Is pull-apart basin tectonic model feasible for the formation of Kashmir basin, NW Himalaya?

A. A. Shah, Mohammad Noor Firdhaus bin Yassin and Muhammad Izzat Izzuddin bin Haji Irwan*

Physical and Geological Sciences, Faculty of Science, Universiti Brunei Darussalam, Jalan Tungku Link, Gadong, BE 1410, Brunei Darussalam

**corresponding author email: afroz.shah @gmail.com*

Abstract

An oval shaped Kashmir Basin in NW Himalaya largely reflects the typical characteristics of Neogene-Quaternary piggyback basin that was formed as a result of the continent-continent collision of Indian and Eurasian plates. However, a new model shows that the basin was formed by a major dextral strike-slip fault (Central Kashmir Fault) that runs through the Kashmir basin. This model is not only unlikely but also structurally unrealistic, and poses problems with the geomorphology, geology, and tectonic setting of the Kashmir basin. Although Shah (2016) has clearly demonstrated that such a model is not feasible for Kashmir basin, however in this article initial works have been further strengthened, and we demonstrate through various evidence, which includes a structural analogue modeling work, that a pull apart basin formation through strike-slip faulting is impractical for Kashmir basin. Further we show that Central Kashmir Fault, a proposed major dextral strike-slip fault, could not possibly exist.

Index Terms: pull-apart basin, Kashmir basin, NW Himalaya, Strike-slip fault

1. Introduction

Kashmir basin of NW Himalaya (***Figure 1***) is located ~100 km away from the Main Frontal thrust (MFT) fault, which is one of the major active south-verging fault systems in the region. The Zanskar shear zone (ZSZ), a major normal fault, lies to the northeast of the basin, whereas the Main Central thrust (MCT), the Main Boundary thrust (MBT), and the Raisi thrust (RT) systems respectively lie on its southwest[1-2]. This structural skeleton of the basin largely fits a piggyback-deformation model because a series of thrusts lies to the south of the young Kashmir basin that sits on top of these faults[3-4]. Sedimentation in Kashmir basin has possibly commenced by ca. 4 Ma and resulted in deposition of >1300 m of sediments (known as Karewas) at inferred average rates of ~16–64 cm/1000 yr[3,5]. These sediments are dominantly of fluvio-lacustrine and glacial origin[6-8] and were deposited on basement rocks composed of Pennsylvanian–Permian Panjal volcanic series[9] and Triassic limestone[10].

The Holocene sediments in Kashmir basin are recently broken, this is shown by a number of ~SE dipping faults, and this makes it a classic example of an out-of-sequence faulting in NW Himalaya[11-14]. Although a piggy-back basin model seems to largely fit the tectonic evolution of Kashmir basin however Alam et al.[15-16] have introduced a pull-apart basin tectonic model where they suggest that Kashmir basin was formed as a result of a large dextral-strike-slip fault that runs ~ through the center of the basin. Such a model, however, is structurally impractical[4] and the present work further shows why Kashmir basin could not fit a pull-apart basin tectonic setting as suggested by Alam et al.[15].

2. Tectonic and geological background

The location of the basin is north of the MFT fault zone, the megathrust structure that accommodates a larger portion of the regional convergence between the Indian and Eurasian plates[17,1], and is considered actively growing[18-20].

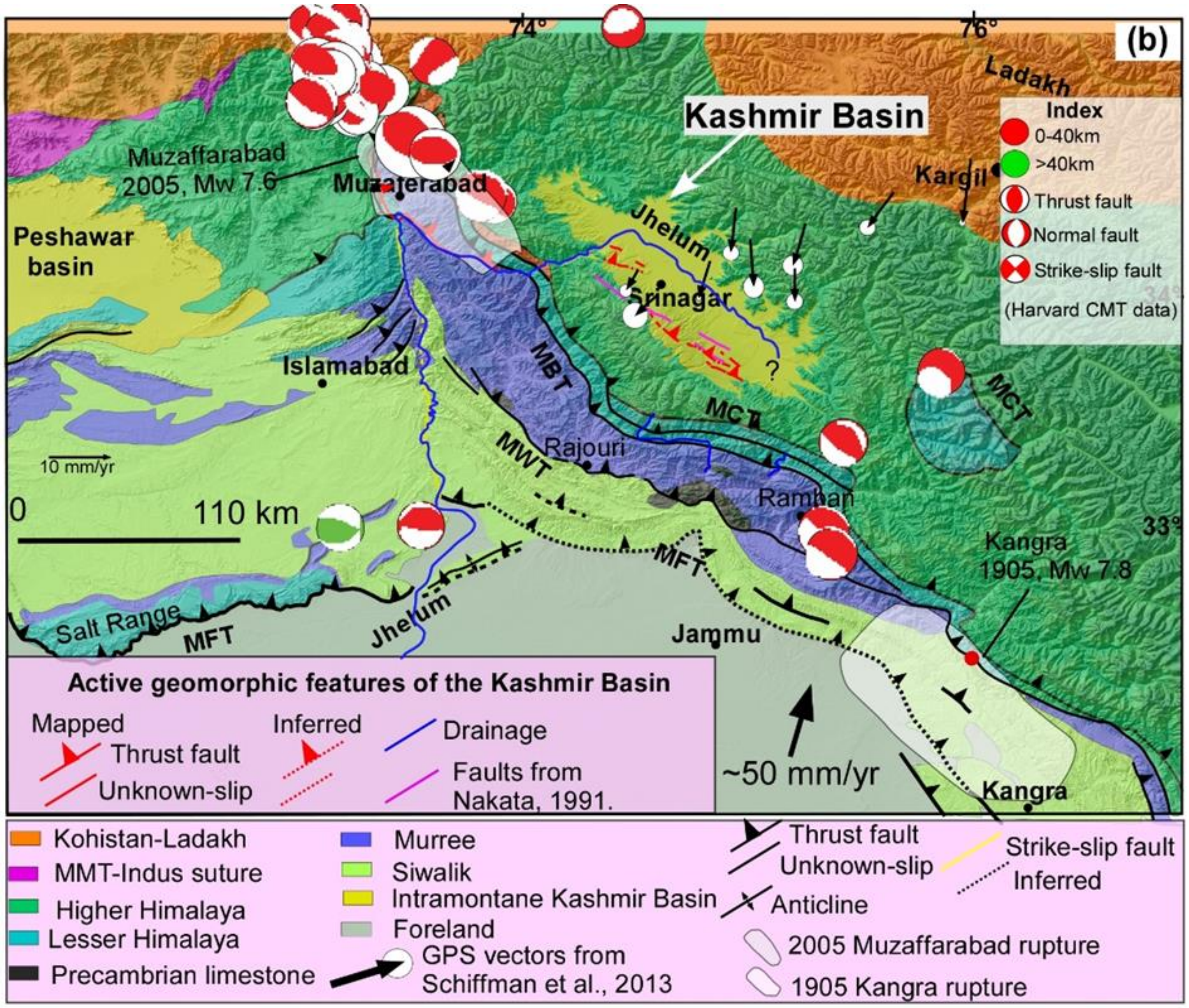

Figure 1. Regional tectonic setting of Kashmir basin, NW Himalaya (after Shah, 2016[14]). MCT—Main Central thrust, MBT—Main Boundary thrust, MWT—Medlicott–Wadia thrust, and MFT—Main Frontal thrust. CMT—centroid moment tensor; GPS—global positioning system.

Until now the surficial trace of the MFT has not been mapped in any part of the Jammu and Kashmir region, and thus it is assumed as a blind tectonic structure under Jammu [1, 14]. Schiffman et al.[17] have demonstrated that MFT fault is presently locked under the Kashmir region, and a major earthquake is anticipated in the future but the timing remain uncertain. A major active fault (Raisi fault) that runs under Raisi ***(Figure 1)*** is also considered to host a major earthquake[1] in the future. And a third major fault runs approximately through the middle of the Kashmir valley ***(Figure 1),*** which also has the potential to host a major earthquake, very similar to the Muzaferabad earthquake of 2005[13]. Since most of the faults are ~S-SW verging and Kashmir basin sits on these structures thus such a structural setting can be explained by a piggyback basin tectonic mode[l8] because a young basin sits on older faults.

Moreover, the geological map (***Figure 1***) of Kashmir basin shows Upper Carboniferous-Permian Panjal Volcanic Series and Triassic limestone are the foundation rocks on which ~1,300-m thick sequence of Plio-Pleistocene fluvio-glacial sediments are deposited[10].

These sediments are mostly unconsolidated clays, sands, and conglomerates with lignite beds unconformably lying on the bedrock with a cover of recent river alluvium[6,8]. The bedrock geology indicates a deep marine depositional setting, where limestone could form, and later such a depositional environment was closed, faulted, and

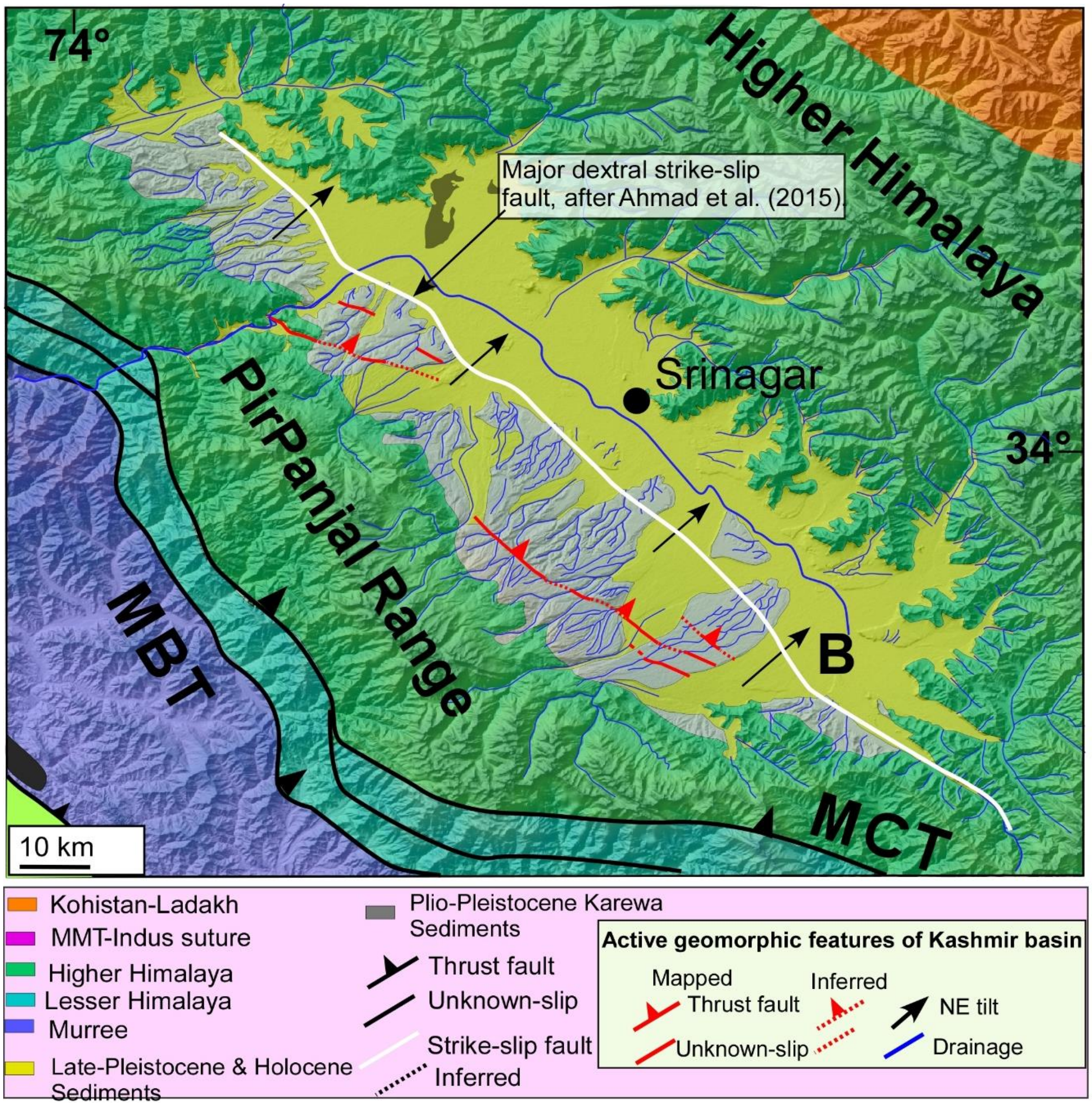

Figure 2. Simplified geology, and structural map of Kashmir basin, NW Himalaya showing the major extent of the major dextral fault (Modified from Thakur et al., 2010, and Shah, 2013a, 2015a), MCT=Main Central Thrust, MBT =Main Boundary Thrust. The Central Kashmir fault (CKF) of Ahmad et al. [15] runs through the basin.

uplifted. The formation of Kashmir basin followed the closure of such a setting, and later it was filled in with Plio-Pleistocene fluvio-glacial sediments are deposited[8]. A typical feature of a piggyback basin.

3. Is pull-apart basin tectonic model possible for Kashmir basin?

3.1. Structural evidence

Central Kashmir Fault (CKF), a proposed major dextral fault of Alam et al.[15], is argued to have formed the Kashmir basin through a pull-apart tectonic style.

The strike-length of Kashmir basin is ~150 km, and the mapped length of the dextral strike-slip fault is ~165 km, which runs through the center of the basin - this however, is structurally unlikely (***Figure 2***). This is because if a major strike-slip fault produces a pull-apart basin, then the trace of that fault should not run through the middle of the basin; it will mostly likely run through the margins of the basin and always away from its center.

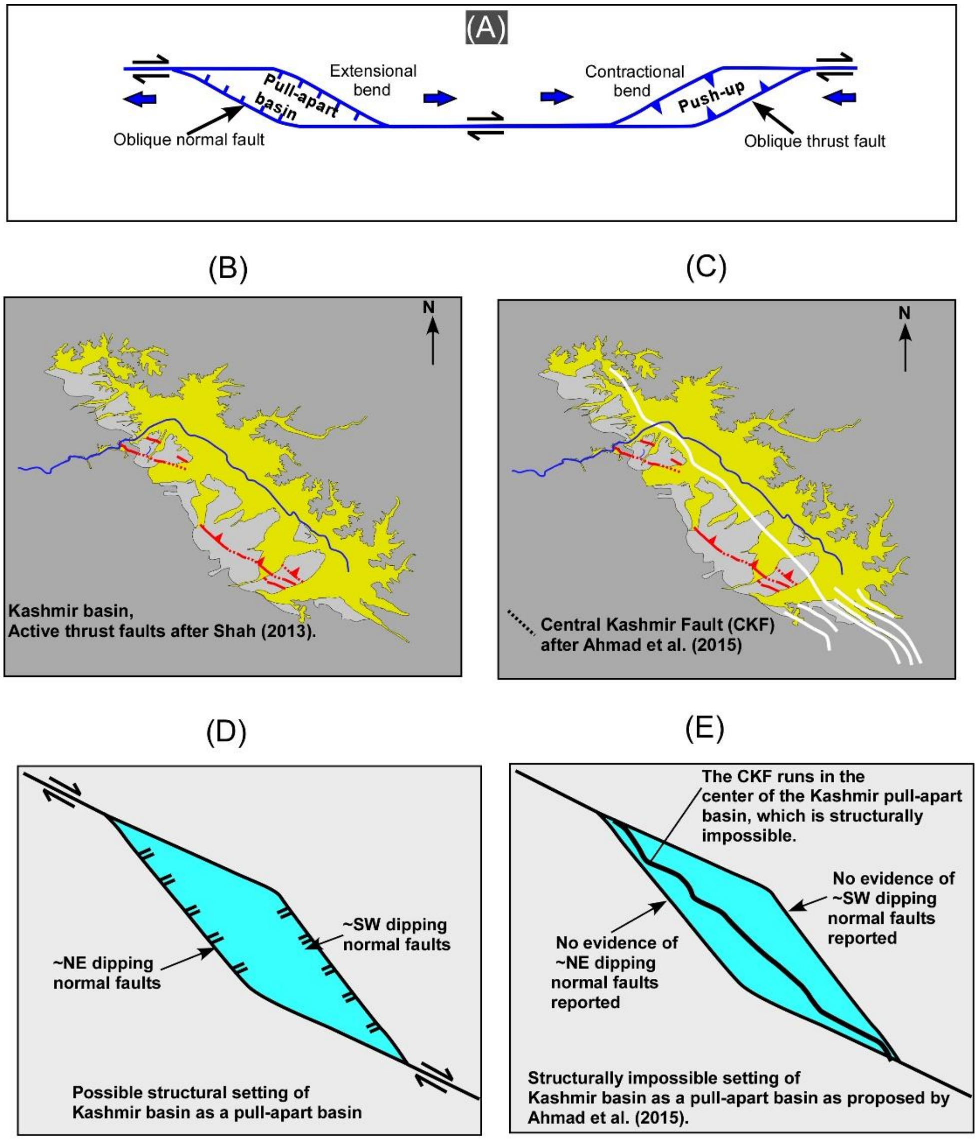

Figure 3. (A) Structures associated with a typical pull-apart basin setting. (B) Kashmir basin with mapped traces of active thrust faults (after Shah, 2013a[12]). (C) Shows the mapped trace of Central Kashmir Fault (CKF) and the associated horsetail structures. (D) A typical example of a dextral strike-slip fault system and a series of normal, oppositely verging faults that accompany such deformation pattern. (E) The mapped trace of the CKF which runs in the middle of the Kashmir basin - a proposed pull-apart basin, which is structurally not practical.

Therefore, the proposed location of the major trace of the CKF through the center of the Kashmir basin (a pull-apart product of CKF) is thus unlikely.

In addition to this, to form a ~165 km long basin usually- a series of ~SW, and ~NE dipping normal faults are required ***(Figure 3)*** in symmetrical extension. However, should the extension be asymmetrical, the normal faults would be expected to have either a ~SW or ~NE dipping fault planes or both. Typically, pull-apart tectonic movements will break the crust, extending it and later forming a series of normal faults. No evidence of such structures are reported in Kashmir basin in the expected orientation. And such structural setup will usually have a unique skeleton that could dominate the observed topography and geomorphology in an area with oppositely dipping normal faults. This, however, has not been reported in the Kashmir basin. Furthermore, the strike-length of the major dextral-strike slip faults is ~planar and contiguous; such geometry cannot cause extension

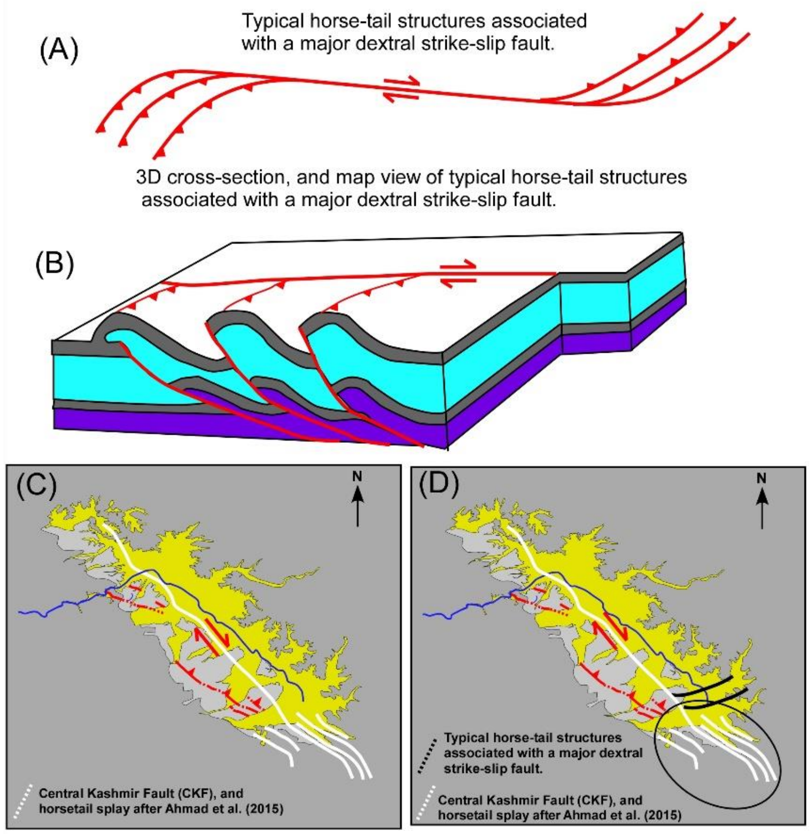

Figure 4. (A) An example of a typical dextral strike-slip fault system and the associated horsetail structures, (B) 3D view of what is shown in (A), (C) Kashmir basin with mapped traces of active thrust faults (after Shah, 2013a)[22] and the major dextral strike slip fault of Ahmad et al. [15]. (D) The orientation of horsetail structures of Ahmad et al.[15] is unlikely for a major dextral-strike slip fault system that has ~ NW-SE strike (horsetails should be at angles to the fault).

to form a pull-apart basin and on the contrary such basins are typical features of step-overs and linkage fault geometries[21,4] (***Figure 3***).

3.2. Horsetail splay faults

When a major strike-slip fault zone terminates in brittle crust, the displacement is usually absorbed along small branching faults. These curve away from the strike of the main fault, and form an open, imbricate fan called a horsetail splay[21]. In a classic dextral strike-slip fault system such faults could be of certain restricted orientation with respect to the trace of the main fault (***Figures 2*** and ***4***). The orientation of the major strike-slip fault of Kashmir basin is reported to be ~NW-SE[15, 16], and the horsetail faults, which appears as imbricate fans, are shown to be of the same orientation as the major fault (~NW-SE). This is not structurally possible (***Figure 4***) and it conflicts with the basic style of such faulting.). Technically, with the ~NW-SE strike of the major fault, the imbricate fans will either have a SW strike with a NW tectonic transport, or NE strike with a SE tectonic transport (***Figure 4c*** and ***Figure 4d***).

3.3. Geologic and geomorphic evidence

The bedrock geology of Kashmir basin shows Upper Carboniferous-Permian Panjal Volcanic Series and Triassic limestone are covered by Plio-Pleistocene fluvio-glacial sediments[10]. There is no evidence of a large scale topographic, or lithology offset which is typically associated with a major dextral strike-slip fault system. Shah[12] mapped dextral offset of streams on the SE of Kashmir basin, however, minor (~20 to ~40 m) offset of these channels are interpreted to have resulted from the regional oblique convergence between India and Eurasia, and it does not suggest or approve of a major dextral strike slip fault system as reported by Alam et al.[15].

3.4. Geodetic evidence

Shah[22] mapped the eastern extent of the KBF fault and argued for a clear right-lateral strike-slip motion for a distance of ~1km which was shown by the deflection of young stream channels. The lateral offset was shown to vary from ~20 to ~40 m. This was suggested to be a classical example of oblique convergence where thrusting is associated with a small component of dextral strike-slip motion.

The recently acquired GPS data from Kashmir Himalaya[17] confirms these observations, and further suggests an oblique faulting pattern wherein a range-normal convergence of 11±1 mm/y is associated with a dextral-shear slip of 5±1 mm/y (***Figure 1***). They also suggest that obliquity is more towards the eastern portion of the valley. This clearly suggests that the regional stress average vector is oblique in Kashmir Himalaya and, thus, the deformation is mainly absorbed by range-normal components, and less so by shear components—a typical feature of oblique convergence. Furthermore, in the case where the existence of Kashmir Central Fault is considered, the GPS data resolve on it show the dominance of normal convergence and not shearing parallel to the strike of this fault.

The reason for there being more dextral slip towards SE of Kashmir basin is possibly because of the regional escape tectonics where India acts like an indenter and, hence, the crustal flow is mostly along the huge strike-slip faults[23]. It could possibly also mean that there might be some large-scale unknown strike-slip faults in NW Himalaya.

3.5. Paper model

A map of Kashmir basin with the actual trace of the CKF[15] shows that any strike-slip movement on it would produce a range of small sized pull-apart basins (***Figure 5***). Such basins are not visible in any portion of Kashmir basin along its strike length (***Figure 1***).

Thus it is now established that a pull-apart genesis of Kashmir basin is unlikely because such a fault cannot pass through the basin; it ought to be at the margins. The paper model shows the possibility of at least 5 small pull-apart basins along the proposed trace of CKF and even at those regions the fault is not shown to cut through the basins but lie at their margins (***Figure 5b***). Such is what should be expected for a typical pull-apart basin.

4. Discussion

The present geological and structural architecture of Kashmir basin is largely consistent with a piggy-back model[8] as Kashmir basin is riding on a number of ~SW verging thrust faults[1,2] (***Figure 1***). Presently, three major fault systems are considered active[12, 13, 14], and from south these are Main Frontal Thrust (MFT), Medlicott-Wadie Thrust (MWT), and Kashmir Basin Fault (KBF).

The new model of Alam et al.[15] proposes a pull-apart tectonic model where a major dextral strike-slip fault (Central Kashmir Fault; CKF) is suggested to have formed the Kashmir basin through pull-apart movement (***Figure 2***). The ~150 km long Kashmir Basin is cut through by the proposed dextral strike-slip fault for ~165 km. And, the fault is proposed to run though the center of the basin, which is unlikely (***Figure 2***). This has also been demonstrated by the paper model that shows a range of small pull-apart basins when CKF moves. The fault that produces the basin lies at its margins and does not cut through the basin (***Figure 5b***). Thus, it poses a strong structural problem for the pull-apart model.

Furthermore, it is problematic to create the present structural skeleton of Kashmir basin by a major dextral strike-slip fault, even if it has an oblique slip component (***Figures 3*** and ***4***). This is because if a major dextral- slip is associated with a normal dip-slip component, which is shown by the pull-apart model[15], then the overall topography and geomorphology should ~ suggest subsidence on hanging-wall portions and relative uplift on foot-wall portions. This requires two scenarios: a) the major fault must be dipping SSW or 2) NNE. The pull-apart model[15] shows topographic depression on the right side of the major fault (NNE side), which requires a NNE dipping fault with a normal faulting component. However, the entire Kashmir basin tilts ~NE (***Figure 1***) and there is no evidence of regional normal faulting. Moreover, there is no

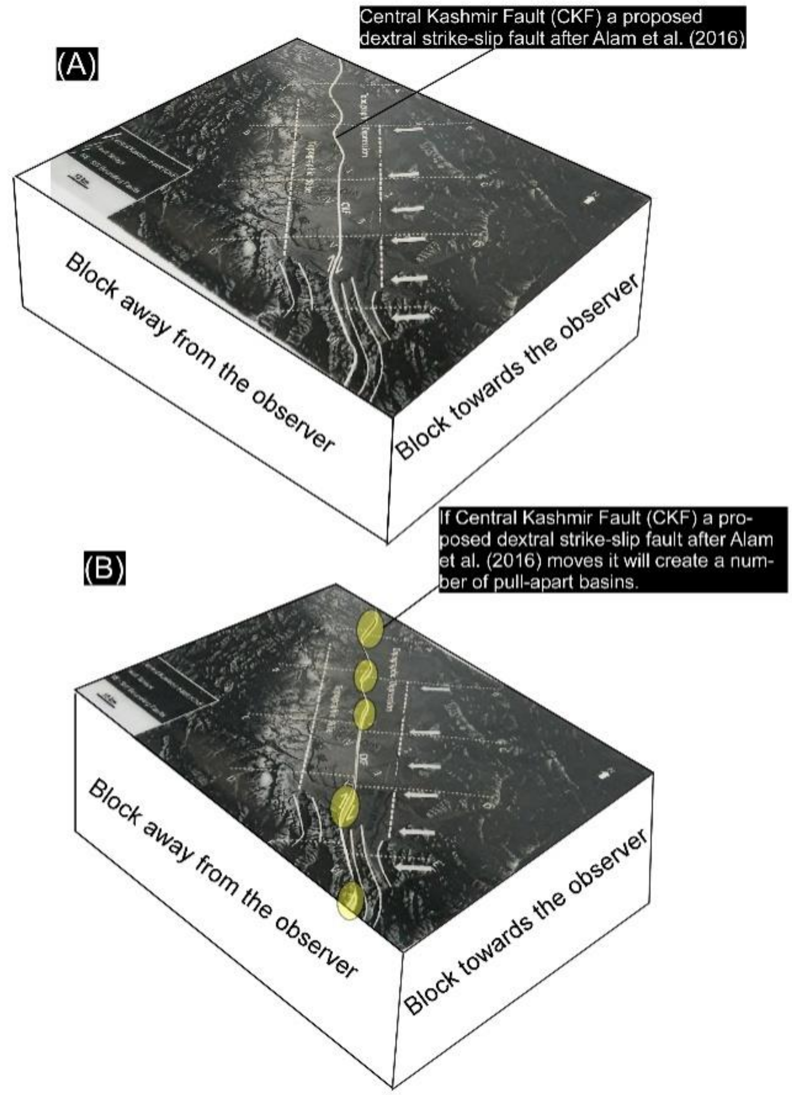

Figure 5. (A) The actual trace of CKF after (Alam et al., 20150[15]. (B) A range of small pull-apart basins expected to form if CKF moves.

reported topographic break or offset with a sufficient amount of slip required relative to the width and length of the Kashmir basin. There is also no evidence of a large scale strike-slip displacement of bedrock units[3].

The horsetail thrust structures (actually imbricate fans) of Alam et al.[15] run parallel with the trend of the main fault trace (***Figure 4***) while they should be at angles to it if the fault was a dextral-slip fault. It is kinematically unlikely to have them on both sides of a major fault tip (***Figure 4***). It is equally unreasonable to have the trace of a major strike-slip fault in the middle of a pull-apart basin (***Figure 2***). The structures mapped by Alam et al.[15] are inconsistent with the orientation of a major dextral-strike-slip fault system and the associated imbricate fans cannot be possible with the proposed orientation of the CKF (***Figure 3*** and ***Figure 4***).

The examination of GPS data in Kashmir Himalaya[17] shows an oblique faulting pattern, wherein a range-normal convergence of 11±1 mm/y is associated with a dextral-shear slip of 5±1 mm/y (***Figure 1***). When GPS data is resolved on the proposed CKF of Alam et al.[15] it shows dominant normal convergence and no shearing parallel to the strike of this fault. This clearly suggests that such a structure cannot be an active major strike-slip fault (***Figure 1***). The structural architecture and the evidences presented above suggest that Kashmir basin does not require a major strike-slip fault. The structures that have been shown in the pull-apart paper model indicate that such a big structure is not possible in Kashmir basin. Thus, the geological and tectonic setting of Kashmir basin is largely consistent with a piggy-back model [8].

Acknowledgements
We are very thankful to two anonymous reviewers for the critical comments, which helped us in polishing of the manuscript. Authors would like to thank AKM Eahsanul Haque for formatting the manuscript.

References

[1] R. Vassallo, J.L. Mugnier, V. Vignon, M.A. Malik, M. R. Jayangondaperumal, and P. Srivastava, *J., Earth Planet. Sc. Lett.*, **2015**, 411, 241-252.
[2] V.C. Thakur, R. Jayangondaperumal, and M.A. Malik, *Tectonophysics*, **2010**, 489, 29–42.
[3] D.W. Burbank and G.D. Johnson, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **1983**, 43, 205-235.
[4] A. A. Shah, *Geomorphology*, **2016**, 253, 553-557.
[5] N. Basavaiah, E. Appel, B.V. Lakshmi, K. Deenadayalan, K.V.V. Satyanarayana, S. Misra, N. Juyal, and M. A. Malik, 2010. *Journal of Geophysical Research*, **2010**, 115(B8)
[6] D.K. Bhatt, *Himal. Geol*., **1979**, 6, 197-208.
[7] D.K. Bhatt, *Geological Survey of India*, 1976, 24,188–204.
[8] D.W. Burbank and G.D. Johnson, G.D, *Nature*, **1982,** 298, 432-436.
[9] C.S. Middlemiss, *Geol. Surv. India*., **1910,** 40, 206–260.
[10] I.A. Farooqi, and R.N. Desai, *J. Geol. Surv. India*., **1974,** 15, 299-305.
[11] A. Shabir, and M.I. Bhat, M.I, *Himal. Geol*., **2012**, 33,162-172.
[12] A. A. Shah, *Int. J. Earth. Sci*., **2013a**, 102, 7, 1957-1966.
[13] A.A. Shah, *Inte Int. J. Earth. Sci*., **2015a,** 104, 1901-1906.
[14] A.A. Shah, *Geol. Soc. Amer. Spl. Papers.*, **2016,** 520, 520-28.
[15] A. Alam, S, Ahmad, M.S. Bhat, and B. Ahmad, *Geomorphology*, **2015**, 239, 114-126.
[16] A. Alam, S, Ahmad, M.S. Bhat, and B. Ahmad, *Geomorphology*, **2016**, 253, 558-563.
[17] C. Schiffman, Bikram Singh Bali, Walter Szeliga, and Roger Bilham., *Geophy. Res. Lett*., **2013**, 40, 5642-5645.
[18] L. Bollinger, S.N. Sapkota, P. Tapponnier, Y. Klinger, M. Rizza, J. Van der Woerd, and S Bes de Berc., *J. Geophys. Res*, **2014**, 119, 7123-7163.
[19] J.N. Malik, A. A. Shah, S.P. Naik, S. Sahoo, K. Okumura and N.R. Patra, *Current Science*, **2014**, 106, 229.
[20] J.N. Malik, A.A. Shah, A. Sahoo, K., Puhan, B., Banerjee, C., Shinde, D. P., and Rath, T*ectonophysics*, **2010,** 483, 327-343.
[21] A.G. Sylvester, *Geol. Soc. Am. Bull*., **1988**, 100, 1666–1703.
[22] A.A. Shah, *PATA days*, **2013b,** 5, 112.
[23] P. Tapponnier, and P. Molnar, *Nature*,**1976**, 264, 319-324.