博 士 論 文 の 内 容 の 要 旨

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論文題目	The provenance and the paleo-environment of the Siwalik Group along the Muksar Khola section, eastern Nepal Himalaya (東ネパール，ムクサー川沿いに分布するシワリク層群の供給源と古環境)

（博士論文の内容の要旨）

The northward moving Indian Sub-continent collided with the Eurasian plate at around 50 Ma. This collision gave rise to the young mountain range known as the Himalaya which is extended 2400 km (approx.) from the Namche Barwa in the east to the Nanga Parbat in the west. After this collision continuous tectonic activities were recorded along this range due to the continuous force exerted by the Indian sub-continent resulting in further uplift and change in the topography. This change in the topography influenced the atmospheric circulation and simultaneously changed the climatic condition of this region. Continuous uplift and the change in the climatic condition resulted in weathering and erosion of the Himalaya which were transported by various axial river systems and deposited in the paleo foreland basin. Siwalik Group consists of these molasses sediments which were deposited in the foreland basin around the middle Miocene to Pleistocene. This Siwalik sediment preserves important information regarding the exhumation history of the Himalaya. At present, the Siwalik Group is uplifted as a southernmost hill range due to the activation of the Main Frontal Thrust and extends east to west co-linear to the main Himalayan range.

Various research suggests major mountain building phenomena and climate change along the Himalaya was observed around Miocene to early Pleistocene. Moreover, these studies also reveal exhumation of the Himalaya, as well as the climatic condition was not laterally synchronous, these phenomena were observed quite early in the western part compared to its eastern counterpart. Sedimentological studies of the Siwalik Group from Pakistan to the eastern Nepal Himalaya shows a change in the river system from meandering to braided which was controlled by the hinterland tectonics and climate. Therefore, these differences in the hinterland exhumation and climate should have been traced in the coeval depositional environment of the foreland basin. Similarly, the depositional environment of the foreland basin is also controlled by sea-level change and the Siwalik Groups along the Darjeeling-Sikkim, Bhutan and north-eastern Indian Himalaya, records deltaic to open marine deposits. Considering the proximity of the eastern Nepal Himalaya to the Darjeeling-Sikkim area, the Siwalik Group of the eastern Nepal Himalaya should also be influenced by the change in the sea level. Though hinterland tectonics has an influencing role in the foreland fluvial environment, the Miocene to early Pleistocene exhumation history of eastern Nepal Himalaya is little understood. Few studies were carried out along the Siwalik Group in the eastern part of the Nepal Himalaya. Among these studies, few tried to decipher the exhumation history based on the provenance change, but the limited data set of these studies either fail to properly define the exhumation history of the Himalaya or resulted in contradictions. Therefore, the present study is focused on the Siwalik Group along the Muksar Khola section in the eastern Nepal Himalaya and mainly deals with the establishment and classification of the lithostratigraphy, determination of the sediment provenance using multiple proxies and decipher the hinterland exhumation history and interpretation of the fluvial environment. The outcome of the present study is compared with the results of the other Siwaliks section to further disclose the Himalayan phenomena.

In the present study, the geological traverse was carried out and the route map along with the detailed sedimentological log of an entire section was prepared so that the boundary of the litho units could be precisely marked. This resulted in the classification of the Siwalik Group into the Lower Siwaliks, the Middle Siwaliks, and the Upper Siwaliks. The classification was done based on lithological characteristic and their proportion. Compared with the preexisting depositional age of the Muksar Khola section, the Lower Siwaliks was deposited before 10 Ma. This unit is mainly characterized by the domination of grey to olive black mudstone to siltstone which is interbedded with light-grey, very fine- to fine-grained sandstone. Apart from this lithology's the Lower Siwaliks in the present study also record the occurrence of the very thick succession of the intraformational conglomerate made up of grey to reddish-brown mudstone clast and medium- to coarse-grained sand matrix. The occurrence of such a thick succession of intraformational conglomerate is not reported in the Lower Siwaliks of any section till this study. The Middle Siwaliks was observed to be deposited in between 10.0–3.5 Ma and is characterized by the domination of sandstone. In the present study, this sub-group is divided into the lower member and the upper member based on the variation on the lithology and their thickness, its composition, and sandstone induration degree. The lower member deposited before 5.9 Ma consists of fine- to medium-grained "salt and pepper" textured sandstone with greenish-grey to olive-grey mudstone. This member also preserves the episodic occurrence of a very thick succession of amalgamated sandstone beds. Whereas the upper member is characterized by less indurated, light grey to white, medium- to very coarse-grained sandstone with grey, dark grey to black mudstone. This member shows a dramatic increase in the thickness of sandstone beds as well as an increase in the mudstone proportion compared to that of the lower member. The sandstone of this member lacks a "salt and pepper" texture whereas variegated mudstone with carbonate concretion is observed to increase. The Upper Siwaliks consists of a poorly sorted, clast supported conglomerate associated with very thickly bedded coarse- to very coarse-grained sandstone and very thickly bedded dull yellowish-grey to grey colour mudstone. Conglomerate clasts are subrounded to subangular and mostly consists of quartzite clast with few amounts of sandstones, mudstones and purple meta-sandstones and very coarse-grained to granule matrix.

For the study of the provenance, sandstone petrography, heavy mineral assemblage, chemical composition of detrital tourmaline and garnet, and Sr-Nd isotope analysis was carried out. In this study, the chemical composition of the detrital garnet was considered as the main provenance indicator and other proxies were used as a guide for minimizing the overinterpretation of the provenance shift. Among these proxies, sandstone petrography revealed recycle orogeny as the provenance similar to the results from the previous studies of the Siwalik Group. The heavy mineral assemblage showed a uniform zircon-tourmaline-rutile index and variation in the amount of the detrital kyanite+sillimanite and epidote. The chemical composition of detrital tourmaline shows a slight increase in the tourmaline composition from the igneous origin towards the younger succession. Detrital garnet chemical composition displayed wide variation in its composition regarding the depositional age. Similarly, Sr-Nd isotopic signature showed decreasing trend of the ΣNd(0) values towards the younger succession. These changes reveal a continuous shift of the provenance indicating simultaneous denudation of the Himalaya in the eastern Nepal Himalaya around the middle Miocene–Pliocene. First provenance change was observed around 10.6 Ma, both the chemical composition of detrital garnet and heavy mineral assemblage records this change as a shift of the provenance from shallow to the deeper part of the Higher Himalayan Crystalline. After 7.5 Ma the provenance was concentrated towards the Lesser Himalaya Sequence. This change was revealed from both the chemical composition of detrital garnet and heavy mineral assemblage as well as Sr-Nd isotopic signature. After 4.0 Ma, all the proxies collectively show a considerable increase in the sediments from both the shallow and the deeper part of the Higher Himalayan crystalline. This change in the provenance was controlled by the exhumation of eastern Nepal Himalaya, which was observed in two stages: first around 11.0 Ma due to activation of the Out-of-sequence Thrust known as the Sunkoshi Thrust and second after 4.0 Ma due to the formation of the duplex structure at the rear part of the Himalaya in the underlying Lesser Himalaya Sequence. The activation of the Sun Koshi Thrust uplifted the overlying Higher Himalayan crystalline resulting in the denudation of the shallow part and exposure of the deeper part around 10.6 Ma. Moreover, the continuation of this thrusting resulted in the exposure of the Lesser Himalaya Sequence around 7.5 Ma, but the occurrence of detrital heavy minerals like zoisite and more negative ΣNd(0) values only in the samples from younger succession suggests deeper part of the Lesser Himalaya Sequence was exposed only after late Pliocene to Pleistocene. Similarly, the formation of the duplex structure at the rear part of the Himalaya after 4.0 Ma resulted in the overall uplift of the overlying Higher Himalayan Crystalline enhancing the sediment supply from both of its shallow and the deeper part. The occurrence of volcanic lithic fragments and the uniform occurrence of heavy minerals like titanite and the Zircon-Tourmaline-Rutile index in this study reveals Tibetan Tethys Himalaya was a continuous source. Similarly, the occurrence of detrital chromian spinel in the older section and extreme Ca-rich garnet (Grs+And>90) in the younger section suggests Indus Tsangpo Suture Zone as a potential source. This provenance study reveals the chemical composition of detrital garnet is very suitable for determining the provenance in the Siwalik sediments as it traces every minor change that occurred in the Himalaya, which is hardly defined by other proxies. Similarly, a comparison of the Sr-Nd isotopic values of the present study with the previous study suggests these values are highly dependent on the grain size of the Siwalik sediments. Due to the hydraulic shorting of the sediments by the flowing water, different grain sizes carry varying ΣNd(0) values reflecting different provenance even in the sediments of coeval deposition age.

The fluvial environment was established based on lithofacies and architectural elements. Lithofacies were identified based on the grain size and texture of the beds and associated sedimentary structures. Architectural elements were classified based on the nature of the internal and external geometry of the beds and the bounding surfaces. Altogether 12 lithofacies and five facies associations were discovered in this study. These facies associations are interpreted as the flood plain dominated fine-grained meandering river (FA1), flood dominated overbank environment (FA2), Sandy meandering river (FA3), anastomosing river (FA4), and debris flow dominated braided river (FA6). The fluvial environment in the present study shows the domination of the meandering river system with the absence of a sandy braided river system. This study also reveals these fluvial environments are directly related to the contemporary Himalaya tectonics and climate, and the change in the sea level. The meandering river system and domination of the flood plain observed during the deposition of the Lower Siwaliks is regarded as the result of the low gradient of the foreland basin due to the absence of hinterland exhumation and rise in the sea level and week monsoon. Similarly, asymmetric subsidence due to the activation of the out-of-sequence thrust in the eastern Nepal Himalaya and starvation of sediment supply was regarded as the reason for the domination of the sandy meandering river system during the deposition of the lower member of the Middle Siwaliks. Anastomosing river system observed during the deposition of the upper member of the Middle Siwaliks is regarded to be controlled by the overall rise in the base level of the foreland basin due to the rise in the sea level and subsidence of the foreland basin as a result of the Main Boundary Thrust activation and the strengthening of the monsoon. Debris flow dominated braided river system in the present study reveals deposition in the inner fan very close to the hinterland and occurrence of the thick succession of sandstone and mudstone in between the conglomerate beds suggest either the mixing of small river fans in the basin of a big river system or the progradation of the gravel to a longer distance due to decrease in the subsidence rate of the foreland basin as the thrusting of the Main Boundary Thrust reduces due to the formation of the duplex structure at the rear of the Himalaya.

The occurrence of the intraformational conglomerate in the present study indicates the intensification of the monsoon in the eastern Nepal Himalaya occurred around 10.5 Ma. Its genesis suggests it was formed due to the collapse and deposition of the alluvial terrace in the overbank environment resulting from the large flood. This alluvial terrace was the result of a river incision formed due to the climatic factor where regression of the sea level enhanced the incision process. The variation in effects of sea-level change on the lithology as well as continuous increase in the sediment grain size in the younger succession suggests the foreland basin was continuously drifting towards the hinterland shifting the position of sediment deposition area. This continuous shifting of the location of the foreland basin towards the hinterland resulted in the coarsening upward succession in the sediments of the Siwaliks sediments. Further, comparing the result of the present study with the published result from the other sections shows a difference in the exhumation history of the eastern Nepal Himalaya compared to central-western Nepal and north-eastern Indian Himalaya. Central and western Nepal and north-eastern Indian Himalaya experienced the formation of the Lesser Himalayan duplex structure around 12–11 ma, in contrast in eastern Nepal Himalaya the thrust breached to the surface resulting in the Out-of-sequence thrust. Moreover, late exhumation of the Himalaya due to the formation of duplex structures in the eastern Nepal Himalaya was observed. This difference in the hinterland exhumation subsequently brought the difference in the fluvial environment of the foreland basin resulting in the domination of the meandering river system in the present study area.