International Research Journal of Earth Sciences ______________________________________ISSN 2321 – 2527
Vol. **6(8),** 11-19, August **(2018)** *Int. Res. J. Earth Sci.*

Review Paper

Indian-Eurasian collision, structure, and convergence in the western Himalayan syntaxis along Pamir-Tajikistan -A short review

Syed Tallataf Hussain Shah[1,3,4*], Junmeng Zhao[1,2,4], Baral Upendra[1,2], Nangyal Ghani Khan[1,3,4], Zahid Imran Bhatti[1,4]
[1]Key Laboratory of Continental Collision and Plateau Uplift, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China
[2]CAS Center for Excellence in Tibetan Plateau Earth Sciences, Beijing 100101, China
[3]COMSATS University Islamabad, Abbottabad-Campus 22060, Pakistan
[4]University of Chinese Academy of Science,No.19(A) Yuquan Road, Shijingshan District, Beijing, P.R. China 100049

Available online at: www.isca.in
Received 26th April 2018, revised 30th July 2018, accepted 20th August 2018

Abstract

The Indian-Eurasian collision resulted in several geological structures along the collisional belt. and among them, Pamir is one of the remarkable features developed along the western syntaxis. Pamir shares a similar trend of the tectonic evolution of the Indian plate subduction beneath the Tibetan plateau during the Cenozoic era. Pamir is subdivided into northwestern, central, eastern and southwestern parts according to its structural variation. According to the fundamentals of plate tectonics, the crustal shortening results in thickening of the mantle; although the principal factor is mostly related to the rheology of the crust-mantle and the collisional rate. During the continental-continental collision, both plates resist subduction due to their buoyancy and the only justification for the resultant subduction is Wilson last cycle. The difference in the Indian-Eurasian tectonics is mainly due to the reduction in convergence rate i.e. 110mm/yr prior to 50Ma, which was reduced to 50mm/yr in 30-40Ma. The average magnitude of crustal shortening between Pamir and Tien Shan orogenic belt is estimated to be 10-700km. Different geophysical and geological studies reveal that the western segment of the Indian-Eurasian collisional belt is experiencing double subduction mechanism; a steeply northward dipping Indian plate under the Hindukush region and the southward-dipping Eurasian plate under the Pamir. The initial breakage of Indian plate was during the early stages of collision (44-48Ma) while the second break-off event occurred during the middle-Miocene (~15 Ma). Moreover, in the westernregion, the subduction process was continued until it reached the present state of the Hindukush region i.e. ~8Ma, that could be the possible reason for the structural similarities between the central and the western collisional regions. The paleomagnetic studies reveal the counter-clockwise rotation of the Pamir plateau as much as ~52º during Miocene.

Keywords: Pamir, western Himalayan Syntaxis, structure and Tectonics, Indian Eurasian collision.

Introduction

Pamir marks the northern junction of the greatly active collisional zone of the world. Along with its southern margin, the Indian plate is subducting underneath the Eurasian plate and the area is experiencing intermediate seismicity[1,2]. The northern boundary of Pamir is marked by the Trans- Alay Range and cut by Kyzyl-Soo (Sourhob or Vakhsh) river and the southern boundary is the transacts Panj/Amu-Darya river and terminates at the northernmost ridges of Karakorum Ranges of the Afghan border (Figure-1). The *Eastern* Pamir ends at the borders of Ex-USSR and China; while *Western* Pamir terminates into the ridges of Peter- The- Great and Darvazsky. The Western part of Pamir is composed of the highest ridged and massive glaciers while Western Pamir is occupied by Plateau of 4000m height. Since last century, the scientists are taking a keen interest in mapping the subsurface behavior of the Tibetan plateau in-order to understand the subduction pattern of the Indian plate beneath Eurasia. The indo-Eurasia collision caused crustal shortening along the suture zone and resulted in the formation of spectacular mountain series of Himalayas, Karakorum, The first ever model for the collisional pattern of Indian-Eurasian plate was provided by Argand[3,4], in which he proposed that the reason behind the uplift of Tibetan plateau was the subduction of Indian Plate underneath the Eurasian plate. Although numerous geophysical/geological studies have been carried out, in pursuit of finding the main reason behind the Tibetan plateau's uplift through modeling it[5-7], reasons provided are still controversial.

The phenomenon of crustal shortening occurs as a result of collisional tectonics and results in thickening of the crust at the suture zone as well as shortening of the mantle lithosphere at the region, however, this factor is related to the rheology of the crust and mantle of the collisional plates and their rate of collision. In case of the Continental-Continental subduction, the situation becomes more complex as the continental plate resists subduction due to its buoyancy and the only reason justifying the subduction of the continental plate is following the last cycle of Wilson[8-10]. In this cycle, a cold and dense oceanic plate drags down the continental slab along with it after being subducted, which is likely to be the case with the Indian-Eurasian collisional zone and result in its complex behavior. The reduction in convergence rate between India and Eurasia from 110mm/yr (50Myr ago) to 50mm/yr (30-40Myr), is believed to be the result of the Indian-Eurasiancollision. Due to this collision, the estimated magnitude of crustal shortening between Pamir and Tien Shan orogenic belt is calculated to be 10-700km[7,11-14].

Tectonic Evolution of Pamir

Pamir is located in the northeastern part of the highly active collisional zone of the world, which is experiencing the intermediate-depth earthquakes (≤250km) and comprising a series of structures that are parallel in strike to the Tibetan plateau. Pamir is accommodating Paleozoic to Mesozoic sutures, crustal blocks and magmatic belts[15,16]. The tectonic evolution of Pamir was initiated in Cenozoic era along with that of Tibetan plateau under the same tectonic event of Indian plate subduction (with approximate 300km length, 45° SSE dip and crustal thickness of ~70km) underneath Eurasia[6,7,15]. The area that is most affected by this Cenozoic convergence is Pamir-Pundjab syntax. The facies studies carried out at the Tajik basin, confirmed the presence of a Tajik shallow-sea-basin between the Pamir and Tien Shan. This basin was closed during the Late-Cretaceous convergence. It comprises a bay of Turan Sea, that was located at the current position of Afghan-Tajik basin in Early Aptian, while the eastern edge of Pamir was 600-700km further east in the Late Cretaceous[2,6,7,15,17].

At western part of the Indian-Eurasia collisional belt, the results from geophysical and geological studies suggested the presence of two opposite dipping subduction zones; Indian plate steeply dipping towards the north under the Hindukush region while Asian plate dipping towards the south under Pamir[1]. Through the seismic imaging study, it appeared the first breakage of Indian plate occurred during subduction in the early stages of collision (44-48Ma ago) while the second break-off event occurred about ~15Ma ago that disconnected the Central Indian slab from its margins[1,6]. The subduction of the Indian plate underneath the Eurasian plate in the western region remained and reached its present state of Hindukush region. Subduction process is estimated to be initiated around 8Ma ago with steep and rapid rates in Hindukush region while comparatively slower at Pamir, whereas no slab has been imaged in the eastern margin. That may be the reason behind the structural similarities between central and western regions of the collisional suture. Along Main-Pamir-Thrust (MPT), the interior of the Pamir is in anarched shape and thrust onto the Tajik depression and Tarim basins[1,6,17,18].

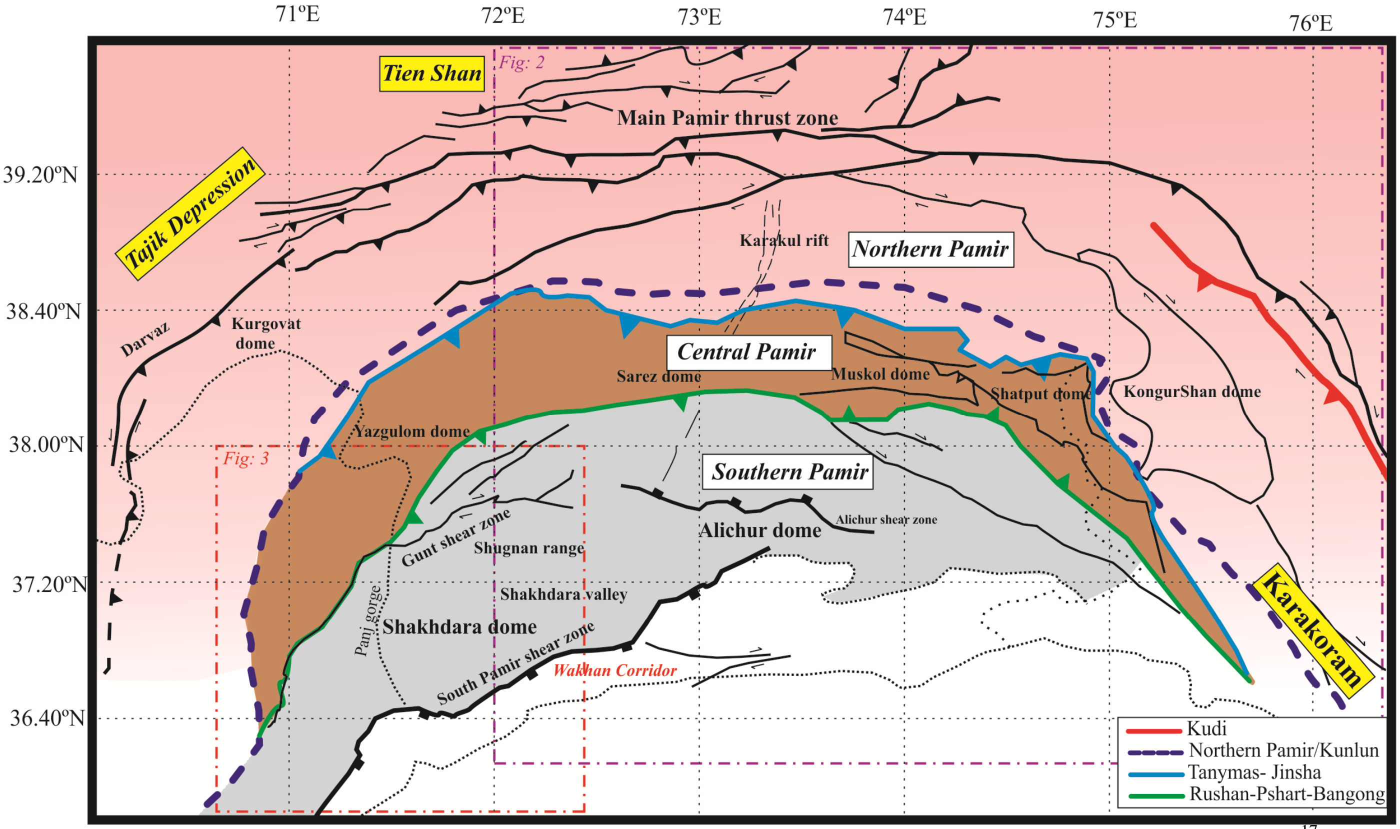

Figure-1: Structural map of Pamir along with the position of magmatic domes and major structuresmodified after[17].

The evidence of convergence marked in the northern Pamir initiated in Paleozoic era and retained through the Mesozoic era, resulting in the generation of a magmatic arc development of rift basin and clastic deposition of volcanics. Thrusting of northern Pamir over Tian Shan along the MPT is still ongoing and contributing 10% of the total convergence[15,19,20].

Structural conditions of the NE Pamir are quite complex, and there are numbers of major thrust, normal and strike-slip faults present in the area (Figure-2). The Zircon data acquired from the NE Pamir at location of Oytag (Wuyitake, West China) suggests that the deformational age of NE Pamir could be early to middle Miocene while, reorganization of the atmospheric circulation in the area believed to be initiated during Eocene ~ Oligocene which is possibly related to the uplift of Central-Southern Pamir or the retreat of Paratethys Sea[19]. The Paleomagnetic data shows that since Miocene the Pamir plateau was rotated ~52^0 counterclockwise from its initial position. The small-circle reconstruction technique of Palaeomagnetic studies revealed the oroclinal bending in northern Pamir, clockwise rotation in Muzkol area of central Pamir while counter-clockwise in the northern folded sequences of southern Pamir. Local-scale variation has been observed in different regions of Pamir, possiblydue to local block rotation resulting in NS shortening[21]. During late Miocene, the EW extension in the Pamir initiated and is evident along Kongur Shan normal fault due to the radial expansion of thickening crust underneath Pamir[15,19,20,22].

Seismotectonic imaged the Western Pamir, as highly deformed zone and is evident from the NS crustal shortening in the region with NE trending sinistral strike-slip conjugate faults, and EW extension resulting normal faults which are generated due to gravitational collapse. Shear deformational distribution in western Pamir and the activation of Sarez-Karakul fault system is the indication of the northeastern propagation of western margin of Indian plate, linking all the deformational sequence to the south up to the Chaman Fault of Afghan-Pakistan region[22,23].

Thermobarometry of the lower-crustal-xenoliths showed that the southern Pamir was well thickening at ~50Ma ago, right after the Indo-Eurasian plates collision ~54Ma[19].

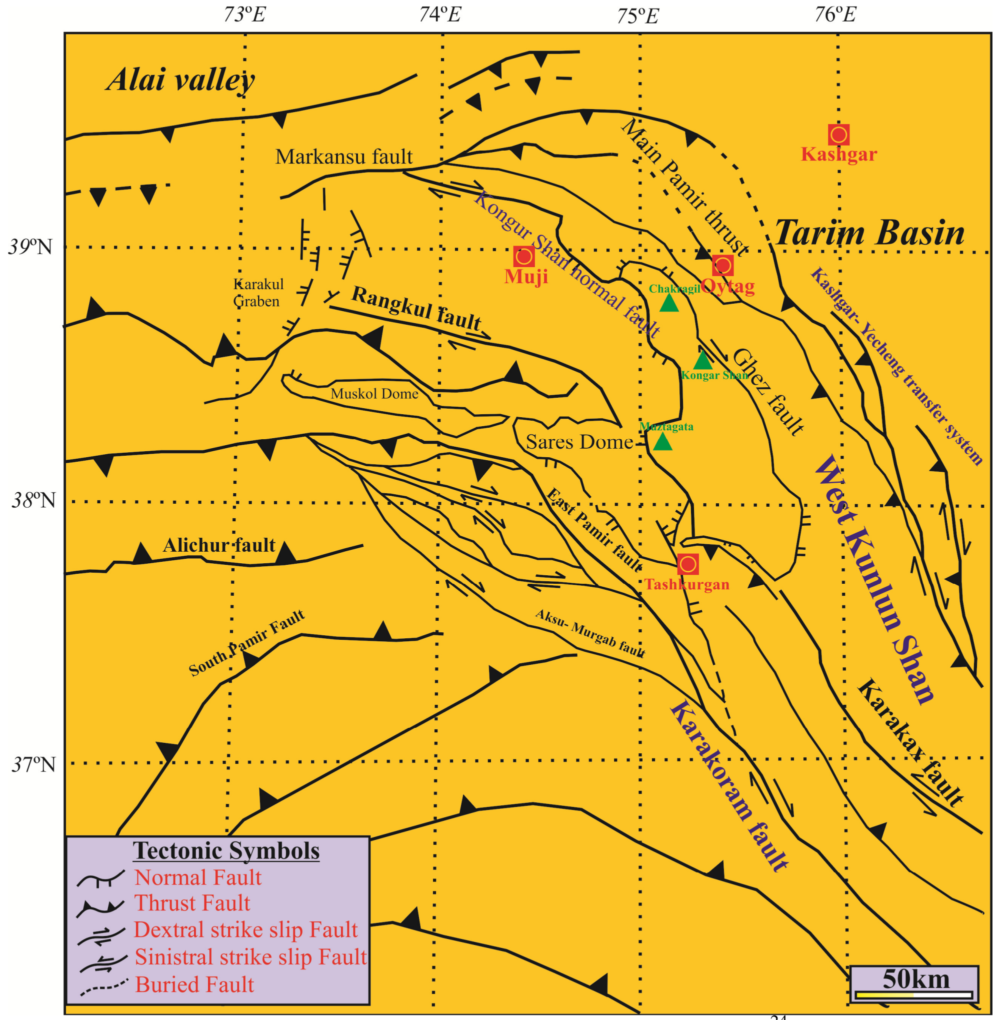

Figure-2: Structural map of Central to Eastern Pamir[24].

Structure Geology of Pamir

There are a lot of structural similarities between Tibet and Pamir, such as, the presence of Cretaceous arc-type-granitoid in the central-southern Pamir are equivalent to the Tibet, similar striking structure of Qiangtang block in both Pamir and Tibet, having anticlinorium structures of Muskol and Sares domes which contain metamorphic facies similar to that of Karakul-Mazar-Songpan-Ghanzi system. The northern Pamir and NW Tibet contain north facing Kunlun-suture, south dipping Jinsha-suture and Carboniferous-Triassic Karakul-Mazar subduction accretion system; this set of geology and structure is related with that of Songpan Ghanzi–HohiXi system of Eastern Tibetan plateau. The Kunlun volcanic arc in the Pamir is a result of volcanic activity in Mid-Paleozoic (~370-320Ma) that continue until Triassic[16,20].

Although there are some notable dissimilarities as well for example Tibet is high elevated area while Pamir has high relief, also the differential scale of NS crustal shortening between Tibet (~19-28%) and Pamir (~55-64%). Tibet mostly consists of sedimentary rocks while Pamir it is chiefly composed of crystalline and metamorphic rocks[17].

Tectonically the Pamir is further divided into 4 regions, namely: Northern, Central, Southern and the Eastern Pamir (Figure-1).

Northern Pamir: The Northern Pamir is bounded on the northby the Pamir-Thrust (Cenozoic), while in the south by the Tanymas thrust system. The Tanymas thrust triggered the reactivation of Tanymas-Jinsha-suture-zone. The Pamir thrust has been marked as the most active fault with highest strain rates of entire Indian-Eurasian suture zone with GPS calculations of ~13-15mm/yr which is one-third of the total convergence rate (~34mm/yr measured at the same location)[22]. Calculated through the GPS data, the convergence between Pamir and Tien-Shan orogenic belt is estimated to be 300-400km during the Late Cenozoic with the rate of 13±4 mm/yr[24]. Due to the emplacement of Pamir thrustalong the northern margin of the Pamir, it clasped the area between Afghan-Tajik basin and the Tarim basin. The remaining of these basins are now found enfolded between the northern Pamir and the southern Tien Shan at Alai valley of former Tajik-Yarkand basin, bounded by the 7100m high leading edge of northern Pamir "Trans Alai ranges"[22]. The most affected area by this Cenozoic convergence is Pamir-Pundjab syntax, which is the part of Alpide fold belt between Tibet and Tarim basin. Thrusting of the northern Pamir over Tian-Shan orogenic beltalongside the southern margin of the Alai valley throughMain Pamir Thrust (MPT) is still ongoing and contributing 10% of the total convergence with the estimated rate of ~10-15mm/yr[7,11,20,22,25,26].

The Paleomagnetic data suggests the crustal shortening and rotation factor among the Pamir and Tien-Shanorogenic belt during the subduction in Late Cretaceous, resulted in the generation of Vakhsh-Trans-Alay thrust and Darvaz-strike-slip faults. These faults cut through the sequences of Late Cenozoic, Cretaceous and Paleogene strata with over-thrusting of Pamir massif on Tajik basin. The Vakhsh thrust system is the epicenter of 7.4 magnitude earthquake of Khait in 1947. The left lateral strike-slip Darvaz separates the Pamir from Afghan-Tajik basin in the west where the GPS measured shear effects are ~10mm/yr. The Quaternary slip rates of Darvaz fault are ~13mm/yr, which are uncertain due to lack of data and difficulty in dating the feature[7,22].

Domes act as the main source of exposure for the crystalline basement and metamorphic rocks in the Pamir and cover about 20-30% of the plateau (Figure-1). The Kurgovat dorm of Northern Pamir exposes the Triassic high-grade metamorphosed rocks with the Thermobarometric pressure of 6.5-8.2Kbars and temperature of 600-650°C[16,20,27].

Central Pamir: The Central Pamir is bounded on the north by Tanymas thrust while in the south by Sarez-Murghab thrust system, which reactivated the Rushan-Pshart suture zone. Stratigraphy of the eastern Pshart zone is similar to that of Bangong- Nujiang suture zone (BNS) of central Tibetan area. Zircon dating of xenoliths found in the Cretaceous aged Plutons in the central and southern Pamir showed the Cambrian-Ordovician magmatism (~410-575Ma). This magmatism is the resultant of subduction along the Jinsha suture zone and of Middle Jurassic (~147-195Ma) aged, as a result of subduction along Rushan- Pshart suture zone[20,22].

In east at the border of Pamir and Tarim basin, the Karakorum fault adjoins with the Sarez-Murghab thrust fault via right lateral Kashghar-Yecheng, and Aksu-Murghab fault systems, resulting in the crustal shortening of ~280km[19,22,28].

Another prominent feature of central and southern Pamir is gneiss domes that are formed by N-S middle to an upper crustal extension in the region at depth of ~30-40km, and the exhumation initiation was ~20Ma. The Yazgulom, Sarez, Muskol and Shatput domes of the central Pamir exhibit the high-grade metamorphosed rocks of Oligoceneto Miocene age[11,16,26]. Thermobarometric pressures and temperature calculated for west-central Yangulom dome is 9.4kbar and 588°C, while for the east-the central Muskol dome is 9.1-11.7kbar and 700-800°C[27]. By comparisons of tilt axis of Paleomagnetic technique, the amount of crustal shortening in central Pamir is calculated to be ~60% while that of the southern Pamir as ~40%[21].

Southern Pamir: On the north, the southern Pamir is constrained by Rushan-Pshart suture zone while on the souththru Southern Pamir shear zone (SPSZ) and Zebak-Munjab fault as shown in Figures-1 and 3[29].

SPSZ variants in a dip along its rupture trace on the west at Badakhshan-Afghanistan) from <60° to sub-horizontal along dome axis in the east at Gorno- Badakhshan. The SPSZ contains north trending open folds having an amplitude of <3km and wavelength >25km[17].

The Shakhdara and Alichur domes are parted by a low-strain horst. Shakhdara exposed ~250x80km of the crust with the depth of ~30-40km, while Alichur exposures are of ~125x25km[17]. The southwestern Pamir is predominantly characterized by "white-schist (talc-kyanite)" with Cretaceous aged high-grade metamorphosed orthogenesis/ granitoid (~750 °C) rocks at Shakhdara dome whereas at Alichur dome it is characterized by low-grade (20-30°C) Cretaceous aged felsic orthogenesis/ granitoid metamorphosed rocks[17,29].

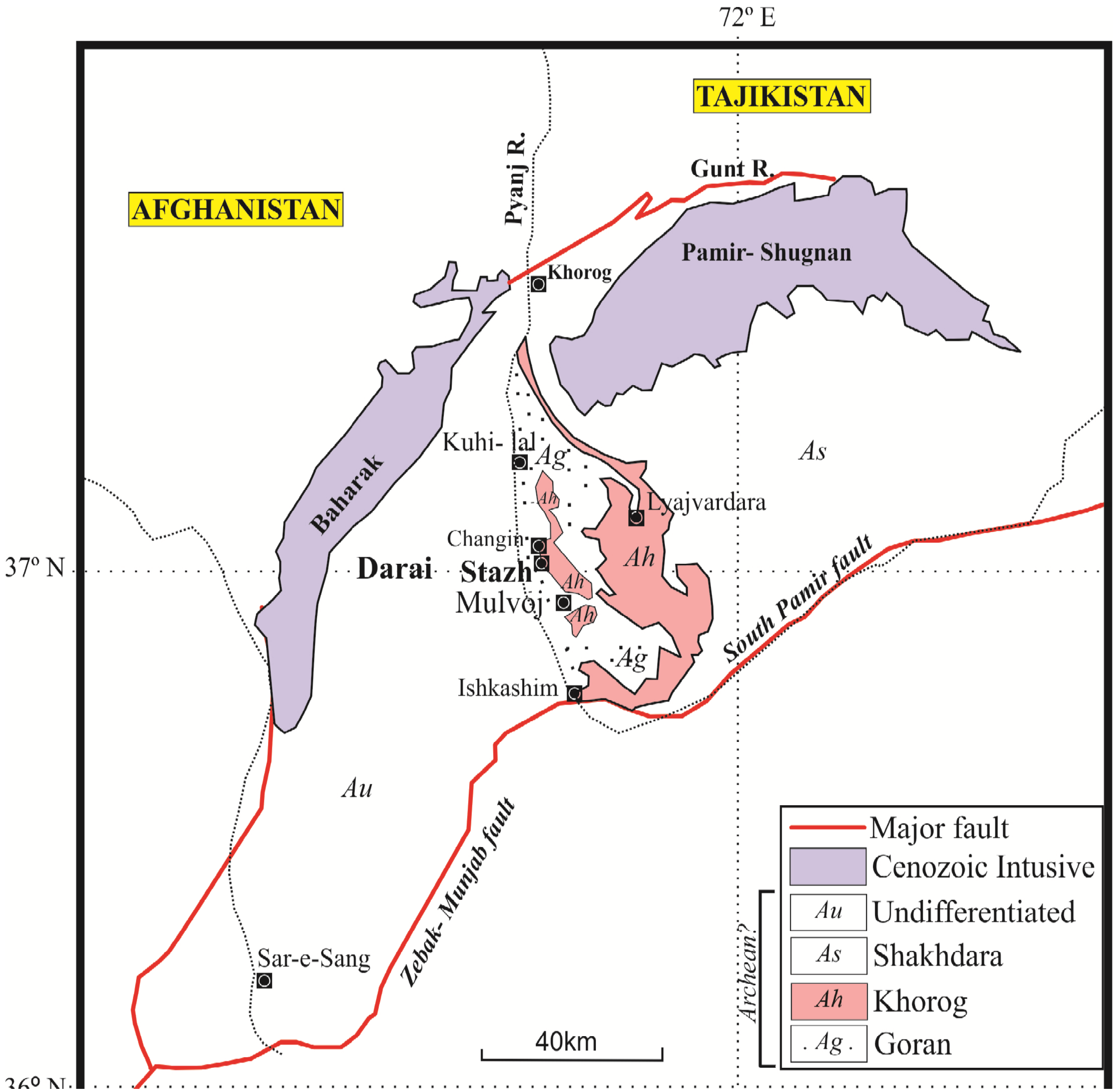

Figure-3: Structural map of southwestern Pamir[29].

Similar to the central Pamir the Shakhdara and Alichur domes of the southern Pamir also exhibit the high-grade metamorphosed rocks of Oligocene to Miocene age. The exhumation in dorms terminated early in central Pamir (15-10 Ma) as relative to the southern Pamir (~2Ma)-at Shakhdara-Alichur dorm. These dorms are associated with the 90% accumulation of NNE-SSW extension in the region. Thermochronological results reveal the peak age of exhumation in Shakhdara and Yazgulomdomes to be about ~15Ma till ~2Ma[11,16,18,20]. Thermobarometric pressures and temperature calculated for Shakhdara dome are 6.5-14.6kbar and 700-800°C[27].

Eastern Pamir/ Chinese Pamir

The north-eastern Pamir is also known as "Chinese-Pamir-Tien-Shan". It marks the northern extent of the Main Pamir Thrust system (MPT) while in the east it is separated from Tarim basin thru the Kashgar-Yecheng Thrust system (KYTS). Eastern Pamir is accommodating several major fault zones which are controlling the Pamir's northward drift with reference to the Tarim basin (Figure-2)[25,30].

Karakoram Fault (KKF): On the West, the Eastern Pamir is bounded by a right-lateral Karakoram strike-slip fault, having controversial initiation age of 15 ±1 to 23 ±1 and offset of 149-167km. The slip direction in KKF is not in the northern direction and is believed not to have any possible contribution in the northward movement of the Eastern Pamir with respect to Tarim basin. Whereas KKF does accumulate ~300km northward drift of the Southern-Pamir. However, KKF does add up the slip of Rushan-Pshart and Aksu-Murghab faults systems in the south[25].

Karakax Fault (KXF): The 400km WNW striking left-lateral strike-slip Karakax fault separates the NW Tibetan plateau from the Tarim basin. It is marking the westernmost segment of AltynTagh fault of northern Tibet and is a highly active fault. It acts as a source for numerous seismic activities in the area with the largest magnitude recorded of 7.4-7.6Mw earthquakes, with average slip rates of 6-9mm/yr. The epicenter for 2008, earthquake of 7.1Mw magnitude along the Yutian normal fault was located at the junction of two major strike-slip fault zones (Altyn Tagh and Karakax) at the south of Tarimbasin[31]. The Karakax fault is believed to be the reason for the eastward movement of Tibetan plateau. The movement resulted in response to the escape-tectonics-factor in order to accommodate the NS crustal shortening of the western Tibet, triggered by the northward indention of Indian plate into Eurasia[31-33].

Kashgar-Yecheng Thrust system (KYTS): During 2010, Cowgill renamed the middle portion of Main-Pamir-Thrust-Kumtag thrust system (MPT-KTS) as the "Kashgar-Yecheng Thrust system". The Tarim basin is separated from eastern Pamir via dextral strike-slip fault system named as Kashgar-Yecheng_Thrust-System (KYTS), having estimated thermochronological slip rates of 11-15mm/yr and ~280km offset[34]. The slip rates of KYTS was reduced during the late Miocene or Pliocene. The KYTS consists of three major faults; Since 3-5Ma ago inactive dextral strike-slip faults of Kumtag and Kusilaf, and, a Aertashi dextral strike-slip fault, with slip rates of 1.7-5.3mm/yr (since last 3-5Ma)[24-26,30].

Kongur Extension System (KES): The Kongur extension system (KES) consists of several faults including Muji fault (oblique right-lateral/normal), Kongur-Shan normal fault (west dipping), Taheman normal fault (NW-dipping) and Tashkorgan normal fault (Eastdipping). The Kongur Shan normal fault runs parallel to KYTS and MPT with a dip of 20-45°W and NW-SE strike. Thermochronological dating thru^{40}Ar/^{39}Ar dated the EW extension alongside northern Kongur-Shan fault as 7-8Ma with the slip rate of 6.5mm/yr[24,30,35].

Domes: In the southwest of KYTS, Kongur-Shan and Muztagh Ata domes are the marker features of the eastern Pamir. These domes are elevated to >7500m and about 60% covered area of them is heavily glaciated. Four possible reasons suggested for the origin of these domes; i. the thrusting and normal faulting at Pamir front causing the crustal-scale ramp stacking, ii. extension and domes formation due to crustal thickness caused by northward under thrusting in Pamir, ii. forced erosion and exhumation creating the high relief under the process named "a tectonic aneurysm", and finally iv. rollover along the footwall of Kongur-Shan normal fault during the EW extension of Pamir[35,36].

The exhumation of Muztagh Ata dome was initiated during 7-9Ma ago, while of Kongur Shan dome (KES) was around 5-8Ma. The recent exhumation rates of KES are highest with thermochronological results of 1.5-4mm/yr, but these rates decrease to the north to ~2-0.5mm/yr along King-Ata-Tagh section (KATS) and also to the south of KES to ~1-0.5mm/yr at Muztagh-Ata massif and 0.5-0.4^{+-1}mm/yr to the south of Muztagh-Ata. Thermochronological results show that a cooling window of ~450-120°C from southern Muztagh Ata (~10-7Ma) to Kongur Shan domes (~3-1Ma). The exhumation pattern suggests that the Muztagh-Ata dome was cooled earlier and its temperature was near to the surface temperature while Kongur-Shan dome was still at a temperature of >650°C[30,36].

Conclusion

Pamir is situated in the northwestern segment of the Indian-Eurasian collisional belt and strikes parallel to the Tibetan Plateau. It is accommodating several Paleozoic-Mesozoic sutures, crustal blocks, and magmatic belts. Two dominant tectonic activities in the region are, subduction of the Indian plate beneath the Hindukush and subduction of the Eurasian Plate beneath the Pamir. The rupture of Indian plate under the Pamirinitiated during the early collisional time (i.e. ~44-48Ma) and its complete detachment from the central Indian slab occurred during the middle Miocene (~15Ma). The Pamir is tectonically divided into four major parts namely; Northern, Central, Southern, and Eastern. The Northern Pamir is thrust over the Tian-Shan along the Main-Pamir-Thrust and contributing ~10% of the convergence with the rate of ~10-15 mm/yr and it marks the northern boundary of N-Pamir. The Main-Pamir-Thrust is having the highest strain rates of ~13-15 mm/yr. The Tanymas Thrust reactivated the Tanymas-Jinsha suture zone and separates the Northern Pamir from the Central Pamir. There is thepresence of Cambro-Ordovician magmatism in the Central and Southern Pamir, which is aresult of the subduction along Jhinsa suture during the middle Jurassic. The Southern Pamir extends from Serz-Murghab Thrust; a boundary thrust between southern and central Pamir, up to Rushan-Pshart suture zone. The post-collisional crust of Southern Pamir is thicker due to the subduction of Indian plate underneath the Eurasian plate. The Eastern Pamir is bounded between Main-Pamir-Thrust and Kashgar-Yecheng Thrust system, a dextral strike-slip fault (slip rate of 11-15mm/yr., reduced during the late Miocene-Pliocene), towards its north and south respectively. There are numerous thrustfaults in the northeast Pamir and since Miocene, it was rotated ~52º Clockwise while in late Miocene southern Pamir experienced a counterclockwise rotation. The EW extension in Pamir initiated due to radial expansion of thickening crust underneath the Pamir. The Karakoram Fault lies west of the eastern Pamir, that was active 15±1 to 23±1Ma and is linked with Murghab thrust and yielded ~280Km of crustal shortening. Karakax Fault separates the Tibetan Plateau from Tarim basin and it is the westernmost segment of the Althy Tagh Fault and is believed to be the source of eastward movement for Tibetan Plateau. The Kongur Extension System is a group of faults that run parallel to the Kashgar-Yecheng Thrust System and Main Pamir Thrust and was active around7-8 Ma ago, with a slip rate 6.5 mm/yr.

Abbreviations: Main Pamir Thrust (MPT), Global positioning system (GPS), Bangong- Nujiang suture zone (BNS), Southern Pamir shear zone (SPSZ), Kashgar- Yecheng Thrust system (KYTS), Karakoram Fault (KKF), Karakax Fault (KXF), Kongur extension system (KES), King-Ata-Tagh section (KATS).

Acknowledgment

This work was supported by Major Program of National Natural Science Foundation of China (41490611), Projects of International Cooperation and Exchanges NSF-PSF (41661144026) and the National Key R&D Program of China (2016YFC0600301). We sincerely thank you all.

References

1. Negredo A.M., Replumaz A., Villaseñor A. and Guillot S. (2007). Modeling the evolution of continental subduction processes in the Pamir–Hindu Kush region. *Earth and Planetary Science Letters*, 259(1-2), 212-225. doi:http://dx.doi.org/10.1016/j.epsl.2007.04.043.
2. Sarkar I. and Sanyal S. (2004). Static stress transfers in the Pamir Hindu Kush seismic zone. *Journal of Asian Earth Sciences*, 23(4), 449-459. doi:http://dx.doi.org/10.1016/S1367-9120(03)00178-0 .
3. Powell C.M. and Conaghan P.J. (1975). Tectonic models of the Tibetan plateau. *Geology*, 3(12), 727-731.
4. Argand E. (1924). La tectonique de l'Asie. *Internat. Geol. Cong., 13th, Brussels, Comptes Rendus,* 5, 171-372.
5. Taylor M. and Yin A. (2009). Active structures of the Himalayan-Tibetan orogen and their relationships to earthquake distribution, contemporary strain field, and Cenozoic volcanism. *Geosphere*, 5(3), 199-214.
6. Replumaz A., Capitanio F.A., Guillot S., Negredo A.M. and Villaseñor A. (2014). The coupling of Indian subduction and Asian continental tectonics. *Gondwana Research*, 26(2), 608-626. doi:http://dx.doi.org/10.1016/j.gr.2014.04.003.
7. Burtman V.S. (2000). Cenozoic crustal shortening between the Pamir and Tien Shan and a reconstruction of the Pamir–Tien Shan transition zone for the Cretaceous and Palaeogene. *Tectonophysics*, 319(2), 69-92. doi:10.1016/s0040-1951(00)00022-6.
8. Wilson J.T. and Burke K. (1972). Two types of mountain building. *Nature,* 239, 448-449.
9. Wilson J.T. (1968). Static or mobile earth: the current scientific revolution. *Proceedings of the American Philosophical Society*, 112(5), 309-320.
10. Wilson J.T. (1973). Mantle plumes and plate motions. *Tectonophysics*, 19(2), 149-164.
11. Sippl C., Schurr B., Tympel J., Angiboust S., Mechie J., Yuan X. and Haberland C. (2013). Deep burial of Asian continental crust beneath the Pamir imaged with local earthquake tomography. *Earth and Planetary Science Letters*, 384, 165-177. doi:http://dx.doi.org/10.1016/j.epsl.2013.10.013.
12. Toussaint G., Burov E. and Avouac J.P. (2004). Tectonic evolution of a continental collision zone: A thermomechanical numerical model. *Tectonics*, 23(6).
13. Burov E. and Toussaint G. (2007). Surface processes and tectonics: forcing of continental subduction and deep processes. *Global and Planetary Change*, 58(1-4), 141-164. doi:http://dx.doi.org/10.1016/j.gloplacha.2007.02.009.
14. Lee C. and King S.D. (2011). Dynamic buckling of subducting slabs reconciles geological and geophysical observations. *Earth and Planetary Science Letters*, 312(3-4), 360-370. doi:http://dx.doi.org/10.1016/ j.epsl.2011.10.033.
15. Burtman V.S. and Molnar P. (1993). Geological and geophysical evidence for deep subduction of continental

crust beneath the Pamir. *Geological Society of America Special Papers,* 281, 1-76.

16. Fuchs M.C., Gloaguen R., Krbetschek M. and Szulc A. (2014). Rates of river incision across the main tectonic units of the Pamir identified using optically stimulated luminescence dating of fluvial terraces. *Geomorphology*, 216, 79-92. doi:10.1016/j.geomorph.2014.03.027.

17. Stübner K., Ratschbacher L., Rutte D., Stanek K., Minaev V., Wiesinger M. and Gloaguen R. (2013). The giant Shakhdara migmatitic gneiss dome, Pamir, India□Asia collision zone: 1. Geometry and kinematics. *Tectonics*, 32(4), 948-979. doi:10.1002/tect.20057.

18. Verma R.K. and Sekhar C.C. (1985). Seismotectonics and focal mechanisms of earthquakes from Pamir-Hindukush regions. *Tectonophysics*, 112(1-4), 297-324. doi:http://dx.doi.org/10.1016/0040-1951(85)90184-2.

19. Bershaw J., Garzione C.N., Schoenbohm L., Gehrels G. and Tao L. (2012). Cenozoic evolution of the Pamir plateau based on stratigraphy, zircon provenance, and stable isotopes of foreland basin sediments at Oytag (Wuyitake) in the Tarim Basin (west China). *Journal of Asian Earth Sciences*, 44, 136-148. doi:http://dx.doi.org/10.1016/j.jseaes.2011.04.020.

20. Schwab M., Ratschbacher L., Siebel W., McWilliams M., Minaev V., Lutkov V. and Wooden J.L. (2004). Assembly of the Pamirs: Age and origin of magmatic belts from the southern Tien Shan to the southern Pamirs and their relation to Tibet. *Tectonics*, 23(4). doi:Artn Tc4002: 10.1029/2003tc001583.

21. Waldhör M., Appel E., Frisch W. and Patzelt A. (2001). Palaeomagnetic investigation in the Pamirs and its tectonic implications. *Journal of Asian Earth Sciences*, 19(4), 429-451. doi:Doi 10.1016/S1367-9120(00)00030-4.

22. Schurr B., Ratschbacher L., Sippl C., Gloaguen R., Yuan X. and Mechie J. (2014). Seismotectonics of the Pamir. *Tectonics*, 33(8), 1501-1518. doi:10.1002/2014tc003576.

23. Schoenecker S.C., Russo R.M. and Silver P.G. (1997). Source-side splitting of S waves from Hindu Kush-Pamir earthquakes. *Tectonophysics*, 279(1-4), 149-159. doi:http://dx.doi.org/10.1016/S0040-1951(97)00130-3.

24. Cao K., Wang G.C., van der Beek P., Bernet M. and Zhang K.X. (2013). Cenozoic thermo-tectonic evolution of the northeastern Pamir revealed by zircon and apatite fission-track thermochronology. *Tectonophysics,* 589, 17-32. doi:http://dx.doi.org/10.1016/j.tecto.2012.12.038.

25. Sobel E.R., Schoenbohm L.M., Chen J., Thiede R., Stockli D.F., Sudo M. and Strecker M.R. (2011). Late Miocene–Pliocene deceleration of dextral slip between Pamir and Tarim: Implications for Pamir orogenesis. *Earth and Planetary Science Letters*, 304(3-4), 369-378. doi:http://dx.doi.org/10.1016/j.epsl.2011.02.012.

26. Sobel E.R., Chen J., Schoenbohm L.M., Thiede R., Stockli D.F., Sudo M. and Strecker M.R. (2013). Oceanic-style subduction controls late Cenozoic deformation of the Northern Pamir orogen. *Earth and Planetary Science Letters*, 363, 204-218. doi:http://dx.doi.org/10.1016/j.epsl.2012.12.009.

27. Schmidt J., Hacker B.R., Ratschbacher L., Stübner K., Stearns M., Kylander-Clark A. and Minaev V. (2011). Cenozoic deep crust in the Pamir. *Earth and Planetary Science Letters*, 312(3-4), 411-421. doi:http://dx.doi.org/10.1016/j.epsl.2011.10.034.

28. Khurshid A., Yielding G., Ahmad S., Davison I., Jackson J.A., King G.C.P. and Zuo L.B. (1984). The seismicity of northernmost Pakistan. *Tectonophysics*, 109(3-4), 209-226. doi:Doi 10.1016/0040-1951(84) 90141-0 .

29. Hubbard M.S., Grew E.S., Hodges K.V., Yates M.G. and Pertsev N.N. (1999). Neogene cooling and exhumation of upper-amphibolite-facieswhiteschists' in the southwest Pamir Mountains, Tajikistan. *Tectonophysics*, 305(1-3), 325-337. doi:Doi 10.1016/S0040-1951(99)00012-8.

30. Schoenbohm L.M., Chen J., Stutz J., Sobel E.R., Thiede R.C., Kirby B. and Strecker M.R. (2014). Glacial morphology in the Chinese Pamir: Connections among climate, erosion, topography, lithology and exhumation. *Geomorphology*, 221, 1-17. doi:10.1016/j.geomorph.2014.05.023.

31. Furuya M. and Yasuda T. (2011). The 2008 Yutian normal faulting earthquake (Mw 7.1), NW Tibet: Non-planar fault modeling and implications for the Karakax Fault. *Tectonophysics*, 511(3-4), 125-133. doi:10.1016/j.tecto.2011.09.003.

32. Li H., Van der Woerd J., Sun Z., Si J., Tapponnier P., Pan J. and Chevalier M.L. (2012). Co-seismic and cumulative offsets of the recent earthquakes along the Karakax left-lateral strike-slip fault in western Tibet. *Gondwana Research*, 21(1), 64-87. doi:10.1016/j.gr.2011.07.025.

33. Lin A., Kano K.I., Guo J. and Maruyama T. (2008). Late Quaternary activity and dextral strike-slip movement on the Karakax Fault Zone, northwest Tibet. *Tectonophysics*, 453(1-4), 44-62. doi:http://dx.doi.org/10.1016/ j.tecto.2007.04.013.

34. Khan N.G., Bai L., Zhao J., Li G., Rahman M.M., Cheng C. and Yang J. (2017). Crustal structure beneath Tien Shan orogenic belt and its adjacent regions from multi-scale seismic data. *Science China Earth Sciences*, 60(10), 1769-1782.

35. Robinson A.C., Yin A. and Lovera O.M. (2010). The role of footwall deformation and denudation in controlling cooling age patterns of detachment systems: An application to the Kongur Shan extensional system in the Eastern Pamir, China. *Tectonophysics*, 496(1-4), 28-43. doi:http://dx.doi.org/10.1016/j.tecto.2010.10.003 (2010).

36. Cao K., Bernet M., Wang G.C., van der Beek P., Wang A., Zhang K.X. and Enkelmann E. (2013). Focused Pliocene–Quaternary exhumation of the Eastern Pamir domes, western China. *Earth and Planetary Science Letters*, 363, 16-26. doi:http://dx.doi.org/10.1016/j.epsl.2012.12.023 (2013).