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Sedimentary facies changes recorded in the Plio-Pleistocene Kathmandu Basin Group in the southern part of the Kathmandu Valley, Nepal

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ABSTRACT

Sedimentological study has revealed vertical and lateral sedimentary facies changes of the Plio-Pleistocene Kathmandu Basin Group in the southern part of the Kathmandu Valley, Nepal. The field observation and analyses of XRD, carbon content, C/N ratio and diatom fossils indicate that depositional environments of muddy sediments in this area can be classified into four categories: i) open lacustrine, ii) shallow lacustrine, iii) swamp-shallow lacustrine, and iv) environment strongly affected by fluvial system. Distributions of sedimentary facies in Lukundol, located in the southern margin of the Kathmandu Basin, show that fluvial facies dominant sequence in the Tarebhir Formation changed to a marginal lacustrine facies in the Lukundol Formation at 2.8 Ma, and a fluvial facies in the Itaiti Formation developed at 1 Ma following the deposition of the Lukundol Formation. In the area 5 km north of Lukundol, an open lacustrine facies in the Kalimati Formation dominated during the deposition of the Lukundol and Itaiti formations. The relation between the vertical sedimentary facies changes and palaeoclimate estimated from clay mineral crystallinity indicates: (1) the termination of fluvial facies dominant sequence at 2.8 Ma corresponds to the time where a wet climate turned to a drier climate, (2) fluvial environments developed under the wet climate and swamp-shallow lacustrine environments expanded under the dry climate during the deposition of the Lukundol Formation.

INTRODUCTION

The Kathmandu Valley, located in the central part of Nepal, has been pointed out as a suitable area for the studies of tectonic history and palaeoclimatic changes during the Himalayan orogeny (Yoshida and Igarashi 1984; Sakai et al. 2001, 2002). The Kathmandu Basin is one of the largest intermontane basins developed in the south of the Himalayan Range (Fig. 1), and is filled with unconsolidated sediments more than 500 m thick in the central part (Moribayashi and Maruo 1980), which range from Late Pliocene to present in age. Recent studies based on the data obtained from several boreholes, which were drilled in the central part of the basin, have provided new knowledge of the geological history of the Kathmandu Basin in the last 2.5 Ma (Fujii and Sakai 2001; Sakai 2001; Sakai et al. 2001, 2002). These studies suggest that an ancient lake, named the Palaeo-Kathmandu Lake (Fujii and Sakai 2001), had existed in the Kathmandu Valley since late Pliocene to Quaternary.

On the other hand, the southern part of the Kathmandu Valley, where the Plio-Pleistocene basin-fill sediments extensively crop out, is also an important area for the study of the geological history of the Kathmandu Basin (Fig. 1 and 2). The depositional age and environment of the basin-fill sediments in this area have been revealed by the studies of magnetostratigraphy (Yoshida and Igarashi 1984; Yoshida and Gautam 1988), pollen analyses (Yoshida and Igarashi 1984; Igarashi et al. 1988), vertebrate fossils (Fort and Gupta 1981; Dongol 1985, 1987) and sedimentology (Sakai et al. 2002). However, many of the studies have dealt with limited areas or exposures, and few publications have dealt with extensive area in the southern part of the Kathmandu Valley. Furthermore, there is a need for a detailed sedimentological study involving not only coarse sediments such as gravel and sand beds but also muddy sediments to link up with the central part of the basin where boreholes have been drilled.

This paper reports sedimentary facies changes of the Plio-Pleostocene basin-fill sediments in the southern part of the Kathmandu Valley based on sedimentological analyses of the muddy sediments and discusses the relation between

Fig. 1: Location map of the study area

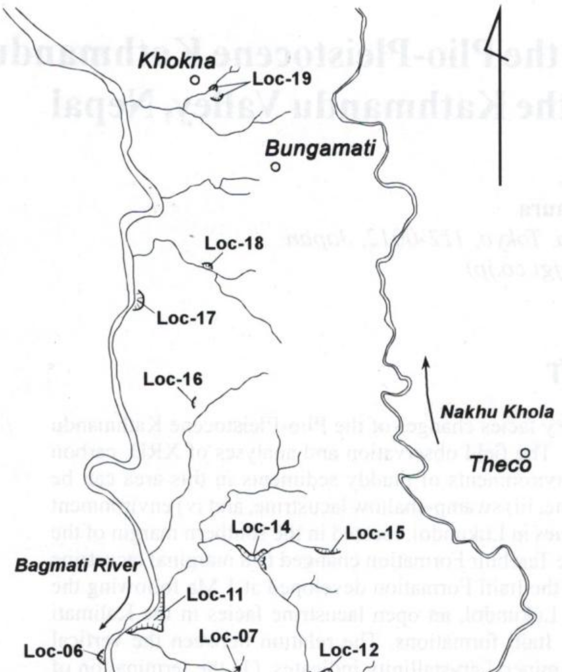

Fig. 2: Location of columnar sections as shown in Fig. 3

facies change and palaeoclimate estimated from clay mineral crystallinity.

STRATIGRAPHY

The basin-fill sediments, named the Kathmandu Basin Group, are divided into four formations; the Tarebhir, Lukundol, Itaiti and Kalimati formations (Sakai 2001). They are dipping to northeast with a dip ranging from 10 to 12 degrees along the Khahare Khola, and with an angle gradually decreasing to the north.

Around Lukundol village, which is located in the southern margin of the Kathmandu Basin, the basin-fill sediments are divided into three divisions (Fig. 2 and 3). The lower part, the Tarebhir Formation of Sakai (2001), is dominated by gravel and sand with minor muddy sediments. Gravel beds are composed of imbricated and fining-upward boulders and pebbles of granite, quartzite, black shale and phyllite. Cross-bedded sand beds are composed of medium to coarse sands of quartz, plagioclase, muscovite and tourmaline with small amounts of granules and pebbles. The lowermost horizon of the Tarebhir Formation is assigned to the middle Gauss Epoch (about 3 Ma) based on the magnetostratigraphic study of Yoshida and Gautam (1988). According to Sakai et al. (2001), the Tarebhir Formation varies drastically in thickness from 350 m, at the margin of the valley, to 1 m, within a distance of 1 km.

The middle part, the Lukundol Formation of Sakai (2001), is mainly composed of an alternation of medium to coarse sand beds and silt to clay beds intercalating lignite beds. Vertebrate fossils such as *Elephas cf. hysudricus, Rhinoceros cf. sivalensis* (Dongol 1985, 1987) are found in the lignite beds. The sand and gravel beds show the same lithological characteristics as those of the Tarebhir Formation. The Lukundol Formation is 120 m thick and the lowermost horizon is assigned to the middle Gauss Epoch (2.8 Ma) based on the magnetostratigraphic study of Yoshida and Gautam (1988).

The upper part corresponds to the Itaiti Formation of Sakai (2001). Although the Itaiti Formation is characterized by a gravel dominant sequence, the composition of detrital grains is different from those of the Tarebhir and Lukundol formations. Granitic gravel and muscovite flakes, which are common in the Tarebhir and Lukundol formations, are not found in this formation (Sakai et al. 2002). Gravel beds are composed of imbricated and fining-upward boulders and pebbles of meta-sandstone and limestone. Yellowish to brownish grey, partly cross-bedded fine to very fine sand beds and silt-silty clay beds are intercalated with the gravel beds. The Itaiti Formation is more than 160 m thick and the lowermost horizon is assigned to the top of the Jaramillo Event (0.99 Ma) by the magnetostratigraphic study of Yoshida and Gautam (1988).

In comparison with the southern area, where thick sand and gravel beds are distributed, the muddy sediments are dominant around Bungamati village, 5 km north of Lukundol village (Fig. 2 and 3). This mud dominant sequence corresponds to the Kalimati Formation of Sakai (2001).

DEPOSITIONAL ENVIRONMENTS OF THE MUDDY SEDIMENTS

Various kinds of muddy sediments ranging from late Pliocene to Pleistocene in age are distributed in the southern part of the Kathmandu Valley. For the purpose of interpretation of detailed vertical and lateral sedimentary facies changes in the study area, it is necessary to determine the depositional environments of the muddy sediments. The author classified the muddy sediments into five lithofacies types and estimated their depositional environments by the field observation and analyses in the laboratory.

Lithofacies classification

The muddy sediments in the study area are classified into five lithofacies types as follows:

(1) M-1: Parallel laminated silt. Each lamina is light grey or grey and ranges from 1 to 5 mm in thickness.

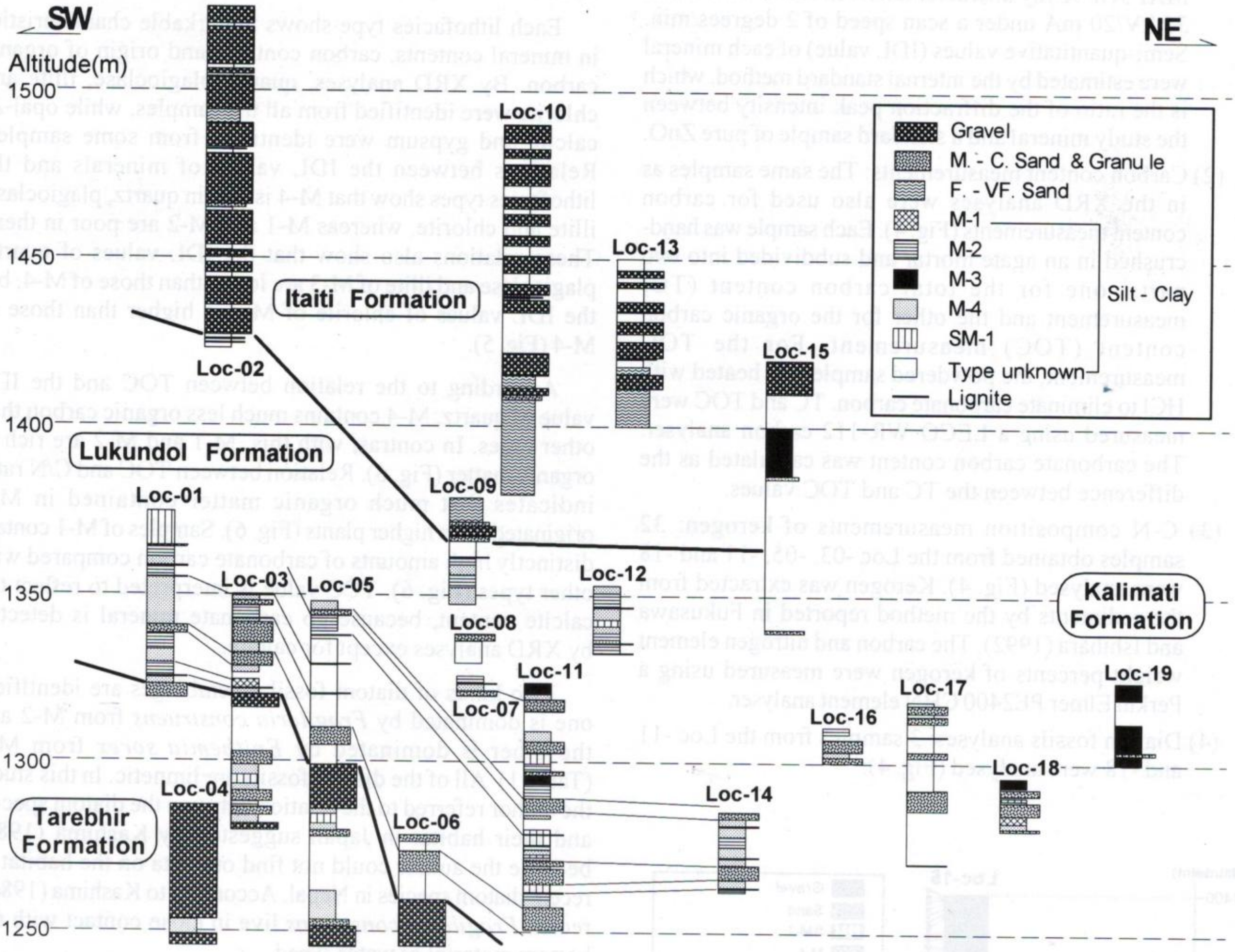

Fig. 3: Columnar sections in the study area (see Fig. 2 for locations).

Abundant opercula of gastropods are found parallel to the lamina.

(2) M-2: Parallel laminated silty clay. Each lamina shows various colours such as light grey, grey, dark grey and black, and alternate rhythmically, ranging from 1 to 5 mm in thickness, with abundant plant fragments.

(3) M-3: Massive or broad banded dark grey and black, well-sorted silty clay to clay. Parallel laminated beds with light grey silty clay are also occasionally found. Each bed ranges from 10 to 200 cm in thickness. M-3 yields some shell fragments, but few plant fragments.

(4) M-4: Massive and poor-sorted silt to fine sand. Each bed is grey to dark grey, and contains abundant mineral fragments such as muscovite, quartz and feldspar and also contains plant fragments.

(5) SM-1: Alternation of cross-laminated light grey, fine to medium sand beds and massive dark grey silt beds, ranging from 5 to 30 cm in thickness. Sand beds thicken upward and grade into massive medium sand beds.

Materials and methods of analyses

Analyses of minerals, organic carbon and fossils in the sediments provide a lot of information for making a clear characterization of lithofacies types. X-ray diffraction (XRD) analyses enable qualitative and semi-quantitative evaluation of minerals. Carbon content measurements indicate the quantitative values of organic matter and carbonate carbon. The carbon and nitrogen composition of kerogen (insoluble organic matter) is a good index to estimate the origin of organic matter, because the carbon to nitrogen ratio (C/N ratio) of terrestrial higher plants composed of lignin is higher than that of lower plants such as algae. Diatom fossil analyses are available to estimate their habitat in comparison with recent diatom species. The materials and methods of the analyses are described below.

(1) XRD analyses: 121 samples obtained from the Loc - 03, -05, -11, -15 and - 18 were analysed by XRD (Fig. 4). Diffraction profiles were made from 2 to 60 degrees (= 2θ) for each sample using a MacScience

MXP3HF X-ray diffractometer. All scans were run at 35 kV/20 mA under a scan speed of 2 degrees/min. Semi-quantitative values (IDL value) of each mineral were estimated by the internal standard method, which is the ratio of the diffraction peak intensity between the study mineral and a standard sample of pure ZnO.

(2) Carbon content measurements: The same samples as in the XRD analyses were also used for carbon content measurements (Fig. 4). Each sample was hand-crushed in an agate mortar and subdivided into two parts, one for the total carbon content (TC) measurement and the other for the organic carbon content (TOC) measurement. For the TOC measurement, the powdered sample was heated with HCl to eliminate carbonate carbon. TC and TOC were measured using a LECO WR-112 carbon analyser. The carbonate carbon content was calculated as the difference between the TC and TOC values.

(3) C-N composition measurements of kerogen: 32 samples obtained from the Loc -03, -05, -11 and -18 were analysed (Fig. 4). Kerogen was extracted from the sediments by the method reported in Fukusawa and Ishihara (1992). The carbon and nitrogen element weight percents of kerogen were measured using a Perkin Elmer PE2400 CHN element analyser.

(4) Diatom fossils analyses: 3 samples from the Loc -11 and -18 were analysed (Fig. 4).

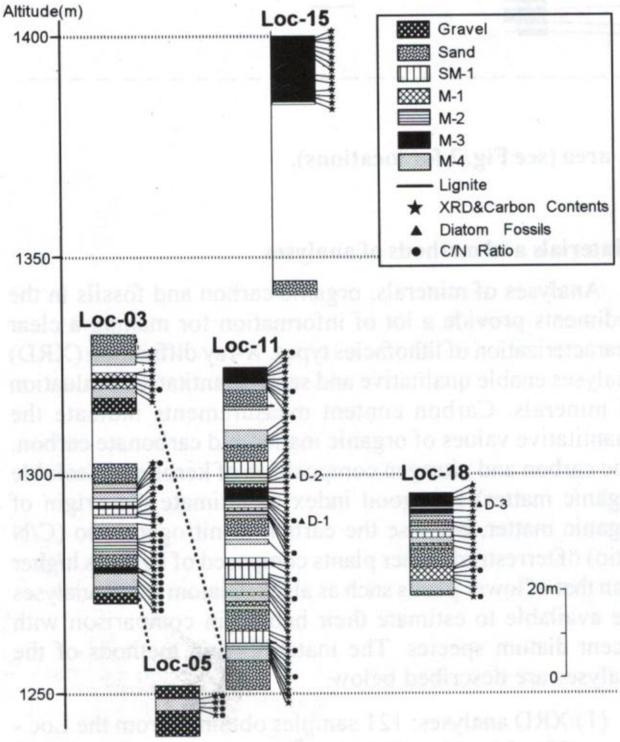

Fig. 4: Columnar sections showing horizons of samples collected for analyses (see Fig. 2 for the locations).

Results of analyses

Each lithofacies type shows remarkable characteristics in mineral contents, carbon contents and origin of organic carbon. By XRD analyses, quartz, plagioclase, illite and chlorite were identified from all the samples, while opal-A, calcite and gypsum were identified from some samples. Relations between the IDL values of minerals and the lithofacies types show that M-4 is rich in quartz, plagioclase, illite and chlorite, whereas M-1 and M-2 are poor in them. These relations also show that the IDL values of quartz, plagioclase and illite of M-3 are lower than those of M-4, but the IDL values of chlorite of M-3 is higher than those of M-4 (Fig. 5).

According to the relation between TOC and the IDL value of quartz, M-4 contains much less organic carbon than other types. In contrast with this, M-1 and M-2 are rich in organic matter (Fig. 6). Relation between TOC and C/N ratio indicates that much organic matter contained in M-4 originated from higher plants (Fig. 6). Samples of M-1 contain distinctly high amounts of carbonate carbon compared with other types (Fig. 6). TCC value is interpreted to reflect the calcite content, because no carbonate mineral is detected by XRD analyses except for calcite.

Two kinds of diatom fossil assemblages are identified, one is dominated by *Fragilaria construens* from M-2 and the other is dominated by *Epithemia sorex* from M-3 (Table 1). All of the diatom fossils are limnetic. In this study, the author referred to the relation between the diatom species and their habitat in Japan suggested by Kashima (1986) because the author could not find out data on the habitat of recent diatom species in Nepal. According to Kashima (1986), recent *Fragilaria construens* live in close contact with the bottom material or water-weed.

Depositional environments of lithofacies types

According to the field observation and analyses of minerals, organic carbon and fossils, it is revealed that the muddy sediments in the study area have been deposited under the various kinds of environments, as described below.

M-2 is interpreted as swamp-shallow lacustrine deposits. Remarkably low amounts of minerals such as quartz and plagioclase, and rhythmic alternation of silty clay indicate a calm environment with a little detritus influx. A low C/N ratio indicates that most of plant fragments have not originated from higher plants derived with detritus. Diatom fossil assemblage also shows that M-2 was deposited in a shallow depth. M-1 is interpreted as shallow lacustrine deposits with less terrestrial influence than M-2. This type has similar characteristics to M-2, such as low amounts rock-forming minerals and low C/N ratio. M-1 also has been deposited in an environment with a little detritus influx. However, M-1 contains abundant opercula of gastropods and less plant fragments than M-2. M-3 is interpreted as open lacustrine deposits. This type is composed of well-sorted fine grains such as silty clay or clay with few plant fragments. Each bed is rather thick in comparison with the other types and some

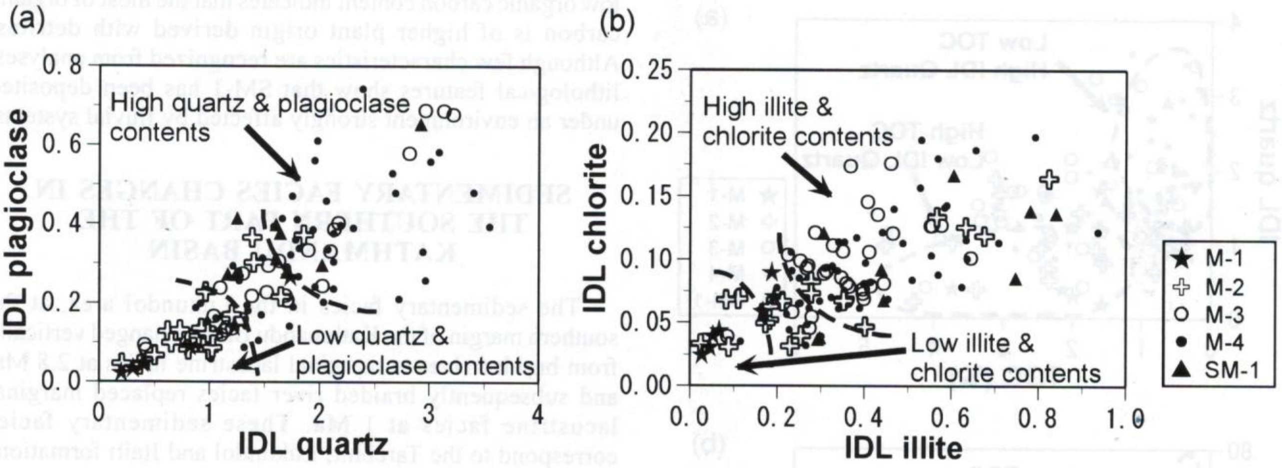

Fig. 5: (a) Diagram showing the relations between quartz and plagioclase content (b) Diagram showing the relations between illite and chlorite content. Mineral contents are represented by semi-quantitative value (IDL value) estimated by XRD.

Table 1: Diatom fossils from D-1, -2 and –3 samples. See Fig. 4 for the localities of samples.

	D-1	**D-2**	**D-3**
Achnanthes lanceolata (BRÉBISSON) GRUNOW			5
Achnanthes grischuna (WÜTHRICH)			2
Amphora ovalis (KÜTZING) KÜTZING	1		
Aulacosira glanulata (EHRENBERG) SIMONSEN	3	1	43
Cocconeis placentula (EHRENBERG)	3	1	11
Cymbella cistura (HEMPRICH) GRUNOW		6	
Cymbella silesiaca (BLEISCH)			5
Cymbella tumida (BRÉBISSON) VAN HEURCK		1	
Epithemia adnata (KÜTZING) BRÉBISSON			5
Epithemia sorex (KÜTZING)	16	5	77
Eunotia sp.			1
Fragilaria brevistriata GRUNOW		1	
Fragilaria capucima DESMAZIÉRES			10
Fragilaria construens (EHRENBERG) HUSTEDT	166	184	23
Fragilaria ulma (NITZSCH) LANGE-BERTALOT			8
Gomphonema tenue FRICUEI			1
Navicula mericana EHRENBERG		2	
Navicula spp.			3
Nitzschia sp.			2
Rhopalodia gibba (EHRENBERG) O.F. MÜLLER	1		
Total number of valves	**190**	**201**	**196**

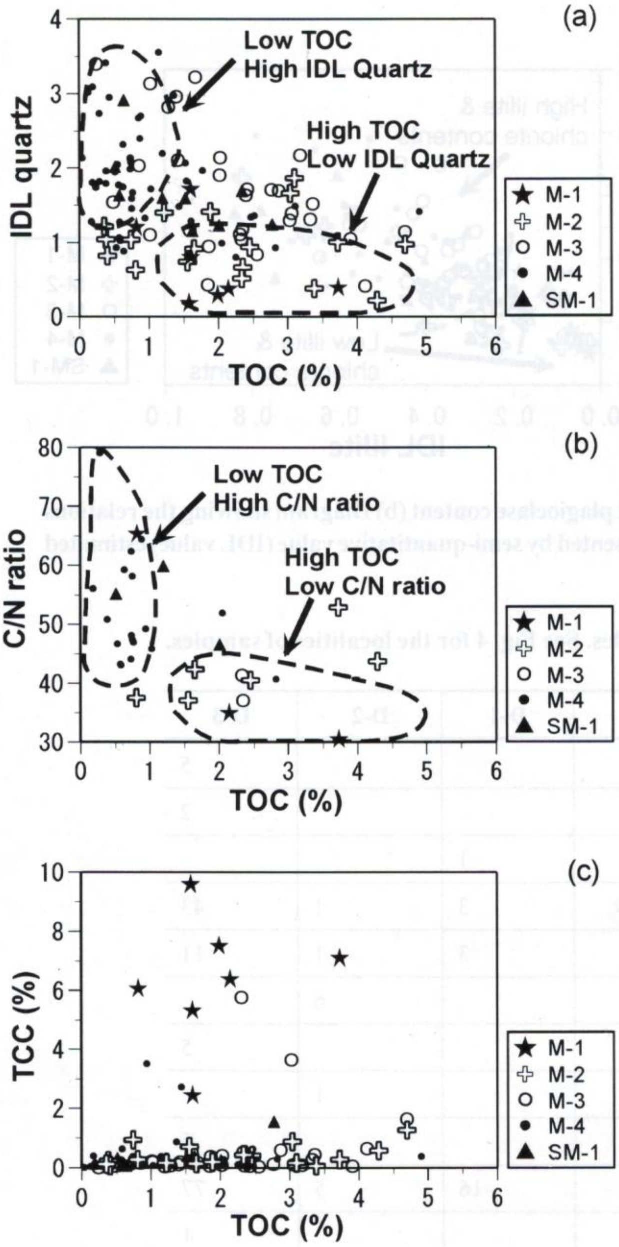

Fig. 6: (a) Diagram showing the relation between organic carbon and quartz content; (b) Diagram showing the relation between organic carbon content and C/N ratio; and (c) Diagram showing the relation between organic carbon and carbonate carbon content.

of beds are banded. These characteristics indicate that the sedimentary environment was calm and remote from terrestrial areas. Diatom fossil assemblage is dominated by *Epithemia sorex*. Although the habitat of *Epithemia sorex* is unknown, this assemblage is different from that of M-2. It is interpreted that M-4 has been deposited under an environment strongly affected by fluvial systems. In many cases M-4 overlies or underlies the sand and gravel beds, and is rich in rock-forming minerals. A high C/N ratio and low organic carbon content indicates that the most of organic carbon is of higher plant origin derived with detritus. Although few characteristics are recognized from analyses, lithological features show that SM-1 has been deposited under an environment strongly affected by fluvial systems.

SEDIMENTARY FACIES CHANGES IN THE SOUTHERN PART OF THE KATHMANDU BASIN

The sedimentary facies in the Lukundol area, at the southern margin of the Kathmandu Basin, changed vertically from braided river to marginal lacustrine facies at 2.8 Ma, and subsequently braided river facies replaced marginal lacustrine facies at 1 Ma. These sedimentary facies correspond to the Tarebhir, Lukundol and Itaiti formations in ascending order (Fig. 7).

The Tarebhir Formation is dominated by coarse gravel and sand. According to Sakai et al. (2002), these coarse sediments show braided river and alluvial fan facies. The composition of detrital grains and the palaeocurrent directions indicate they were transported from the east and the northwest (Sakai et al. 2002). The muddy sediments are dominated by M-4 and SM-1, which have been deposited under an environment strongly affected by the fluvial system. During deposition of the Tarebhir Formation, a fluvial system flowing to the south developed in the Lukundol area.

The Lukundol Formation, overlying the Tarebhir Formation, is composed of sand beds and the silt-clay beds. Frequent appearances of swamp-shallow lacustrine deposits of M-2 in the Lukundol Formation indicate that this area was located in the southern margin of the Palaeo-Kathmandu Lake. The sedimentary facies change from braided river, and alluvial fan facies to marginal lacustrine facies occurred at 2.8 Ma, the boundary between the Tarebhir and Lukundol formations. Sakai et al. (2002) has proposed that the coarse sediments are fluvial deposits and that detritus have been derived from the same sources as those of the Tarebhir Formation.

The Itaiti Formation is dominated by coarse gravel and sand. They are braided river and alluvial fan deposits (Sakai et al. 2002). According to Sakai et al. (2002), the composition of detrital grains and the palaeocurrent direction in the Itaiti Formation, which is different from underlying the Lukundol and Tarebhir formations, indicate that these coarse sediments were transported from the south and that a depositional system change occurred at 1 Ma, the boundary between the Lukundol and Itaiti formations.

The open lacustrine facies of M-3 is dominant in the Bungamati area, about 5 km north of Lukundol village (Fig. 7). Because of a few data available for correlation it is difficult to clarify the detailed stratigraphic position of the open lacustrine facies in the Kalimati Formation. However, these sediments are roughly correlated to the same horizon as the Lukundol and Itaiti formations. Intercalation of open

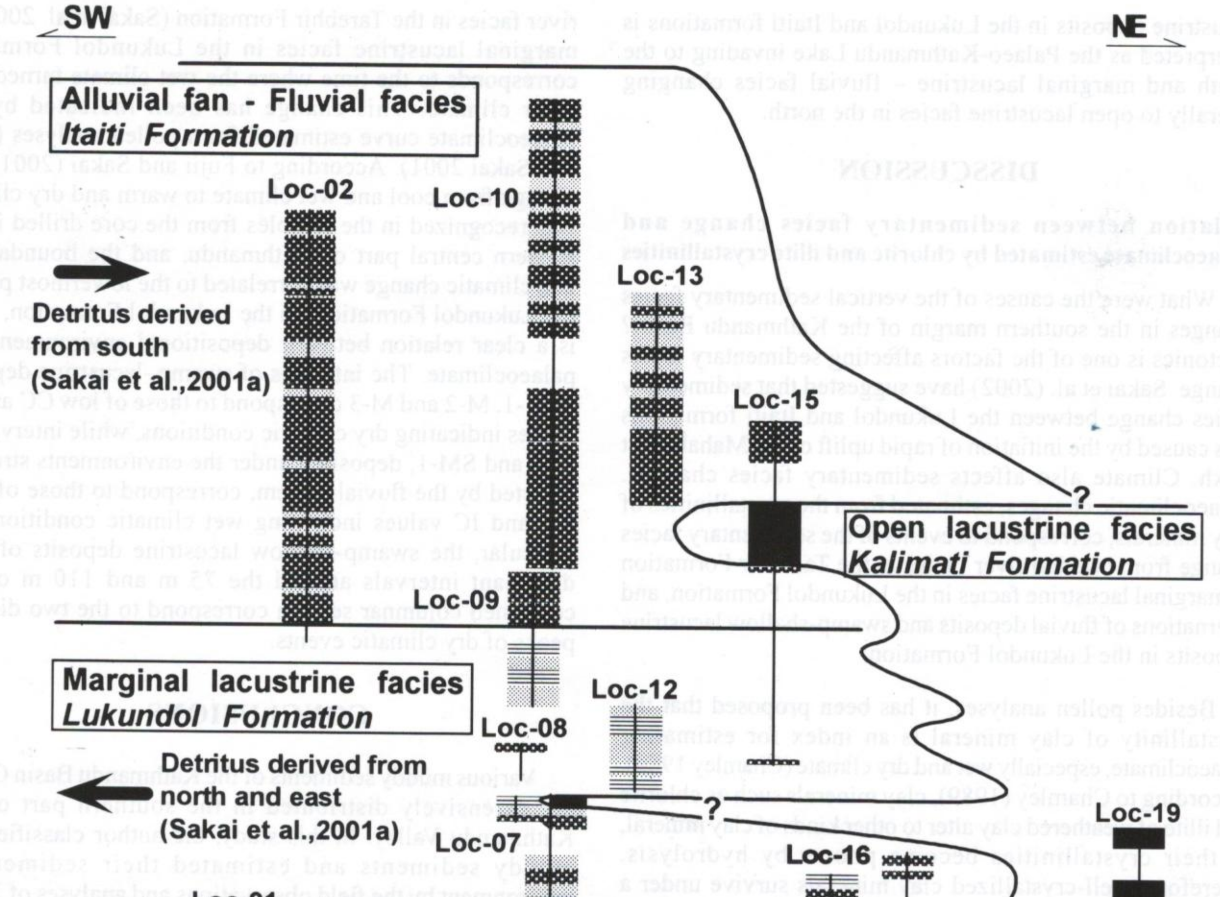

Fig. 7: Vertical and horizontal distributions of the sedimentary facies in the southern part of the Kathamndu Valley

lacustrine deposits in the Lukundol and Itaiti formations is interpreted as the Palaeo-Kathmandu Lake invading to the south and marginal lacustrine – fluvial facies changing laterally to open lacustrine facies in the north.

DISSCUSSION

Relation between sedimentary facies change and palaeoclimate estimated by chlorite and illite crystallinities

What were the causes of the vertical sedimentary facies changes in the southern margin of the Kathmandu Basin? Tectonics is one of the factors affecting sedimentary facies change. Sakai et al. (2002) have suggested that sedimentary facies change between the Lukundol and Itaiti formations was caused by the initiation of rapid uplift of the Mahabharat Lekh. Climate also affects sedimentary facies changes. Palaeoclimatic changes, estimated from the crystallinities of clay minerals, correspond to events of the sedimentary facies change from braided river facies in the Tarebhir Formation to marginal lacustrine facies in the Lukundol Formation, and alternations of fluvial deposits and swamp-shallow lacustrine deposits in the Lukundol Formation.

Besides pollen analyses, it has been proposed that the crystallinity of clay mineral is an index for estimating palaeoclimate, especially wet and dry climate (Chamley 1989). According to Chamley (1989), clay minerals such as chlorite and illite of weathered clay alter to other kinds of clay mineral, or their crystallinities become poorer by hydrolysis. Therefore, well-crystallized clay minerals survive under a dry climate, but alter to poor-crystallized minerals under a wet climate due to hydrolysis. In this study, the author evaluated the crystallinities of chlorite and illite in the muddy sediments in the Tarebhir and Lukundol formations. Chlorite crystallinity is represented by the values of the chlorite crystallinity index (CC value: $\Delta°2\theta$) that is the half-height width of the 7.10 Å chlorite peak. Illite crystallinity is represented by the values of the illite crystallinity index (IC value: $\Delta°2\theta$) that is the half-height width of the 10 Å illite peak. Smaller CC or IC values indicate a high degree of crystallinity. Samples for measurements of CC and IC values were obtained from Loc -03, -05 and -11. The samples were hand-crushed and separated by hydraulic elutriation and centrifugal separation, and air-dried specimens were prepared by pipette mounting. Diffraction profiles were made from 2 to 27 degrees ($=2\theta$), five times for each sample, using a MacScience XP3HF X-ray diffractometer. All scans were run at 35 kV/20 mA with a 2 degrees/minute scan speed.

The relation between the vertical sedimentary facies changes and palaeoclimate indicates that a fluvial environment was developed under a wet climate, whereas the swamp-shallow lacustrine facies expanded under the dry climate during the deposition of the Tarebhir and Lukundol Formations in the southern margin of the Kathmandu Basin (Fig. 8). The CC and IC values in the Tarebhir Formation are rather higher than those in the Lukundol Formation. It is interpreted that the sedimentary facies changes from braided river facies in the Tarebhir Formation (Sakai et al. 2002) to marginal lacustrine facies in the Lukundol Formation corresponds to the time where the wet climate turned to a drier climate. This change has been indicated by the palaeoclimate curve estimated from pollen analyses (Fujii and Sakai 2001). According to Fujii and Sakai (2001), the change from cool and wet climate to warm and dry climate was recognized in the samples from the core drilled in the western central part of Kathmandu, and the boundary of this climatic change was correlated to the lowermost part of the Lukundol Formation. In the Lukundol Formation, there is a clear relation between depositional environment and palaeoclimate. The intervals of swamp–lacustrine deposits of M-1, M-2 and M-3 correspond to those of low CC and IC values indicating dry climatic conditions, while intervals of M-4 and SM-1, deposited under the environments strongly affected by the fluvial system, correspond to those of high CC and IC values indicating wet climatic conditions. In paticular, the swamp-shallow lacustrine deposits of M-2 dominant intervals around the 75 m and 110 m of the combined columnar section correspond to the two distinct peaks of dry climatic events.

CONCLUSIONS

Various muddy sediments of the Kathmandu Basin Group are extensively distributed in the southern part of the Kathmandu Valley. In this study, the author classified the muddy sediments and estimated their sedimentary environment by the field observations and analyses of XRD, carbon content, C/N ratio and diatom fossils. Sedimentary environments of various muddy sediments are classified into four categories; open lacustrine, shallow lacustrine, swamp-shallow lacustrine and environments strongly affected by fluvial systems.

The distribution of the muddy sediments and coarse gravel and sand indicate that the fluvial facies dominant sequence in the Tarebhir Formation changed to marginal lacustrine facies in the Lukundol Formation at 2.8 Ma, and subsequently the fluvial facies in the Itaiti Formation replaced it the marginal lacustrine facies at 1Ma in the southern margin of the Kathmandu Basin. In the north, the open lacustrine facies in the Kalimati Formation dominated during the deposition of Lukundol and Itaiti formations. Intercalations of open lacustrine deposits in the Lukundol and Itaiti formations indicate the invasion of the Palaeo-Kathmandu Lake to the south.

There is a clear relationship between palaeoclimate estimated from crystallinities of the clay minerals and the vertical sedimentary facies change in the southern margin of the Kathmandu Basin. The termination of fluvial facies dominant sequence at 2.8 Ma corresponds to the time where a wet climate has turned to a drier climate. During deposition of the Lukundol Formation, fluvial environments developed under the wet climate whereas swamp-shallow lacustrine environments expanded under the dry climate.

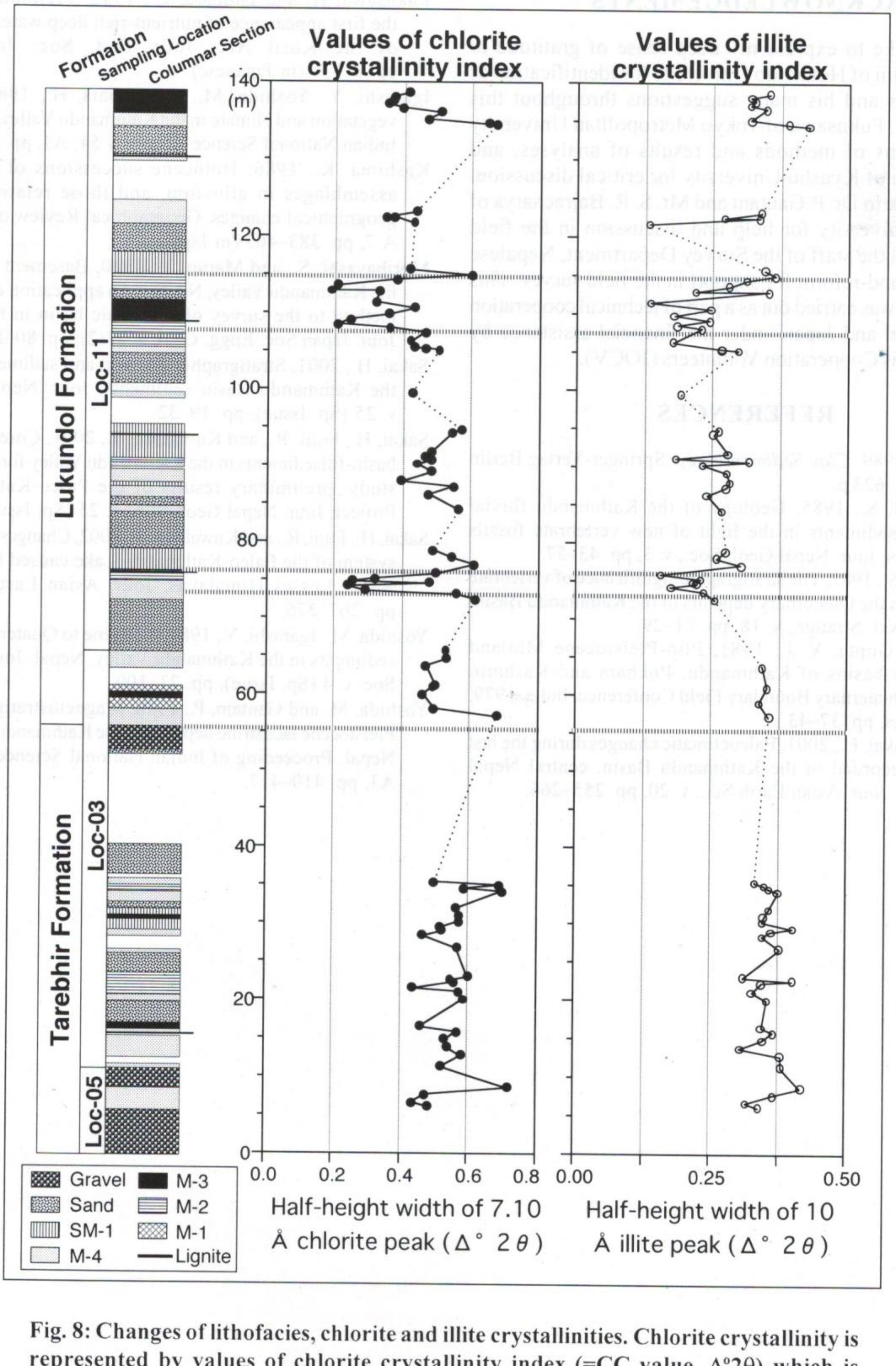

Fig. 8: Changes of lithofacies, chlorite and illite crystallinities. Chlorite crystallinity is represented by values of chlorite crystallinity index (=CC value, Δ°2θ) which is half-height width of the 7.10 Å chlorite peak. Illite crystallinity is represented by values of illite crystallinity index (=IC value, Δ°2θ) which is half-height width of the 10.00 Å illite peak. A smaller half-height width indicates well-crystallinity.

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