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Particle-Size Distribution of Late Pleistocene Loess-Paleosol Deposits in Attock Basin, Pakistan : Its Paleoclimatic Implications

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A section of the late Pleistocene loess-paleosol deposits exposed along the Haro river, Attock basin, northern Pakistan, was studied for stratigraphy, particle-size distribution analysis by sieving and centrifugal analyser, and paleoclimatic investigation. The section is mostly composed of less-weathered loess while at least seven highly-weathered paleosol beds, PS-1－7 in descending order, are intercalated. Particle-size distribution analysis of the loess-paleosol deposits shows that loess beds have generally unimodel, well-sorted, leptokurtic, and negatively-skewed particle-size population whereas the paleosols have bimodel and poorly-sorted population. Loess deposits are generally composed of high percentage of silt-size particles while paleosols are rich in sand-size particles. On the basis of median particle-size (Md in ϕ scale), silt content (in weight %), and modal analysis, the loess-paleosol sequence can be divided into two part : The lower part, below the PS-4 paleosol bed show relatively coarser population with smaller Md(ϕ) values and larger sand-content (wt%). On the other hand the upper part, above the PS-4, gives relatively finer population with larger Md(ϕ) values and larger silt-content. Cyclic upward-fining sequences in each interval between the paleosol horizons are also recognized by modal analysis of the population.

The drastic change in particle-size distribution between the upper and lower parts of the loess-paleosol sequence possibly provides a terrestrial record of continental paleoclimate in the area during late Pleistocene : *i.e.* it can be interpreted in terms of relative strength of paleo-monsoon winds by the model in Chinese Loess Plateau. That is, the lower part is marked by intense summer monsoon winds whereas the upper part is dominated by stronger winter monsoon winds. This climatic deterioration in the section may correspond to the climatic change from the Last Interglacial to the Last Glacial epoch.

Key Words : Pakistan, late Pleistocene, loess, paleosol, particle size, paleo-monsoon

I. Introduction

The term loess is applied to the unconsolidated, porous quartz-rich silt of the aeolian origin, commonly buff to light brown in color and characterized by a lack of distant stratification (Smalley, 1983). So-called loess deposits are widely distributed in the Himalayan foothills in northern areas of Pakistan and have been recognized from the Charsada in west to the Jhelum river in the east (Rendell,

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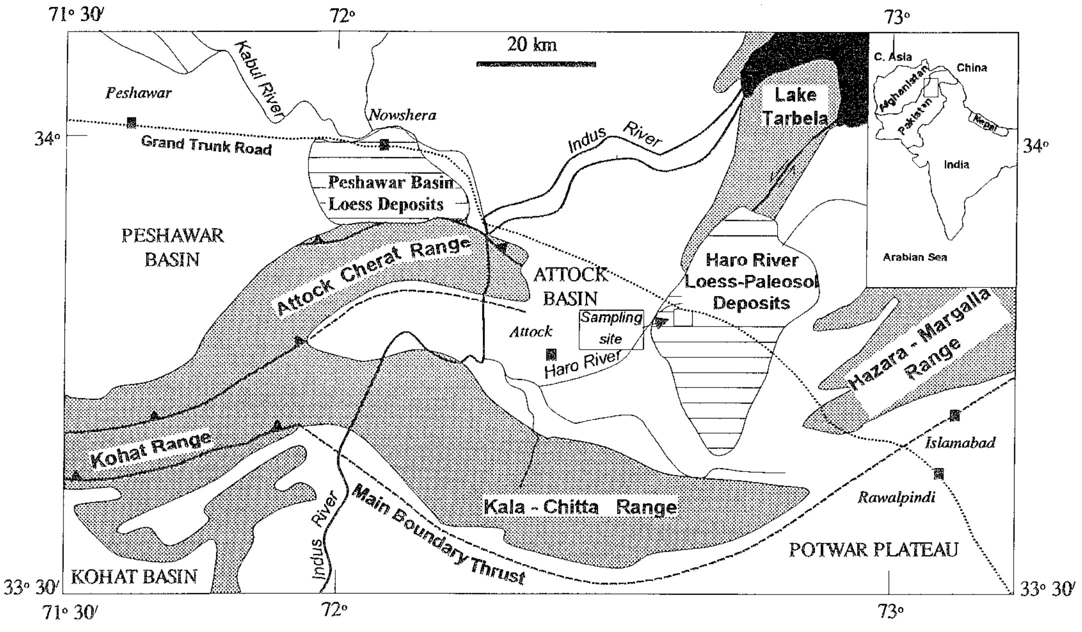

Fig. 1 Distribution of Late Quaternary loess-paleosol deposits in northern Pakistan and the location of Haro river loess-paleosol section

1989). However, in strict sense of fine-grained aeolian deposits, loess is exposed around Nowshera (southern Peshawar basin), in the upper Haro river valley (Attock basin), and in the area south west of Rawalpindi near Riwat (northern Potwar basin) (Figure 1). These deposits have previously been reported by a number of workers (De Terra and Paterson, 1939; Allen, 1964; Said and Majid, 1977; Rendell, 1988, 1989, 1993).

Loess deposition is probably essentially continuous, although the rate of accumulation varies with time. It has been widely accepted that a succession of loess deposits marks a duration of high aeolian dust influx while paleosols represent a stage of decreased accumulation rate of influx when enhanced pedogenic activity (or weathering) leads to the development of accretionary soil profiles. It means a sequence of loess-paleosol potentially represents a paleoclimatic change. In this context, Xiao *et al.* (1995) carried out particle-size distribution analysis of the loess in central China and interpreted the median size and maximum grain size of the silt-size grain as a proxy index of paleo-monsoon wind strength during the deposition of the loess deposits.

The loess-paleosol deposits exposed in the upper Haro river valley has been selected for the current study. In this paper, we describe the result of particle size distribution analysis of the loess-paleosol deposits and discuss its paleoclimatic significance.

II. Previous Works

Loess-paleosol deposits in northern Pakistan have been studied by a number of researchers. De Terra and Paterson (1939) were first worked extensively on the deposits of Potwar and Attock basins, and classified them as loess deposits against the previously proposed lacustrine origin (Theobald, 1877). They proposed a glacial origin for these loess deposits and correlated them to a product of the "third phase (Rias)" of Himalayan glaciation.

De Terra and Paterson (1939) also assigned an early Pleistocene age to these deposits on the basis of fossils pollen and archaeological remains "Levallois-type paleolithic tools". Said and Majid (1977) worked on the loess deposits in the Peshawar basin and proposed that these loess deposits were of glacial origin and early Pleistocene in age. Rendell (1988, 1989) studied the loess deposits of Potwar and Peshawar basins. The loess deposits were dated late Pleistocene (130-16ka) by thermoluminescence(TL) dating method. She disagreed with the previously proposed glacial origin and assumed that the loess deposits were the product of active weathering and erosion in the uplifted Himalayas. This intense erosion and weathering has supplied the fine-grained material to the foothills.

Granulometric studies and its paleoenvironmental interpretation have been made by some reseachers. Said and Majid (1977) presented the particle size distribution analysis of the Peshawar basin loess deposits. The result shows that Peshawar loess deposits are com posed of 75% silt-size particles. Rendell (1989) and Rendell *et al.* (1989) reported the particle size distribution analysis of the Potwar, Peshawar, and Kashmir loess deposits. According to the result, the Potwar loess had median particle size range of 16−19μm and comprised 90-87% silt-size particles whereas the Peshawar basin loess had the median particle size range of 14−20μm with 75% silt-size particles. The Kashmir basin loess had the median particle size range of 16−80μm with 70−80% silt-size particles.

III. Haro River Section

The loess-paleosol section studied is located on the west bank of the Haro river (Latitude N33° 48' 56", Longitude E 72° 32' 24"), south of the Islamabad-Peshawar Grand Trunk Road (Figure 1). The section was measured and sampled by the collaborative research team of the Geoscience Laboratory, Geological Survey of Pakistan, Islamabad. The dominant lithologies for the loess-paleosol deposits are silt and clay with subordinate calcareous concretions known as loess 'dolls' (Derbyshire, 1983). A few beds of very fine sands are present in the lower part, which are of fluvial in origin. The base of the section is not exposed while the top of the section is covered with surface soil and grass. The section measured is 18.5 meter thick and intercalates at least seven paleosol layers PS-1, 2, 3, 4, 5, 6, and 7 in descending order (Figure 2).

Loess beds are generally light brown to brown in color and are composed mainly of the silt-size and clay-size particles with minor calcareous concretions (both primary and secondary). Loess beds are generally poorly-stratified, porous, and calcareous. Individual loess beds vary considerably in thickness. This variation in the thickness of the beds represents local changes in the rate of supply of the aeolian materials.

Paleosols are generally dark reddish brown in color and composed mainly of sandy silt-size particles. They have vertical partings and solution cavities. Calcareous nodules are abundant. The upper boundaries are marked by a presence of distinct erosional surfaces while lower boundaries are transitional. Seven paleosols in the Haro river section can be classified into three paleosol zones based on stratigraphic position ; the upper zone (PS-1−PS-3), the middle zone (PS-4) and the lower zone (PS-5−PS-7).

There is no direct geochronological data in the present section. However TL ages of equivalent loess deposit in adjacent areas, the Peshawar and Potwar basins, were dated 130−16ka (Rendell, 1988, 1989)which indicates that the Haro river loess deposits probably accumulated in late Pleistocene time.

IV. Analytical Procedure

The following procedure was adopted

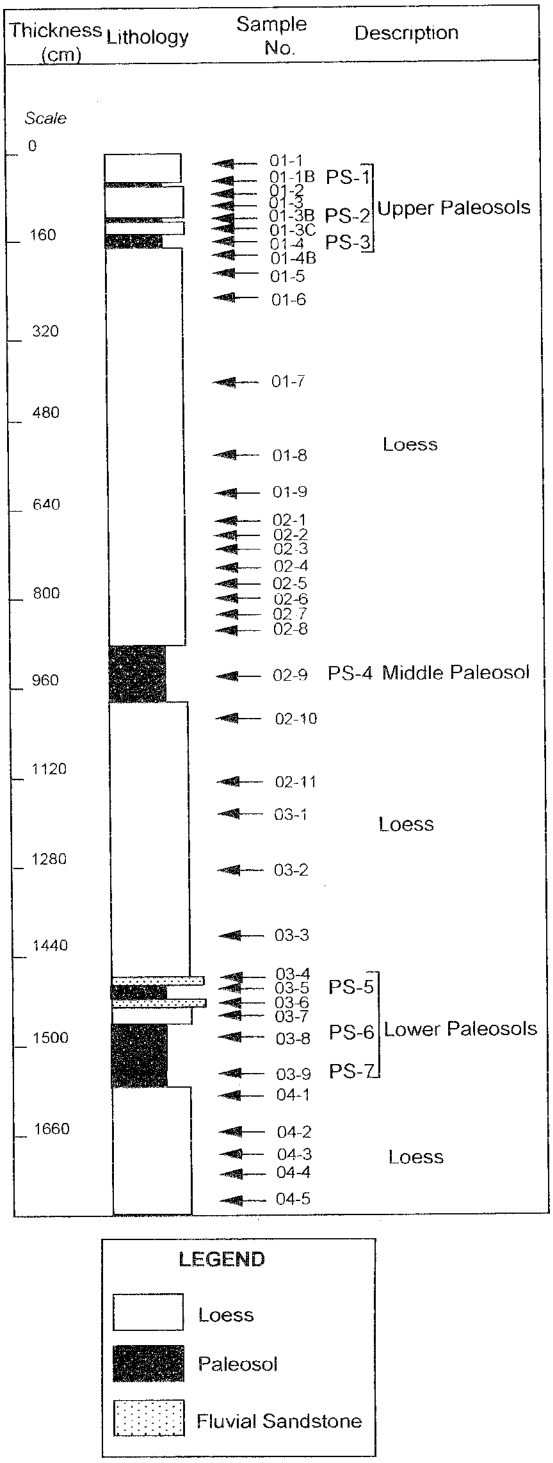

Fig. 2 Columnar section of the Haro river loess-paleosol deposits

for particle size distribution analysis of the loess-paleosol samples.

Air-dried samples were gently crushed with a mortar for desegregation. Organic matters was removed by treating the samples with 6% solution of hydrogen peroxide (H_2O_2) at 110°C. About 400 grams of the sample were separated from the bulk sample by coning and quartering method. The sample was then sieved through sieves of 2.00 mm, 1.00 mm, 0.425 mm, 0.250 mm, 0.125 mm, 0.063 mm, 0.045 mm mesh, for ten minutes in sieve-shaker, to separate the particles into the particular sizes. The weight of each fraction was measured with the help of electronic balance and weight percentage of each fraction was calculated.

From the finest fraction remaining in the sieve, i.e. under the 0.045mm mesh, about 0.15−0.20 grams of the sample were taken for further analysis. The sample was put into 100ml of distilled water. The mixture was stirred and left for 15 hours for the complete dispersion of the particles. The particle size distribution analysis of the finer fraction up to 0.0003 mm in diameter was done by a centrifugal particle distribution analyzer Horiba/CAPA-300 which is based on the principle of liquid phase sedimentation. Detailed procedure is described in Yoshida *et al.* (1995). The numerical data both sieving and sedimentation (CAPA-300; by volume-basis) was combined together in a single format with Udden-Wenthworth's Phi(ϕ) scale as follow:

$$\phi = -\log_2 S$$

where S denotes the particle size in millimeters.

The weight percentages and cumulative weight percentages for each sample were calculated. Microscopic observations of the thin sections proved that the dominant mineral present in the loess-paleosol deposits is silt-size fragmented quartz.

V. Particle Size Distribution

The frequency curves and cumulative

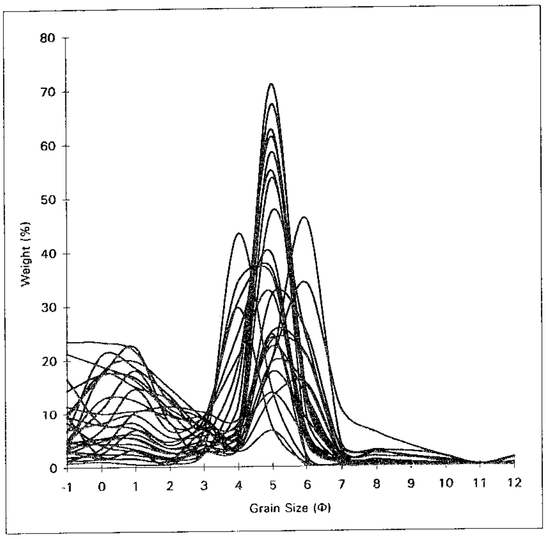

Fig. 3-a Frequency (weight %) curves of grain size (ϕ) for loess deposits in the Haro river section

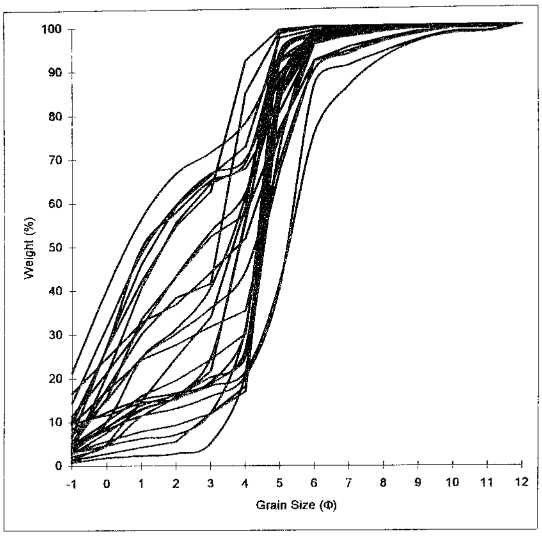

Fig. 3-b Cumulative frequency (weight %) curves of particle size (ϕ) for loess deposits in the Haro river section

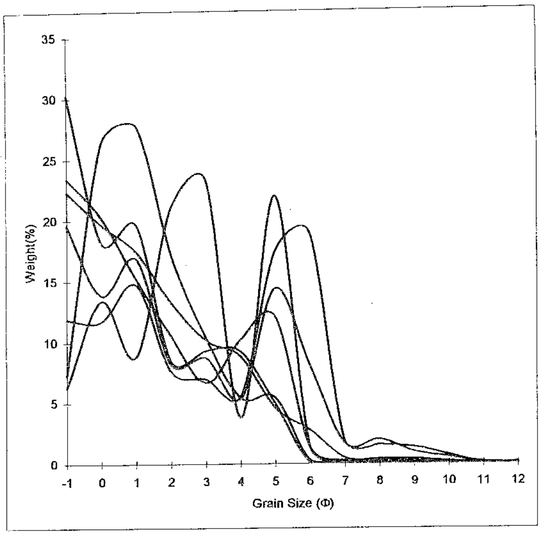

Fig. 4-a Frequency (weight %) curves of particle size (ϕ) for paleosols in the Haro river section

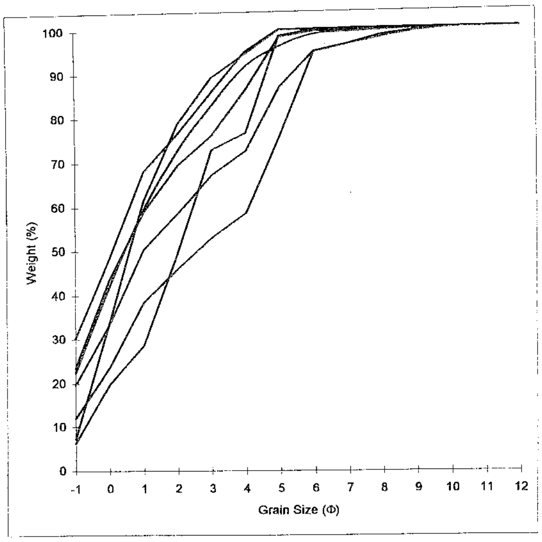

Fig. 4-b Cumulative frequency (weight %) curves of particle size (ϕ) for paleosols in the Haro river section

frequency curves are drawn for each sample (Figures 3-a and 3-b, Figures 4-a and 4-b, Figures 5-a and 5-b). The frequency curves of the loess and paleosols show a considerable difference. The particle size distribution of loess is generally unimodal while paleosols are invariably bimodal. Loess beds immediately below the paleosols also exhibit bimodal distribution suggesting an influence of the pedogenic activity. Loess beds has sandy silt (3.8−6.0ϕ, 0.600−0.0156mm) as dominate particle size while paleosols have sand-size(−1.0−4.0ϕ, 2−0.0625mm). The frequency curves (Figures 3-a and 4-a) show that sandy silt-size particles is predominant in the grain population. The cumulative frequency curves (Figure

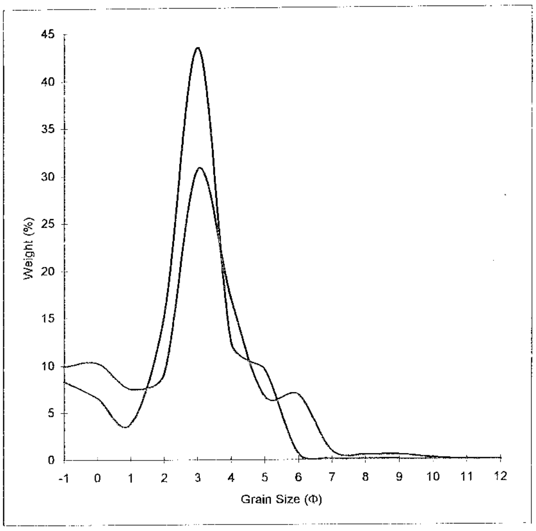

Fig. 5-a Frequency (weight %) curves of particle size (ϕ) for fluvial sand in the Haro river section.

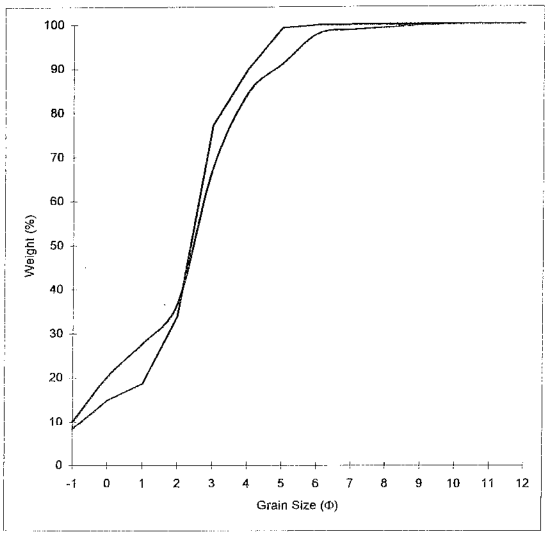

Fig. 5-b Cumulative frequency (weight %) curves of particle size (ϕ) for fluvial sand in the Haro river section.

3-b) of the loess show that sand-size is 10−50%, silt-size (4.0−8.0ϕ, 0.0625−0.0039mm) is 40−90% and clay-size (8<ϕ, 0.0039>mm) is less than 10%, while the cumulative frequency (Figure 4-b) curves of the paleosols show that sand-size is 10−70%, silt-size is 20−50%, and clay-size is less than 10%.

From the cumulative frequency curve of the each sample, graphic mean, median size, sorting, skewness, and kurtosis were calculated by applying Folk-Ward's formulae (Tucker, 1992). Loess materials are generally moderately-sorted, negatively-skewed and leptokurtic while paleosols are moderately to poorly-sorted[1].

The change of median size (Md., Tucker, 1992) within the loess-paleosol sequence was plotted against the columnar section (Figure 6). Median size (Md) of the loess deposits above the PS-4 horizon varies between 4−6ϕ (62.5−15μm) while that of paleosols varies between 0−2ϕ (1−0.25mm). Below the PS-4 horizon, on the other hand, median size of loess varies 2−4ϕ(0.25−0.0625 mm) while that of paleosol remains constant.

The percentages of the sand-size, silt-size, and clay-size are determined for each sample and plotted against the stratigraphic columnar section (Figure 6) as well as on a ternary diagram (Figure 7). Sand-size is more dominant in paleosols, *i.e.* more than 50%, while silt-size is dominant in normal loess, *i.e.* more than 60%. However the weight percentage of clay-size is small (1−2% in average, maximum 8%) and show little fluctuation. The change in weight percentage of sand fraction is almost inversely proportional to that of the silt fraction. According to Folk classification (Folk, 1974) the weight percentages of the sand, silt, and clay reveal that the Haro river loess-paleosol deposits are dominantly of sandy silt in particle-size above the PS-4 horizon while below the PS-4 are mainly silty sand in particle size.

The result of modal analysis of particle population is summarized in Figure 6. Mode shows a peak of population which is potentially useful parameter to identity episodes in continuous deposition. The change of mode within the loess-paleosol

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[1] Paleosols show bimodel grain size distribution, so the skewness and kurtosis were not calculated.

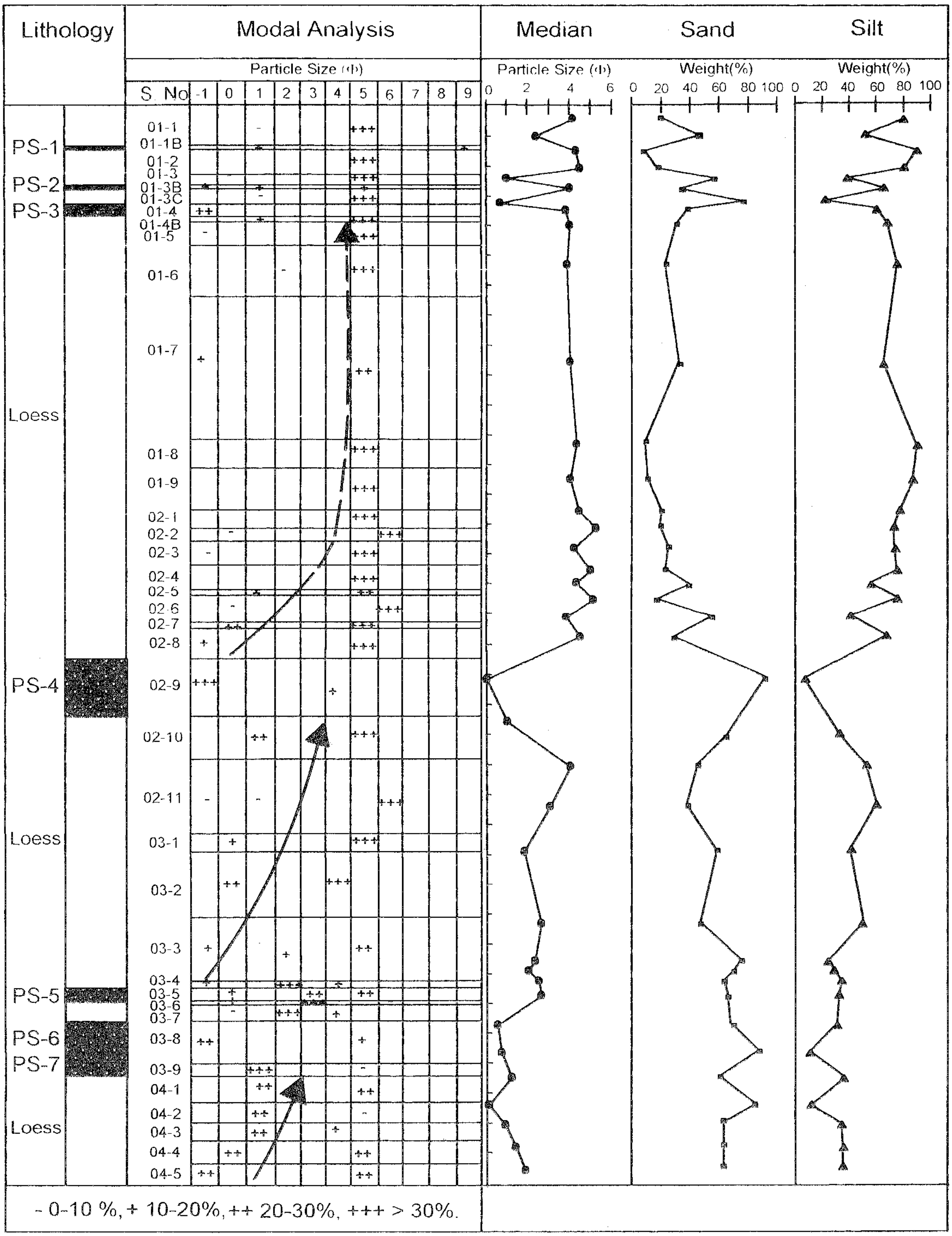

Fig. 6 Variation for mode of particle size distribution, median size (ϕ), and weight percentages of sand and silt in the Haro river loess-paleosol sequence
Arrows depict upward-fining sequence in mode distributions.

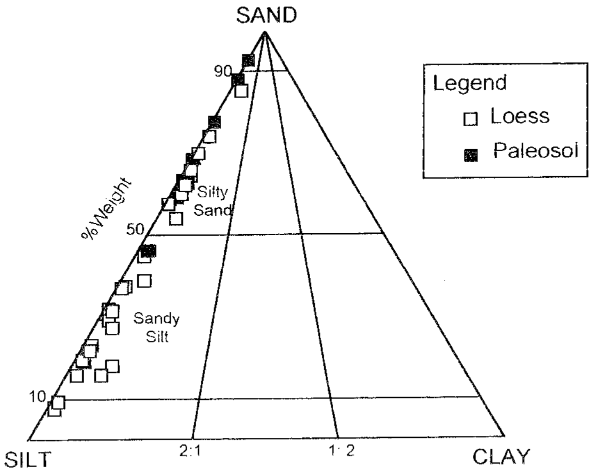

Fig. 7 Sand-silt-clay ternary plot (after Folk, 1970) for the particle size distribution of the Haro river loess-paleosol deposits

section exhibits cyclic upward fining sequence of coarser peaks of population which involve three major phases of the loess deposition alternating with pedogenic phases represented by three paleosol zones.

VI. Discussion

The Indian ocean monsoon dominates the seasonal wind and precipitation pattern and restricts the land environment in the southern Asia (Prell and Kutzbach, 1992). The seasonal change of monsoon is basically caused by the interaction between continents and oceans (Budyko, 1977). In the south-central Asia the atmospheric temperature in summer is considerably higher over the continent than over the ocean, while in winter it is lower. This is due to the high thermal capacity and conductivity of the water (ocean), causing the ocean to absorb a great amount of solar energy in the summer season and to discharge it during the winter season. This effect in thermal regime causes the formation of high surface pressure over the relatively cool ocean and low surface pressure over the warmer inland area in the summer season. Resulted gradient in surface pressure envokes a dominance of moist wind from ocean to internal continent in the summer season (summer monsoon). On the other hand, in the winter season, relatively high surface pressure in the continent gives a strong dry wind from inland to the oceanic coast (winter monsoon). It has been assumed that the long term evolution and variability of the monsoon can be attributed to change in orbital cycle of the solar radiation, the development of Himalaya-Karakoram-Tibet topography, and the changing configuration of the land and sea resulting from glacial eustatic changes of sea level. These amplify or dampen the seasonal processes of heating, latent heat transport, and moisture convergence over the southern Asia as well as the Asian continent. These factors have led to the strong monsoon wind into the southern Asian continent during summer while the strong monsoon wind out of the southern Asian continent during winter (Prell and Kutzbach, 1992). The summer monsoon in the southern Asia leads to high precipitation rate especially during months of June, July, and August. However winter monsoon leads to severe cold especially during months of October, November, and December (Nawaz, 1990).

The winter monsoon circulation is naturally responsible for the deflation and transport of the dust to the inner southern Asia that accumulates on land as loess. Simultaneously the summer monsoon circulation is mainly responsible for increased pedogenic activity. Loess units, therefore, mark times of high dust influx under a strengthened winter monsoon conditions. Paleosols, in contrast, represent times of decreased sediment flux when enhanced pedogenic activity under a strengthened summer monsoon conditions which leads to the development of accretionary soil profiles.

It is general observation that primary aeolian dust is predominantly composed of silt-size particles and dust transported by stronger winds during the winter monsoon has higher content of the coarse-silt-size particles. Based on this observation, it has been inferred by Xiao *et al.* (1992) and Xiao *et al.* (1995) that the silt contents and median size (Md(mm)) of dust in the loess-paleosol sequence are greater when the winter monsoon is strong. They further inferred that median size record reflects variations of average wind (winter monsoon) strength in the loess sequence in Chinese Loess Plateau.

The diagram showing variations of ϕ value of median size (Md(ϕ)) and weight percentage (wt%) of sand, silt, and clay in the Haro river loess-paleosol sequence (Figure 6) discloses that the sequence can be divided into two parts, above and below the PS-4 (middle paleosol) horizon, on the basis of the characteristics in particle size distribution. The lower part (below the PS-4 horizon) is characterized by low silt contents (wt%) and fluctuating low values of Md(ϕ), while the upper part (above the PS-4 horizon) by high silt contents with steady high values of Md(ϕ). In the Haro river loess-paleosol sequence, the variation of Md(ϕ) values corresponds well to that of sand contents (wt%), which means the change of Md(ϕ) mainly depends on the weight percentage of sand fraction in the particle population. The enhancement of sand fraction and also lower Md(ϕ) values probably attribute to an increase of local input of coarser materials and/or aggregating fine particles caused by relatively active pedogenesis during the accumulation of loess deposits, which suggests weaker winter monsoon and stronger summer monsoon. On the other hand, the augmentation of silt contents (wt%) probably represents greater influx of primary aeolian dust by winter monsoon and lower pedogenic activity during the deposition. These features indicate an environment of stronger winter monsoon and weaker summer monsoon. Therefore, the variations of Md(ϕ) values and silt contents (wt%) from the Haro river loess-paleosol sequence reveal that the winter monsoon was relatively weak during the periods before forming the middle paleosol zone (PS-4) but it became stronger after the formation of the PS-4.

The results of the modal analysis is consistent with the division described above. Identified three upward-fining sequences in the modal analysis (Figure 6) possibly indicate long term cyclic changes of the strength of winter monsoon. Thus the loess-paleosol sequence in the Haro river section possibly record a climatic deterioration phase from the Last Interglacial epoch to the Last Glacial epoch. Owing to a lack of direct geochronologic data from the section, it is difficult to determine the age of PS-4 but the section can be correlated with the late Pleistocene based on TL ages (18−75ka; Rendell, 1988, 1989) of loess deposits in adjacent area.

A summary of the paleoclimatic interpretations of the Haro river loess-paleosol deposits is given in Figure 8.

VII. Conclusions

The particle size composition of late Pleistocene loess-paleosol sequence of Haro River section shows distinct pattern of changes in median size, silt-size content, and mode, which constitutes a proxy

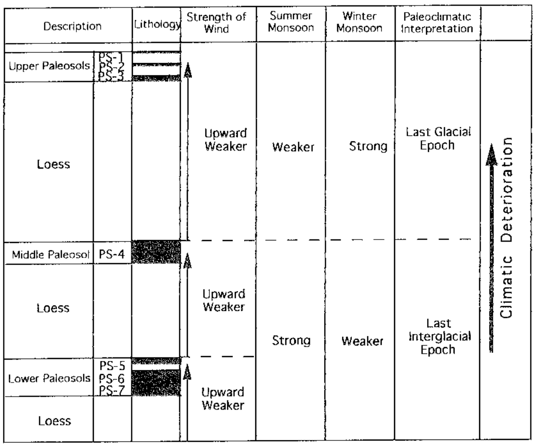

Fig. 8 Summary of paleoclimatic interpretation based on particle size distribution data of the Haro river loess-paleosol deposits

record that documents variation in strength of the Indian summer and winter monsoons. The paleosols were probably formed during intervals of enhanced summer monsoon circulation, whereas the loess units were developed at the time of increased winter monsoon strength. The median size and the weight percentage of silt-size particles can be used as a proxy for average winter and summer monsoon strengths and the change of mode for particle size population can be interpreted as a indicator for winter monsoon strength. Therefore particle size distribution analysis of loess-paleosol sequence is considered to be important for interpreting the paleoclimatic history of loess distributed region.

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パキスタン北部アトック盆地に分布する後期更新世レス・古土壌堆積物の粒度組成とその古気候解析

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要　旨

アトック盆地ハロ川流域に分布する後期更新世のレス･古土壌堆積物（約130～16ka）の層序を検討し，篩い法および遠心分離沈殿法による粒度分析を行い，これらの結果から古気候解析を行った．本レス・古土壌堆積物は7層準に古土壌を挟む（上位よりPS-1～PS-7と命名）厚いレス堆積物より構成されている．粒度組成の特徴は，レスと古土壌で明瞭な差異を呈し，レスは一般に淘汰度が良く，unimodal, leptokurtic, negatively-skewedの組成を示すのに対し，古土壌は淘汰度がやや不良で，顕著なbimodal組成の傾向を示す．また，レスは相対的に細粒でシルト質成分に富むのに対し，古土壌は砂質成分に富む組成を示す．ハロ川のレス･古土壌堆積物の粒度組成（モード，Median粒径，シルト成分含有量，砂質成分含有量）の層序変化を検討したところ，PS-4古土壌層を境にして下部レス層と上部レス層に大局的に区分できることが明らかになった．下部レス層は砂質成分に富み，Median粒径が不規則に変化し，比較的粗粒であるのに対し，上部レス層はシルト質成分に富み，Median粒径が相対的に安定し，細粒である．また，モード組成の変化に注目すると，各古土壌層を境にしてレス堆積物の粒度組成に周期的な上方細粒化の傾向が認められる（図6）．

下部レス層から上部レス層への粒度組成変化，特にシルト含有量の変化とMedian粒径の変化は，後期更新世における本地方の内陸性気候の変化を示している可能性がある．すなわち，レスを形成した南アジア・モンスーン気候の変化がレスの粒度組成に反映していると考えることができる．中国黄土高原でのモデルを援用するならば，下部レス層の時代は夏季モンスーンが卓越していたのに対し，上部レス層の時代は冬季モンスーンが支配的であったと解釈される．この下部から上部への気候の変化は，北部パキスタンにおける最終間氷期から最終氷期への移行を示すものかもしれない．

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