Structure and evolution of the Bukhara-Khiva region during the Mesozoic: the northern margin of the Amu-Darya Basin (southern Uzbekistan)

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Abstract: The Bukhara-Khiva region forms the northern margin of the Mesozoic Amu-Darya Basin. We reconstructed several cross-sections across this margin from subsurface data. The objectives included examining the structure of the Bukhara and Chardzhou steps and determining the tectonic–sedimentary evolution of the basin during the Jurassic. Subsequent to the Cimmerian collision in the Middle Triassic, an extensional event controlled the deposition of the Early–Middle Jurassic siliciclastic succession in the Bukhara-Khiva region. The main Late Palaeozoic inherited structures were reactivated as normal faults during this period. Continental coarse-grained siliciclastic sediments are mainly confined to the basal Lower Jurassic section, probably Pliensbachian–Toarcian in age, whereas marine siliciclastic sediments occur in the early Late Bajocian. In the Early–Middle Jurassic the Bukhara and Chardzhou steps were predominantly sourced by areas of relief, the remains of Late Palaeozoic orogens located to the north. The rate of extension significantly declined during the Middle Callovian–Kimmeridgian period. Deposition of the overlying Lower Cretaceous continental red-coloured clastic sediments was related to the interaction of basin subsidence, a fall in eustatic sea-level and sediment supply. Subsequent marine transgression in the Late Barremian, partially related to broad thermal subsidence in the Amu-Darya Basin, resulted in the deposition of an extensive Late Cretaceous clay–marl succession.

The Bukhara-Khiva region in southwestern Uzbekistan constitutes the northern margin of the Amu-Darya Basin (Fig. 1). This basin, one of the largest sedimentary basins in western Central Asia, is mainly located in eastern Turkmenistan, although its northern and southern margins are in southern Uzbekistan and northwestern Afghanistan, respectively. The main part of the basin (360 000 km^2 of a total of 400 000 km^2) is located in Turkmenistan and Uzbekistan (Ulmishek 2004). The Amu-Darya Basin is shaped like a parallelogram (Fig. 1) and is bounded to the SW by the Kopet-Dagh fold belt, to the north by the Kuldzhuktau Mountains and to the east by the Southwestern Gissar Range.

The Bukhara-Khiva oil–gas province, according to the nomenclature used in Uzbekistan (e.g. Babayev 1993; Shayakubov & Dalimov 1998; Abidov & Babadzhanov 1999), is the biggest hydrocarbon province of the Republic of Uzbekistan and is predominantly gas-prone. The province corresponds to the Bukhara and Chardzhou steps (e.g. Babayev 1993), an area which is well studied because of its importance to the oil and gas industry of Uzbekistan. Although subsurface data are abundant, little has been published about this region in the international literature.

To study the northern margin of the Amu-Darya Basin, we reconstructed several cross-sections through the Bukhara-Khiva region (Fig. 2) (1) to examine the structure of the Bukhara and Chardzhou steps and (2) to understand the Mesozoic (particularly the Jurassic) tectonic–sedimentary evolution of this region.

Geological setting

The Amu-Darya Basin developed on the southeastern part of the Turan Platform, which extends westwards into the Caspian Sea. This platform is limited

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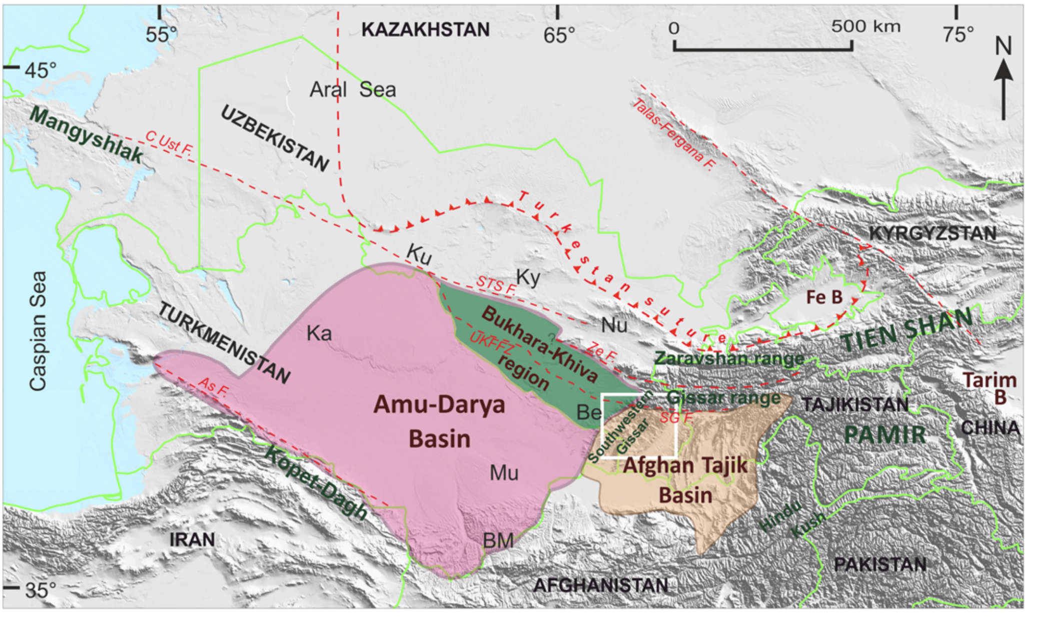

Fig. 1. Location of the study area in western Central Asia. The Amu-Darya Basin is located on the southern edge of the stable Eurasian platform, north of the Arabia–Eurasia active collision zone, whereas the Afghan-Tajik Basin is included in the India–Eurasia active collision zone. The Bukhara-Khiva region consists of the northeastern margin of the Amu-Darya Basin in Uzbekistan. Be, Beshkent Trough; BM, Badkhyz-Maimana step; Fe B, Fergana Basin, Ka, Central Karakum High; Ku, Kuldzhuktau Mountains; Ky, Kyzylkum high; Mu, Murgab depression; Nu, Nuratau Mountains. Sutures and faults are shown in red: As F, Ashgabat Fault; C Ust F, Central Ustyurt Fault; SG F, South Gissar Fault; STS F, South Tien Shan Fault; UKFFZ, Uchbash-Karshi Flexure Fault Zone; Za F, Zaravshan Fault. White rectangle: location of the map for Figures 5, 6 and 14.

to the south by the Kopet-Dagh and to the north by the Mangyshlak ranges. Its northeastern boundary is not clearly defined. Thomas *et al.* (1999) have suggested that this boundary corresponds to the Turkestan Ocean suture, whereas other researchers have suggested that the boundary can be traced northwards into the Altaids (Talwani *et al.* 1998; Natal'in & Şengör 2005). The Amu-Darya Basin has been extensively studied as a result of its economic importance. Several papers give an overview of the stratigraphy and tectonics of the basin (Clarke 1988; Dyman *et al.* 1999; Thomas *et al.* 1999; Brookfield & Hashmat 2001; Ulmishek 2004; Brunet *et al.*, this volume, in press).

The Amu-Darya Basin consists of several structural elements, including steps, highs and depressions forming sub-basins, which vary both in terms of their size and orientation (e.g. Clarke 1988, 1994; Ulmishek 2004; Brunet *et al.*, this volume, in press). The main structural elements present within the basin include the Central Karakum High in the west, the Kopet-Dagh foredeep in the SW, the Murgab depression in the central, deepest, part of the basin and the Badkhyz-Maimana step along the southern margin of the basin. The northeastern margin is composed of the Bukhara and Chardzhou steps, which deepen towards the east into the Beshkent Trough. These steps comprise the Bukhara-Khiva region bordered to the north by the Kyzylkum High (e.g. Clarke 1988; McCann 2016*a*, *b*).

The Jurassic–Cretaceous basin is underlain by several troughs, possibly rifts, filled with up to several thousand metres of poorly dated continental siliciclastic sediments and possibly volcanics, generally considered as Mid–Late Carboniferous to Triassic in age (Babadzhanov *et al.* 1986; Clarke 1988, 1994; Shayakubov & Dalimov 1998; Dyman *et al.* 1999; Thomas *et al.* 1999; Brookfield & Hashmat 2001; Ulmishek 2004; Natal'in & Şengör 2005; Zanchetta *et al.* 2013; Brunet *et al.*, this volume, in press). The exact geometry and depths of these troughs are neither well known nor constrained. The Late Triassic (Eo-Cimmerian) unconformity (e.g. Clarke 1988, 1994; Thomas *et al.* 1999; Brookfield & Hashmat 2001; Garzanti & Gaetani 2002; Ulmishek 2004; Zanchi *et al.* 2009; Zanchetta *et al.* 2013; Siehl 2015; Brunet *et al.*, this volume, in press) separates the successions within these pre-Jurassic troughs from the overlying

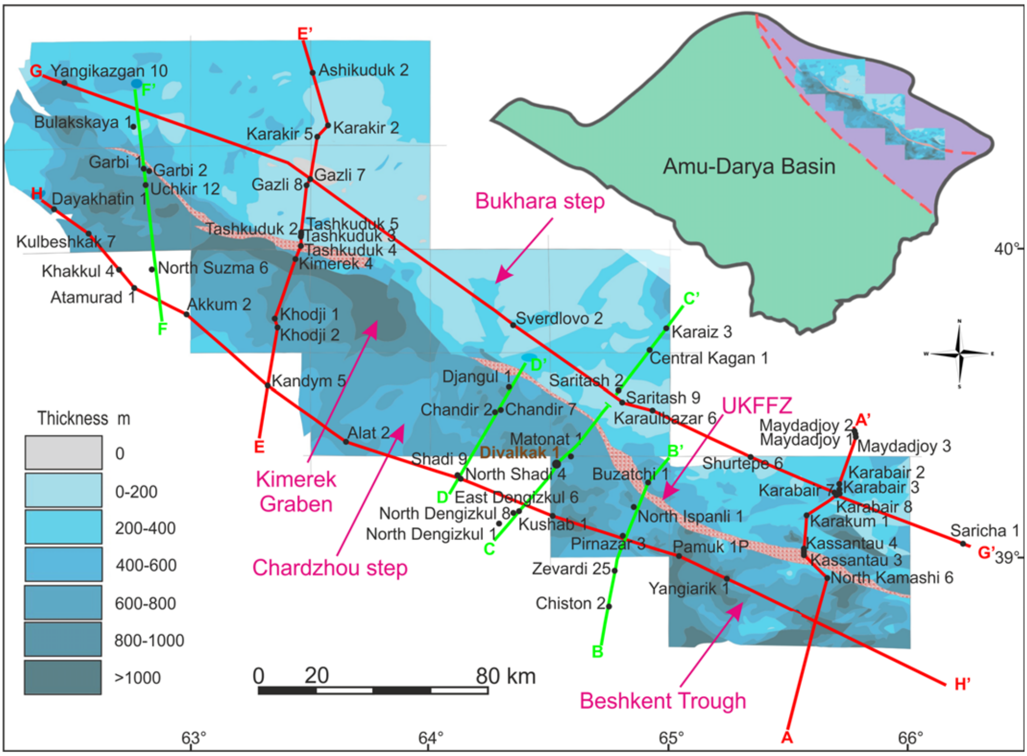

Fig. 2. Isopach map of the Jurassic siliciclastic and carbonate succession in the Bukhara-Khiva region and location of seismic profiles and wells used in the reconstruction of the sections. Isopachs are shaded in blue. From Mordvintsev (2015), modified after Mordvintsev (2012). Green lines are cross-sections based on seismic profiles; red lines are cross-sections based on maps and wells. Blue background indicates thickness of the Jurassic siliciclastic and carbonate units; black dots indicate well locations and Divalkak 1 (see Fig. 4). UKFFZ, Uchbash-Karshi Flexure Fault Zone.

Jurassic–Cenozoic succession, which comprises the bulk of the Amu-Darya basin-fill. This latter succession attains a thickness of *c.* 7 km (e.g. Clarke 1988; Ulmishek 2004) in its deepest part in the east–west-oriented Murgab depression (subbasin).

The northern margin of the Mesozoic Amu-Darya Basin consists of two distinct domains: the Bukhara-Khiva region and the Southwestern Gissar Range (Fig. 1). The Bukhara-Khiva region, mainly known from subsurface data, is divided into two broadly NW-oriented parallel steps, the Bukhara and Chardzhou steps (Fig. 2). These steps are separated by a major fault zone: the Uchbash-Karshi Flexure-Fault Zone (UKFFZ) (Abidov & Babadzhanov 1999), also termed the Bukhara or Bukhara-Gissar Fault (e.g. Babadzhanov & Abdullaev 2009), a complex shear zone that includes a series of normal faults and related flexures. The vertical displacement along this major fault zone is commonly of the order of 1500–2000 m during the Mesozoic, as indicated by the thickening of sedimentary units, mainly Jurassic in age, in the Kimerek Graben of the Chardzhou step (Fig. 2).

The Bukhara step constitutes the northeastern part of the Bukhara-Khiva region. It is 400 km long with a maximum width of 60–70 km. Palaeozoic to Cenozoic sediments cover the Bukhara step. The complete thickness of the pre-Jurassic succession, including the Palaeozoic, cannot be precisely determined, although the base of the Jurassic is at *c.* 1500–2200 m depth. The Jurassic sediments have a maximum thickness of *c.* 500 m, whereas the Cretaceous thickness ranges from 500 to 1600 m. The Cenozoic deposits are *c.* 900 m thick.

The Chardzhou step occupies the southern part of the Bukhara-Khiva region. It is 500 km long with a width of 110 km in its eastern part. In the SE, bordering the Southwestern Gissar, much of the Chardzhou step is occupied by the Beshkent Trough. The Palaeozoic succession is represented mainly by Carboniferous and Permian deposits (e.g. Babadzhanov & Abdullaev 2009). The complete thickness of the Palaeozoic sequence cannot be estimated precisely, but may be up to 3 km or more in localized sub-basins (e.g. Abidov *et al.* 1996; Babadzhanov & Abdullaev 2009). An almost complete Mesozoic–Cenozoic sedimentary succession, unconformably overlying the Palaeozoic deposits, exists in the Chardzhou step. The Jurassic succession, which is almost stratigraphically complete, is >2500 m thick in the SE of the Beshkent Trough (Shayakubov & Dalimov 1998; Mirkamalov *et al.* 2005), whereas the Cretaceous sediments are *c.* 2000 m thick. The Cenozoic succession is similar to that of the Bukhara step area.

The Southwestern Gissar Range constitutes the part of the Bukhara and Chardzhou steps in the northern margin of the Amu-Darya Basin that was inverted and uplifted during the Late Cenozoic orogeny (Fig. 1). It separates the northern part of the Amu-Darya Basin from the Afghan-Tajik Basin, which together formed a distinct basin during the Mesozoic. The Southwestern Gissar Range is a 200 km long and 150 km wide thick-skinned orogenic belt, where elevations increase to the NE from *c.* 2000 m in the SW at the Uzbekistan–Turkmenistan border to >4000 m in the north near the Uzbekistan–Tajikistan border. The main phase of the Late Cenozoic orogeny can be related to the indentation of the Asian margin by the Pamir salient in Neogene–Quaternary times (Shein 1985). The Southwestern Gissar Range consists of a series of NE-oriented anticlines and synclines (Tevelev & Georgievskii 2012) where the Mesozoic–Cenozoic sedimentary succession is well preserved, with excellent and abundant outcrops.

Stratigraphy of the Bukhara-Khiva steps

Much of the northern margin of the Amu-Darya Basin in Uzbekistan (Fig. 1) is overlain by Cenozoic sediments. Knowledge of the deepest pre-Palaeozoic to Cenozoic sediments can therefore only be attained from subsurface investigations, except in the area to the SE (Southwestern Gissar Range), where outcrops of Palaeozoic, Mesozoic and Lower Cenozoic deposits are abundant (Brookfield 2000; Tevelev & Georgievskii 2012). It is for this reason that most of the principal type sections of the northern margin of the Amu-Darya Basin have been defined in this latter area.

The pre-Jurassic rocks include a range of metamorphic, magmatic, volcanoclastic or Palaeozoic sedimentary units (Babadzhanov & Abdullaev 2009) unconformably overlain by Lower Jurassic (possibly also Upper Triassic) siliciclastic sediments. The Mesozoic and Cenozoic sedimentary strata consist of siliciclastic, carbonate and evaporitic rocks deposited in a range of different sedimentary environments.

The Jurassic sediments unconformably overlie all of the pre-Jurassic units, including the Permian and the Permo-Triassic units (Fig. 3). Along the northern Amu-Darya Basin margin, the Jurassic succession can be subdivided into three units (Figs 3–5): a Lower–Middle Jurassic siliciclastic unit; a Middle–Upper Jurassic carbonate unit; and an Upper Jurassic evaporite unit. The Jurassic succession is mainly found on the Chardzhou step; it is thinner on the Bukhara step.

The siliciclastic Lower–Middle Jurassic sequence (possibly locally Upper Triassic) generally consists of mud-rich sediments, which include intercalations of claystone, siltstone and sandstone beds as well as rarer conglomerates or gravels. It is subdivided into five formations (Fig. 3). The lower part of the succession, which is widely distributed, is continental, with frequent coal seams and coal-bearing beds (the Sanjar and Gurud formations), which were deposited under warm and humid climatic conditions (Egamberdiev & Ishniyazov 1990; Fürsich *et al.* 2015). These continental clastics were deposited across a range of environments, including distal alluvial fans, fluvial systems (including floodplains), lacustrine and delta settings. This variety of continental facies indicates that, during the Early Jurassic, the Southwestern Gissar Range area was one of emergence, with a well-developed palaeotopography (i.e. highs), freshwater lakes and rivers.

Initial marine transgression resulted in the deposition of the lower part of the siliciclastic-rich Degibadam Formation, dated as Late Bajocian (Krymholts *et al.* 1988; Egamberdiev & Ishniyazov 1990; Fürsich *et al.* 2015; McCann 2016*a*). The upper part of the Degibadam Formation consists of marginal to shallow marine mixed carbonate–clastic sediments dated as Late Bajocian to Early Bathonian (Krymholts *et al.* 1988; Fürsich *et al.* 2015) or possibly just Late Bajocian (Mirkamalov *et al.* 2005) (Fig. 3). The Lower Bathonian (Krymholts *et al.* 1988) or Lower to Middle Bathonian (Mirkamalov *et al.* 2005) Tangiduval Formation, which is similar to the underlying Degibadam Formation, is characterized by a higher carbonate content. The overlying Middle Bathonian (Fürsich *et al.* 2015) to Lower Callovian Baysun Formation consists of a greater proportion of carbonate sediments. This formation represents the transition zone between the siliciclastic and carbonate units. The top of the succession, consisting of clay with intercalated limestone lenses, is dated as Early Callovian.

Middle–Upper Jurassic carbonates overlie the Middle Jurassic marine clastics (Figs 3 & 5). Carbonate deposition had ended by Oxfordian times and the evaporite unit above is considered to be

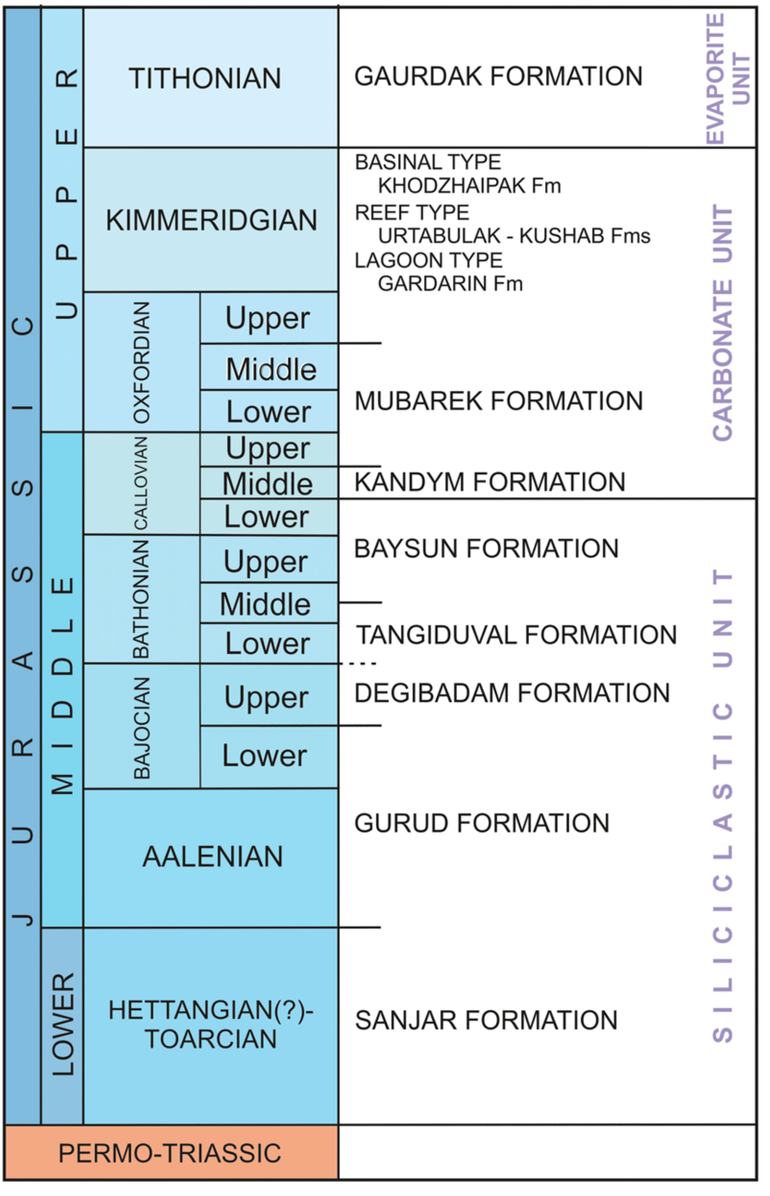

Fig. 3. Jurassic stratigraphic chart used in this work. Modified after Mirkamalov *et al.* (2005); the age of the base of the Baysun Formation is from Fürsich *et al.* (2015).

Kimmeridgian–Tithonian in age (e.g. Luppov 1957; Clarke 1988; Krymholts *et al.* 1988). However, this latter age does not agree with work from the northern margin of the Amu-Darya Basin in Uzbekistan, which suggests extending it to the Early Kimmeridgian (Shayakubov & Dalimov 1998) or even as far as the end Kimmeridgian (e.g. Abdullaev 2000; Mirkamalov *et al.* 2005). It is this latter date that we have chosen to use in this paper, with the carbonates thus extending from the Middle Callovian through to the end of the Kimmeridgian (Fig. 3).

The carbonate succession can be subdivided into two parts (lower and upper carbonates), corresponding to the Middle Callovian to Middle Oxfordian and the Late Oxfordian–Kimmeridgian intervals, respectively. The lower and upper carbonates were formerly termed the Lower Kugitang and Upper

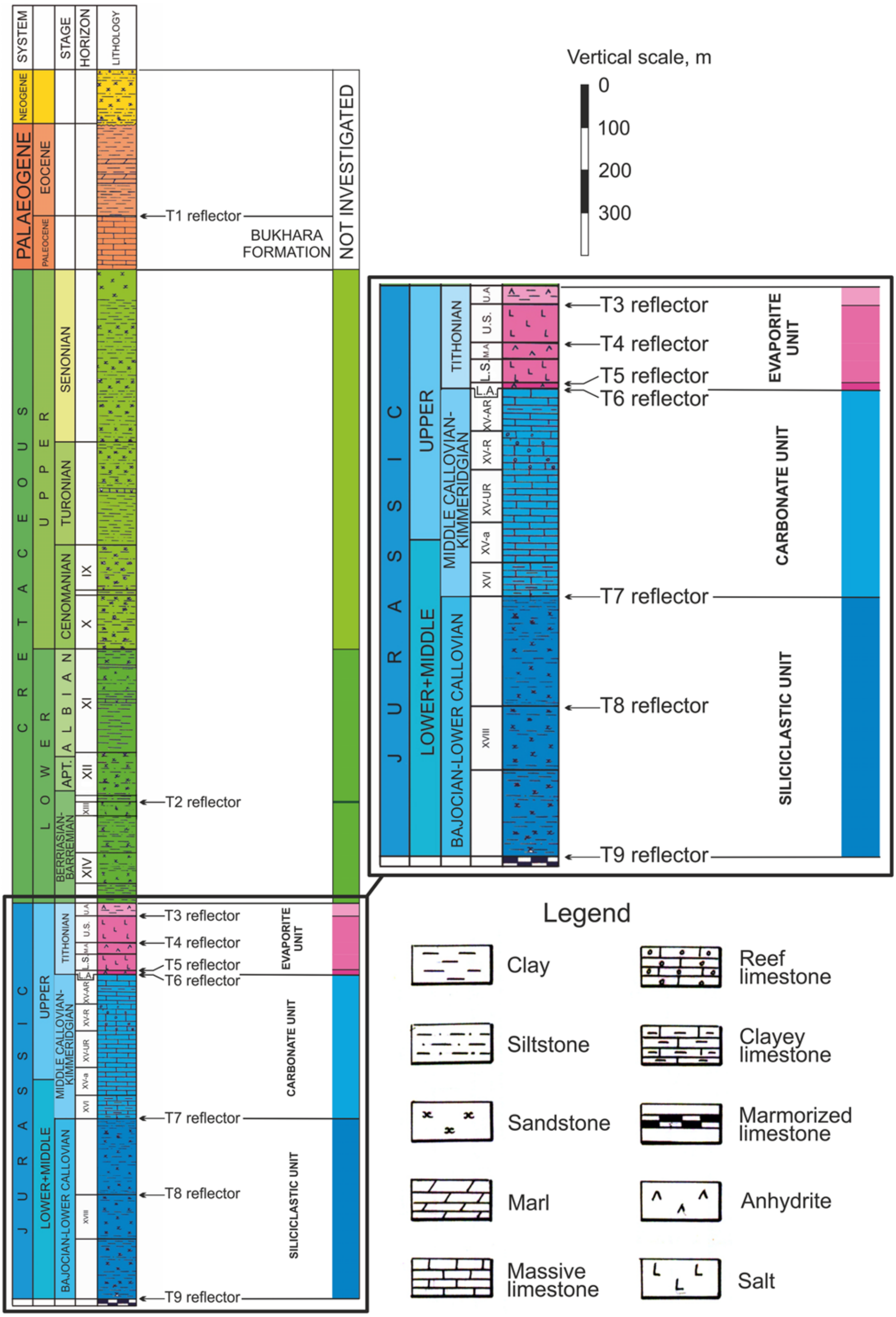

Fig. 4. Location of the main seismic reflectors T in the Mesozoic–Cenozoic stratigraphic column. Schematic model from the lithostratigraphic column of well Divalkak 1 (see Fig. 2 for location). XVIII–IX horizon names determined by hydrocarbon exploration industry. AR, above reef; LA, lower anhydrite; LS, lower salt; MA, middle anhydrite; R, reef; UA, upper anhydrite; US, upper salt; UR, under reef.

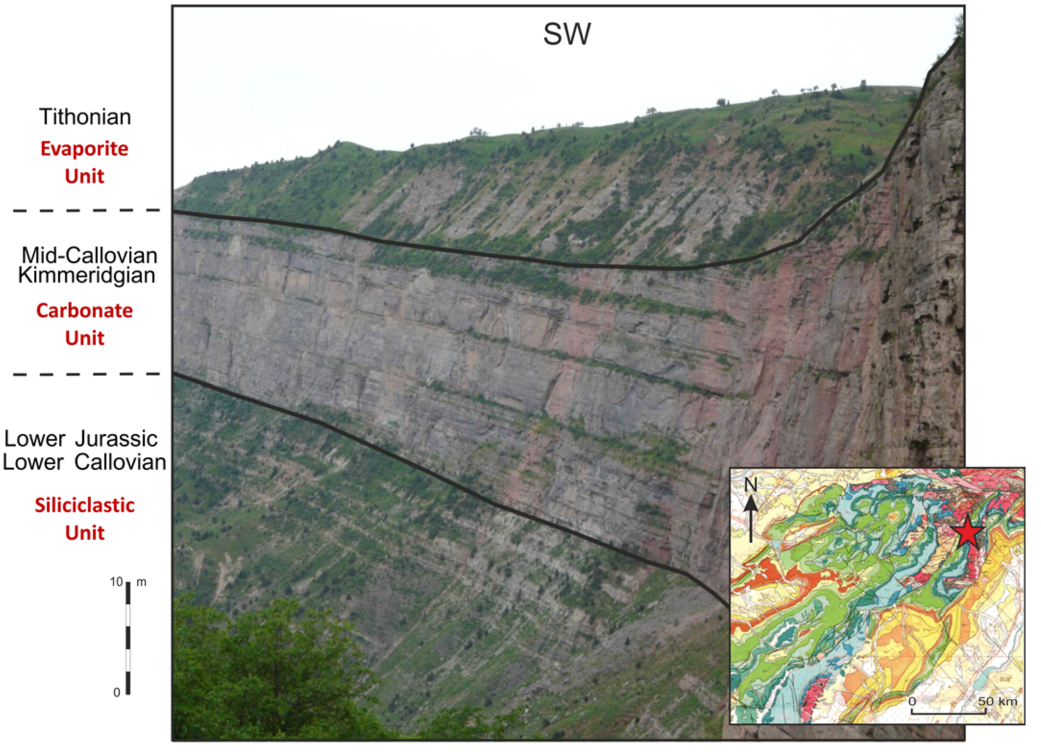

Fig. 5. Jurassic section in northern Southwestern Gissar near Khanjizza, showing the siliciclastic, carbonate and evaporite units. In the northern Amu-Darya margin the Jurassic succession forms a petroleum system, primarily gas-prone. The main source rocks are the Lower–Middle Jurassic coaly shales and coals and the Upper Jurassic black shales. The principal reservoirs are the Middle–Upper Jurassic reef and shelf carbonates and the Lower Cretaceous red clastic sediments. The main seal rocks are the thick Upper Jurassic evaporites. Inset: location of the section shown by a red star on a fragment of the geological map of Uzbekistan (Shayakubov 1998); area coverage shown by white rectangle in Figure 1.

Kugitang series (e.g. Nugmanov 2009, 2010). The carbonate unit is lithologically complex with common lateral facies changes, especially in the upper part where three depositional environments – reef, lagoon and basin settings – have been recognized (Fig. 3). These three environments pass laterally into one another across the region and were coeval (Middle Oxfordian–Kimmeridgian). The three depositional environments correspond to the Urtabulak, Gardarin and Khodzhaipak formations, respectively (Fig. 3), named after their locations with respect to a model of a barrier reef system (Abdullaev & Mirkamalov 1998; Abdullaev 2004; Mirkamalov *et al.* 2005; Fortunatova 2007; Abdullaev *et al.* 2010; Evseeva 2015). The reef environment consists of massive, light coloured, biomorphic, bioclastic detrital limestones, with high porosity and rare intercalations of ammonite-bearing clays. The lagoonal setting is characterized by interbedded limestones and anhydrites, whereas the basinal setting is represented by dark calcareous marine mudstones (the so-called black shale clays, e.g. Besnosov & Mitta 1995). These latter sediments are laminated ammonite-bearing shales deposited under anoxic conditions and are the likely source rocks for the oil of the Chardzhou step (Isaksen & Khalylov 2007). The precise relationships between the various facies (depositional environments) of the carbonate unit, as well as their synchroneity and ages, have not been unequivocally established. The age of the overlying evaporite unit is also debatable.

The lithology of the overlying salt–anhydrite formation (Gaurdak Formation) is represented by intercalations of salt and anhydrite with some intercalated clays (Figs 3 & 5). According to Mirkamalov *et al.* (2005), the age is Tithonian (Fig. 3). This formation represents several evaporite facies deposited in a large salt-bearing basin (e.g. Clarke 1988; Gavrilcheva & Pashaev 1993; Fortunatova 2007; Abdullaev *et al.* 2010), which occupied part of the Afghan-Tajik Basin (e.g. Klett *et al.* 2006). The evaporites are generally characterized by a five-member sequence (e.g. Clarke 1988; Gavrilcheva & Pashaev 1993), including lower anhydrite–lower salt–middle anhydrite–upper salt–upper anhydrite (Fig. 4). Some of these members are locally missing in the Bukhara and Chardzhou steps. The evaporite unit is extremely thin in the Bukhara step, where it is represented by a single salt–anhydrite sequence. However, in some parts of the Bukhara-Khiva region, where lagoon-type sections have been observed, there is a marked increase in the thickness of the salt–anhydrite sequence.

The Lower Cretaceous sediments disconformably overlie the Upper Jurassic deposits, with an erosional surface along the contact (Khayitov 2006, 2013). The succession commences with continental red beds, several hundred metres thick and Berriasian–Valangian in age, including clays and siltstones with intercalated conglomerates, sandstones and gypsum (Fig. 6). The overlying Hauterivian is characterized by continental and marine sediments. From Barremian to Albian times a shallow marine environment, characterized by the deposition of sandstones, siltstones, limestones and associated coquinas, existed across the region. The overlying Upper Cretaceous succession is rather monotonous, consisting of mainly dark grey clay–marl–sandstone units with rare interbedded limestones and coquinas containing abundant faunas. During this period, deposition mainly occurred in marine to lagoonal settings, although continental environments have also been recognized.

The Cenozoic sediments almost completely overlie the northern margin of the Amu-Darya and Tajik basins. They consist of a 4000 m thick series dominated by Neogene sediments. The shallow marine Palaeogene series consists of intercalations of marls, siltstones, sandstones, limestones and evaporites. The continental Neogene red clastic sediments, the deposition of which can be related to the evolving Pamir orogeny, unconformably overlie the marine Palaeogene sediments.

Seismic reflectors and facies

On the seismic profiles used as part of this study, the three major lithological units of the Jurassic series, i.e. the siliciclastic, carbonate and evaporite units, have characteristic seismic facies and reflectors that allow them to be traced across the region (Fig. 4). In the classification established by Uzbek geologists, the main reflectors on the seismic

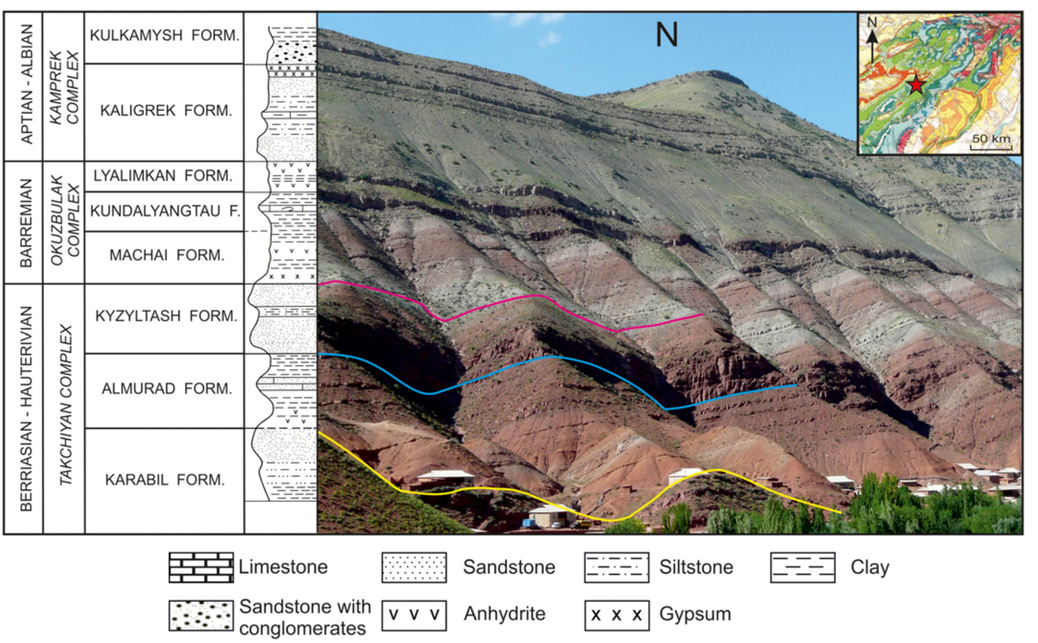

Fig. 6. Lower Cretaceous succession near Machay village (central part of Southwestern Gissar). Stratigraphy after Mirkamalov (1975). The continental to marine transition occurred during the Barremian. The Barremian gypsum layers probably correspond to the T2 reflector (see Fig. 4). The scale is given by the houses and cars at the bottom. Inset: location of the section shown by a red star on a fragment of the geological map of Uzbekistan (Shayakubov 1998); area coverage shown by white rectangle in Figure 1.

profiles are referenced from bottom to top as T9–T1 (Fig. 4). Only reflectors T2–T7 have been used in this study, T1 being Cenozoic in age and T8–T9 being poorly determined on the seismic profiles.

The uppermost picked reflector T2 separates two contrasting lithologies (siliciclastic at the base and carbonate at the top) and as such displays a characteristic seismic signature easily traceable on all of the lines. It corresponds to the roof of the so-called XIII horizon, located within the Lower Cretaceous strata (Figs 4 & 6). The roman numerals indicate the position of the horizons (numbered from the top) in the stratigraphic column defined by Uzbek hydrocarbon exploration companies (Fig. 4). The XIII horizon generally corresponds to red–brown sandstones with interbedded red clays, siltstones and locally limestones, located in the Berriasian to Barremian interval. These continental rocks are characterized by strong reflectors (high continuity, high amplitude) with a transparent interval at the top corresponding to the Barremian evaporitic layers (Fig. 6), thus allowing them to be distinguished from the marine Lower Cretaceous deposits lying above.

The T4 and T3 reflectors, located within the evaporite unit, correspond to the top of the middle anhydrite layer and the upper salt layer, respectively (Fig. 4). In general, the evaporites produce a weak seismic signature and can only be weakly traced across the seismic lines used in this study. The T5 reflector marks the top of the lower anhydrite layer.

The T6 reflector represents the top of the Jurassic carbonate unit. The Middle–Upper Jurassic carbonates generally display a moderately thick package of continuous and high amplitude reflectors. Commonly only the top (T6) of this unit is well marked by a single strong seismic reflector. However, in some seismic lines this reflector is difficult to determine because of interferences with the T5 horizon, resulting from the reduced thickness of the lower anhydrite unit.

The T7 reflector marks the top of the Jurassic siliciclastic unit. This reflector is often of poor quality and is consequently difficult to ascertain. This is probably due to the fact that this reflector generally appears in the deepest part of the profiles. In addition, because most of the potential reservoirs are located above the Jurassic siliciclastic unit, the data below the productive horizons have been poorly investigated.

Data and methods

The Bukhara-Khiva area is the main hydrocarbon province of Uzbekistan and has been intensively explored over the last 50 years. We used mainly subsurface data to investigate the structure of the Bukhara and Chardzhou steps, including wells and seismic profiles generally provided by Uzbekgeofizika and IGIRNIGM of Tashkent. We also integrated a variety of other subsurface data, including the common depth point (CDP) seismic reflection data, vertical seismic profiling sections, depth–structure maps (depths below the mean sea-level) of different pre-Jurassic–Mesozoic surfaces and borehole data. Most of these data are from unpublished internal reports of Tashkent institutes.

Seismic profiles are abundant in this area, particularly two-dimensional seismic profiles. Most were shot by the CDP method. However, some seismic lines were obtained by the deep seismic sounding (DSS) and earthquake converted-wave (ECW) methods. Most of these seismic profiles were acquired in the 1980s to 1990s. Some of them, especially the DSS and DSS–ECW profiles, were designed to investigate the deep structure of the basin. The available seismic profiles are generally not accurate enough to perform a detailed stratigraphic analysis. However, they clearly display the main reflectors and the seismic grid is dense enough to identify the main stratigraphic units, structures and faults across the Amu-Darya Basin margin,

Intensive exploration activity in the Bukhara-Khiva region has resulted in the presence of a dense array of drilled wells, some of them aimed at deep targets. However, only a few were accessible for this study and some of these have incomplete lithological columns. The only lithologies described in any detail are often those from the oil- and gas-bearing horizons. In many cases only the well stratigraphy is available and this is generally based on old stratigraphic charts. Thus to provide a good stratigraphic framework for the calibration of the reflectors and for subsequent depth calculations, we selected wells within the limits of the lines that provided good coverage along much of the cross-sections (Fig. 2).

Taking into account the low quality and irregularity of the seismic information, we integrated cartographic information to complement that derived from the seismic lines and well data. We have mainly used maps provided by Uzbekgeofizika, including depth–structure maps (depths below mean sea-level) of the pre-Jurassic, the Jurassic siliciclastic and carbonate surfaces, and the XII horizon top. These maps were constructed using much more subsurface data than was made available to us, as well as gravity and magnetic models for the deepest levels. These various maps have been mainly used to determine the main subsurface relief structures and the locations of the main faults.

Cross-sections

We constructed eight cross-sections (Mordvintsev 2015) taking into account the location of the available seismic profiles and wells in the Bukhara-Khiva

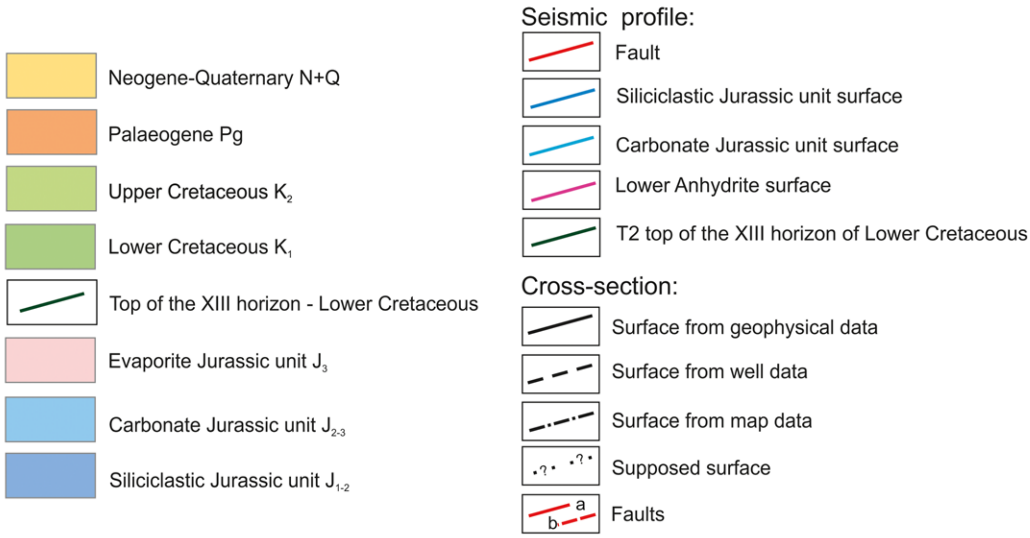

Fig. 7. Legend for Figures 8–12 and colours of stratigraphic layers for Figures 8–12. The right-hand panels shows the meaning of lines in Figures 9–11; seismic lines with interpreted depth sections.

region (Fig. 2). Six sections are oblique to the Bukhara and Chardzhou steps and oriented NE–SW and NS. Four of these six sections (green lines on Fig. 2) were based on seismic profiles, whereas the remaining two cross-sections (red lines on Fig. 2) were reconstructed using just geological and well data. The two NW–SE-oriented cross-sections are located along the Bukhara and Chardzhou steps, respectively. Both of these sections were constructed using geological and well data.

Six constructed cross-sections are presented here (see Figs 7–12). Four of these (A–A′, C–C′, E–E′

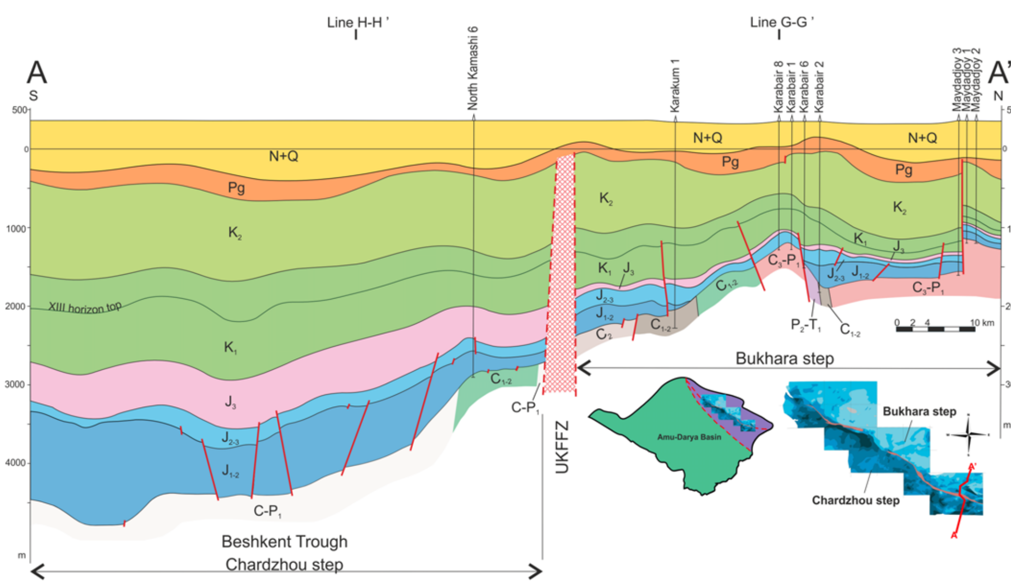

Fig. 8. Cross-section A–A′ through the Bukhara and Chardzhou steps reconstructed from depth–structure maps (depths below the mean sea-level) and borehole data. Location on Figure 2; for legend, see Figure 7. C, Carboniferous; P, Permian; T, Triassic; UKFFZ, Uchbash-Karshi Flexure-Fault Zone.

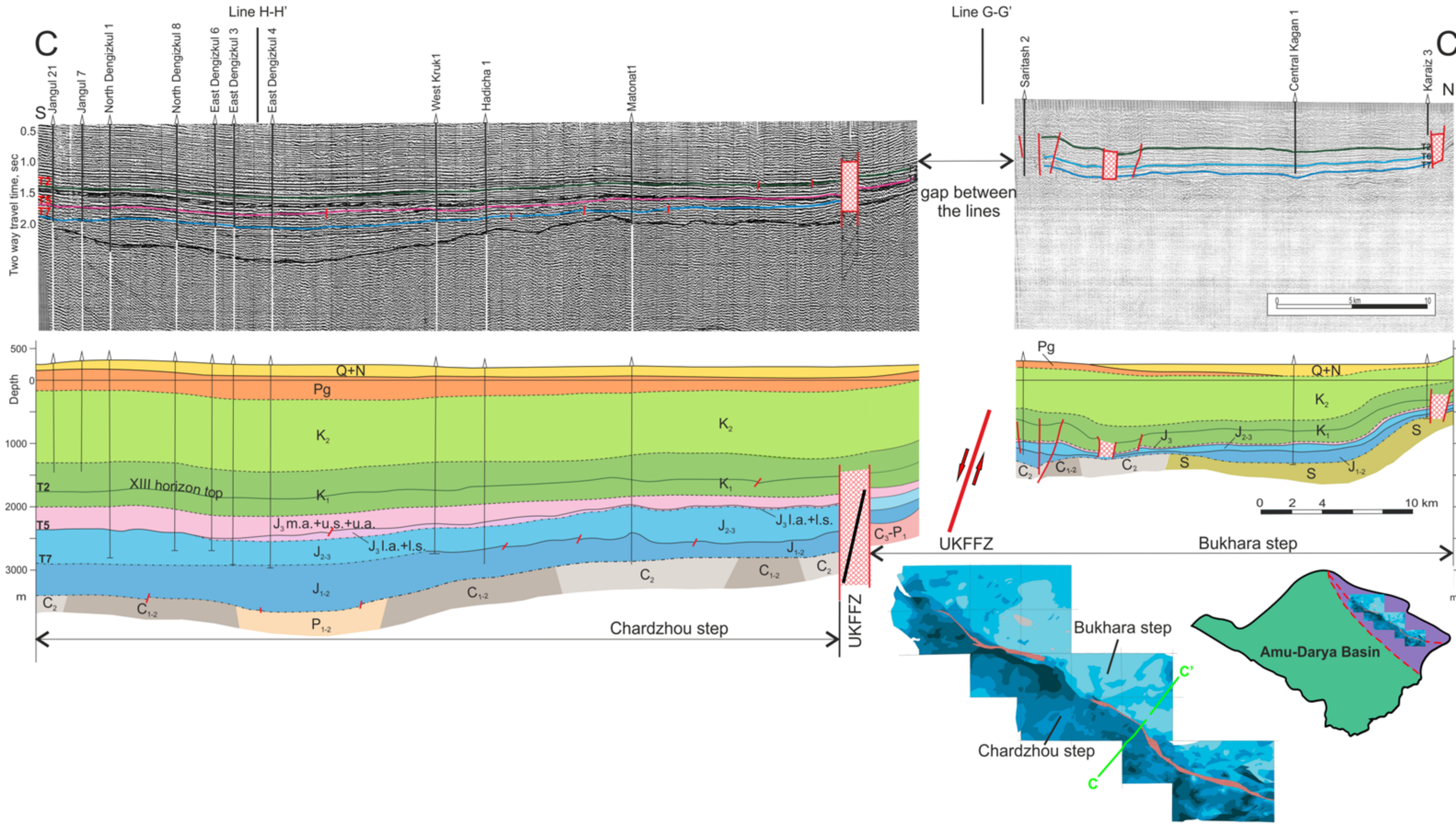

Fig. 9. Cross-section C–C′ through the Chardzhou and Bukhara steps reconstructed from two seismic profiles, depth–structure maps and borehole data. The top section shows the seismic profiles in time (two-way travel time in seconds) from zero altitude. The bottom section is interpreted and converted in depth (m). Location shown on Figure 2; for legend, see Figure 7. C, Carboniferous; l.a., lower anhydrite; l.s., lower salt; m.a., middle anhydrite; P, Permian; S, Silurian; u.a., upper anhydrite; UKFFZ, Uchbash-Karshi Flexure-Fault Zone; u.s., upper salt.

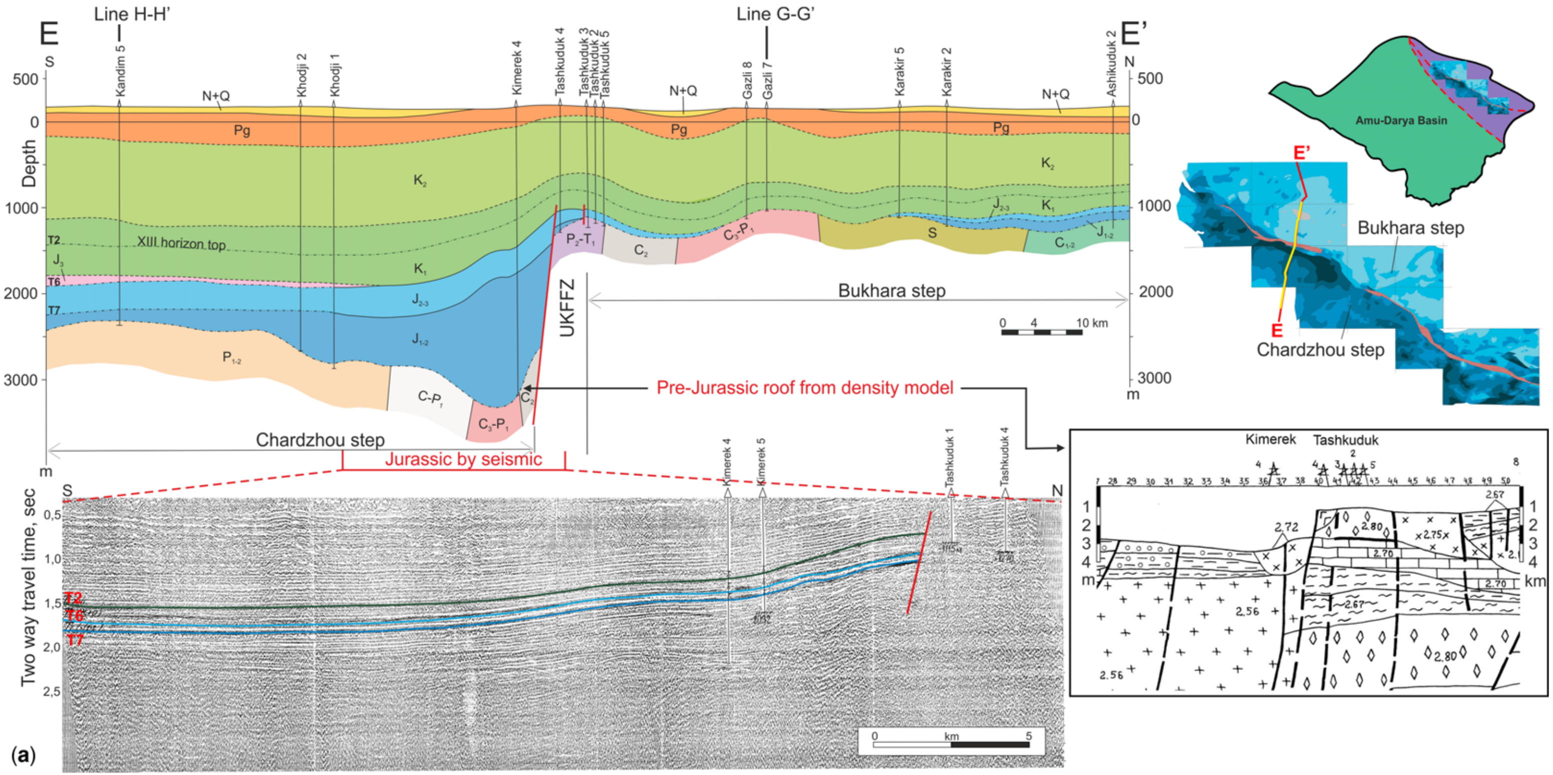

Fig. 10. (**a**) Cross-section E–E′ through the Chardzhou and Bukhara steps reconstructed from depth–structure and geological maps, seismic profile for a small part and borehole data. Pre-Jurassic surface from gravity model. Bottom right, enlargement of the central part (red rectangle) of the model of Figure 10b; modified from Mordvintsev O.P. in Babadzhanov (2008). Depths from zero altitude. Location is shown on Figure 2; for legend, see Figure 7. C, Carboniferous; P, Permian; S, Silurian; T, Triassic; UKFFZ, Uchbash-Karshi Flexure-Fault Zone.

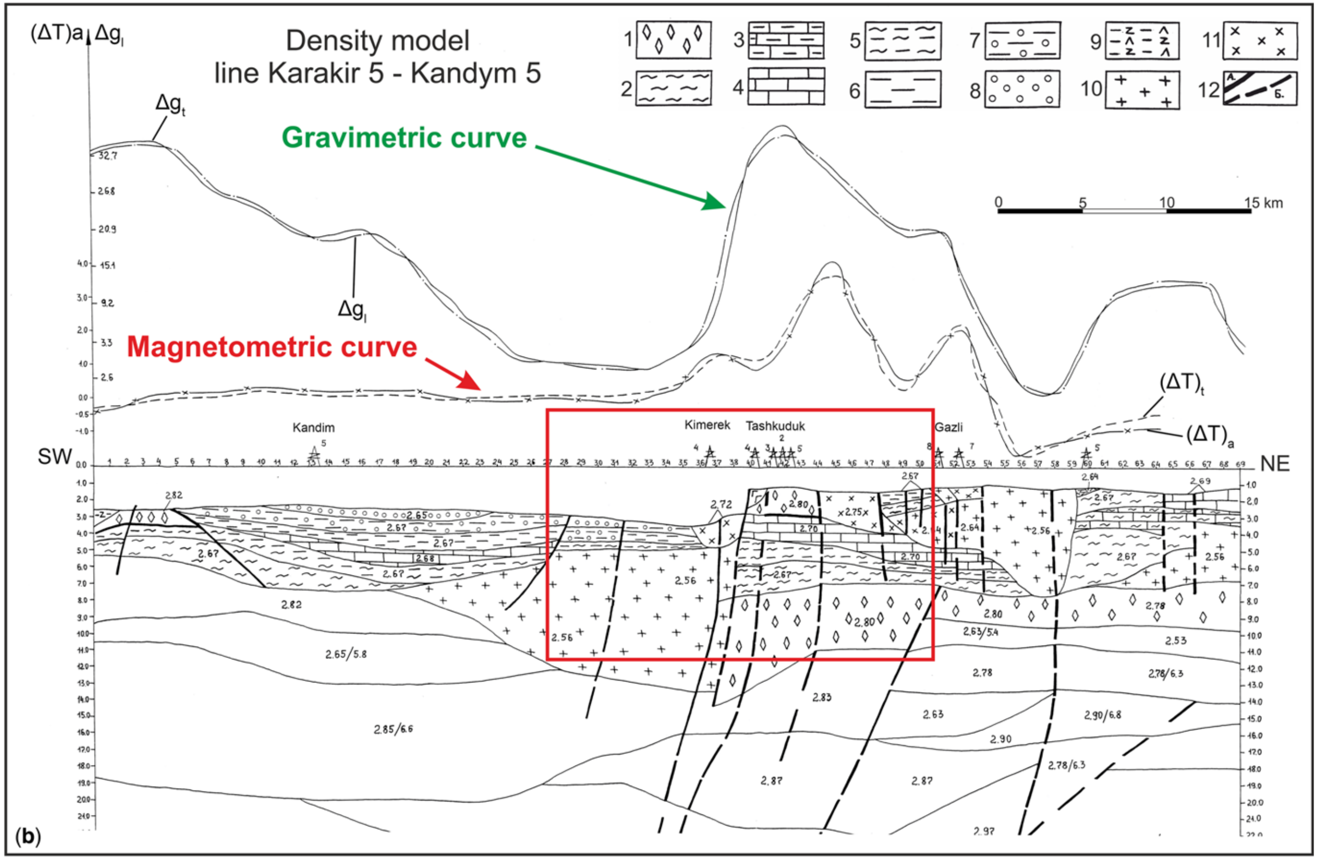

Fig. 10. (*Continued*) (**b**) Crustal-scale geophysical model along a cross-section of the Bukhara and Chardzhou steps cutting the Kimerek Graben (after O.P. Mordvintsev in Babadzhanov 2008). Location is yellow line on E–E′ line (Fig. 10a). $(\Delta T)_a$ – observed magnetic field; $(\Delta T)_t$ – theoretical curve of the magnetic field from the model; Δg_l observed local Bouguer gravity anomaly; Δg_t theoretical gravimetric anomaly from the model. The central part (red rectangle) of the model is enlarged in Figure 10a, bottom right. This density model shows an intrusion in the Palaeozoic sediments of the Kimerek Graben linked to the position of the UKFFZ, north of the Kimerek Graben; the empty layer below the zero altitude line corresponds to the Meso-Cenozoic sediments. 1, Crystalline basement rocks; 2, Palaeozoic clastic rocks; 3, carbonate–clastic rocks of D_3–C_1; 4, D_3–C_1, carbonates; 5, C_1–C_{1-2} clastic rocks; 6, C_2, C_{2-3} sandy–shaly rocks; 7, C_3–P_1, P_1 sandstone, siltstone, clay and shale; 8, P_{1-2}–T conglomerate and sandstone; 9, volcaniclastic rocks with intermediate and acid effusives; 10, granites; 11, diorites; 12, faults.

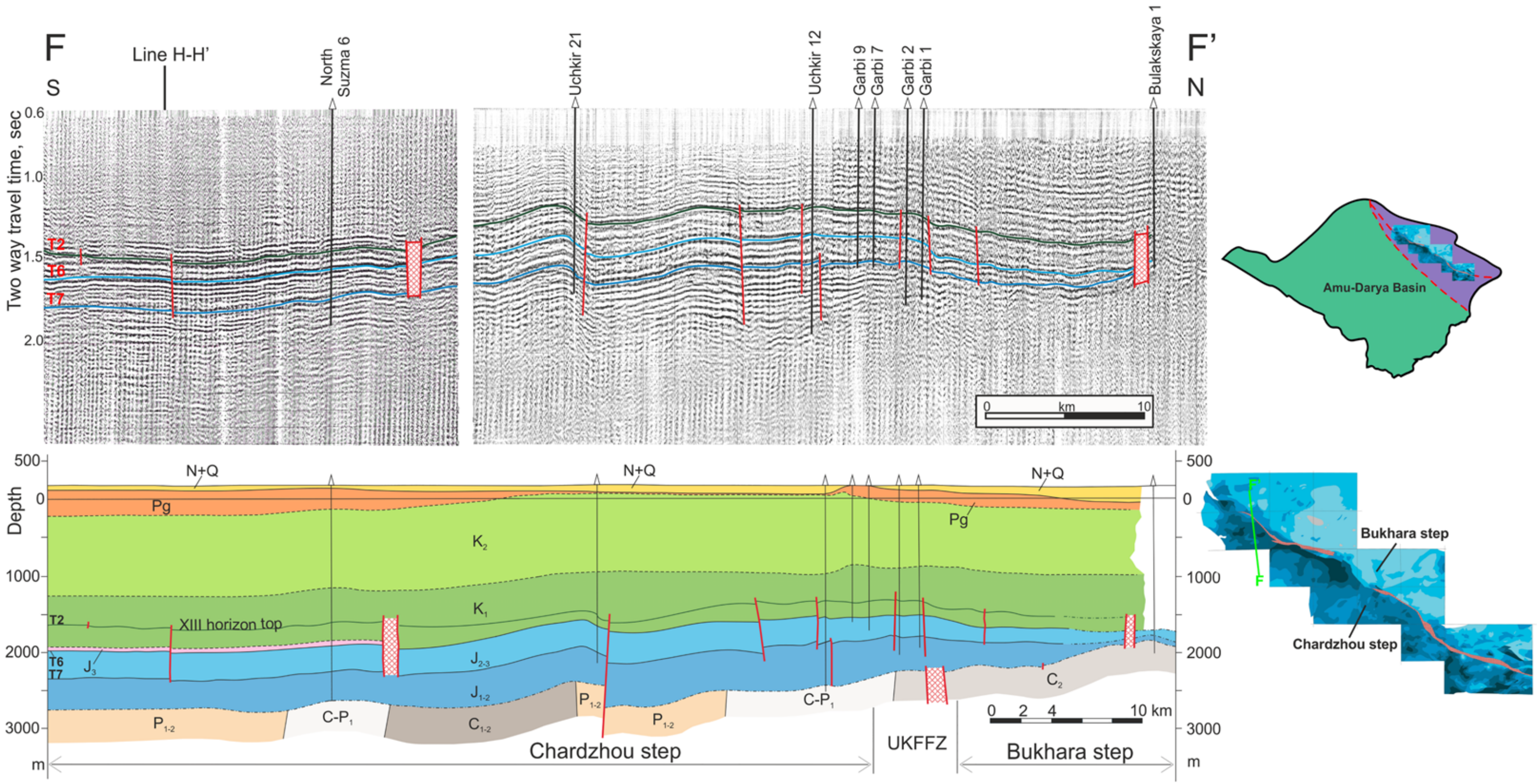

Fig. 11. Cross-section F–F′ through the Chardzhou and Bukhara steps reconstructed from seismic profiles, depth–structure maps and borehole data. Depths from zero altitude. Location shown on Figure 2; for legend, see Figure 7. C, Carboniferous; P, Permian; UKFFZ, Uchbash-Karshi Flexure-Fault Zone.

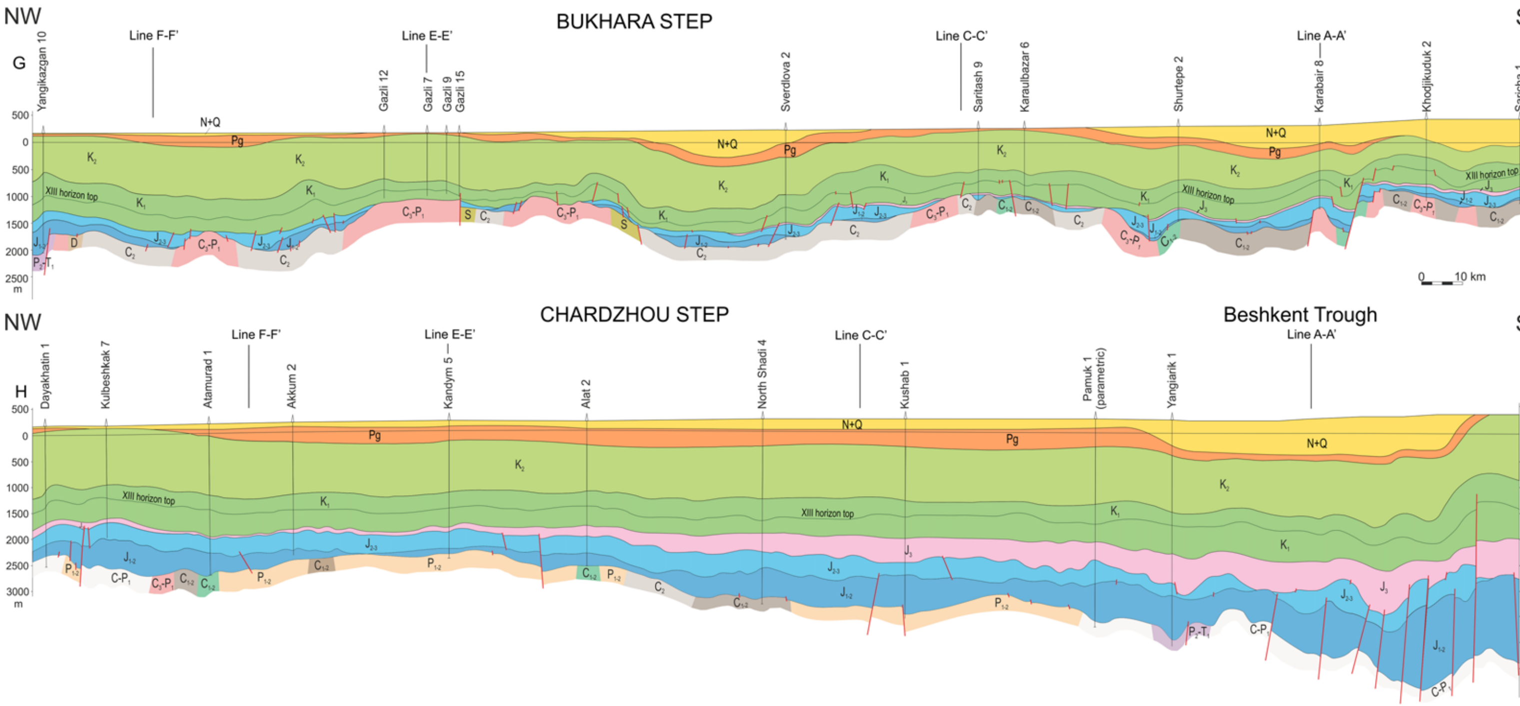

Fig. 12. Cross-sections G–G′ and H–H′ along the Bukkhara and Chardzhou steps, respectively. Both cross-sections are reconstructed from depth–structure and geological maps and well data. Depths from zero altitude. Location shown on Figure 2. C, Carboniferous; P, Permian; S, Silurian; T, Triassic.

and F–F′) are almost perpendicular to the Bukhara and Chardzhou steps (Figs 8–11), whereas two are oriented parallel to the trend of the steps, thus allowing us to correlate between the other lines (G–G′ and H–H′, Fig. 12). We focus here on the Mesozoic successions, the period during which the most interesting tectono-stratigraphic events of the Amu-Darya Basin took place.

Cross-section A–A′

This easternmost section is located close to the Southwestern Gissar Range. This line was constructed using geological data, borehole data and depth–structure maps only because no seismic profile was available in this area (Fig. 8).

This section can in general be characterized by the significant thickening, in a southwards direction, of the entire Mesozoic succession, from *c.* 850 m in the north to >4000 m in the south. This thickening is not homogeneous, neither in time nor in space. The Bukhara and Chardzhou steps are clearly separated by a major normal fault zone, the UKFFZ.

The Jurassic succession, which includes the siliciclastic, carbonate and evaporite units, is rather thin in the area of the Bukhara step, ranging from <200 to 600 m, whereas it increases in thickness south of the UKFFZ in the Chardzhou step from 700 to *c.* 2000 m. In contrast with the Jurassic, the Cretaceous succession shows a more gentle trend, increasing from 800 m in the north in the area of the Bukhara step to *c.* 2400 m in the south without any major break in thickness, even where it crosses the UKFFZ.

In the area of the Bukhara step, the thickness of the Jurassic units generally shows large variations. The clastic sediments of the siliciclastic unit were not deposited everywhere across the step, but were rather localized in the areas of the Early–Middle Jurassic graben (maximum thickness 300 m), which thus preserve the pre-existing palaeotopography. The highs (e.g. on the Karabair structure, Fig. 8) were areas of non-deposition. By contrast, the carbonate and evaporite deposits cover the entire area of the Bukhara step. Both of these units are rather thin (100–200 and 10–20 m, respectively) and they generally increase in thickness to the south.

In the Chardzhou step, the basal siliciclastic and upper evaporite units are significantly thicker, attaining thicknesses in the south of 1200–1300 and 600 m, respectively. The Middle–Upper Jurassic carbonates located between the basal siliciclastic and upper evaporite units are, in contrast, relatively thin, with thicknesses varying between 100 and 160 m, but remaining relatively constant. This thickening of the lower and upper units is likely to have been related to periods of extension in the Jurassic, as evidenced by the presence of normal faults bounding the graben in the siliciclastic and carbonate units. The evaporites attain a thickness of 400–600 m to the south of the UKFFZ.

The main tectonic feature of this cross-section is the UKFFZ, which abruptly separated the Bukhara and Chardzhou steps during the Jurassic. The thickening observed in the southern hanging wall block of the evaporite unit indicates that normal faulting was Late Jurassic in age. The UKFFZ was a major NW–SE-oriented normal fault zone that partly controlled sedimentation during the Jurassic. Normal faults appear to offset the Jurassic succession on both of the steps. Most of these faults disappear into the evaporites, indicating that the extensional phase possibly continued into the Late Jurassic. It is not clear from this section when precisely the phase of normal faulting commenced (e.g. whether or not it began in Early Jurassic times).

Several reverse faults that cut through the entire Mesozoic succession in the northernmost part of the section (i.e. in the Bukhara step) have been noted. These are probably Late Cenozoic in age and correspond to the NE-trending north-vergent thrusts that frame the northern edge of the Southwestern Gissar Range.

In the A–A′ section the Cretaceous units conformably overlie the Jurassic succession. The Cretaceous is characterized by a relatively regular north–south thickening along the section, from 250 m in the north to 1200 m for the Lower Cretaceous and from 500 to 1200 m for the Upper Cretaceous. It is possible that an Early Cretaceous extensional event occurred, as suggested by the presence of normal faults that cut the sediments of this age and which are absent in the Late Cretaceous strata. By contrast, the general thickening of the Upper Cretaceous succession may indicate the prevalence of either a thermal or a long wavelength subsidence of the area during this period.

Cross-section C–C′

Located 80–100 km west of the A–A′ cross-section, the C–C′ section was reconstructed from two seismic profiles, depth–structure maps and well data (Fig. 9). This section could not be entirely reconstructed because of the gap existing between the two seismic profiles.

In the northern part of the line, corresponding to the Bukhara step, the Jurassic succession is up to 200 m thick and displays a complete sequence, including the siliciclastic, carbonate and evaporite units. Several faults and fault zones have been observed in the Bukhara step, cutting the Jurassic as well as the lower part of the Cretaceous. We assume that these normal faults formed during the Early–Middle Jurassic period because they are associated with syntectonic thickening of the Jurassic deposits – for example, along the Saritash structure (Fig. 9). In this latter feature, some of the normal faults were reactivated as reverse or strike-slip faults during the phase of Late Cenozoic compression.

In the area of the Chardzhou step, the Mesozoic units are well developed and are well imaged (series of high continuity, high amplitude, broadly horizontal reflectors). The average thickness of the Jurassic succession in the Chardzhou step region is 1000–1200 m, but may be locally thicker (e.g. 1400 m towards the SE). In the Chardzhou step, the C–C′ section is characterized by a lack of major normal faults. We only observed several south-dipping normal faults with minor displacements. However, as the maximum thickness of siliciclastic sediments is observed where these faults are frequent (between the West-Kruk 1 and East Dengizkul structures), we suggest that they, at least partly, controlled sedimentation during the Jurassic.

The Cretaceous units conformably overlie the Jurassic succession, exhibiting an almost constant thickness of 1700–1800 and 1200–1300 m in the Chardzhou and Bukhara steps respectively. The main vertical displacements related to normal faulting in the region are observed in the northeastern part of the Chardzhou step, where the cross-section intersects the UKFFZ. Here, the base of the siliciclastic unit exhibits a vertical displacement of *c.* 400 m in the Lower–Middle Jurassic siliciclastic succession. This vertical displacement decreases markedly towards the top of the Jurassic succession. It is probably related to movement along a SW-vergent normal fault, which presumably forms part of the UKFFZ. Another branch of the UKFFZ is probably located in the gap between the two seismic profiles (Fig. 9). At the southwestern edge of this gap the base of the siliciclastic unit is *c.* 650 m lower than along the northeastern edge. This significant difference suggests that a SW-dipping normal fault system (possibly a northern branch of the UKFFZ) existed in Jurassic times, revealing the complex nature of this regional fault zone.

Cross-section E–E′

This cross-section images the structure of the western part of the northern margin of the Amu-Darya Basin and clearly shows the presence of a Jurassic trough in the region (Fig. 10). This line was reconstructed from well data, depth–structure map data, as well as unpublished seismic profiles.

The thickness of the Mesozoic increases from 1000 m in the northern part of the section to 2300 m in the south. This marked variation in thickness is due to the significant thickening of the Jurassic succession, particularly the siliciclastic part of the succession, to the south. In the Bukhara step area, the Jurassic deposits are thin (<200 m) or absent. The siliciclastic Lower Jurassic unit never exceeds 100 m. The main thickening of the Jurassic sequence in the Chardzhou step area is observed where the E–E′ section (Fig. 10a) crosses the Kimerek Basin, (=Kimerek Graben, but renamed herein as it is, in fact, a half-graben). This latter basin is bounded to the north by the UKFFZ, where it is expressed as a major south-dipping normal fault. As the bulk of the sediments deposited in this basin are Early–Middle Jurassic in age (up to 1700 m of Lower–Middle Jurassic from a total Jurassic thickness of 1900 m), we suggest that the UKFFZ was active during this period. Fault activity decreased during the Late Jurassic and probably stopped in the Kimmeridgian (the age of the top of the carbonate unit).

The carbonate unit, which is only partly present in the Bukhara step area (where it is <100 m thick), is much thicker in the Chardzhou step area (on isopach maps it is up to 300–350 m). The very thin overlying evaporite unit is only present in the southernmost end of the section (i.e. in the Chardzhou step region).

The Lower Cretaceous either conformably overlies the Jurassic succession in the Chardzhou step or unconformably covers the Palaeozoic units in the Bukhara step where the Jurassic is thin or absent. The Cretaceous succession thickens gently to the south, from *c.* 900 to 1500 m.

The Kimerek Basin is mainly a Jurassic structure because the overlying Cretaceous succession does not appear to have been affected by tectonic activity along the UKFFZ. The basin forms a WNW-elongated trough, about 75 km long, along the western segment of the UKFFZ, the Lower–Middle Jurassic being thinner in the eastern part of the Chardzhou step (Fig. 2). The UKFFZ was already a significant boundary between the Bukhara and Chardzhou steps during the Palaeozoic, as confirmed by the occurrence of intrusions near the UKFFZ, the heterogeneity of both the age and thickness of Palaeozoic sediments on either side of the UKFFZ and the occurrence of geophysical anomalies (Fig. 10b; e.g. Babadzhanov 2008; Babadzhanov & Abdullaev 2009; Brunet *et al.*, this volume, in press).

Cross-section F–F′

This is the westernmost cross-section and has been mainly reconstructed from two seismic lines, well data and depth–structure maps (Fig. 11). One of the main points of interest on this section is the lack of any well-marked geological or morphological boundary between the Bukhara and Chardzhou steps. Furthermore, the UKFFZ does not appear to exist as a significant structure in the Mesozoic succession. The western extension of the UKFFZ is restricted to some minor reverse faults in the area of the Garbi structure, whereas in the other cross-sections it is imaged as a major normal fault zone.

The thickness of the Jurassic siliciclastic unit is only 50–100 m in the northern part of the section, but thickens to *c.* 400–600 m across the remainder of the profile. Similarly, the carbonates, which are *c.* 100 m thick in the north, thicken to 300–350 m along the section. The overlying evaporites are only present in the southern part of the section, where they are very thin (*c.* 60 m). The Cretaceous succession, which conformably overlies the Jurassic, shows a relatively constant thickness (*c.* 1500–1800 m) across the section.

Cross-section G–G′

This WNW–ESE- to NW–SE-oriented section is parallel to the strike of the Bukhara and Chardzhou steps and crosses the former (Fig. 12). It was reconstructed from deep drilling data and depth contour maps. The most important feature noted from the profile is the fact that the sedimentation pattern during the Jurassic in the Bukhara step area appears to have been very heterogeneous. In more detail, the Jurassic deposits are generally thin, discontinuous or commonly absent. The Jurassic siliciclastic sediments were generally deposited in topographic lows, which were oriented obliquely and perpendicular to the main orientation (NW–SE) of the Bukhara step. Clastic deposition in some of these lows was controlled by fault activity in what were probably Early–Middle Jurassic grabens (=palaeovalleys). However, not all of the lows were fault-controlled and some of them do not show any evidence of faulting along their margins. These latter lows were probably Jurassic topographic lows inherited from pre-existing Late Permian–Triassic features. The depositional settings included extensive alluvial plains and associated valleys, with sediments derived from the erosion of adjacent Late Palaeozoic highs. Thus these NE-trending Early–Middle Jurassic valleys supplied the Amu-Darya Basin with clastic detritus sourced from the north in the remnant Palaeozoic topographic highs.

The Middle Jurassic transgression flooded the topographic lows, resulting in the deposition of marine carbonates above the Lower–Middle Jurassic siliciclastic sediments. This transgression locally extends across the intervening basin highs where the sediments appear to unconformably overlie the Palaeozoic units. Both the carbonate unit and the siliciclastic units are discontinuous and are absent on the intra-basinal highs. A number of NE-trending normal faults were still active during the period of carbonate deposition, although fault activity was markedly lower than during the preceding period of siliciclastic sedimentation. The evaporites consist of a very thin layer present only in the southeastern part of the section. During the latest Jurassic the sea almost completely retreated from the Bukhara step, except in the SE.

The thickness of the Cretaceous succession ranges from 1800 m in the NW to 800–900 m in the SE of the section. The Lower Cretaceous beds covered the entire Bukhara step. They conformably overlie the Jurassic deposits and unconformably cover the pre-Jurassic formations on the Late Jurassic highs. The Lower Cretaceous succession is clearly cut by a series of normal faults trending obliquely to the orientation of the Bukhara step (i.e. NE–SW). These normal faults may display significant throws, such as the west-dipping and NE–SW-trending Karabair Fault (Fig. 12). These normal faults provide evidence of an Early Cretaceous extensional event, which can be observed along all of the Bukhara step and through into the Southwestern Gissar Range. The Upper Cretaceous succession is *c.* 1000 m thick across much of the section. In the eastern part of the line its thickness decreases to the SE to *c.* 300 m.

Cross-section H–H′

This NW-trending section along the main direction of the Chardzhou step exhibits a complete Jurassic sequence, which is conformably overlain by a thick Cretaceous succession (Fig. 12). In contrast to the Bukhara step, there is evidence of significant thickening of the Jurassic succession from 600 to 2400 m towards the SE. Across much of the cross-section the Mesozoic units appear to be tectonically undisturbed, apart from the southeastern part of the section (i.e. the Beshkent Trough), where Cenozoic reverse faults offsetting the Mesozoic succession are observed. These faults significantly modify the configuration of the Jurassic strata.

The Jurassic siliciclastic unit is generally 300–500 m thick. Its maximum thickness (1600 m) is reached in the southeastern part of the section in the Beshkent Trough. The thickness of the entire Mesozoic succession also increases towards the SE. The carbonate unit displays an almost constant thickness of 300–400 m (with minor variations) across the section. Some variations were noted in the southeastern part of the line in the area of the Beshkent Trough, where most of the Cenozoic reverse faults are concentrated near the uplifted Southwestern Gissar Range. The evaporite unit also attains its maximum thickness in the Beshkent Trough. This unit, which is *c.* 50 m thick in the northwestern part of the section, gradually increases to 800 m in the SE. The overlying Cretaceous units exhibit an almost constant thickness (*c.* 1500 m) across the region, with continuous, high amplitude reflectors on the seismic section, suggesting possible subsidence on a regional scale.

Structure and Mesozoic evolution of the Bukhara and Chardzhou steps

The cross-sections described in the preceding text have been integrated with field investigations, enabling us to more precisely characterize the structure and evolution of the northern margin of the Amu-Darya Basin during the Mesozoic. In the Bukhara-Khiva region, the onset of the Jurassic was marked by a major change in both the tectonic and depositional regimes. Subsequently, at the end of the Middle Jurassic, a series of changes occurred that were related to the interplay of climatic and tectonic activity and their effects on the lithological character of deposition as well as the sediment thickness and distribution. In the Late Barremian, transgression resulted in flooding of the entire region.

Thickness variations and normal fault tectonics: synrift sedimentation

The results from this study indicate that Lower Jurassic (and possibly the uppermost Triassic) to lower Middle Jurassic continental sediments comprise the lower part of the Mesozoic succession and that these are thicker in the Chardzhou step region than in the area of the Bukhara step. This mainly siliciclastic unit unconformably overlies the pre-Jurassic formations, which include crystalline basement and Palaeozoic sediments. The Early to early Middle Jurassic environments were mainly non-marine and included fluvial systems with related floodplains, lakes and swamps (Egamberdiev & Ishniyazov 1990; Fürsich *et al.* 2015). Coarse clastics are mainly confined to the basal Lower Jurassic section, probably Pliensbachian–Toarcian in age (and possibly – and locally – uppermost Triassic) and commonly containing coal beds.

A clear NE to SW thickening of the entire Jurassic succession is evidenced from the lines A–A′, C–C′, E–E′ and F–F′ (Figs 8–11) as well as on an isopach map (Fig. 2). The Jurassic siliciclastic sediments in the Bukhara step area are generally thin (where present). In addition, they tend to be concentrated in small, localized depressions. The thickness of the Jurassic siliciclastic sediments increases considerably in the region of the Chardzhou step, south of the UKFFZ, where thicknesses >2000 m have been noted in the Beshkent Trough (Figs 2, 12 & 13). At this time, several depocentres developed in the area of the Chardzhou step, mainly as graben and half-graben (e.g. the Kimerek Basin), while, as noted earlier, sedimentation in the Bukhara step was reduced or absent on the localized highs (Figs 2, 8, 10 & 12). The marked thickness variations within the Early–Middle Jurassic siliciclastic succession across the region can be attributed to coeval tectonic activity along NW–SE-trending normal faults (Figs 8 & 10).

The first marine siliciclastic sediments appear in the early Late Bajocian and their occurrence can partly be related to a eustatic rise in sea-level. Egamberdiev & Ishniyazov (1990), who reconstructed the palaeoenvironmental changes during the transgression in the Southwestern Gissar region, have suggested that the lower part of the Middle Jurassic succession consists of continental sediments rich in silty sand deposited in a fluvial system. As subsidence in the Amu-Darya Basin continued throughout the late Middle Jurassic (Brunet *et al.*, this volume, in press), the sea transgressed from the south and the clastic input decreased, with the sediments becoming finer (the overall trend was from coarse- to fine-grained; for details, see Egamberdiev & Ishniyazov 1990; Fürsich *et al.* 2015). On the Bukhara step, the palaeorivers, which had existed in Early Jurassic time, gradually disappeared. The uppermost part of the siliciclastic succession is characterized by the gradual appearance of carbonate facies.

Very thin evaporites were deposited during the Late Jurassic on the Bukhara step; this latter area represented a region of emergence during the Late Jurassic regressive period (cross-section G–G′, Fig. 12). The evaporite unit is generally present across the Chardzhou step, thickening towards the SW (i.e. the centre of the Amu-Darya Basin; Figs 7 & 9–11; e.g. Ulmishek 2004).

There was a general reduction in extensional activity during the Middle–Late Jurassic, but the presence of some normal faults controlling the deposition of the carbonate unit (A–A′ cross-section, Fig. 8) indicate that it had not altogether ceased. Syndepositional normal faults have also been observed in the Middle–Upper Jurassic carbonate units of the Southwestern Gissar Range, where meso-scale normal faults are common (Fig. 14). The thickness of the carbonate unit also significantly increases to the SW in the Chardzhou step (C–C′, E–E′, F–F′ and H–H′ sections, Figs 9–12), but to a lesser degree than that of the siliciclastic unit.

In the Amu-Darya Basin, the Jurassic succession mainly consists of continental and marine siliciclastic sediments, as well as marine carbonates and evaporites (e.g. Clarke 1988; Ulmishek 2004). In the Early–Middle Jurassic, the Amu-Darya and Afghan-Tajik basins were mainly sourced from the main Cimmerian Ranges, located to the south in northern Afghanistan and northern Iran, which were uplifted during the Middle–Late Triassic (Brookfield & Hashmat 2001; Zanchi *et al.* 2009;

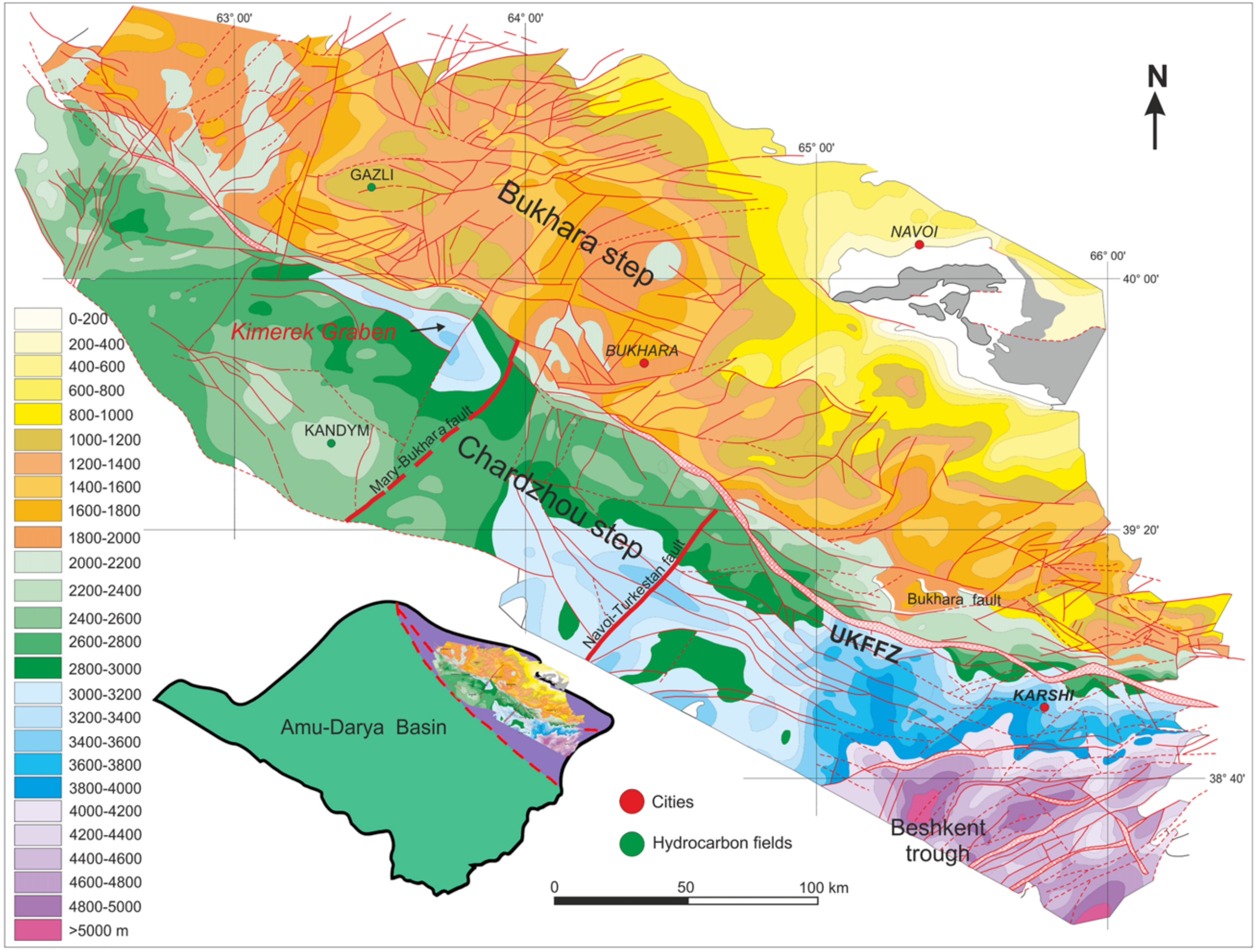

Fig. 13. Depth–structure map of the pre-Jurassic roof (below mean sea-level). This map illustrates the role of the Uchbash-Karshi Flexure-Fault Zone (UKFFZ) as a major boundary between the Bukhara and Chardzhou steps during the Mesozoic. From Mordvintsev (2015), modified after Mordvintsev (2008).

Fig. 14. Example of conjugate system of normal faults in the Callovian limestones. The attitude of the conjugate system with respect to the bedding plane of the limestones is evidence of a pre-tilting activity. Derbent gorge (location shown by red star on the inset map), Southwestern Gissar (southern Uzbekistan).

Zanchetta *et al.* 2013; Siehl 2015). By contrast, the Bukhara and Chardzhou steps were sourced from the remnants of Late Palaeozoic orogens to the NNE (e.g. Natal'in & Şengör 2005; Brookfield 2000; McCann 2016*a*).

The UKFFZ

This nearly 435 km long major fault zone forms the boundary between the Bukhara and Chardzhou steps. It is intersected by all the NE- to north-trending cross-sections reconstructed as part of this study (Figs 8–11). The UKFFZ, which is mainly Late Palaeozoic in age, was probably reactivated as a strike-slip fault during the Late Palaeozoic–Triassic period, as well as subsequently in Late Cenozoic times. However, over much of the UKFFZ there is evidence of normal fault activity during the Early–Middle Jurassic, coeval with the deposition of the siliciclastic succession. In detail, the pattern of normal faulting varied both in terms of its complexity and in its occurrence across the region during Jurassic and Cretaceous times.

In the eastern part of the Bukhara-Khiva region (i.e. the Beshkent Trough), the UKFFZ was active during the Jurassic and Cretaceous (Fig. 8). This activity is evidenced by the presence of significant vertical displacements of several hundred metres of the principal surfaces of the Mesozoic units. To the west of the Beshkent Trough, the rate of normal faulting decreased during the upper part of the Middle Jurassic and finally ceased in the Cretaceous (Fig. 9).

The western segment of the UKFFZ acted as a major normal fault during the Early–Middle Jurassic (Figs 2 & 10). The Kimerek Basin developed within the Chardzhou step as a half-graben during the Early–Middle Jurassic. It is bounded to the north by the UKFFZ and almost 1700 m of siliciclastic sediments were deposited along this fault boundary, which is characterized by a large vertical displacement. This extensional activity also resulted in the formation of a number of other smaller sub-basins (Fig. 2). The F–F′ cross-section shows that the UKFFZ disappears further to the west (Fig. 11), initially being reduced to a minor fault zone before finally disappearing to the NW. Evidence of tectonic activity is rare in this latter area and is mainly confined to the small normal faults that were active during the Mesozoic (Fig. 11).

Extensional activity along the UKFFZ was not only restricted to the period of deposition of the siliciclastic sediments (Early–Middle Jurassic), but continued into Middle–Late Jurassic times, as indicated by the presence of syndepositional features (e.g. sediment bodies thickening towards the fault) observed along the UKFFZ during the deposition of the carbonate unit in the Chardzhou step (C–C′ on Fig. 9; E–E′ on Fig. 10).

The poor quality and low density of the available subsurface data prevent a more accurate assessment of the history of normal faulting along the UKFFZ during the Jurassic and Cretaceous. However, it appears that tectonic activity was variable along the nearly 450 km long fault zone, with some segments being active (and others inactive) during particular periods of the Jurassic. Despite this variability, the UKFFZ can be broadly considered to be a Jurassic normal fault zone within the Bukhara-Khiva region, especially during the Early–Middle Jurassic when the thick siliciclastic succession was deposited. It is the main Jurassic age tectonic feature of the northern margin of the Amu-Darya Basin.

Normal faults and the presence of Middle–Upper Jurassic reefs

Carbonate reefs have been reported in the Chardzhou step since the beginning of hydrocarbon exploration in the first half of the twentieth century. Exploration wells drilled such structures in the southeastern part of the Chardzhou step where it borders the Beshkent Trough (Fig. 15). Some of these reef bodies crop out in the southern part of the Southwestern Gissar Range in southern Uzbekistan and eastern Turkmenistan.

During the Middle–Late Jurassic, carbonates were deposited as reefs and associated lagoonal and basinal environments. In the Middle Callovian–Middle Oxfordian interval a well-developed reef system was deposited in the southeastern part of the Bukhara-Khiva region (Fig. 15). The first patch reefs, which formed in Middle Callovian times, were surrounded by inter-reef bioclastic facies. Subsequently, during the Late Oxfordian–Kimmeridgian, a complex of barrier reefs, pinnacle reefs and atolls developed across the Chardzhou step along the shelf edge and in areas marginal to the deeper water basin. The proposed depositional model suggests that the various environments (e.g. reefs, lagoons) formed part of a larger barrier reef system that developed during Callovian–Kimmeridgian times (Akramkhodjaev *et al.* 1982; Abdullaev & Mirkamalov 1998; Abdullaev 2004; Mirkamalov *et al.* 2005; Fortunatova 2007; Abdullaev *et al.* 2010; Evseeva 2015) (Fig. 15). A number of solitary reef build-ups (pinnacles and atolls) also formed on the deeper water slope. Basinwards the reef system passes laterally into highly organic-rich black shales, which in some places appear to lap onto the reefs (e.g. Besnosov & Mitta 1995; Evseeva 2015).

It is difficult to verify this depositional model, however, because the various seismic profiles that cross the barrier reef system (section C–C′, Fig. 9) poorly image the reef bodies and thus preclude any detailed examination. Figure 15, which shows the main faults of the Bukhara step observed in this study, also reveals that the distribution of the reef barrier facies in the Chardzhou step area forms an inverted U-shaped belt consisting of a series of possible NW- to WNW- and NE-oriented reefs. This particular geometry, when compared with the location and orientation of the main normal faults in the steps (Fig. 15), suggests that reef development was possibly fault-controlled. It appears that the NW–SE- to WNW–ESE-trending normal faults, especially the UKFFZ, correspond to the alignment of the reefal bodies. Similarly, some of the NE–SW-oriented Jurassic normal faults, particularly those of the Beshkent Trough, also may outline the orientation of the barrier reef area (Fig. 15). Based on this close correlation of reef and fault orientation, we suggest that the reefs partly developed on Early–Middle Jurassic fault-controlled highs along the northern margin of the Amu-Darya Basin.

The NE–SW- to ENE–WSW-oriented faults, which controlled the locations of basins and highs along the northern margin of the Amu-Darya Basin, are well imaged on the G–G′ and H–H′ cross-sections, trending parallel to the Bukhara and Chardzhou steps, respectively (Fig. 12). In the Bukhara step (G–G′ section), NE–SW-oriented normal faults locally controlled, at least partly, the deposition of siliciclastic sediments and carbonates within a series of small sub-basins. Some of these Jurassic age normal faults were still active during the Early Cretaceous, particularly during the deposition of the continental red bed series, as indicated by the normal faults bounding the Karabair Basin (see following discussion of the Cretaceous evolution of structure).

In the southeastern part of the Chardzhou step, in the Beshkent Trough, NE–SW-oriented faults with a reverse component are visible on the H–H′ section (Fig. 12). Some of these faults are seen to cut the Lower Cretaceous units, but most appear to be restricted to the Jurassic sedimentary succession. There is also evidence for a progressive ESE-directed thickening of the Lower–Middle

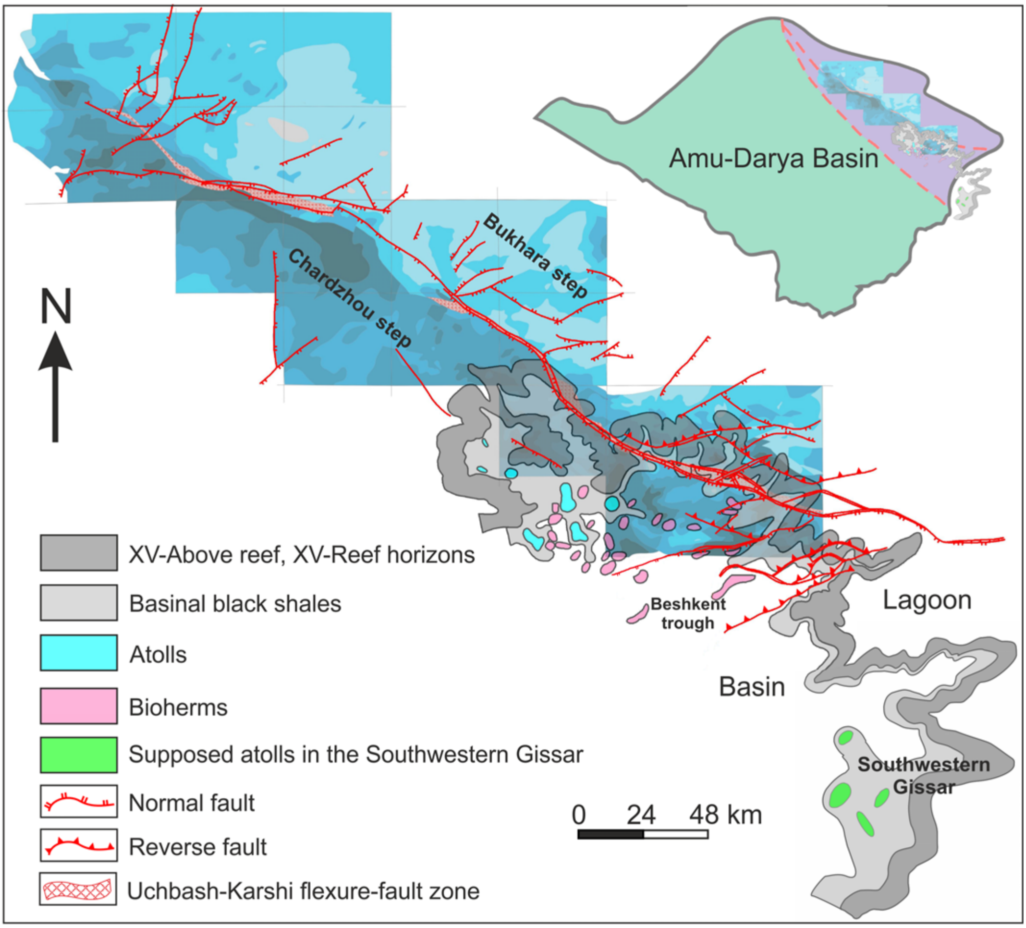

Fig. 15. Map of the main faults evidenced in the Bukhara and Chardzhou steps and location of the reefal facies of the Jurassic carbonate unit (modified from Babadzhanov 2012 and Evseeva 2015). Blue background: isopachs of the Jurassic siliciclastic and carbonate units (legend as in Fig. 2).

Jurassic siliciclastic succession from 600 m to >2 km. This evidence suggests the presence of a NE-oriented Jurassic graben in this area (see the map of Lower Jurassic thicknesses in Brunet *et al.*, this volume, in press). However, taking into account the quality of the data, it is difficult to know whether the poorly characterized faults were NE–SW-oriented Jurassic normal faults reactivated as thrusts during the Neogene or, more simply, newly formed Neogene blind thrusts. In the latter case, the thickening of the siliciclastic Jurassic unit in the Beshkent Trough (Figs 2, 12 & 13) could have been, at least partly, related to tectonic thickening (as a result of compressional thrusting) along the NW front of the Southwestern Gissar Range (Figs 1, 12 & 15) rather than to the development of a Jurassic graben.

Cretaceous evolution

The Berriasian–Hauterivian succession along the northern margin of the Amu-Darya Basin consists of coarse-grained alluvial clastic sediments transported to the SW from uplifted regions to the north. These continental clastic sediments overlie the evaporites, not just in the Bukhara-Khiva region, but across the entire region of western Central Asia, extending as far to the NE as the Talas-Fergana Fault. To the south they cover northern Afghanistan (e.g. Siehl 2015) and to the west the Kopet-Dagh (e.g. Mortavazi *et al.* 2013). From a regional point of view, the continental red beds occupy a broader area than that occupied by the Upper Jurassic carbonates and evaporites, extending over large areas of the southern part of the western Central Asia platform (Barrier & Vrielynck 2017).

There is clear evidence of tectonic activity in the Early Cretaceous, particularly within the continental sediments of the lower part of the succession. On the G–G′ cross-section, the NE–SW-trending faults controlled deposition during the Early Cretaceous in the southeastern part of the Bukhara step. This is indicated by the presence of normal faults bounding the Karabair Basin, east of the Karabair 8 well, particularly during deposition of the continental red bed series (see section G–G′ on Figure 12, thickening of the K_1 layer below the XIII horizon top).

In general, it appears that the Cretaceous succession gently thickens to the SW and centre of the Amu-Darya Basin (e.g. Fig. 8). In the Chardzhou step, the Cretaceous units attain a thickness of up to 2000 m. They generally consist of sequences of nearly constant thickness, especially within the Upper Cretaceous. There is no evidence of a marked change in thickness within the Cretaceous succession on the various cross-sections. Even where crossing the UKFFZ, the thickness of the Cretaceous succession remains constant, suggesting that this major fault zone was no longer active in the Early Cretaceous.

A marine transgression covered the entire Amu-Darya Basin, commencing in the Late Barremian. This transgression was part of a regional event that flooded northern Afghanistan and northern and central Iran to the south, represented by the Orbitolina limestones (e.g. Wilmsen *et al.* 2015), and as far north as the Aral and north Caspian regions. Shallow marine carbonates and evaporites were deposited on the platform areas, whereas in more basinal areas the sedimentation was generally dominated by mudstones. Subsequently, during Aptian–Albian times, well-dated marine shales, siltstones, sandstones, marly limestones and clays were deposited along the margins of the Amu-Darya Basin, as well as in the basin itself (e.g. Ulmishek 2004).

The deposits of the Late Cretaceous in the Amu-Darya Basin are generally characterized by thick accumulations of relatively deep-water clay–marly sediments. Mudstones and siltstones were mainly deposited in the central part of the Amu-Darya Basin, whereas coarser grained sediments accumulated on the margins (Ulmishek 2004). In the Southwestern Gissar Range area, which also forms part of the northern Amu-Darya margin, the Late Cretaceous is represented by siltstones, marly limestones, limestones and clays with interbedded shelly limestones (Tulyaganov & Yaskovich 1980). Only the Cenomanian displays a significant clastic interval represented by the deposition of massive sandstones, siltstones and rare limestones with interbedded conglomerates and gypsum. This clastic interval (e.g. Ulmishek 2004) most probably represents a brief erosional episode of the upland areas surrounding the basin, presumably related to a regional phase of tectonic uplift. The origin of this discrete tectonic event has not yet been explained.

Regional tectonic evolution

In the Late Palaeozoic, a series of collisions involving continental blocks (e.g. the East European, Siberian and Tarim cratons, the Turan and Scythian platforms, and the Kazakh Block) resulted in the formation of the Northern Pangaea supercontinent (e.g. Thomas *et al.* 1999; Filippova *et al.* 2001; Garzanti & Gaetani 2002; Natal'in & Şengör 2005). Subsequently, northwards-directed subduction of the Palaeotethys Ocean beneath the southern margin of northern Pangea commenced. Permian to early Triassic subduction rollback resulted in the development of a north- to NE-oriented extensional stress field behind the subduction zone in the overriding plate. East- to SE-trending back-arc basins developed during this period along the southern margin of northern Pangea. This phase of back-arc extension ended with the onset of Cimmerian compressional activity, which started as early as the Middle Triassic (Berra & Angiolini 2014; Barrier & Vrielynck 2017).

In Mesozoic times, subsequent to the end of Cimmerian collision, extension developed within the Amu-Darya and Afghan-Tajik basins (Hendrix *et al.* 1992; Hendrix 2000; Jolivet *et al.* 2010, 2013; Jolivet 2015). Our analysis suggests that there was a major extensional tectonic event across the region during Early–Middle Jurassic times. This tectonic phase was associated with significant thickening of the Lower–Middle Jurassic siliciclastic unit (mainly as a result of normal fault activity) across the Bukhara-Khiva region. Evidence of extensional activity has also been reported from the deepest part of the Amu-Darya Basin (e.g. Maksimov *et al.* 1986). Subsidence analysis has suggested that there was significant Early–Middle Jurassic tectonic activity across the region (Brunet *et al.*, this volume, in press).

A series of new extensional basins developed along the southern Laurasian platform and margin during the Early–Middle Jurassic (Fig. 16a). The coeval formation of these post-orogenic basins included the Great Caucasus to the west, as well as the South Caspian basins bordering northern Iran (e.g. Brunet *et al.* 2003, 2010; Ershov *et al.* 2003; Taheri *et al.* 2009; Barrier & Vrielynck 2017).

The Early–Middle Jurassic extensional stress fields that developed in the continental crust reactivated pre-existing zones of weakness. Some of these zones probably corresponded to the main

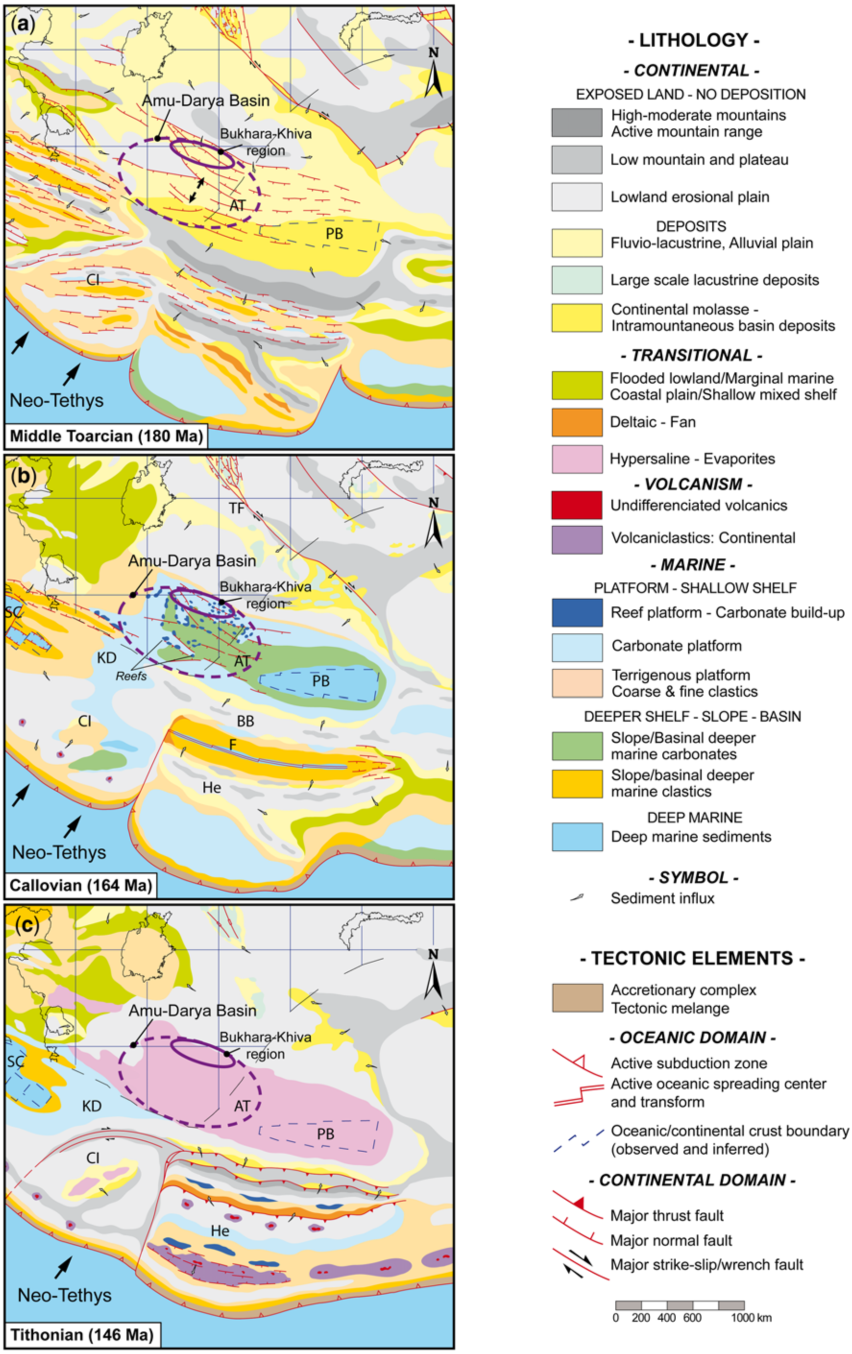

Fig. 16. The Amu-Darya Basin and Bukhara-Khiva region in the western Central Asia region at different stages of the Jurassic. Modified after Barrier & Vrielynck (2017). The areas are outlined by oval shapes with dotted and solid lines for the Amu-Darya and Bukhara-Khiva regions, respectively. Segments of the southern Laurasia margin during the deposition of (**a**) the siliciclastic unit in the Early Jurassic (Middle Toarcian), (**b**) the carbonate unit in the Middle Jurassic and (**c**) the evaporite unit in the Late Jurassic. AT, Afghan-Tajik Basin; BB, Band-e-Bayan block; CI, Central Iran blocks; F, Farah Basin; He, Helmand Block; KD, Kopet-Dagh Basin; PB, Pamir Basin; SC, South Caspian Basin; TF, Talas-Fergana Fault.

Palaeozoic structures (e.g. the Zaravshan, South Tien Shan and South Gissar faults) related to the collisional Central Asian Orogenic Belt (e.g. Brookfield 2000; Windley *et al.* 2007). The normal faults active during the Jurassic rifting period are often inherited structures related to this Carboniferous–Early Permian orogenic belt that were subsequently reactivated (Hendrix *et al.* 1992; Allen & Vincent 1997; Thomas *et al.* 1999; Allen *et al.* 2001; Brookfield & Hashmat 2001; Ulmishek 2004; De Grave *et al.* 2007). The Palaeozoic South Tien Shan and Zaravshan faults (see Fig. 1) form the northern limit of the Early–Middle Jurassic extensional domain of the Amu-Darya Basin. The rifting that developed during the Early–Middle Jurassic along the northern margin of the Amu-Darya Basin either resulted in the reactivation of older structures (i.e. Late Palaeozoic to Early Triassic faults) or the development of new normal faults. Much of the extension was accommodated along east–west- to NW–SE-oriented normal faults (Figs 15 & 16). The most significant example of such fault reactivation in the Bukhara-Khiva region is the UKFFZ, which was active as a normal fault during Early–Middle Jurassic times. Rifting stopped almost entirely during the Middle Jurassic (Fig. 16b) and this was associated with a decrease in the rate of subsidence during the Middle Callovian–Kimmeridgian period (Brunet *et al.*, this volume, in press).

The effects of the broader regional Jurassic tectonic evolution impacted directly on the pattern of sedimentation across the Bukhara and Chardzhou steps. Most of the mountain ranges formed during the Triassic Cimmerian orogeny were being actively eroded during the early part of the Jurassic. There was a marked reduction in the rate of erosion in the Middle Jurassic, possibly related to a more arid climate and reduced topography, which led to a gradual decrease in the amount of clastic input to the Amu-Darya Basin. This reduction was coincident with the ongoing replacement of siliciclastic sediments by carbonates from Bathonian times onwards, together with a switch from a humid to a more arid climate during the Middle Jurassic (e.g. Fürsich *et al.* 2015). The marine transgression that began in the Late Bajocian resulted in the deposition of a carbonate succession that extended northwards onto the Bukhara step (until Kimmeridgian times). This transgression is not fully synchronous with the late Early Bajocian eustatic rise in sea-level (Hallam 2001) and was thus very much related to the increased subsidence at this time (Fürsich *et al.* 2015; Brunet *et al.*, this volume, in press). In the Southwestern Gissar Range region, the Callovian–Oxfordian platforms are carbonate ramps with flat profiles and progressive facies transitions (Carmeille *et al.* 2014, 2016). These carbonate facies belts thin towards the north (Egamberdiev & Ishniyazov 1990). From the Late Callovian, and particularly during the Late Oxfordian–Kimmeridgian, the Amu-Darya Basin was topographically partitioned into a shallow marine shelf in the north, where carbonate reefs and related bodies developed on NW–SE-, WNW–ESE- and NE–SW-oriented horsts, whereas to the SE the basin was characterized by deeper marine sediments (Fig. 16b) (e.g. Evseeva 2015; Brunet *et al.*, this volume, in press).

The final phase of Jurassic sedimentation across the region began with the deposition of the Tithonian evaporites (Fig. 16c). The presence of such extensive evaporites reflects the major changes in climatic conditions and regional palaeogeography that occurred at this time, which were related to the decrease in the rate of subsidence. The thickness of the deposited evaporites corresponds to the filling of the depression created during the Early–Middle Jurassic (Brunet *et al.*, this volume, in press). Arid conditions continued through to the beginning of the Early Cretaceous. Figure 16c is a palinspastic reconstruction of the Tithonian showing the regional extent of the evaporites in the Amu-Darya and Afghan-Tajik basins. The Tithonian palaeogeography shows that the evaporite basin was almost completely surrounded by continental areas (Fig. 16c). To the south, the neo-Cimmerian orogenic belt was developing in northern Afghanistan (from the end of the Jurassic through to the earliest Cretaceous, e.g. Montenat 2009; Siehl 2015). This orogenic belt separated the Amu-Darya and Afghan-Tajik basins in the north from the Farah-Rud Basin in northern Afghanistan to the south. Thus, during the Tithonian, the Amu-Darya and Afghan-Tajik basins could only be supplied with marine waters from the west through an inlet located in the current Kopet-Dagh area. In this area, a barrier formed by shallow marine carbonates separated the open marine Tethys Sea to the south from the Amu-Darya evaporite lagoons to the north.

Conclusions

A study of subsurface data, predominantly wells and seismic profiles from the Bukhara and Chardzhou steps region of the northern margin of the Amu-Darya Basin, allowed the Mesozoic tectonic evolution of the area, particularly that of the Jurassic, to be reconstructed. There is clear evidence of extensional activity in the Amu-Darya Basin after the end of the Cimmerian orogeny in the Middle Triassic. During the Early–Middle Jurassic, deposition along the northern margin of the basin was controlled by NW–SE- to WNW–ESE-oriented normal faults. The main inherited structures related to the Late Palaeozoic orogeny were reactivated as normal faults during this period, while new normal faults also formed and thick continental siliciclastic successions were deposited in a series of isolated graben. Subsequent marine transgression, initiated during the Late Bajocian, resulted in flooding of the entire basin.

Rifting decreased significantly during the Middle Callovian–Kimmeridgian period. From the beginning of the Late Jurassic through to the Kimmeridgian, marine transgression resulted in the deposition of a carbonate succession extending onto the Bukhara step. From Late Callovian times onwards (and particularly during the Late Oxfordian–Kimmeridgian interval), the Amu-Darya Basin was partitioned into a deep marine area occupying the centre of the basin and surrounded by shallow water shelves along its margins, where reefal bodies developed. These carbonate reefs developed on NW–SE- to WNW–ESE- and NE–SW-oriented horsts controlled by active normal faults. The NE–SW- to north–south-oriented extension (as evidenced along the northern margin of the Amu-Darya Basin) occurred during a regional event, which has been recognized across a broad area extending from the Tajik Basin to the east as far as the Great Caucasus Basin to the west, along the southern margin of Laurasia. The location of the Amu-Darya Basin behind the southern margin of Laurasia suggests that its existence is probably related to the prolonged subduction of Neotethys oceanic lithosphere beneath the southern active Laurasian margin.

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