Tectonic control of Late Pliocene molasse sedimentation in a portion of the Jhelum Re-Entrant, Pakistan

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With 12 figures and 6 tables

Zusammenfassung

Im Gebiet von Jhelum (nördliches Pakistan) reicht das Vortief der neogenen Siwalik-Molasse als Sporn weit in den Faltenbogen des nordwestlichen Himalaya. Die Verfasser untersuchten hier einen Abschnitt des Spätpliozän mit besonderem Hinblick auf laterale Wechsel der fluviatilen Ablagerungen und Sedimentationsraten. Die Obere Siwalik-Molasse enthält hier zwei Leithorizonte mit Tuff, wodurch die Altersgleichheit der fluviatilen Zwischenlagerungen sichergestellt wird. Die Schichtfolge dieser Zwischenlagerungen ist an mehreren Lokalitäten in bezug auf Sedimentationstypen und -raten analysiert worden. Die vorgefundenen Ablagerungszyklen deuten auf ein System von seitlich wandernden Flußläufen. Vollständige Zyklen zeigen Flußbettsedimente (meist Ufersandbänke) gefolgt von feinkörnigen Überflutungssedimenten. Die Feingliederung der Überflutungsfazies zeigt stromnahe Ablagerungszonen einerseits und pedogenetische Randzonen andererseits.

Über das gesamte Untersuchungsgebiet ergibt sich eine klare Abhängigkeit zwischen Raten der Molasseaufschüttung und der Faltenbogentektonik des nordwestlichen Himalaya. Die Ablagerungsraten nehmen in Richtung des Bogenscheitels deutlich zu. Daraus wird geschlossen, daß während des untersuchten Zeitabschnittes die regionale Bogentektonik den Schwerpunkt der Molassesedimentation maßgeblich beeinflußt hat. Flache Flexuren innerhalb des Molassebeckens sind ebenfalls in diesen Zusammenhang zu stellen.

Abstract

A Late Pliocene interval of the Neogene Siwalik (Himalayan) molasse exposed in the Jhelum Re-entrant, Pakistan, is examined for lateral variations in the environment and rate of fluvial sedimentation. A correlative pair of volcanic ash horizons within the Upper Siwalik section defines an isochronous interval of fluvial deposition. Stratigraphic sections measured through the interval at various localities in the Jhelum Re-entrant are analyzed in terms of fluvial stratigraphy and interval thickness, or net sedimentation rate. The stratigraphy indicates a fluvial system of laterally migrating streams leaving behind fining upward sedimentary cycles of lateral and vertical accretion deposits. Fully developed sedimentary cycles display point bar sands (lateral accretion deposits) of the stream channel environment topped by mudstones (vertical accretion deposits) of the overbank (floodplain) environment. The detailed sequence of vertical accretion deposits in these cycles indicates that the floodplain environment consisted of a stream-proximal, sedimentation-dominant zone and a stream-distal, pedogenesis-dominant zone.

Broad lateral variations in the rate of molasse sedimentation appear to be related to the large-scale syntaxial tectonics of the northwestern Himalaya. Sedimentation rate increases toward the apex of the re-entrant, indicating that the syntaxial structure controlled the focus of molasse sedimentation during the examined interval of Late

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Pliocene time. In addition, sedimentation may have been influenced by mild flexures within the molasse basin.

Résumé

Une avant-fosse de la molasse du néogène Siwalik (Himalayen), en éperon dans l'arc plissé du nord-ouest de l'Himalaya, dans la région du Jhelum, Pakistan, a été étudiée quant à ses variations latérales environnantes et son taux de sédimentation fluviale. Dans la section du Siwalik supérieur, deux horizons-repères de tuffs volcaniques délimitent une période isochronique du dépôt fluvial. Les séries stratigraphiques de cet intercalaire ont été analysées en divers points en fonction de la stratigraphie fluviale et de son épaisseur ou en fonction du taux de sédimentation. Les cycles de sédimentation indiquent un réseau fluvial à migration latérale avec dépôts latéraux et verticaux, de plus en plus fins vers le haut. Les cours semblent être en transition avec le type traditionnel de haute et basse sinuosité. On démontre que l'ensemble des dépôts verticaux sont différentiés selon une zone proximale où la sédimentation domine et une zone distale où la pédogenèse domine.

De larges variations latérales dans le taux de sédimentation semblent dues à la tectonique globale de l'éperon associée à la syntexis du nord-ouest himalayen. Une tendance vers une augmentation du taux de sédimentation / subsidence en direction de l'axe de l'éperon délimite un lieu de sédimentation molassique pendant l'intervalle étudié. De plus, l'auteur suggère que la sédimentation du bassin de l'éperon ait été influencée par de légères flexures à la périphérie de la structure régionale.

Краткое содержание

В области Игелюм, северный Пакистан, неогеновые моляссы Сивалик далеко вклиниваются в складчатые дуги северо-западных Гималаев. Авторы изучали отрезок позднего плиоцена, обращая особое внимание на чередование флювиальных отложений и скорость осадконакопления на крыльях. Верхние слои молясса Сивалик содержат два ведущих горизонта, состоящих из туффов, что разрешает проводить возрастную корреляцию флювиальных отложений. Свиты этих прослоев в различных районах исследовали по типам осадков и скорости их накопления. Удалось установить, что эти отложения происходят от боковых притоков рек, меняющих свои русла. Осадки русел рек — чаще всего прибрежные песчаные банки — покрытые осадками различного гранулометрического состава, — сохранили циклы полностью. При проведении более мелкого стратиграфического подразделения фаций этих райодов установили с одной стороны зоны речных отложений, а с другой — почвенные краевые зоны.

Вся исследованная область показывает явную зависимость между скоростью осаждения моляссов и тектоникой складчатых дуг северо-западных Гималаев. Из этого следует, что в течение данного исследованного отрезка времени региональная тектоника дуг сильно повлияла на осадкообразование моляссов. Плоские флексуры внутри бассейнов молясса также связаны с этим периодом.

Introduction

The South Asian alpide system of mountain ranges provides a unique setting for observing the effect of recent compressional tectonics on the timing and characteristics of intramontane and foreland basin development. Late orogenic sediments abound in episutural, foredeep, and Chinese-type basins (Bally, 1975). Thousands of meters of these stratigraphically continuous molassic sediments record the recent morphogenesis and unroofing of this complex terrane (Fig. 1).

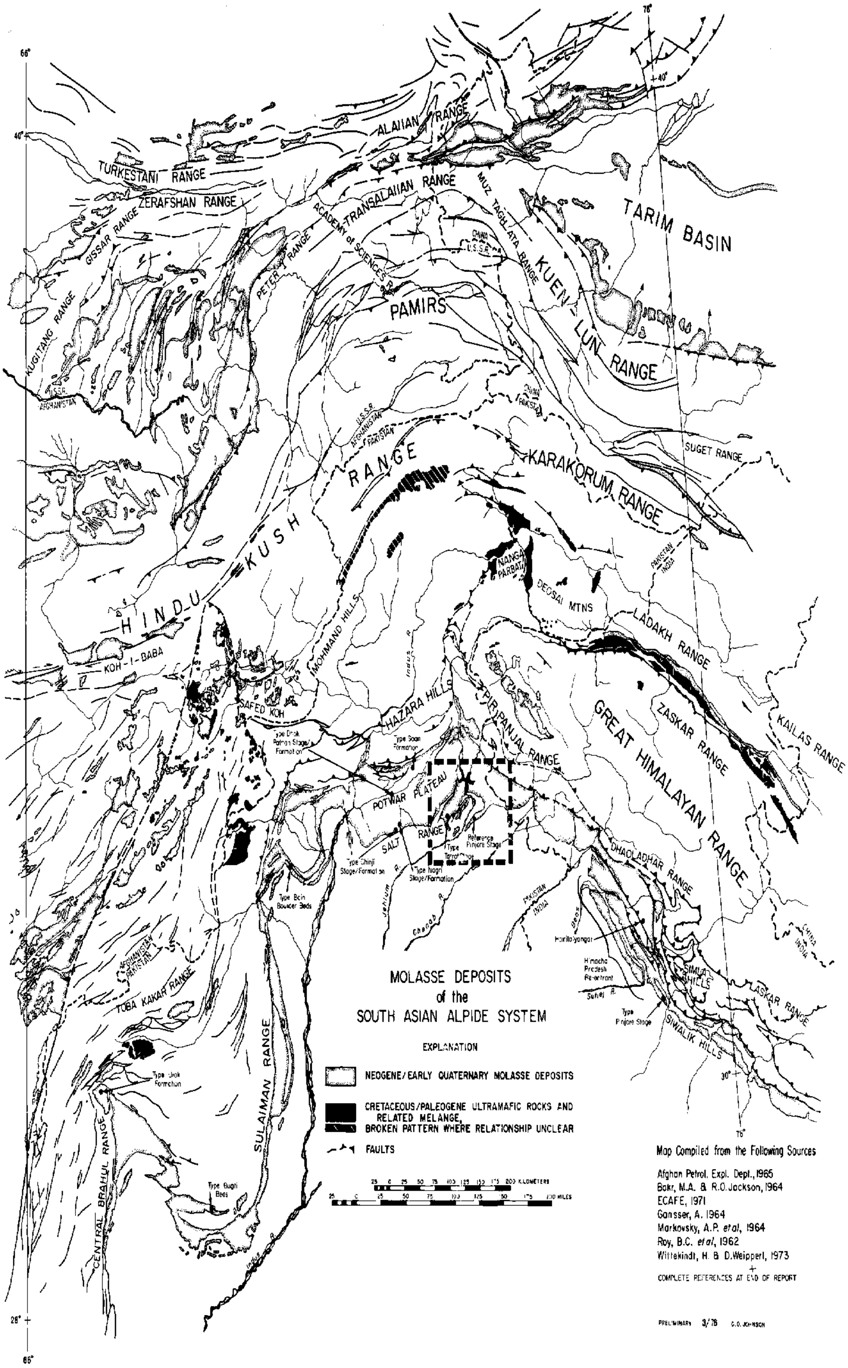

Fig. 1. Distribution of late orogenic molassic rocks within the South Asian alpide system. The Jhelum Re-entrant of this report is outlined to the east of the Potwar Plateau and Salt Range of northern Pakistan.

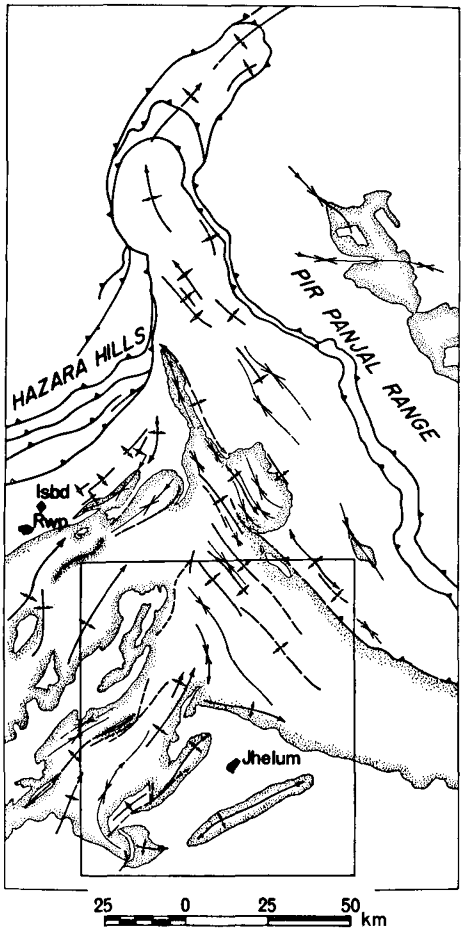

Fig. 2. Sketch map of the Jhelum Re-entrant, northern Pakistan, showing late-orogenic sedimentary facies (stippled). Structural axes shown for intra- and extra-basin structures. Late-orogenic deposits of the Kashmir Valley (N. E. portion of the map) included. Outline shows location of Fig. 3.

The Neogene Siwalik Group, the thick fluvial molasse exposed along the southern margin of the Himalaya, records the progressive uplift and denudation of the Late Cenozoic Himalayan orogen. During the Neogene and Quaternary, south-directed Himalayan tectonism was accompanied by rapid morphogenetic uplift. The consequent unroofing of the compositionally variable complex of Himalayan thrust plates provided source-proximal clastic sediments for a rapidly subsiding foredeep. The foredeep persists today as the Indo-Gangetic basin. Here, the pre-tectonic Early Paleogene carbonates are overlain by Late Paleogene and Neogene molassic rocks of the fluvial-deltaic Rawalpindi Group and the younger, fluvial Siwalik Group. The most recent phase of Himalayan tectonism has affected the northern margin of this foredeep, folding and faulting the entire sequence.

Exposures of the Siwalik Group in southwestern Kashmir and the northern Punjab of Pakistan deserve particular attention in view of the their position within the large-scale tectonic frame of the northwestern Himalaya. The Jhelum Re-entrant is a striking northward indentation in the trend of the outer (southern) Himalayan ranges (Fig. 2). This feature is the southern expression of the northwestern Himalayan syntaxis, a spectacular inflection in the strike of the orogenic belt observed as far north as the Pamir Range [1]) (WADIA, 1928; CRAWFORD, 1974). The Jhelum Re-entrant presently defines the site of debouchment of one of the principle antecedent streams of the Himalaya, the Jhelum River; the structural trough within the re-entrant probably has represented a focus of late-orogenic sedimentation for much of the Late Cenozoic. The Siwalik rocks of this area, then, presumably record the influence of regional re-entrant tectonics on foredeep sedimentation.

The cyclic sandstone/siltstone couplets of the Siwalik Group have been attributed to an aggrading fluvial system resembling the modern Indo-Gangetic plain (GANSSER, 1964; HALSTEAD & NANDA, 1973; LE FORT, 1975). JOHNSON & VONDRA (1972) concluded that Siwalik sediments in the Himachal Pradesh structural re-entrant of India were deposited by streams of varying sinuosity and meander belt development. They suggested a connection between fluvial regime and variables of source area tectonics and foreland basin subsidence. In the context of these previous interpretations, the remarkable tectonic setting of the Jhelum Re-entrant spurs an examination of the Siwalik sediments in this region.

General Geology

The tectonic frame of the Jhelum region is defined by a re-entrant trend of folds and thrust faults in the Hazara Hills to the northwest and the Pir Panjal Range to the northeast (Fig. 2). This structural trend forms an extraordinary hairpin bend 200 kilometers north of Jhelum. Further north, in the High Himalaya, the apex of the syntaxis is displaced eastward and is occupied by the Nanga Parbat massif, a Late Tertiary granitized terrane (MISCH, 1949).

Siwalik rocks of the re-entrant molasse basin outcrop as upturned strata adjacent to the arms of the syntaxial structure and on intra-basin anticlines.

Fig. 3 illustrates the general geology of the study area. The Siwalik strata of the Sub-Himalayan front range (Pir Panjal foothills) strike northwest through the northeastern limits of the area. The southwesterly dip of the front range strata steepens from 25° at Bhimbur to 65° near Kas Guma. The Jammu Fault parallels the front range to the northeast, forming a fault contact between the Siwalik Group and the older Rawalpindi Group. To the south, the Siwaliks emerge from beneath Recent alluvial sediments on four plunging anticlinal flexures, the Mangla-Samwal, Rohtas, Pabbi, and Chambal structures. These

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[1]) "Northwestern Himalayan syntaxis" here refers to the broad arc formed collectively by the Pamir, Hindu Kush, Karakorum, and Himalayan ranges, among others. "The Hazara-Kashmir syntaxis" of CALKINS et al. (1975) is strictly the tight structural loop confining rocks of the Rawalpindi Group near the pivot point of this regional arc.

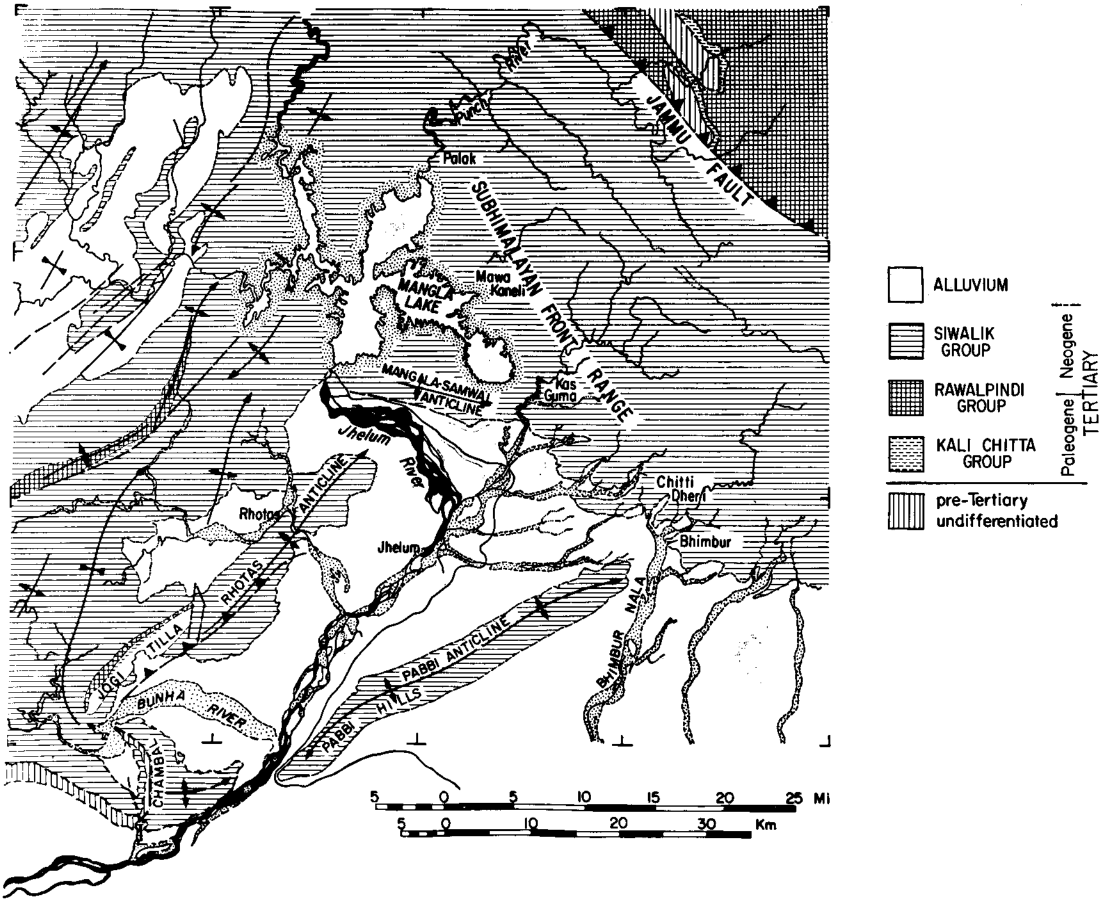

Fig. 3. Geologic sketch map of southern portion of the Jhelum Re-entrant in the vicinity of the Pabbi, Rohtas, Chambal, and Mangla-Samwal structures. Localities discussed in text.

structures, asymmetrical and locally faulted, are the southernmost expressions of the Himalayan structural re-entrant.

Stratigraphic Rationale

Aerial studies of Siwalik fluvial environments to date have been discouraged by a lack of stratigraphic control resulting from highly variable lateral facies changes. Many of the problems encountered have been directly attributable to the multi-storied character of many of the lateral accretion sandstone and overbank mudstone sequences characterizing the aforementioned sandstone/siltstone couplets. Commonly, the sandstones are not single-storied fluvial sands, but are multistoried composite sand bodies reflecting a complex fluvial history. Addition-

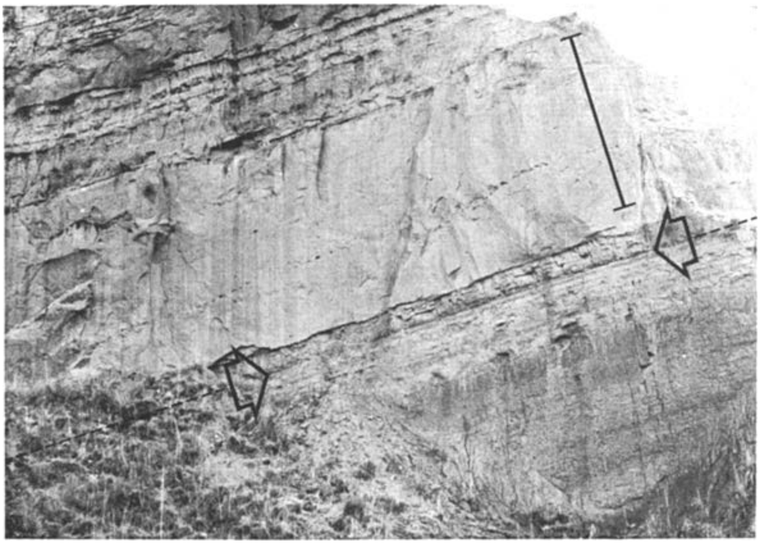

Fig. 4. Outcrop of typical fluvial cycles astride the lower ash (arrow) at locality MP 5 in the Mangla-Samwal anticline, Kashmir. Photo taken along East bank of Jhel Kas, 2 kilometers south of New Mirpur, Kashmir. Above ash, 1.5 meters of vertical accretion (overbank) deposits occur. This is followed by 11.5 meters of lateral accretion deposits of the overlying fluvial cycle. The vertical accretion facies of this uppermost cycle are exposed at top of photo. Rapid lateral variation in facies characterize these sediments. Length of bar, 10 meters.

ally, overbank deposits may not be single-storied, but reflect successive individual events of overbank vertical accretion. Commonly the highly variable fluvial facies can be interpreted to be products of a changing fluvial regime which may have been responding to variations in stream gradient, rates of basin subsidence, and compaction.

The Upper Siwalik sequence of southwestern Kashmir and the northern Punjab contains two bentonitized volcanic ash beds, spaced on the order of 50 meters apart stratigraphically (Fig. 4). The tuff couplet was observed in the Mangla-Samwal anticline, the Rohtas and Chambal structures, and the Pir Panjal foothills of southwestern Kashmir and at all localities appeared lithologically similar. Fig. 5 shows the distribution of measured stratigraphic sections containing the bentonitized tuffs. The tuff couplet defines an isochronous interval of fluvial sedimentation over a large part of the Jhelum Re-entrant. This measure of stratigraphic isochronism facilitated our interpretation of the Upper Siwalik foredeep environment.

ALI et al. (1962) mapped the distribution of the lower tuff bed, tracing approximately 30 kilometers of outcrop in the Mangla-Samwal anticline and more than 60 kilometers in the Sub-Himalayan front range. In the present study mapping of ALI's et al. localities was repeated in order to record the distribution of the bentonitized tuff lying approximately 50 meters higher in the sequence. The distribution of the two beds and the location of measured sections enclosing

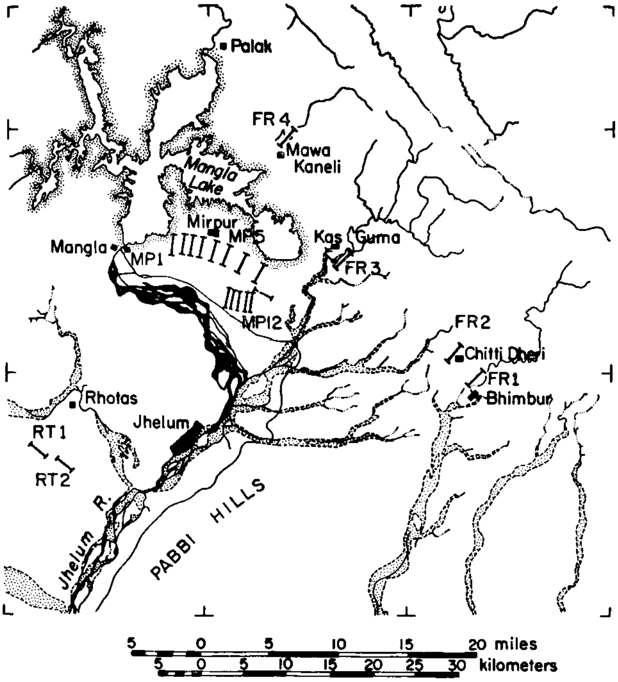

Fig. 5. Location of stratigraphic sections of measured and sampled Siwalik rocks containing the volcanic ash couplet used in this study.

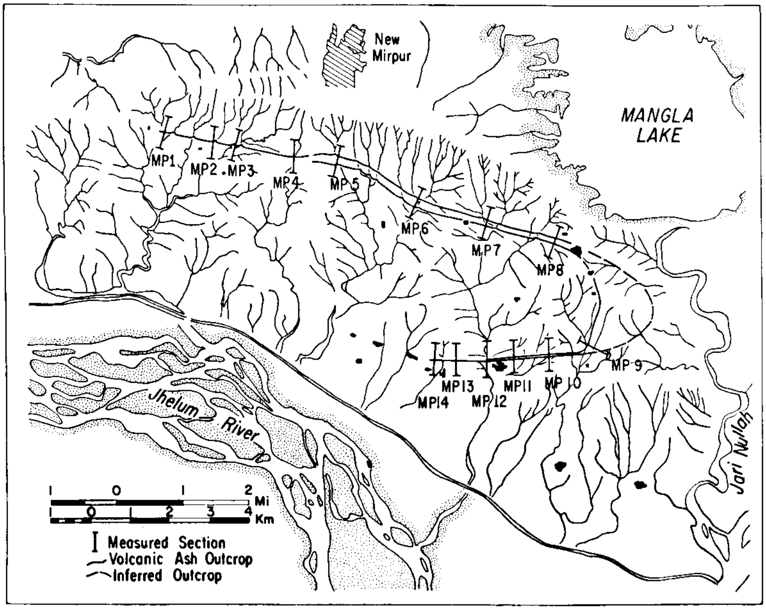

Fig. 6. Location of measured stratigraphic sections in the Mangla-Samwal anticline of Kashmir. Outcrop distribution of volcanic ash couplet found in the Upper Siwalik Group is shown.

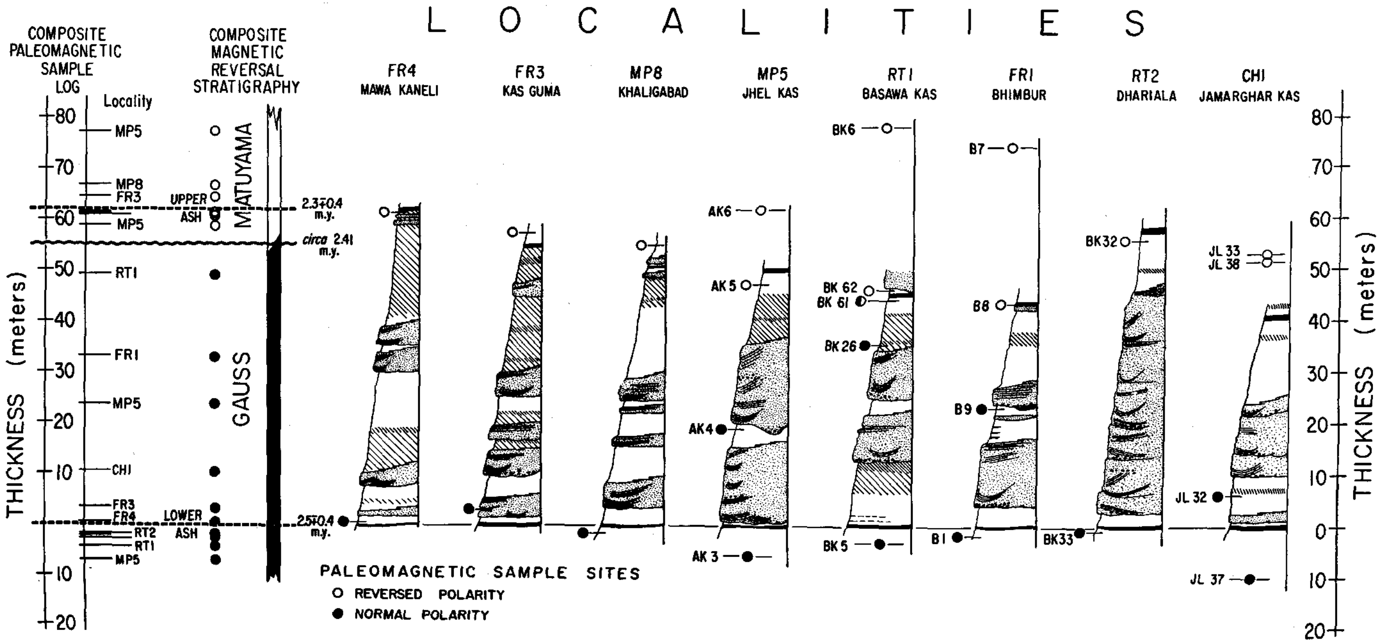

Fig. 7. Lithostratigraphic variation at eight localities in the Jhelum Re-entrant, Pakistan, showing Upper Siwalik rocks bounded by the bentonitic ash couplet discussed in text. Paleomagnetic sampling at each site was in triplicate following procedures outlined by N. M. Johnson et al. (Geol. Soc. America Bull., **86**, 5—12, Denver, 1975). Reliability discussed in G. D. Johnson et al., in preparation. Magnetic determinations by N. D. Opdyke. Data from the eight stratigraphic profiles are projected onto a composite paleomagnetic sample log (left) from which a composite magnetic reversal stratigraphic column for the Jhelum area is erected. This shows the projected position of the Gauss/Matuyama polarity transition relative to the bentonitic tuff couplet of this report. Lithologic symbols: Lateral accretion sandstone facies, stippled pattern showing dominant bedform; Vertical accretion mudstone facies with depositional fabric, no pattern; Vertical accretion mudstone facies with evidence of pedogenic (soil) modification, hatchered pattern. Inferred upper column positions in pedogenically modified mudstones — A or B_1 horizons —, double hatchered pattern. Localities shown an Figs. 5 and 6.

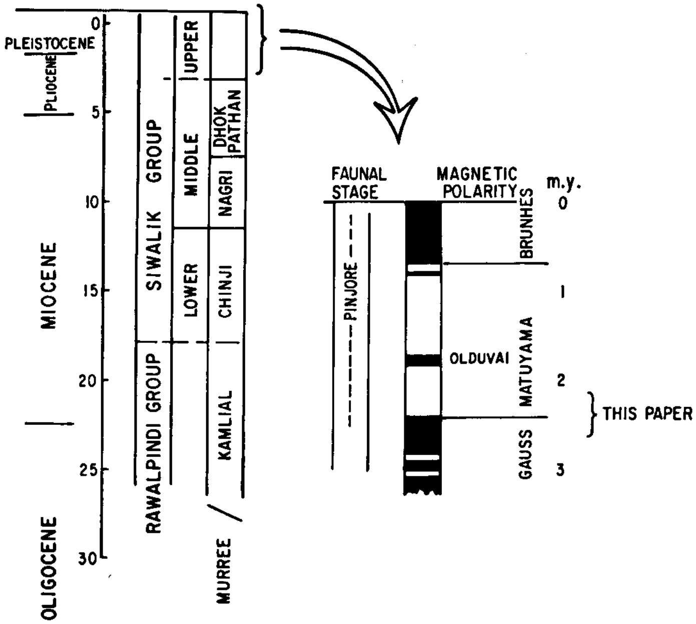

Fig. 8. Stratigraphic terminology applicable to the Neogene molassic succession studied in northern Pakistan.

the two horizons in the Mangla-Samwal area is shown on Fig. 6. Faulting of the western part of the southern limb of the anticline accounts for the absence of the tuffs in that portion of the structure (Ali et. al., 1962). Additional localities exposing the volcanic tuff couplet were located in the Upper Siwalik section exposed on the Rohtas flexure at Basawa Kas and Dhariala and along the Jamarghal Kas on the Chambal flexure (Akbar et al., 1964; Johnson, G. D. et al., in preparation).

Paleomagnetic sampling coupled with radiometric dating of the above tuff horizons have clarified the Siwalik chronology of much of the Jhelum Re-entrant (N. D. Opdyke et al., in preparation; Johnson, G. D. et al., in preparation). Fission track ages of 2.3 ± 0.4 million years B. P. and 2.5 ± 0.4 million years B. P. have been obtained on zircon phenocrysts from the two bentonitized tuffs found in the Siwalik section at Jhel Kas, in the Mangla-Samwal anticline (the two tuffs of site MP 5 of this study). These radiometric dates are in agreement with paleomagnetic results placing the tuffs astride the Gauss-Matuyama polarity transition (2.41 m. y. on the geomagnetic time scale) Opdyke, 1972; N. D. Opdyke et al., in preparation) (Fig. 7). Based upon vertebrate faunal elements characteristic of the South Asian Pinjor land mammal age, the strata examined in the present study occur in the middle part of the Upper Siwalik Subgroup (Johnson, G. D. et al., in preparation; Keller et al., 1977) (Fig. 8).

Fluvial Stratigraphy

Our examination of the Upper Siwalik fluvial sequence has demonstrated the applicability of ALLEN's (1965 a, 1965 b, 1965 c, 1970) concept of fining upward fluvial cycles. According to this scheme, each fining upward cycle represents the lateral migration of an aggrading stream. Coarse channel lag and point bar sands (lateral accretion deposits) are laid down within the stream channel, and overbank mudstones (vertical accretion deposits) accumulate on adjacent floodplains. As the stream thalweg migrates laterally, relict channel and point bar deposits are covered by mudstones of the trailing floodplain. Repeated lateral migration and aggradation in this manner results in a sequence of fining upward cycles. Thus, at any point in the fluvial plain, the vertical sequence of deposits gives a time record of the various fluvial environments crossing the point during stream migration. Commonly erosion takes place at the base of a cycle, rendering the previous cycle incomplete. Elimination of vertical accretion mudstones by this process creates "multistoried" sand units.

The vertical accretion deposits observed in the present study fall into five categories on the basis of field identifiable characteristics (color, grain-size, and internal fabric):

Type R1)	pale red laminated claystones and silty claystones: fine lamination showing varying degrees of soft-sediment deformation; sparse crotovina (animal burrows) and very sparse plant debris; principal Munsell colors 5R6/2 to 5R4/2; lamination is accentuated by fine color variegation and parting; interbedded with brown siltstones (Munsell colors 10YR (5.5—6)/(2—3) of approximate thickness 5 to 10 cm.
Type Rm)	pale red massive claystones and silty claystones: homogenized to massive fabric; Munsell color 5R6/2 to 5R4/2.
Type Yb)	variegated yellowish-brown claystones, silty claystones and clayey siltstones: homogenized to massive fabric; variegated color horizonation; principal Munsell colors 10YR (5—6) (4—6).
Type O)	olive gray, olive brown and dark yellowish-brown pisolitic claystones: homogenized to massive fabric; principal Munsell colors 5Y (4—5)/(1—4) and 10YR (4—5)/(2—4) black to brown pisoliths (3 mm diameter); transitional contacts with type Yb, olive or dark yellowish-brown horizons usually less than one meter in thickness.
Type Sp)	yellow, gray and brown sandstones and silty sandstones (splay deposits): massive fabric; fine to medium grainsize; fining upward, poorly sorted; principal Munsell colors 5Y (6—7)/(1—4), N (5—6), 10 YR (4—6)/(2—3), 5YR (4—5)/(1—4).

The absence of extensive bioturbation in the laminated (type R 1) claystones suggests backswamp deposition with frequence ponding. Homogenized clays of the same color (type Rm) may represent bioturbated sediments of a more "ripened" aspect (see discussion of soil ripening in PONS & ZONNEVELD, 1965).

The homogenized fabric, variegated color horizonation, and the presence of sesquioxide pisolites in claystones of type Yb and type O represent evidence of pedogenic alteration of original depositional fabric. Dark pisolitic zones in particular may be characteristic of illuviation in the B-horizons of these alluvial soils of Al and Fe sesquioxides (Al_2O_3, Fe_2O_3), clays, and some organic matter (JOHNSON, 1977). Dark green and olive-hued overbank sediments suggest reduced conditions typical of poorly drained soils (PAPADAKIS, 1969).

Analyses of other ancient fluvial sequences have shown Markov chain analysis to be an effective means of detecting repetitive processes in multicomponent cyclic deposition (GINERICH, 1969; ALLEN, 1970; SELLEY, 1970; MIALL, 1973). Applied to an array of thin, time-synchronous sections such as the present data base, the procedure derives statistically the principal depositional sequences operating in a region of sub-contemporaneous fluvial deposition. Since the depositional sequence is a result of laterally migrating fluvial environments, the areal distribution of facies in the floodplain can be ascertained. The reader is referred to standard matrix analysis techniques outlined by ANDERSON & GOODMAN (1957) and BILLINGSLEY (1961) and to MIALL (1973) for an example of the technique used in the present analysis.

Applying the method to the present stratigraphy, we consider as depositional components the five above-mentioned vertical accretion lithologies and a single variable for laterial accretion. (Multistoried sand bodies represent several episodes of lateral accretion. However, sufficient discrimination of discrete sand units in a multistoried body is often difficult. Hence, in the matrix analysis we consider multistoried sand bodies as a single unit of lateral accretion. This procedure allows no quantitative results on the frequency of repeated lateral accretion episodes affecting channel facies.)

The number of times one of the six vertical accretion lithologies stratigraphically succeeds another of the six can be recorded in a transition count matrix (Table 1). From the transition count matrix, two probability matrices may be generated. The first, Table 2, represents the calculated probabilities of the various lithologic transitions if developed randomly in the stratigraphic sections. The second matrix, Table 3, yields the actual probabilities of each transition occurring in the sections. Comparison of the two probability matrices reveals the specific lithologic transitions which occur in the sequence more often than would be expected from a random arrangement. These preferred transitions are marked by positive values in Table 4, which records the differences between the actual probabilities and probabilities expected from a random arrangement. The results of Chi-square testing are given in Table 5; the presence of the Markov property in these transitions is clearly evident. The derived facies relationship diagram shows the transitions occurring more often than expected assuming a random model (Fig. 9). Consideration of these data yields the following:

1) Lateral accretion (La) tends to be followed by vertical accretion of type Yb. The fabric of type Yb appears to be a product of pedogenesis (see 2, below). Type R 1 also tends to follow lateral accretion, but with a somewhat lower probability than type Yb.

2) Type Yb tends to be followed by type O. On the basis fabric, color horizonation, and the presence of sesquioxide segregations it appears that type

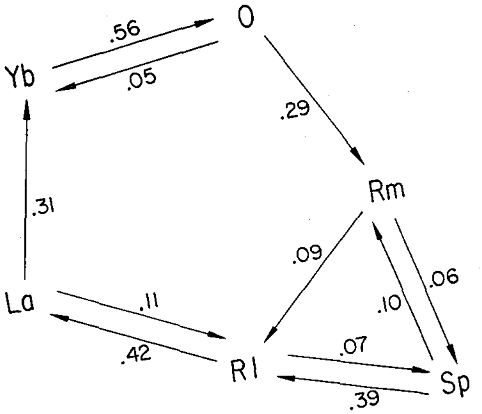

Fig. 9. Facies relationship diagram showing the transitions occurring more often than expected from a random arrangement. Paths of d < 0.5 excluded for clarity. Values give the greater-than-random probabilities of transitions. Arrows point to overlying unit. Facies scheme as follows: La, lateral accretion sandstones; R 1, pale red laminated claystones and silty claystones; Rm, pale red massive claystones and silty claystones; Yb, variegated yellowish-brown claystones, etc.; O, olive gray, etc. pisolitic claystones; and Sp, splay deposits.

Yb/type O couplets represent soil horizonation. There is a slight tendency for type Yb and type O to alternate and in turn be followed by type Rm. The several instances of multistoried type Yb/type O couplets appear to reflect successive episodes of soil horizon development taking place during the increment accumulation of overbank sediment. In this case type Rm occurs as a well-homogenized upper soil solum (A) horizon with the underlyind type O developing as an illuviated (B) horizon.

3) Types Rm, R 1, and Sp tend to alternate with each other. The alternation of these vertical accretion lithologies suggests a multistoried process of successive flooding, coarse slackwater deposition (type Sp), fine slackwater deposition (type R 1) and bioturbation (type Rm). Appropriately, splay sands (type Sp), tend to be followed by a laminated fine-grained lithology (type R 1).

4) Type R 1 tends to be followed by lateral accretion (type La). If pale red laminated clays are the product of slackwater deposition in areas frequently flooded, the data support the tenable conclusion that laterally migrating stream thalwegs are immediately preceded by a frequently flooded proximal environment in which sedimentation overshadows pedogenesis. Marked pedogenic horizonation and disturbed vertical accretion fabrics usually give way to laminated claystones at some distance below the base of lateral accretion units. The exceptional cases, where lateral accretion sandstones overlie pedogenic vertical accretion units, can be explained by basal reworking of laminated topstrata.

Lateral accretion sandstones thus tend to be preceded stratigraphically by undisturbed vertical accretion units indicating a frequently flooded, sedimentation-dominant, flood basin environment. It was observed previously that lateral accretion units tend to be followed by vertical accretion units of type Yb, suggesting a post-migration environment of pedogenesis. Whether the environments preceding and following a laterally migrating thalweg indeed differ is uncertain; pedogenically modified vertical accretion lithologies overlying lateral accretion sandstones may reflect deep pedogenic overprinting occurring at a time much later than the active migration of the stream course.

Table 1. Transition count matrix showing frequencies with which one lithology is overlain by another. Lithologic categories as described in text.

Lithology	R 1	Yb	La	O	Rm	Sp	Row sum
R 1	0	3	23	0	2	7	35
Yb	4	0	1	27	0	3	35
La	10	18	0	0	2	0	30
O	0	9	2	0	12	4	27
Rm	5	5	4	0	0	3	17
Sp	10	3	0	0	4	0	17
						Total	161

Table 2. Independent trials probability matrix showing the probabilities of lithologic transitions assuming a random arrangement of lithologies.

Lithology	R 1	Yb	La	O	Rm	Sp
R 1	0	0.30	0.24	0.21	0.16	0.13
Yb	0.23	0	0.24	0.21	0.16	0.13
La	0.22	0.29	0	0.21	0.15	0.13
O	0.22	0.28	0.22	0	0.15	0.13
Rm	0.20	0.26	0.21	0.19	0	0.12
Sp	0.20	0.26	0.21	0.19	0.14	0

Table 3. Transition probability matrix showing the actual probabilities of lithologic transitions.

Lithlogy	R 1	Yb	La	O	Rm	Sp
R 1	0	0.09	0.66	0	0.06	0.20
Yb	0.11	0	0.03	0.77	0	0.09
La	0.33	0.60	0	0	0.07	0
O	0	0.33	0.07	0	0.44	0.15
Rm	0.29	0.29	0.24	0	0	0.18
Sp	0.59	0.18	0	0	0.24	0

Table 4. Matrix showing the differences between actual probabilities (from Table 3) and the theoretical probabilities expected from a random arrangement of lithologies (from Table 2). Positive values indicate transitions occurring more often than expected from a random arrangement.

Lithology	R 1	Yb	La	O	Rm	Sp
R 1	0	— 0.21	+ 0.42	— 0.21	— 0.10	+ 0.07
Yb	— 0.12	0	— 0.21	+ 0.56	— 0.16	— 0.04
La	+ 0.11	+ 0.31	0	— 0.21	— 0.08	— 0.13
O	— 0.22	+ 0.05	— 0.15	0	+ 0.29	+ 0.02
Rm	+ 0.09	+ 0.03	+ 0.03	— 0.19	0	+ 0.06
Sp	+ 0.39	— 0.08	— 0.21	— 0.19	+ 0.10	0

Table 5. Tests of significance.

	χ^2 (chi-square)	degrees of freedom	limiting *) value
Test Equation 1 **)	180.796	24	36.4
Test Equation 2***)	249.823	19	30.1

*) From table of chi-square values with correct number of degrees of freedom, 95% confidence level.

**) Equation 1 from Billingsley (1961), [Equation 4 of Miall (1973)].

***) Equation 2 from Anderson & Goodman (1957) [Equation 5 (corrected) of Miall (1973)].

Fluvial Stratigraphy and Position in the Jhelum Re-entrant

In searching for large-scale lateral trends in fluvial environment, two variables are especially worthy of consideration: the total thickness of lateral accretion sands preserved in a given section, and the thickness of the interval enclosed by the bentonitized tuff couplet at each locality.

The total thickness of lateral accretion deposits in a given section is influenced by myriad environmental variables. The thickness of individual cross-stratified lateral accretion cycles, neglecting erosion, approximates the depth of the laterally migrating stream (Moody-Stuart, 1966; Allen 1965 c). The number of cycles, observed in single or multistoried units, reflects the frequency of stream transgression (Johnson & Vondra, 1972). The frequency of transgression is probably controlled by such variables as the rate of bank erosion and the degree to which the thalweg is confined to a restricted meander belt or free to sweep the floodplain. Presumably, these factors are in turn related to stream sinuosity and gradient. On a greater scale, it is probable that many of the aforementioned variables are dependent on position in the sedimentary basin.

In spite of the many related factors, the total thickness of lateral accretion deposits appears to be a valid measure of the net proximal stream activity. Localities proximal to major fluvial courses during much of the interval of deposition are likely to display greater total lateral accretion thicknesses than distal, floodplain localities. (Note: this measure is insensitive to the scale of streams; several thin lateral accretion units left behind by encounters of shallow streams could have a cumulative thickness equivalent to the single, thick lateral accretion unit of a deeper stream.)

The thickness of the interval enclosed by volcanic ashes embodies a direct measure of net sedimentation rate.

Table 6 presents the total lateral accretion thickness and interval thickness for several localities in the Jhelum Re-entrant. The site of greatest proximal stream activity is Dhariala (RT 2), with 43 meters of lateral accretion deposits encompassing about two-thirds of the entire interval. The Dhariala lateral accretion component consists of a single multistoried sand, the thickest observed in the study area. At 57 meters the total thickness of the interval is the second greatest observed, indicating a relatively high sedimentation rate. Dhariala was a locality of rapid aggradation and intense, repeated stream encounter.

The interval at Basawa Kas (RT 1), only 3 kilometers to the west, contains 18 meters of multistoried lateral accretion sand in a total interval of 44.5 meters. Compared with Dhariala, Basawa Kas was a locality of significantly lower net proximal stream activity and reduced sedimentation rate during the examined interval. These data demonstrate a marked contrast in fluvial conditions over a horizontal distance of only 3 kilometers.

Table 6. Sedimentary thickness, lateral accretion thickness and sedimentation rates observed for interval enclosed by two volcanic ashes astride the Gauss-Matuyama polarity transition at selected sites within the Jhelum Re-entrant.

Locality	Total Thickness of Lateral Accretion (m)	Interval Enclosed by Volcanic Ashes (m) **)	Sedimentation Rate ($m \cdot 10^{-3}$ yr)
Rohtas Anticline			
Basawa Kas (RT 1)	18.0	44.5	0.34 *)
Dhariala (RT 2)	43.0	57.0	0.43
Sub-Himalayan Front Range			
Mawa Kaneli (FR 4)	11.0	61.5	0.47
Kas Guma (FR 3)	15.0	54.5	0.42
Chitti Dheri (FR 2)	7.0	47.5	0.36
Bhimbur (FR 1)	15.5	43.2	0.33
Palak	> 33.0	> 65.0	> 0.50
Mangla-Samwal Anticline			
Jhel Kas (MP 5)	30.0	49.5	0.38
Podi (MP 6)	29.0	50.0	0.38
Dhok Tarappa (MP 7)	29.0	52.0	0.40
Khaligabad (MP 8)	18.0	51.0	0.39
Dhok Dhara (MP 9)	22.0	49.0	0.38
(MP 10)	15.0	47.0	0.36
(MP 11)	19.0	49.5	0.38
Samwal (MP 12)	15.0	47.5	0.36
Pabbi Anticline			
Khohar Khurd (P 15)		(41.6) ***)	0.32 *)
Chambal Ridge			
Jamarghal Kas (J 1)	16.2	43.0	0.33

*) Calculated from sedimentation rate curves established by magnetic reversal interpretation of measured stratigraphic sections (measurements by N. D. OPDYKE).

**) Depositional interval represents 1.3×10^5 yr, calculated from sedimentation rate and interval thickness data from sites RT 1 and MP 5. Interval thickness measured from base of lower ash to base of upper ash.

***) Calculated from sedimentation rate data applied during the calculated 1.3×10^5 yr duration of the depositional interval. Rate data from KELLER et al., 1977.

The cumulative lateral accretion thickness on the northern limb of the Mangla-Samwal anticline, particularly at sites MP 5, MP 6 and MP 7, is greater than on the southerm limb, suggesting greater proximal stream activity to the north. The similar interval thicknesses throughout the anticline define a region of subequal sedimentation rate. Throughout the anticline, large lateral accretion units are multistoried.

The low total sand thicknesses and the dominance of single-storied units in the Sub-Himalayan front range are particularly striking. The 61.5 meter interval at Mawa Kaneli (FR 4) encloses a mere 11 meters of lateral accretion deposits in three thin single-storied units. While the interval displays the most rapid sedimentation rate observed in the study area, the low total lateral accretion thickness implies an environment generally removed from proximal stream activity. The interval thicknesses in the front range exhibit a trend of regularly increasing sedimentation rate from 0.33 meters/1000 years at Bhimbur (FR 1) to 0.47 meters/1000 years at Mawa Kaneli (FR 4).

Lateral Accretion Morphology

Thirteen stratigraphic sections were measured in the Mangla-Samwal anticline (Fig. 6) in order to outline the morphology of lateral accretion units. Generally, two lateral accretion sand units were observed in the interval defined by the upper and lower bentonitized tuff horizons (Fig. 10). Two lateral accretion sand units were traced over 10 kilometers on the northern limb of the structure (sections MP 1 through MP 8). The sand units were obscured by alluvium near Khaligabad (MP 8), but a sand unit lying a short distance above the lower volcanic ash was traced for 2 kilometers around the nose of the fold and a further 4 kilometers along the southern limb to Chabrian (MP 13). The lateral accretion units were traced 500 meters further to site MP 14, but the section was not measured. The upper lateral accretion unit was not traced in the plunging nose of the fold.

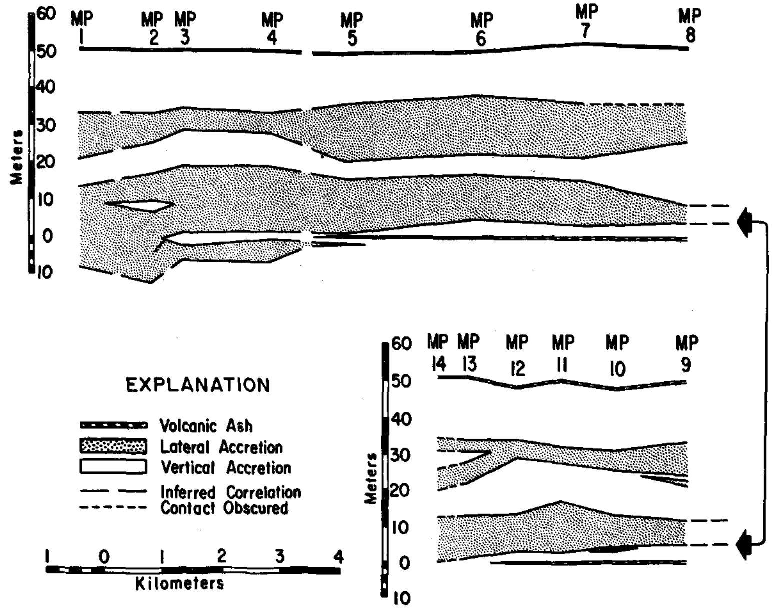

Fig. 10. Composite cross-sectional morphology of the lateral accretion units within the ash enclosed interval exposed in the Mangla-Samwal anticline, Kashmir. Location of measured sections shown in Fig. 6.

Although a multilateral composite sand body, the lower lateral accretion unit is, to a reasonable degree of certainty, everywhere correlative, indicating considerable areal extent.

Discussion:

Fluvial Environment

The greater fluvial environment of the southern Jhelum Re-entrant area during the examined interval is characterized by extensive lateral migration of streams. The general constancy of grain-size in many of the lateral accretion units and the absence of significant conglomerate facies implies deposition in a relatively low gradient environment. Vertical accretion deposits reflect multipe episodes of slack water floodplain sedimentation and distinct lateral differentiation into a proximal, sedimentation-dominant zone and a distal, pedogenesis-dominant zone. Together, the lateral and vertical accretion components imply frequent modification of the local fluvial environment in response to lateral migration of stream thalwegs.

The character of the streams responsible for Upper Siwalik sedimentation in the study area is problematic. Keller et al. (1977) working in somewhat younger Upper Siwalik rocks of the Pabbi Hills, concluded that the general alternation of upward-fining fluvial cycles is good evidence for Allen's (1965 b) fluvial system of high sinuosity streams, yet the lateral extent of the sand bodies is suggestive of relatively low sinuosity streams. It is evident that neither model is appropriate without modifications. The presence of thick, well-developed vertical accretion units implies the relatively prolonged existence of a differentiated floodplain environment, a feature of meandering streams. However, the great lateral extent of lateral accretion bodies implies that streams were not confined to a narrow meander belt but rather to a broad alluvial plain much like the present Indo-Gangetic plain.

Multistoried lateral accretion sands were observed in many of the sections. Allen (1965 b) considers multistoried lateral accretion sequences preserving few vertical accretion clays a feature of the low-sinuosity association. Johnson & Vondra (1972) used multistoriedness as one criterion for assigning the Lower Siwalik Nahan sandstone at Haritalyangar, H. P., India to a low sinuosity regime. However, in the sections of the present study, multistoried lateral accretion units are often preceded or followed by significant intervals of vertical accretion; multistoried sand deposition is not the rule, rather it represents one possible product of the fluvial system.

Re-entrant Tectonics and Sedimentation

Wadia (1928, 1931) demonstrated the striking continuity of lithologic and tectonic elements across the northwestern Himalayan syntaxis. He attributed the spectacular flexure to the deflection of Himalayan folding by a "tongue-like projection from the Archaean peninsular shield" (Wadia, 1931). Wadia's classic notion is clearly similar to one contemporary view: a north projecting spur of the Indian lithospheric plate colliding with the Eurasian plate. Crawford (1974),

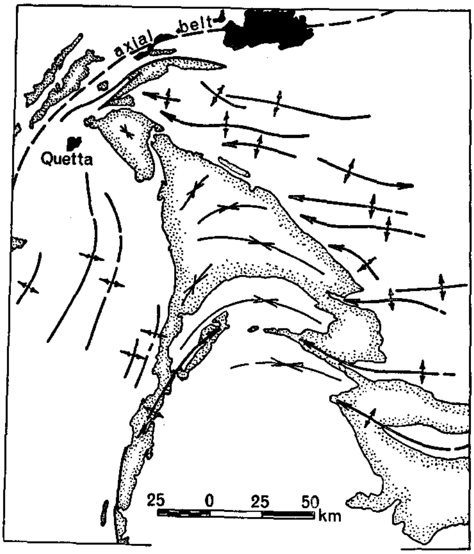

Fig. 11. Sketch map of late orogenic sedimentary facies (stippled) of the Sibi Re-entrant, Baluchistan. Structural axes shown for both intra- and extra-basin structures. Black area along Axial Belt represents outcrop position of ultrabasic rocks.

on the other hand, considers the syntaxis a secondary feature formed between converging Eurasian crustal blocks to the east and west of the syntaxis.

A recent study of a portion of the syntaxis by Calkins et al. (1975) has clarified the timing of part of this major tectonic feature. Deformation in the syntaxial zone of Hazara and Kashmir is first evidenced in the clastic rocks of the Rawalpindi Group (Oligocene to Miocene) with the main deformation occurring somewhat later. Deformation of the Siwalik strata represents the latest phase of tectonism. In spite of this extensive work, the full history of the greater syntaxial region remains enigmatic.

A general lessening of tectonic severity occurs southward from the apex of the syntaxis to the foreland plains of Kashmir and the Punjab. The tectonic influence of the syntaxis attains its southernmost expression in the low-lying flexures in the Jhelum molasse basin, among them the Pabbi Hills and the Mangla-Samwal and Rohtas anticlines of this study. These mild foreland flexures display axial trends transverse to the strike of the syntaxial arms. Work on re-entrant trends elsewhere in the South Asian alpide system has revealed similar transverse flexures. The Sibi Re-entrant of Baluchistan is especially noteworthy since it resembles the Jhelum Re-entrant in shape and structural setting (Fig. 11). The Sibi Re-entrant underwent a period of syntaxial folding and re-entrant basin molasse deposition roughly coincident with the Himalayan Orogeny (Auden, 1974).

A reconaissance survey of the Sibi Re-entrant (Hunting Survey Corp., 1961) revealed three types of structures in the Neogene molassic rocks of the re-entrant basin:

(a) peripeheral flexure with axes parallel to the strike the syntaxial arms,

(b) inward-plunging en echelon flexures protruding from the arms of the syntaxial structure,

(c) anticlines and synclines bridging toe re-entrant transverse to the strike of the syntaxial arms.

The survey concluded that the transverse flexures developed in response to triaxial horizontal compression in the syntaxial zone. Stratigraphic thinning of the sedimentary section atop the transverse anticlinal structures indicates that folding took place contemporaneous with molasse deposition (Movshovitch & Malik, 1965).

The anticlinal structures in the molasse basin of the Jhelum Re-entrant, namely the Mangla-Samwal Rohtas, Pabbi anticlines and others, hold a similar relationship to the regional syntaxial structure (compare Figs. 2 and 11). These anticlines are oblique to the general trends of the eastern and western syntaxial arms. The Mangla-Samwal anticline strikes west-northwest, 40 to 60 degrees oblique to the strike of the Subhimalayan front range. The Rohtas flexure diverges from the northern Salt Range trend, plunging northwest toward the axis of the re-entrant. The transverse, doubly plunging Pabbi anticline separates the re-entrant basin from the Punjab plains to the south.

The effects of structural re-entrants on fluvial molasse sedimentation have been described in the Canadian Cordillera of North America (Eisbacher et al., 1974), where re-entrants were preferential sites for the passage of major longitudinal intermontane rivers into the molasse basin. Accordingly, re-entrants define major foci of molasse sedimentation, although longitudinal sediment transport may take place along a foredeep basin. In addition, the convergence of tectonic compression in a syntaxial zone may contribute to the progressive deepening of the re-entrant trough, permitting thick sediment accumulation (Hunting Survey Corp., 1961). Isopachs constructed for the Sibi Re-entrant indicate a pronounced trough of molasse accumulation (Movshovitch & Malik, 1965).

In the Jhelum Re-entrant, the interval spanned by the volcanic ash couplet provides a convenient measure of relative sedimentation rates during a portion of Late Pliocene time (i. e. circa 2.4 million years B. P.). The distribution of interval thicknesses is presented in Fig. 12 and Table 6. With minor exceptions, the sedimentation rate increases regularly toward the re-entrant apex. Late Pliocene molasse deposition intensified in the direction of the re-entrant apex, precisely the pattern expected if a focus of sedimentation was centered within the developing re-entrant structure.

The exceptions to this pattern are of particular interest. Sites RT 1 and RT 2 in the Rohtas flexure display a significant contrast in sedimentation rate over a short horizontal distance. The Dhariala site lies on the downthrown southeastern limb of the faulted Rohtas structure. Differential syndepositional subsidence on opposite sides of the reverse fault could produce the observed contrast in interval thickness. This is the best supporting evidence for the penecontemporaneous deformation of the Rohtas structure during latest Pliocene/earliest Pleistocene time. Keller et al. (1977) dated the initiation of the surface expression of the Pabbi Hills at 0.4 to 0.6 million years B. P., much later than the interval under consideration. However, the subsurface development and growth of the Pabbi uplift certainly occurred somewhat earlier.

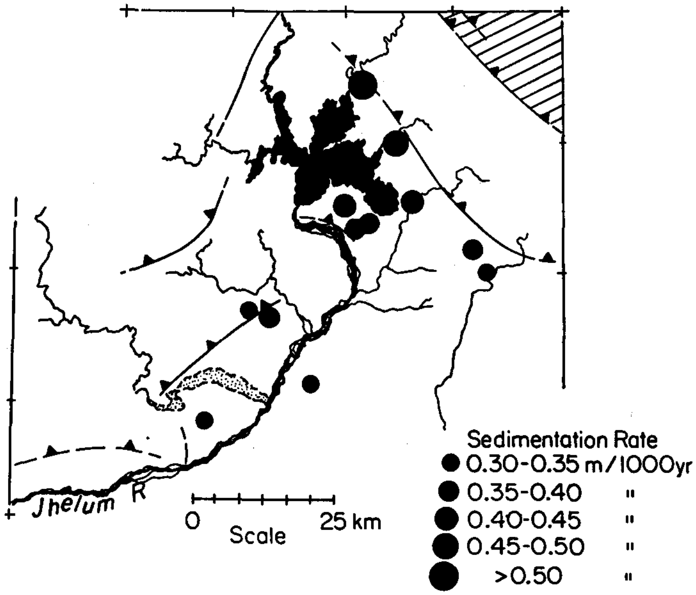

Fig. 12. Areal distribution of observed sedimentation rate at 2.41 m. y. B. P. (Gauss/ Matuyama magnetic polarity transition) within the Jhelum Re-entrant. Localities discussed in text.

Sedimentation rates are quite regular in the sections in the Mangla-Samwal anticline. The Mangla-Samwal region underwent lower sedimentation rate than the northernmost front range sites (FR 3, FR 4). At present there is no evidence for stratigraphic thinning due to contemporaneous uplift of the Mangla-Samwal transverse structure.

Regardless of the interpretation assigned to various features of the basin contour, it is obvious that local fluvial environment and sedimentation rate are generally only loosely related. The thick intervals exposed in the Sub-Himalayan front range display anomalously low thicknesses of lateral accretion. Mawa Kaneli (FR 4), for example, was the site of the highest sedimentation rate observed in the study, yet the section contained one of the smallest lateral accretion components, indicating a predominantly distal floodplain environment. Section MP 5 in the Mangla-Samwal anticline exhibits a lower sedimentation rate than Mawa Kaneli, yet at was obviously the site of greater proximal stream activity. These observations demonstrate that sedimentation rate in the re-entrant basin is to some degree independent of local fluvial conditions.

Conclusions

The examined interval of Late Pliocene Siwalik deposition records rapid aggradation by a fluvial system adjacent to a developing regional tectonic feature, the northwestern Himalayan syntatis. Molasse sedimentation during the interval reflects frequent modification of the fluvial environment in response to extensive lateral migration of streams. The pattern of Late Pliocene sedimentation rates in the study area suggests influence by syntaxial tectonism and possibly by mild flexures within the re-entrant basin. Further investigation of the late-orogenic sedimentary record in the Jhelum Re-entrant may aid in clarifying the enigmatic history of the northwestern Himalayan syntaxis.

Acknowledgments

Appreciation is extended to Professor R. A. K. TAHIRKHELI, Director, National Institute of Geology and Mineralogy, Peshawar University, for his continuing interest in and support of this project. N. M. JOHNSON. N. D. OPDYKE, D. M. SUMMERS and M. A. MIRZA contributed variously to this research. Access to unpublished geologic reports of the Pakistan Oil and Gas Development Corporation was provided by A. KEMAL. This research was suppported by U.S. National Science Foundation Grants GF-44168, GA-43445 and EAR 76—20717, Peshawar University and Dartmouth College.

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Intraplate wrench deformation in Iran, Afghanistan and Western Pakistan

By COLIN J. HOLCOMBE, London *)

With 5 figures

Zusammenfassung

Das Muster der größeren Blattverschiebungen im Iran, in Afghanistan und Pakistan ist das Ergebnis einer Konvergenz der Arabischen, Indischen und Eurasischen Platten. Zur Analyse der Verschiebungen wird ihre Bewegung auf Rotationspole bezogen. Die Rotationsbewegungen lassen sich quantifizieren, indem man die Verschiebungsbeträge proportional zur Länge der Störungen setzt und die Rotationen als Vektoren addiert. Die Gesamtrotation soll vom geometrischen Zentrum der Fläche ausgehen, die von den Blattverschiebungen umgrenzt wird. Setzt man für diese Bewegungen die Geschwindigkeiten, die für Plattenbewegungen berechnet wurden, so kann man daraus die einzelnen Verschiebungsgeschwindigkeiten an den Blattverschiebungen ableiten.

In West-Pakistan und Afghanistan kann man daraus erschließen, daß die Chaman-Störung seit dem Eozän aktiv gewesen sein muß. Dieser Schluß wird auch durch die geologischen Befunde gestützt. Diese Methode der tektonischen Analyse kann auf alle mobilen Plattenzonen angewandt werden und bietet eine Erklärung für geschwungenen Störungsverlauf und anomale Verschiebungsgeschwindigkeiten.

Abstract

The pattern of major wrench faults in Iran, Afghanistan and Pakistan is shown to result from convergence between the Arabia, India and Eurasia plates. A method is introduced of treating fault movement as rotations about fault poles. The rotations are quantified by assuming fault movement to be proportional to active fault length, and these rotations summed by vector addition. The resultant rotation is considered to act at the geometric centre of the area enclosed by the faults. By equating movement here with plate convergence calculated from the usual circuit of plate spreading velocities the individual fault movements may be quantified. An area of west Pakistan and Afghanistan so treated suggests that the Chaman fault was initiated in the Eocene, a conclusion independently indicated by the geology. The method is of general application in non-rigid plate areas and offers explanations for fault curvature and anomalous fault movement.

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