middle Jurassic facies patterns in the northwestern Afghan-Tajik Basin of
southern Uzbekistan and their geodynamic context**

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Abstract: Based on eleven sections, the palaeoenvironments and depositional history of the northwestern Afghan-Tajik Basin in southern Uzbekistan have been reconstructed for the time interval Early Jurassic to Early Callovian. The earliest sediments, resting on Palaeozoic basement rocks, date from the Early Jurassic Period. Up to the end of the Early Bajocian time up to more than 500 m of non-marine sediments accumulated due to extensional tectonics inducing active subsidence. In the Late Bajocian time interval, transgression led to the establishment of siliciclastic ramps that were influenced by storm processes. After a condensed unit in the Middle Bathonian, sedimentation resumed in an outer carbonate ramp □ basinal setting as the subsidence rate outpaced the diminished siliciclastic sediment supply. The change from siliciclastic to carbonate sedimentation in the Middle Jurassic Period is thought to be multifactorial, reflecting levelling of relief in the hinterland, the subsidence moving to a thermally more quiet stage, and a change from humid to arid climatic conditions. These features are also observed in the area of present-day Iran. Similarly, the timing of the transgression coincides with that in eastern and northern Iran stressing the regional significance of this event.

After the collisions of the Cimmerian terranes with Eurasia in the Late Triassic (e.g., Stampfli & Borel 2002; Barrier & Vrielynck 2008; Wilmsen *et al.* 2009a; Zanchi *et al.* 2009, 2012) a number of new or re-activated sedimentary basins formed north of the collision zone in central Asia. Two of these basins are the Amu Darya Basin stretching across Turkmenistan and Uzbekistan and the Afghan-Tajik Basin extending across Uzbekistan, Tajikistan, and Afghanistan (e.g., Brookfield & Hashmat 2001; Ulmishek 2004; Klett *et al.* 2006) (Fig. 1). These two basins had a very close evolution from the Late Palaeozoic onwards. During the Jurassic, the Amu Darya Basin was connected with the Afghan-Tajik Basin in the east (e.g., Ulmishek 2004). The important difference stems from Cenozoic shortening and indentation in the east due to the collision of India: The Pamirs evolution induced folding/thrusting of the sedimentary cover in the Afghan-Tajik Basin (Nikolaev 2002; Klett *et al.* 2006).

In the west, the Amu Darya Basin is bordered by the Kara Bogaz-Karakum High, in the south by the Kopet Dagh Foldbelt, and in the north by the Kyzyl Kum High (Ulmishek 2004). The Afghan-Tajik Basin is bordered to the north by the western part of the Tien Shan (the West Gissar), in the east by the Pamirs and in the south by the North Afghanistan High and Bande Turkestan Mountains (Klett *et al.* 2006; Montenat 2009; Siehl 201X). The southwestern Gissar range stretches southwesterly between the northern parts of the Amu

Darya and Afghan-Tajik basins. Western and southwestern Gissar are the main areas where Jurassic sediments crop out and may be studied in the field. On the northern and southern margins of the Amu Darya and Afghan-Tajik basins they have been reached by wells. Sedimentation started in Permian-Triassic rift basins that formed in the folded and metamorphosed Palaeozoic basement. During the Jurassic Period the Amu Darya and Afghan-Tajik basins subsided very rapidly and became filled with a thick succession of siliciclastic (Lower and early Middle Jurassic), mixed carbonate-siliciclastic (Bathonian to Lower Callovian), carbonate (Middle Callovian-Kimmeridgian), and finally evaporitic (Kimmeridgian?-Tithonian) sediments. Due to their importance as hydrocarbon source and reservoir rocks (for summaries see Ulmishek 2004; Klett *et al.* 2006), the strata have been extensively studied since the Middle of the last century (e.g., Egamberdiev & Ishniyazov 1990; Mitta 2001; D.P. Ishniyazov, pers. comm. 2011; V. Kharin, pers. comm. 2011; Tevelev & Georgievskii 2012), but mainly from a stratigraphic point of view and often published in Russian journals or reports not easily available internationally. No detailed palaeoenvironmental analysis of these rocks exists, but in several review papers the evolution of these sedimentary basins has been briefly outlined, usually in context with their petroleum potential (e.g., Brookfield & Hashmat 2001; Ulmishek 2004; Klett *et al.* 2006).

The aim of the present study is to provide a palaeoenvironmental reconstruction of the Lower and Middle Jurassic part of the basin fill in southern Uzbekistan, to relate the results to the palaeoclimatic and palaeotectonic setting, and to discuss the geodynamic framework governing the evolution of the basin. We do this with an integrated approach using, apart from sedimentological data, also biostratigraphic, ichnological, and taphonomic information.

Material and methods

Altogether, eleven sections in five areas were measured (Fig. 1, Table 1): two sections (Vandob, Shalkan) in the Kugitang Mountains of southern Uzbekistan close to the Turkmenistan border, one section at Panjab (northern Kugitang Mountains), two sections in the southeastern part of Uzbekistan close to the border to Tajikistan (Sangardak, Shargun), two sections in the southernmost part of the Gissar Mountains (Iron Gate, Dalut Mine), and four sections at Vuariz in the west-central part of the Gissar Mountains, ESE of Shahrisabsz (Fig. 1). Of these sections the Vandob, Shalkan, Shargun, and Sangardak sections span the complete succession from the basement to the base of the upper Middle Jurassic carbonate

platform, with a thickness between 335 and 920 m. In the remaining sections either the base or the transition to the Upper Jurassic carbonates is missing. Strictly speaking the study area forms the western margin of the Afghan-Tajik Basin, but during the Jurassic the Amu Darya and Afghan-Tajik basins formed a single unit.

Field data were collected in the course of five field trips to the area in the years 2010, 2011, 2013, and 2014. Sections were logged in detail, bed by bed wherever possible, but in some sections part of the fine-grained succession, consisting of argillaceous silt or silty marl, was overgrown or deeply weathered and could be measured only cursorily. Data retrieval involved recording of lithology, sedimentary structures, trace fossils, body fossils, and taphonomic features. Laboratory work involved analysis of thin-sections and preparation and identification of body fossils.

Litho-, bio- and chronostratigraphy

Lithostratigraphy

Several lithostratigraphic frameworks exist for the Jurassic succession in southern Uzbekistan, which is best developed in the Kugitang Mountains. Here, we follow the classification in Krymholts *et al.* (1988), who subdivided the Jurassic succession into seven formations (Fig. 2). The succession starts with the Hettangian □ Pliensbachian (possibly also lowermost Toarcian) Sandzhar Formation (also called Sanjar Formation; continental conglomerates, breccias, red mudstones and siltstones; Resolutions 1977), which is only locally present and apparently constitutes the fill of rifts and small basins developed at the top of the underlying basement. It was not encountered in the investigated area. The overlying Gurud Formation, again a non-marine siliciclastic unit, represents fluvial to lacustrine environments with local development of coal deposits. It comprises the time span Toarcian to early Bajocian. The Gurud Formation, 290 to 450 m thick in the Kugitang Mountains, is overlain by the marginal- to shallow-marine siliciclastic to mixed carbonate-siliciclastic, Upper Bajocian □ Lower Bathonian Degibadam Formation (~200 m), characterized by argillaceous silt, silt, and sandstones with occasional marine fossils (ammonites, bivalves). The overlying Lower Bathonian Tangiduval Formation (~30-80 m) is difficult to differentiate from the Degibadam Formation, the major difference being a greater carbonate content in form of silty marl and calcareous and/or bioclastic sandstones. The carbonate and fossil

content increases gradually so that the boundary between the two formations is somewhat arbitrary. This is particularly true of the sections at Sangardak and Shargun. Carbonate sediments (lime mudstones, marl, and subordinate bioclastic and oncolitic floatstones) characterize the following Baysun Formation (50-225 m). According to the literature (e.g., Krymholts *et al.* 1988), the formation starts in the Late Bathonian, but based on ammonite finds the base is here regarded still Middle Bathonian, the top extending to the Lower Callovian. The succession continues with thick-bedded carbonates of the Middle Callovian – Kimmeridgian Kugitang Formation, followed by anhydrites, dolostones, limestones, and salt deposits of the Kimmeridgian – Tithonian Gaurdak Formation (approximately 1000 m), and by continental red beds of the Karabil Formation, the latter spanning the Jurassic-Cretaceous boundary.

For the Middle Callovian – Tithonian part of the succession in the northern part of the Afghan-Tajik Basin and the Uzbekistan northern margin of the neighbouring Amu Darya Basin a new, more elaborate classification scheme has been proposed, taking into account lateral facies variations within the carbonate complex and a Tithonian age for the Gaurdak evaporites (Abdullaev & Mirkamalov 1998). As this part of the succession is not the subject of the paper, we continue to use the term Kugitang Formation for the sake of simplicity.

Bio- and chronostratigraphy

The biostratigraphic zonation of the marine part of the sedimentary succession is based on ammonites, which have been investigated in great detail (e.g., Krymholts & Zakharov 1971; Mitta 2001; Mitta & Besnosov 2007). They allow a relatively detailed subdivision of the strata and can be used to define the ages of the lithostratigraphic units. Unfortunately, ammonites were found only sporadically in the field, thus only a rough correlation of sections, based largely on lithological features, could be achieved. Finds of the ammonite *Parkinsonia parkinsoni* near the base of the marine succession (Degibadam Formation) in the Iron Gate section confirmed the Late Bajocian age of the transgression in the area (see also Krymholts *et al.* 1988), and ammonites such as *Procerites* provided a Middle Bathonian age for the condensed base of the Baysun Formation. As no age-diagnostic ammonites were recorded from sections at Vuariz, Shargun, and Sangardak it cannot be evaluated whether, and if to what extent, the marine transgression and the boundaries of the lithostratigraphic units are diachronous.

The lower, non-marine parts of the sections were more difficult to date. Russian workers subdivided this part into stages based on macroscopic plant remains and pollen and spore assemblages (e.g., Gomolitzky & Lobanova 1969; Renzhina & Fokina 1978; for a summary see Vakhrameev *et al.* 1988). However, during our field work no well preserved plant remains were found that could have been used for dating the succession. The age assignments of the non-marine formations are therefore taken from Krymholts *et al.* (1988).

Several regional stages have been proposed for the Jurassic succession defined either on the basis of land plant associations and freshwater molluscs (Sandzhar and Gurud regional stages) or on ammonites (in ascending order Sarydiirmen, Baysun, Kugitang, and Gaurdak regional stages) (Krymholts *et al.* 1988).

The sections

In the following, the eleven sections are briefly described (for their precise position see Table 1). In the Kugitang Mountains two sections have been measured, one at Vandob, the other at Shalkan. In both cases the Jurassic rocks rest with angular unconformity on Palaeozoic metamorphic basement.

(1) *Shalkan section (923 m; Figs. 3, 5a).* – At Shalkan, these metamorphic rocks are overlain by up to 2 m of brown soil; clay with scattered gravel-sized rounded quartz grains and of poorly exposed silty clay. Four thick cross-bedded, conglomeratic to gravelly, coarse-grained sandstone units fining to medium-grained sandstones occur from 30-56 m and are followed by argillaceous silt with several carbonaceous levels and some fine-grained sandstone intercalations. The overlying, predominantly argillaceous-silty sediments with occasional thin sandstone interbeds are poorly exposed and contain some coal layers. From 375 to 394 m another conglomeratic to gravelly sandstone package is present. Up to 453 m it is overlain by finer-grained coarsening-upward hemi-cycles. Apart from plant and wood fragments and occasional rootlets no fossils are present. All these sediments belong to the non-marine Gurud Formation. From 453 m onwards marine trace fossils and shell fragments occur and rare ammonites indicate a Late Bajocian age of the rocks, which consist of silt alternating with hummocky cross-stratified sandstones, arranged in thickening- and coarsening-upward cycles. From 554 m onwards, the thickness of the sandstones increases and hummock cross-stratification (HCS) is replaced by large-scale trough cross-stratification. Fine-grained units

are commonly black and rarely carbonaceous. These rocks belong to the Degibadam Formation. Its boundary with the overlying Tangiduval Formation has been drawn where shell fragments, bivalves, and carbonate cement increase in abundance. A richly fossiliferous unit (729-733 m) with abundant ammonites and bivalves forms the base of the next stratigraphic unit, the Baysun Formation. The ammonites indicate a Middle Bathonian age of this condensed unit. The Baysun Formation is composed of silty marl, which is deeply weathered. It appears unfossiliferous, but fresh samples display numerous small infaunal bivalves preserved as internal moulds. Intercalated between the silty marl are nodular oncoidal float- to micritic rudstones. The boundary to the overlying carbonates of the Kugitang Formation is gradual.

(2) *Vandob section (799 m; Fig. 6).* – The Vandob section, situated 18 km SSW of Shalkan, is very similar to the Shalkan section except that the coarse-grained conglomeratic sandstones rest directly on the deeply weathered metamorphic basement. Much of the argillaceous-silty part of the Gurud Formation is overgrown. The upper part of the Degibadam Formation and the Tangiduval Formation are organized in well developed coarsening-upward cycles. The condensed base of the Baysun Formation contains, as in the Shalkan section, numerous ammonites. The silty marl of the lower half of the formation gives way in the upper half to nodular floatstones and marlstones. The find of the ammonite *Macrocephalites* two-thirds up indicates an Early Callovian age.

(3) *Panjab section (330 m; Fig. 7).* – Situated 27 km northeast of Shalkan, the well exposed Panjab section starts in the middle of the Degibadam Formation. Except for differences in thickness the section mirrors those at Vandob and Shalkan. The upper part of the Baysun Formation displays hemi-cycles characterized by increasing carbonate content (marl to marlstone or wackestone). The Lower Callovian ammonite *Macrocephalites* occurs 130 m above the base of the formation.

(4) *Dalut Mine section near the village of Toda (572 m; Fig. 8).* – The incomplete section, situated 83 km SW of the Shargun section and 35 km NE of Panjab, has been measured on the northwestern limb of a large NE-SW trending anticline. At two levels the rocks are heavily folded and faulted and the recorded thickness probably contains some error. The base of the Jurassic succession is not exposed, but the 24-m-thick basal sandstone package (Fig. 9a) most likely corresponds to the coarse siliciclastic unit overlying the basement wherever the contact

has been observed. The thickness of the Gurud Formation is comparable to that of the Kugitang sections. The formation is composed of an alternation of argillaceous silt, sandstones, and thin coal layers. Root horizons are widespread and plant fragments are ubiquitous. Only the lower 37 m of the marine Degibadam Formation could be measured. It is characterised by alternations of argillaceous silt and fine-grained sandstone, the latter displaying HCS or parallel-lamination followed by ripple lamination. The following part of the section is too steep for measuring. Moreover it is disrupted by a major fault. The total thickness of the Jurassic succession up to the Kugitang Formation is in the order of 900-950 m, taking into account information provided by the neighbouring Derbent section.

(5) *Derbent (Iron Gate) section (411 m; Fig. 10).* – The section north of Derbent at the so-called Iron Gate, situated 9 km WNW of the Dalut mine section, exposes the upper part of the Jurassic succession. The section has been measured on the western flank of a deeply cut valley which dissects a NE-SW trending anticline. The section starts close to the base of the Degibadam Formation, which consists of fine-grained siliciclastics with thin sandstone intercalations and a 45-m-thick sandstone package in the middle. The base of the Tangiduval Formation has been placed at the first limestone bed. The formation is largely organised as asymmetric coarsening-upward cycles. The top beds contain bivalves and ammonites. The boundary to the overlying Baysun Formation is sharp. The Baysun Formation is similar to that in the Kugitang Mountains, i.e. dominated by silty marl and marl with some intercalations of oncoidal floatstones and micritic rudstones. The transition to the Kugitang Formation is gradual (Fig. 5h). The Iron Gate section and the close-by Dalut Mine section together represent a complete section through the investigated succession with a thickness of approximately 935 m (Figs. 8, 10).

(6)-(7) *Shargun sections (358 m; Fig. 11).* – The coal mine north of the town Shargun lies 115 km NE of Panjab. The metamorphic basement rocks are overlain by a thin conglomeratic gravelstone followed by lenticular coarse-grained sandstone with tree trunks, wood remains, abundant plant fragments, rootlet horizons, and a 2-m-thick coal bed. From 40 m to 290 m the succession is dominated by stacked, several-m-thick sandstone packages with erosional base, large-scale trough cross-bedding, and abundant wood pieces and wood logs (Fig. 5c). Towards the top these sandstone packages become thinner and fine-grained, and occasional carbonaceous intercalations increase in thickness. The marine part of the succession is merely 64 m thick and consists of 14 m predominantly siliciclastic sediments

(Degibadam/Tangiduval Formation) followed by 50 m of fine-grained, mixed carbonate-siliciclastic sediments of the Baysun Formation. Unfortunately, no ammonites were recovered. Quite possibly, the boundaries of the formations are diachronous when compared with the sections in the Kugitang Mountains.

(8) *Sangardak section (328 m; Fig. 12).* – The section has a similar thickness as the close-by Shargun section, but coarse-grained sandstones are mainly restricted to the lower 60 m of the section, the remaining non-marine part of the succession being dominated by argillaceous silt. The marine part is twice as thick (131 m) as at Shargun (64 m), and the Baysun Formation is missing. The sandstones in the mixed carbonate-siliciclastic Tangiduval Formation are coarser than in the other sections. The base of the overlying Kugitang Formation contains, in contrast to most other sections, planar cross-bedded oo-grainstones.

(9)-(10) *Vuariz sections (84 m; Figs. 13, 14).* – Four short sections, 1.5 to 2.5 km apart, were measured north and northeast of the Vuariz village. The distance to the Dalut Mine section is 61 km. The first two sections, which strongly overlap, comprise the Gurud Formation (82 m) up to the base of the Degibadam Formation (Fig. 13a, b). The Palaeozoic basement is overlain by a thin conglomerate and a few metres of poorly exposed carbonaceous argillaceous silt followed by a 48-m-thick stack of coarse-grained, partly conglomeratic sandstones, with erosional bases. Towards the top fine-grained siliciclastics with plant debris and root horizons, which are subordinate in the lower half, dominate. Remarkable is the strongly reduced thickness of the Gurud Formation.

The transgression is indicated by trace fossils and shell concentrations. The Degibadam and Tangiduval formations cannot be differentiated and comprise only around 25 m of sandstones, bioclastic sandy siltstones and soft silt (Fig. 13c). The Baysun Formation starts with nearly 40 m of bioturbated limestones, mainly onco-floatstones, -rudstones, and fine-grained intra-packstones topped by nearly 5 m of oo-grainstones. The following approximately 50 m to the base of the Kugitang Formation have been removed by faulting. A 26-m-thick lateral equivalent of the carbonates, largely developed as peritidal packstones with birdseyes and fenestral fabrics, has been measured beyond the northeastern end of the pass at N 38°49'29.6'', E 67°11'26.3'' (Fig. 14). The following approximately 50 m up to the base of the Kugitang Formation are largely covered by scree, but are clearly composed predominantly of soft, fine-grained sediments (?marl/silty marl). The base of the Kugitang Formation

consists of 6 m of coarse-grained, partly gravelly, large-scale trough cross-bedded sandstones alternating with sandy lime mudstone beds.

Facies associations and palaeoenvironments

The investigated succession consists of continental facies in the lower part and of fully marine environments in the upper part. The transgressive surface is difficult to pinpoint sedimentologically but can be identified with the help of trace fossils. The following chapter is a brief description and discussion of the main environments. A summary can be found in Table 2.

Braided river deposits (e.g., basal parts of Vuariz, Shalkan, and Vandob sections; lower part of the Shalkan section; Fig. 15a)

Coarse-grained to gravelly or conglomeratic sandstone bodies that fine up to medium or fine grain size are composed of stacked units with convex erosional bases and lateral variations in thickness. They form packages up to 35 m in thickness and occur mainly at the base of the Jurassic succession. The degree of maturity strongly varies: In some areas (e.g., at Vandob) sand grains and pebbles consist mainly of quartz and mica flakes are common, in others the sandstones are arkosic or lithic and the pebbles consist of black chert, metamorphic rock fragments and subangular to subrounded quartz (e.g., at Shalkan, and Vuariz; Fig. 16a). Wood fragments are abundant and locally tree trunks may be found at the base of the individual units. Large-scale trough cross-stratification is pervasive. It may grade into ripple lamination in the finer-grained top parts.

The sandstones can be interpreted as the fills of amalgamated shallow braided river channels. The commonly immature nature of the sediments points to a close-by source area. The stacking pattern of the channels (e.g., at Vandob and Shargun; Fig. 5g) reflects equilibrium conditions between subsidence and deposition.

Meandering river deposits (e.g., base of Shargun section, Dalut Mine section at 154 m; Fig. 15b)

331

332 In the Gurud Formation, fine- to coarse-grained, commonly arkosic sandstones with erosional
333 base, several metres to decametres in thickness, exhibit large-scale trough cross-stratification.
334 They fine up into ripple-laminated silty sandstone or siltstone, and in some cases the top is
335 rooted. Plant debris and wood fragments are common, and wood logs occur occasionally near
336 the base of the sandstone bodies. Distinct epsilon cross-bedding is developed in some cases
337 (e.g., in the Dalut Mine section; Fig. 9b). Stacking of several-metres-thick sandstone bodies is
338 commonly seen. In the valley immediately W of the Shargun section intercalated dark-grey
339 silty clay with some indistinct siltstone beds may laterally grade into intercalations of thick
340 siltstone-sandstone beds with epsilon cross-bedding.

341 The sandstone bodies clearly are the fill of fluvial channels (Miall 1996). Epsilon
342 cross-bedded units can be interpreted as point-bar deposits produced by lateral migration of
343 the channel. The fine-grained, thinner-bedded top parts of individual units with occasional
344 rootlets correspond to levee deposits. These fluvial channels are clearly of the meandering
345 type. The lenticular fine-grained deposits that laterally grade into point-bar deposits are
346 interpreted as the fills of abandoned channels (oxbow lakes).

347

348

349 *Flood plain deposits (e.g., Dalut Mine section at 70-82 and 86-97 m; Fig. 15c)*

350

351 Dark-grey argillaceous silt and silty clay with intercalations of cm- to dm-thick siltstones and
352 fine-grained sandstones with sharp, commonly erosional base, rich in plant debris, are
353 widespread in the Gurud Formation. The sandstones exhibit large-scale trough cross-bedding
354 or current ripple-lamination and occasionally are topped by a rootlet horizon. The fine-grained
355 sediments in-between are, in some cases, highly carbonaceous and may contain thin layers of
356 coal. Rarely, strongly ferruginous, mottled, fine-sandy silt layers with rootlets form
357 conspicuous horizons. At the base of the Shalkan section (Fig. 3) brown clay with scattered
358 quartz granules fills pockets of the underlying deeply weathered metamorphic Palaeozoic
359 basement.

360 The argillaceous silt is an alluvial deposit. The sandstone/siltstone interbeds
361 correspond to overbank deposits (crevasse splays) that formed on a swampy flood plain with
362 vegetation (rootlets) that was occasionally so dense that highly carbonaceous to coaly rocks
363 resulted. Mottled ferruginous siltstones are interpreted as soil horizons on a wet flood plain. A
364 different kind of paleosol occurs at the base of the Shalkan section. The very poorly sorted

brown gravely clay is a brown soil, rich in iron, that today forms in temperate climates (e.g., Schaetzl & Anderson 2005). Together with the strongly altered basement it points to a prolonged phase of weathering on the incipient flood plain.

Swamps (e.g., Dalut Mine section at 40-47 m, 267 m, 418 m, 500 m; Shargun section at 17-19 m; Fig. 15d)

Coal layers and dark-grey to blackish, highly carbonaceous clay or silty clay, rich in plant fragments and underlain by rootlet horizons, are interpreted as swamp deposits. Commonly, such swamps formed at the margins of lakes as can be seen from their stratigraphic context (e.g., in the Dalut Mine section at 267 m), but also developed on wet flood plains (e.g., Dalut Mine section at 500 m). The thickest coal layer recorded in any of the sections was 120 cm thick.

In many of the coal layers and highly carbonaceous fine-grained siliciclastics of the Gurud Formation the plant material is, however, allochthonous. This assumption is corroborated by their occurrence within lake successions (e.g., Dalut Mine section at 318-322 m) and by a lack of rootlet horizons. Apparently, the plant material has been transported into the lakes from swampy coastal areas or has been introduced by rivers that reworked swamp deposits on the flood plain.

Lake deposits (e.g., Dalut Mine section at 24-40 m, 234-267 m, 396-429 m, Shalkan section 395-453 m, Fig. 15e, f)

Monotonous dark-grey argillaceous silt and silty clay, in some horizons strongly carbonaceous or with dm-thick coal layers, are the dominant facies types in the Gurud Formation of the Shalkan and Dalut Mine sections. The fine-grained siliciclastics are occasionally interrupted by cm- to dm-thick fine-grained sandstones that exhibit ripple lamination and may contain wood fragments. Large orange carbonate and claystone concretions occur at some levels; small ferruginous concretions are rare. A second very common facies association in these two sections are m-scale coarsening-upward cycles. They start with dark-grey argillaceous silt or silty clay and grade upward into silt, fine-sandy silt and fine-grained sandstone. Plant fragments, carbonaceous beds and thin coal layers are common. Rarely, finely interlayered bedding is developed at the base of such cycles. The silty-sandy beds commonly are ripple-laminated and the top sandstones often exhibit large-

scale trough cross-stratification and occasionally rootlets. In some cases (e.g. Shalkan section at 356 m) bedded fine-grained sandstones are parallel-laminated with sharp erosional base or display hummocky cross-stratification. Some of the large-scale cross-bedded sandstones on top of the cycles display a sharp erosional base.

The facies associations described above are best interpreted as deposits of various lake subenvironments. The monotonous fine-grained siliciclastic sediments clearly correspond to basinal parts of lakes. Thin coal layers, common plant debris, and the carbonaceous nature of some beds indicate that much plant material was introduced into the lakes which must have been surrounded by dense vegetation. The coarsening-upward sequences are progradational cycles that record shallowing of the lake from basinal to marginal environments. They also document an increase in water energy as is shown by the primary sedimentary structures. Rootlet horizons at the top of the some of the cycles indicate a transition to swampy areas. Rare HCS and parallel-laminated beds are evidence that parts of the lakes were influenced by storm-waves and storm-induced flows. These coarsening-upward successions document the development from offshore to shoreface and foreshore environments and are probably related to lacustrine delta progradation. A distinction between the two developments is difficult, if no fluvial channel is found on top of the shallowing sequence.

The size, depth, and duration of these lakes differed considerably, judging from the variable thicknesses of the lacustrine sediments. Small shallow lakes and large lakes, persisting for thousands of years, apparently existed side by side. Moreover, the common development of progradational cycles (see below) points to repeated phases of contraction and expansion of these lakes.

Following the transgression in the Late Bajocian, several marine facies associations are documented in the Degibadam, Tangiduval, and Baysun formations.

Distributary channel deposits (e.g., Iron Gate section at 97-115 m, Vandob section at 378-388 m, Shalkan section at 617-634 m; Fig. 15g)

Ten- to twenty-metres-thick packages of immature sandstone with a sharp erosional base, fining up-section from medium or coarse to a fine grain size are found in the marine Degibadam Formation of the Iron Gate (Fig. 9d top), Vandob, and Shalkan sections. Sedimentary structures change up-section from large-scale trough cross-bedding to ripple-lamination. Wood pieces are common, particularly near the base.

433 Their erosional base and fining-upward nature identify the sandstones as channel
434 deposits. At Vandob and Iron Gate they are underlain by coarsening-upward successions
435 interpreted as delta front deposits (see below). Consequently the channel deposits represent
436 distributary channels of the delta plain.

437
438 *Prodelta and delta front deposits (e.g., Iron Gate section 55-97 m, Vandob section at 370-388*
439 *m; Fig. 15h, i)*

440
441 In the case of the Iron Gate section, the coarse-grained sandstones interpreted as fill of a
442 distributary channel are underlain by six metre-scale coarsening-upward sequences grading
443 from fine-grained ripple-laminated sandstone to medium-grained large-scale trough cross-
444 bedded sandstone (Fig. 16g). In one sequence, HCS was encountered in the basal part, in
445 another sharp-based parallel-laminated sandstone beds occur in the same position. Wood
446 pieces are present in two of the cycles. Trace fossils include *Thalassinoides* and *Gyrochorte*.

447 Below these units bioturbated silty clay prevails. It contains cm- to dm-thick
448 intercalations of ripple- or parallel-laminated sandstone, spaced 1 to 2 m, with *Gyrochorte*,
449 some wood fragments, and rare ammonites.

450 The strongly bioturbated fine-grained units are interpreted as prodelta deposits which
451 are occasionally punctuated by coarser hyperpycnal flow deposits which may reflect flooding
452 events in the hinterland and a corresponding greater discharge of sediment-laden waters (e.g.,
453 Mutti *et al.* 2003). They grade upwards into stacked lower to upper delta-front cycles. The
454 increase in grain size and the change from ripple lamination to large-scale cross-bedding
455 indicates an increase in the energy level due to shallowing. In the Vandob section, the delta
456 front deposits are composed of amalgamated HCS sandstones which develop from
457 bioturbated silty fine-grained sandstone. At Shalkan, in contrast, the distributary sandstones
458 are underlain with sharp boundary by argillaceous silt, which documents a sudden lowering of
459 the base level.

460
461 *Deposits of the tide-influenced inner siliciclastic ramp (e.g., Panjab section at 24-39 m;*
462 *Vandob section at 483-494 m; Fig. 15j)*

463
464 In the Panjab section interlayered bedding is prevalent for about 15 m near the base of the
465 exposed succession. It is developed either as coarsely interlayered bedding consisting of 2- to
466 5-cm-thick ripple-laminated fine-grained sandstone beds and thin argillaceous interbeds or as

a finer variety where sandstones are 0.5-1 cm and argillaceous silt interbeds 1-2 cm in thickness. Near the top of this facies type a 50-cm-thick ripple-laminated, medium-grained sandstone occurs. It has a sharp base, contains mud clasts, and displays some lenticular bedding in the middle. Lenticular bedding and flaser bedding usually occur associated with the interlayered bedding in the Panjab and Vandob sections.

The interlayered, flaser, and lenticular bedding points to regular changes in water energy suggestive of some tidal influence (but not necessarily of intertidal conditions). The medium-grained sandstone with clay pebbles may be the submarine continuation of a tidal channel.

Protected low-energy inner ramp deposits (e.g., Shalkan section at 571-574 and 577-596 m, Vandob section at 406-452 m; Panjab section at 34-36 m; Fig. 15k)

In the upper part of the Degibadam Formation of the Kugitang Mountains dark-grey, partly bioturbated, argillaceous silt and fine-sandy silty clay predominate. At Vandob they are rich in plant fragments. Highly carbonaceous levels are also present. Intercalated between these fine-grained sediments are cm-thick fine-grained sandstone beds. In the Shalkan section they are parallel laminated and form the top of metre-scale coarsening-upward sequences that start with argillaceous silt, which grades into ripple-laminated siltstones as an intermediate facies.

The scarcity of large-scale sedimentary structures, the predominantly fine-grained sediment, and the pervasive bioturbation point to prevalent low-energy conditions. The high organic carbon content, including highly carbonaceous beds, suggests that the sediments were deposited nearshore, most likely in a protected embayment. The coarsening-upward cycles record shallowing and the intermittent influence of storm-induced flows.

Submarine dune deposits of the inner to middle siliciclastic ramp (e.g., Panjab section at 95-98.0 m, and 102.5-104 m, Vandob section at 542-545.5 m, Shalkan section at 646-648.5 m; Fig. 15l)

Dm- to m-thick, commonly bioclastic, fine- to medium-grained sandstones with large-scale cross-stratification and sharp base occur repeatedly in the Tangiduval Formation of the Panjab, Shalkan, and Vandob sections. They are commonly associated with shell debris, more rarely with pavements and lenticles of disarticulated bivalve shells, and form the upper part of coarsening-upward sequences. The top of the sandstones exhibits, in some cases, oscillation

ripples. Beds lower down in the succession may also be thoroughly bioturbated (e.g., Fig. 16c).

The sedimentary structures indicate deposition during high-energy conditions and, at the top, occasional wave influence. Abundant bioclasts and mollusc remains point to fully marine conditions. Found at the top of coarsening- and shallowing-upward cycles they are interpreted as small submarine dunes that developed on the middle to partly inner siliciclastic ramp. Alternatively, they may represent upper shoreface deposits.

Storm-wave dominated middle siliciclastic ramp deposits (e.g., Vandob section at 503-514 m, Shalkan section at 454-513 m, 524-540 m; Fig. 15m)

In the Kugitang Mountains the lower part of the marine succession is characterised by bioturbated argillaceous silt or silt with numerous intercalations of fine-grained cm- to dm-thick sandstones. The latter have a sharp base and exhibit HCS (e.g. Fig. 16b), in some cases ripple lamination. The thicker HCS beds are commonly amalgamated. Bedding planes occasionally are developed as shell pavements, whereas in the bioturbated parts scattered bivalves (e.g., *Myopholas*, *Pseudolimea*, *Pleuromya*), rare ammonites, some wood fragments, and the trace fossils *Chondrites* and *Taenidium* occur. Generally, the HCS sandstones are arranged as thickening-upward cycles.

The fossils indicate a fully marine environment. The finer-grained, high bioturbated sediment document low-energy conditions, whereas the sandstones with HCS can be interpreted as products of storm waves (e.g., Aigner 1979; Aigner & Reineck 1982). The depositional environment can therefore be classified as the middle ramp below the fair-weather wave-base.

Storm-flow influenced outer siliciclastic ramp deposits (e.g., Iron Gate section at 14-39 m, Panjab section at 4-16 m, Dalut Mine section at 552-562 m, Vandob section at 461-483 m; Fig. 15n)

A facies association composed of highly bioturbated argillaceous silt alternating with cm-thick fine-grained sandstones that exhibit ripple lamination or parallel lamination topped by ripple lamination is common in the Bajocian marine succession of southern Uzbekistan. The sandstones have a sharp base and are commonly associated with flute casts and/or tool marks. Sand-filled structures, semicircular in cross-section and often with a shell lag at the base,

535 occur isolated or at the base of the sandstone beds. Trace fossils include *Gyrochorte*,
536 *Chondrites*, *Thalassinoides*, and *Rhizocorallium irregulare*. Bivalves such as *Meleagrinella*
537 commonly form shell pavements, ammonites are rare.

538 As in the case of sandstones produced by storm-waves (see above), the parallel- and/or
539 ripple-laminated sandstones indicate brief high-energy events that episodically disturbed a
540 generally low-energy environment. The sharp base with flute casts and the semi-circular
541 sandstones are indicative of erosional events produced by a high flow regime, whereas normal
542 grading and the change from parallel to ripple lamination within single beds is evidence of
543 flow deceleration. The semi-circular sandstones are interpreted as gutter casts, i.e. narrow,
544 elongated erosional structures (Aigner 1982). All these features are characteristic of the outer
545 ramp under the episodic influence of storm-induced offshore-directed currents that originate
546 after the waning of storms (e.g., Aigner & Reineck 1982). The fine-grained bioturbated
547 background sediment, in contrast, indicates low energy conditions.

548
549 *Low-energy mixed carbonate-siliciclastic outer ramp deposits (e.g., Shalkan section at 732-*
550 *830 m, Vandob section at 580-696 m, Panjab section at 142-207 m; Fig. 15o)*

551
552 The lower part of the Baysun Formation in all sections is characterized by monotonous fine-
553 grained, partly shaley, partly bioturbated silty marl. Poorly preserved small bivalves such as
554 *Corbulomima* and *Nicaniella* occur scattered or concentrated in thin bands.

555 The sediments clearly belong to the low-energy outer ramp. The silt has been most
556 likely introduced by suspension clouds, possibly in connection with storms, or by bed-load
557 transport in form of thin laminae and streaks which subsequently were destroyed by
558 bioturbation. The thin shell concentrations testify that occasionally winnowing took place,
559 probably produced by distal storm-induced flows.

560
561 *Condensed mixed carbonate-siliciclastic outer ramp deposits (e.g., Vandob section at 573-*
562 *579 m, Shalkan section at 729-733 m, Panjab section at 141-144 m; Fig. 15p)*

563
564 At the base of the Baysun Formation, several metres of strongly bioturbated, rubbly, partly
565 nodular, fine-sandy bio-wacke- to biofloatstone with interbeds of marly silt are developed in
566 the Kugitang Mountains and at Panjab. The beds are highly fossiliferous with common
567 bivalves (e.g., *Entolium*, *Pleuromya*, *Ctenostreon*, large *Liostrea*, and *Bucardiomya*),
568 ammonites (mainly large *Procerites*), brachiopods, and some gastropods (e.g., *Obornella*).

Many of the bivalves are articulated and some of the burrowing bivalves are preserved in growth position.

Considering that ammonites are generally rare in the succession, the abundant ammonites and in situ preserved benthic faunal elements point to low rates of sedimentation persisting for quite some time. This increased the proportion of biogenic hardparts in the sediment. The facies is clearly condensed compared to the sediments below and above, but stratigraphic condensation i.e., mixing of taxa belonging to different zones or subzones, has not been observed. Both sediment and taphonomic features indicate a low-energy outer ramp environment.

Low-energy marl and mud- to wacke-/floatstones of the outer carbonate ramp (e.g., Vandob section at 696-799 m, Iron Gate section at 280-409 m, Panjab section at 207-330 m; Fig. 15q)

This facies association is similar to the last one except that the silt fraction is negligible. Bioturbation is pervasive and primary sedimentary structures are absent. The wacke- to floatstones are bioclastic and commonly contain oncoids (Fig. 16e, f). Occasional packstone beds consist mainly of bioclasts. The carbonates commonly have a nodular texture. Trace fossils include *Thalassinoides*, and body fossils occasional bivalves (e.g., *Pleuromya*, *Protocardia*, *Corbulomima*, oysters), rare gastropods (*Pseudomelania*), corals, and ammonites (*Macrocephalites*).

Occasionally, bio-onco-rudstones are intercalated within the succession (e.g., Fig. 16d). As their matrix is, in most cases, micritic and as they exhibit a nodular texture it is likely that they formed in-situ on the outer ramp. In contrast, rare, thin beds of rudstone with sparitic matrix and small coated grains or oyster fragments most likely were introduced from shallower areas of the ramp by storms.

Low-energy, peritidal lagoonal carbonates (Vuariz section IV; Fig. 14)

Sediments of peritidal origin are rare in the investigated succession. They have been encountered only in the Baysun Formation of Vuariz. The sediments consist of very fine-grained packstones, rarely of carbonate mudstones, with scattered birdseyes and laminoid fenestral fabrics (Fig. 14). Repeatedly, cm-thick, irregularly laminated bands are intercalated

as are rare beds of oncoid rudstones. Scattered gastropods are the only faunal element. The birdseye limestones develop from onco-floatstones embedded in a fine packstone matrix.

Birdseyes, laminoid fenestral fabrics, and fine, irregular lamination are typical of algal origin and generally interpreted as having formed in the intertidal to very shallow subtidal zone (e.g., Shinn 1983; Flügel 2010). At Vuariz they are the lateral equivalent of ooid grainstones (Vuariz section III; Fig. 13c). This suggests that they formed in a low-energy lagoonal environment protected by ooid bars. Their occurrence in the Baysun Formation, which at most other sections represents offshore environments, supports the interpretation of the Vuariz area as being close to the basin margin.

Macroflora and benthic macrofauna

Several land plant associations have been recognised in the non-marine part of the succession, but no identifiable macroflora has been encountered during the field work. Thus, Gomolitzky (in Shayakubov & Dalimov 1998) recognised the Kamyshbash Flora (with e.g., *Osmundopsis*, *Phlebopteris*, *Dictyophyllum*, *Thaumatopteris*, and *Nilssonina*) and the Shurab Flora (documented by *Neocalamites*, *Marattiopsis*, *Coniopteris*, *Phlebopteris*, *Clathropteris*, *Dictyophyllum*, *Hausmannia*, *Cladophlebis*, and *Anomozamites gracilis*) in the Lower Jurassic Sandzhar Formation and another association with *Equisetum*, *Mazattina*, *Coniopteris*, *Cladophlebis*, *Ptilophyllum*, and *Nilssonina* in the Gurud Formation. According to Vakhrameev *et al.* (1988) floral associations allow to differentiate between the Hettangian-Sinemurian, Toarcian, Aalenian, Bajocian, and Bathonian stages. These associations have been used extensively to date the non-marine rocks.

No benthic macrofauna has been found in the non-marine part, in which Martinson and Mikulina (in Shayakubov & Dalimov 1998) recorded molluscan assemblages characterized by the bivalves *Unio*, *Ferganoconcha*, and *Sibireconcha* (Kim *et al.* 2007). In the marine part of the succession bivalves are common at some levels. In the Upper Bajocian they commonly form pavements of disarticulated valves, common elements being the infaunal *Myopholas* and the epibyssate *Camptonectes*. Bivalves increase in abundance in the Tangiduval Formation and particularly in the condensed basal beds of the Baysun Formation. Common taxa include *Pholadomya* (*Bucardiomya*), *Pleuromya*, *Homomya*, *Inoperna*, *Integricardium*, *Protocardia*, *Actinostreon*, *Liostrea*, and *Nanogyra*. These genera are typical elements of the benthic macrofauna occurring in shallow-marine environments of the Jurassic epicontinental seas from western and eastern Europe to Iran. Gastropods (e.g., *Obornella*) are comparatively rare as are

brachiopods, the latter occurring mainly in the condensed base of the Baysun Formation where they are represented by at least five genera.

At a first glance, the marls and silty marls of the Baysun Formation appear to be devoid of fossils, but in fresh material small infaunal bivalves such as *Corbulomima* and *Nicaniella* are common at numerous levels as poorly preserved composite or external moulds. They constitute typical softground assemblages, well known from numerous fine-grained Jurassic successions elsewhere (e.g., Fürsich 1977; Fürsich & Werner 1986; Fürsich *et al.* 2004). As the percentage of endemic faunal elements appears to be low, the Amu Darya and Afghan-Tajik basins appear to have been well connected with other shelf seas situated on the southern margin of the Turan Platform.

Cycles

As has been mentioned in the facies descriptions, the various facies are commonly organised into cycles. These cycles are highly asymmetric and represent either thickening-/coarsening-upward cycles or fining-/thinning-upwards sequences.

Fluvial cycles (Fig. 17a, b)

Fining-upward cycles are nearly exclusively developed in the non-marine part of the succession. They start with fine-to coarse-grained, large-scale trough cross-stratified sandstones, which may be gravelly or pebbly, and exhibit an erosional base. Up-section they fine to ripple-laminated sandstone or siltstone and, finally, to argillaceous silt.

These cycles can be interpreted as classical fluvial cycles, the basal sandstone representing channel deposits which fine upwards into levee deposits, which may be rooted, and into fine-grained sediments of the flood plain. Commonly these cycles are stacked on top of each other and the fine-grained parts often have been cannibalized by the next channel generation (e.g., in the Shargun section at 0-32 m and the Vandob section at 0-12 m). This applies particularly to braided river channels as at Vandob, but is also seen in the point-bar deposits composing the lower 32 m of the Shargun section. In the latter case, the flood plain must have been relatively narrow so that laterally migrating channels repeatedly cut into older channel deposits.

Progradational lacustrine cycles (Fig. 17 c, d)

Coarsening- and thickening-upward cycles are widespread in the lacustrine successions of the Gurud Formation. Starting with argillaceous silt to silty clay, these sediments are followed by intercalations of thin ripple-laminated siltstone to fine-grained sandstone beds which thicken upwards into m-thick fine-grained sandstone, the top of which may be rooted and followed by coal. In some cases, the latter is overlain by large-scale trough cross-bedded fine- to medium-grained sandstones with erosional base.

These cycles indicate a shallowing of the lake, commonly caused by progradation of small deltas. This is confirmed where the top sandstone is a lenticular deposit, which can be interpreted as a distributary channel. In other cases, the shallowing was a result of lacustrine coastline progradation and led to the development of swamps as is demonstrated by root horizons and/or coal layers. The fact that these lacustrine progradational cycles are often only a few metres thick and alternate with fluvial channel and flood plain deposits indicates that most of the lakes were shallow and of limited extent and duration.

Marine deltaic cycles (Fig. 17e)

Large-scale, decametre-thick thickening- and coarsening-upward cycles are comparatively rare and restricted to the Degibadam Formation (e.g., in the Iron Gate and Vandob sections). They start with bioturbated silty clay to fine-sandy silt, followed by ripple-laminated, parallel-laminated or hummocky to large-scale trough cross-stratified sandstones. The latter are cut by distinctly incised large-scale trough cross-bedded medium- to coarse-grained sandstones, which in the case of the Vandob example contain large wood fragments. In the case of the Iron Gate section, this nearly 20-m-thick sandstone body fines upwards into ripple-laminated fine-grained sandstones (Fig. 20).

The described successions are classical delta cycles (e.g., Reading & Collinson 1996), starting with bioturbated prodelta deposits which are replaced up-section by delta-front sandstones, partly under storm-wave influence and end with large distributary channels. In the Iron Gate section (Fig. 10 at 70-96 m) several delta-front sandstone cycles are stacked on top of each other recording either autocyclic switching of the position of the nearby distributary channel or small-scale sea-level fluctuations.

Progradational cycles of the storm-wave influenced ramp (Fig. 17f)

Much of the Degibadam Formation is composed of cycles which are usually a few metres in thickness and start with strongly bioturbated silty clay to silt with sporadic intercalations of cm-thick HCS sandstones. These sandstones thicken up-section and become more common. The top bed often is a dm- to m-thick fine-grained sandstone composed of amalgamated HCS beds. Modifications of this cycle type consist of bioturbated silt coarsening-upward into fine-grained sandstone with only the top bed exhibiting HCS (e.g., Vandob section at 296-302 m and 337-370 m).

The widespread hummocky cross-stratification indicates that these cycles developed on the storm-wave influenced middle ramp. The increase in grain size, bed thickness, and abundance of HCS beds up-section either record shallowing and a shift of the depositional environment towards the inner part of the middle ramp or else increasing storm intensity, in this case being a climatic signal and not necessarily involving changes in relative sea level (resulting from local vertical movements due to tectonics and from eustasy). However, even changes in relative sea level may be ultimately climatically controlled in shallow-water areas by greater erosion and run-off during more humid phases.

Cycles where only the top part exhibits HCS, the rest being thoroughly bioturbated, probably represent the outer middle ramp close to the storm wave-base, where much evidence of storm-wave sedimentation was subsequently destroyed by bioturbation.

Cycles of the outer to middle siliciclastic ramp (Fig. 17g)

Metre-scale cycles composed of bioturbated argillaceous silt which grades into bioturbated to ripple-laminated fine-grained sandstone and end with large-scale trough cross-bedded sandstone occur commonly in the Tangiduval Formation. Bivalves and brachiopods may occur in the bioturbated parts, while in the cross-bedded top part shell debris prevails.

The cycles reflect an increase in the energy level, most likely in connection with shallowing. The cross-bedded top unit is interpreted as megaripples or small dunes, which may have migrated across the ramp during times of elevated water energy such as storms.

Cycles of the storm-flow dominated outer siliciclastic ramp (Fig. 17h)

Cycles of the siliciclastic outer ramp consist mainly of bioturbated argillaceous silt with occasional intercalations of 2-5 cm thick sharp-based ripple-laminated fine-grained sandstones. Towards the top, the density of the sandstone intercalations increases and the top

sandstone bed may reach 10 cm or more in thickness. Occasionally the sandstones represent couplets whereby a parallel-laminated lower part is overlain by a ripple-laminated upper part. The lower surface of the sandstones exhibits flute casts and tool marks. In some cases, gutter casts are associated with the sandstones.

The sedimentary structures and lower surface features are indicative of short-lived high velocity currents produced by storm processes, which transport sand in an offshore direction (e.g., Walker & Plint 1992). The increase in thickness and density of the sandstone beds reflects increasing storm intensity which most likely is related to shallowing but as discussed above might also be due to climatic changes. As HCS is not encountered, an outer ramp position of the cycles is envisaged.

Cycles of the outer carbonate ramp (Fig. 17i, j)

Cycles are also developed in the fine-grained mixed carbonate-siliciclastic part of the succession (Baysun Formation). They are several decimetres to metres in thickness and start with marl or silty marl, commonly shaley but also containing some winnowed pavements of small infaunal bivalves. Towards the top of the cycles the carbonate content increases, which is documented by bioturbated carbonate mudstones to bio-wackestones and onco-floatstones, commonly of a nodular texture.

These cycles are characterized by directed changes in the carbonate-clay ratio. They are interpreted as reflecting a decrease in the input of fine-grained siliciclastic material. This may have been brought about by an increasing distance of the sediment source and thus would correspond to a deepening, assuming that carbonate production remained more or less constant. The cycles can, however, be also explained to reflect shallowing, assuming that this led to increased carbonate production. The latter view is favoured due to the widespread occurrence of microbial oncoids, which are never present in the marls and which are evidence that the depositional environment was at least in the lower part of the photic zone. As in the case of some other cycles discussed above, an alternative explanation involving a reduced terrigenous input due to climatic changes is also feasible. The latter alternative would not require changes in water depth.

Discussion

Lateral and temporal facies pattern (Fig. 18)

The study area comprises only the northwestern part of the Afghan–Tadjik Basin. In this area, the greatest thickness of the Lower Jurassic – Lower Callovian succession is found in the Kugitang Mountains with 924 m (Shalkan section), the smallest at Sangardak (328 m), although at Vuariz, where only part of the marine succession could be measured (the rest could just be estimated), it is even considerably less (probably around 200-210 m). Palaeogeographic facies maps have been produced by Egamberdiev and Ishniyazov (1990). Their facies interpretations are, however, not always supported by our data.

Gurud Formation. The non-marine part of the succession reaches 453 m at Shalkan as opposed to 290 m at Vandob, situated only 18 km further SSE. At the Dalut Mine near Baysun (Fig. 1) the thickness of the formation is 534 m, although this figure may not be quite correct as the section is disturbed by folding and faulting at two levels. Towards the border with Tajikistan at Shargun Mine the thickness of the formation is 290 m and at Vuariz a mere 88 m. These figures suggest that the Palaeozoic basement exhibited a considerable relief and that the age of the lowest Jurassic sediments may differ considerably between the various areas. The facies pattern in the Kugitang Mountains and at the Dalut Mine is very similar: Alternations of fluvial sandstones, fine-grained flood plain deposits, thin coal seams indicative of swamps, and argillaceous-silty, often organic-rich, to sandy lacustrine deposits. Many of these lakes appear to have been small and to have become infilled rapidly, but the thick, uniform silty clay succession at Shalkan and probably also at Vandob must represent a large and deep lake persisting for a considerable period of time. At Shargun and Vuariz, in contrast, the Gurud Formation is strongly dominated by coarse-grained to gravelly fluvial channel deposits with fine-grained floodplain deposits being of only minor importance. Where the latter occur, they also contain coal beds, but lake deposits are rare.

The thickness and facies variations indicate that the area of the northern part of the SW Gissar Mountains was a high area during the Early and early Middle Jurassic where erosion took place at the time when further south, in the Kugitang Mountains, the Palaeozoic relief became already filled with sediment. At Vuariz and Shargun a short distance to the source area is also indicated by the coarse, highly immature sediment. The presence of meandering river deposits at Shargun as opposed to braided stream deposits at Vuariz and the very small thickness of the formation at the latter locality suggest that the Vuariz area was very close to the sediment source.

807

808 *Degibadam and Tangiduval formations.* At the top of the Gurud Formation the morphological
809 relief appears to have largely been levelled as the change to marine conditions was more or
810 less synchronous across the study area, from the Kugitang Mountains to the Dalut Mine and
811 the Iron Gate where Late Bajocian ammonites were found very close to the transgressive
812 surface. At the remaining sections either no ammonites have been recorded (e.g., Vuariz,
813 Shargun) or the transgressive surface is not exposed (e.g., at Panjab).

814 The thickness of the two formations is fairly uniform (276-284 m) except at Sangardak
815 (143 m) and Shargun (14 m) where it is greatly reduced. In most of the study area the
816 sedimentation pattern was mosaic, oscillating between partly tidal-influenced, partly high-
817 energy inner ramp deposits, storm-wave influenced middle ramp deposits, and storm-flow
818 dominated outer ramp deposits. The common arrangement of the sediments in coarsening-
819 upward parasequences indicates that this sedimentation pattern was governed by changes in
820 relative sea level and probably also by cyclic changes in climate. From the Kugitang
821 Mountains to the Iron Gate the carbonate content of the sediment increases towards the top as
822 does the amount of molluscs, mainly bivalves.

823

824 *Baysun Formation.* The thickness of the Baysun Formation from Vandob to Panjab is similar
825 (195-226 m), but at Iron Gate it is reduced to 130 m and at Shargun to 51 m,. The fairly
826 uniform sediment (marl or silty marl with intercalations of carbonate mud- and wackestones,
827 the latter increasing towards the top) continues the trend of strong reduction of even fine-
828 grained terrigenous input towards the top. In parts of the formation cycles recording an
829 increase in carbonate are developed which most likely reflect shallowing. At present it is not
830 clear how the strongly reduced Baysun Formation at Shargun should be explained. Due to the
831 lack of age-diagnostic fossils no statement can be made whether the boundaries of the
832 formation are isochronous or diachronous when compared with the remaining sections.
833 Moreover at close-by Sangardak, a fine-grained mixed carbonate-siliciclastic succession
834 resembling the Baysun Formation below the massive walls of the Kugitang Formation is
835 repeatedly interrupted by intercalations of medium- to coarse-grained ripple-laminated to
836 large-scale trough cross-bedded quartz sandstones. The latter feature points to a close-by
837 source area and a steep bathymetric gradient, underpinning that we are adjacent to a land area.
838 This view is corroborated by the fact that also in the basal part of the overlying Kugitang
839 Formation sandy intercalations are common and the carbonate microfacies (including oo-
840 grainstones) and sedimentary structures are indicative of a high energy setting (pers. comm.

R. Bourillot, Dec. 2013). Similar features can be seen at Vuariz. Oo-grainstone intercalations between marl and wackestones in the Baysun Formation at Vuariz and Shargun point to partly shallow-water environments. At Vuariz, oo-grainstones and packstones, interpreted as high-energy bars, are laterally replaced by algal limestones with birdseyes and fenestral fabrics (Fig. 14), which are interpreted as representing lagoonal deposits of peritidal origin. Despite these local differences in facies all localities show a gradual transition to the overlying thick-bedded limestones of the Kugitang Formation. In the Kugitang Mountains this transition is characterised by the complete lack of terrigenous input into the basin.

Palaeoenvironmental evolution of the northwestern Afghan-Tajik Basin: Interplay of tectonics, eustatic sea-level changes, and climate (Fig. 19)

The evolution of the northwestern Afghan-Tajik Basin during the Jurassic has been shaped mainly by tectonics, subsidence, eustatic sea-level changes, and climate. Extensional tectonics (?back-arc rifting; Brookfield & Hashmat 2001) starting in the Late Permian–Triassic was responsible for the formation of the basin (Ulmishek 2004; Klett *et al.* 2006), which was apparently subdivided into a number of grabens and horsts. No Triassic sedimentary rocks have been encountered in the study area (see also Dzhililov *et al.* 1982) and sedimentation appears to have started only in the Toarcian on the northern margin of the basin. The basement consists mainly of Palaeozoic metamorphic rocks. Judging from the distinct differences in thickness of the non-marine succession between some of the sections a considerable relief must have existed during the Early Jurassic; consequently, the base of the succession most likely is highly diachronous, although this cannot be proven by index fossils.

Non-marine stage. During the Late Early Jurassic erosion of elevated areas produced plenty of sediment, and low-lying areas were filled with deposits of braided or meandering river. The coarse-grained, highly immature sediment points to short transport distances. The stacking of fluvial channels, a common feature in the lower part of the non-marine succession, can be explained by relatively narrow river plains. In the Kugitang and Baysun areas levelling of the relief must have occurred comparatively soon, as the mean grain size decreased distinctly after a few tens of metres as did the sandstone-shale ratio. Up to the Early Bajocian extensive flood plains existed which were dotted with lakes. Some of these lakes were apparently of considerable size and duration, others only short-lived. The flood plains were also crossed by

875 numerous streams, which commonly emptied into lakes where they built small deltas.
876 Swampy areas developed on the flood plain and especially at the margins of the lakes. The
877 dark-grained, organic-rich lake sediments, common root horizons, carbonaceous silt and coal
878 layers, and the ubiquitous plant and wood remains point to the presence of a dense vegetation
879 and consequently to a fairly humid climate. Subsidence and rate of sediment accumulation
880 appear to have been close to equilibrium. The cyclic nature of many lake deposits is the result
881 of lacustrine delta or shoreline progradation.

882 The comparatively thin non-marine successions at Shargun, Sangardak and especially
883 at Vuariz with their high sandstone-shale ratio suggest that sedimentation in these areas
884 started much later and that the sediment source was very close. Most likely, the central parts
885 of the Gissar Mountains were the main source area for the sediments delivered to the Baysun
886 and Kugitang mountains.

887
888 *Marine stage.* The sea invaded the area in the Late Bajocian. Evidence are the presence of
889 marine shells and trace fossils and finds of the ammonite *Parkinsonia* close to the lowermost
890 marine beds. As nowhere a transgressive conglomerate is developed and the transgressive
891 surface is very inconspicuous, a flat coastal plain must have existed at the time of
892 transgression. Wherever ammonite evidence is available, it suggests that flooding of the basin
893 took place at roughly the same time. A distinct transgression at this point in time is also
894 recorded from neighbouring basins such as the Kashafrud Basin in the Kopet Dagh area and
895 the southern margin of the South Caspian Basin (i.e., the Alborz Mountains) (Fürsich *et al.*
896 2009a). As the global sea-level started to rise in the late Early Bajocian (Hallam 2001), it is
897 tempting to relate the transgression to this eustatic signal. However, the two events are not
898 strictly synchronous. Moreover, the transgression in the Alborz area and in the Kopet Dagh
899 has been explained by Fürsich *et al.* (2009b) by a distinct subsidence pulse caused by the
900 onset of seafloor spreading in the South Caspian Basin. Similarly, in the Afghan-Tajik Basin
901 increased subsidence is thought to be the main factor causing the change to marine conditions
902 in the basin as well as in the Amu Darya Basin (Brunet *et al.* 201X).

903 The marine sediments were initially purely siliciclastic and range from argillaceous
904 silt to fine-grained sandstone. Abundant HCS and parallel-/ripple-laminated sandstones and
905 gutter casts indicate that for long time depositional environments corresponded to the storm-
906 wave and storm-flow influenced ramp. Commonly the sediments are organised in thickening-
907 and coarsening-upward parasequences which indicate to shallowing and thus correspond to
908 small-scale relative sea-level fluctuations. These parasequences may either reflect a eustatic

909 signal or else climatic conditions which oscillated between dryer and wetter periods. During
910 the latter, sediment influx into the basin was higher and the storm intensity greater. The
911 greater storm intensity might have contributed to disperse coarser-grained coastal sediments
912 across the ramp.

913 Within the Upper Bajocian Degibadam Formation a thick deltaic complex is
914 developed in several sections (Vandob, Shalkan, Iron Gate, to a lesser extent also at Panjab).
915 These deltaic sandstones are most likely not coeval but are part of a succession with an inner
916 ramp character (shown e.g., by tidal influence and allochthonous coal layers). Apparently, at
917 this time the sedimentation rate exceeded subsidence on the margins of the basin resulting in
918 progradation of the shoreline.

919 The increasing carbonate content in the Tangiduval Formation does not go hand in
920 hand with a decreasing grain size of the siliciclastic material. It therefore appears that the
921 mixed carbonate-siliciclastic sediment is above all the result of increased carbonate
922 production and only secondarily due to a reduction in terrigenous input. Both features point to
923 a gradual change in climate from humid to increasingly drier and warmer conditions. The
924 input of siliciclastic material, however, decreased distinctly from the Middle Bathonian
925 onwards. This led to the formation of a several-metres-thick condensed unit at the base of the
926 Baysun Formation. This is the only level within the investigated time slice where ammonites
927 are common, associated with abundant benthic elements such as bivalves, gastropods and
928 brachiopods. During the Late Bathonian the percentage of silt gradually decreased so that by
929 the Early Callovian only clay-sized terrigenous material reached the southern part of the study
930 area which occupied an outer ramp to basinal position. The occurrence of concentrations of
931 small infaunal bivalves suggests that the sea floor was intermittently winnowed by currents.
932 The presence of bio-floatstones and, more rarely, bio-rudstones in a cyclical manner points to
933 phases during which the input of terrigenous fines ceased completely. The shell debris that
934 abounds in some of these carbonates is clearly of shallow-water origin and is commonly
935 associated with oncoids. Thus the depositional environment was within the photic zone. As
936 has been argued above, climatic changes are the most plausible cause for these carbonate
937 cycles.

938 The Baysun Formation at Sangardak and Shargun differed not only in a reduced
939 thickness from the remaining localities but also by intercalations of medium- to coarse-
940 grained quartz sandstones in the silty marl. The sharp base, sedimentary structures such as
941 ripple lamination and large-scale cross-bedding, and associated trace fossils (*Ophiomorpha*)
942 at Sangardak indicate episodic influx from a very nearby source area and a considerable relief.

As this influx is very sudden, the most likely explanation is a tectonic origin that led to uplift of a close-by land area. At Vuariz, in turn, the basin was considerably shallower leading to the establishment of high-energy ooid bars and peritidal carbonate flats. Intercalations of coarse-grained sandstones at the base of Kugitang Formation are interpreted in a similar way as at Sangardak.

By Middle Callovian times, the terrigenous influx had ceased completely. As result a carbonate regime became established across the study area. In most areas, the thick-bedded limestones of the Kugitang Formation record low to moderate energy conditions below the fair-weather wave-base which persisted until the Kimmeridgian, as subsidence and rate of sedimentation continued to be close to equilibrium.

Sequence stratigraphic aspects (Fig. 20)

Both the marine and non-marine part of the succession exhibit a pronounced cyclicity. In the non-marine part, this cyclicity is documented mainly by progradational lacustrine cycles which might be partly autocyclic, partly reflecting changes in base level. As there is, however, at present only a very coarse biostratigraphic control of the succession and the fine-grained lacustrine succession in the Kugitang Mountains is only partly exposed no attempt at a sequence stratigraphic interpretation is made.

In the marine succession two 3rd-order sequences spanning the Late Bajocian to Early Callovian time interval can be recognised. They are very well seen in the Iron Gate section (Fig. 20), although the transgressive systems tract (TST) of the lower sequence is missing. It is represented in the Shalkan and Vandob sections by storm-influenced ramp sediments. The maximum flooding zone (MFZ) is represented by bioturbated argillaceous silt. The highstand systems tract (HST) starts again with storm-influenced ramp deposits, which grade into prodelta, delta-front, and delta-top sediments (Iron Gate), the latter characterised by being fine-grained and often carbonaceous with minor coal beds or exhibiting tidal influence. The TST of the second sequence more or less coincides with the base of the Tangidival Formation and typically consists of sandy sediments with a calcareous matrix and common shell debris and oyster shells. The MFZ is a several-metres-thick condensed unit, rich in ammonites and benthic macrofauna and forms the base of the Baysun Formation. The HST comprises the sediments of the Kugitang Formation. In contrast to what would be expected the terrigenous input decreases towards the top. This, however, does not reflect increasing distance from the shoreline but is the result of the distinct change to a more arid climate (see below). The base

of the next sequence corresponds to the onset of a large carbonate ramp system (Kugitang Formation), which is studied in detail in a companion project (Bourillot pers. comm.; Carmeille *et al.* 2014).

As has been shown above, the 3-rd order sequences are composed of numerous parasequences. Most likely, higher-order sequences may also be discernable in some cases, but a more detailed analysis is beyond the scope of this paper.

Tectonics, sea-level fluctuations, and climate as driving mechanisms of the sedimentation pattern

The main factors for the formation of the Afghan-Tajik Basin were extensional tectonics and resulting subsidence (Brookfield & Hashmat 2001; Ulmishek 2004). Differential uplift due to block faulting influenced the sedimentation pattern as it created basins and uplifted areas, the former receiving the sediment eroded from the latter. This setting must have created a mosaic sediment pattern with areas close to horsts receiving coarser sediment than areas further away. Apart from Vuariz and Shargun-Sangardak the study area must have occupied a relatively basinal position as basement rocks are nowhere overlain by alluvial fan deposits but either by paleosol or braided river deposits. Moreover, soon after deposition of the initial sandstones fine-grained lake and flood plain deposits became conspicuous elements indicating little relief. Tectonic activity appears to have been restricted to the major fault systems and affecting sedimentation within the basin mainly by changes in the supply of coarser siliciclastic material. A tectonic influence, documented by an angular unconformity, apparently affected the area of Sangardak-Shargun somewhere in the Callovian (Fig. 9h). This unconformity is developed between the Baysun and the Kugitang Formation and can be explained by slight tilting of a fault block. How much sediment has been eroded prior to deposition of the carbonates of the Kugitang Formation cannot be reconstructed due to the insufficient stratigraphic control. Differential tectonic uplift is also documented by the thickness differences of the marine part of the succession which changed from >400 m at the Iron Gate to 130 m at Sangardak and to 65 m at Shargun along a distance of 90 km.

Several factors appear to have shaped the overall basin development. According to Hardenbol *et al.* (1998) the peak of a transgressive-regressive megacycle occurred in the Late Bajocian. This major sea-level rise probably contributed to the flooding of the basin to some extent. In addition, the change to marine conditions could also have been caused by active subsidence or else by a general reduction of sediment input into the basin caused by an

1011 increasingly lower relief of the hinterland and less humid conditions. A major change in
1012 climate towards drier and possibly warmer conditions is indicated by the change from
1013 siliciclastic to carbonate sedimentation from the Early to the late Middle Jurassic. This trend
1014 to increasing aridity continues into the Kimmeridgian and Tithonian when widespread
1015 evaporites and red beds dominated the sedimentation pattern.

1016 Controversial is the origin of the numerous parasequences that compose much of the
1017 rock succession. In the marine environments they correspond to relative changes in sea level
1018 which could be eustatic-, tectonic- or else climatic-controlled. As no clear pattern is visible
1019 that allows grouping these parasequences into higher hierarchy cycles a climatic control is
1020 thought to be more likely. In the non-marine part of the succession, in contrast, the fining-
1021 upward cycles developed on the flood plains and the progradational lacustrine cycles are
1022 thought to be largely the result of autocyclic processes but probably steered by an underlying
1023 climatic pattern that regulated the sediment supply.

1024 In conclusion, the Jurassic fill of the North Afghan-Tajik Basin reflects the interplay
1025 of extensional tectonics creating a syn-rift subsidence, a subsequent more regular thermal
1026 subsidence, eustatic sea-level changes, and climate, whereby the importance of the various
1027 factors varied through time.

1029 *Comparison with sedimentary basins in northern Iran*

1031 In order to put the Jurassic history of the investigated northwestern part of the Afghan-Tajik
1032 Basin into a broader perspective, it is compared with the Jurassic history of neighbouring
1033 basins. For this reason, the geological development of two sedimentary basins in northern
1034 Iran, the Kashafrud Basin (Kopet Dag) and the southern passive margin of the South
1035 Caspian Basin (Alborz Mountains), is briefly commented upon (Fig. 21).

1036 In the southern Alborz Mountains, marine conditions became established in some
1037 areas as early as the Hettangian (Fürsich *et al.* 2009a). In the Early Jurassic Alasht Formation
1038 and in the Early Bajocian Dansirit Formation terrestrial environments with lakes, fluvial
1039 systems and widespread coal swamps similar to those in the Afghan-Tajik Basin prevailed.

1040 In both basins a pronounced transgression took place in the Late Bajocian following
1041 the Mid Cimmerian tectonic event in the Early Bajocian (Fürsich *et al.* 2009a, b; Taheri *et al.*
1042 2009). In the case of the Alborz Mountains the origin of this transgression has been explained
1043 by these authors as related to the onset of sea-floor spreading in the South Caspian Basin. At
1044 the same time rifting, most likely related to Neotethys back-arc rifting, started in the Kopet

Dagh area and initiated the Kashafrud Basin, which has been interpreted as the eastward extension of the South Caspian Basin (Brunet *et al.* 2003, 2007; Taheri *et al.* 2009). In both basins siliciclastic sediments prevailed until they were gradually replaced by carbonates. This replacement started in the Kashafrud Basin in the Callovian with fine-grained mixed carbonate-siliciclastics of the Chaman Bid Formation and continued into the Late Jurassic with the establishment of a large carbonate platform system, the Mozduran Formation.

On the southern passive margin of the South Caspian Basin, marine siliciclastic sediments overlying the Mid-Cimmerian unconformity are usually only a few metres thick, except in the eastern Alborz where the so-called Bashkalateh Formation (Afshar-Harb 1994), a lateral equivalent of the Kashafrud Formation of the Kopet Dag (Seyed-Emami *et al.* 2001), represents a largely fine-grained deep-marine environment with turbiditic intercalations. The change to a carbonate regime started already in Late Bajocian times, as is indicated by the silty marls and marls of the Dalichai Formation. Initially representing basinal sediments these marls change up-section to allodapic carbonates of the slope and finally to the shallow-water platform of the Callovian–Tithonian Lar Formation. A similar change from fine-grained mixed carbonate-siliciclastic sediments to shallow-water carbonates occurs also in the Binalud Mountains of north-eastern Iran (pers. obs.). Moreover, the widespread replacement of siliciclastic sediments by carbonates towards the end of the Middle Jurassic can also be observed on the Tabas and Lut blocks of the Central-East Iranian microcontinent where the silty to marly Bathonian to Lower Callovian Baghamshah Formation grades up-section into the Upper Callovian to Oxfordian Esfandiar Limestone Formation (Wilmsen *et al.* 2009). As in the Afghan-Tajik Basin, the carbonates in the Iranian basins are generally followed by red beds and evaporites towards the end of the Jurassic.

The replacement of siliciclastic sediments by carbonates is therefore a widespread feature and occurred not only in the Afghan-Tajik Basin as well as the Amu Darya Basin but also in various basins of Iran. This strongly suggests that the change in sedimentation pattern is due to a regional change towards more arid conditions.

In the sedimentary basins east of the Afghan-Tajik Basin, e.g. in southern Kyrgyzstan, the situation is different: There, non-marine siliciclastic rocks similar to those of the Gurud Formation characterize the complete Jurassic succession (pers. obs.). A direct comparison is, however, hampered by still missing chronostratigraphic information. Thus, it is not clear whether the several-thousand-metres-thick siliciclastic succession cropping out in the Jerzy River area near the border to China represents the whole or only part of the Jurassic Period. A palynological analysis to clarify this problem is in progress.

Geodynamic framework

The Afghan-Tajik and Amu Darya basins are situated on the southern part of the Turan Platform. Their early extensional history during Late Permian – Early Triassic is not well known as these deposits, possibly filling grabens, are deeply buried. Permian and Triassic sediments occur on the southern margins of the Amu-Darya and Afghan-Tajik basins in south Turkmenistan and North Afghanistan where they unconformably overlie Palaeozoic beds (Brookfield & Hashmat 2001; Ulmishek 2004; Klett *et al.* 2006; Abdullah *et al.* 2008). The narrow grabens were linked to intra-arc and back-arc extension behind subduction of the Palaeotethys towards the North, below the Turan Platform.

Several Cimmerian blocks became detached from Gondwana during the Permian and collided with Eurasia leading to the formation of the Eo-Cimmerian unconformity and the Eo-Cimmerian belt (Zanchi *et al.* 2009; Zanchetta *et al.* 2013 and references herein). First the Iranian blocks collided in Late Triassic, followed by the Central Afghanistan and Central Pamir blocks at the end of the Triassic, accounting for a slightly younger unconformity, deformation and post-collisional magmatism towards the East (Klett *et al.* 2006; Zanchi *et al.* 2009, 2012; Zanchetta *et al.* 2013; Siehl 201X). From the eastern part of Iran and the Amu Darya Basin towards the East, Palaeozoic and Triassic sediments are unconformably covered by Jurassic sediments (Brookfield & Hashmat 2001; Ulmishek 2004; Klett *et al.* 2006; Abdullah *et al.* 2008; Zanchi *et al.* 2009, 2012; Zanchetta *et al.* 2013; Siehl 201X). Eo-Cimmerian reliefs were uplifted and eroded, providing Jurassic siliciclastic sediments that filled the new basins (Amu Darya and Afghan-Tajik basins) created by extensional tectonics (Brookfield & Hashmat 2001; Ulmishek 2004; Klett *et al.* 2006; Brunet *et al.* 201X).

The northwestern Afghan-Tajik Basin of the study area in southern Uzbekistan was shaped by this framework of horst and grabens created in the Early Jurassic as result of the dismembering of a part of the Eo-Cimmerian orogenic belt. Here no Triassic sedimentary rocks have been encountered; sedimentation started in the Toarcian and was probably diachronous. Extensional tectonics induced active tectonic subsidence. This explains the observed variations in thickness, the progressive deepening, and the onset of marine conditions in the Late Bajocian. The area of the Kugitang Mountains occupied a deep part of the extensional margin which shallowed towards the North-East. The extension ceased during the Middle Jurassic to give way to a more continuous thermal subsidence.

During Mesozoic and Early Palaeogene times, the Afghan-Tajik and Amu Darya basins formed a single basin (Ulmishek 2004). The Late Palaeogene-Neogene collision of the Indian Plate with the Eurasian Plate uplifted the southern margins of the basins, mainly shaped the southwestern Gissar range, which divided the northern portion into the two basins, and strongly deformed the Afghan-Tajik Basin, situated nearest to the Pamirs (Klett *et al.* 2006).

Conclusions

The Lower Jurassic to Lower Callovian sedimentary succession of the Afghan-Tajik Basin in southern Uzbekistan records the history of an extensional basin with pronounced topography. The non-marine siliciclastic rocks overlying the Palaeozoic basement rocks represent environments ranging from braided and meandering streams to floodplains, swamps, and lakes. The latter are either short-lived or long-ranging and wide-spread. Their sediments are commonly arranged in progradational cycles. Plant growth was ubiquitous as is documented by rootlets, coal layers, wood pieces and plant debris and indicates a humid climate.

In the Late Bajocian the sea flooded the basin. Initially, the sedimentation regime remained siliciclastic, representing storm-influenced ramp environments that shallowed into a deltaic setting, locally with paralic coal. With the return to a storm-influenced ramp setting the siliciclastic sediment influx decreased and mixed carbonate siliciclastic sediments were deposited.

Part of the Middle Bathonian time interval is marked by sediment starvation. The Late Bathonian to Early Callovian interval represents an outer ramp to basinal setting, characterized by an increasing carbonate content of the sediment. It is followed by a thick carbonate unit, which is beyond the scope of this study. The marine unit is composed of metre-scale parasequences and corresponds to two third-order depositional sequences.

Marked lateral thickness changes of the investigated succession point to a pronounced relief of the basement. Maximum subsidence occurred from the Kugitang Mountains in the South to the Baysun area in the North, whereas further north in the Gissar Mountains and north of Denau strongly reduced thicknesses with a dominance of coarse-grained fluvial channel deposits indicate the margin of the basin.

The replacement of siliciclastic sediments by carbonates in the course of the Bathonian to Early Callovian time interval is interpreted to partly reflect a reduced topography of the hinterland, partly a change in climate from humid to arid.

A similar shift in sediment composition occurs also in central-east Iran, the Alborz Mountains, Kopet Dag, and Binalud Mountains of Iran and demonstrates that this climate shift was of at least regional significance. Furthermore, flooding of these Iranian basins and the Afghan-Tajik Basin around the Early-Late Bajocian boundary suggests a more or less synchronous active subsidence and some shared geodynamic history.

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Fig. 1. Position of the study area in the framework of the Amu Darya and Afghan-Tajik basins **(a)** and section localities in southern Uzbekistan **(b)**; see also Table 1). **(a)** Outlines of the Amu Darya and Afghan-Tajik basins according to Klett *et al.* (2012), topography background from USGS SRTM-3 http://dds.cr.usgs.gov/srtm/version2_1/SRTM3/. **(b)** Background topography from USGS SRTM3, geology according to geological map of Uzbekistan 1:500 000 (Shayakubov 1998). Jurassic rocks are shown in blue colour.

Fig. 2. Lithostratigraphic subdivisions (formations) of the Jurassic succession in southern Uzbekistan (after Krymholts *et al.* 1988, modified). H: Hettangian; PL: Pliensbachian; T: Toarcian; A: Aalenian; BAJOC: Bajocian; CALL: Callovian; O: Oxfordian; K: Kimmeridgian; T: Tithonian; CR: Cretaceous; L: Lower; M: Middle; U: Upper.

Fig. 3. Section of the Jurassic succession near Shalkan, Kugitang Mountains. For position see Table 1 and Fig. 1, for key of symbols Fig. 4. Siliciclastic sediments: cl, clay; s, silt/siltstone; f, fine-grained sandstone; m, medium-grained sandstone; c, coarse-grained sandstone; g, gravelly sandstone; carbonate microfacies: m, mudstone; w/f, wackestone/floatstone; p, packstone; g, grainstone; r, rudstone. K., Kugitang Formation.

Fig. 4. Key of symbols.

Fig. 5. (a) Jurassic succession near Shalkan (see Fig. 3 for litholog). The arrow points to the top of the Palaeozoic metamorphic basement, the vertical wall is the Callovian-Oxfordian Kugitang Formation. Below is the softer Early Jurassic to early Callovian succession which is dominated by fine-grained, often poorly indurated siliciclastic sediments and therefore weathers more easily. **(b)** Jurassic succession at Panjab (see Fig. 7 for litholog). The lower part of the section corresponds to the Upper Bajocian - Lower Bathonian Degibadam Formation, the recessive middle part to the silty marl of the Baysun Formation. The vertical cliff is composed of limestones of the Kugitang Formation. **(c)** Succession of stacked fluvial sandstones displaying lateral accretion; basal part of the Shargun section (see Fig. 11 for litholog). The individual sandstone bodies are separated by thin, often lenticular, carbonaceous mudstone units. **(d)** Palaeosol (brown soil) overlying the Palaeozoic

metamorphic basement and followed by a sharp-based sandstone unit representing the fill of a small fluvial channel; Shalkan section. (e) Thin conglomerate overlying weathered metamorphic basement rocks west of Vuariz. (f) Upper part of the non-marine Jurassic succession, strongly reduced in thickness, at Vuariz. The figured succession consists mainly of fine-grained floodplain deposits, with occasional intercalations of carbonaceous lacustrine mudstones and fluvial channel sandstones. The transgressive surface at the top of the cliff is marked with an arrow. (g) Stacked fluvial channel sandstones separated by finer-grained floodplain deposits, south-west of the village Vuariz. (h) Transition from the marly-calcareous Baysun Formation to the thick-bedded limestones of the Kugitang Formation; Iron Gate section (see Fig. 10 for litholog).

Fig. 6. Section of the Jurassic succession at Vandob, Kugitang Mountains. For position see Table 1 and Fig. 1, for key of symbols Figs. 3, 4. TR, transgressive surface. K., Kugitang Formation.

Fig. 7. Section of the Jurassic succession at Panjab, northern Kugitang Mountains. For position see Table 1 and Fig. 1, for key of symbols Figs. 3, 4. K., Kugitang Formation.

Fig. 8. Section of the Jurassic succession at the Dalut Mine near the village Toda. For position see Table 1 and Fig. 1, for key of symbols Figs. 3, 4. c., ch., river channel; s., sw., swamp.

Fig. 9. (a) Thick fluvial sandstone sharply overlain by fine-grained lake deposits; base of Dalut Mine section (Fig. 8). (b) Point bar deposits displaying lateral accretion: Dalut Mine section at 154 m (see Fig. 8 for litholog). (c) Rootlets in overbank sediments; Dalut Mine section. (d) Several coarsening-upward cycles of prodelta mudstones to bedded deltafront sandstones overlain by cross-bedded sandstones of a large distributary channel (upper two-fifths of section); Iron Gate section (see Fig. 10 at 70-115 m). (e) Sediments of the storm-flow dominated outer ramp. Between the argillaceous silty background sediments gutter casts (arrowed) and graded parallel-laminated sandstones are intercalated. Degibadam Formation of the Iron Gate section (see Fig. 10 at 18-27 m). (f) Hummocky cross-stratified sandstone; Degibadam Formation, Dalut Mine section. (g) The trace fossil *Diplocraterion parallelum* in the basal marine sandstone at the Shalkan section, first evidence of the marine transgression. (h) Angular unconformity between the Baysun Formation (below) and the Kugitang

Formation (above) near Khanjizza, north of Denau, indicative of synsedimentary tectonic movements produced by the slight tilting of a fault block.

Fig. 10. Section of the Jurassic succession near Derbent at the "Iron Gate". For position see Table 1 and Fig. 1, for key of symbols Figs. 3, 4. K., Kugitang Formation.

Fig. 11. Sections of the Jurassic succession at the Shargun Mine. For position see Table 1 and Fig. 1, for key of symbols Figs. 3, 4. K., Kugitang Fm; tr, transgression.

Fig. 12. Section of the Jurassic succession near Sangardak. For position see Table 1 and Fig. 1, for key of symbols Figs. 3, 4.

Fig. 13. Sections of the Jurassic succession near Vuariz. For position see Table 1 and Fig. 1, for key of symbols Figs. 3, 4. D., Degibadam Fm.

Fig. 14. Middle part of the Baysun Formation NE of Vuariz (Vuariz section IV; co-ordinates: N 38°49'29.6'', E 67°11'26.3''). The fine-grained packstones exhibit birdseyes and laminoid fenestral fabrics characteristic of a peritidal environment. For key of additional symbols see Figs. 3, 4.

Fig. 15. Examples of the main facies associations and their corresponding environments in the Jurassic of southern Uzbekistan. **(a)** Braided river deposits (Vuariz section at 0-14 m). **(b)** Meandering river deposits (Dalut Mine section at 225-231 m). **(c)** Flood-plain deposits (Dalut Mine section at 86-98 m). **(d)** Swamp deposits (Dalut Mine section at 263-268 m and 298-304 m). **(e)** Offshore lake deposits (Shalkan section at 190-202 m). **(f)** Lake margin deposits (Shalkan section at 348-360 m). **(g)** Distributary channel deposits (Iron Gate section at 96-110 m). **(h)** Delta front deposits (Vandob section at 370-379 m). **(i)** Prodelta - lower delta-front deposits (Iron Gate section at 63.5-75.5 m). **(j)** Tide-influenced inner ramp deposits (Panjab section at 40.5-52.5 m). **(k)** Protected inner ramp deposits (Panjab section at 34-46 m). **(l)** high-energy deposits of the inner to middle ramp (Panjab section at 94.5-99.5 m). **(m)** storm-wave dominated middle ramp (Vandob section at 503-513 m). **(n)** storm-flow dominated outer ramp (Dalut Mine section at 552-562 m). **(o)** Low-energy outer mixed carbonate-siliciclastic ramp deposits (Shalkan section at 740-745 m). **(p)** Condensed outer ramp deposits

(Shalkan section at 728-733 m). **(q)** Low-energy outer carbonate ramp (Vandob section at 740-753 m).

Fig. 16. (a-f) Microphotographs of characteristic facies. Scale: 5 mm. **(a)** Poorly sorted, immature, conglomeratic gravelly sandstone with abundant metamorphic clasts. Basal part of Gurud Formation, Shalkan section at 31.1 m (see Fig. 3). **(b)** Hummocky cross-stratified, very fine-grained sandstone with *Chondrites* at the base. Degibadam Formation, Shalkan section at 485 m (see Fig. 3). **(c)** Bioclastic fine-grained sandstone. Degibadam Formation, Vandob section at 528.5 m (see Fig. 6). **(d)** Onco-rudstone strongly affected by pressure solution. Baysun Formation, Panjab section at 221.2 m (see Fig. 7). **(e)** Onco-bio-floatstone with abundant coral fragments. Oncoids mainly immature. Baysun Formation, Panjab section at 288 m (see Fig. 7). **(f)** Bio-onco-floatstone with abundant shell fragments. Baysun Formation, Iron Gate section at 321.5 m (see Fig. 9). **(g)** Coarsening- and thickening-upward prodelta-deltafront succession. Degibadam Formation, Iron Gate section at 79-84 m (see Fig. 10).

Fig. 17. Examples of cycles developed in the non-marine **(a-d)** and marine parts **(e-j)** of the Jurassic succession. **(a)** Fluvial cycle (braided stream) (Vandob section at 0-6 m). **(b)** Fluvial cycle (meandering river) (Vuariz section at 17.5-23.7 m). **(c-d)** Progradational lacustrine cycles (Dalut Mine section; c: at 160-166 m; d: at 396-398 m). **(e)** Marine deltaic cycle (Vandob section at 370-388 m). **(f)** Progradational cycle of the storm-wave influenced ramp (Vandob section from 296-302 m). **(g)** Progradational cycle of the outer to middle siliciclastic ramp (Iron Gate section at 52.5-55 m). **(h)** Progradational cycle of the storm-flow influenced ramp (Iron Gate section at 16-20 m). **(i-j)** Cycles of the outer carbonate ramp (Panjab section; i: at 263.8-268.2 m; j: at 274-278 m). c to j represent parasequences.

Fig. 18. Correlation of the Lower and Middle Jurassic succession within the study area. From Vandob (Kugitang Mts.) in the south to Iron Gate/Dalut Mine (Ghissar Spur) in the north the thickness is relatively uniform (800-950 m), but decreases distinctly towards the northeast (Shargun/Sangardak; ~350 m) and even more so towards Vuariz in the north (<100 m for the non-marine part). The latter areas clearly represent the margin of the basin, which is supported by the coarser grain size of the sediment.

Fig. 19. Schematic development of the sedimentary environments in the Afghan-Tajik Basin of southern Uzbekistan during the Early to early Late Jurassic. **(a)** During the Early Jurassic,

non-marine conditions prevailed. Close to the basin margin coarse-grained fluvial deposits were deposited, whereas extensive fine-grained lake deposits with coal swamps formed towards the centre of the basin. **(b)** Flooding of the basin in the Late Bajocian, increased levelling of the morphology of the hinterland, and a change from humid to more arid conditions led to gradual replacement of the siliciclastic regime by a mixed carbonate-siliciclastic regime. **(c)** By the late Callovian, a predominantly low-energy carbonate platform covered the study area. Sporadic influx of siliciclastic material remained confined to margins of the basin with a steep morphological gradient, whereas in deeper parts of the basin locally organic-rich mudstones formed.

Fig. 20. Sequence stratigraphic interpretation of the marine Middle Jurassic succession at the Iron Gate near Derbent. The siliciclastic to mixed carbonate-siliciclastic succession records two highstand systems tracts and one transgressive systems tract within the Late Bajocian □ Early Callovian time interval. Another transgressive systems tract, recording the initial flooding of the basin, is not exposed here. These 3rd-order sequences are composed of numerous parasequences (see Fig. 10). Note the large deltaic succession representing prodelta, delta front, and distributary channel in the lower part of the section.

Fig. 21. Comparison of Jurassic successions of Iran, southern Uzbekistan, and southwestern Kyrgyzstan. CEIM, Central East Iranian Microcontinent; U.J., Upper Jurassic.

Table 1. Co-ordinates of the section localities.

Table 2. Palaeoenvironments and their main features in the Lower to Middle Jurassic successions. ss: sandstone.

Gurud Fm.

Tangiduval Fm.

outer middle ramp

Baysun Fm.

section shifted several 100 m
further north to
N 37°52'52.0"''
E 66°38'13.7"''

basin

outer ramp

Nanogyra

covered
with
scree

covered
with
scree

basin

	limestone		oscillation ripples		corals
	nodular limestone		parallel lamination		belemnites
	marlstone		gutter cast		brachiopods
	marl		lenticular bedding		wood fragments
	clay		interlayered bedding		wood logs
	silt/siltstone		flaser bedding		plants/plant debris
	sandstone		desiccation cracks		root horizon
	pebbles		rubbly		bioturbation
	coal		concretion		<i>Thalassinoides</i>
	highly carbonaceous		flute cast		<i>Gyrochorte</i>
	oncoids		shells/shell concentration		<i>Ophiomorpha</i>
	ooids		bivalves		<i>Planolites</i>
	bioclasts/shell debris		bivalves in growth position		<i>Scoyenia</i>
	planar cross-bedding		gastropods		<i>Rhizocorallium irregulare</i>
	large-scale trough cross-bedding		ammonites		<i>Skolithos</i>
	hummocky cross-bedding		serpulids		finig-/coarsening upward
	ripple bedding		crinoids

Gurud Fm.

Gurud Fm. Degibadam Fm.

Degibadam Fm. : Tangiduval Fm.

Baysun Fm.

Baysun Fm.

Baysun Fm. I.K.

Gurud Fm.

Gurud Fm. | Degibadam Fm.

Degibadam Fm.

Degibadam Fm. | Tangiduval Fm.

Tangiduval Fm. | Baysun Fm.

Baysun Fm. iK.

Gurud Fm.

Gurud Fm.

cl s f m c g p

cl s f m c g p

cl s f m c g p

Degibadam Fm.

Tangiduval Fm.

Tangiduval Fm. | K.

Baysun Fm.

algal lamination

birdseyes

fenestral fabrics

Depositional cycles (c-j: parasequences)

Dalut Mine

Sangardak

Shargun

Vuariz

Late Jurassic

c

Middle Jurassic

b

investigated segment

Early Jurassic

a

investigated segment

low-energy
carbonate ramp

Kugitang Fm.

Baysun Fm.

Tangiduval Fm.

Lower Callovian

Middle Bathonian

Lower Bathonian

Upper Bajocian

HST

increasing carbonate
content

condensation level (MFZ)

mixed carbonate-
siliciclastics

TST

HST

storm-dominated
shelf

distrib. channel

delta front

prodelta

Degibadam Fm.

Table 2

Continental palaeoenvironments	lithology (facies associations)	sedimentary structures	fossils/trace fossils
braided river channels	fine- to coarse-grained arkosic or quartz-rich ss, partly gravely to conglomeratic, immature	large-scale trough cross-bedding, erosional base, fining-upward, vertical stacking common	wood fragments, tree trunks
meandering river channels with levee deposits	fine-grained ss, partly silty, moderately to well sorted; levee deposits: interbedded fine-grained ss and silty clay	lateral accretion, large-scale trough cross-bedding, ripple lamination, erosional base, fining-upward	plant fragments, rootlets
flood plain with crevasse splays	silty clay to argillaceous silt with cm- to dm-thick, sharp-based fine-grained ss and siltstone intercalations, partly lenticular	current ripple lamination, rootlets,	plant fragments common
flood plain with palaeosol	(a) ferruginous fine-sandy silt (b) brown clay with scattered quartz granules		(a) rootlets
floodplain swamp, swampy lake margin	coal, strongly carbonaceous clay or silty clay		rich in plant debris
lake margin	fine-grained ss, siltstone, coarsening-upward	ripple lamination, top occasionally rooted	plant debris common
lacustrine delta	coarsening-upward succession of silty clay to thin-bedded fine-sandy silt or fine-grained sandstone	coarser layers with ripple lamination, top bed in some cases with large-scale trough stratification and erosional base	plant debris common
storm-influenced lake	argillaceous silt with cm-scale fine-grained ss intercalations	ss parallel- or ripple-laminated, with sharp base; some with HCS	plant fragments common
low-energy offshore lake	argillaceous silt to silty clay, partly with claystone concretions, rarely silty micrite	partly shaly, partly bioturbated	plant debris common
Marine palaeoenvironments			
distributary channel	medium- to coarse-grained immature ss	base sharp, erosional, fining-upward, large-scale trough cross-stratification, top ripple-laminated	wood pieces common
protected embayment	fine-sandy silty clay, locally carbonaceous; silt,	bioturbated; silt commonly ripple-	plant debris

	fine-sandy silt, with occasional cm- to dm-thick fine-grained ss intercalations	laminated ss commonly parallel-laminated	
delta front	arkosic fine- to medium-grained ss	ripple-lamination, low-angle large-scale trough cross-stratification, coarsening-upward	wood pieces, thin bioturbated intervals (<i>Thalassinoides</i>)
prodelta	argillaceous silt with occasional cm-thick fine-grained ss interbeds	ss ripple-laminated, argillaceous silt bioturbated	ammonites
tide-influenced inner siliciclastic ramp	interlayered bedding of fine-grained ss (0.5-5 cm) and argillaceous silt (1-2 cm); fine-grained sandstone	ss ripple-laminated; flaser-bedding, lenticular bedding, oscillation ripples	<i>Gyrochorte</i>
high-energy inner carbonate ramp	m-thick bio-oo-grainstone	large-scale planar cross-bedding, sharp base	
low-energy lagoonal intertidal carbonate flats	carbonate mudstones and fine-grained packstones	birdseyes and laminoid fenestral fabric, thin, irregular algal laminae	scattered gastropods
submarine dunes of the inner to middle siliciclastic ramp	dm- to m-thick fine- to medium-grained ss, partly bioclastic	large-scale trough cross-bedding	disarticulated bivalves, crinoid ossicles, <i>Ophiomorpha</i>
storm-wave influenced middle siliciclastic ramp	argillaceous to fine-sandy silt with intercalations of dm- to m-thick fine-grained ss	ss with hummocky cross-stratification and sharp base; beds partly amalgamated; fine-grained sediments bioturbated	<i>Thalassinoides</i> , <i>Skolithos</i>
storm-flow influenced outer siliciclastic ramp	argillaceous silt with cm-thick well sorted, fine-grained ss intercalations	ss with sharp, erosional base, either parallel-laminated, ripple-laminated or developed as couplets; partly with gutter casts, flute casts, tool marks; argillaceous silt bioturbated	<i>Thalassinoides</i> , <i>Planolites</i> , <i>Chondrites</i> , <i>Rhizocorallium irregulare</i> , wood fragments scattered bivalves; shell concentrations as fills of gutter casts
low-energy mixed carbonate-siliciclastic outer ramp	silty marl, marly silt,	bioturbated, loosely packed shell concentrations,	small softground fauna (e.g., the bivalves <i>Corbulomima</i> , <i>Nicaniella</i>), <i>Arcomytilus</i> , <i>Integricardium</i> , <i>Ph.</i> (<i>Bucardiomya</i>), <i>Plagiostoma</i> , <i>Chlamys</i>)
low-energy carbonate outer ramp	marl, marlstone, biofloatstone, oncofloat-/rudstone, biowackestone	bioturbated, partly with nodular texture	ammonites (rare) occasional bivalves (e.g., <i>Plagiostoma</i>)
condensed mixed carbonate-siliciclastic outer ramp	bioclastic silty to fine-sandy micrite	highly bioturbated, in places nodular	ammonites (mainly <i>Procerites</i>) and bivalves common (e.g., <i>Entolium</i> , <i>Bucardiomya</i> , <i>Pleuromya</i> , <i>Ctenostreon</i> , <i>Liostrea</i>); brachiopods and gastropods

			(<i>Obornella</i>) occur
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Table 1. Section localities

1	Shalkan, Kugitang Mountains	N 37° 51' 58.5'' N 37° 52' 58.4''	E 66° 38' 06.0'' (base) E 66° 38' 11.4'' (top)
2	Vandob, Kugitang Mountains	N 37° 43' 07.9'' N 37° 43' 13.3''	E 66° 33' 45.1'' (base) E 66° 32' 46.3'' (top)
3	Panjab, northern Kugitang Mts.	N 38° 02' 07.4''	E 66° 49' 44.1''
4	Dalut Mine near the village of Toda, South Gissar Mts.	N 38° 15' 09.1''	E 67° 07' 36.7''
5	Gorge N of Derbent, southern tip of Gissar Mts. (Iron Gate)	N 38° 15' 35.5''	E 67° 01' 34.8''
6	Shargun section, coal mine N of Shargun, SE Gissar Mts	N 38° 36' 54.3''	E 67° 57' 48.1''
7	Sangardak, SE Gissar Mts.	N 38° 31' 57.9''	E 67° 34' 47.4''
8	Vuariz section I, ESE of Shahrissabsz	N 38° 48' 41.5''	E 67° 10' 04.4''
9	Vuariz section II, ESE of Shahrissabsz	N 38° 48' 20.6''	E 67° 10' 49.4''
10	Vuariz section III, ESE of Shahrissabsz	N 38° 48' 50.3''	E 67° 09' 41.9''
11	Vuariz section IV, ESE of Shahrissabsz	N 38° 49' 29.6''	E 67° 11' 26.3''