by O.N. Bhargava and Birendra P. Singh*

Geological evolution of the Tethys Himalaya

Department of Geology (CAS), Panjab University, Chandigarh 160014, India

*corresponding author Email: v_ruh@rediffmail.com

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Rifting during the late Precambrian created the Tethyan basin in which the sedimentation continued up to Middle Cambrian (Cambrian Series 3). Onset of the late Cambrian- lower Ordovician Kurgialk orogeny terminated the sedimentation and also deformed the late Precambrian and Cambrian sediments.

A shallow marine transgression during the lower-middle Ordovician resumed the sedimentation with a prominent conglomerate horizon. The conglomerate horizon is absent in the Byans (Kalapani) and Bhutan sectors. The lower Ordovician siliciclastic sediments are succeeded by siliciclastic-algal-coral buildups during the Katian, indicating deepening of the basin; at this juncture the Bhutan and Byans areas too were submerged.

There was another subaerial break around the Wenlock, which extended up to the early Devonian. Shallow sea returned in the early-middle Devonian, manifested by the Muth Formation in the western Himalaya. The sea level relatively rose in the Givetian, heralding the siliclastic-carbonate sedimentation that continued upto the Tournaisian. In majority of the areas, there is a hiatus at the end of the Tournaisian. In the distal parts of Spiti-Zaskar sub-basin and Kashmir, however, the sedimentation continued up to Visean/Serpukhovian. In Spiti-Zaskar, a late Carboniferous-early Permian diamictite horizon is present. The diamictites are assigned glacial origin by many workers.

The areas where the sedimentation had ceased during the Tournaisian, witnessed a marine transgression during the Asselian-Sakmarian. It was followed by outpouring of the 289 Ma Panjal Volcanics in parts of Kashmir, Zaskar and Lahaul. The 289 Ma interval represented by a break between the Sakmarian and the Wuchiapingian sediments in the areas where the Panjal volcanics are absent. The Wuchiapingian transgression was extensive;

it covered the Tandi, Chamba and Bhadarwah areas also.

Save Kashmir, the Changhsingian is absent in the Tethyan Himalaya and there is a marked hiatus between Wuchiapingian and the Induan. The Induan-Lias succession is characterized mainly by carbonate sediments throughout the Tethyan sector. The sedimentation ceased towards the Lias; the hiatus spanned the Late Oxfordian-Kimmeridgian.

The Kimmeridgian transgression, barring Kashmir, covered the remaining Tethyan sector. In the Cretaceous, the plate margin became active, thereafter the deeper water sediments were deposited in Spiti-Zaskar and Garhwal. With a Danian break, the Cretaceous sediments were succeeded by shallow marine Paleocene and the fresh water Eocene in Zaskar. Obducted ophiolite klippen were emplaced over the Cretaceous sediments in the Zaskar and Malla Johar areas. In Malla Johar the ophiolite has carried the deep water Triassic-Cretaceous sediments—termed as exotic blocks of Kiogad and Chitichun facies.

Introduction

The late Precambrian to Eocene succession (Table 1), that rests over the crystallines of the Higher Himalaya (variously designated as the Salkhala, Vaikrita, Kathmandu, Thimphu groups), is designated as the Tethyan succession. The Higher Himalayan crystallines (HHC), towards the south/southwest are delimited by the Main Central Thrust (MCT). Physiographically, the Tethyan successions, except those of the Tandi, Chamba-Bhadarwah, lie north of the Higher Himalaya (Fig. 1). The Palaeozoic sequences in the Tethyan sector bear multiple names with varying stratigraphic ranges. Table 2 shows the correlation of the sequences of different sub-basins.

Opinions vary regarding: (i) geographical location and the spatial relationship of the Tethyan Himalaya with the Lesser Himalaya, (ii) creation of the Tethyan basin and (iii) the nature of contact of the Tethyan succession with the HHC.

The important contributions to the Tethyan successions are by Middlemiss (1909, 1910, 1911), Nakazawa et al (1975) and

Table 1. Precambrian to Eocene lithostratigraphy of the Spiti, being the best worked out Tethyan succession.

Group /Supergroup	Formation	Lithology	Age
Kanji	Dumbar	Red beds, conglomerate	Lutetian
	Kelcha	Limestone, sandstone, marl	Thanetian-Ypresian
-----Disconformity-----			
Lagudarsi	Chikkim	Limestone, shale	Cenomanian-Early Maastrichtian
	Giumal	Sandstone	Late Valanginian-Albian
	Spiti	Shale	Oxfordian-Early Valanginian
-----Disconformity-----			
Kioto	Tagling	Limestone, dolomite	Lias
	Para	Limestone, dolomite	Late Rhaetic
Nimoloksa	Nunuluka	Sandstone, siltstone, limestone	Late Noric-Early Rhaetic
	Alaror	Shale, sandstone, limestone	Late Noric
	Hangrang	Limestone, dolomite	Middle Noric
	Rangrik	Shale, sandstone, limestone	Early-Middle Noric
	Rongtong	Dolomite, limestone	Middle-Late Carnic
Sanglung	Rama	Shale, sandstone, limestone	Early-Middle Carnic
	Chomule	Limestone	Ladinic-Early Carnic
TambaKurkur	Kaga	Shale, siltstone, limestone	Ladinic
	Mikin	Limestone	Induan-Anisian
-----Disconformity-----			
Kuling	Gungri	Shale	Dzulfian-?Early Dorashamian
-----Disconformity-----			
Kuling	Gechang	Sandstone	Asselian-?Sakamarian
-----Disconformity-----			
Kanawar	Ganmachidam	Conglomerate, sandstone, shale	Late Carboniferous
	Po	Shale, sandstone	Visean-Serpukhian
	Lipak	Limestone, sandstone, shale	Givetian-Tournaisian
	Muth	Sandstone	Early Devonian
-----Disconformity-----			
Sanugba	Takche	Limestone, sandstone, shale	Ashgill-? Wenlockian
	Thango	Conglomerate	Early Ordovician
-----Angular unconformity-----			
Haimanta	Kunzam La	Sandstone, shale, limestone	Early-Middle Cambrian
	Batal	Sandstone, siltstone, shale	Ediacaran-Early Cambrian

Table 2. Correlation of Tethyan Palaeozoic sequences of different sectors.

Period	Salt Range / Raj.	Kashmir	Zaskar-Spiti-Kinnaur	Kumaon-Garhwal	Nepal	Bhutan	Peshawar
Permian	L	Zaluch Gr.	Khunamuh	Gungri	Kuling Sh.	Nenjung	Barishong
	M		Panjal Volc.	Panjal Vol.			
	E	Nilawahan Gr. Bhadaura	Nishat Bagh & Mamal Beds Pindabol	Gechang	Girthi	Senja	
Carboniferous	L		Ganmachidam			Thini Chu	
	M		Fenestella Sh.	Po			Zaffar Kando
	E		Sytingothyris L.	Lipak		Ice Lake	Khybar L.
Devonian	L		Wazura		Kali		
	M		Wazura-Muth	Lipak-Muth		Tilicho Pass	
	E		Muth	Muth			
Silurian	L						Nawshera
	M		Gugaldhar	Takche	Shiala-Yong-Varigated	Chandragiri	
	E				Chitlang Dark Band L.	Wachi La	Kandar
Ordovician	L						Panjpir
	M		Hallamulla	Thango	Ralam	Damgad	
	E						Misri Banda
Cambrian	L					Quartzite	
	M						
	E	Jhelum Gr. Nagaur Gr.	Hapatnar Gr.	Haimanta Gr.	Milam Gr.	?-?	Maneting
							Amber

Figure 1. Lesser to Tethyan Himalaya showing the different sub-basins in the Tethyan domain.

Bhargava (2015) in Kashmir, Griesbach, (1889), Stoliczka (1865), Hayden (1904), Srikantia (1981), Gaetani et al (1986), (Garzanti et al., 1998) and Bhargava and Bassi (1998) in Spiti-Zaskar, Heim and Gansser (1939), Valdiya and Gupta (1972), Banerjee (1974) and Kumar et al (1977) in Utrakhand, Bodenhausen et al (1964), Fuchs (1967), Hagen (1968), Bordet et al (1971), Garzanti (1999), Gradstein et al (1991) and Dhital (2015) in Nepal and Gansser (1983), Nautiyal et al (1964) and Bhargava (1995) in Bhutan.

Relationship between the Tethyan and the Lesser Himalaya

Following models have been conceived to explain the relationship of the Tethyan Himalaya vis-à-vis the Lesser Himalaya:

1. Auden (1935) referred the Lesser Himalaya as the Peninsular Himalaya, separated from the Tethyan part by a barrier constituted of the Precambrian rocks (Fig. 2a). This model is followed by many to account for the differences in the geological setup of these two sectors (Saxena 1971; Bhargava et al. 1998, Bhargava 2008a, 2008b, 2011a, 2011b, and references therein).
2. Brookfield (1993), Myrow et al. (2003, 2009, 2015), Hughes et al. (2005), and Hughes (2016) conceived one continuous basin from the Lesser to the Tethyan Himalaya (Fig. 2b).
3. DeCelles et al. (2000) visualized the Tethyan basin to be far away from the Lesser Himalaya, brought to its present position due to thrusting along the MCT, they termed it as Accreted Terrain Model (Fig. 2c).

There are certain anomalies which have not been addressed in all the above referred models. For example, in each model, the Tethyan terrain is visualized to be closer to the Tibetan/ Chinese terrain as compared to the Lesser Himalayan. The Tethyan sequences, thus, are expected to have similarities with those of the Tibetan/Chinese part. On the contrary, the sequences of the Blaini Formation (Cryogenian), the Krol Group (Ediacaran) and the phosphorite bearing Tal Group (lower Cambrian) of the Lesser Himalaya display noteworthy similarities with their Chinese counterparts, whereas the Tethyan part has different facies.

Figure 2. Tectonic models explaining the relationship of the Tethyan basin vis-à-vis the Lesser Himalayan basin (modified after Myrow et al., 2003).

Creation of the Tethyan Basin

Srikantia (1981) regarded the Tethyan sediments as an extension of HHC.

Ganju and Khar (1985) considered the Tethyan Kashmir aperiatic basin that originated in the late Precambrian time due to movements along the deep-seated NW-SE trending Jhelum and other collinear lineaments.

Presence of >150 m thick Singhi Volcanics in Bhutan, minor basic flows in Spiti (Batal Formation), magnetite tuffs in Kinnaur and Khewra Traps in Salt Range (Pakistan) were regarded to imply a rifting in "Eocambrian" time that created the Tethyan Basin (Bhargava and Bassi, 1998).

Nature of contact of the Tethyan succession with the HHC

Srikantia (1981) in Zaskar-Spiti and Gansser (1983) in Bhutan observed a gradational contact between the Tethyan sediments and the underlying HHC.

A nonconformity, in view of presence of the volcanics in the basal part of the Tethyan succession, was proposed by Bhargava and Bassi (1998). The apparent gradation from HHC to the Tethyan succession (cf. Srikantia, 1981, Gansser, 1983) is possibly due to later metamorphism which embossed similar characters to HHC and the Tethyan sedimentary sequence along the contact zone (Bhargava and Bassi, 1998).

Burchfiel et al. (1992) propounded that all over the Himalaya a low-angled normal fault, designated as South Tibetan Detachment System (STDS), separates the Tethyan sequence from the underlying HHC. In Bhutan, this plane is marked all around the Tethyan 'basin' making it a klippe (Kellett et al., 2009). We find that in most cases unrelated thrust planes at different tectonic levels have been identified as STDS. Fuchs (2011) doubted the regional significance of the STDS. Bhargava (2015) considered the STDS a phenomenon of basement cover detachment, which is not ubiquitously present.

Paleotectonic position of the Kashmir sub-basin

It is universally accepted that the open sea lay to the north/northeast of the Tethyan basin and Indian craton was located south/southwest of it. The basin profile from the craton to towards the open sea will show deepening towards north/northeast. The Kashmir sub-basin, located southwest of the Spiti-Zaskar, being closer to the coast, is supposed have shallower litho- and biofacies. However, both the facies from the Cambrian to the lower Permian (Sakmarian) are similar to the corresponding sequences in Spiti-Zaskar. The post-Panjal

Volcanic sequences in Kashmir, on the other hand, show shallower facies as compared to the Spiti-Zaskar. To explain such a distribution of the facies in space and time, Bhargava (2011) suggested that till early Permian, the Kashmir sub-basin formed lateral extension of the Spiti-Zaskar basin (Fig. 3). During the Panjal volcanicity, associated with the gondwanaland rifting, the Kashmir sub-basin got sheared to the present site (Bhargava, 2011).

Description of the Tethyan successions in space and time

Salient temporal and spatial aspects of the Tethyan succession are given below. For detailed fossil contents reference may be made to Bhargava (2008; 2015)

Cambrian

The Cambrian sequences are well developed from Kashmir in the west to Garhwal and Bhutan in the east. There have been some uncertainties regarding the identification of the Cambrian succession east of Kinnaur. Prior to linking of the Ordovician Thango Conglomerate with the Ralam Conglomerate (Bhargava and Bassi, 1998), the latter was considered Precambrian and the overlying Garbyang Formation was assigned a Cambrian age, though no diagnostic fossil was known. The Garbyang Formation in Garhwal is now assigned an Ordovician age.

The Cambrian age to the Garbyang Formation in Kumaun (Kalapani) (Valdiya and Gupta, 1972) similarly needs revision, where no Cambrian fossil is known. In Nepal too, no fossil is known, the Cambrian age to the metasediments is interpreted due to their infra-Ordovician position (Dhital, 2015). The Cambrian sediments, if present in Kalapani and Nepal, their identification may be difficult as the metamorphism and also profuse granitic activity camouflaged the original characters.

The youngest Cambrian sediments (latest middle Cambrian-earliest Furongian) occur in two corners of the Tethyan Himalaya *i.e.* Kashmir in NW and Bhutan in the E. The older Cambrian sediments are present in central part of the Tethyan Himalaya in Zaskar-Spiti and Kinnaur-Garhwal.

The Furongian-lower Ordovician Kurgiahk Orogeny (Srikantia et al., 1976), terminated the Cambrian sedimentation and deformed the Cambrian and older sequences (Bhargava et al., 2011). The presence of youngest Cambrian sediments in two extremities and older part in the central part could be either due to the regression being diachronous, commencing in the central part of the basin and progressing towards the extreme corners or due to greater erosion in the central part. Bhargava (2011) preferred combination of these two processes.

Figure 3. Cartoon to show late early-middle Cambrian basin. Position of conjectured subaerial ridge and path of regression of the Cambrian sea.

The precise time span of the Kurgikh Orogeny is not known; possibly it commenced in Furongian and lasted till lower Ordovician as revealed by Sm/Nd 479.7 ± 8.5 Ma age of the garnets in the Jutogh (Bhargava et al., 2016). The Cambrian and the Himalayan folds are co-axial (Wiesmayr and Grasemann, 2002), hence difficult to distinguish.

Ordovician-Silurian

The Ordovician-middle Silurian succession forms the succeeding cycle in the geological history of the Tethyan Himalaya. It began with a widespread transgression, heralding the sedimentation with a conglomerate (Fig. 4), observed from Peshawar to Garhwal (Bhargava, 2011). In Spiti there are two levels of conglomerate intervened by red-coloured quartzarenite succession. The lower conglomerate has clasts from the Cambrian and the older formations. The upper conglomerate encloses pebbles of red colored quartzarenite also, which suggests a pre-upper conglomerate sedimentologic cessation. The hiatus was long enough to form a horizon simulating ferricrete in Spiti (Bhargava and Bassi, 1998).

The conglomerate horizon is absent in Byans and Bhutan (Bhargava, 2005), though present in the intervening area of Nepal. The conglomerate suggests steep uplift of the provenance along the slopes of which the mountainous rivers traversed.

The quartzarenite sequence is largely unfossiliferous. Lower Ordovician age assigned to this sequence is based on *Phycodes circinatum* (Bhargava et al., 1984) and *Prismocorollina* sp. (Sinha and Misra, 2006).

The quartzarenite sequence is succeeded by a siliciclastic-carbonate succession indicating a relative deepening of the basin. Coral-algal-stromatoporoid buildups were formed during this phase. There were at least two episodes of flooding as suggested by conodonts levels (Suttner, 2007; Suttner et al., 2007), maximum flooding occurred during the Llandovery (early Silurian). During the first flooding, the Kalapani and Bhutan areas were in undated with carbonate dominated sedimentation. The Ordovician-Silurian boundary lies within this cycle. Bodo event has been recognized in Spiti (Suttner, 2007; Suttner et al., 2007; Myrow et al., 2018).

Several shoaling cycles commenced from mid-lower shoreface and terminated in upper shoreface, sedimentation varies from microfacies belt 7 of Wilson (1975) to the subtidal-intertidal interface with periodic storms (Bhargava, 2011) to zero energy carbonate sedimentation (Kumar et al., 1977). The thickness of the Ordovician-Silurian sediments gradually increases from the west to the east together with increase in carbonate contents. In the Lahaul- Zaskar there is not only conspicuous reduction in thickness of the Ordo-Silurian sequence, it also is intermittently developed. Uneven thickness and intermittent development may be attributed to pre-Devonian erosion, whereas the increase in carbonate content may indicate relative deepening of the basin eastwards, where prominent buildups are recorded in Yong (Garhwal) and Bhutan. The Nilgiri Massif in Nepal possibly formed the distal part of the basin until at least in late Llandovery, as revealed by the graptolite fauna (Bhargava, 2011).

Regionally, the sedimentation in the Tethyan Himalaya ceased around the Llandovery-Wenlock (early-middle Silurian) (Bhargava, 2011); only in the Peshawar Basin the sedimentation extended up to the Ludlow-Pridoli (late Silurian), thereafter this part too underwent a regressive cycle leading to withdrawal of the sea (Talent and Bhargava, 2003). The hiatus above the Ordovician-Silurian covers the late Silurian-early Devonian interval.

In the upper part of the Silurian succession, syn-depositional folds are present over a vast region—stretching from Spiti (Khar and Pin sections, Bhargava and Bassi, 1998) to Garhwal (Kumar et al., 1977) to Kalapani (Banerjee, 1974). These are considered paleoseismites related to the tectonic activity, which caused the regression and a sedimentological breakstraddling the late Silurian-early Devonian interval.

Devonian-Carboniferous

A shallow marine transgression is recorded in the early Devonian-? early-late Devonian. During the pre-Givetian-middle Devonian, the terrain between Kashmir and Kumaun (characterized by the Muth Formation) formed a vast stable beach or barrier island (Bhargava and Bassi, 1998; Draganits et al., 2002, 2003). This interval seems to be unrepresented in Bhutan (Bhargava, 1995). There was a relative

Figure 4. (a) Angular contact between the Cambrian (Kunzam La Formation) and the Ordovician (Thango Formation) the Shian village, Pin valley, Spiti, (b) close-up view of the conglomerate at the base of the Thango Formation.

deepening of the basin in the Givetian with introduction of carbonate contents (Bhargava, 2008b). Multiple hardgrounds are present close to Devonian-Carboniferous boundary in Spiti (Bhargava and Bassi, 1998). These hardgrounds were interpreted to represent sea level high-strand condition and condensation of horizons (Shanker et al., 1993). The overlying sequence, represented by siliciclastic-carbonate sequence, shows several shoaling cycles, punctuated with flooding events. The sequence has yielded Tournaisian conodonts (Draganits et al., 2002). In Spiti, the sequence culminates in thick gypsum deposits during the late Tournaisian (Bhargava and Bassi, 1998). Barring the evaporite facies, the Tournaisian sequence is identical in all the areas.

In Kashmir and Zaskar-Lahaul-Spiti the siliciclastic-carbonate sequence is overlain by a thick sandstone-shale sequence (*Fenestella* Shale in Kashmir/ Po Formation in Zaskar-Spiti) comprising several prograding cycles. This sequence encloses plant fossils in the basal part. Based on brachiopod remains, it is assigned a Viséan-Serpukhovian (early Carboniferous) age (Bhargava and Bassi, 1998). With appearance of granules and pebbles the sandstone-shale succession grades in to a sequence of conglomerate, sandstone and shale. It is designated as the Pindabol Formation (Agglomeratic Slates) in Kashmir and Ganmachidam Formation in Zaskar-Spiti. The late Carboniferous-early Permian Gondwanaland ice age lowered the sea-level and raised the shallower parts of the basin. The raised parts contributed clasts to the Ganmachidam conglomerates deposited in the deeper parts of the basin (Bhargava, 2008b). The clasts in the conglomerate are of local origin and water-worn. The deposit could be of fluvio-glacial to shallow marine origin.

The Po-Ganmachidam sequence (late Carboniferous) is present only in the northern part of the Zaskar-Spiti, which formed the deeper parts of the basin (Bhargava, 2008a, 2008b). The conglomerate and underlying sandstone-shale sequence are intimately associated, forming one continuous sequence, both together are either present or absent (Bhargava and Bassi, 1998). In the southern part (Parahio-Pin valleys, Kinnaur), the Tournaisian (earliest Carboniferous) sequence is overlain by the Asselian (early Permian) sandstone (discussed in sequel).

The conglomerate in Kashmir encloses *Eurydesma* of Asselian (early Permian) age. In Lahaul, Spiti and Kinnaur, *Eurydesma* occurs much above the conglomeratic horizon (Bhargava and Bassi, 1998). The sequence thus is regarded a diachronous. In view of its gradational relationship with the underlying Viséan/Serpukhovian (middle Carboniferous) sequence, the conglomeratic sequence is interpreted to range from the late Carboniferous to early Asselian (Bhargava, 2008a, 2008b).

The equivalents of the Viséan/Serpukhovian (early Carboniferous) and the overlying conglomeratic sequences are absent in Uttarakhand and Bhutan. Part equivalence of the Ripakha Formation with the Po Formation in Bhutan is uncertain. A minor sandstone sequence in Kalapani sector was assigned a Viséanage (early Carboniferous) (Valdiya and Gupta, 1972). The age assignment is suspect, as stated above the Viséan sequence never exists sans conglomerate, moreover, the sandstone beds are quite common in the Tournaisian (earliest Carboniferous) sequence also (Bhargava and Bassi, 1998).

Permian

As mentioned earlier, the Agglomeratic Slates/Pindabol/Ganmachidam Formation ranges in age from the late Carboniferous

to earliest Permian (Asselian). During this period the raised pre-Viséan sediments contributed clasts to the Ganmachidam Formation, being deposited in distal parts of the basin. In Asselian-Sakmarian (early Permian), the sea level rose and flooded most of the areas. In this enlarged basin, sandstone with local basal lag was deposited over the Devonian and early Carboniferous sediments.

The Asselian-Sakmarian (early Permian) sandstone in Zaskar-Lahaul is overlain by the ca. 289 ± 3 Ma Panjal Volcanics (Shellnutt et al., 2011). The Panjal Volcanics include volcanic and volcanogenic rocks. In basal part, volcanics are moderately thick layered having basalt-andesitic composition. In the upper part the volcanics comprise thick layered, fine to medium grained non-porphyrific, epidotised basalt-andesite flows with local volcanic breccias, top part is amygdaloidal (Singh, 1996). Locally, trachyte, keratophyre, rhyolite and acid tuffs are also present. Bhat and Zainuddin (1978) classified volcanics under tholeiitic. Honegger et al. (1981) also considered the volcanics to have alkaline trend and affinity to Mid-Ocean Ridge Tholeiite. Singh (1996) regarded the Panjal Volcanics to have erupted in terrestrial and subaqueous environments. Extensive spread and low pyroclastic nature of the volcanics suggests a fissure type eruption associated with subsiding central vent (Singh, 1996), caused by rifting in the Gondwanaland activity of ca. 289 ± 3 Ma (Shellnutt et al., 2011).

The volcanic flows of uneven thickness formed undulatory topography. The depressed portions became sites of fresh water lakes in Kashmir in which plant beds were deposited (Kapoor and Maheshwari, 1991, Kapoor et al., 1993, 2004).

The Panjal volcanicity was followed by an extensive Wuchiapingian transgression, which covered Precambrian terrains in the Chamba-Bhadarwah and Tandi areas (Bhargava and Bassi, 1998). The Wuchiapingian sediments are ubiquitously represented by black shale with some silt input, deposited mainly in mid-shelf environment (Kumar et al., 1977, Bhargava and Bassi, 1998). In Spiti it is deposited over the Asselian-Sakmarian sandstone along a disconformity. In other parts of the Tethyan Himalaya, the Wuchiapingian black shale rests over still older formations. In Kinnaur (Bhargava and Bassi, 1998) and Byans (Srivastava and Kumar, 2004), the Wuchiapingian shale rests over the early/middle Devonian sediments.

Only in Kashmir a full sequence of the Changhsingian (Khunamuh Formation) is preserved marking a transition to the Induan (Nakazawa et al., 1975). In other areas, a break between Wuchiapingian and the Triassic is recorded. In Spiti, the late Changhsingian is absent (Ghosh et al., 2016) and the break is demonstrated by a ferruginous layer (Bhargava and Bassi, 1998). There are evidences of wildfires in the late Permian (Changhsingian) Zewan Formation (Jasper et al., 2016) and also of tsunamis (Brookfield et al., 2013). The sedimentological break in Spiti is regarded as sub-marine (Bhargava and Bassi, 1998, Ghosh et al., 2016).

Sedimentological, geochemical, chemostratigraphic and biostratigraphic studies including carbon, oxygen, lead isotope data, framboidal pyrites, fossils of the late Permian shales indicate deeper anoxic depositional environment.

Similarities of this shale with other Neo-Tethyan sections from Trans-Caucasia and Iran indicate subaqueous oxidation of shallow marine sediments on a regional scale. $\delta^{13}\text{C}_{\text{org}}$, trace element and Pb isotope record from Spiti indicate catastrophic changes in sediment sources and facies, which affected the carbon cycle and support an abrupt episode of marine regression.

Induan-Lias/Dogger

In the Kashmir sub-basin, the Changhsingian sediments conformably pass in to the Triassic succession. In other areas, the Triassic succession succeeds the Wuchiapingian shale with a submarine break. The Triassic sequence is well known in Kashmir, Zaskar-Spiti, Kinnaur-Garhwal (Painkhanda-Babmanag-Shalshal), Byans and Nepal (Table 3). In Sikkim, Triassic fossils are known (Pascoe, 1959), but no stratigraphic details exist. In Bhutan, Nautiyal et al., (1964) and Hanny (in Gansser, 1983) reported Triassic fossils from the Lingshi Formation. Of all the Triassic sequences, the Spiti section is best studied lithostratigraphically and biostratigraphically (Bhargava et al., 2004), in Garhwal, the biostratigraphic details are available (Pascoe, 1959), in Malla-Johar (Kumaun) the lithostratigraphy is available in great detail (Kumar et al. 1977) with some paleontological inputs (Srivastava and Kumar, 2004), in Byans (Valdiya and Gupta, 1972; Banerjee, 1974) and in Nepal fairly detailed lithostratigraphy and biostratigraphy have been worked out (see Dhital 2015, for detailed references). Minor Triassic occurrences are known in the Tandi, Chamba and Bhadarwah sectors. The basal part (Induan-early Ladinian) mainly comprise carbonate and minor shale, the latter is conspicuous in early Ladinian, late Ladinian and Carnian parts are Carbonate dominated, followed by shale and carbonate (early Norian), in Kashmir, Zaskar-Spiti and Kinnaur, the middle Norian is represented by Coral reefs, it is followed by shale-sandstone with little limestone (late Norian) and quartzarenite (late Norian-early Rhaetic), the youngest part (Rhaetic-Liassic) is carbonate dominated. The sequence in Byans, overall has larger component of shale, particularly in the Noric.

The thickness of the Triassic sequence is quite variable. The lower Triassic is 100 m thick in Kashmir, 12-15 m in Zaskar-Spiti and around 50 m in Byans. The Muschelkalk is 300 m thick in Kashmir, 30 m in Zaskar-Spiti, and Painkhanda in 25 m. The Ladinian part has a thickness of 90 m in Spiti, 6m in Painkhanda and almost negligible in Byans. Carnic is around 500 m thick in Spiti, around 245 m in Painkhanda, and still less in Byans. The thickness of Noric-Rhaetic sequence in Kashmir, Spiti-Zaskar, Painkhanda and Byans is 1300 m, 800 m, 600 m and 450 m respectively. The sequences of Zaskar-Spiti, Kinnaur-Babmanag-Painkhanda and Nepal are biostratigraphically and lithostratigraphically are more or less identical and have affinity with the Oman sections. The Byans section, sandwiched between Babmanag and Nepal, strangely is different and

is more akin to Timor (Indonesian Archipelago). Besides these anomalies, both the Carnian and Norian fossils are found within a thin bed in the Byans sector. (Pascoe, 1968).

The Triassic sedimentation in general commenced in a shallow marine environment and underwent rapid deepening. The deeper water conditions continued up to early Carnian. Thereafter, there was gradual shallowing of the basin, with flooding during early Norian and briefly in late Norian. The middle Norian is characterized by coral reefs in Tandi, Kashmir and Zaskar-Spiti. In early Rhaetic, beach conditions were achieved. Slight deepening led to Rhaetic-Liassic carbonate, which transgressed and overlapped some older formations. The cycle terminated in Lias. Sciunnach and Garzanti (2012) considered Middle Permian to Middle Triassic a drift sequence with low sedimentation rates; accumulation rates increased during the Carnian-Norian.

Jurassic-Cretaceous

The Rhaetic-Liassic sequence was submerged, which led to formation of hardground and a submarine break (Bhargava, 2008b; Krishna, 2017). The Kashmir part being located further south in shallower portion remained a positive area. The sedimentation commenced in mid-shelf environment with low rate of sedimentation and poor circulation with occasional hurricane and local turbidity currents/mudflows. In Bhutan, the basin seems to be closer to the coast and received plant detritus (Bhargava, 1995). Based on rich ammonoid fauna, Pascoe (1959) regarded the black shale sequence to range from Oxfordian to Valanginian. Berriasian-Valanginian elements are known from Spiti (Pathak and Krishna, 1993). Based on faunal affinities Krishna (1983) proposed a continuous Indo-East African province.

The Spiti Formation in Spiti-Zaskar-Garhwal is conformably succeeded by a sandstone sequence (Guimal Formation, Fig. 5). In Spiti, it has oolitic limestone in the basal part, in upper part it is glauconitic. Pathak (2007) marked Jurassic-Cretaceous boundary near the contact of the black shale (Spiti Formation) with the overlying sandstone (Guimal Formation) on the bases of last appearance of *Virgatosphinctes* and first appearance of *Odontodiscoceras* and/or *Neoccosmoceras*. Pandey and Pathak (2016, 2017) assign Berriasian – Early Aptian age range to the sandstone sequence. The sandstone (Guimal Formation) is interpreted as proximal turbidites in Utrakhand (Kumar et al, 1977) and Zaskar (Gaitani et al, 1983, 1986), and a shallow marine deposit in Spiti (Bhargava, 2008a).

Table 3. Tethyan Mesozoic sequences of different areas

Age	Kashmir (Bhargava, 2015)	Tandi (Srikantia & Bhargava, 1979)	Zaskar-Spiti-Kinnaur (Bhargava and Bassi, 1998)	Byans (Kumar et al., 1977)	Nepal (Dhital, 2017)	Bhutan (Bhargava, 1995)
Cretaceous			Ophiolites	Ophiolitic exotic block	Ophiolites	
			Chikkim Fm. Giumal Fm.	Chikkim Fm. Giumal Fm.	Upper flysch Giumal Fm.	
Jurassic		Dilburi Fm.	Spiti Fm.	Spiti Fm.	Spiti Fm.	Sha Fm.
Triassic	Vihi Gr.	Gushal Fm.	Lilang S.group	Riwalibagar Gr.	Triassic	Lingshi

The plate margin had become active by this time and sedimentation of shelf to off-basinal limestone and shale of Campanian/?Early Masstrichtian age ensued. This part is preserved only in Zaskar-Spiti. The limestone represents sedimentation in open shelf to off-basinal environment with occasional periods of restricted circulation.

The shale was deposited in outer shelf (Bhargava and Bassi, 1998). In the Zaskar area, it shows signs of shallowing in upper part.

Paleogene

Under the Kanji Group, Ganesan et al (1981) classified Kelcha (=Spanboth Formation of Gaetani et al. 1983) and Dumbur formations.

Gaetani et al (1983) divided Kelcha Formation in three members. Lower Member (140 m in Spanboth Chu section; 45 m in Dibling section) comprises nodular to planar, dark burrowed mudstone to bioclastic wackestone with *Omphalo-cyclusmacroporus*, followed by dark marly clay interbedded with bioclastic packstone. Trace fossil *Zoophycus* is common. West to east there is a reduction in the carbonate contents. It represents an environment transition from inner to outer shelf (Dibling area). The Middle Member is made up of white, brown, weathered cross-bedded quartzarenite increasing in thickness towards east (13 m in Spanboth section, 59 m in Dibling section), deposited in the mouth bar of fluvial dominated delta (Gaetani et al. 1986). The Upper Member in basal part consists of nodular, dark gray marly- bioclastic wackestone with local marly horizon, followed by dark gray, planar bedded, locally bioturbated bioclastic wackestone/packstone. The upper part is constituted of gray-greenish clay and marly clay with thin beds of bioclastic packstone and fine cross-bedded, locally graded siltstone. It was deposited in shallow, somewhat protected marine environment. The Kelcha Formation contains *Daviesina* assemblage; it is assigned a Thanetian to early Ypresian age.

The Dumbur Formation (Chunglung La Formation of Gaetani et al. 1983) comprises gray, marls with minor calcareous siltstone with parallel/cross-bedded lenses of rip-up clasts/bioclasts, overlain by greenish siltstone (56 m in Spanboth; 10 m in Dibling) showing poorly developed fining upward sequences capped by thin vuggy carbonate beds. The main sequence is made up of about 100 m thick fining up red beds, locally overlain by thin intraformational conglomerate or fine-grained sandstone, coarse siltstone showing climbing ripples. It is succeeded by red shale/claystone with local calcrete levels. The channel fill beds are generally two to three meters thick. The sandstone is composed of moderately sorted volcanic arenites with rich albitised plagioclase grains, volcanic quartz, hematite rip-up clasts, minor ophiolitic detritus and rare globotruncanid clasts. Diagenetic changes include early formation of tectosilicate cements (quartz-albite) and late replacement by authigenic calcite, chlorite and epidote. Deformation and recrystallisation of silicate along with epidote growth are more prominent in Spanboth area due to high diagenetic temperature beneath the ophiolitic klippe (Gaetani et al., 1983). It

Figure 5. Spiti-Guimal gradational contact near Domal village, Spiti.

represents ?late Ypresian-Lutetian (Eocene) age deposited in fluvial dominated deltaic system of a shallow lagoon in a tropical climate.

Ultramafic (Ophiolitic) rocks of the Shilakong /Spongton occur as klippe over the Paleocene-Eocene (Kanji Group) in the Zaskar area. Some fine-grained limestone is associated with the ultramafic klippe (Srikantia and Razdan, 1981). In Malla Johar and Nepal, the ophiolitic klippe rests over the Cretaceous rocks. In Malla Johar obducted ophiolite contains sediments with deeper water fauna. These nappes represent squeezed up ophiolitic material from the deep-sea regime along the Indus Tectonic Zone, obducted to form the highest allochthon in the Himalaya.

The Spiti valley preserves the best section and can termed as the type section of the Tethyan Himalaya. Climatostratigraphy, sea level curve and important events as deciphered in Spiti are summarized in Table 4.

The Tethyan sequence is folded in several anticlines and synclines. Several faults exist within the Zaskar part, most important being the Lingti-Sarchu (located along the Lingti-Sarchu streams) and Spiti (between Hal and Schling). The faults in the area are high angled, though some of them show minor sinuous outcrop pattern. Such faults are considered as basement controlled simulating listric folded faults (Bhargava and Bassi, 1998). However, Steck et al., (1993; 1998) consider these planes of dislocation as thrust planes involving considerable translation.

As compared to other sequences the rocks of the Lilang Supergroup are intensely folded. This feature is attributed to the detachment of the Lilang rocks at the base and also at the top from the carbonaceous Gungri and Spiti Formations respectively.

The last phase of the folding seems to be quite young as the folds formed during this period retain first order topography (Fig.6).

Basin Model

The Tethyan Basin, as per classification of Kingston et al. (1983) can be placed under Margin Sag Basin, formed along the passive margin of the Indian Plate due to rifting that thinned the crust in the late Precambrian. In view of clastics exceeding the volume of volcanic rocks, the rifting in Spiti-Zaskar part can termed as lithospheric-

Table 4. Climostratigraphy, sea level curve and important events recorded in the Spiti valley, which is the type section of the Tethyan Himalaya (modified after Bhargava and Bassi, 1998; Bhargava and Singh, 2019).

Figure 6. Anticlinal hill and synclinal valley—examples of first order topography formed by the last phase of folding.

activated (cf. Condie, 1982), however in the east in Bhutan, where volcanics (Singhe Volcanics) dominate, the rifting was mantle generated. The Tethyan basin witnessed three stages: i) late Precambrian-early late Cambrian basin due to rifting. This basin was obliterated on the onset of late Cambrian Kurgakhi orogeny (Bhargava et al., 2011). This tectonic phase developed highs and lows and divided the basin into several blocks, which exercised control not only the sedimentation (upto late Carboniferous) but also the deformation during the Himalayan orogeny (Bhargava et al., 1991), ii) development of the Ordovician (foreland?) basin in which initially the coarser clastics were deposited, it passed into the siliciclastic-carbonate succession that supported coral buildups (early Ordovician-middle Silurian) and iii) middle Permian rifting (Panjal Volcanics) with fossils of Tethyan affinity in the overlying sequences; the blocks that were formed during the Kurgakhi orogeny were reactivated and some new ones were created. The Tethyan basin developed in an active margin only in the late Cretaceous.

The lithofacies and isopach maps of the Palaeozoic sequences (Bhargava et al., 1991) of Spiti suggest that the basal axis was

parallel to the axis of the Spiti synclinorium. The litho-facies of all the formations outcropping at different locations across the depositional dip direction are more or less identical. The southernmost and northern most outcrops in paleotimes, prior to crustal shortening, must have been hundreds of kilometers apart. Identical facies of such distant outcrops in depositional dip direction is remarkable and reveals that the basin shelf was not only exceptionally broad but also had a very gentle slope (Bhargava, 2008b). Only in the lower Triassic, though the lithofacies are broadly identical, radiolarian appear in NE sections indicating relatively greater depth in that direction. This tilting can be related to rifting tectonics that caused outpouring of the Panjal Volcanics in the Permian time. Except Kashmir, the Permian/Triassic break is universally present. The Triassic sequence is essentially carbonate dominated. Followed by a short submarine break, the sedimentation took place in barred mid-shelf. Tethyan basin developed an active margin only in late Cretaceous. As the Indian and Asian plates collided, ophiolitic mass was obducted mainly over the Cretaceous sediments. In Malla-Johar the ophiolite carried deeper facies sediments of Triassic-Cretaceous age.

The Paleocene-Eocene sediments, though the basin might have been extensive, are confined to the Zaskar. The Paleocene sediments are shallow marine, while the Eocene sediments vary from fluvial to deltaic.

Summary

1. The Tethyan basin evolved in three stages: (i) Rifting in late Precambrian, (ii) late Cambrian-early Ordovician orogeny and (iii) rifting in early Permian. The basin was obliterated as a consequence of collision of Indian Plate with the Asian Plate.
2. The Cambrian-Eocene sequence is intervened by five subaerial unconformities; (i) Above the Cambrian, covering Furongian-earliest Ordovician (ii) Above the Wenlock, covering late Silurian and early Devonian, (iii) Above the Lipak Formation, covering late Carboniferous, (iv) Above Asselian, covering period up to Wuchiapingian, (v) Above the Cretaceous, covering late Massstrichtian-Danian.
3. The Tethyan sequence is also punctuated by two submarine breaks; (i) Above the Changhsingian-Wuchiapingian, covering late Wuchiapingian, (ii) Above the Liassic Tagling Formation, covering the late Oxfordian to a part of the Kimmeridgian.
4. Carbonate buildups are scattered from (i) Cambrian (stromatolitic), (ii) late Ordovician-Wenlock (algal, coral, stromatoporoids, bryozoa), (iii) middle Norian (coral, hydrozoa).
5. Beach/near shore environment were acquired during early Ordovician (Thango Formation, Middle Devonian (Muth Formation) and late Norian to early Rhaetian age (Nunuluka Formation).
6. Deeper water sediments were deposited during (i) Induan-Carnic (Mikkin-Chomuleformations), (ii) Albian-Campanian/early Massstrichtian (Chikkim Formation).
7. Fresh water facies are recorded during Permian in Kashmir and partly during the Eocene in Zaskar.

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Om N. Bhargava an Honorary Professor and INSA Honorary Scientist at Geology Department of Geology (CAS), Panjab University Chandigarh is concentrating on Palaeozoic and Triassic sequences of the Spiti Valley. Earlier while in the Geological Survey of India, he worked extensively in Himachal Pradesh, Bhutan and parts of Kashmir, and Ladakh. His main interest was regional geology, stratigraphy, tectonics and palaeontology. He recorded geoseismological observations of 1975 Kinnaur Earthquake and studied the causes and remedies of glacial lakes bursts in Bhutan as a part of environmental studies.

Birendra P. Singh is an Assistant Professor at the Department of Geology (CAS), Panjab University Chandigarh. His contributions pertain to the Cambrian trilobites, chronostratigraphy of the Cambrian Series 3, Stage 5, spatial and temporal distribution of trace fossils and their use in deciphering the palaeoenvironments of the Himalaya and Peninsular India. Recently he has focused on Ediacaran–Cambrian and the boundary between the Cambrian Series 2 and 3 in the Himalaya. He was the first to report Ordovician sediments in the Lesser Himalaya.