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Stratigraphic division and sedimentary facies of the Kathmandu Basin Group, central Nepal

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ABSTRACT

On the basis of core drillings for academic purpose and surface geological survey in the Kathmandu Basin, I propose separate stratigraphic schemes of the basin-fill sediments for the southern, central and northern part of the basin. In the south, the late Pliocene to Pleistocene Kathmandu Basin Group is divided into three formations: the Tarebhir, redefined Lukundol and Itaiti Formation in ascending order. The Tarebhir Formation is mainly composed of fluvial gravel and sand beds deposited by the Proto-Bagmati River. The Lukundol Formation is mainly comprised of carbonaceous muddy sediments showing their deposition in marginal shallow lake environments. The uppermost fluvial sandy beds of the Lukundol Formation are overlain by boulder beds of alluvial fan deposit, which was newly named as the Itaiti Formation. The continuous drill core and previous drill data obtained from the central part of the basin has allowed to lithologically divide the sediments into three: the Bagmati, Kalimati and Patan Formation from bottom to top, respectively. The Bagmati Formation is the northern continuation of the Tarebhir Formation, and overlain by the 200 to 400 m thick lacustrine Kalimati Formation. The basal part is characterized by lignite and bituminous pebbly mudstone beds, which is named as the Basal Lignite Member.

On the other hand, in the north and central parts, sand dominant lacustrine delta deposits called the Gokarna and Thimi formations are accumulated over the Kalimati Formation. In the central part of the valley, both Kalimati and Thimi formations are disconformably overlain by the mainly fluvial Patan Formation.

The Palaeo-Kathmandu Lake has existed since 2.8 Ma in the central part of the Kathmandu Valley, and it was existing till about 10 kyr B.P. after which it finally drained out. However, in the south, there are no open lacustrine deposits, and marginal lacustrine deposits of the Lukundol Formation were directly overlain by alluvial fan deposits spread over the northern slope of the Mahabharat Lekh.

INTRODUCTION

The basin-fill sediments of the Kathmandu Valley have been studied from various view points since mainly 1970's. Fort and Gupta (1981) and Boesh (1974) carried out geomorphological studies and discussed on the morphogenesis of the river terrace and fault topography. Dongol (1985, 1987) reported occurrence of vertebrate fossils from the Lukundol Formation and briefly described its lithology.

The first comprehensive works on the basin-fill sediments of the valley were carried out by Yoshida and Igarashi (1984); Igarashi et al. (1988); Yoshida and Gautam (1988); as a part of research project entitled "Study on the crustal movements in the Nepal Himalayas". They compiled geomorphic map of the Kathmandu Valley and gave the name to each geomorphic surface. Yoshida and Igarashi (1984) proposed the stratigraphic division of the fluvial and lacustrine sediments on the basis of surface geological survey and palaeomagnetic studies, and estimated that the age of the Lukundol Formation is dated back to the Gauss Chron, i.e. older than 2.58 Ma. Furthermore, palynological studies were undertaken by Igarashi, and palaeoclimatic record of the valley was outlined (Igarashi et al. 1988).

A gravitational survey of the Kathmandu Basin was done by Moribayashi and Maruo (1980) and Maruo et al. (1999), and they estimated the maximum thickness of the basin fill sediments at more than 650 m. Recent activities of active faults in and around the valley were studied by Yagi et al. (2000) and Saijo et al. (1995). They estimated an average vertical displacement rate of 1 mm/yr on the Kathmandu South Fault running along the southern margin of the Kathmandu Basin (Yagi et al. 2000).

The Kathmandu Basin sediments have considerable potential for the exploration of natural gas and lignite, and several exploratory studies were carried out by the Department of Mines and Geology under international cooperation projects (SILT Consult 1996; Natori et al. 1980 a, b). Several compilations of drill-well data were undertaken for the purpose of groundwater exploration and engineering geological studies (Kharel et al. 1998; Katel et al. 1996; Koirala et al. 1993). In 1998, the first engineering and environmental geological map of the Kathmandu Valley (1:50,000) was published by the Department of Mines and Geology (Shrestha et al. 1998) under the technical cooperation with Federal Institute for Geosciences and Natural Resources, Hannover, Germany.

Before the academic drilling was done in 2000, a precursory study of the basin-fill sediments was also carried out by our team. The sedimentological and palynological studies of slimes taken from a 284 m deep drill-well (drill-well No. JW-3, Fig. 1) and surface geological studies in the Kathmandu Valley showed that the sediments have a great potential as an archive of palaeoclimate and tectonic history of the Central Himalaya (Fujii and Sakai 2002, Sakai et al. 2002, Kuwahara et al. in press).

These previous studies, however, face several important problems on the stratigraphic division and nomenclature of the formations, mainly because of lack of information on the subsurface geology and insufficient description on definition of each formation. In this paper, we review the problem of the stratigraphic divisions, and propose new divisions based on the academic drillings and detailed stratigraphic studies on the Lukundol Formation and Thimi Formation. It is hoped that this new stratigraphic scheme will help to clear the existing confusion and provide a sounder stratigraphic base for the Kathmandu Basin sediments.

PROBLEMS ON STRATIGRAPHIC DIVISION

The problems on the previous stratigraphic divisions of the basin-fill sediments of the Kathmandu Valley are summarized as follows:

- Ambiguous definition of formation names and insufficient description on the characteristic lithology and formation boundary

- Loosely used formation names based on only similarity of lithology or geomorphic division

One of the examples is the nomenclature of the Lukundol Formation. The formation name was first used by Dhoundial (1966) in his unpublished report of the Geological Survey of

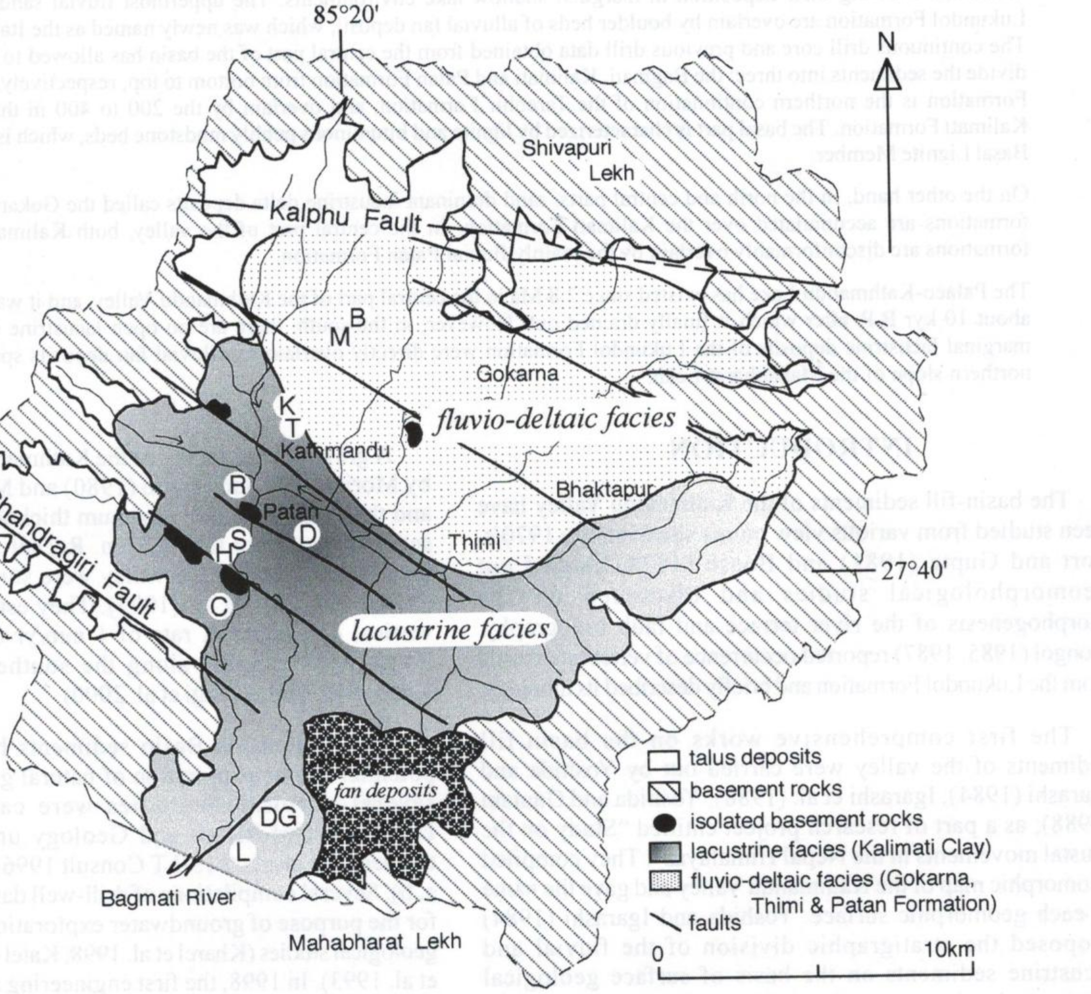

Fig. 1: Geological outline map of the Kathmandu Basin and location of drill-well shown in Fig. 4. Location of faults is after Arita et al. (1973), Saijo et al. (1995), Yagi et al. (2000) and unpublished drilling data. DG: Danuwargaun Fault. B: Basbari, M: Maharajgunj, T: Tri-Chandra Campus, K: Kanti Path, R: Rabibhawan, D: Disaster Prevention Technical Centre, S: Sundarighat, H: Horticulture Centre, C: Himal Cement, and L: Lukundol.

India. He designated the formation as a weakly consolidated clay, silt and sand beds with lignite layers well exposed around the village of Lukundol. Yoshida and Igarashi (1984) extended this formation also to include the gravel beds which are overlying and underlying the muddy sequence, and regarded that its continuation is widely distributed in the subsurface of the Kathmandu Valley. Koirala et al. (1993) used the name of the Lukundol Formation only to include the carbonaceous silty-sandy clay and sandy-clayey silt beds that overlie the gravel bed. According to their geological map, the Lukundol Formation is extensively distributed in the central part of the valley, though the sedimentary facies and age of the sediments in the central part are different from those in the Lukundol area as discussed in the following section. In the engineering and environmental geological map by Shrestha et al. (1998), the Lukundol Formation is shown as narrowly distributed unit in the eastern bank of the Bagmati River and along the Nakhu Khola in the southern part of the valley. They named the sediments that lie to the eastern bank of the Bagmati River as the Lukundol Formation whereas the sediments on the opposite bank was called the Kobgaon Formation, though both formations show almost the same lithology and structure. It is curious that the formation boundary is drawn along the Bagmati River without any explanation on interrelationship of the two formations. Also, Shrestha et al. (1998) used the name Kalimati Formation to a thick muddy sequence distributed in the central part of the valley. This formation is nearly same as my newly defined Kalimati Formation except that their formation includes marginal lacustrine facies deposits, such as boulder beds. It is highly possible that a part of their Kalimati Formation distributed in the southeastern and eastern margin of the basin is the lake margin deposits similar to the Lukundol Formation. It is thus clear that the name "Lukundol Formation" has been used in different ways by previous workers.

Another problem is definition of the Gokarna, Thimi, and Patan formations. Yoshida and Igarashi (1984) considered that the fill top plain of each formation forms the Gokarna, Thimi and Patan geomorphic surface (terrace), respectively. The problem is that the Thimi Formation, for example, is not only distributed in the Thimi geomorphic surface. Similarly, the Gokarna and Patan Formations are not restricted to the Gokarna and Patan geomorphic surfaces.

These ill-defined and inconsistencies in the usage of formation names have given rise to many confusions and misunderstandings on the stratigraphy of the Kathmandu Basin sediments. There are many more names of formations that are used to define the basin-fill sediments of the valley, besides those mentioned above. The above problems show that no due care was taken while new stratigraphic divisions and names were proposed. While defining a new formation, if established norms such as designation of type locality and type stratigraphic section, description of stratigraphic relationship to the overlying and underlying formations, examination of the synonym and previous stratigraphic division were carefully taken into account, these problems would not have arisen.

NEW STRATIGRAPHIC DIVISION

The sedimentary facies and lithology of the sediments differ from the central part to the marginal part of the basin. Therefore, I propose separate stratigraphic schemes for the southern, central and northern part of the valley and an attempt has been made to correlate the formations.

Southern part of the Kathmandu Basin

According to Yoshida and Igarashi (1984), the basin-fill sediments distributed in the southern part of the Kathmandu Basin are divided into two: the Lukundol Formation and overlying terrace deposits named Pyangaon, Chapagaon and Boregaon Terrace Deposit (Table 1). Dongol (1987) divided the same sequence into four lithostratigraphic units: the Tarebhir Basal Gravel, Kaseri-Nayankhar Lignite, Nakkhu khola Mudstone and Champi-Itahari Gravel. The uppermost unit of the Champi-Itahari Gravel Table 1 corresponds to the Terrace Deposit and Members VI and VII of the Lukundol Formation by Yoshida and Gautam (1988).

In the present study, the Lukundol Formation has been redefined and a three-fold stratigraphic division of the entire basin-fill sequence in the southern part of the valley (Plate II) has been proposed. On the basis of distinct lithologic differences, the sediments are divided into the following three formations: the Tarebhir Formation, the Lukundol Formation and the Itaiti Formation, in ascending order Table 1. Each formation is equivalent to the Lower, Middle and Upper Member of the Lukundol Formation of Sakai et al. (2002), respectively (Fig. 2).

The Tarebhir Formation is the oldest basin-fill sediments and is unconformably overlying the Pre-Cambrian Tistung Formation (PlateI-4b). It nearly corresponds to the Tarebhir Basal Gravel of Dongol (1987) and Member I and basal part of Member II of the Lukundol Formation by Yoshida and Gautam (1988) Table 1. The formation is mainly composed of boulder and cobble bed and minor amount of lenticular sand beds. The thickness drastically varies from 350 m at Dukuchhap area to less than one meter at Tokalmat area where the black organic mud or sand bed of the Lukundol Formation directly rests on the basal talus breccia of the basement rocks (Plate I-4a). The great difference of thickness of this fluvial gravel, within 1 km from the southern margin of the basin means that the gravel was thickly deposited in the valley and thin on the basement high. The top of the Tarebhir Formation is marked by a cobble and boulder bed of about 14-m-thick, which is underlain by 18-m-thick cross-stratified coarse- to very coarse-grained sand beds with dark grey mud interbeds (Plate I-2).

The redefined Lukundol Formation is a mud dominant sequence of marginal lacustrine facies which is conformably overlying the Tarebhir Formation at the type locality along the Khahare Khola (Fig. 2; Sakai et al. 2002; Sawamura 2001). The redefined Lukundol Formation corresponds to Kaseri-Nayankhar Lignite and Nakkhu khola Mudstone of Dongol (1987) and Members III, IV, V and upper part of Member II of

Table 1: Correlation of newly proposed stratigraphy of the Kathmandu Basin sediments with that by the previous workers.

Yoshida and Igarashi (1984) Yoshida and Gautam (1988)	Member	Dongol (1985, 1987)	Shrestha et al. (1998)	Sakai et al. (2001)	Sakai (2001) southern part	Sakai (2001) central part
Patan Fm		Kalimati Clays	Gokarna Fm, Takha Fm, Kalimati Fm & Chapagaon Fm			Patan Fm
Thimi Fm						Kalimati Fm
Gokarna Fm						
Boregaon Terrace Deposit		Champi-Itahari Gravel		Lukundol Formation: Upper Member	Itaiti Fm	
Chapagaon Terrace Deposit						
Pyanggaon Terrace Deposit						
Lukundol Fm	VII					
	VI					
	V	Nakhu Khola Mudstone & Kaseri-Nayankhandi Lignite	Lukundol Fm & Kobgaon Fm	Middle Member	Lukundol Fm	Basal Lignite Member
	IV					
	III					
	II					
	I	Tarebhir Basal Gravel	Basal boulder bed	Lower Member	Tarebhir Fm	Bagmati Fm

the Lukundol Formation by Yoshida and Gautam (1988) Table 1. The formation attains a total thickness of 115 m and is composed of black to grey organic mud, rhythmite of sand and silt, coarse-grained sand and granule (Fig. 2). Eight to ten beds of disorganized massive pebbly mud, so called diamictite (Plate I-3), are intercalated, and are interpreted to be distal part of the debris flow deposits. Common occurrence of lignite beds ranging in thickeness from 1 to 50 cm and vertebrate fossils such as ancient elephant, crocodile, deer and artiodactyls are characteristic features of the Lukundol Formation. The uppermost beds consist of 80 cm thick, parallel- and ripple-drift cross-laminated micaceous sand bed and an overlying large-scale cross-stratified granitic sand bed of 1 m in thickness (Fig. 3). These beds are underlain by diatomaceous silt and lignite beds (Fig. 3).

The cliff-forming gravel dominant thick sequence resting on the Lukundol Formation has been separated from the "Lukundol Formation" of Yoshida and Igarashi (1984) and Yoshida and Gautam (1988), and newly defined as the Itaiti Formation (Plate II-3), named after Itaiti village. The formation comprises repetition of fining-upward sequence of gravel, fine sand and silty clay with carbonaceous mud in ascending order, and interpreted to be gravelly braided river deposits on an alluvial fan spreading toward the north (Sakai et al. 2002). One important difference of the Itaiti Formation from the underlying formations is lack of granitic grains which were derived from the Shivapuri Lekh to the north (Sakai et al. 2002). At the base, pebble and cobble of meta-sandstone derived from the Mahabharat Lekh to the south rest on the erosion surface of the cross-bedded sand of the Lukundol Formation. Although Yoshida and Igarashi (1984) separated the terrace deposits from their Lukundol Formation, we have included the terrace-forming gravel beds at Pyangaon, Chapagaon and Boregaon within the Itaiti Formation (Table 1), because there are no lithological and facies differences between the gravelly beds and the Itaiti Formation.

In the boundary area between the southern and central part of the Kathmandu Basin, 30 to 50 m thick sand dominant fluvio-deltaic sediments are distributed. These sediments are extensively distributed around Harisiddhi and Sunakothi area, ranging in altitude from 1,325 m to 1,370 m. In the lithological log of a drill hole at Harisiddhi, 10 m thick sand and gravel beds overlying the Kalimati Formation are shown (Katel et al. 1996). Sawamura (1994) reported that this formation rests on the mud dominant Lukundol Formation and is overlain by terrace gravel of the Itaiti Formation, and named it as the Sunakothi Formation. In this paper, the present author tentatively interprets it as the southern extension of the Thimi Formation as shown in Fig. 4. Further investigation is needed to clarify the stratigraphic relationship to the other formations and geological age of this formation.

Central part of the Kathmandu Basin

The compilations of a large number of drilling data obtained from the Kathmandu Basin sediments show that the basin-fill sediments in the central part of the Kathmandu Basin can be roughly divided into three parts (Natori et al. 1980a, Katel et al. 1996, Kharel et al. 1998) (Fig. 5). They are: 1) sandy lower part, 2) muddy middle part, and 3) sandy thin cover. However, the precise lithologic characters and stratigraphy were not well known, because the cores have never been recovered during previous drillings. The core drillings, carried out by our team in 2000, enabled us to collect continuous cores of mud-predominant sequence, and the nature and characteristics of subsurface sediments beneath

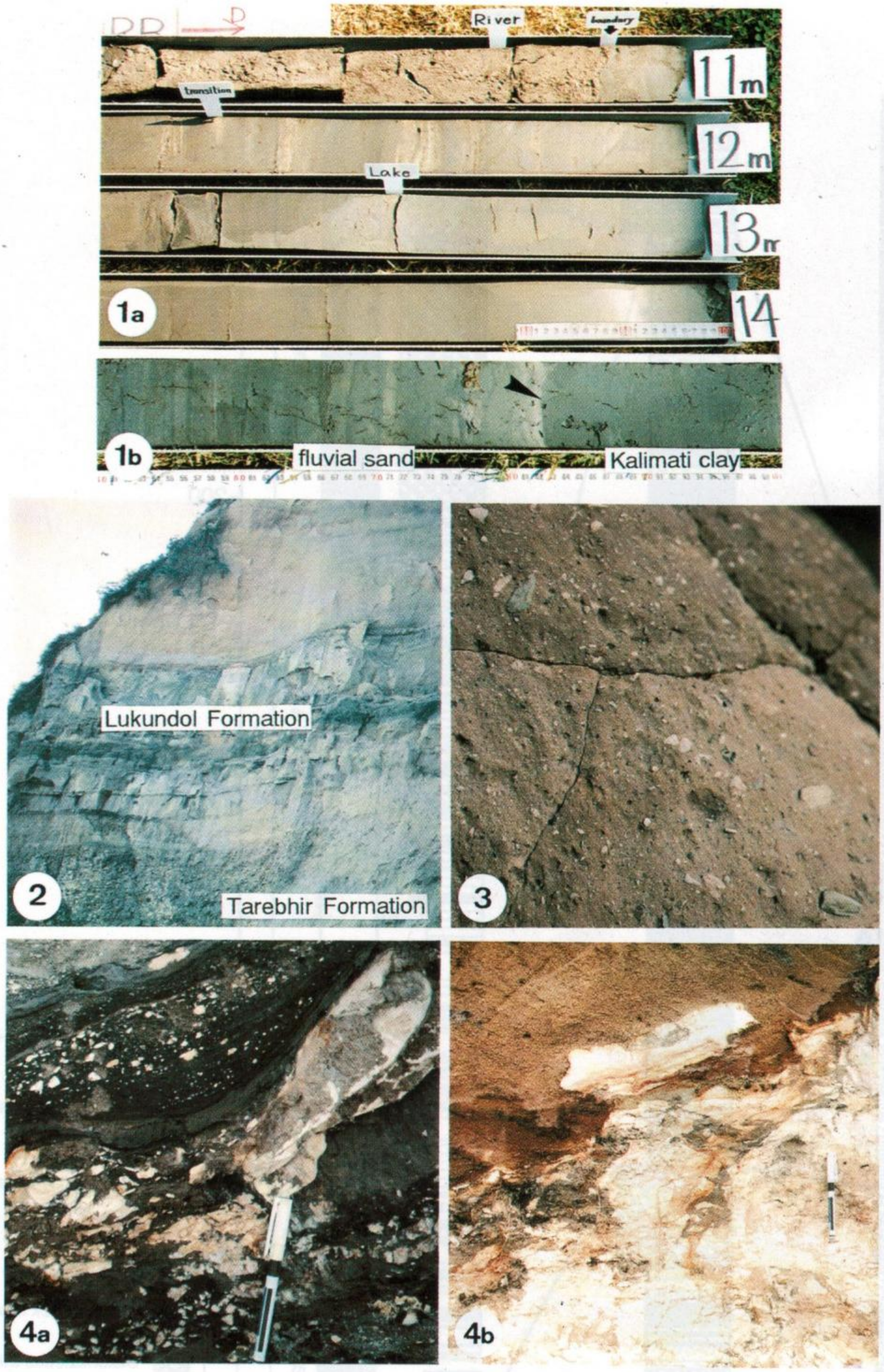

Plate I: 1: A boundary (arrow) between the clayey Kalimati Formation deposited in the Palaeo-Kathmandu Lake and overlying sandy fluvial Patan Formation in drill-cores at Rabibhawan (a) and Tri-Chandra Campus (b). In the core of Rabibhawan (a), there is a 1 m-thick transition zone, which is characterized by intercalation of sand beds in the Kalimati clay, 2: A boundary between gravel bed of the Tarebhir Formation and overlying mud dominant Lukundol Formation. Imbrication of gravel shows flow from the north and northeast (Sakai et al. 2002), location- west of Adhikarigaun, 3: Lithofacies of diamictite bed at 12 m below the top of the Lukundol Formation. Intermittent intercalation of diamictite beds is indicative of event deposits, probably formed by debris flow, at Lukundol, and 4a: Lithofacies of the basal bed of the Kathmandu Basin Group which is overlying the Pre-Cambrian Tistung Formation. Bituminous mud beds probably deposited in swamp are mixed with talus deposits comprising of breccia derived from the Tistung Formation, at Tokalmat; 4b: Unconformity between the Tistung Formation and the Tarebhir Formation. Fluvial sand beds rest on the erosion surface of the white quartzose sandstone, at Tokalmat.

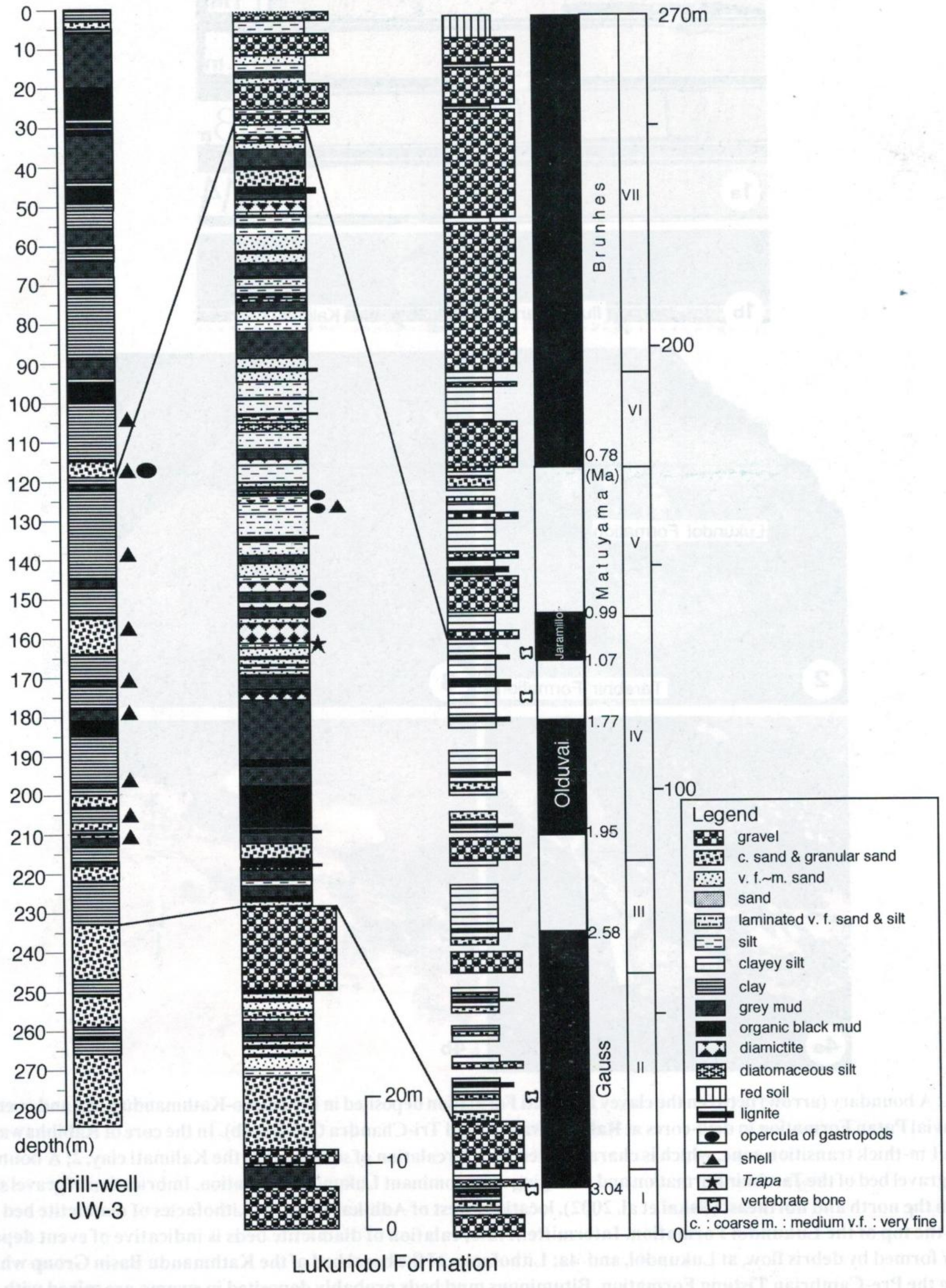

Fig. 2: A detailed lithostratigraphic section of the Lukundol Formation and its correlation with the litho- and magneto-stratigraphy by Yoshida and Gautam (1988) (modified from Sakai et al. 2002).

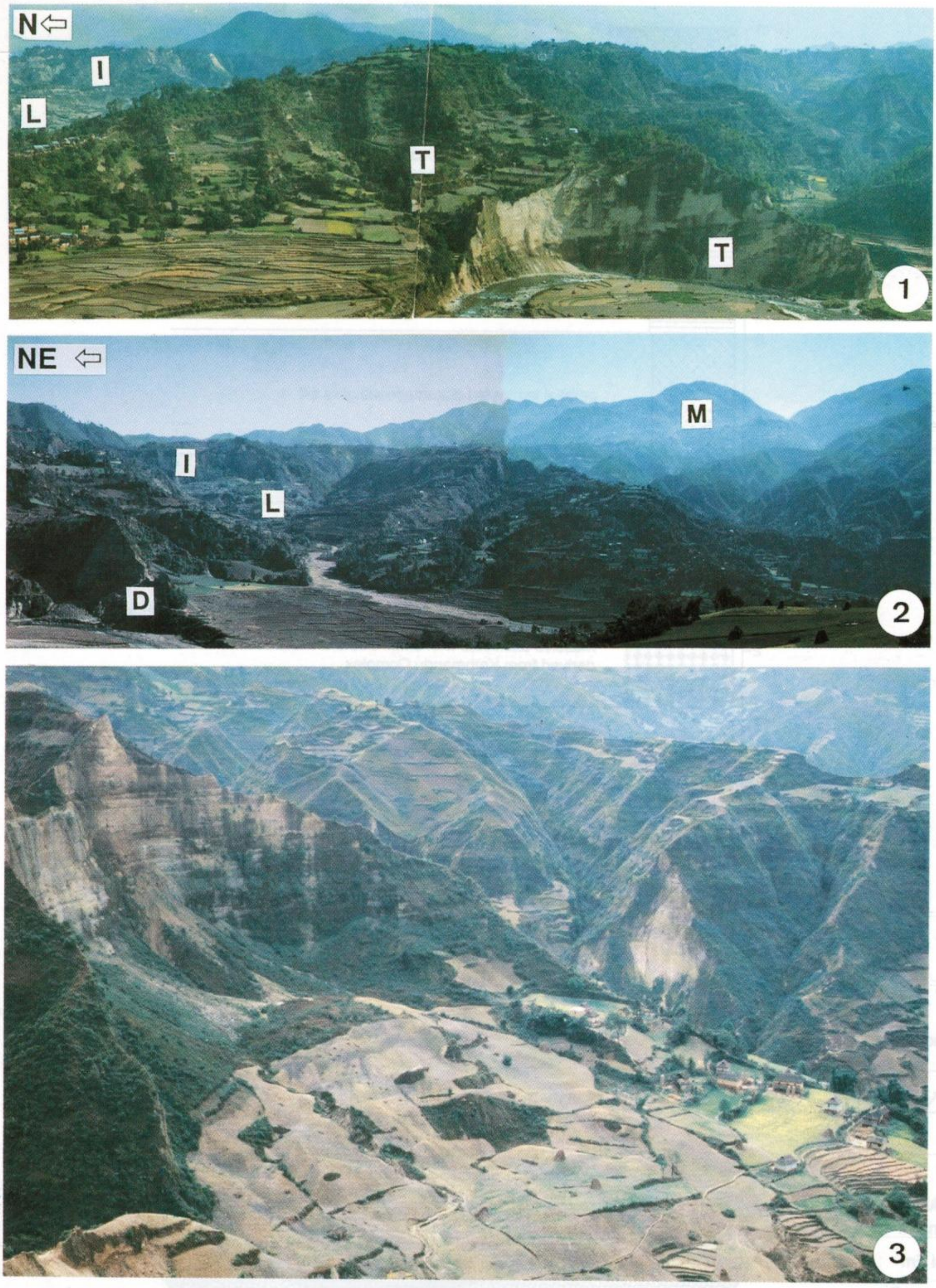

Plate II: 1: Boulder beds of the Tarebhir Formation (T) deposited by the Proto-Bagmati River. Note the northward tilting of beds caused by uplift of the Mahabharat Lekh during the last one million years. (L): Lukundol Formation, (I): Itaiti Formation, location- at Danuwargaun near the southern end of the valley; 2: Topography of the southern margin of the Kathmandu Valley and the Mahabharat Lekh (M) around Lukundol Village (L). Gently northerly dipping alluvial fan deposits of the Itaiti Formation (I) form flat terrace at around 1,500 m in altitude. An exposure of the Danuwargaun fault (D) is located on the left bank of the Bagmati River; and 3: Cliff-forming alluvial gravel bed of the Itaiti Formation and underlying gentle-slope-forming Lukundol Formation showing marginal lacustrine facies. Initiation of deposition of the alluvial gravel is estimated to have been caused by uplift of the Mahabharat Lekh at around 1 Ma (Sakai et al. 2002). Location- at Lukundol Village.

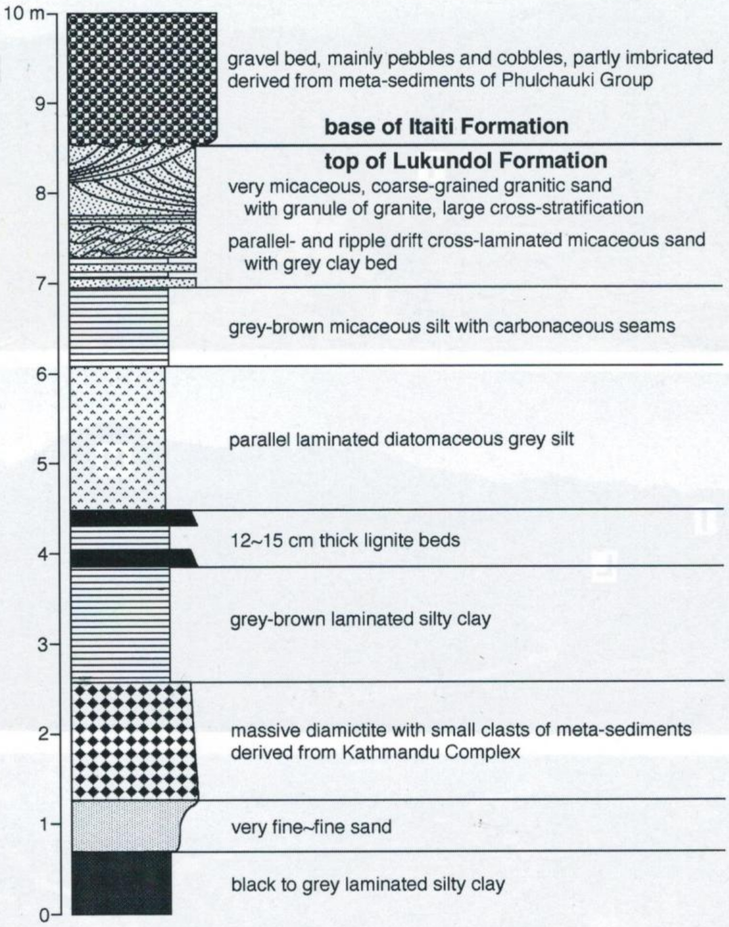

Fig. 3: A detailed geologic column of the upper part of the Lukundol Formation at Lukundol. The uppermost section is composed of fluvial sediments characterized by cross-stratified granular sand, lignite and diatomaceous beds.

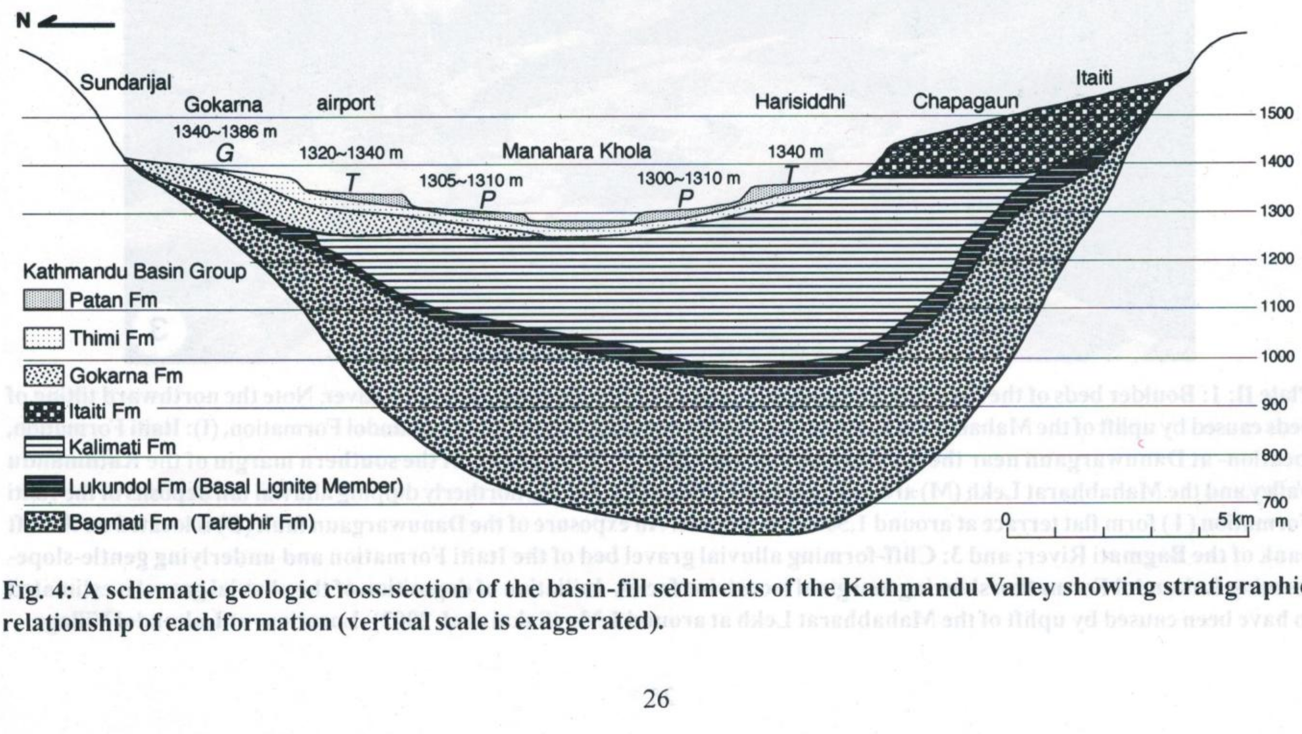

Fig. 4: A schematic geologic cross-section of the basin-fill sediments of the Kathmandu Valley showing stratigraphic relationship of each formation (vertical scale is exaggerated).

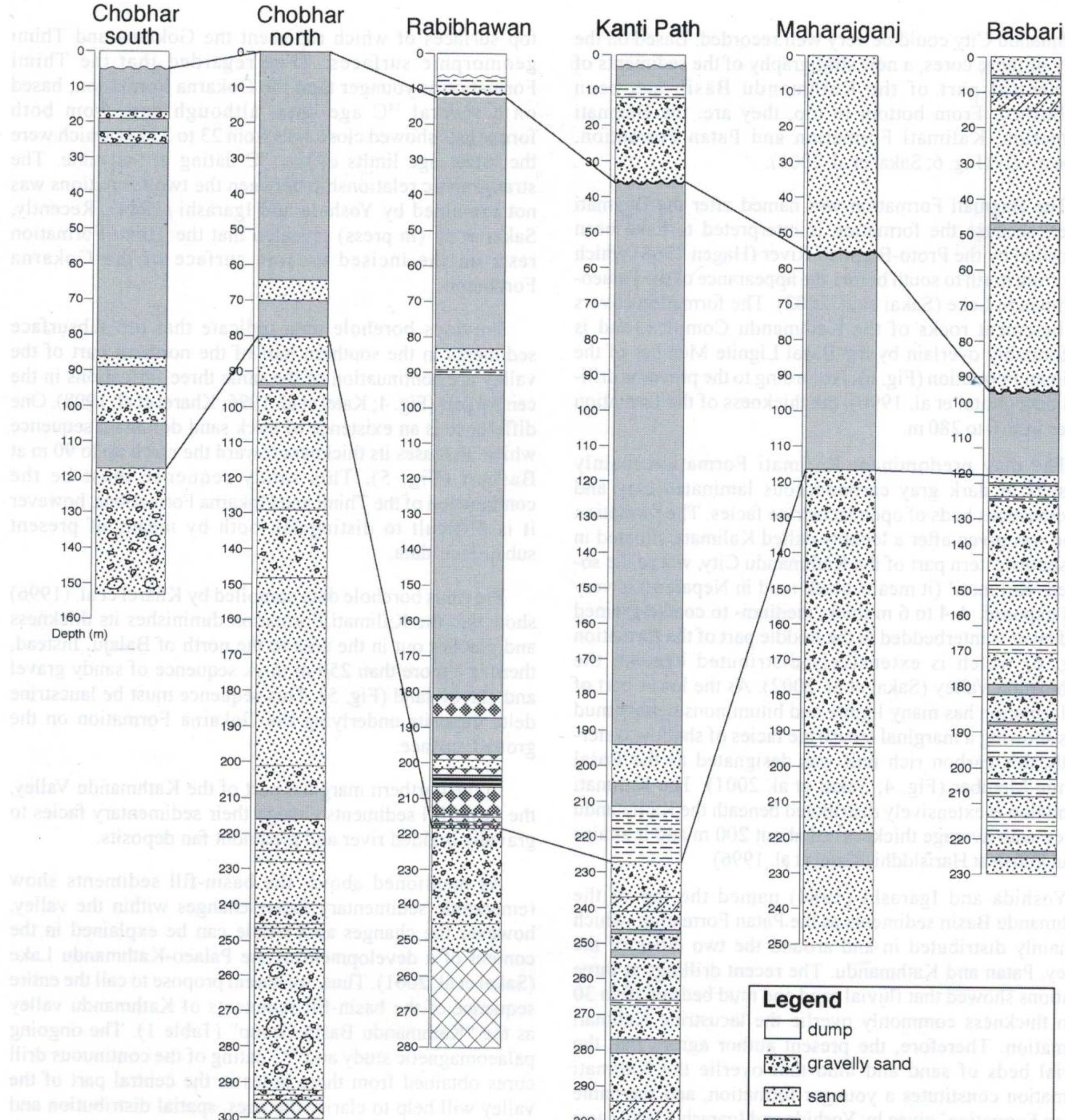

Fig. 5: Lithostratigraphic changes of the Kathmandu Basin Group shown by drill-well data. The lacustrine deposit of the Kalimati Formation decreases its thickness toward the south and north directions. On the other hand, the Gokarna and Thimi formations of the fluvio-deltaic sediments increase their thickness towards the north. Note the boulder bed near the Chobhar where the basement rocks are exposed along the active fault (see Fig. 1).

Kathmandu City could be very well recorded. Based on the study of these cores, a new stratigraphy of the sediments of the central part of the Kathmandu Basin has been established. From bottom to top, they are: the Bagmati Formation, Kalimati Formation and Patan Formation, respectively (Fig. 6; Sakai et al. 2001).

The Bagmati Formation was named after the Bagmati River, because the formation is interpreted to have been deposited by the Proto-Bagmati River (Hagen 1968) which flew from north to south before the appearance of the Palaeo-Kathmandu Lake (Sakai et al. 2002). The formation covers the basement rocks of the Kathmandu Complex, and is conformably overlain by the Basal Lignite Member of the Kalimati Formation (Fig. 6). According to the previous drill-well data (Katel et al. 1996), the thickness of the formation varies from 0 to 280 m.

The clay predominant Kalimati Formation mainly consists of dark gray carbonaceous laminated clay and diatomaceous beds of open lacustrine facies. The formation name was given after a locality called Kalimati, situated in the southwestern part of the Kathmandu City, where the so-called 'Kalimati' (it means black mud in Nepalese) is very well exposed. A 4 to 6 m thick, medium- to coarse-grained sand layer is interbedded in the middle part of the formation (Fig. 6) which is extensively distributed beneath the Kathmandu Valley (Sakai et al. 2002). As the lower part of the formation has many lignite and bituminous pebbly mud beds showing a marginal lacustrine facies of shallow water-depth, this carbon rich unit was designated as the Basal Lignite Member (Fig. 4; Sakai et al. 2001). The Kalimati Formation is extensively distributed beneath the Kathmandu Valley with average thickness of about 200 m and it attains about 400 m at Harisiddhi (Katel et al. 1996).

Yoshida and Igarashi (1984) named the top of the Kathmandu Basin sediments as the Patan Formation, which is mainly distributed in and around the two cities of the valley, Patan and Kathmandu. The recent drillings at three locations showed that fluvial sand and mud beds of 10 to 30 m in thickness commonly overlie the lacustrine Kalimati Formation. Therefore, the present author agrees that the fluvial beds of sand and mud that overlie the Kalimati Formation constitutes a younger formation, and the name 'Patan Formation' given by Yoshida and Igarashi (1984) gets the priority. In two sites, a distinct erosion surface and rip-up clasts of the Kalimati clay were contained in the basal sand beds of the Patan Formation (Plate I-1). Therefore, there is no doubt that these fluvial beds belong to the Patan Formation of Yoshida and Igarashi (1984).

Northern part of the Kathmandu Basin

Previous workers reported that terrace-forming sand dominant fluvio-deltaic or fluvio-lacustrine sediments are extensively distributed in the northern and central parts of the Kathmandu Valley (Fig. 1; Natori et al. 1980a; Yoshida and Igarashi 1984). Yoshida and Igarashi (1984) called them as the Gokarna Formation, and according to them, the fill top surfaces of which represent the Gokarna and Thimi geomorphic surfaces. They regarded that the Thimi Formation is younger than the Gokarna Formation, based on a several ^{14}C age data, although data from both formations showed close ages from 23 to 33 kyr which were the lower age limits of the ^{14}C dating at that time. The stratigraphic relationship between the two formations was not examined by Yoshida and Igarashi (1984). Recently, Sakai et al. (in press) revealed that the Thimi Formation rests on the incised erosion surface of the Gokarna Formation.

Previous borehole data indicate that the subsurface sediments in the southern half of the northern part of the valley are continuation of the same three formations in the central part (Fig. 4; Katel et al. 1996; Kharel et al. 1998). One difference is an existence of thick sand dominant sequence which increases its thickness toward the north up to 90 m at Basbari (Fig. 5). This sandy sequence must be the continuation of the Thimi and Gokarna Formations, however it is difficult to distinguish both by means of present subsurface data.

Previous borehole data compiled by Kharel et al. (1996) show that the Kalimati Formation diminishes its thickness and pinches out in the area to the north of Balaju. Instead, there is a more than 250 m thick sequence of sandy gravel and clayey sand (Fig. 5). This sequence must be laucstrine delta deposits underlying the Gokarna Formation on the ground surface.

In the northern marginal part of the Kathmandu Valley, the basin-fill sediments change their sedimentary facies to gravelly braided river and piedmont fan deposits.

As mentioned above, the basin-fill sediments show remarkable sedimentary facies changes within the valley, however the changes as a whole can be explained in the context of a development of the Palaeo-Kathmandu Lake (Sakai et al. 2001). Thus, we herein propose to call the entire sequence of the basin-fill sediments of Kathmandu valley as the "Kathmandu Basin Group" (Table 1). The ongoing palaeomagnetic study and ^{14}C dating of the continuous drill cores obtained from three holes in the central part of the valley will help to clarify the ages, spatial distribution and stratigraphy of each formation, and will bring a much better understanding of the basin development of the Kathmandu Valley.

SEDIMENTARY FACIES

For the purpose of construction of three-dimensional architecture of sedimentary basin, it is necessary to interpret sedimentary facies change of the formations and their interrelationship in the basin development. We herein attempt to interpret the lateral and vertical sedimentary facies changes in the Kathmandu Basin, and discuss the depositional environmental changes in the basin.

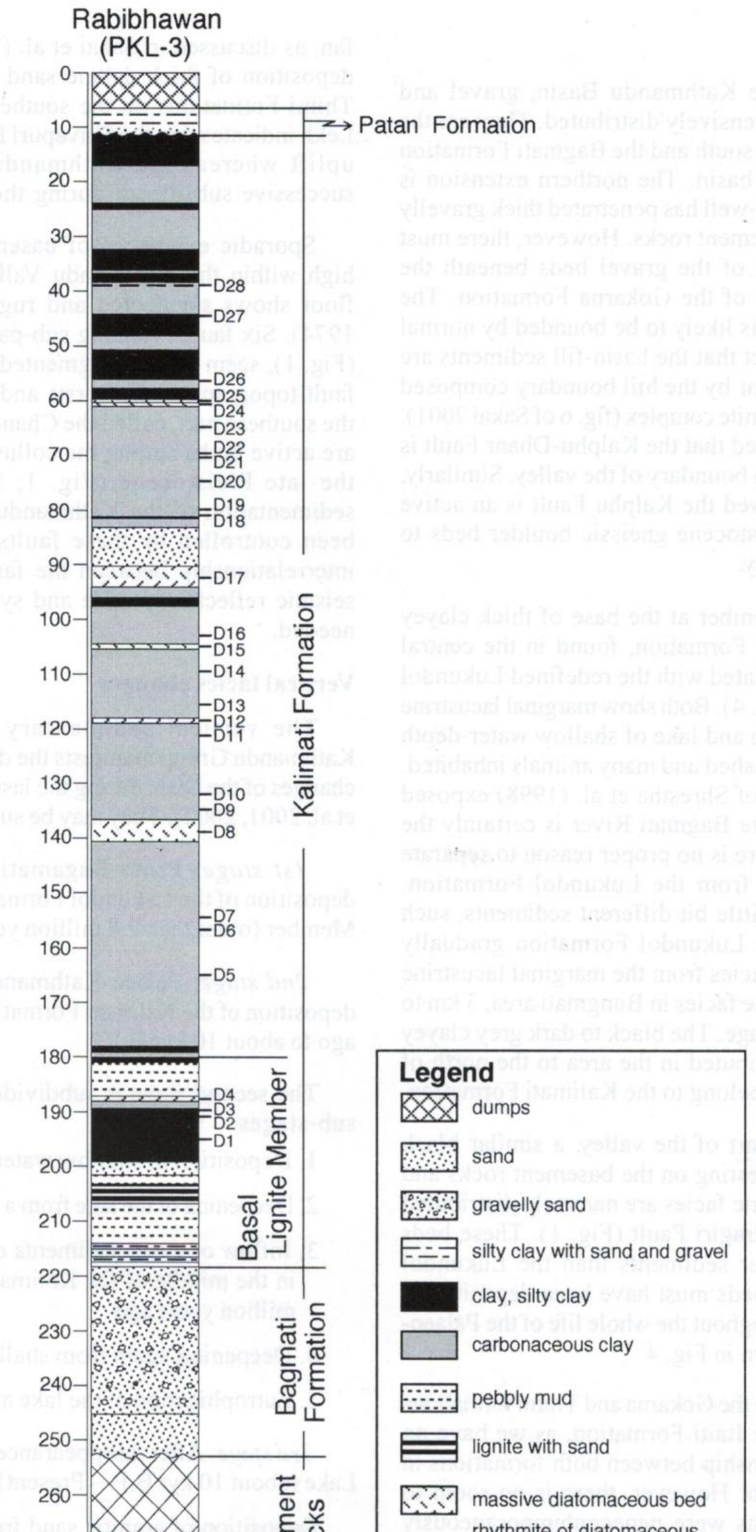

Fig. 6: A lithostratigraphy at Rabibhawan of the Kathmandu Basin Group in central part of the valley based on a drill-core PKL-3 and previous drill-well data.

Lateral facies changes

On the bottom of the Kathmandu Basin, gravel and gravelly sand beds are extensively distributed. They are the Tarebhir Formation in the south and the Bagmati Formation in the central part of the basin. The northern extension is unknown, because no drill-well has penetrated thick gravelly sand body and hit the basement rocks. However, there must be northern continuation of the gravel beds beneath the sandy fluvio-deltaic beds of the Gokarna Formation. The northern end of the basin is likely to be bounded by normal faults as judged by the fact that the basin-fill sediments are thickly deposited even near by the hill boundary composed of Shivapuri gneiss and granite complex (fig. 6 of Sakai 2001). Arita et al. (1973) estimated that the Kalphu-Dhanr Fault is running along the northern boundary of the valley. Similarly, Nakata et al. (1984) showed the Kalphu Fault is an active fault cutting the late Pleistocene gneissic boulder beds to the northwest of the valley.

The Basal Lignite Member at the base of thick clayey sequence of the Kalimati Formation, found in the central part of the valley, is correlated with the redefined Lukundol Formation in the south (Fig. 4). Both show marginal lacustrine facies deposited in swamp and lake of shallow water-depth where aquatic plants flourished and many animals inhabited. The Kobgaon Formation of Shrestha et al. (1998) exposed on the western bank of the Bagmati River is certainly the Lukundol Formation. There is no proper reason to separate the Kobgaon Formation from the Lukundol Formation, though the former has a little bit different sediments, such as thin gravel beds. The Lukundol Formation gradually changes its sedimentary facies from the marginal lacustrine facies to the open lacustrine facies in Bungmati area, 3 km to the north of Lukundol village. The black to dark grey clayey beds are extensively distributed in the area to the north of Bungmati, and they must belong to the Kalimati Formation.

In the southwestern part of the valley, a similar black carbonaceous mud beds resting on the basement rocks and showing marginal lacustrine facies are narrowly distributed to the north of the Chandragiri Fault (Fig. 1). These beds seem to be much younger sediments than the Lukundol Formation. Similar mud beds must have been deposited in the margin of the lake throughout the whole life of the Palaeo-Kathmandu Lake, as shown in Fig. 4.

It is difficult to correlate the Gokarna and Thimi formations with the upper part of the Itaiti Formation, as we have no data on exact time-relationship between both formations in the north and in the south. However, there is no room to doubt that both formations were penecontemporaneously deposited during the late Pleistocene (Yoshida and Igarashi 1984). I consider that the difference of the sedimentary facies in the northern and southern parts of the valley was caused by difference of tectonic condition of the Shivapuri Lekh and the Mahabharat Lekh. Accumulation of thick gravel beds of the Itaiti Formation on the northern slope of the Mahabharat Lekh reflects the rapid uplift of the frontal range of the Lesser Himalaya and deposition of gravel on the alluvial fan, as discussed in Sakai et al. (2002). On the other hand, deposition of thick deltaic sand beds of the Gokarna and Thimi Formations on the southern slope of the Shivapuri Lekh indicates that the Shivapuri Lekh did not undergo rapid uplift whereas the Kathmandu Basin had undergone successive subsidence during the Pleistocene.

Sporadic exposures of basement rocks and basement high within the Kathmandu Valley suggest that the basin floor shows segmented and rugged topography (Boesch 1974). Six faults, running sub-parallel to the Kalphu Fault (Fig. 1), seem to have segmented the basin and produced a fault-topography with horsts and grabens. Two of them in the southern part, called the Chandragiri and Chobar Faults, are active faults cutting the colluvial slopes and terraces of the late Pleistocene (Fig. 1; Saijo et al. 1995). The sedimentation of the Kathmandu Basin Group must have been controlled by these faults. In order to clarify the interrelationship between the faulting and sedimentation, seismic reflection profile and systematic core-drilling are needed.

Vertical facies changes

The vertical sedimentary facies changes of the Kathmandu Group manifests the depositional environmental changes of the basin during the last three million years (Sakai et al. 2001, 2002). They may be summarized as follows:

1st stage: Proto-Bagamati River stage before the deposition of the Lukundol Formation and the Basal Lignite Member (older than 2.8 million years ago)

2nd stage: Palaeo-Kathmandu Lake stage during the deposition of the Kalimati Formation (from 2.8 million years ago to about 10 kyr B.P.)

The second stage is subdivided into the following five sub-stages:

1. Deposition in shallow water environment
2. Deepening of the lake from a shallow water environment
3. Inflow of event sediments of a fossiliferous sand bed in the middle of the Kalimati Formation at about one million years ago
4. Deepening again from shallow water depth
5. Eutrophication of the lake after about 30 kyr B.P.

3rd stage: After disappearance of the Palaeo-Kathmandu Lake (about 10 kyr B.P. ~ Present)

Deposition of granitic sand from the Shivapuri Lekh by present rivers.

In the southern part of the valley, deposition of gravel beds over the Lukundol Formation started about one million years ago, as a rapid uplift of the Mahabharat Lekh initiated at the same time (Sakai et al. 2002). Successive uplifting of the range gave rise to northward progradation of the alluvial fan, and the fluvial gravel successively covers the Lukundol and Kalimati formations (Fig. 4). Previous drill-well data from Thimi and Bodegaun suggest existence of ancient Manahara Khola, because thick lenticular sand bodies are enbedded in the Kalimati Formation (Katel et al. 1996).

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