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Abstract: The geological evolution of Central Asia commenced with the evolution of a complex Precambrian–Palaeozoic orogen. Cimmerian blocks were then accreted to the southern margin during the Mesozoic, leading to tectonic reactivation of older structures and discrete episodes of basin formation. The Indian and Arabian blocks collided with Asia during the Cenozoic, leading to renewed structural reactivation, intracontinental deformation and basin development. This complex evolution resulted in the present-day setting of an elongated Tien Shan range flanked by large Mesozoic–Cenozoic sedimentary basins with smaller intramontane basins distributed within the range. The aim of this volume is to present multidisciplinary results and reviews from research groups in Europe and Central Asia that focus on the western part of the Tien Shan and some of the large sedimentary basins in that area. These works elucidate the Late Palaeozoic–Cenozoic tectono-sedimentary evolution of the area. Emphasis is placed on the collision of terranes and/or continents and the ensuing fault reactivation; the impact of changes in climate on the sedimentation is also examined.

The Central Asian region includes an extensive orogenic belt, the Tien Shan, and a series of large, economically valuable, sedimentary basins including the South Caspian Basin in the west (providing a bridge to Europe), the Amu Darya Basin, the Afghan-Tajik Basin and the Fergana Basin, as well as basins further east (e.g. Junggar Basin, Tarim Basin) and south (e.g. Maskhel Basin) (Fig. 1). Within these basins, gas, gas condensate and oil fields have been found, with plays largely located within the Jurassic–Palaeogene-age successions (e.g. Ulmishek & Masters 1993; Clarke 1994). However, with the exception of work by Soviet field geologists (e.g. Vialov 1948; Markowski 1959; Davidzon *et al.* 1982), in terms of recording the complex regional evolution, the sedimentary successions within many of these basins have been largely untouched. Prior to 1989, the entire area was extremely difficult to physically access for foreigners; published papers were largely in Russian and Chinese, while geological and topographic maps were forbidden to foreigners. Today, the ranges and accompanying basins lie in China, Kazakhstan, Kyrgyzstan, Uzbekistan, Tajikistan, Afghanistan and Turkmenistan. While it is now possible to travel throughout much of this region, access to some parts remains problematic. Older maps of the region are sometimes available, but very few new sheets are published in the former Soviet area due to the financial collapse in the early 1990s. In addition, the remote, mountainous topography, the vast desert basins and the inconveniently placed, uncrossable borders contribute to the challenges of working in this area. Despite the obvious geological importance of the region, the western segment remains surprisingly poorly represented in English-language publications. Even the spelling of the range is a subject of debate, providing a metaphor for the contentious geological interpretations. Tian Shan (Pinyin) and Tien Shan (Wade-Giles) are the two dominant spellings for the Heavenly or Celestial Mountains, so named because the peaks often appear to be floating on clouds of vapour or dust. The preferred Russian transliteration, used in this volume, is Tien Shan.

The ancient Silk Road delineates the oldest pathways through the region. This anastomizing trade route is ideally placed to study the proximal portions of many of the basin-bounding ranges; the main range-crossing routes follow major river systems, also providing access to the rugged interior. Transport along these routes is being improved

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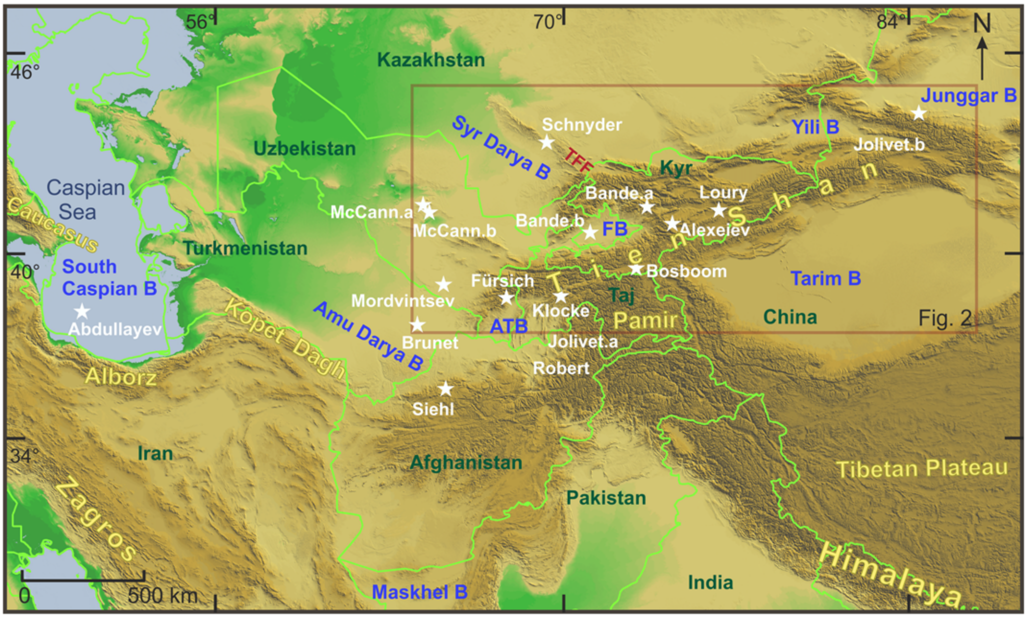

Fig. 1. Location map for the papers presented in this volume, superimposed on a shaded relief background. Stars indicate the approximate regions presented in the papers included in this volume. We provide only the name of the first author. Two papers (**Jolivet 2015**; **Robert *et al.* 2015**) dealing with a wide area are positioned in the middle of the map without stars. The location of Figure 2 is shown. Green line: political borders and Caspian Sea shoreline; ATB: Afghan Tajik Basin; B: Basin; FB: Fergana Basin; Kyr: Kyrgyzstan, Taj: Tajikistan; TFF: Talas–Fergana Fault.

with the building of new highways and planned railways and pipelines. Trade is once again crossing the numerous borders, partially driven by the presence of the large, still poorly studied petroliferous basins in the area.

The Phanerozoic tectonic history of the region commenced with the accretion of the main units of northern Asia. These accretionary events were associated with the subduction/collision of various microcontinents, terranes and island arc complexes during Palaeozoic and Mesozoic times. Many of these events remain poorly defined, leading to obvious confusion in the literature with various reconstructions and collision timings being proposed (e.g. Zonenshain *et al.* 1990; Berzin *et al.* 1994; Şengör & Natal'in 1996; Buslov *et al.* 2004; Natal'in & Şengör 2005; De Grave *et al.* 2012; Zanchetta *et al.* 2013; Şengör *et al.* 2014; Yang *et al.* 2017). The southern margin of Eurasia contained a range of pre-Cenozoic structures, including suture zones and/or large-scale fault zones between blocks, some of which were Gondwana-derived (e.g. Audet & Bürgmann 2011). These structures were particularly susceptible to subsequent Cenozoic-age intraplate deformation related to the India–Eurasia (Early–Middle Eocene) and Arabia–Eurasia (Late Eocene–Early Oligocene) collisions (e.g. Molnar & Tapponnier 1975; Tapponnier & Molnar 1979; Şengör & Natal'in 1996; Windley *et al.* 2007; Allen 2010; Dupont-Nivet *et al.* 2010; van Hinsbergen *et al.* 2012; Kröner *et al.* 2014). These latter events were marked by the docking of strong and resistant Archaean–Proterozoic continental lithosphere with the weaker southern margin of Eurasia. The consequence of these collisions was the formation of two major topographical features – the Zagros and Himalaya orogenic belts – both of which are outside of our immediate area of investigation. The various tectonic events, including terrane collisions, major continent–continent collisions (including the Pamir Spur) and the related oceanic closures (e.g. Tien Shan Ocean, Mongol–Okhotsk Ocean, Palaeotethys, branches of Neotethys) all combined to broadly reshape a continental mass whose tectonic history was already complex.

The Tien Shan is one of the world's largest mountain belts comprising the well-exposed southern portion of a much larger Phanerozoic-age orogenic belt, the so-called Central Asian Orogenic Belt (CAOB) (e.g. Jahn *et al.* 2000, 2004; Windley *et al.* 2007; Kröner *et al.* 2014). The Tien Shan stretches over 2800 km along an E–W axis from Xinjiang in NW China through to the Aral Sea in Uzbekistan via Kazakhstan, Tajikistan and

Kyrgyzstan, with the highest peaks exceeding 7000 m asl and the lowest point at 154 m bsl in the eastern Tien Shan. The chain has had an extremely complex evolution, commencing with the formation of the various small, scattered Precambrian blocks, followed by a Palaeozoic history involving the development of accretionary belts, marine sedimentary basins and relatively minor collisions. To the west the Central Tien Shan Ocean closed completely in the latest Carboniferous, and closure was followed by a phase of Early Permian post-collisional exensional magmatism (e.g. Dolgopolova *et al.* 2017; Konopelko *et al.* 2017). The subsequent Mesozoic history of the Tien Shan is characterized by episodes of intracontinental tectonism, with the final phase in Cenozoic times related to far-field effects of the India–Asia collision (e.g. Burtman 1980, 1997; Bazhenov *et al.* 1999; Buslov *et al.* 2008; Jolivet *et al.* 2010; Macaulay *et al.* 2014). During this last phase older structures were often preferentially reactivated, creating the misleading impression that the Palaeozoic and Cenozoic belts are identical.

The Tien Shan is often subdivided into three sectors, namely: the Western, Central and Eastern Tien Shan. The Talas–Fergana Fault, a notable strike-slip feature, marks the boundary between the Western and Central Tien Shan sectors. However, depending on where a study is located, different concepts have been used for both the geographic and geological subdivisions (i.e. as a result of the different authors), leading to potential confusion. In particular, the Chinese and the ex-Soviet terminologies are not compatible. Here we follow the subdivisions depicted in Figure 2. These three geographic regions can be further subdivided into the North, Middle and South Tien Shan. This latter subdivision is broadly based on the regional Palaeozoic evolution; the ensuing amalgamation of various terranes resulted in the formation of distinctive tectonic zones (e.g. Şengör *et al.* 1993; Wang *et al.* 2006; Windley *et al.* 2007; Xiao *et al.* 2008; Burtman 2010).

The North Tien Shan, situated east of the Talas–Fergana Fault, comprises several Precambrian-age blocks as well as Cambrian–Lower Ordovician ophiolites and marine sediments (Biske & Seltmann 2010), overlain by Ordovician-age sediments and volcanic rocks, and cut by I-type granites. The region includes the southern margin of the Kazakh–Kyrgyz continent, which was deformed as a result of subduction and accretion during the Late Carboniferous and Early Permian (i.e. accretion of Turan, Alai, Tarim area to Kazakh–Kyrgyz continent, e.g. Thomas *et al.* 1999*a*; McCann *et al.* 2013; Burtman 2015). To the north, the Late Palaeozoic-age Yili volcanic belt or Yili Block represents a continental arc, which overlaps Early Palaeozoic

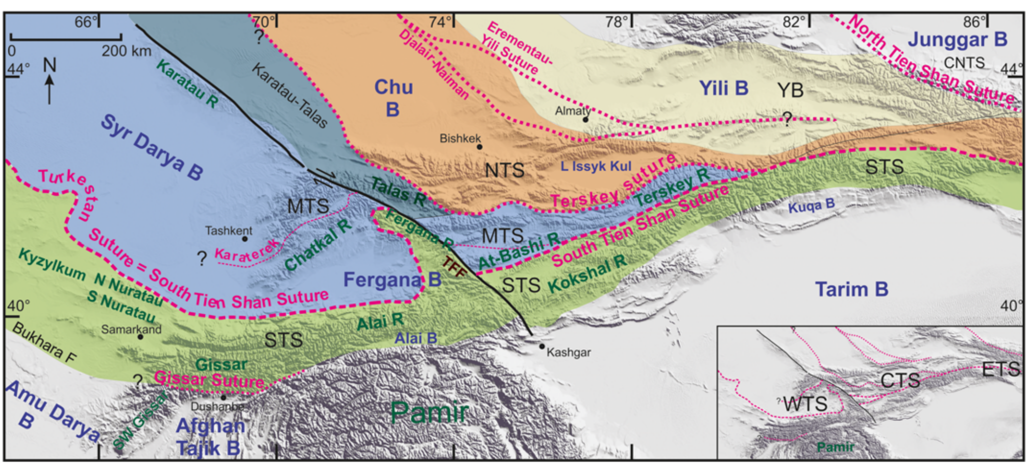

Fig. 2. Location map showing the major structures of the western Tien Shan and regional subdivisions on a USGS SRTM (Shuttle Radar Topographic Mission) topography background, projection World Mercator, scale bar at latitude 45°. Suture zones are represented by magenta dotted or dashed lines; North Tien Shan (NTS) becoming Chinese Central Tien Shan in China in light brown; Middle Tien Shan in blue (MTS); Karatau–Talas terrane in grey blue; South Tien Shan in green (STS); and Yili Palaeozoic volcanic belt (YB) in light yellow. Terrane boundaries sometimes do not correspond exactly to sutures due to post-collisional nappe tectonics. B: Basin; CNTS: Chinese North Tien Shan; F: Fault; L: Lake; R: Range; TFF: Talas–Fergana fault (black line). Inset map shows the location of geographic subdivision of the Tien Shan Range. WTS: Western Tien Shan; CTS: Central (Kyrgyz) Tien Shan; ETS: Eastern (Chinese) Tien Shan. Compiled from **Bande *et al.* (2015*a*)**, **Loury *et al.* (2015)**, Alexeiev *et al.* (2016).

accretionary collages and sutures in the region of SE Kazakhstan (e.g. Alexeiev *et al.* 2016).

The Middle Tien Shan (=Syrdarya, Naryn or Ishim–Middle Tien Shan microcontinent) comprises a range of Neoproterozoic units which include tillites and acid volcanic rocks (Biske & Seltmann 2010). It is separated from the North Tien Shan by the Terskey Suture (suture of the Terskey Early Palaeozoic ocean; e.g. Burtman 2010; Glorie *et al.* 2011). The Middle Tien Shan wedges out eastwards near the border of Kyrgyzstan with China; further east, it has no recognized equivalent (Xiao *et al.* 2013). To the NW, the Karatau–Talas terrane (e.g. Alexeiev *et al.* 2016) is considered to form a marginal part of the Middle Tien Shan microcontinent, based on similarities in terms of the Early Palaeozoic depositional facies from both areas. From Middle Devonian to Late Carboniferous times, the Middle Tien Shan probably formed part of the passive margin of the Kazakh–Kyrgyz continent and was characterized by shallow-marine carbonate and siliciclastic sediments (e.g. Alekseev *et al.* 2009; Biske & Seltmann 2010).

The South Tien Shan, separated from the Middle Tien Shan by the South Tien Shan Suture (=Turkestan Suture, characterized by Early Ordovician–Early Carboniferous ophiolites; Kurenkov & Aristov 1995; Gao *et al.* 1998; Chen *et al.* 1999), is a Late Palaeozoic-age, fold-and-thrust belt formed during the closure of the Turkestan Ocean (=Central Tien Shan Ocean; Zonenshain *et al.* 1990; Kheraskova *et al.* 2010; Seltmann *et al.* 2011; McCann *et al.* 2013). The direction of subduction vergence of the Central Tien Shan Ocean is uncertain, and both northerly directed (e.g. Windley *et al.* 1990; Allen *et al.* 1992; Xiao *et al.* 2004; Hegner *et al.* 2010) and southerly directed (e.g. Charvet *et al.* 2007, 2011; Lin *et al.* 2009; Ma *et al.* 2014) models have been proposed. The South Tien Shan is situated along the SW margin of the Central Asian Orogenic Belt (CAOB, =Altaids; Şengör *et al.* 1993, 2014), a key region for our understanding of both the amalgamation of Eurasia (see above) and the Phanerozoic growth of the CAOB (Windley *et al.* 1990, 2007; Bazhenov *et al.* 1999; Gao *et al.* 2009; Kröner *et al.* 2014). Only the South Tien Shan is continuous along the whole length of the belt (e.g. Xiao *et al.* 2013); the Middle and North Tien Shan are not always present. In its western part, the South Tien Shan can be subdivided into several units from west to east (Konopelko *et al.* 2007, 2017): the Kyzylkum, Gissar, and Alai (=Alay) segments west of the Talas–Fergana Fault; and the Kokshal segment to the east. Lithologically they are all similar, comprising Ordovician–mid-Carboniferous pelagic sediments, partly associated with intraplate volcanics, and thick carbonate platforms (mainly Late Devonian–Early Carboniferous in age) which are best developed in the latter two segments (Biske & Seltmann 2010; Seltmann *et al.* 2011). Post-collisional intrusions east and west of the Talas–Fergana Fault are dated as Early Permian (e.g. Konopelko *et al.* 2007, 2017; Dolgopolova *et al.* 2017). Seltmann *et al.* (2011) have noted that the South Tien Shan region contains deformed forearc accretionary complexes as well as passive margin sediments.

Lateral variations within the South Tien Shan serve to illustrate the complexity of the regional geology. The Chinese part of the South Tien Shan, for example, was separated from the Tarim block by a South Tien Shan Ocean, which opened in a back-arc setting and probably closed in the Late Carboniferous–Early Permian (e.g. Xiao *et al.* 2013). In the Kyrgyz part of the South Tien Shan, the presence of minor Devonian-age ophiolites (on the China map of Tien Shan; Wang *et al.* 2007) may represent the westward continuation of the suture between the Tarim block and the Chinese South Tien Shan as suggested by Käßner *et al.* (2017). To the west of the Talas–Fergana Fault, the small Gissar Ocean (e.g. Brookfield 2000) formed as a result of Carboniferous-age rifting, possibly in a back-arc setting. This ocean was located to the south of the South Tien Shan and to the north of the Karakum Block. It subsequently closed in the latest Carboniferous, forming the Gissar Suture (e.g. Burtman 2010; Dolgopolova *et al.* 2017; Konopelko *et al.* 2017).

This volume assembles the results from projects supported fully, or in part, by the DARIUS Programme as well as invited external studies. The DARIUS Programme (2009–14) was a multidisciplinary geological programme that comprised original scientific projects, executed by academic scientific teams involving more than 350 scientists representing 150 research institutions from 25 countries in Europe, the Middle East and western Central Asia. The DARIUS consortium was sponsored by major oil companies (BHP Billiton, BP, ENI, Maersk Oil, Petronas Carigali, Shell, Statoil, Total) and French research organizations (Centre National de la Recherche Scientifique-INSU, University Pierre & Marie Curie). The main objective of DARIUS was to characterize the tectonostratigraphic evolution of a vast domain around the central Tethys extending from the eastern Black Sea in the west to western Central Asia in the east, and to reconstruct the post-Late Palaeozoic geodynamic evolution of the domain. The priority was to investigate the 6000 km long continuous orogenic belt extending from Crimea/Anatolia in the west to the western Tien Shan in the east, including the surrounding basins, through the collection of original data and the development of regional syntheses.

The present volume is one of the end-products of the DARIUS Programme, which also gave rise to three other special volumes – one on Cimmerian Terranes (Zanchi *et al.* 2015); one on Anatolia (Robertson *et al.* 2016); and one on the Eastern Black Sea–Caucasus domain (Sosson *et al.* 2017) – as well as an atlas of 20 palaeotectonic maps ranging in age from the Late Permian through to the Pliocene (Barrier & Vrielynck 2017).

The papers in the present volume represent up-to-date work and reviews on some of the geological elements (see Fig. 1 for locations) of the western part of the Tien Shan as well as some of the large basins of Central Asia, with the overarching goal of attaining a better understanding of the regional geological evolution. The volume is subdivided into four sections and these and their constituent papers are discussed in order in the following sections.

Regional evolution and extensional sedimentary basins

The volume commences with a synthesis of the main geodynamic episodes which occurred during the Late Palaeozoic–Mesozoic in Central Asia, providing a general framework for the other, more localized, studies in the book. This is followed by a detailed review of the post-Variscan evolution of the Afghan orogenic segments. Such a review is long overdue in the international literature, given the difficulties of working in present-day Afghanistan. The subsequent three papers analyse the evolution of two major extensional sedimentary basins in the western part of the studied area: the Amu Darya Basin and the South Caspian Basin.

Jolivet (2015) reviews the various geodynamic episodes which occurred across the region of Central Asia and Tibet during the Late Palaeozoic–Mesozoic and which induced either large-scale compression or widespread extension. The various events, including the Late Palaeozoic final amalgamation of the Central Asian Orogenic Belt, the accretion of the Cimmerian blocks, the closure of the Mongol–Okhotsk Ocean and the accretion of the Neocimmerian blocks, determined the structural pattern of the region. These Mesozoic events were significant in the localization and evolution of Tertiary deformation (e.g. Tapponnier *et al.* 2001; Searle *et al.* 2011; van Hinsbergen *et al.* 2011). In many areas, the degree of post-Mesozoic exhumation has been sufficiently small that it is still possible to discern relict low-relief landforms that formed over *c.* 100 Ma ago. This, in turn, evidences the long-lasting aridity and low levels of erosion outside of the extremely localized deformation zones.

The Afghan orogenic segment is located within the collision zone of Eurasia and the Gondwana-derived continental blocks. **Siehl (2015)** points out that this zone has remained active up to the present day as a result of the northward drift of India to the east and Arabia to the west (Stöcklin 1977; Şengör 1984; Boulin 1991). He reviews the geology of the Afghan portion of the Afghan–Tajik Basin, and examines the period following the Variscan orogenic events at the end of the Palaeozoic Era. These events heralded the onset of successive suturing events (Eo-Cimmerian, Late Cimmerian) and involved the accretion of Gondwana-derived fragments to the southern margin of Eurasia and the closure of the Palaeotethys Ocean, as well as branches of the Neotethys Ocean. Additionally, these tectonic events were related to the development of the Cimmerian and Himalayan ‘Tethyside Orogenic Zone’ of Şengör *et al.* (1988). The successive collages and sutures resulted in the formation of the *c.* 1300 km long Afghan orogenic segment, which extends in a west–east direction from the eastern Iranian Kopet Dagh to the Pamir–Punjab region in southern Kyrgyzstan–northern Pakistan. It has a width of *c.* 1100 km in a north–south direction from the North Afghan–Tajik Basin in the north to the Maskhel Basin of Balochistan in the south.

Brunet *et al.* (2017) use a set of depth-structure maps and isopach maps as well as regional cross-sections to examine the tectono-sedimentary evolution of the Amu Darya Basin during the Late Palaeozoic and the Mesozoic. The evolution is considered from the point of view of basin subsidence, and can be explained by two main extensional events. The first, and most important, event probably occurred during the Late Palaeozoic–Triassic after closure of the Turkestan Ocean, and resulted in the deposition of several kilometres of sediments. This event followed the final amalgamation of the Turan Platform, composed of several individual crustal blocks of varying sizes, thus creating an inhomogeneous basement. Inherited structures were reactivated during subsequent periods of extension as well as during collisions. The second extensional event took place in Early–Middle Jurassic times, following the Eo-Cimmerian orogeny. This event was concentrated in the eastern half of the Amu Darya Basin, and resulted in the deposition of thick Jurassic-age successions which subsequently formed the main petroleum system of the basin.

Detailed analysis of a series of cross-sections from the Bukhara-Khiva area allows **Mordvintsev *et al.* (2017)** to examine, in detail, the evolution of the northeastern margin of the Amu Darya Basin during the Mesozoic (focusing mainly on the Jurassic). Sections are based on subsurface data: seismic lines, boreholes and depth-structure maps. The structures of the Bukhara step and the deeper Chardzhou step, which together form the basin margin, are described and compared. An extensional event controlling the deposition of the Early–Middle Jurassic-age series is clearly documented by the cross-sections. This event resulted in the formation of new normal faults and/or the reactivation of a series of Late Palaeozoic structures, accommodating the infill of the topographic lows by siliciclastic successions, initially continental and later marine. Subsidence declined markedly from Middle Callovian times onwards, coeval with the deposition of the Middle Late Jurassic carbonate succession, passing upwards into a phase of thermal subsidence during the Cretaceous.

Abdullayev *et al.* (2015) integrate geophysical observations as well as subsidence and gravity modelling of selected 2D profiles from the South Caspian Basin region. Based on their results, they suggest that the observed pattern of subsidence and sedimentation within the basin can be explained by a process of thermal subsidence following Jurassic rifting, and a period of enhanced subsidence that resulted from sediment-induced loading in the Late Tertiary. The western and eastern parts of the South Caspian Basin have different subsidence histories, partly related to variations in the underlying crust type. Gravity modelling reveals that the South Caspian Basin crustal density is compatible with an oceanic composition in the western part, while the crust in the eastern part is thicker. The observed subsidence and sedimentation patterns within the basin can therefore be interpreted in terms of thermal subsidence and sedimentary loading of ‘oceanic type’ or attenuated continental crust. Forward modelling of lithospheric extension and gravity modelling confirm the presence of the variable crustal types, and the authors infer a tentative Jurassic age for the rifted margin and its basin.

Modelling the collisional and sedimentary evolution of the western part of the Tien Shan

Models of the tectono-sedimentary evolution of the Tien Shan region are complex and incomplete (see also Xiao *et al.* 2010). This is due to a combination of factors including the complex geology (see Nurtaev *et al.* 2013), problems of access (to some areas) and the lack of published and accessible information (particularly in English and/or in western scientific journals). Additionally, there are significant problems correlating the different geological subdivisions between the various countries through which the Tien Shan runs (see Xiao *et al.* 2010 for a Chinese version of the main terminologies). From east to west, two papers in the volume examine the suture zones and the vergence of subduction in the Tien Shan. Another paper takes a broad regional approach, examining the entire area while also extending further to the south to include the colliding Arabian and Indian plates.

Loury *et al.* (2015) present two crustal-scale cross-sections of the Kyrgyz portion of the Central Tien Shan and correlate the major faults and units eastwards from Kyrgyzstan to China. Based on field and seismic data, they suggest that the broad structure conforms to that of a doubly vergent mountain belt where the Chinese and Kyrgyz areas show identical structural and metamorphic histories. This double-vergence appears to be inherited from two major steps: (1) subduction towards the south of the Central Tien Shan Ocean; and (2) strike-slip kinematics, mainly during the Early Permian. Based on the structure and kinematics of the South Tien Shan belt, they suggest that the Central Tien Shan Ocean was subducted during the Late Carboniferous, resulting in continental collision at *c.* 320–310 Ma when the Tarim block collided with the Kazakh–Kyrgyz continent. Top-to-north thrusting and top-to-south detachment within the accretionary prism resulted in the exhumation of a large continental unit which had been metamorphosed under eclogite facies conditions. This tectonic evolution is broadly consistent with a published numerical model by Vogt & Gerya (2014). The time span for this collision–accretion orogeny is at least 27 Ma between the onset of subduction and final exhumation.

Alexeiev *et al.* (2015) examine passive-margin Devonian–Permian-age carbonate successions in the Middle Tien Shan region of Kyrgyzstan. These sediments record *c.* 150 Ma of tectonic history in the region and provide important insights into the reconstructions of the sedimentary basins and the regional geodynamic framework in one of the least-understood regions of the Central Asian Orogenic Belt. Major reorganizations in the architecture of the carbonate platform were caused by eustatic drowning events in the early Tournaisian, early Visean and near the Visean–Serpukhovian boundary. Similar carbonate deposits are also observed in South Kazakhstan and the North Caspian Basin, suggesting a common origin and hence a similar petroleum reservoir potential. A convergent margin formed in the middle Bashkirian; subsequently, flexurally driven subsidence documents the encroachment of an orogenic thrust wedge. Deposition is superceded by deformation and plutonism after the Asselian, documenting the onset of the final hard collision.

Robert *et al.* (2015) analyse crustal and lithospheric thickness maps for Central Eurasia combining elevation and geoid anomaly data and thermal analysis. Their results are constrained by older data derived from seismological and seismic experiments, tomographic imaging and integrated geophysical studies. These include one-dimensional spot estimates (e.g. Nasrabadi *et al.* 2008), 2D transects across the Himalaya–Tibet (e.g. Kind *et al.* 2002) and the Zagros–Iran (e.g. Paul *et al.* 2006, 2010) regions and 3D regional studies (e.g. Zor *et al.* 2003), although less than 19% of the region has crustal thickness data coverage better than one measurement per 50 000 km^2. Robert *et al.*'s maps show that crustal thickening is at a maximum beneath the high topographic areas across the region (e.g. Zagros, Himalaya, Tien Shan, Tibetan Plateau). The crustal and lithospheric thickness patterns are however variable, highlighting the strain partitioning which has occurred within the lithosphere. The Arabia–Eurasia collision zone is characterized by a thick lithosphere beneath the Zagros belt, whereas a thin to non-existent lithospheric mantle is observed beneath the Iranian and Anatolian plateaux. Conversely, the India–Eurasia collision zone is characterized by a very thick lithosphere below its southern part as a consequence of the underplating of the cold and stiff Indian lithosphere.

Fault reactivation and far-field effects

As noted in the introduction, the Tien Shan region is characterized by a complex orogenic history. The various collisional episodes, coupled with strike-slip activity, resulted in the development of a significant fault zone, the Talas–Fergana Fault, examined in detail below. Additionally, the role of far-field effects – particularly related to the Cenozoic collisions occurring along the southern margin of the Eurasian continent, especially that of the Pamir indentation – and their role in the development of the broader orogeny are also examined.

Bande *et al.* (2015*a*) examine the role of major structural features, in particular the role of regional strike-slip faults in continental interiors in the region. The Talas–Fergana Fault is of great significance in terms of understanding the hinterland kinematics of the India–Asia collision. New apatite fission track data from mountain ranges bounding the northern end of the Talas–Fergana Fault suggest that there was a rapid exhumation event there at *c.* 25 Ma. This can be correlated with a synchronous pulse of cooling and thrust belt propagation in the South Tien Shan, implying that both ranges underwent coeval and rapid exhumation. Strike-slip motion along the Talas–Fergana Fault commenced at *c.* 25 Ma, facilitating anticlockwise rotation of the Fergana Basin as well as exhumation of the linked horsetail splays. Pamir indentation was underway by *c.* 20 Ma. The Talas–Fergana Fault was therefore largely responsible for transferring Pamir-induced shortening to the NW Tien Shan.

The link between fault reactivation and far field effects is explored by **Bande *et al.* (2015*b*)** in their analysis of Cenozoic deformation within the Fergana Basin. Deformation is concentrated along thrusts on the northern and southern basin margins, while the eastern margin is transpressive. All of the observed deformation can be associated with movement along the Talas–Fergana Fault. The close association of the Fergana Basin with the Talas–Fergana Fault resulted in the development of a basin morphology that differs from that of other Cenozoic-age intramontane basins within the Tien Shan typically bounded by north- or south-verging faults (e.g. Cobbold *et al.* 1996; Burbank *et al.* 1999; Macaulay *et al.* 2014). The Fergana Basin is located due north of the Pamir, suggesting a possible tectonic link between indentation of the latter and basin evolution. While folding and thrusting in the Tajik Basin is clearly related to the indentation of the Pamir Mountains, no convincing mechanism has, thus far, been proposed for tectonic linkage between compression and the morphology of the Fergana Basin. It would however now appear that shortening (beginning in the Oligocene) was transferred along the Talas–Fergana Fault, reaching the western Kyrgyz and Uzbek Tien Shan and resulting in exhumation in the Chatkal and Fergana ranges by *c.* 25 Ma.

Sedimentation, environment and climate

Sedimentary basins, and the depositional successions within them, provide the most tangible and accessible records of the lithospheric, geographical, oceanographic and ecological developments which occur in a specific area over a specific period of time (McCann & Saintot 2003). Investigation of the sedimentary successions contained with the basins which formed within the broader Tien Shan orogen thus provide overviews of the Mesozoic (five papers) and Cenozoic (two papers) history across the region, focusing as they do on the interlinkage of sedimentation, tectonics and climate.

Schnyder *et al.* (2016) examine palynological and high-resolution carbon isotope data measured on bulk organic matter from the Lower Jurassic continental succession in the Leontiev Graben of Kazakhstan. The two datasets are in agreement, allowing the recognition of the transition zone between the Pliensbachian and the Toarcian. The major palaeoclimatic changes associated with large carbon-cycle perturbations at the Pliensbachian–Toarcian transition have, to date, been primarily studied in marine settings. This study presents one of the best continental sequences in the world for documenting this transition. Identification of the transition also facilitates correlation with the worldwide Toarcian Oceanic Anoxic Event and negative (organic) carbon isotope excursion, as well as identifying a warming trend.

Fürsich *et al.* (2015) reconstruct the Early Jurassic–Early Callovian palaeoenvironmental and depositional history of the NW Afghan–Tajik Basin in southern Uzbekistan. The oldest sediments date from the Early Jurassic through the end of the Early Bajocian, during which >500 m of non-marine sediments were deposited in an extensional setting. During the Late Bajocian, transgression led to the establishment of storm-influenced siliciclastic ramps. Following the deposition of 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 deposition in the Middle Jurassic was influenced by a number of factors, including the levelling of relief in the hinterland, and the subsidence evolution shifting into the thermal phase. However, the change from humid to arid climatic conditions was also of great importance.

Jurassic outcrops are rare in central Uzbekistan and **McCann (2016*a*)** details the succession from one of these: the Sarbatyr inlier in the Kyzylkum area. The succession comprises mainly continental sediments deposited in a distal, but prograding, alluvial fan setting. These sediments were derived from the weathering and erosion of the adjacent Kyzylkum Massif. The alluvial sediments interfinger with nearshore/lagoonal marine sediments which are rich in both fossils and glauconite, suggesting varying sea levels over time. Three transgressive events can be recognized. While it is possible that these events correspond to global eustatic patterns, the effects of local tectonic activity must also be considered. This work demonstrates the influence of marine activity in the Kyzylkum region of Uzbekistan during the Bajocian–Bathonian.

McCann (2016*b*) examines a Cretaceous sedimentary succession from the Kyzylkum and Nuratau regions of central Uzbekistan. The region formed the westernmost part of an ancient Asian landmass bordered by the Tethys Ocean and the Turgai Strait (which opened during the Late Cretaceous). The region was dominated by a broad coastal plain with topographic highs (Kyzylkum and Nuratau massifs), adjacent to a marine area. Frequent transgressions resulted in the intercalation of continental and marine deposits, with advances and retreats of the coast related to major marine eastward incursions (as far as the Tarim Basin). However, the complex sedimentary pattern was also influenced by tectonic activity along the evolving northern margin of the Amu Darya Basin, which formed subsequent to the closure of the Turkestan Ocean, as well as by climatic variations.

Within the Tien Shan region, **Jolivet *et al.* (2015)** note that the Jurassic–Early Cretaceous period was marked by complex, low-intensity tectonic deformation and major climate changes from humid (Middle Jurassic) to arid conditions (Late Jurassic) to semi-arid conditions (Cretaceous). Using the sediment record in the Junggar, Tarim and Fergana basins to describe the tectonic evolution of the Tien Shan therefore requires differentiation between tectonic and climatic influences on sedimentation. Tectonic deformation in the region commenced during the Middle Jurassic, leading to basin inversion and the recycling of older sedimentary successions. The change to a humid climate in Middle Jurassic times favoured the development of extensive vegetation cover and the establishment of permanently flowing rivers. However, by Late Jurassic times there was a shift towards a monsoon-type, semi-arid climate with the development of desert environments, with an aridity peak at the Late Jurassic–Early Cretaceous boundary. Aridity coincided with an increase in alluvial fan deposition, the timing of which cannot be related to the most-often-proposed geodynamic event (i.e. the Early Cretaceous accretion of the Lhasa Block) since fan growth would appear to predate this event.

Klocke *et al.* (2015) study a *c.* 10 km section of sediments deposited in the NE part of the Tajik Basin. This comprises an Upper Cretaceous–Oligocene pre-tectonic shallow-marine to continental succession and a younger syntectonic succession of clastic deposits derived from the uplifting mountain ranges of the Tien Shan in the north and the Pamir in the south and east. The evolution of the Tajik Basin is documented by facies, palaeotransport directions and provenance analysis. The Cenozoic-age sediments within the basin reflect large fluvial plains running from the margins of the northern Pamir and the southern Tien Shan mountains. Subsequently, in Neogene times the basin fill was progressively deformed by folding and thrusting.

Bosboom *et al.* (2015) investigate the Cretaceous and Palaeogene sedimentary successions in three areas (Tarim Basin, China; Fergana Valley and the Alai Valley, Kyrgyzstan; Afghan–Tajik Basin, Tajikistan) in order to reconstruct the epicontinental sea that was present across the region at that time. The results indicate that the various locations, while geographically distant, shared a similar palaeogeographical evolution, one characterized by a long-term stepwise retreat punctuated by short-term shallow-marine incursions. The final Late Eocene disappearance of this sea probably occurred (with a degree of diachroneity) prior to the isolation of the Paratethys Sea. This shifting of the coast towards the west would have had profound effects on the climate of Central Asia, resulting in reduced moisture supply to the interior.

Geological evolution of Central Asian Basins and the western Tien Shan Range: integration of new results

The Palaeozoic Tien Shan forms part of the extensive Central Asian Orogenic Belt (CAOB) (Jahn *et al.* 2000, 2004). The CAOB formed as a result of continuous subduction-accretion from the Neoproterozoic through to the Late Palaeozoic, culminating with the final amalgamation of the East European Craton in the west, the Siberian Craton in the east and the Karakum and Tarim continents to the south (Konopelko *et al.* 2007). Subsequent accretion and associated oceanic closures were often related to the movement of Cimmerian terranes, which became detached from Gondwana during the Permian due to the opening of the Neotethys Ocean and subsequently collided with the southern margin of Eurasia. The earliest collisional episode, involving the various Iranian blocks, occurred in the Late Triassic. This was followed by the collision of the Central Afghanistan and Central Pamir blocks at the end of the Triassic. These two events resulted in the formation of the Eo-Cimmerian unconformity and the Eo-Cimmerian Belt (e.g. Zanchi *et al.* 2009; Zanchetta *et al.* 2013). Coevally, the end of the Indosinian Orogeny in SE Asia as well as the accretion of the Qiangtang Block in Tibet during the Triassic–Early Jurassic (e.g. **Jolivet 2015**) marked the end of this initial Mesozoic-age deformational phase in Central Asia. Subsequent tectonic activity was more diffuse, and would appear to have been partly driven by far-field processes associated with a series of events, including: the poorly understood closure of the Mongol–Okhotsk Ocean in Siberia (Late Jurassic–Early Cretaceous, van der Voo *et al.* 2015; Early Cretaceous, **Jolivet 2015**); the accretion of the Lhasa Block along the southern Tibet margin (Early Cretaceous); and slab pull along the palaeo-Pacific and 'Meso-Tethys' subduction zones (e.g. Hendrix *et al.* 1992; Sobel 1999; **Jolivet 2015**; van der Voo *et al.* 2015). The Cenozoic-age collision of India and Eurasia resulted in significant deformation across the region (e.g. Liu *et al.* 2013; Yang *et al.* 2013, 2014), with far-field effects being traced as far north as the Sea of Okhotsk (e.g. Worrall *et al.* 1996). The regional evolution of the Tien Shan region is therefore characterized by two major orogenic phases: the Early Mesozoic Eo-Cimmerian Orogeny and the Cenozoic collision of India and Eurasia (e.g. Dumitru *et al.* 2001; Jolivet *et al.* 2010; **Jolivet 2015**; **Siehl 2015**). These two major events are separated by a transitional period characterized by a series of less-well-understood events (in terms of their far-field effects) extending from the Jurassic through the Cretaceous. The impact of these events, related to the accretion of smaller blocks (e.g. Lhasa Block) to Eurasia, is unclear; published reconstructions and timings for the various events often vary. In summary, the various accretionary events from Late Palaeozoic times onwards varied both in terms of their timing as well as their location, resulting in variations both in deformation as well as the related post-collisional magmatism towards the east (Klett *et al.* 2006; Zanchi *et al.* 2009, 2012; **Siehl 2015**).

Deformation in Central Asia related to the various accretionary events outlined above has been significant, ranging from crustal thickening through to more localized effects related to fault reactivation. In addition to lithospheric changes, far-field effects related to the various continental collisions are also of significant importance since pre-existing discontinuities may transfer stress from distant geodynamic processes, both compressional (e.g. accretion of the Cimmerian, Qiangtang, Lhasa and Indian blocks) and extensional (e.g. back-arc extension, slab roll-back). The far-field effects of continental collision (e.g. Molnar & Tapponnier 1975; Allen *et al.* 1991; Hendrix *et al.* 1994) and the role of older structures (e.g. Jolivet *et al.* 2010; Selander *et al.* 2012; Macaulay *et al.* 2013) have been extensively studied in the Tien Shan region, particularly on the Eastern (Chinese) Tien Shan (e.g. Allen & Vincent 1997; Yin *et al.* 1998; Chen *et al.* 2007; Sun *et al.* 2009) and the Central (Kyrgyz) Tien Shan (e.g. Abdrakhmatov *et al.* 1996; Cobbold *et al.* 1996; Sobel *et al.* 2006*a*, *b*; De Grave *et al.* 2011; Macaulay *et al.* 2014). In contrast, far less has been published on the western Tien Shan. **Robert *et al.* (2015)** provide evidence of crustal thickening in both major frontal ranges (Himalayas, Zagros, Pamir, Caucasus) as well as more distal ranges, such as the Alborz, Kopet Dagh and the Tien Shan, while also noting that crustal thinning is restricted to the Arabian and Indian oceanic domains, the South Caspian Sea, the Red Sea and the Black Sea. The width of the zone of deformation (>1200 km) highlights the extent of the area affected by crustal thickening, which is also a testament to the efficient transfer of tectonic forces for hundreds to thousands of kilometres from the respective collisional zones. **Robert *et al.* (2015)** also note that within these broad zones of deformation some tectonic blocks (e.g. Central Iran, Tarim) exhibit only slightly thickened crust and relatively uniform topography, suggesting only moderate deformation. This would suggest that these blocks have a degree of rheological resistance to the ongoing deformation.

During the Mesozoic and Early Cenozoic, parts of the Tien Shan were periodically reactivated in response to distal collisions (e.g. Hendrix *et al.* 1992; Sobel & Dumitru 1997; Allen *et al.* 2001; Dumitru *et al.* 2001; Glorie *et al.* 2011). Indeed, the role of Palaeozoic structures and sutures is particularly important during later Cenozoic deformation. In central parts of Asia, major structures such as the Talas–Fergana or the Altyn Tagh faults were reactivated with strike-slip motion. The Talas–Fergana Fault, which is *c.* 2000 km long, is one of the best examples of a reactivated intra-continental strike-slip fault, and a prominent morphological feature within the western Tien Shan. Deformation along the fault trace during the Late Oligocene–Early Miocene (e.g. Hendrix *et al.* 1994; Sobel & Dumitru 1997; Sobel *et al.* 2006*a*; Heermance *et al.* 2008; Amidon & Hynek 2010; Wei *et al.* 2013; **Bande *et al.* 2015*a***) and again in the Late Miocene (e.g. Bullen *et al.* 2003; Heermance *et al.* 2008; Macaulay *et al.* 2014) can be linked to the evolution of the Pamir (**Bande *et al.* 2015*b***).

In southern Tajikistan the sinistral strike-slip Darvaz Fault marks the boundary between the North Pamir and the Tajik Basin, along which 200–300 km of left-lateral offset has been estimated (Burtman & Molnar 1993). Stratigraphic work by **Klocke *et al.* (2015)** suggests that there was Late Oligocene uplift of the northern Pamir. Generally, strike-slip faults within continental interiors often move in response to distal plate collisions (e.g. Burtman *et al.* 1996; Yin *et al.* 2002). Constraining the spatio-temporal distribution of activity along such faults is therefore of great significance in terms of our understanding of how oblique deformation is accommodated in transpressional settings. Strike-slip movements and fault reactivation also affected large sedimentary basins in the region, such as the Amu Darya Basin, from Late Palaeozoic through to Cenozoic times (Thomas *et al.* 1999*a*, *b*; Natal'in & Şengör 2005; **Brunet *et al.* 2017**; **Mordvintsev *et al.* 2017**), although the precise effects on basin evolution are difficult to document.

The reactivation of older structures under changing geodynamic conditions is examined by **Loury *et al.* (2015)** for the Kyrgyz portion of the South Tien Shan. They note that reactivation of Palaeozoic-age structures in Permian–Mesozoic times occurred mainly in a strike-slip regime, featuring left-lateral motion localized in the centre of the South Tien Shan. Subsequently, in Cenozoic times a flower structure developed as a result of the reactivation of former top-to-the-north Carboniferous thrusts to the north of the South Tien Shan. This was coeval with the development of top-to-the-south thrusts in a fold-and-thrust belt propagating over the Tarim block, south of the South Tien Shan.

Subsequent to the collisions of the Cimmerian terranes with Eurasia in the Late Triassic (e.g. Stampfli & Borel 2002; Barrier & Vrielynck 2008, 2017; Wilmsen *et al.* 2009; Zanchi *et al.* 2009, 2012), a number of new or rejuvenated sedimentary basins formed north of the main collision zone in Central Asia, including the Amu Darya Basin (extending mainly across Turkmenistan and Uzbekistan) and the Afghan-Tajik Basin (extending across Uzbekistan, Tajikistan and Afghanistan) (e.g. Thomas *et al.* 1999*a*; Melikhov 2000, 2013, 2017; Brookfield & Hashmat 2001; Ulmishek 2004; Klett *et al.* 2006; **Fürsich *et al.* 2015**; **Brunet *et al.* 2017**). The evolution of these two basins was closely linked from the Late Palaeozoic onwards; indeed, during Jurassic times the two basins were connected. A similar connection existed to the WSW between the South Caspian and the Kopet Dagh basins, which formed in the Jurassic (Brunet *et al.* 2003; Taheri *et al.* 2009; Robert *et al.* 2014; **Abdullayev *et al.* 2015**). The Jurassic–Cretaceous was characterized by a general planation of the previously formed relief (e.g. Makarov 1977; Chediya 1986; Burbank *et al.* 1999; Allen *et al.* 2001; Cunningham *et al.* 2003; Jolivet *et al.* 2010, 2013, **2015**), providing sediments to these newly forming extensional basins (Brookfield & Hashmat 2001; Klett *et al.* 2006; **Fürsich *et al.* 2015**; **Brunet *et al.* 2017**).

The deposits within sedimentary basins related to orogenic systems provide a record of the evolution of uplift and subsequent erosion of the adjacent mountain ranges, as well as the history of changing depositional systems, subsidence, tectonic deformation, sea-level variations (e.g. **Alexeiev *et al.* 2015**) and climate within the basins themselves (e.g. DeCelles & Giles 1996; Schlunegger *et al.* 1997; Pfiffner *et al.* 2002; Sinclair & Naylor 2012). In Central Asia, the Mesozoic period was marked by pronounced tectonic activity but also by climatic changes, specifically, the transition from a humid climate during the Middle Triassic–Middle Jurassic to a semi-arid-arid climate through to the Late Jurassic–Early Cretaceous (e.g. Hendrix *et al.* 1992; Shao *et al.* 2003; Cecca *et al.* 2005; **Fürsich *et al.* 2015**; **Jolivet 2015**; **Jolivet *et al.* 2015**; **McCann 2016*a*, *b***; **Schnyder *et al.* 2016**; **Brunet *et al.* 2017**). Subsequently, during the early Cenozoic regionally well-correlated marine transgressions occurred (Bosboom 2013; **Bosboom *et al.* 2015**). These transgressive events have been linked to Paratethys Sea which was open to the west (Black Sea, Caucasus, Caspian Sea) and extended eastwards through the Amu Darya, Tajik, Fergana and Tarim basins of Central Asia (Popov *et al.* 2004).

Concluding remarks

This Special Publication was prepared as a contribution to our understanding of the geological evolution of selected Central Asian basins and the western Tien Shan Range. There are very few international publications which focus on the evolution of Central Asia, especially its Mesozoic evolution, and this volume aims to fill some of the gaps in our existing knowledge on this dynamic and key region. It combines the results obtained by interdisciplinary groups from numerous institutions in Europe and Central Asia. Structural, geophysical, sedimentological, stratigraphical, palaeontological, thermochronological, geochemical and subsidence analyses are all used to decipher the complex tectono-sedimentary evolution of the area and to unravel the complete history of the collisions and subsequent intra-continental deformation that commenced in Late Palaeozoic times across Central Asia.

This history began with the assemblage of the Late Palaeozoic Central Asian Orogenic Belt, which in itself involved a complex series of collisional events. In the Mesozoic, the first significant orogenic event can be linked to the docking of the Cimmerian blocks to Asia during Triassic–Early Jurassic times. The main central Asia sedimentary basins therefore developed prior to the onset of the India–Eurasia collision during the Cenozoic.

New evolutionary models are presented, examining the timing of the various tectonostratigraphic events and emphasizing the reactivation of inherited structures. They illustrate the diversity of processes involved in the ongoing construction of the mountains and the adjacent basins and the mutual relationship between internal and external mechanisms, as well as far-field deformation, mountain building, topographic evolution, basin development and climatic conditions.

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