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Paleozoic collisional belt of the South Tien Shan: A review

Yury S. Biske [a], Dmitry L. Konopelko [a,b], Reimar Seltmann [c,*]

[a] *St. Petersburg State University, 7/9 University Embankment, St. Petersburg 199034, Russia*
[b] *Novosibirsk State University, 1 Pirogova St., Novosibirsk 630090, Russia*
[c] *Natural History Museum, Centre for Russian and Central EurAsian Mineral Studies (CERCAMS), London SW7 5BD, UK*

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ABSTRACT

The South Tien Shan was formed by the late Paleozoic (Hercynian) collision between the Precambrian continents of Karakum and Tarim in the south and the early Paleozoic Kazakhstan continent in the north. The most eye-catching geological features of the South Tien Shan include various Silurian to Carboniferous marine sedimentary formations, which are tectonically juxtaposed with fragments of ophiolites; suprasubduction and intraplate volcanics and crosscut by Carboniferous to Permian orogenic granitoids. Major tectonic cycles can be traced through the entire South Tien Shan belt over 2000 km from west to east. The Late Proterozoic accretionary events at the active margins of Rodinia were followed by continental rifting in the early Paleozoic. The opening of new oceanic basins known as the Turkestan Ocean took place from the late Ordovician to early or middle Devonian and was accompanied by active subduction in island arcs and active continental margins. Input of materials from eroded island arcs into sedimentary basins is registered in lower-middle Paleozoic and younger sediments. Devonian intraplate magmatism made another significant contribution to the formation of continental crust of South Tien Shan. Precambrian microcontinents that existed within the Turkestan Ocean during the early Paleozoic as separate blocks were later accreted to continental margins together with island-arcs and made up a basement, on which the Middle Paleozoic carbonate platforms were formed. The last episode of suprasubduction magmatism, which started in the Lower Carboniferous (Visean) and reached its peak in Serpukhovian - Bashkirian, was followed by collision and final closure of the Turkestan Ocean in early Permian.

1. Introduction

The Central Asian Orogenic Belt (CAOB) is a major Phanerozoic accretionary orogen comprising numerous continental blocks and island arcs that amalgamated as a result of the Late Paleozoic, collision and final closure of the Paleo-Asian Ocean (Zonenshain et al., 1990; Şengör et al., 1993; Jahn et al., 2000, 2004; Windley et al., 2007; Safonova and Santosh, 2014).

In the southern part of the CAOB, Late Paleozoic events formed the South Tien Shan orogenic belt (STS). The STS was formed by the late Paleozoic (Hercynian) collision between the Precambrian continents of Karakum and Tarim in the south and the early Paleozoic Kazakhstan (-Yily) continent in the north (Burtman, 1975; Biske and Seltmann, 2010; Han et al., 2011). The most eye-catching geological features of the STS include various Silurian to Carboniferous marine sedimentary formations, which are tectonically juxtaposed with fragments of ophiolites; suprasubduction and intraplate volcanics, and crosscut by Carboniferous to Permian *syn*-, late and postcollisional granitoids.

During the last decades a great amount of new geochronological and geochemical data for the key areas of the STS belt have been published, which helped to constrain tectonic evolution of the belt and allowed for reconstruction of the most important tectonic events (Windley et al., 2007; Charvet et al., 2007; Charvet et al., 2011; Wilhem et al., 2012; Han and Zhao, 2017; Xiao et al., 2013; Wang et al., 2011). However existing geodynamic models for the Paleozoic tectonic evolution of the Tien Shan (Windley et al., 2007; Burtman, 2015; Samygin et al., 2015) are mostly of a regional character and do not fully take into account specific features of particular tectonic domains within the STS. Accordingly, the aim of this review paper is to present an integrated picture of the geological history of STS from late Proterozoic to the end of Paleozoic based on the published contributions as well as on our own extended work in this area.

The Southern Tien Shan orogenic belt is a linear elongate structure that stretches for >2000 km, from the western deserts of Uzbekistan to China in the east (Biske and Seltmann, 2010; Burtman, 2010; Xiao et al., 2013; Kröner et al., 2014). The northern boundary of the STS is outlined

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* Corresponding author.
E-mail address: R.Seltmann@nhm.ac.uk (R. Seltmann).

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by the ophiolite-marked Turkestan (Burtman, 2006) or South Tien-Shan suture (STSS) (Han and Zhao, 2017) that was transformed into a shear zone by strike-slip motions during Mesozoic and Cenozoic. The southern boundary of the STS belt is traditionally positioned along the southern foothills of the Hissar, Alai, Kokshaal and Halyktau (Harkeshan) Ranges marking the transition from southern continents of Tarim and Karakum to the folded structure of STS (Figs. 1, 2). Given the great length of the Tien Shan structures, the following linear segments are traditionally delineated within the belt from west to east: 1) the Kyzylkum segment stretching from the Sultan-Uvais to southern Kyzylkum mountains, 2) the western segment, from the Nuratau, Baisun and Hissar Ranges in the west to the Ferghana Range in the east, 3) the central segment occupying the Kyrgyz part of the belt east of the Ferghana Range, and 4) the eastern segment, located in the Chinese territory, where the western (west of the Bozdon Lake) and eastern parts are also distinguished in the vast literature (Xiao et al., 2013 and references therein). Herein, the geological descriptions are given accordingly, utilizing the generally accepted tectonic subdivisions as well as the local names used in the literature.

2. Continental blocks derived from Rodinia and early oceanic basins

The STS orogenic belt includes the Neoproterozoic continental blocks formed at the active margins of Rodinia and remnants of the Neoproterozoic oceanic basins (Kiselev, 2001; Ge et al., 2014).

It is generally accepted (Pecherskiy and Didenko, 1995; Ge et al., 2014; Samygin et al., 2015) that the Neoproterozoic continental blocks of the Tien Shan and Kazakhstan originally belonged to the northern Gondwana, which was a part of the Rodinia supercontinent. They separated from Rodinia in the late Precambrian-early Paleozoic, forming a series of continental blocks and oceanic basins, including the newly-formed Turkestan Ocean. An indication of Rodinia breakup might be exemplified by the ca. 750 Ma bimodal alkaline magmatism that affected the northern Tien Shan and Kazakhstan (Samygin et al., 2015; Konopelko et al., 2014).

The northern boundary of the STS orogenic belt separates it from the Paleo-Kazakhstan (also known as Kazakhstan-Yily or Kyrgyz-Kazakh) continent, formed in the late Ordovician. The Middle Tien Shan (MTS)

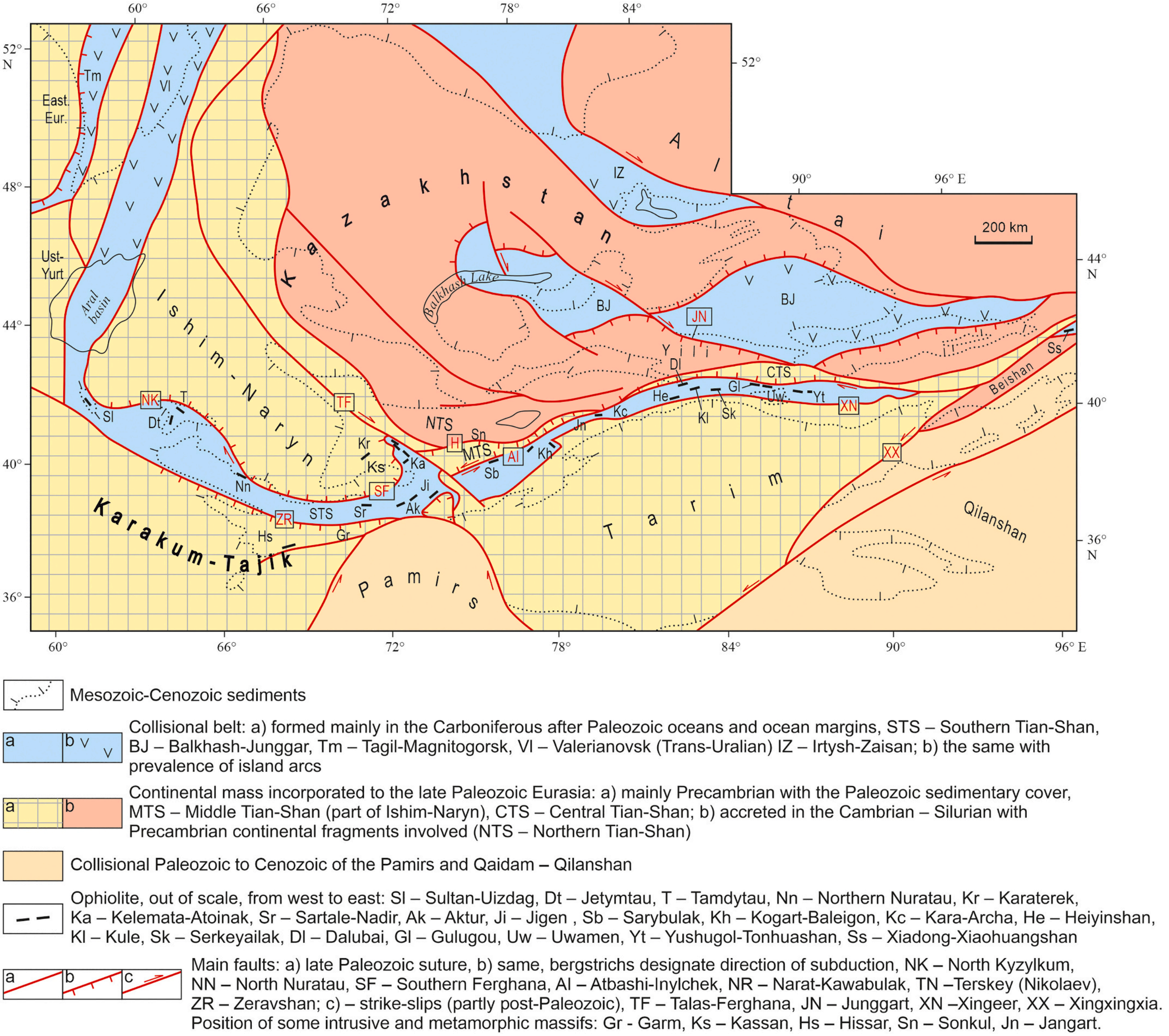


Fig. 1. Position of the Southern Tien Shan in the Central Asian Orogenic Belt (modified from Hwang et al., 2008; Han and Zhao, 2018).

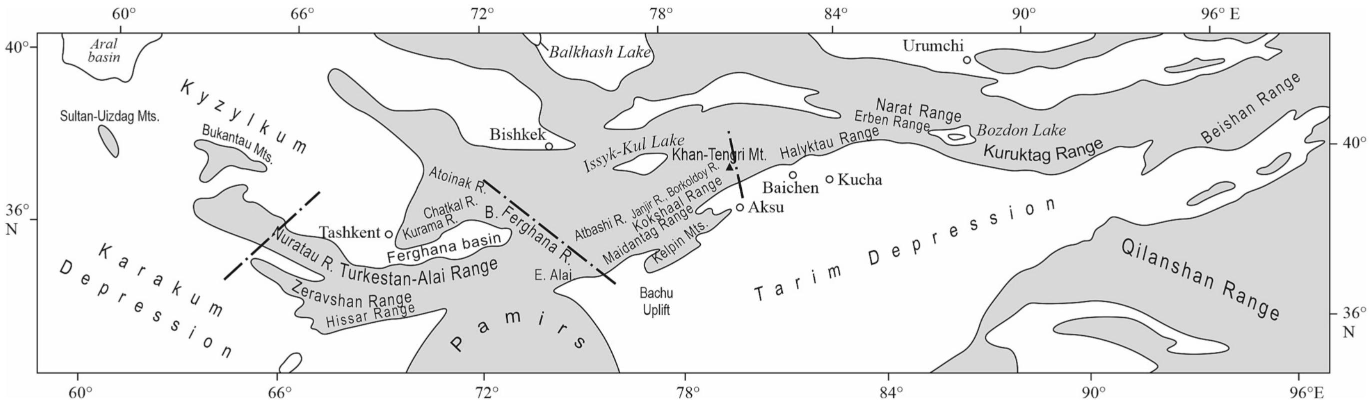


Fig. 2. Orography of the Southern Tien Shan.
E. Alai – Eastern Alai Mountains, Bz – Baubashata Mountains.
Dash-dotted lines divide segments of the STS belt (see explanation in the text).

terrain (also known as Ishim-Naryn, or Syr-Daria block) forms the southwestern part of the Paleo-Kazakhstan. The early Precambrian continental crust of the MTS is known from rare outcrops in the eastern Kyrgyzstan (Kuilyu River), where it includes Early Proterozoic granites and gneisses, dated at 2330–1800 Ma (Kröner et al., 2017). The rarity of Mesoproterozoic rocks is a characteristic feature, whereas magmatic events of ca. 750–700 Ma are distinctly represented by bimodal, mainly acid and alkaline volcanics of the Greater Naryn.

Formation, possibly related to the rifting on the active Rodinia-Gondwana margin (Kiselev, 2001; Konopelko and Klemd, 2016; Konopelko et al., 2017a; Mikolaichuk et al., 2020).

The MTS terrain thins out to the east of the Kyrgyz-Chinese border and is replaced to the east by the Central Tien Shan (CTS) block on the territory of China. The Proterozoic rocks of the CTS are exposed in the Narat (Nalati) and Erben ranges, as well as in the Baluntai area and in the Xingxingxia block located to the east. The CTS contains Paleoproterozoic orthogneisses of ca. 2466 Ma, and there are also known occurrences of metamorphic rocks with ages of ca. 1812 Ma (Wang et al., 2017b). Mesoproterozoic rocks are rare (Kröner et al., 2013), although xenogenic zircons with ages around 1400 have been reported from the younger granitoids of Xingxingxia (Lei et al., 2011). Neoproterozoic granitic gneisses with ages from 900 to 800 Ma predominate in the basement of the CTS block (Long et al., 2011; Alexeiev et al., 2015; Wang et al., 2017b; Li et al., 2018; Zhong et al., 2017; He et al., 2018).

Several authors (Wang et al., 2014; Zhong et al., 2015; Han et al., 2016; Zhong et al., 2017; Wang et al., 2017a) believe that MTS and CTS were parts of a single continental block by the early Paleozoic. Other researchers pay attention to Mesoproterozoic granitic magmatism and detrital zircon age spectra in the CTS and prefer to compare the CTS with the Kyrgyz Northern Tien Shan (NTS), where the main magmatic events took place in the late Mesoproterozoic (1300–1000 Ma), and thus can be considered as Grenvillian in age (Kröner et al., 2013; Yarmolyuk and Degtyarev, 2019; Zhu et al., 2019; Alexeiev et al., 2019). However, in both reconstruction scenarios, after Grenvillian events, the NTS and CTS were parts of a single continental block together with Tarim (Kröner et al., 2013; Sun et al., 2021).

The basement of the Tarim paleocontinent is exposed along the southern foothill of the Tien Shan and to the east in the Kuruktag Range. The oldest continental crust within the Tarim is represented by Archaean TTG gneisses with ages generally between 2800 and 2600 Ma, but locally as old as 3600–3700 Ma and by granites dated at 2530 Ma (Wu et al., 2021). Archaean gneisses are surrounded by younger (2000–1800 Ma) paragneisses. Magmatic and metamorphic events with ages between 1100 and 900 Ma affected the southwestern part of the Tarim and were interpreted as related to Grenvillian (Tarimian) collision or orogeny that completed the amalgamation of Rodinia supercontinent (Shu et al., 2011; Zhang et al., 2012; Wu et al., 2021).

However, in the latest post-Grenvillian Neoproterozoic times an active continental margin with subduction zone has developed in the newly formed supercontinent. The subducted oceanic crust was studied in the eastern part of the Kelpintag (Kepin) mountains on the northern margin of the Tarim depression whereby the Aksu Group blue schists have been reported by Ge et al. (2014). The *E*-MORB-type metabasalts of the Aksu Group with an age of about 900 Ma (Sm—Nd) are overlain by metasediments with depositional age of ca. 730 Ma (Zhu et al., 2011) and an Ar—Ar age of the blueschist-facies metamorphism estimated at ca. 745 Ma (Zhang et al., 2012). Crustal thickening, granulite-facies metamorphism, and anatectic granitoid magmatism with ages between 835 and 785 Ma, reported from the Kuruktag Mts. in the NW Tarim by Xiao et al. (2019), also support existence of Neoproterozoic active continental margins. Slightly younger A-type granites and basaltic dikes with ages in the range 820–770 Ma may indicate crustal stretching that led to the opening of a marginal sea north of the modern Kuruktag (Ge et al., 2014) (Fig. 3).

Mafic intrusions and A2-type granitoids with ages in the range 700–615 Ma belong to bimodal magmatic series that formed in the Tarim in the latest Neoproterozoic (Chen et al., 2000; Ge et al., 2014; Huang et al., 2013; Xiao et al., 2019). At the northern margin of the Tarim block, these rocks supposedly associated with a back-arc rift (Ge et al., 2012, 2014; Zhu et al., 2017; Sun et al., 2021). The age spectra of detrital zircons in Paleozoic sandstones also reflect two distinct periods of the Neoproterozoic magmatism. Detrital zircon ages in the sediments from the northern Tarim margin show peaks at 704 and 638 Ma (Huang et al., 2018), while peaks at 740 and 605 Ma were also established at the

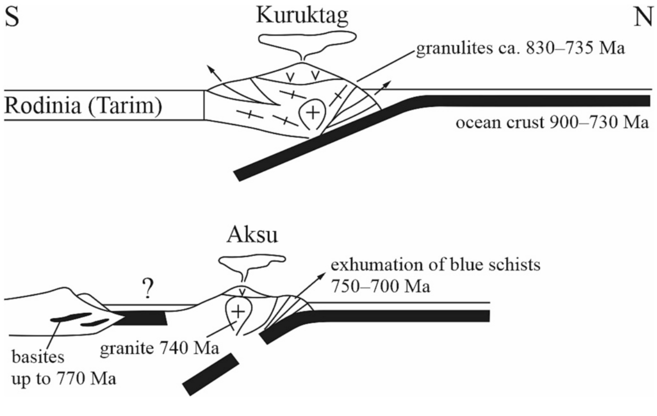


Fig. 3. Two proposed stages of late Proterozoic development of the Rodinia margin in the modern northern Tarim area, according to data compiled by Ge et al. (2014).

NW Tarim margin (Biske et al., 2019). Bimodal magmatic series with ages around 750 Ma were also reported from the Northern Tien Shan and Kazakhstan (Samygin et al., 2015; Konopelko et al., 2014).

The Karakum-Tajik continental block frames the STS belt from the southwest and is often considered as the western continuation of Tarim (Han et al., 2016; Zhong et al., 2017; Wang et al., 2017a). The metamorphic complexes of the southwestern Hissar Range, as well as those of the Garm block (Fig. 1) were considered as the basement of the Karakum-Tajik continent. The gneisses and migmatites of these localities were mapped as the Early Precambrian basement (Bel`kova et al., 1969). However, the recent results have shown a much younger age of the Karakum-Tajik basement. The Garm paragneisses include Late Neoproterozoic-Early Cambrian rocks, with the youngest detrital zircons ages in the range 650–535 Ma (Konopelko et al., 2015; Worthington et al., 2017). Similar depositional ages of 570–540 Ma were obtained for metasedimentary rocks in the southeastern Hissar Range (Konopelko et al., 2019). However, early Precambrian zircon clusters in the range 2700–2400 and 2300–1700 Ma, are also well pronounced in the Baisun metasedimentary rocks (Konopelko et al., 2019) showing that these sediments undoubtedly originated from the destruction of the Lower Proterozoic continent.

Abundant early Proterozoic and Grenville-age detrital zircons reported from the Karakum-Tajik basement may indicate that it can be similar in age and composition to the basement of Tarim. However, the Paleozoic sandstones of central Tajikistan are dominated by detrital zircons derived from a different source of the latest Precambrian and lower Cambrian age. Similar ages of detrital zircons have been reported from metasediments of the Fan-Karategin belt in Zeravshan-Hissar mountains (Obizarang and Yagnob Fms.), where the most abundant ages of detrital zircons range between 650 and 550 Ma (Konopelko et al., 2015; Worthington et al., 2017; Biske et al., 2021). In addition, a well pronounced population of Ediacaran detrital zircons was also found in Devonian sandstones from the STS (Biske et al., 2019).

Thus, based on the available data, it can be concluded that both the Tarim and the Precambrian blocks of the Northern Tien Shan were not affected by significant magmatic and/or metamorphic events with ages younger than 700–650 Ma corresponding to the latest Neoproterozoic-early Cambrian time span. However, in contrast to Tarim, such latest Neoproterozoic-early Cambrian magmatic activity has been clearly shown to take place in the Karakum-Tajik continent. Therefore, we can assume possible connection between the Karakum-Tajik continent and the western parts of Rodinia, which developed as active margins in the latest Neoproterozoic-early Cambrian (Biske et al., 2021). In accordance with this assumption, the Ediacaran-Cambrian arcs of the Karakum-Tajik continent could represent the eastern continuation of the Cadomian orogenic belt stretching from the Central and Southern Europe to the east (Murphy et al., 2004; Wu et al., 2023). Ediacaran magmatic rocks and detrital zircons were reported from Greater Caucasus (Kheraskova et al., 2010), Armenia, Elbrus, central Iran, and the Lut massif (Meinhold et al., 2008; Galoyan et al., 2020; Chu et al., 2021), which may represent possible links between the Cadomian terrains of Europe and the Karakum-Tajik continent. It is not precluded that Cadomian-age blocks of the SE Urals, including ca. 529 Ma granites and ca. 615–515 Ma Beloretsk metamorphic complex (Ryazantsev et al., 2019) belonged to the same peri-Gondwanan chain of active margins.

Although the existence of the latest Neoproterozoic - early Cambrian magmatic arcs in the Karakum-Tajik block is well documented, relatively little is still known about the remnants of the oceanic crust of this age. A preliminary age estimate of 757 ± 21 Ma was obtained for the Jetymtau ophiolites in Kyzylkum desert by Mirkamalov et al. (2012). This is in accordance with Neoproterozoic age of microfossils from the overlying sediments of the Taskazgan Formation (Abduasimova, 2001). We suggest that oceanic lithosphere of this age can be also represented by metabasalts of the Gorif and Yagnob Fms in Zeravshan-Hissar mountain. These metabasalts are overlain by volcaniclastic schists with depositional ages between 600 and 580 and 530 Ma (Worthington et al., 2017; Biske et al., 2021).

3. Late Neoproterozoic - Lower Paleozoic sedimentary cover

Cryogenian strata of the northern Tarim margin contain ca. 740–725 Ma bimodal volcanic rocks, which change upsection to the 3000–4000 m thick diamictites of the Marinoan glacial epoch. Elevated thickness of the diamictites suggests their formation in a rift-related environment. Diamictites of the Kichitaldysu Formation described by Osmonbetov (1982) in the MTS terrain in eastern Kyrgyzstan probably also formed during the Marinoan glaciation. The oldest depositional ages of the Tarim diamictites, estimated from detrital zircon studies, are younger than 725 Ma while the youngest glacial deposits yielded depositional ages of ca. 542 Ma (Zhang et al., 2012; Rojas-Agramonte et al., 2014).

The Ediacaran sediments, exposed at the northern Tarim margin, unconformably overlie Cryogenian diamictites and represent the post-rift platform cover. However, they also include minor basaltic flows dated at 615 Ma in the Aksu area and in the Kuruktag Mts. (Zhu et al., 2017), and were displaced with formation of semi-grabens, as shown by seismic profiles across the Tarim cover at the level of Cambrian strata (Gao and Fan, 2012). The Upper Ediacaran (?) and Lower Paleozoic shelf-type carbonate sediments within the Tarim and MTS terrains have moderate thickness. In the central Tarim these carbonates are partially replaced by evaporates (Gao and Fan, 2012), and in the Lower Ordovician this sequence was overlain by bathyal graptolite shales (Zubtsov, 1961; Repina et al., 1975; Osmonbetov, 1982; Bukharin et al., 1985; Li and Xu, 2007; Abduasimova, 2001; Popov et al., 2009; Neyevin et al., 2011; Gao and Fan, 2012).

Paleogeographical reconstructions of Samygin et al. (2015) and Domeier (2017) suggest that Tarim and Precambrian microcontinents of southern Kazakhstan were separated from each other long before the beginning of Paleozoic and were located at significant distance during the Cambrian and Ordovician times. On the other hand, there are eye-catching similarities in the stratigraphy of Cambrian sediments of Tarim and MTS (Ishim-Naryn) terrains. It was also noted that fossil fauna of Tarim, Kazakhstan, and northern China was fairly homogeneous until the Ordovician (Popov et al., 2009) suggesting that these continental blocks were located close to each other. Figs. 4 and 5 show the separation of the MTS (Ishim-Naryn) terrain from Tarim at the beginning of the Cambrian, and subsequent deposition of the Middle Cambrian to Lower Ordovician shelf sediments according to Neyevin et al. (2011).

In contrast to Tarim and southern Kazakhstan, the Lower Paleozoic sediments of the Karakum-Tajik continent do not contain Cambrian limestones, and the deposition of shallow carbonates and mature sandstones in this area began only in the Upper Ordovician - Lower Silurian (Baratov, 1976; Abduasimova, 2001).

The STS fold belt is located between the Karakum-Tajik continent in the south and the MTS terrain in the north (Fig. 1). Within the STS, in the Turkestan Range, the Cambrian sediments are represented by thin limestones and shelf-type silt- and sandstones. It was suggested that these rocks deposited on a Precambrian microcontinent defined as the Rabut terrane (Biske, 1996; Biske et al., 2021) (Figs. 4, 5). In the western part of the Turkestan Range and in the Nurata Mts., the Cambrian strata within the STS terrain (namely the Kaltadavan, Zhivachisay, and Rukhshif Fms) mostly consist of the continental slope- and deep-shelf type sediments and are overlain by the Lower Ordovician bathyal clays with graptolites. Further west, in the Kyzylkum segment in the STS, the Cambrian strata are represented by the turbidites of the Besapan Formation (Bukharin et al., 1985; Abduasimova, 2001). It was suggested that these continental slope and bathyal sediments could have been formed at the passive margin of the Rabut terrain, which was probably a fragment of the Karakum-Tajik landmass (Fig. 4).

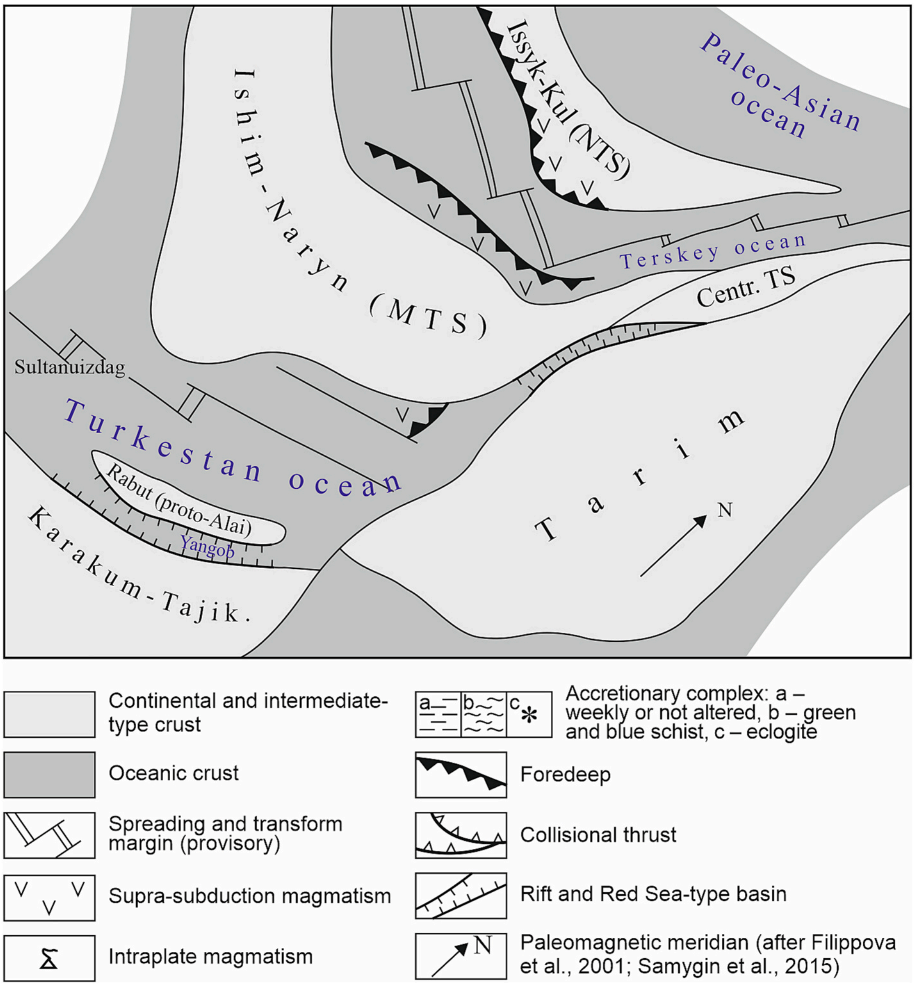


Fig. 4. Geodynamic reconstruction for the Southern Tien Shan: beginning of Cambrian (540–520 Ma). Legend serves Figs. 4, 5, 7 and 8.

4. Birth of the Turkestan Ocean

An oceanic basin that presumably existed between the continental blocks of Tarim and Karakum-Tajik in the south and Kazakhstan in the north was described as the Turkestan Ocean since the early works of Burtman (1975) and Kurenkov (1983) based on the findings of the early Paleozoic ophiolites in the western Tien Shan. This paleo-oceanic basin, also known as the South Tien Shan Ocean (Ge et al., 2014; Han et al., 2016; Wang et al., 2018), is a part of the large Paleo-Asian Ocean, the remnants of which can be traced from Urals to Mongolia and further east (Burtman, 2006; Wilhem et al., 2012).

In the western Tien Shan, dismembered ophiolites can be traced along the STS suture for >2000 km from west to east. An age of 505 Ma has been obtained for plagiogranite in the ophiolite from the Sultan-Uizdag (or Sultan-Uvais) Mts located to the south of the Aral Sea (Dolgopolova et al., 2017). Younger biostratigraphic ages varying from Lower to Upper Ordovician were reported for the flints of the Sartale ophiolite based on studies of radiolarians and conodonts (German and Budianskiy, 1990; Abakumova and Shinkarev, 1994; Kurenkov and Aristov, 1995). Similar age of ca. 448 Ma, reported for metagabbro from the Majerum ophiolite (Mirkamalov et al., 2012), probably register the same stage of the active spreading in the Turkestan Ocean.

5. Middle Paleozoic (late Ordovician-early Carboniferous) oceanic basins and subduction complexes

The dating and geochemical study of the remnants of the oceanic crust and island arc volcanic series that escaped destruction as a result of tectonic erosion in the late Paleozoic showed a rather complicated history of the opening and subsequent evolution of different parts of the Turkestan ocean. Evidence of subduction, recorded by suprasubduction magmatism, accretion of turbidites, and local unconformities, has been clearly manifested in the region since the late Ordovician (Chen et al., 2015).

The Kyzylkum and the Western STS segments. The traces of subduction of the Turkestan Ocean lithosphere to the south, under the active margin of the Karakum-Tajik continent, can be observed on the southern flanks of the Zeravshan River valley. The oldest Paleozoic strata are represented here by calc-alkaline acid volcanics and shallow clastic sediments with interlayers of limestone (Alty-Aul Formation of Zirabulak Mts. (Mukhin et al., 1991; Abduasimova, 2001)). Eastern continuation of these suites is possibly comprised by the greenschist-facies volcanogenic and sedimentary rocks described in the eastern part of Zeravshan-Hissar Ranges as the Norvat Formation of the Yagnob or Fan-Karategin Complex (Baratov, 1976; Volkova and Budanov, 1999). The Late Ordovician age of the Norvat meta-andesits is confirmed by U—Pb dating at 450 Ma (Worthington et al., 2017). This age also corresponds to the age of the youngest zircon grains in the Katarmai metasandstones of Zirabulak-Katarmai Mts. (Konopelko et al., 2019), similar to the Yagnob schists. Later, in middle Silurian and Devonian, this northern boundary of the Karakum-Tajik continent developed passively and was covered with mature quartz sandstones and carbonates, with predominance of lagoonal dolomites. The turbidites of the Ust-Koksu Formation in the eastern Alay Range (Osmonbetov, 1982)

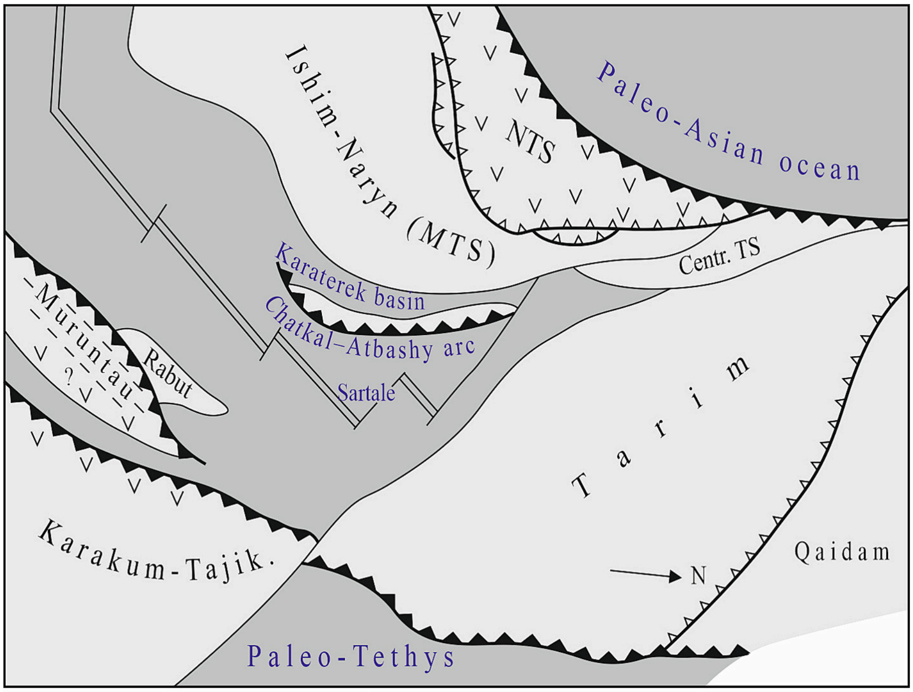


Fig. 5. Geodynamic reconstruction for the Southern Tien Shan: end of Ordovician (460–445 Ma). See Fig. 4 for legend.

possibly represent the only formation that formed in the Silurian-Devonian continental slope environment (Fig. 6, A).

Folded Ordovician-Silurian volcanic and sedimentary rocks, formed in the Turkestan Ocean, can be observed to the north of the Zeravshan valley. Compositions of these rocks indicate that they formed in the island arc, continental slope and bathyal environments. Initiation of subduction in the Turkestan Ocean took place not later than in the Early Ordovician. This is in agreement with an age of 472 Ma reported for the island arc-type granodiorite from exotic block found in the melange of the Alai Range (Alexeiev et al., 2019). Younger, Middle and Upper Ordovician, sandy turbidites are widespread in the Nuratau Ranges (Baratov, 1976; Biske, 1996; Shayakubov and Dalimov, 1998; Abduasimova, 2001), where they overlap Lower Ordovician graptolite shales. After the Ediacaran to Cambrian ones, these turbidites represent the second flysch formation in the history of the Turkestan Ocean. Upsection, the turbidites are again replaced by black graptolitic shales deposited at the beginning of Silurian (Ruddan - Aeron).

As seen in reconstructions presented in Figs. 5–7, it is suggested that sedimentary formations described above were accreted to the Late Ordovician-Early Silurian island-arc within the Turkestan Ocean. This arc was separated from the Karakum-Tajik continent by a series of marginal basins including the Vashan, or Zeravshan - Eastern Alai oceanic basin. Bathyal clays and flints deposited in this basin comprise the sedimentary sequence exposed on the left flanks of the Zeravshan Valley and also to the east, along the strike, on the southern slopes of the Alai Range (Biske, 1996). Minor occurrences of Silurian island-arc volcanics intercalated with graptolitic shales were described along the whole STS accretionary complex from the Muruntau Mts. in the west to the Ferghana Range in the east (Bukharin et al., 1985; Biske, 1991, 1996; Alexeiev et al., 2019). However, extensive recycling of Silurian magmatic arcs is illustrated by the detrital zircon age spectra reported from the flysch sediments of the Zeravshan turbidite suite studied the axial parts of the Turkestan Range and in the southern part of Ferghana valley (Fig. 6, A) (Shvanov, 1983; Biske, 1996; Biske et al., 2019). The studied age spectra of detrital zircons in the Silurian and younger sandstones register a well-pronounced episode of late Ordovician – early Silurian arc magmatism, with peaks from 448 to 442 Ma (Alexeiev et al., 2020) to 430–420 Ma (Käßner et al., 2016; Biske et al., 2019). Accretion of Silurian arcs and termination of suprasubduction magmatism took place in the early-middle Devonian. The youngest Devonian arc-type volcanics are known in the Turkestan Range where this event was also marked by deposition of the thick turbiditic sequences with olistostromes and conglomerates of the Jidale-Karajegach and Dauda formations (Biske, 1996). Accretion of Silurian arcs and subsequent erosion formed a basement of the Kyzylkum-Alai microcontinent, on which the late Paleozoic sedimentary piles were deposited during the late Devonian and Carboniferous.

Silurian ophiolites and overlying bathyal sediments of the inner parts of the Turkestan Ocean were included in collisional tectonic nappes of the STS that formed during the final closure of the Turkestan Ocean in the late Paleozoic. Gabbro with juvenile isotopic signatures from the Teskuduk ophiolite of the Muruntau Mts. in the Kyzylkum desert was dated at 438 Ma by Dolgopolova et al. (2017). Similar age of 440 ± 6 Ma was reported for ophiolitic gabbro from the Akjol River in the Atoinak Range in the northern Ferghana valley where the boninitic affinity of the rock was related to initial stages of subduction (Hegner et al., 2019).

Similar to the southern margin, on the northern margin of the STS belt, Middle to Late Ordovician convergence formed extensive magmatic arc that was recognized by Alexeiev et al. (2016) as the Ordovician Chatkal-Atbashi volcanic arc (Fig. 5). The remnants of this arc are represented by acid volcanics described in the Bozbutau Mts. in the northern slopes of the Fergana valley, and in the northern part of the Atbashi Range where they were dated at 467–445 Ma (Alexeiev et al., 2016). Similar ages of ca. 450 Ma were obtained for metadacites and granites of the Kassansay River Valley in the Chatkal Range (Alexeiev et al., 2016). The Chatkal-Atbashi arc was built up on continental basement as evidenced by ancient model ages and Nd—Hf isotopic data from magmatic rocks. Between the Chatkal-Atbashi arc and the MTS block of the paleo-Kazakhstan continent, in the northern part of the Chatkal Range, the MORB-type Karaterek ophiolite was recently described by Hegner et al. (2022). The rocks of the Karaterek ophiolite are overlain by the late Cambrian-Middle Ordovician siliceous

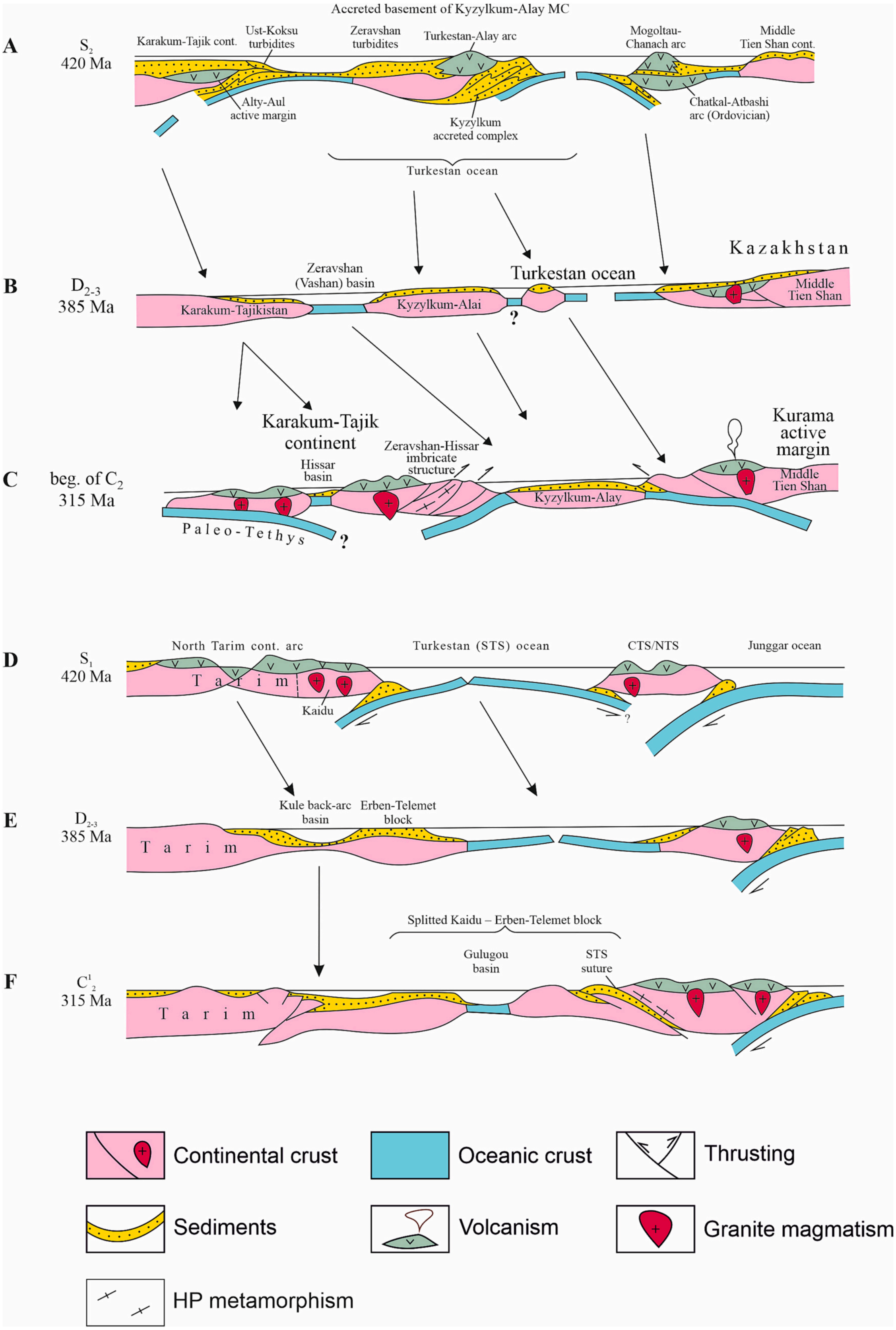
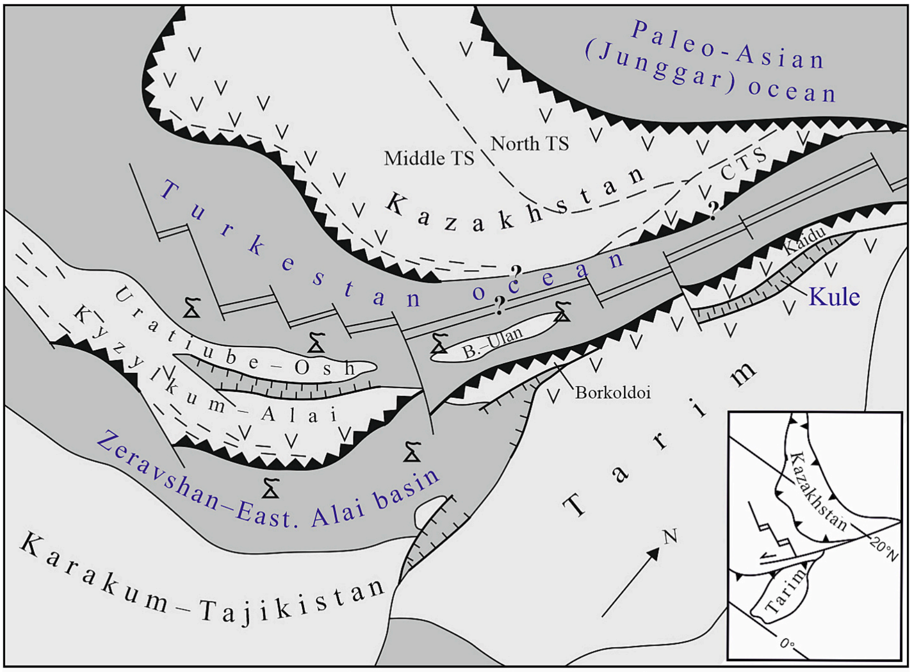


Fig. 6. The evolutionary model for the Southern Tien Shan in the middle Paleozoic.

A – C: the Kyzylkum and the western segments; D – F – the eastern segment. Modified after Alexeiev et al. (2015) and Dolgopolova et al. (2017).



For captions see Fig. 4. B.-Ulan — Baubashata-Ulan terrane

Fig. 7. Geodynamic reconstruction for the Southern Tien Shan: end of Silurian to beginning of Devonian (425–400 Ma).
See Fig. 4 for legend. In the box: Possible position of Kazakhstan and Tarim continents, in accordance with compilation of paleomagnetic data in Burtman and Dvorova (2018). Note that Kazakhstan Orocline (Li et al., 2018) and proposed left strike-slip along the Turkestan suture formed later in the Carboniferous-Permian.

sediments indicating significant width of the Turkestan Ocean in the early Paleozoic.

Upper Ordovician (Llandoveri) volcanomictic turbidites (Rinenberg, 1990; Shayakubov and Dalimov, 1998) containing large blocks of andesites dated at 442–435 Ma (Urubulak Formation in Mogoltau mountains, Biske et al., 2021) can be observed on the northern slopes of the Fergana valley. These rocks were accreted to the northern continent during Silurian and then intruded by the late Silurian – early Devonian granites with ages in the range 425–397 Ma, which are typical for suprasubduction granites of the Chatkal active margin of paleo-Kazakhstan continent (Shayakubov and Dalimov, 1998; Alexeiev et al., 2016; Dolgopolova et al., 2017; Konopelko et al., 2017b). The granites have Neoproterozoic model ages and mixed isotopic compositions characteristic for granites formed at active continental margins (Dolgopolova et al., 2017).

The fore-arc turbidites of the Silurian arcs were accreted to the northern paleo-Kazakhstan continent in the early Devonian. These rocks were involved in the next episode of subduction during the Carboniferous and experienced high-P low-T metamorphism in subduction zones. Later, in the middle Carboniferous, they were exhumed as a result of Hercynian collision and comprised a metamorphic belt including green and blue schists of the Kan, Mailisu and other metamorphic suites, described in the uppermost nappes of the collisional STS structure (Osmonbetov, 1982; Biske, 1996; Biske and Seltmann, 2010; Biske et al., 2019).

Central and eastern segments of the STS. The oceanic crust of the eastern part of the Turkestan Ocean can be observed as ophiolitic fragments along the Atbashi-Inylchek suture (Alexeiev et al., 2007) (Fig. 1). Further east, this suture is known as the Narat - Kawabulak or Akeyaz - Tonhuashan failt (Jiang et al., 2014; Han and Zhao, 2017; Wang et al., 2018). Ages of the ophiolites along this fault vary significantly. However, some of them, such as the oldest Ediacaran Dalubai ophiolite in the Narat Range (Yang et al., 2005; Wang et al., 2011) probably formed not in the Turkestan ocean but the Kyrgyz-Terskey ocean, which existed north of the Ishim-Naryn (MTS) block in the early Paleozoic (Fig. 4). In this area, ophiolites of the two sutures, the Terskey (Nikolaev) suture and the Narat-Kawabulak suture, are closely spatially associated due to later sinistral displacements that created the Nikolaev structural line separating the MTS and CTS blocks.

Taking this into consideration, we can tentatively consider the late Ordovician volcanics of the Atbashi Range as the oldest evidence for the opening of the Turkestan Ocean and initiation of subduction of the oceanic crust under the Chatkal-Atbashi arc (Alexeiev et al., 2016). Further east, this suture includes the MORB-type Wuwamen ophiolites in the Baluntai area, intruded by the early Silurian (442 Ma) island-arc gabbros and plagiogranites (Wang et al., 2018). Other ophiolitic fragments in the central and eastern parts of the STS are Silurian or younger in age. They include 422–397 Ma gabbro from the Janjir Range (Wang et al., 2018), the ca. 400 Ma Yushugou and Tonghuashan ophiolites in the east STS (Han et al., 2016; Zhang et al., 2019), and MORB-type ophiolites in the Sarybulak River valley of the Atbashi Range that are overlain by bathyal flints and slates of Middle-Upper Devonian age (Alexeiev et al., 2007).

Thus, the eastern part of the Turkestan Ocean was opened not later than in the beginning of the Ordovician. This age estimate is in agreement with the lack of evidence for the early Paleozoic passive margin formations in this area. The oldest bathyal sediments in the eastern part of the STS comprise the Silurian (Aeronian) graptolitic shales, known in the Kokshaal and Ulan Ranges (Biske et al., 1986). Deposition of the carbonate platforms began in the upper Silurian (Ludlovian) in the central segment of the STS and in the upper Silurian – lower Devonian (Przhidolian-Lochkovian) in the eastern Chinese STS.

In the central and eastern STS, there is also another southern group of the ophiolites located closer to the margin of the Tarim craton. This group includes the Kule, Serkeyailak, and Heyinshan ophiolites with ages in the range 424–392 Ma (Han et al., 2011; Ge et al., 2012; Ge et al., 2014; Zhao et al., 2015; Wang et al., 2017a; Wang et al., 2018) and somewhat isolated Jigen ophiolite in the Chinese part of the Eastern Alai Ridge, dated at 392 ± 15 Ma (Han and Zhao, 2017). In the Kyrgyz territory, the same southern group is represented by the poorly studied Karaarcha and Kogart ophiolites. In the southern slope of the Kokshaal Range, this group includes the Baleigong ophiolite with an age of ca.

450 Ma (Wang et al., 2007).

It is still not clear whether these two groups of the ophiolites formed in the same oceanic basin (Han and Zhao, 2017), or the southern group of the ophiolites with younger ages evolved in a separate marginal sea basin (Wang et al., 2011; Alexeiev et al., 2015; Wang et al., 2018) as it is shown in reconstructions given in Fig. 6, D and Fig. 7. According to our model, the marginal-sea ophiolites of the Kule-Heyinshan group formed as a result of the back-arc rifting on the active margin of the Tarim continent in the Late Ordovician to Silurian. Calc-alkaline magmatism at the Tarim margin was active from 460 to 410 Ma and terminated in the Middle Devonian, reaching its peak intensity in Silurian (Telychian), at about 432 Ma, as evidenced by the age spectra of detrital zircons from middle-upper Paleozoic sediments (Lin et al., 2013; Alexeiev et al., 2015; Wang et al., 2016; Zhong et al., 2019). Volcanic series of this age, studied at the Tarim margin, are known in the literature as the Kaidu Arc (Alexeiev et al., 2015; Zhong et al., 2019). These volcanics are exposed the Greater Yulduz (or Bainbuluk basin) area and can be traced westward to the headwaters of the Aksu river (Biske and Shilov, 1998; Pu et al., 2011). The volcanic rocks have Nd—Hf isotopic compositions typical for continental arc series and Nd model ages in the range 1600–1380 Ma (Ge et al., 2014). In addition, ages of xenocrystic zircons in these rocks are characteristic for those derived from the Tarim continental basement (Zhong et al., 2019). Similar isotopic compositions were reported for 460–400 Ma gabbro-diorite intrusions located along the northern Tarim margin in the Halyktau (Harkeshan) and Kuruktag Ranges (Lin et al., 2013; Ge et al., 2012; Zhao et al., 2015; Dong et al., 2016).

Based on the age spectra of detrital zircons from the late Paleozoic sediments, the termination of suprasubduction magmatism in the northern Tarim took place in the middle Devonian (Han et al., 2015; Dong et al., 2016). The studied rocks have similar crustal isotopic characteristics (Xiao et al., 2019; Huo et al., 2019). Comparable results were also reported for the northeastern margin of Tarim by Biske et al. (2019).

The data on magmatic and sedimentary processes in the northern margin of the Tarim generally complement each other. After the uplift that followed the termination of the late Ordovician magmatism, Silurian and Devonian predominantly clastic sediments of the Kelpintag and Kuruktag Ranges were unconformably deposited (Carroll et al., 2001; Lin et al., 2012; Liu et al., 2012). To the south, in the central part of the Tarim platform, the uplifts continued until the middle Devonian, and the whole thickness of eroded rocks in this area was approximately estimated as 3–5 km (Lin et al., 2012). Transfer of the debris was especially noticeable on the northwestern slopes of the Tarim continent, facing the Turkestan Ocean. Locally, the transfer of debris from central Tarim is registered in younger strata up to the Carboniferous (Mississippian) (Biske et al., 1986). Thick sedimentary piles consisting of Devonian sandy turbidites can be observed along the Tarim margin from the East Alai Range in the west to the Kokshaal Range and Kuche River valley in the east (Biske et al., 1986; Biske, 1996; Alexeiev et al., 2015; Huo et al., 2019). Upsection, the Devonian turbidites change to bathyal siliceous sediments deposited until the middle Carboniferous (Mississippian) (Biske, 1996; Alexeiev et al., 2015). The same shift in the sedimentary record can be observed to the north of the continent, in the Kule-Heyingshan marginal basin, which is bordered from the north by the Ulan, Borkoldoy and Erben-Telemet blocks of the STS (Figs. 6, 7). These blocks are made up of thick Devonian to Carboniferous carbonate strata overlying continental arc-type Silurian volcanics of the Haidu arc. Supposedly, this entire area is built up on the Precambrian continental basement.

In the northeast, the STS is bound to the Central TS block where, according to new geochronological data, the Precambrian basement was intruded by Late Ordovician monzogranites and granodiorites. Formations of the Ordovician to Silurian active margin of the Central TS block were overlain by unconformably deposited Devonian sandstones, andesites, and rhyolites with ages in the range 406–390 Ma (Lei et al., 2011; Ma et al., 2014; Chen et al., 2015; Zhong et al., 2015; Zhong et al., 2017; Wang et al., 2017b; Wang et al., 2020). Devonian and Lower Carboniferous sandstones in this area contain populations of detrital zircon grains with peaks at ca. 478–355 Ma (He et al., 2018). Subduction-related I-type granitoids with ages in the range 370–346 Ma are also present. Famennian to Mississippian suprasubduction magmatism in this region may be rather related to subduction from the north that occurred in the Northern TS Ocean, which represent another branch of the Paleo-Asian Ocean separating the Central TS block and paleo-Kazakhstan in the late Paleozoic.

In general, we can conclude that the eastern part of the Turkestan (or the South Tian-Shan) ocean was opened (Han et al., 2015; Shu et al., 2007) or significantly expanded (Alexeiev et al., 2015) during the Ordovician – Devonian time span. The opening of the ocean was a result of back-arc rifting at the active margin of the “Greater Tarim” block, which at that time included micro-continents of CTS and STS and was bordered from the north by the Junggar basin, another branch of the Paleo-Asian Ocean (Fig. 7).

The back-arc rifting might be also responsible for the formation of the youngest ophiolites known along the suture bordering the STS from the north and dated at ca. 334 Ma in Gulugou (Fig. 6, F) and at 342 Ma in Yushugou (Jiang et al., 2014; Han and Zhao, 2018). This Carboniferous marginal sea was probably opened along the Yili volcanic belt at the southern active margin of the paleo-Kazakhstan continent (Wang et al., 2006; Zhong et al., 2017).

6. Silurian-Carboniferous sedimentation and Devonian hot spots

Thick carbonate platforms formed on the marginal shelves and around volcanic seamounts in the Turkestan (STS) ocean from Silurian to Carboniferous (Khristov and Mikolaichuk, 1983; Biske, 1996; Biske and Seltmann, 2010; Alexeiev et al., 2015; Alexeiev et al., 2017; Biske, 2018). A characteristic feature was the steady growth of the carbonate platforms, starting from the Silurian (Wenlockian to Pridolian). The transition from compressional to extensional environment at the end of Silurian was also revealed by the results of seismic profiling in the Tarim continental cover (Han et al., 2015).

The general structure, stratigraphic sequences, and faunistic complexes of the Upper Silurian to Middle Carboniferous (up to Moscovian) carbonate platforms are similar along the entire strike of the SST, including its Chinese segment. Middle to Late Devonian and Mississippian transgressions resulted in the change of sedimentation. In particular, shallow-water limestones were replaced upsection by flints and flint micrites. Lateral transition from the shallow-water, locally riffogenic, carbonates to continental slope turbidites and then to bathyal siliceous and clayey limestones was described for carbonate platforms located at the margins of Tarim and Karakum-Tajik continents and for those that formed in the inner parts of the STS ocean (Baratov, 1976; Biske, 1996; Bardashev, 2008). The northern passive margins of the Paleo-Kazakhstan (the MTS block) are characterized by similar stratigraphy but lack deep water facies, which were probably destroyed by subduction erosion (Alexeiev et al., 2017).

Another specific feature of the STS comprises the OIB basaltic series (Fig. 7) with ages in the range from Upper Silurian to upper Devonian that formed in the internal parts of the Turkestan Ocean in the hot spot settings (Porshnyakov, 1973; Khristov and Mikolaichuk, 1983; Biske, 1996; Biske and Seltmann, 2010; Safonova et al., 2016). The OIB basalts are found in association with pelagic sediments and within carbonate platforms, where they intercalate with limestones (Safonova et al., 2016). The Early Devonian basalts are locally (e.g., in the Janjir Range, Baubashata Mts.) accompanied by rhyodacites that reach up to 20% of the total volume of volcanic rocks. Because geochemical data do not show significant contamination of acid and intermediate volcanics with crustal material, they were interpreted as derivatives of the Iceland-type hot-spot basaltic magma formed in the inner parts of the Turkestan Ocean (Safonova et al., 2016). On the other hand, to the north of the

STS, along the Paleo-Kazakhstan margin, Devonian intraplate basalts were erupted in continental settings, and in this region they demonstrate signatures of contamination with Precambrian crustal material (Zhong et al., 2017; Cao et al., 2019).

The peak of the OIB magmatism took place in the Early Devonian when numerous basalt seamounts formed in the Turkestan Ocean. The remnants of these seamounts can be observed in the upper nappes comprising the structure of the STS from Kyzylkum desert in the west to Han-Tengri Mt. in the east. Slightly younger Middle and Upper Devonian seamounts are known in the Kokshaal segment of the STS. The evidence for younger, ca. 330 Ma, basalts reported from the Atbashi - Janyjer Ranges (Sang et al., 2020a) is questionable because it is based on the dating of few youngest zircon grains, whereas the well-pronounced population of youngest zircon grains in these samples yielded an age of 375 Ma. Therefore, the conclusion of Wan et al. (2020) suggesting that Devonian mantle plume was active until the Carboniferous and could be related to the Early Permian Tarim plume, is unconvincing.

7. Convergence and the continental collision in the Carboniferous

The link of events connected with lithosphere convergence and ocean closing was traced first time on the base of paleontological data through the ages of uppermost shelf carbonates and of the youngest turbidites with olistostromes in foredeeps (Biske, 1996; Biske et al., 2003). Later exploration and dating of magmatic and metamorphic Carboniferous formations added much to the knowledge before obtained.

Development of volcanic margins and accretion on the southern flank of the STS (350–320 Ma). The wide volcanic belt of the Karakum-Tajik active margin in the southwestern (Zeravshan – Hissar) STS was the most prominent result of the initial lithosphere plate convergence in the Early Carboniferous. Volcanic rocks of Siomin sequence now presented in the axial Hissar Range, also Zoi and Vakhshivar Formations of the Baisun block in the SW Hissar were formerly dated as Visean (Baratov, 1976). New U—Pb zircon ages of the thermal metamorphism, granites and basic dikes in the Baisun, Lolabulak and Garm metamorphic area (Mirkamalov et al., 2012; Käßner et al., 2016; Konopelko et al., 2017a, 2019; Worthington et al., 2017) corroborate well with former paleontological data. The followed development of the Karakum-Tajik margin led it to splitting, and the small ocean-type Hissar basin emerged in the Serpukhovian (Fig. 6 and Fig. 8) where presented now as ophiolitic fragments of the South Hissar (Kundajuaz) suture. A certain analogy with the Gulugou basin in the eastern segment of the STS (see before) is possible here. The Gulugou basin could have been formed during the splitting of the previously formed Erben-Telemet arc, as shown in Fig. 6F, simultaneously with subduction to the south within the Turkestan or Dzhungarian Ocean (Zhong et al., 2017; Wang et al., 2020). Visean gabbro and plagiogranites on the SW margin of the STS present also the first intrusive impulse of the huge Hissar granite batholite emplaced into the volcanic belt. The magmatism progressed after 321 Ma (Konopelko et al., 2017b).

Lower Carboniferous magmatic belt of Hissar Range has eastern continuation to the northern Pamirs and the western Kunlun (Burtman, 2010): so, in accordance with more accepted idea, it was a wide Andean-type margin were the northern subduction of the Paleo-Tethys ocean took place (Dolgopolova et al., 2017). Another possibility is that the back south-directed subduction of the southern Turkestan ocean basin (presented now as Zeravshan suture) also took place and impacted on the magmatism (Figs. 6, 7). Anyway, the thrust structure of the Fan Mountains and Zeravshan Ridge (Volkova and Budanov, 1999; Biske and Seltmann, 2010) embraces the Silurian -Devonian sediments of the Tajik shelf and was formed in the for-arc position at the same Early Carboniferous time. If take so, we can better understand the position of aforementioned Yagnob schists and HP glaucophane rocks of Zeravshan-Hissar and Eastern Alay Ranges: they were a part of the accretionary wedge in the northern front of the Hissar continental arc. Yagnob schists together with slates of middle Paleozoic marbles were then exhumed in the late Visean, eroded and sealed by molasses and carbonates of Jizhikrut piggy-back basin in the northern Hissar Range (Biske, 1996;

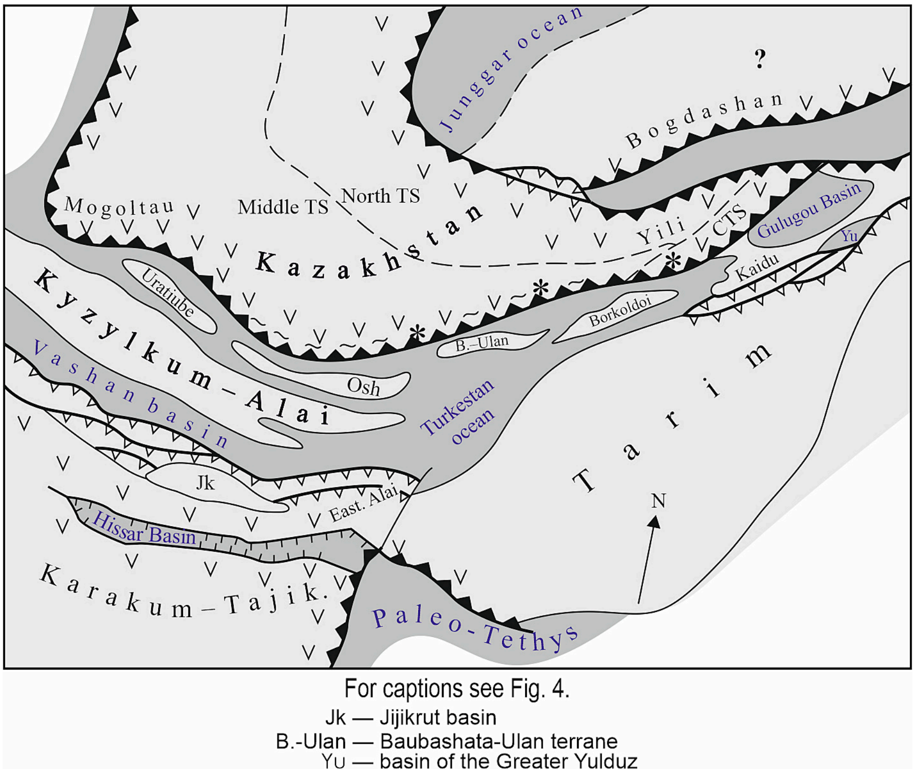


Fig. 8. Geodynamic reconstruction for the Southern Tien Shan: beginning of Pennsylvanian (ca. 315 Ma). See Fig. 4 for legend.

Worthington et al., 2017).

Collisional structure of Zeravshan-Hissar and Eastern Alai Ranges was completed during late Pennsylvanian when Paleozoic formations herein were thrusted to the north or NW upon thick turbidites of the recent Zeravshan and Gulcha river valleys (Biske and Seltmann, 2010) and so closed the southern branch of the Turkestan Ocean. Early Permian granites cut the structure. Later tectonic modifications occurred after Permian red molasses were laid unconformably and then again in the Cenozoic when Pamir masses were pressed to the Tian-Shan.

The eastern segments of the STS also show some signs of the late Paleozoic subduction and accretionary processes along the Tarim northern continental margin. This is top-to-the-north thrust complex in the Heyingshan – Kuche locality where ophiolites of the Southern STS belt embraced (Wang et al., 2011) together with Paleozoic up to lower Bashkirian turbidites (see Fig. 10 in Alexeiev et al. (2015)). The thrust event may correspond to the Visean to Bashkirian break of continuity in the Tarim cover when also rough clastic was laid (Carroll et al., 2001; Brenckle, 2004). Subductive volcanic rocks of this time span are not found upon the Tarim and have very poor presentation in zircon spectra (Han et al., 2015; Han et al., 2016), but HP-LT metamorphism up to amphibolite stage evolved here after 395 Ma (the youngest zircons in the Devonian Wulagen metasandstone in the Wuqia area (Huo et al., 2019)) and possibly at ca. 371 Ma (amphibole Ar—Ar age (Han et al., 2011)). Everywhere in the north Tarim this accretionary thrust complex sealed

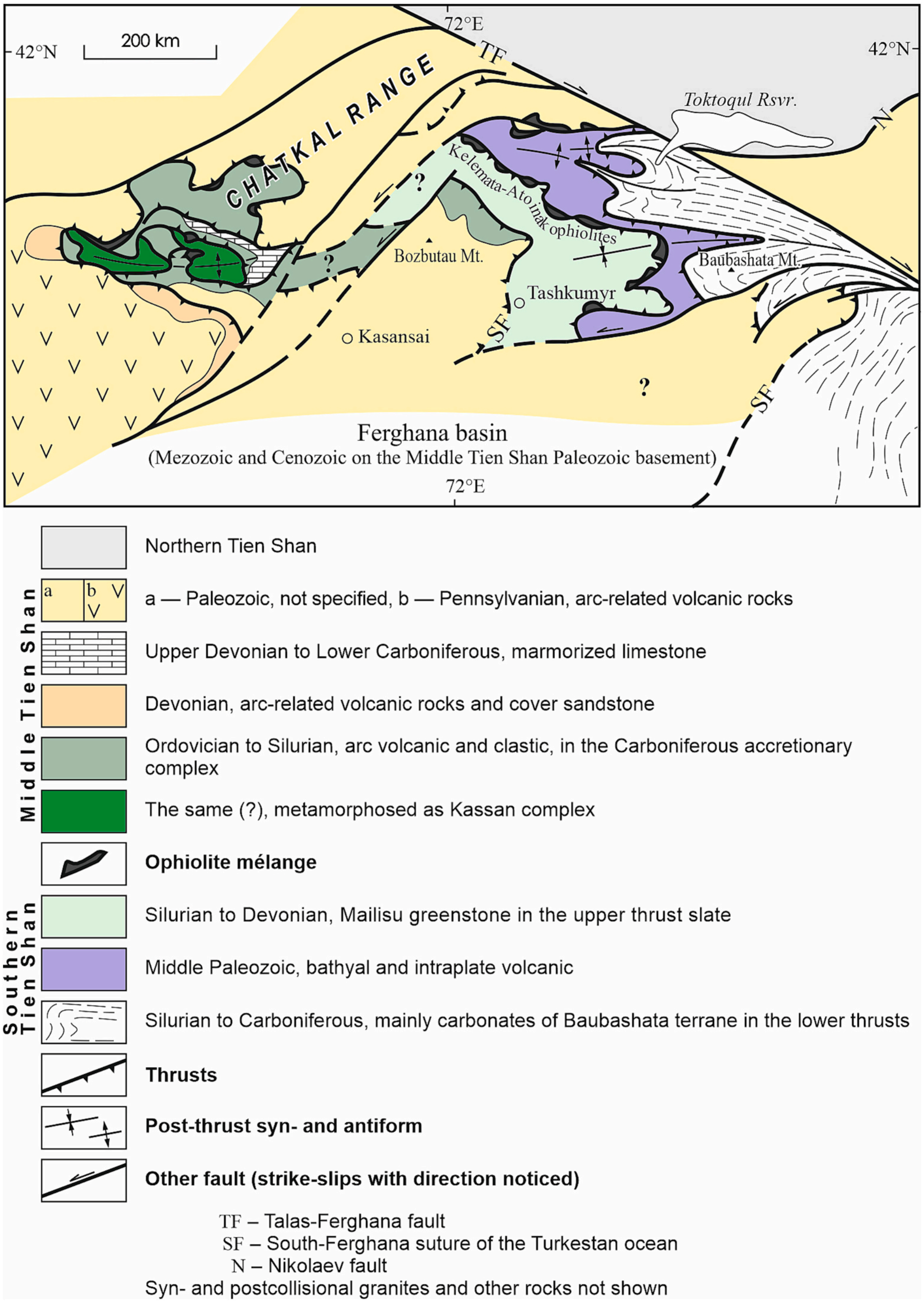


Fig. 9. Paleozoic collisional tectonics of the Northeastern Ferghana valley. Modified after Tursungaziev and Petrov (2008).

by lower Moscovian molasse (Alexeiev et al., 2015). We can only propose it was completed in the Bashkirian soon after analogues in the Zeravshan-Hissar.

Turkestan ocean subduction to the north, collision and nascence of the Bukantau – Kokshaal – Halyktau thrust belt (320–295 Ma). The structure of this northern belt of the western segments of STS is presented in Biske and Seltmann (2010) and more thoroughly in Biske (1996), but some general features and newly found peculiarities are to be noticed especially in the eastern segment.

1. Some data obtained from the most representative and examined blue schists in Akeyaz territory of Chinese STS (zircon rims of 360 Ma and younger) may indicate that ocean subduction to the north terminated before this time (Tan et al., 2019), but the Devonian active marginal magmatism is not presented in the CTS block and also not after ca. 390 Ma in the Kyrgyz MTS. Anyway, the convergence of Tarim and Kyzylkum-Alai continents with Kazakhstan-Yily was well manifested from the end of the Early Carboniferous and provoked a row of roughly synchronous events. The main episode of uplift and exhumation of high pressure (HP) metamorphic complexes happened during the short time along the whole length of the collisional STS northern suture. The debris of green and blue (glaucophane) schists is presented in the Serpukhovian molasses in the Southern Ferghana (Djenchuraeva and Getman, 1993), eclogite-bearing metamorphites of the Atbashi Range were exhumed ca. 316 Ma and denuded no later than in the Kasimovian (Fig. 8) (Hegner et al., 2010; Alexeiev et al., 2019), and ca. 311 Ma as it was found in the Akeyaz River in the Chinese Tian-Shan (Klemd et al., 2011; Wang et al., 2014).

In some cases, reversal uplift of highly metamorphosed rocks could take place with thermal diapirs located in the rear of the subduction belt. This model (Figs. 9, 10) may be proposed for the Kassan metamorphic dome in the Chatkal Range superimposed on the accretion-to-subduction structure and located inside the Kazakhstan margin (Alexeiev et al., 2016). It was then demonstrated by Sm—Nd and 40Ar—39Ar dating (Mühlberg et al., 2016) that metamorphism reached eclogite stage and then retrograde alteration in the time span of 317–313 Ma. Other metamorphic rocks located in the northern STS suture zone and mapped formerly as Precambrian in age (Bakirov, 1978; Osmonbetov, 1982), such as Atbashi gneisses and schists complex, Kan – Mailisu green schists and other, later were dated by youngest zircons as being formed after Ordovician to Devonian magmatic or sedimentary substrates (Hegner et al., 2010; Rojas-Agramonte et al., 2014; Alexeiev et al., 2016). Meta-sandstones of Wuwamen mélange in the Eastern STS deposited after ca. 325–310 Ma (Wang et al., 2018) possibly presents the youngest object of this group.

2. The accretionary imbricated complex consisted of metamorphic, ophiolite and other magmatic and sedimentary rocks, was completed along the whole length of southern Kazakhstan active margin in the Bashkirian (Fig. 8). Then we can record its transformation into nappes, top-to-the-south promotion and thrusting upon the Kyzylkum-Alai and other minor continental blocks of the STS in the early Moscovian (Porshnyakov, 1973; Biske and Seltmann, 2010; Hnylko et al., 2019) and finally upon the Tarim continent in the East. Otherwise stated, these blocks were docked to Kazakhstan, establishing the event marking the start of collision. As to the end of the collisional process, it has followed in the earlymost Permian when last residual foredeeps of the Turkestan ocean were fulfilled with turbidites and then also covered by thrusted nappes (Fig. 11) (Biske, 1996; Biske et al., 2012; Alexeiev et al., 2016). An alternative point of view is that top-to-the-south thrusting in the STS develops only secondarily, at the end of the Paleozoic or even in the Cenozoic (Wang et al., 2008; Wang et al., 2010) is not consistent with the geological data, especially for the western STS regions. The large-amplitude nappes of the STS cannot be Cenozoic in age, since they are cut off by pre-Mesozoic leveling surfaces and sealed by Mesozoic-Paleogene deposits. At the same time, top-to-the north thrusts have indeed been observed since the end of the Early Carboniferous along the northern margins of the Karakum-Tajikistan (Biske and Seltmann, 2010) and Tarim (Alexeiev et al., 2016). At the end of the collision, in the Permian, top-to-the north thrusts were also formed together with recumbent folds (Fig. 12) in the northern STS, such as Turkestan-Alai, Atbashi, and Han-Tengri Ranges.

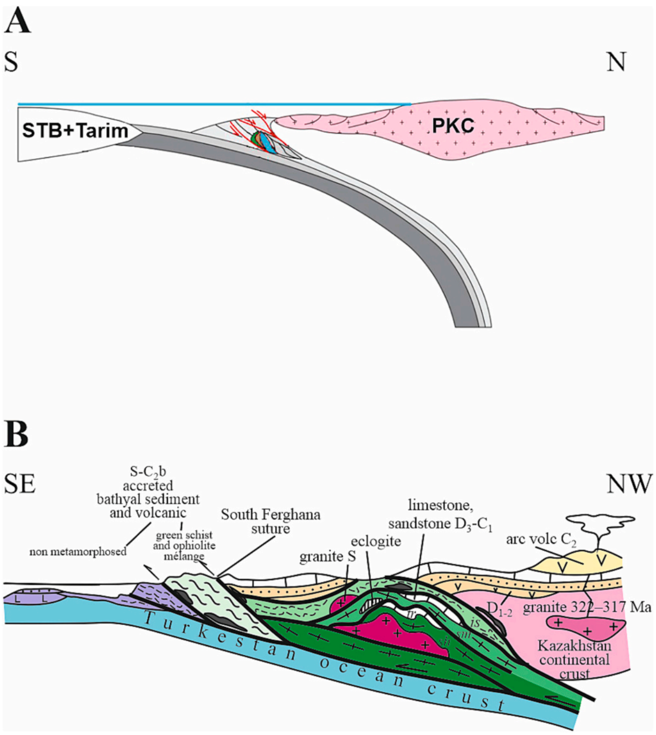


Fig. 10. Structure of the accretionary complex on the northern flank of Western STS in the Northern Ferghana valley, shown in Fig. 9, at the beginning of Pennsylvanian.

A. Final exhumation of the SW Chinese Tien Shan HP/UHP-LT accretionary complex (coloured fragments) during the period 300–280 Ma (after Tan et al., 2019). PKC – Paleo-Kazakhstan continent, STB – South Tianshan Belt. Note that preservation of a residual ocean basin at that period is not sustained by geological data.

B. Accretionary complex embraces exhumed and imbricated Kassan metamorphosed rocks of Ordovician to Silurian. Further subduction of the Turkestan ocean crust adds volcanic edifices and bathyal sedimens (left side of the profile) to the accretionary complex. The recent SO – NW orientation of the subduction connected with post-collisional counterclockwise local rotation in the Northern Ferghana.

sh – Shaldyr gneiss, garnet amphibolite; tr - Tereksai marble; sm – Semizsai gneiss and amphibolite with granulite relics; is – Ishtamberdy quartzite and schist (Tursungaziev and Petrov, 2008; Alexeiev et al., 2016; Mühlberg et al., 2016). See Fig. 9 for legend.

3. Subduction magmatism in the marginal belt, mainly in the Chatkal-Kurama areal, started at 343 Ma (?) or 337–328 Ma (Shayakubov and Dalimov, 1998; Alexeiev et al., 2016; Cheng et al., 2017) when sedimentation environment of the carbonate shelf yet longed in the southern margin of Kazakhstan. The main masses of volcanic rocks and also ore-bearing granitoids in the Kurama Range (Fig. 6) manifested in the 325–305 Ma time span (Seltmann et al., 2011; Konopelko et al., 2017b; Zu et al., 2019). But the magmatism of this time is rare (Terbishalieva et al., 2020) or not presented to the east of Naryn town in the central STS. The possible reason may be relative narrow Turkestan Ocean in the Eastern segment and small amount of the oceanic lithosphere subducted here: for example, collapse and suturing of the narrow Piemont and Valais Oceans in the Alps (Stampfli et al., 1998) evolved no active-marginal volcanism. Further to the East, the Carboniferous magmatism of the Central TS might be connected both with Junggar Ocean subduction to the south (Wang et al., 2006; Wang et al., 2017b) and with Turkestan Ocean subduction to the north.

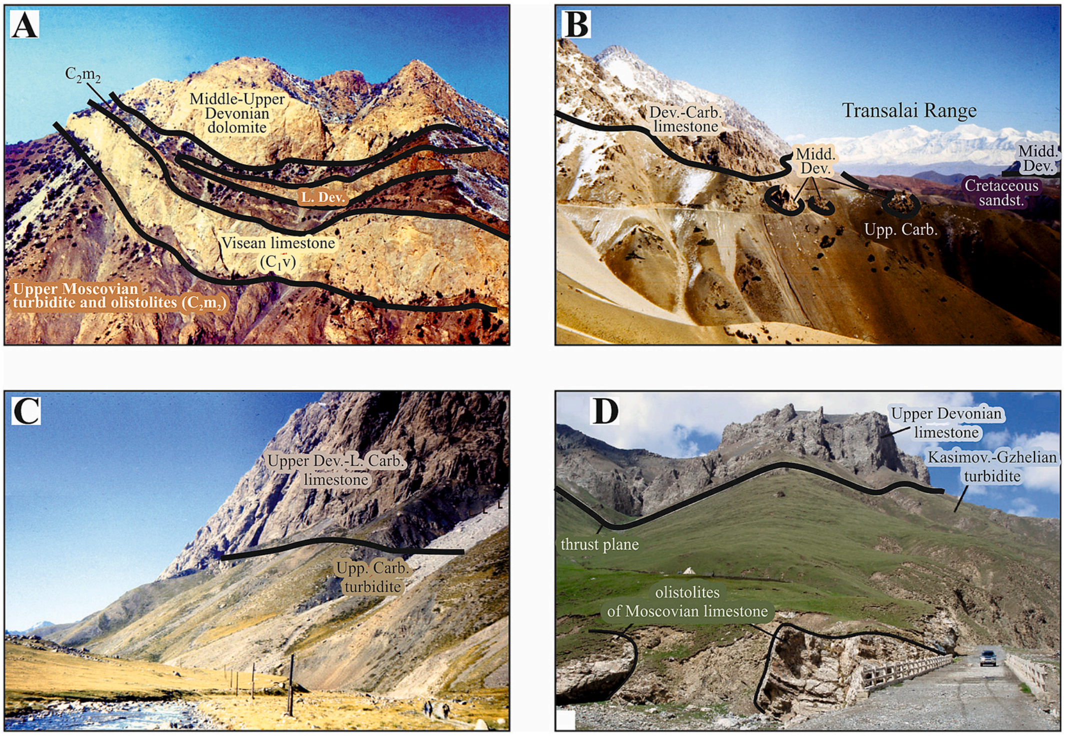


Fig. 11. Frontal view of the main collisional belt (Bukantau – Kokshaal) in the Southern Tien Shan. Upper Moscovian to Gzhelian foredeep turbidites with limestone olistolites covered by thrusts of Devonian to Carboniferous carbonates.
A – Turkestan Range, Urta-Chashma River; B – Alai Range, southern slope about the Tegermach pass; C – Kokshaal Range, Pikertyk River; D – Khalyktau Range in the eastern STS, Kukinek River along the Du-Ku road.

Fig. 12. Recumbent top-to-the-North folds in the Devonian to Moscovian carbonate cover of the Alai microcontinent, west of Isfairam River valley.

General transition of the STS into the collisional stage manifested with statistically abrupt fall of εHf (t) in the magmatic products in the eastern STS and close environment, noticed at ca. 310 Ma (Han et al., 2016). Geologic and petrographic data on the western STS at least do not contradict this. The closure of the ocean and so mainly or exclusively continental origin of new magma types was a certain reason.

In general, the collision of the continental borders in the STS lasted for a long time. This time span may be constrained between first nappes formed in the Zeravshan-Hissar SW of the STS in the Visean and the last bathyal turbidite basin collapsed on the passive Tarim margin (in the East) and Zeravshan – Eastern Alai basin in the West: the last event happened in the Gzhelian to Asselian. Imbricated thrust and fold structure then formed was partly covered by marine to continental sediments of piggy-back basins emerged in the rear of thrusts, and later sealed by granites of 290–280 Ma age.

A similar scenario is supported possibly by most authors (Han et al., 2011; Liu et al., 2014). Another point of view (Xiao et al., 2009, 2013, 2015; Sang et al., 2018) is that the STS (Turkestan) ocean existed up to the Middle or Late Triassic and the STS folds and thrusts represent the accretionary complex of its northern margin. We criticized (Alexeiev et al., 2019) arguments presented in favor of such a late collision. Between them, discovery of Late Permian radiolarian (Li et al., 2005) in bathyal cherts of the Maidantag Range (NW Tarim margin) seems to be a paleontological misconception, because the same sediments on the neighbor (by strike) Kyrgyzstan territory content fossils no younger than Mississippian. Massive intrusion of sealing-type Early Permian granites in the STS, angular unconformity under Permian red molasses, may be the best indicators of the collisional time. As to the angular discordance inside or under the Triassic, it may be very spectacular somewhere in the North-Eastern Tian-Shan, or in the northern Tarim cover (Wen et al., 2019), but yet divides similar intracontinental clastic series. Late Permian and Triassic tectonic and thermal events connected with development of main sutures (see below) may be also reflected in the regional mineralogy (Sang et al., 2018), but shows very poor expression in detrital zircon material of the region (Ren et al., 2017). Nevertheless, two zircon grains of 221–217 Ma in age found in the mélange of the Atbashi suture were again presented as an argument for Late Triassic seamounts in the STS ocean (Sang et al., 2020a).

The opposite image is a «scissor-like» collision, started as early as in the Late Devonian – Early Carboniferous in the East of the Chinese STS and then progressed to the West (Charvet et al., 2007; Charvet et al., 2011; Ju and Hou, 2014). Some magmatic and metamorphic rocks of 399 Ma and 356 Ma may mean events at the northern STS suture in the Kymysh area.

Evidently the Devonian to early Mississippian tectonic and thermal events at the eastern termination of the STS marine Paleozoic (Li and Xu, 2007; Li et al., 2020) presents only the early convergent stage in the eastern STS. These are the 390 Ma metamorphism when basic granulites in the Yushugol –Tonghuashan massive formed, also 368–361 Ma granites, hornblende metamorphism and deformations fixed by unconformity under rough-clastic Early Carboniferous in the STS area to the East of the Bozdon Lake. But the presence of open sea limestones in this sedimentary complex (Li and Xu, 2007) and absence of Devonian detrital zircons younger than 400 Ma in Tarim sedimentary cover (Han et al., 2015) bears witness against collision and closing of the ocean proposed in the Late Devonian.

The idea of the Early Carboniferous collision cannot explain persistence of continuous carbonate and turbidite sedimentation of the Mississippian to Pennsylvanian immediately to the west, around the recent Greater Yulduz depression (Fig. 8) (Alexeiev et al., 2015). The concept of such "scissor-like" collision also runs counter the existence of the foredeep basin of the northern Tarim margin up to the very end of the Pennsylvanian. This foredeep could exist yet more to the east but then covered by collisional thrusts and completely consumed before the Permian.

Eastern termination of the STS. The marine middle Paleozoic (Devonian?) of the STS terminates to the east of 91°E owing to the South Tian-Shan (or Turkestan) ocean crust together with unknown part of its continental margins were subducted here in the late Paleozoic. The possible idea is that the Xiadong – Shibanjing – Xiaohuangshan (XSX) suture in the northern Beishan presents an eastern extension of the STS (Han and Zhao, 2017) and links it with late Paleozoic basins of Paleo-Asian Ocean (PAO) in the east, such as the Solonker and others. The XSX ocean-type basin existed from 368 Ma and was closed at 345–336 Ma or some later after north-directed subduction (Liu et al., 2019) under the Hanshan continental block, the last accounted as the possible eastern continuation of the Central Tian-Shan and so of the Yily-Kazakhstan continental massive.

As to more southern blocks of Beishan (Liu et al., 2019), they may present continental fragments separated in the Paleozoic at the southern (or SE) margin of Tarim. Ophiolite sutures presented here might be formed after ocean- or rift-type basins not connected with the Turkestan Ocean. The southern Liuyuan suture of Beishan may be a remnant of the last in the region ocean-type basin closed in the Permian (Liu et al., 2019; Mao et al., 2012). Both continental blocks and sutures were replaced after the collision by high-scale left strike-slips of Altuntag, Xingxingxia and other faults. Possible western analogues of the southern Beishan may be preferably Paleozoic basins of the northern Pamirs and western Kunlun, not of the STS.

Anyway, there are no Devonian to Carboniferous passive continental margin formations in the eastern STS and in the Beishan. At the same time, these margins are well developed in the western STS. Only remnants of magmatic arcs and back-arc short-living basins survived in the east. We admit this corroborates better with the usually accepted idea of narrow ocean basin between Tarim and Kazakhstan in the east (Ge et al., 2014) than with our previous reconstruction (Biske and Seltmann, 2010).

8. Wrench faults and thermal processes of the late Permian and Triassic

The discussion about the age of main and most extended wrench faults of the STS and its margins (Fig. 1), as much as the rate and direction of lateral replacement, has a long history (Burtman, 2006, see references therein). Some of these faults were primarily ophiolite sutures formed in the late Paleozoic, then emphasized or replaced by strike-slips in the Permian to the early Mesozoic and complementary rejuvenated in the Cenozoic. Along strike east-west or SW-NE wrench faults of the left-lateral type are characteristic in the central and western STS, mainly in Kyrgyzstan. Collisional sinistral replacements follow here and associate with the completion of S-type steep-pitching (plunging) folds (Fig. 13), that is also expressed through the different rotation of paleomagnetic declinations in Lower Permian relatively the rest of STS (Burtman, 2006; Biske and Seltmann, 2010; Burtman, 2015). Most obvious here is the Great East Ferghana sigmoidal bend that may be a horizontal extrusion (Burtman, 2015) and evidently took place before Talas-Ferghana strike-slip or partly at the same time (Porshnyakov, 1973). We may postulate such a structural feature of the western to central STS to be a result of northern Tarim indenting motion: this might be expressed less than modern Pamirs` influence upon post-Paleozoic masses in the Tajik depression but evoked in the same manner the narrowing of the STS belt in the east and squeezing to the west. But such an idea cannot exhaust left-side strike-slip movement that also developed along the north-eastern margin of the Tarim platform, the Xingxingxia fault among them (Han and Zhao, 2017), and may be partly responsible for the eastern wedging out of the STS belt. Large amplitude of left strike-slips could substantively change the primary position of MTS and CTS as much as other continental blocks around the STS. General left replacement between the Paleozoic Kazakhstan and Tarim blocks might be also considerable (see chapters 4, 5, Fig. 7, and also reconstructions in Filippova et al., 2001).

Main oblique wrenches presented in the STS are Talas-Ferghana and Junggar faults, the last also known as the North-Tianshan or the Main Tianshan fault (Laurent-Charvet et al., 2002; Charvet et al., 2011). They are younger in age and with right-side direction. 40Ar/39Ar dating of syntectonic minerals from the wrench zone of the Talas-Ferghana strike-slip showed that replacement developed here formerly as early as from 310 Ma, but mainly in the time span of 290–260 Ma (Rolland et al., 2013) and then up to 240–199 Ma (Konopelko et al., 2013). Right-side replacement without thermal manifestations recovered in the Cenozoic (Burtman et al., 1996; Burtman, 2006).

The northern Atbashi-Inylchek suture in the central STS segment shows signs of the early right replacements developed about 300–250 Ma and then left-side movement followed in the time span of 240–235 Ma (Loury et al., 2018). Rims of zircon grains from the Atbashi wrench zone determine the age of the hydrothermal activity, possibly connected with the strike-slip about 255 Ma or as late as 224–217 Ma (Sang et al., 2016; Sang et al., 2020a; Sang et al., 2020b). Feathering SW-NO faults in the southern wing of Atbashi suture zone are left-side strike-slips as it is evident on the geological maps of Atbashi – Janjir Ranges (Tursungaziev

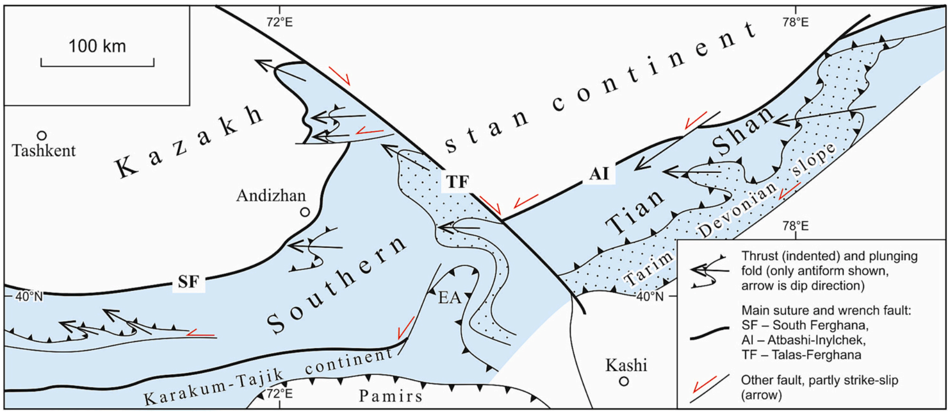


Fig. 13. Sketch map of main strike-slip faults in the western – central STS and associated tectonic elements.
EA – Eastern Alai Range and synform. Note that the STS fold and thrust belt (blue) embraces some terranes with Precambrian continental crust.

and Petrov, 2008). To the east, late lateral displacements are dated (40Ar/39Ar) as 257–248 Ma in the Inylchek glacier valley (Loury et al., 2018). In the Chinese segment the same suture (here the Narat – Kawabulak, or South Central Tianshan Shear Zone) changes its direction to the east-west and some structural features define it as the right-lateral strike-slip (Charvet et al., 2011). Late thermal activity along this zone demonstrated by 256 Ma muscovite 40Ar/39Ar plateau age (Li et al., 2021). The Xingeer fault in the southern STS margin also interpreted as the right-lateral and connected minerals were crystallized (40Ar/39Ar) in the time interval 290–270 Ma (Han and Zhao, 2017).

General idea of the late Paleozoic postcollisional wrenching in the STS and neighbor continental blocks may comprise (Fig. 13): i) oblique left strike-slip of Kazakhstan as relating to Karakum-Tajik and Tarim continents, consorted with S-form ductile plunging folds, feathering W – E or SW - NE faults and a certain general extrusion of the STS masses to the west, then ii) more brittle dextral SE-NW replacements that lasted throughout the Permian and possibly until the end of the Triassic.

Somewhere in the western segments of the STS, the lattermost hydrothermal events not connected immediately with main sutures or strike-slip faults were found and dated until 225–220 Ma (Seltmann et al., 2011; Vrublevskii et al., 2018). In general, such a suspended accomplishment of the tectonic and thermal activity may be explained through forming of the active margin of the late Paleo-Tethys, where Middle – Late Triassic volcanic rocks and then Triassic – Early Jurassic granites emplaced in the Northern Pamirs and Kunlun (Osmonbetov, 1982; Schwab et al., 2004; Burtman, 2006). To the North, in the Eurasian rear of this margin only rare granites of the Triassic presumably were formed in the intraplate environment.

9. Conclusions

Paleozoic collisional belt of the Southern Tien Shan (STS) formed in the southern part of the Central Asian Orogenic Belt. The STS is characterized by a large volume of carbonate sediments deposited on the continental shelves or displaced on the slopes. The STS structure is highly compressed and locally reduced in cross-section to the size of a relatively narrow suture zone.

Throughout the STS belt, it exhibits the following features: i) the presence of marine and partly bathyal (turbidites, flints) Middle to Upper Paleozoic sediments, up to the Pennsylvanian to Asselian in the roof of the stratigraphic sections, and ii) the presence of the Bukantau - Kokshaal - Halyktau belt of collisional nappes, thrust on the Tarim in the south, and obducted on the Kazakhstan continental margin in the north. The history of the STS (Turkestan) ocean, which is revealed by the ages of the oceanic basins, the nature of continental margins and subduction polarity, was different in various segments of the STS. The Turkestan Ocean was older and broader in the western STS compared to the east, where only remnants of the back-arc basin, opened within the time span between 450 and 300 Ma did exist.

Major tectonic cycles can be traced through the entire STS belt over 2000 km from west to east. The Late Proterozoic accretionary events at the active margins of Rodinia, which are known in the Tarim (800–600 Ma) and within the Karakum-Tajik microcontinents (> 550 Ma) gradually changed to continental rifting in the early Paleozoic. From the late Ordovician to early or middle Devonian (ca. 440–400 Ma), the opening of new oceanic basins was accompanied by active subduction in island arcs and active continental margins including those of the Tarim craton. Input of materials from eroded island arcs into sedimentary basins is registered in lower-middle Paleozoic and younger sediments. Devonian intraplate magmatism has also made a significant contribution to the formation of continental crust of STS. Precambrian microcontinents that existed within the Turkestan Ocean during the early Paleozoic as separate blocks were later accreted to continental margins together with island-arcs and made up a basement, on which the Middle Paleozoic carbonate platforms were formed. The next episode of suprasubduction magmatism, which started in the Lower Carboniferous (Visean) and reached its peak in Serpukhovian - Bashkirian, was followed by collision and final closure of the Turkestan Ocean in early Permian.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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