Geologische Rundschau **80/3** | 623–638 | Stuttgart 1991

Models of aggradation versus progradation in the Himalayan Foreland

By DOUGLAS W. BURBANK and RICHARD A. BECK, Los Angeles*)

With 7 figures

Zusammenfassung

Ein häufiges Ziel der Dekompaktionsanalyse ist es die Beckenabsenkung und die tektonische Belastung zu rekonstruieren. In marinen Ablagerungsräumen limitieren eustatische und paläobathymetrische Unsicherheiten die Auflösung der Rekonstruktion. Bei terrestrischen Becken fehlen diese Zweideutigkeiten; es ist aber trotzdem notwendig, Rechenschaft über den Ablagerungshang zwischen verschiedenen Lokalitäten abzulegen, um dreidimensionale Subsidenzmuster zu analysieren. Wir definieren zwei Endglieder von Ablagerungsflächen: Aggradation und Progradation. Die relative Wichtigkeit des jeweiligen Endglieds ist eine Funktion des Zusammenspiels zwischen der Nettorate der Sedimentakkumulation und der Beckensubsidenz. Die Modelle sagen die Hauptentwässerungsmuster (quer- oder längsverlaufend) vorher, sowie den Weg in dem die Sedimentherkunft innerhalb verschiedener Bereiche des Beckens berücksichtigt werden sollte. Folglich können Paläoströmungs- und Herkunftsdaten alter stratigraphischer Überlieferungen benutzt werden, um zwischen den Endgliedern zu unterscheiden. Die subhorizontale Ablagerungsfläche welche zur Zeit der Aggradation dominant ist, liefert einen gut definierten Referenzrahmen für die regionale Analyse von dekomprimierten Formationen und der damit verknüpften Subsidenz. Ablagerungshänge während Progradation können nicht präzise spezifiziert werden und beinhalten daher größere Unsicherheiten bei der Rekonstruktion der Subsidenz. Diese Modelle wurden übertragen auf das miozäne bis pliozäne Vorgebirgsbecken des nordwestlichen Himalayas, wo Sequenzen von isochronen Schichten durch das gesamte Becken analysiert werden konnten. Diese zeitkontrollierten Daten schildern eine ganz bestimmte Entwicklung, die von einer hauptsächlich aggradierenden zu einer progradierenden Ablagerungsgeometrie verlief, während der die Deformation schrittweise in Richtung Vorland übergriff. Diese Rekonstruktion von ehemaligen Ablagerungsflächen liefert einen guten Referenzrahmen für die folgende Integration der Subsidenzgeschichte des gesamten Vorlands.

Abstract

A frequent goal of decompaction analysis is to reconstruct histories of basin subsidence and tectonic loading. In marine environments, eustatic and paleobathymetric uncertainties limit the resolution of these reconstructions. Whereas in the terrestrial basins, these ambiguities are absent, it is still necessary to account for depositional slopes between localities in order to analyze three-dimensional patterns of subsidence. We define two end-members for depositional surfaces: aggradation and progradation. The relative importance of either end-member is a function of the interplay between the rate of net sediment accumulation and the rate of basin subsidence. The models predict the patterns of major drainages (transverse versus longitudinal) and the way in which provenance should be reflected within different portions of a basin. Consequently, paleocurrent and pro-

---

*) Authors' address: D. W. BURBANK and R. A. BECK, Department of Geological Sciences, University of Southern California, Los Angeles, CA, 90089-0740, U.S.A.

Manuscript received: 17. 01. 91; accepted: 17. 06. 91

venance data from the ancient stratigraphic record can be used to distinguish between these end-members. The subhorizontal depositional surfaces that dominate during times of aggradation provide a well defined reference frame for regional analysis of decompacted stratigraphies and related subsidence. Depositional slopes during progradation can not be as precisely specified, and consequently yield greater uncertainties in reconstructions of subsidence. These models are applied to the Mio-Pliocene foreland basin of the northwestern Himalaya, where sequences of isochronous strata have been analyzed throughout the basin. These time-controlled data delineate a distinctive evolution from largely aggradational to largely progradational depositional geometries as deformation progressively encroaches on the foreland. Such a reconstruction of past depositional surfaces provides a well constrained reference frame for subsequent integration of subsidence histories from throughout the foreland.

Résumé

L'analyse de décompaction a souvent pour but de reconstituer l'histoire de la subsidence d'un bassin et de la charge tectonique. Dans les milieux marins, de telles reconstitutions sont limitées par des incertitudes de caractère eustatique et paléobathymétrique. Par contre, ces ambiguïtés ne se présentent pas dans le cas des bassins continentaux, où il convient néanmoins de tenir compte de la pente de la surface de dépôt entre les divers points considérés pour établir un schéma tridimensionnel de la subsidence. Nous définissons deux situations extrêmes pour les surfaces de dépôt: l'aggradation et la progradation. L'importance relative de ces deux extrêmes est fonction de l'interaction entre le taux d'accumulation net des sédiments et le taux de subsidence du bassin. Les modèles prévoient la répartition des drainages principaux (transverse ou longitudinal) et la manière dont l'origine des sédiments peut se répercuter dans les diverses parties d'un bassin. Il en résulte que des informations fournies par les relevés stratigraphiques à propos des paléocourants et de la source des sédiments peuvent être utilisées pour faire la distinction entre les deux cas extrêmes. Les surfaces de dépôt subhorizontales, qui prédominent pendant les périodes d'aggradation, fournissent un bon cadre de référence pour les analyses régionales de formations décompactées et de la subsidence qui leur est associée. Les surfaces de dépôt inclinées qui se présentent au cours des progradations ne peuvent pas être définies de manière aussi précise et engendrent par conséquent plus d'incertitude dans la reconstitution de la subsidence. Les auteurs appliquent ces modèles au bassin mio-pliocène d'avant-pays de l'Himalaya nord-occidental, dans lequel des séquences de couches isochrones ont été suivies à travers tout le bassin. Ces données, chronologiquement définies, fournissent l'image d'une évolution nette, depuis des géométries typiques d'aggradation jusqu' à des géométries typiques de progradation, au fur et à mesure de l'emprise progressive de la déformation sur l'avant-pays. Une telle reconstitution des surfaces de dépôt anciennes fournit un bon cadre de référence en vue de l'intégration ultérieure de l'histoire de la subsidence dans l'ensemble de l'avant-pays.

Краткое содержание

Целью анализа по разуплотнению пород часто является реконструкция проседания бассейна и тектонической нагрузки. Но в бассейнах морских отложений такую реконструкцию затрудняет отсутствие точных данных об эвстатическом изменении уровня моря и палеобатометрии. Эти неточности отсутствуют в случае материковых бассейнов; тем не менее, чтобы проанализировать трехразмерную схему проседания, требуется установить течение процесса отложения между двумя регионами. Авторы называют два завершающих отрезка плоскости отложения »аградацией« и »проградацией«. Относительная значимость этих отрезков заключается в зависимости между скоростью накопления отложений и проседанием бассейна. По моделям можно предсказать основную схему обезвоживания, проходящую поперек или вдоль басссейна, как и учесть пути появления отложений на различных участках его. Следовательно, чтобы различать эти два завершающие отрезка, можно применять данные о палеотечениях и об области сноса отложений, основываясь на стратиграфическом материале прошлого. Субгоризонтальные плоскости отложения, господствующие в период аградации, дают хорошо различаемые рамки для регионального анализа процессов разуплотнения формаций и связь с ними процессов проседания. Склоны отложений во время процесса проградации очертить точно не удается, и здесь появляются неточности при реконструкции проседания. Эти модели перенесли на бассейны предгорья Гималаев миоценового и плиоценового возраста, где свиты изохронных слоев можно анализировать во всем бассейне. Эти управляемые временем данные описывают известное развитие, протекающее от аградающей до проградающей формы мест отложения в то время, как форма деформации постепенно передвигается в направлении предгорья. Такая реконструкция бывших мест отложения дает более менее удовлетворительную рамку для последующей истории погружения всего предгорья в данной области.

Introduction

For many decades, geologists have realized that histories of sediment accumulation and basin subsidence can provide valuable insights into the tectonic controls on basin development and into the geometrical evolution of the basin through time. Until recently, however, highly detailed analyses of subsidence histories have been limited by three problems. First, post-depositional compaction of the sedimentary pile has not usually been accounted for adequately. For example, because marine shales compact much more extensively than do typical sandstones (e. g., VAN HINTE, 1978), failure to consider such lithologically dependent variability leads to inaccurate reconstructions of former sedimentary thickness. Second, precise chronological data and reliable time control of the stratigraphic record has been limited. Relevant radiometric dates are frequently unavailable and, even when determined, often have analytical errors of >1 Myr. The inability to verify assumptions critical to the correct interpretation of a date, such as closure of the radiometric system since deposition, add further uncertainties. Traditional reliance on paleontological data for time control has often limited the practical resolution of subsidence histories to several million years due to imprecision in biostratigraphic ages (HARLAND, ARMSTRONG, COX, CRAIG, SMITH & SMITH, 1982; BERGGREN, KENT, FLYNN & VAN COUVERING, 1985). This imprecision limits the possibilities for reliable analysis of the fine structure of subsidence records. Third, it has often been difficult to define a reliable reference framework for the decompacted sections. At any single locality in a former marine basin, uncertainties in eustatic variations and paleobathymetry limit the resolution of the subsidence curve. In terrestrial settings, the effects of eustasy and water-depth variations are frequently minimal, but the depositional slope with respect to an external reference frame still needs to be defined.

Solutions to all three of these problems are now available. First, decompaction techniques for realistic restorations of former sedimentary thicknesses (VAN HINTE, 1978; STECKLER & WATTS, 1978; SCLATER & CHRISTIE, 1980; JORDAN, FLEMINGS & BEER, 1988) permit us to address problems caused by post-depositional thickness changes. Second, markedly improved and/or new radiometric dating techniques and magnetic polarity stratigraphy have increased the temporal resolution that can be realized in sedimentary sequences (LABREQUE, KENT & CANDE, 1977; MANKINEN & DALRYMPLE, 1979). Increasingly detailed calibration of the biostratigraphic record also has permitted more precise chronological inferences to be drawn from the fossil record (HARLAND, ARMSTRONG, COX, CRAIG, SMITH & SMITH, 1990; BARRY, JOHNSON, RAZA & JACOBS, 1982; BARRY, LINDSAY & JACOBS, 1985; BERGGREN, KENT, FLYNN & VAN COUVERING, 1985). Third, new stratigraphic insights in some basins allow improved constraints to be placed on the geometrical shape of the depositional surface for each setting and time that is studied. The development of a regional reference frame against which to judge the data from individual sites permits the three-dimensional evolution of a basin to be examined.

In any effort to reconstruct a detailed history of thrusting in the hinterland and on the fringes of a foreland, a record of the timing, magnitude, and geometry of tectonically induced subsidence in the adjacent basin can provide very useful constraints. In order to discern as clearly as possible the regional signature of loading events, a reliable framework on which to »hang« decompacted stratigraphies is required. In this paper, we describe an approach used to develop a regional reference frame for the terrestrial foreland basin of the northwestern Himalaya. This foreland is of particular interest because it holds an accessible stratigraphic record of deposition during much of the Indo-Asian collision. Given its position at the toe of one of the world's largest and most rapidly growing Cenozoic mountain ranges, the Himalayan foreland is yielding a wealth of information on the history of structural deformation and on the interactions between sedimentation and tectonics at the local and regional scale, e.g., JOHNSON, JOHNSON, OPDYKE & TAHIRKHELI, 1979; BURBANK & RAYNOLDS, 1984, 1988; RAYNOLDS & JOHNSON, 1985; BEHRENSMEYER & TAUXE, 1982. As the result of over a decade of research during which more than 40 magnetic polarity stratigraphies have been generated (KELLER, TAHIRKHELI, MIZRA, JOHNSON, JOHNSON & OPDYKE, 1977; BARNDT, JOHNSON, JOHNSON, OPDYKE, LINDSAY, PILBEAM & TAHIRKHELI, 1978; OPDYKE, LINDSAY,

JOHNSON, JOHNSON, TAHIRKHELI & MIZRA, 1979; JOHNSON, JOHNSON, OPDYKE & TAHIRKHELI, 1979; JOHNSON, OPDYKE, JOHNSON, LINDSAY & TAHIRKHELI, 1982; JOHNSON, STIX, TAUXE, CERVENY & TAHIRKHELI, 1985; RAYNOLDS, 1980; TAUXE & OPDYKE, 1982), this particular basin is probably the most precisely dated foreland in the world. This time control permits essentially isochronous (<200 Kyr) depositional surfaces to be examined across the entire basin and facilitates detailed comparisons between widely separated localities containing coeval strata. Consequently, this temporal control provides a critical basis for formulating a regional reference frame.

End-member models for depositional surfaces

In terrestrial basins which, like the northwestern Himalayan foreland, do not contain significant lacustrine successions, the impact of bathymetric changes on the positions of the depositional surface can be ignored. The importance of eustatic changes in modulating the position of the depositional surface in terrestrial basins is largely a function of the basin's proximity to the marine environment. Whereas the terrestrial portions of a coastal environment would be profoundly affected by eustatic variations, we maintain that the actively aggrading Indo-Gangetic foreland stretching for >1000 km from the northwestern Himalaya to the sea would have acted as an effective buffer against short-term, eustatically controlled changes in the depositional surface within the studied area in northwestern Pakistan. Moreover, a bedrock threshold in the lower Ganges drainage (ALAM, 1989) effectively restricts the extent to which the effects of eustatic lowering can be transmitted upstream. Finally, because the long-term rates of sediment accumulation and basin subsidence (0.1–1.0 mm/yr) generally overwhelm the documented rates of Neogene eustatic changes (HAQ, HARDENBOL & VAIL, 1987), the potential effect of eustasy on the northwestern Himalayan foreland can be considered to be negligible.

Consequently, in order to create a regional reference framework, the primary variable that needs to be constrained is the geometry of former depositional surfaces and changes in these geometries through time. Initially, we assume an asymmetric sediment-filled foreland basin created by crustal flexure due to thrust loading (Fig. 1A). The distal margin of the basin is defined by a low-amplitude peripheral bulge or by non-flexural topography, whereas the proximal margin is defined by the deformational front. Two contrasting configurations (progradation and aggradation) that could result from the addition of a new packet of sediment to the basin can function as end-members of a continuum of possible depositional geometries. We assume that the new packet of sediments is wedge-shaped in cross-section, rather than rectangular, because both flexural considerations (e.g., FLEMINGS & JORDAN, 1989) and empirical data dictate that a greater thickness of sediments will accumulate in the proximal portion of the basin.

Progradational Model

The volume of sediment added above or below the base-level of a marginally sourced clastic sedimentary basin and the resulting syn-depositional topography depend upon the relative magnitudes of subsidence and sedimentation throughout the basin. If the rate of net sediment accumulation, inclusive of progressive compaction, is greater than the rate of subsidence (relative base-level rise) along a profile perpendicular to the basin margin, then a wedge of new sediment will prograde transversely across the basin. In this case, the upper surface of the wedge, i.e., the depositional surface, will have a topographic slope away from the basin margin. In foreland basins characterized both by asymmetric subsidence and by sediment accumulation greater than subsidence, the resulting topographic surface slopes from the hinterland source area toward the distal margin.

A clear geological implication of the condition where marginally sourced sedimentation exceeds subsidence in alluvial foreland basins (Fig. 1B) is that transverse drainages will dominate the fluvial network. Any trunk drainage should be constrained to a position beyond the toe of the prograding wedge. The precise position of such an axial river, if it were to exist, would also depend in part on the amount of sediment progradation that has occurred from the peripheral bulge towards the hinterland. In situations where sediment supply truly overwhelms the rate of subsidence, transverse streams may spread across the entire foreland basin.

Aggradational Model

If the rate of net sediment accumulation is less than or just equal to the rate of subsidence along a profile perpendicular to the basin margin, then a wedge of new sediment will aggrade beneath a series of subhorizontal surfaces (in transverse sections), rather than along basinward-dipping surfaces. Given a series of subhorizontal depositional surfaces and a

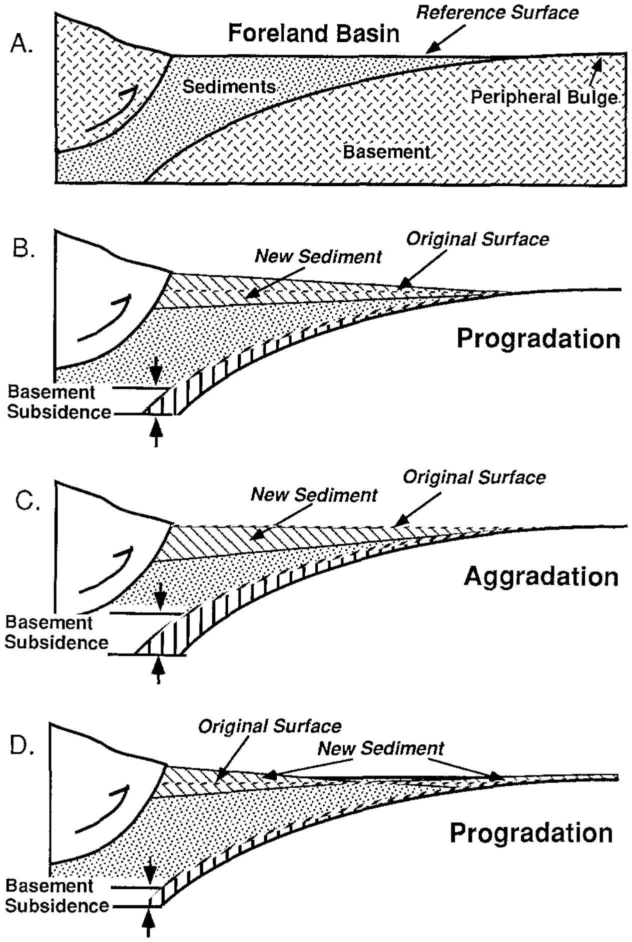


Fig. 1. Progradational and aggradational models for depositional geometries. A. Starting point prior to addition of new packet of sediments. A foreland basin has resulted from thrust loading and is filled with sediments to a horizontal datum. B. Progradational wedge model. Sediment accumulation occurs upon a depositional slopes which tilt toward the distal margin. Fluvial system flow is at high angles to the basin's structural axis. Vertically hachured area represents basement subsidence (relative to 1A) caused by this depositional geometry. C. Aggradational wedge model. Sediment accumulation takes places on surfaces of very low to negligible transverse slope. Fluvial system flows at low angles to the basin's structural axis. D. Progradational model with significant progradation from the peripheral bulge. Fluvial flow will be transverse on the progradational surfaces and axial where the fans meet.

volume of sediments that is equal to the newly added sediment in the previously described progradational model, a greater amount of basement subsidence is implied. This results from the fact that none of the sediments accumulate significantly above the local base-level in the aggradational scenario. Because the depositional surface is essentially horizontal, paleoflow directions would be loosely constrained, but would have an overall longitudinal, rather than transverse, orientation.

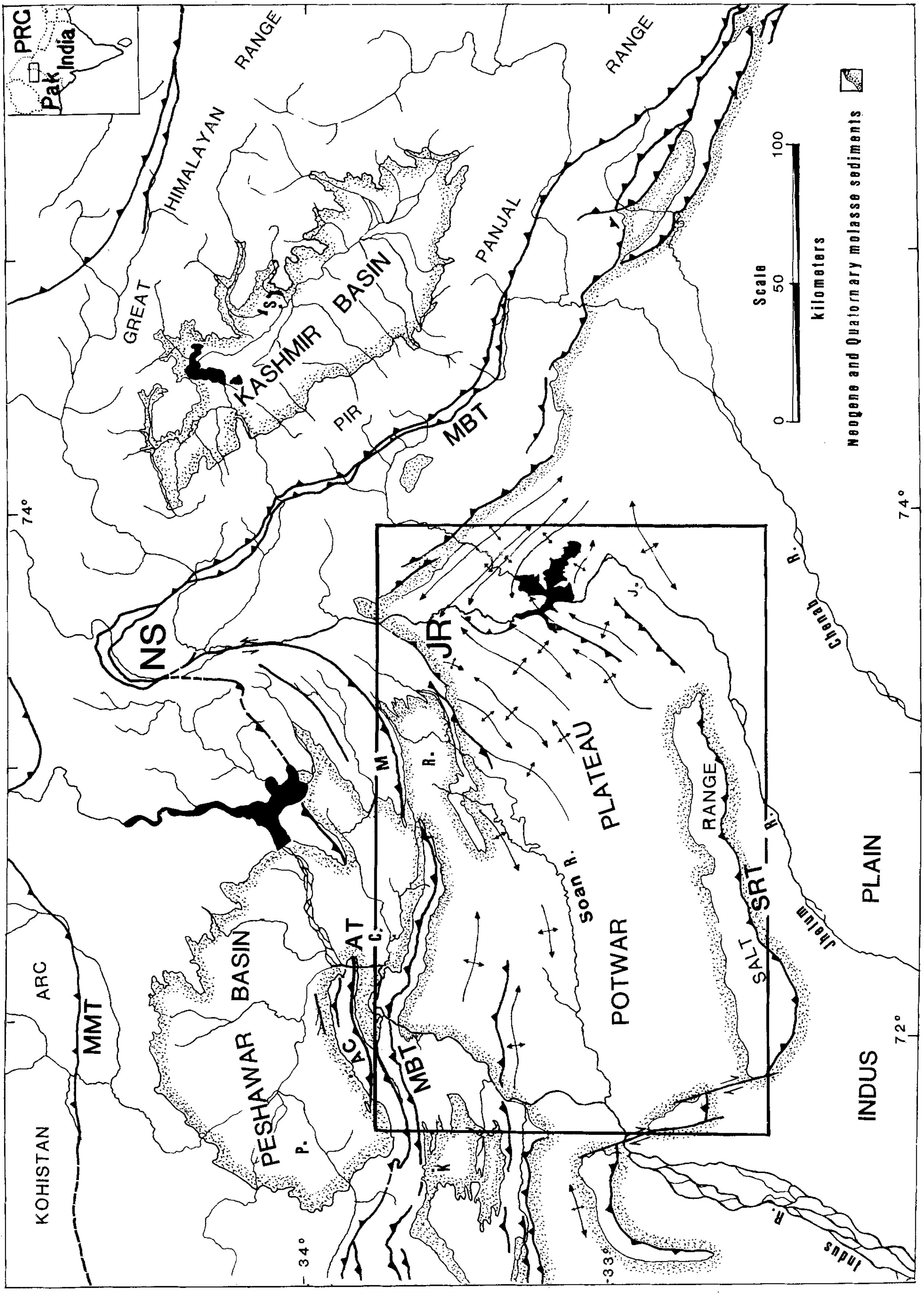
Applications of Models to Foreland Basins

In reality, some combination of the progradational and aggradational models is likely to characterize the foreland depositional surface, and it would be expected that the geometry of this surface would evolve through time. At all times, progradational fans are likely to be found along both margins of the basin. In reconstructing the surface geometry, the critical issue to resolve is the relative proportion of the marginal, transverse fans to the more medially positioned, subhorizontal aggradational surface.

It is important to realize that the preservation potential of different portions of the foreland in the stratigraphic record is likely to change as deformation continuously impinges on the proximal basin margin. The likelihood of preserving strata deposited in the distal to the medial portion of the basin is considerably greater than that of preserving the strata resulting from proximal deposition, which are likely to have been either overthrust by subsequent shortening or uplifted and eroded during continuing deformation. Most of our analyses, especially with older strata, therefore, relate to the medial-distal parts of the basin. It is also necessary to distinguish between the net rate of sediment accumulation and the rate of supply of sediments. Because sediments can be exported out of a foreland basin (i.e., sediment bypassing), it is possible for aggradational geometries to persist even if sediment supply exceeds the rate of subsidence.

Depositional geometries in the Himalayan foreland

In order to reconstruct former depositional geometries and to distinguish between predominantly transverse versus largely axial drainage networks, data related to paleocurrents, facies, and provenance need to be gathered. Using the chronologic data derived from previous and ongoing magnetic studies, we have examined isochronous depositional surfaces across much of the northwestern Himalayan foreland (Fig. 2), where a series of latest Miocene-Pleistocene thrusts (BURBANK & BECK, 1989) expose sections of Mio-Pleistocene molasse. Strata that are 14–7 Myr old are preserved in numerous localities in the central, southern, and eastern Potwar Plateau. Dated strata ranging from 5–2 Myr old are found primarily in the eastern Potwar Plateau and in the Jhelum Re-entrant. Two contrasting paleocurrent geometries are


PRC
Pak
India
KOHISTAN
ARC
MMT
PESHAWAR
BASIN
P.
AC
AT
C.
MBT
K
M
R.
NS
JR
J.
POTWAR
PLATEAU
Soan R.
SALT
RANGE
SRT
R.
INDUS
PLAIN
Jhelum
R.
Chenab
R.
Indus
R.
GREAT
HIMALAYAN
RANGE
KASHMIR
BASIN
S.
PIR
PANJAL
RANGE
MBT
34°
33°
72°
74°
Scale
0
50
100
kilometers
Neogene and Quaternary molasse sediments

2 A

2 B

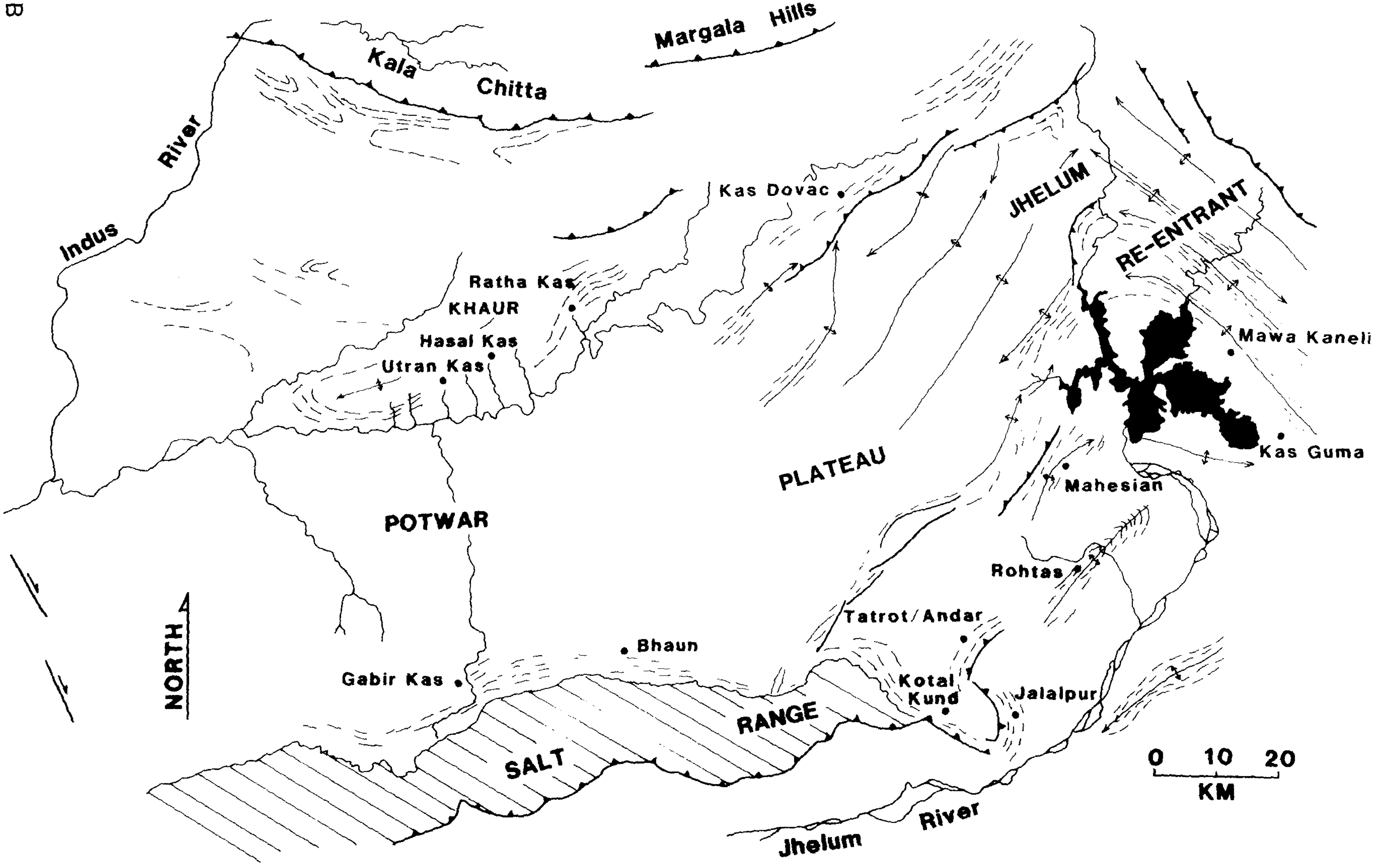
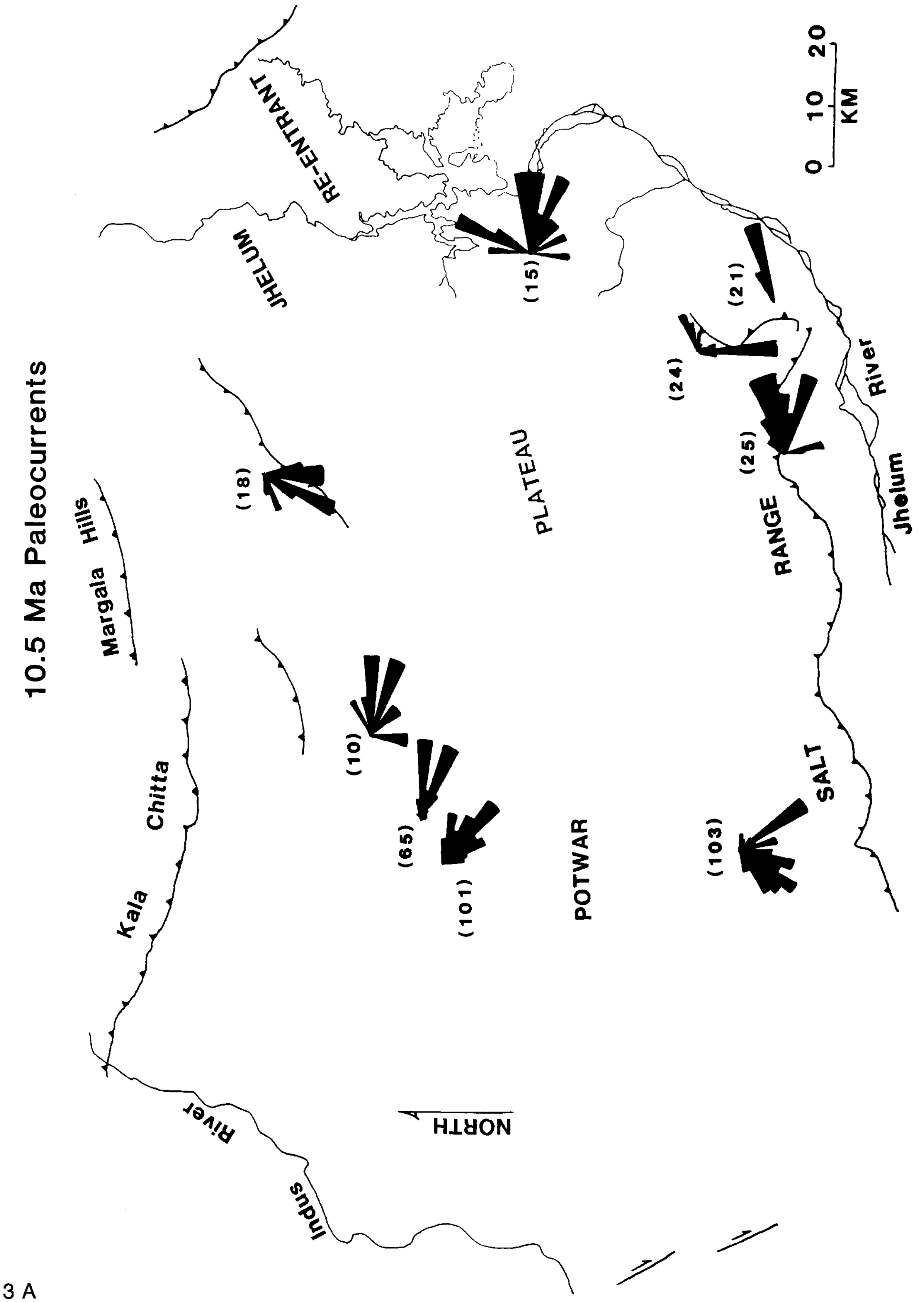


Fig. 2. A. Location map of the northwestern Himalayan foreland basin and adjacent mountain ranges. AC = Attock-Cherat Range; AT = Attock Thrust; C = Campbellpore; J = Jhelum; JR = Jhelum Re-entrant; M = Margala Hills; MBT = Main Boundary Thrust; MMT = Main Mantle Thrust; NS = Northwest Syntaxis; P = Peshawar; R = Rawalpindi; S = Srinagar; SRT = Salt Range Thrust. Box indicates location of figure 2B. B. Map of the Potwar Plateau and Jhelum Re-entrant showing location of studied sections and major structural features.


10.5 Ma Paleocurrents
Margala Hills
Kala Chitta
Indus River
NORTH
JHELUM RE-ENTRANT
POTWAR PLATEAU
SALT RANGE
Jhelum River
(15)
(18)
(21)
(24)
(25)
(10)
(65)
(101)
(103)
0 10 20
KM

3 A

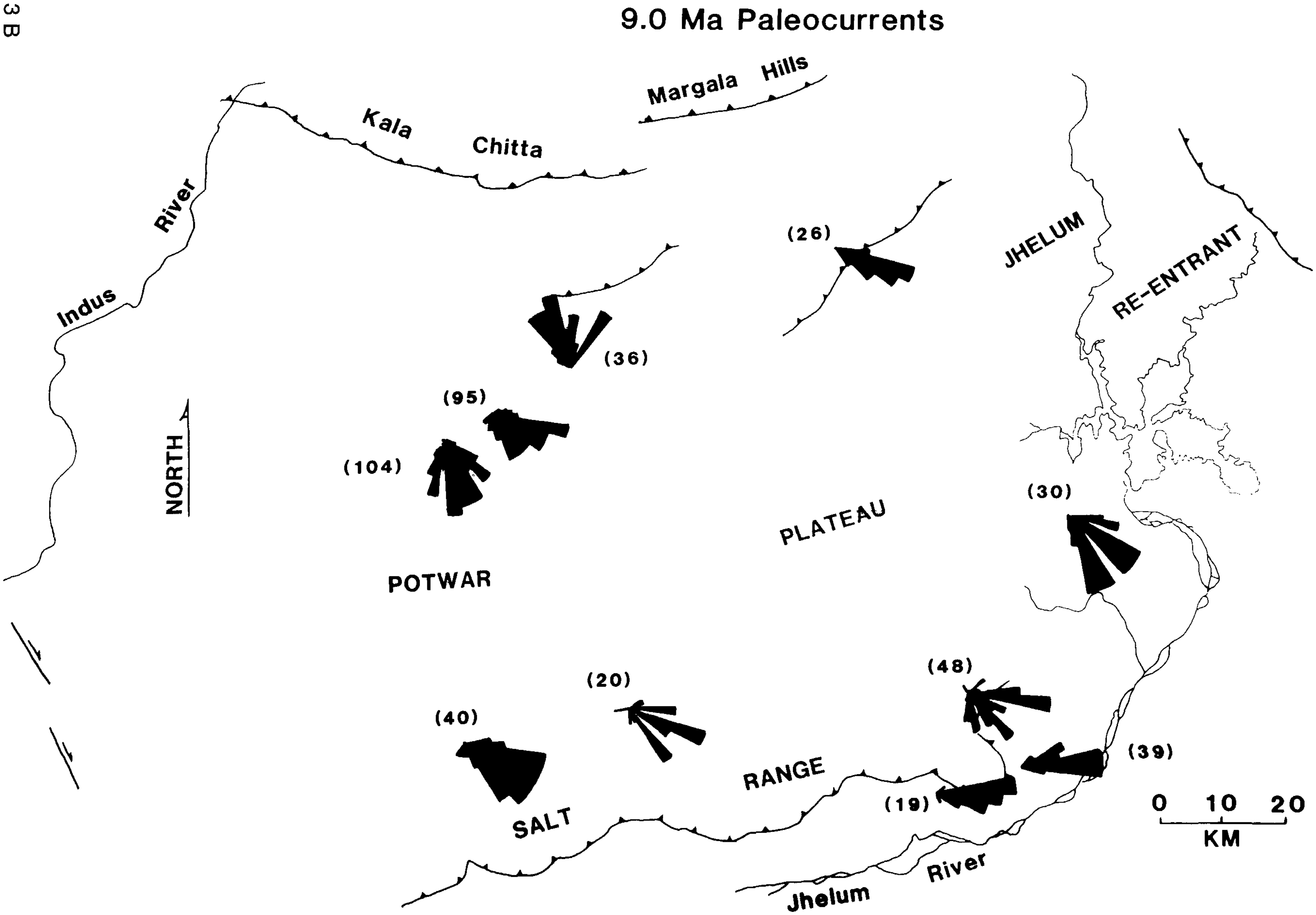


Fig. 3. Paleocurrent directions for middle to upper Miocene strata. Tectonic rotations have been subtracted from measured directions. N = the number of measurements at each locality. A. Paleocurrents at 10.5 Ma. B. Paleocurrents at 9.0 Ma.

found during these intervals. In combination with provenance and facies information, they indicate that a largely aggradational geometry prevailed during the Miocene and was superseded by a progradational geometry in the Pliocene.

Miocene Geometries

Paleocurrent data were gathered from essentially isochronous surfaces dated at ~ 10.5 and 9 Ma across the Potwar Plateau. Generally, three to four sandstone units that straddled the magnetic boundary defining each time line were sampled. At most localities. the sandstones are typically 10–50 m thick, multi-storied, and traceable over many kilometers. We interpret these sandstones to represent deposits generated by a large river system, probably the ancestral Indus River. Data was collected from trough cross bedding, generally > 1 m in width and exposed along dip slopes. Measurements made on dipping strata were restored to their prefolding orientation, and post-depositional tectonic rotations, as defined by paleomagnetic measurements (e.g., JOHNSON, OPDYKE, JOHNSON, LINDSAY & TAHIRKHELI, 1982, 1985; OPDYKE, LINDSAY, JOHNSON, JOHNSON, TAHIRKHELI & MIZRA, 1979) at each locality, were also removed in order to reconstruct the predeformational configuration of the former fluvial systems.

The results for each of these Late Miocene time slices (Fig. 3) indicate an overall paleoflow direction toward the southeast. Grain-size trends also indicate downstream fining toward the southeast. Although there is little ambiguity concerning the orientation of the mean vector, there is considerable scatter for individual localities at any given time, for different times at a locality, and among all of the localities for a given time slice. Nonetheless, the mean paleocurrent pattern suggests the presence of an axial drainage system oriented subparallel to the Himalayan Range. The large-scale orientation also suggests that, during the Miocene, the ancestral Indus River was flowing parallel to the Himalaya and into the Ganges drainage, a conclusion in accord with a similar analysis of Miocene strata in the Jhelum Reentrant (RAYNOLDS, 1981). The scatter within the data appears to indicate that the axial river system was rather loosely constrained on a broad floodplain within a topographic depression.

These paleocurrent data appear to conform with our model for an aggradational, subhorizontal depositional surface. Because some progradation must occur at the edge of the basin, however, the full width of this subhorizontal surface can not be reliably specified. Moreover, the possibility exists that, when only paleocurrent data are considered, the longitudinal, primary drainage defined here may have been pinned between large transverse systems prograding from both margins of the basin (Fig. 1D and 4). Such a situation might be expected in an underfilled (COVEY, 1986) sediment-starved foreland, where the rate of sediment supply was much less than the rate of load-induced subsidence (BECK, VONDRA, FILKINS & OLANDER, 1988).

Provenance data helps to clarify further the Miocene basin geometry. Detrital zircons collected from magnetically dated strata in the southern Potwar Plateau have been recently dated using the fission-track method (CERVENY, NAESER, ZEITLER, NAESER & JOHNSON, 1988). The oldest samples were taken from 18-Myr-old fluvial strata that onlap the Eocene limestones exposed in the northern flank of the Salt Range and that represent the distal pinchout of the Middle Miocene foreland strata. Fission-track dates for zircon indicate when a grain last cooled through the ~200 °C isotherm (NAESER, 1978). Except when dealing with juvenile volcanic material (of which there is very little in the Miocene of northern Pakistan), this cooling is usually attributed to

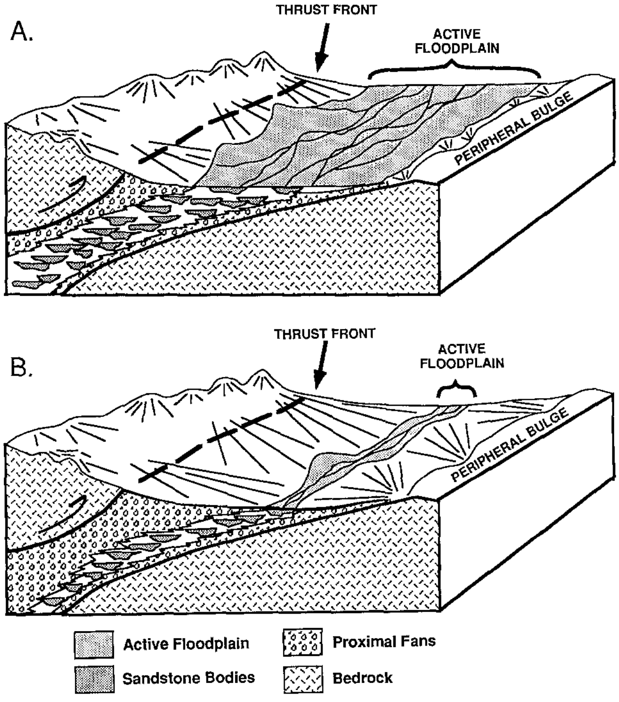


Fig. 4. Two different scenarios for axial drainages. A. Broad active, aggradational floodplain with limited progradational fans on its margins. Sediments with a hinterland source will accumulate across the entire floodplain, including the distal basin margin. B. Restricted axial floodplain with large progradational fans. Sediments with a hinterland source will not accumulate above the toes of the fans prograding from the peripheral bulge.

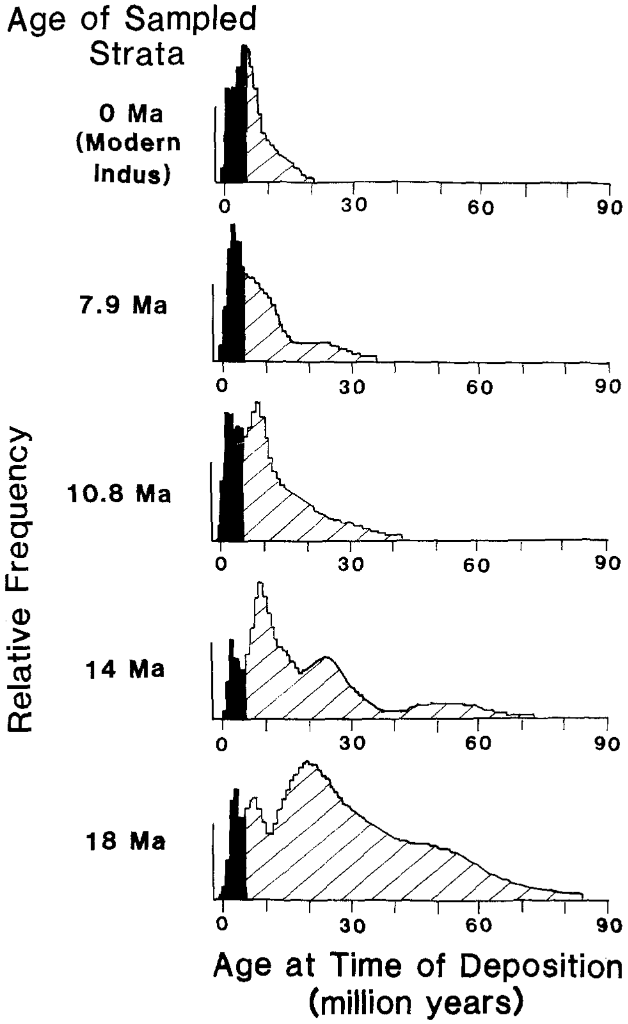


Fig. 5. Histograms of fission-track dates for detrital zircons collected from the modern Indus River and from dated strata at Gabir Kas (for location, see Figure 2B). The dates for all older strata have been recalculated (McGee, Johnson & Naeser, 1985) to restore the age spectrum that would have been present *at the time of deposition.* All sections contain zircons (shown in black) that annealed less than 5 Myr prior to the time of deposition. (Modified from Cerveny, Naeser, Zeitler, Naeser & Johnson, 1988).

uplift and erosion. Detrital zircons in the Potwar area consistently indicate that at least some of the zircons at each stratigraphic level were deposited within 3 Myr of cooling below 200 °C (Fig. 5, Cerveny, Naeser, Zeitler, Naeser & Johnson, 1988). Because a Precambrian shield borders the southern margin of the foreland, the only reasonable source for such young zircons is the rapidly rising Himalaya to the north.

Given the combination of this detrital source area with the locations of the sampled strata along the southern limit of the Miocene foreland, it can be concluded that rivers with a Himalayan provenance either reached fully or very nearly to the southern margin of the Potwar Plateau throughout the Middle and Late Miocene. This indicates that, despite the overall longitudinal character of the major drainage system which was flowing toward the east-southeast, the rivers that constituted it were indeed loosely constrained and that a subhorizontal floodplain (Fig. 4A), rather than a largely concave transverse profile (Fig. 4B), extended across the entire 70–80 km width of the present Potwar Plateau. This situation compares favorably with the observable geometries along the modern Gangetic foreland, where floodplains are essentially horizontal in transverse profiles and extend for > 100 km across the medial and distal parts of the basin (Fig. 6).

Given these results, after decompacting and correlating individual sections, they can be referenced to the same subhorizontal depositional surface. Such a situation facilitates analysis of the geometry of load-driven subsidence of arbitrary time planes and permits direct reconstructions of basement-slope histories. Although this approach for transverse gradients, it ignores downstream, longitudinal gradients. We have found no way to define this accurately from the stratigraphic record. By analogy with the modern Ganges or Indus Rivers, however, this slope would be < 0.0005. We choose to ignore this downstream gradient, and, in the context of the rapid rates of accumulation that prevailed in the Miocene Himalayan foreland, incluson of this factor would only slightly modify our reconstructed depositional surface.

Pliocene Geometries

By 5 Ma, structural disruption had begun to modify the depositional patterns in the foreland of northern Pakistan. Incipient uplift of the Salt Range (Burbank & Beck, 1989) created a southern source

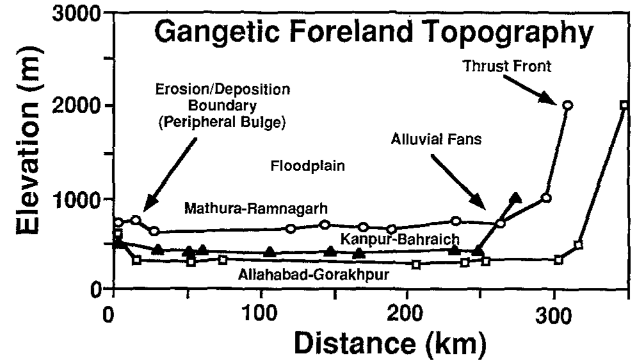
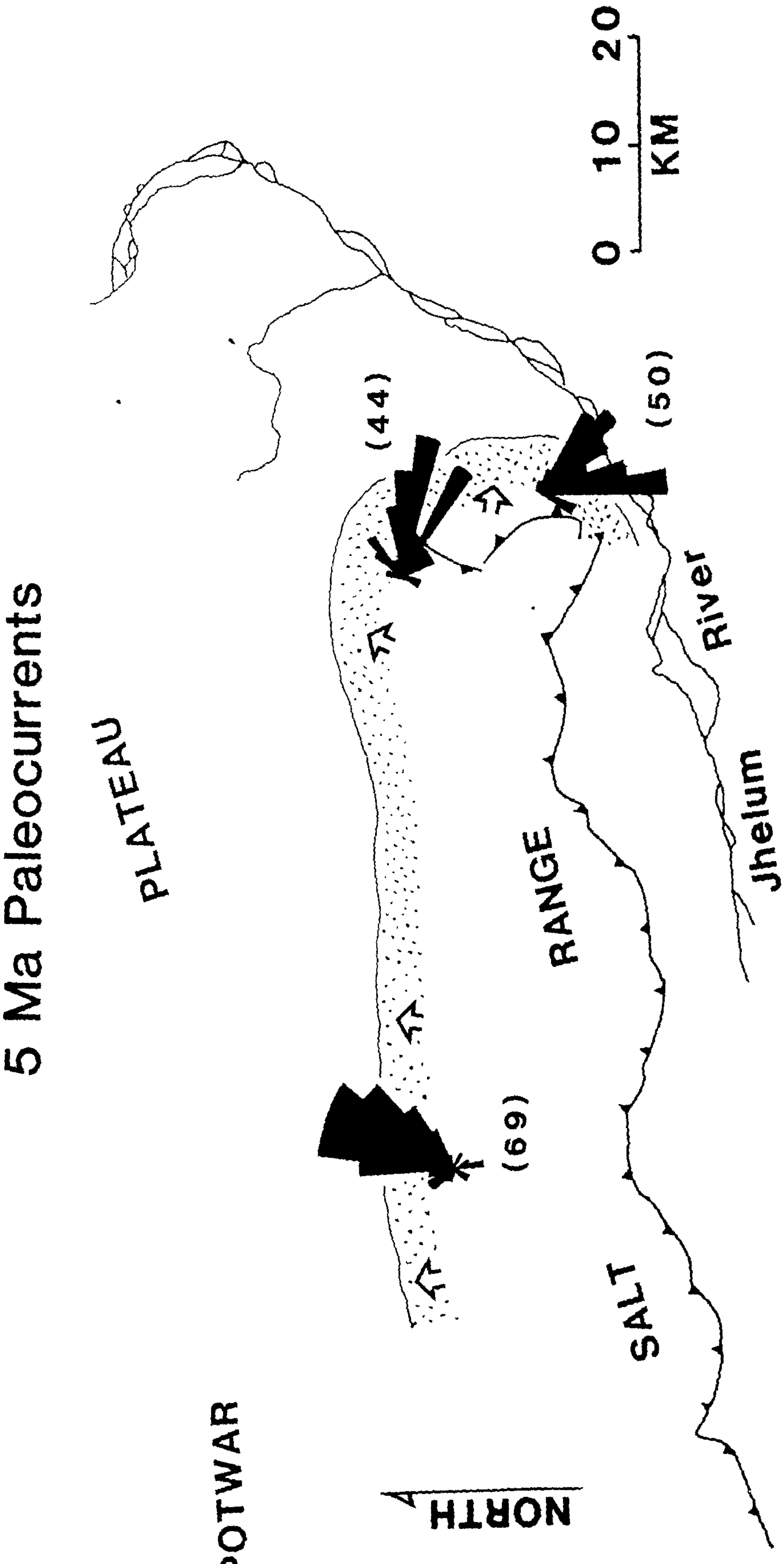


Fig. 6. Topographic transects across the modern Gangetic plain from the Himalayas to the distal margin of the foreland. Note the flat profile stretching across 100–200 km of the medial and distal portions of the basin. Marginal fans along the proximal margins have slopes of <0.005 when they enter into the zone of net accumulation.


5 Ma Paleocurrents
POTWAR
PLATEAU
SALT
RANGE
Jhelum
River
NORTH
(44)
(50)
(69)
0
10
20
KM

7 A

7 B

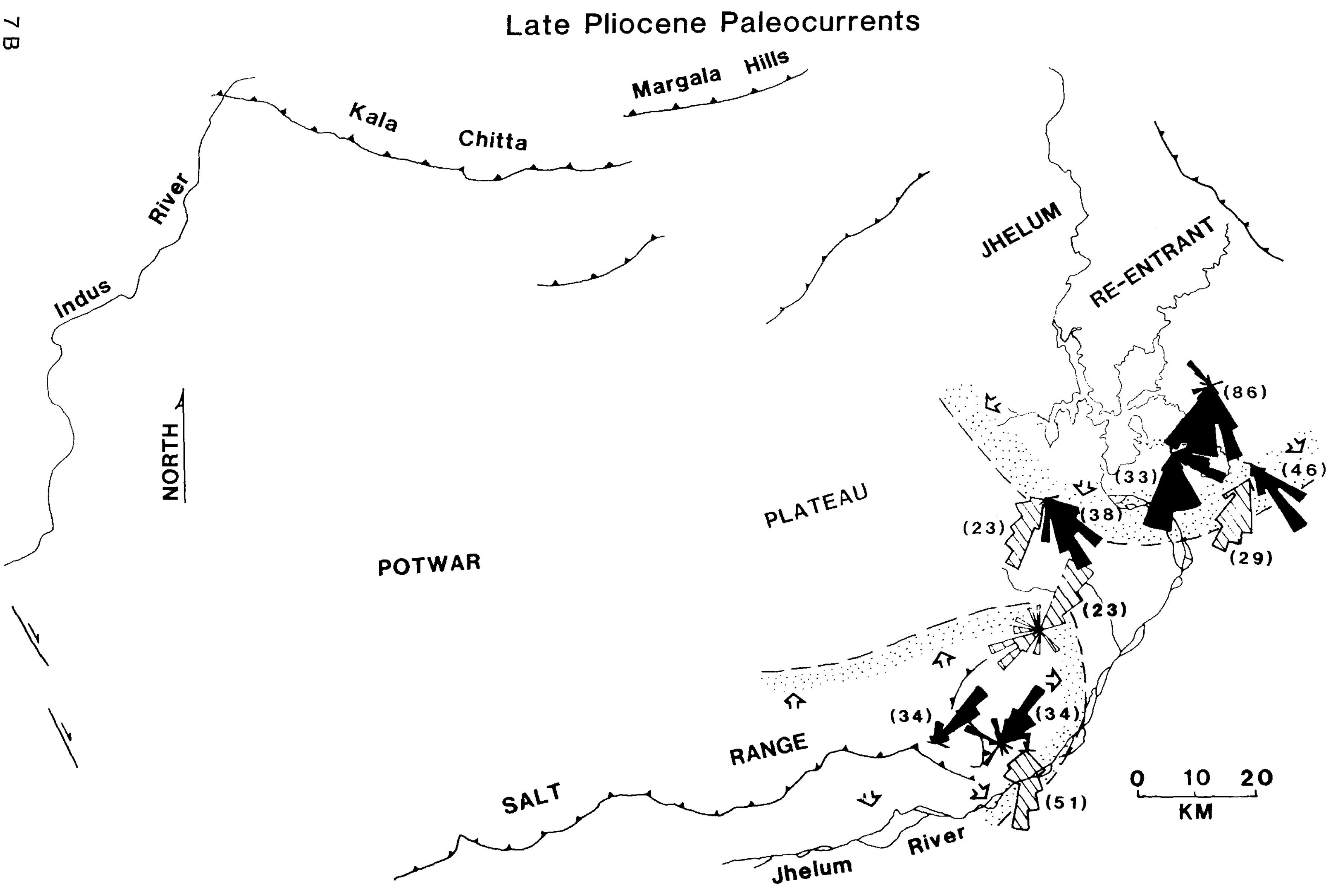


Fig. 7. Pliocene paleocurrents corrected for tectonic rotations. Arrows and stippling indicate areas and directions of progradation. A. 5 Ma paleocurrents from the Salt Range region reflecting its initial uplift. B. 3.0–1.8 Ma paleocurrents. Those derived from strata dated to 1.8–1.6 Ma are shown by hachured paleocurrent roses.

area for the Potwar Plateau (Fig. 2), which itself had consequently become a piggyback basin (ORI & FRIEND, 1984). Large-scale uplift of the Pir Panjal Range along the Main Boundary Thrust system began at this time (BURBANK & RAYNOLDS, 1988) along the northeastern side of the Jhelum Re-entrant. During the Pliocene, this deformation caused a major transformation in the depositional geometries within the northwestern Himalayan foreland. Paleocurrent measurements on 5-Ma strata (Fig. 7A) indicate that the initial uplift of the Salt Range caused hinterland-directed flow off the northern margin of the uplift. In the central portion of the piggyback basin, at least some measure of axial flow of a major river system was maintained, whereas, in the northeastern areas, a largely southerly flow system began to dominate the region (RAYNOLDS, 1981; BURBANK & RAYNOLDS, 1988). These paleocurrent inferences are reinforced by provenance data indicating that the rather homogeneous, Himalayan source that prevailed during the Miocene was being superseded by local source areas along both flanks of the basin. Consequently, we would interpret a 5-Ma depositional geometry that was a blend of the aggradational and progradational models. In the central Potwar, an axial flow direction and a generally aggradational situation still prevailed, whereas along the basin margins, increasingly large, progradational fans were beginning to encroach more extensively on to the formerly aggradational floodplain.

By late Pliocene, these progradational fans had encroached considerably farther toward the central portion of the basin (Fig. 7B). A very large fan, containing clasts primarily derived from the Pir Panjal Range, extended across the northeastern 120 km of the basin (BURBANK, BECK, RAYNOLDS, HOBBS & TAHIRKHELI, 1988). Continued uplift of the eastern Salt Range caused considerably smaller fans to grow northwards into the piggyback basin.

As progradation begins to supersede aggradation, reliable definition of the geometry of past depositional surfaces becomes increasingly difficult. Calculations of depositional slopes typically are based on the geometry of former channels, mean discharge, and the grade of sediment being transported (e.g., SCHUMM, 1968, 1972; PAOLA, 1990). Because some of these quantities can not be specified reliably in the ancient record, modern analogues are perhaps preferable guides to former depositional slopes. Several types of large-scale (> 10 km) fans are found along the margins of the Indo-Gangetic foreland. Some, like the Kosi fan (GOLE & CHITALE, 1966; WELLS & DORR, 1987), are > 100 km in length, generally fine grained, and display average gradients of < 0.001. The upper limit for gradients on large fans is more difficult to define. Analysis of numerous modern river profiles along the length of the Himalaya (SEEBER & GORNITZ, 1983) shows that, even within the degradational portions of the rivers before they debouch on to the Indo-Gangetic foreland, their gradients typically range from 0.003–0.008. Persistent slopes of this magnitude can generate elevational differences of 300–800 m over a distance of 100 km and, therefore, can not be completely ignored when reconstructing former depositional surfaces. In the absence of better control on large fans (>20 km), we assume a logarithmically decreasing gradient (MACKIN, 1948) from 0.005 at the fan apex to 0.001 at the toe. Thus, through portions of the foreland where progradational fans are defined, a calculated topographic accumulation above the regional base-level can be subtracted from the decompacted thickness in order to determine the slope of the basement between different localities, as well as the absolute amount of subsidence.

Discussion and conclusions

One of the primary uses of decompaction techniques is to reconstruct basement subsidence as reflected by sediment accumulation and to delineate intervals of tectonic loading. To do this on a basin-wide scale, it is necessary to define the geometry of the depositional surface across terrestrial basins in order to provide a spatial reference frame within which to compare decompacted records from separate geographic localities. Because terrestrial foreland basins lack the water-depth ambiguities that are often associated with past eustatic and bathymetric changes, they can provide a better opportunity to delineate past depositional surfaces with more precision than is commonly found in marine basins.

End-member models for aggradation and progradation in terrestrial basins provide a useful conceptual framework within which to analyze past geometries of sediment accumulation and basement subsidence. They serve to predict relationships between particular patterns of deposition and specific modes of sediment accumulation. These modes (aggradation versus progradation) can, in turn, be interpreted as a reflection of the relative rate of basement subsidence versus net sediment accumulation in the basin. It is necessary to determine the relative blend of these end-members, because the amount of subsidence inferred from the depositional record varies according to which end-member is dominant in a given portion of the basin in each time interval considered. In general, it appears that the appropriate depositional geometry can be chosen based on data derived from paleocurrents, provenance, and facies analysis. When these data can be integrated on high-resolution time planes, a highly detailed record of subsidence can be reconstructed.

The extensive chronologic data base derived from previous magnetostratigraphic studies in the northwestern Himalayan foreland basin permits isochronous stratigraphic surfaces to be defined. Using these time planes, we have determined the paleocurrent orientation for several different time slices, ranging from 10.5 to 2 Ma. In combination with provenance data based on detrital zircons and petrographic associations, these data serve to define a broad, subhorizontal aggradational surface that prevailed from at least > 10.5 to ~ 7 Ma across the Potwar Plateau. Consequently, decompacted sequences from this time interval can all be referenced to a series of subhorizontal surfaces.

The relative proportion of the basin covered by an aggradational surface diminished greatly during the Pliocene. As progradational fans encroached progressively across the basin, they restricted the subhorizontal aggradational surface to successively smaller areas within the study area. Because the longitudinal profiles of these ancient fans can only be loosely constrained, additional errors are introduced into any reconstruction of the depositional surface. Nonetheless, when compared with marine basins or with less well-dated terrestrial basins, the series of isochronous depositional surfaces defined here provides a higher quality reference frame for detailed analysis of subsidence histories than has commonly been achieved in the past.

Finally, it has been suggested in the past that the Himalayan foreland basin, with its extensive aggradational surfaces, axial drainage system, and limited marginal progradational wedges, should be considered an »underfilled« foreland (e.g., FLEMINGS & JORDAN, 1990), whereas foreland basins characterized entirely by progradational surfaces and large transverse drainages could be considered »overfilled«. These terms imply that the rate of sediment delivery to the foreland is less than the subsidence rate in underfilled basins and greater than the subsidence rate in overfilled basins. When two-dimensional cross sections of forelands are considered, such descriptions appear to be reasonable. The classification of foreland basins as underfilled or overfilled, however, should depend on a regional, three-dimensional assessment of sediment delivery versus generation of accommodation space for those sediments. In the case of the Himalaya, the colossal volume of Miocene to Recent sediment stored in the Bengal and Indus fans clearly indicates that much of the sediment delivered to the Himalayan foreland was transported along its axis and deposited beyond the geographical limits of the thrust-load-generated basin itself. This efficient bypassing of large quantities of sediment results in two-dimensional, transverse profiles that correspond to those expected for underfilled forelands basins. Any inference that the rate of sediment supply was therefore less that the rate of subsidence would, however, be likely to be incorrect.

Acknowledgements

This research was supported by National Science Foundation Grants EAR-8720970 and EAR-8916690 and National Geographic Research Grant 3677–87 to the D. W. Burbank and by a Fulbright Fellowship to R. A. Beck. Logistical support was provided by the Centre of Excellence in Geology of the University of Peshawar and by the Geological Survey of Pakistan. Special thanks are extended to R. A. K. Tahirkheli, J. Khan, Q. Jan and M. Raza. We thank the Department of Earth Sciences at the University of Cambridge who provided facilities and stimulating conversation during the preparation of this manuscript.

References

ALAM, M. (1989): Geology and depositional history of Cenozoic sediments of the Bengal Basin of Bangladesh. – Palaeogeo., Palaeoclim., Palaeoeco., **69**, 125–139.

BARNDT, J., JOHNSON, N. M., JOHNSON, G. D., OPDYKE, N. D., LINDSAY, E. H., PILBEAM, D. & TAHIRKHELI, R. A. K. (1978): The magnetic polarity stratigraphy and age of the Siwalik Group near Dhok Pathan Village, Potwar Plateau, Pakistan. – Earth Plan. Sci. Lett., **41**, 355–364.

BARRY, J. C., JOHNSON, N. M., RAZA, S. M. & JACOBS, L. L. (1985): Neogene mammalian faunal change in southern Asia: Correlations with climatic, tectonic, and eustatic events. – Geology, **13**, 637–640.

—, LINDSAY, E. H. & JACOBS, L. L. (1982): A biostratigraphic zonation of the middle and upper Siwaliks of the Potwar Plateau of northern Pakistan. – Palaeogeo., Palaeoclim., Palaeoecol., **37**, 95–130.

BECK, R. A., VONDRA, C. F., FILKINS, J. & OLANDER, J. (1988): Syntectonic sedimentation and Laramide basement thrusting: timing and deformation. – In: Interaction of the Cordilleran thrust belt and Rocky Mountain foreland, Geol. Soc. Amer. Spec. Pap., **171**, 465–487.

BEHRENSMEYER, A. K. & TAUXE, L. (1982): Isochronous fluvial systems in Miocene deposits of northern Pakistan. –Sedimentology, **29**, 331–352.

BERGGREN, W. A., KENT, D. V., FLYNN, J. J. & VAN COUVERING, J. A. (1985): Cenozoic geochronology. – Geol. Soc. Am. Bull., **96**, 1407–1418.

BURBANK, D. W. & RAYNOLDS, R. G. H. (1984): Sequential late

Cenozoic structural disruption of the northern Himalayan foredeep. – Nature, **311**, 114–118.

— & RAYNOLDS, R. G. H. (1988): Stratigraphic keys to the timing of deformation: an example from the northwest Himalayan foredeep. – In: Kleinspehn, K. L. & Paola, C. (eds.), New perspectives in basin analysis, Springer-Verlag, 331–351.

—, BECK, R. A., RAYNOLDS, R. G. H., HOBBS, R. & TAHIRKHELI, R. A. K. (1988): Thrusting and gravel progradation in foreland basins: a test of post-thrusting gravel dispersal. – Geology, **16**, 1143–1146.

— & — (1989): Early Pliocene uplift of the Salt Range: Temporal constraints on thrust wedge development, northwest Himalaya, Pakistan. – In: Malinconico, L. L. & Lillie, R. J. (eds.), Tectonics and Geophysics of the Western Himalaya, Geol. Soc. Am. Spec. Pap., **232**, 113–128.

CERVENY, P. F., NAESER, N. D., ZEITLER, P. K., NAESER, C. W. & JOHNSON, N. M. (1988): History of uplift, relief and provenance of the Himalaya during the past 18 million years: evidence from fission track ages of detrital zircons from Siwalik Group sediments. – In: Kleinspehn, K. L. & Paola, C. (eds.), New perspectives in basin analysis, Springer-Verlag, 43–61.

COVEY, M. (1986): The evolution of foreland basins to steady state: evidence from the western Taiwan foreland basin. –In: Allen, P. A. & Homewood, P. (eds.), Foreland basins, Inter. Asso. Sed. Spec. Pub., **8**, Blackwell Scientific, 77–90.

FLEMINGS, P. B. & JORDAN, T. E. (1989): A synthetic stratigraphic model of foreland basin development. – J. Geophys. Res., **94**, 3851–3866.

— & — (1990): Stratigraphic modeling of foreland basins: interpreting thrust deformation and lithospheric rheology. – Geology, **18**, 430–434.

GOLE, C. V. & CHITALE, S. V. (1966): Inland delta building activity of the Kosi River. – Jour. of Hydraul. Div., Am. Soc. Civ. Eng. Proc., **4**, 111–126.

HAQ, B. U., HARDENBOL, J. & VAIL, P. R. (1987): Chronology of fluctuating sea levels since the Triassic. – Science, **235**, 1156–1166.

HARLAND, W. B., ARMSTRONG, R. L., COX, A. V., CRAIG, L. E., SMITH, A. G. & SMITH, D. G. (1990): A geologic time scale 1989. – Cambridge University Press, Cambridge, U. K., 263 p.

JOHNSON, G. D., JOHNSON, N. M., OPDYKE, N. D. & TAHIRKHELI, R. A. K. (1979): Magnetic reversal stratigraphy and sedimentary tectonic history of the Upper Siwalik Group, Eastern Salt Range and Southwestern Kashmir. –In: Farah, A. & DeJong, K. A. (eds.), Geodynamics of Pakistan, Geol. Sur. Pak., Quetta, Pakistan, 149–165.

—, RAYNOLDS, R. G., BURBANK, D. W. (1986): Late Cenozoic tectonics and sedimentation in the northwestern Himalayan foredeep: I. Thrust ramping and associated deformation in the Potwar region. – In: Allen, P. & Homewood, P. (eds.), Foreland Basins, Int. Assoc. Sed. Spec. Pub., **8**, 237–291.

JOHNSON, N. M., OPDYKE, N. D., JOHNSON, G. D., LINDSAY, E. & TAHIRKHELI, R. A. K. (1982): Magnetic polarity stratigraphy and ages of the Siwalik group rocks of the Potwar plateau, Pakistan. – Palaeogeog., Palaeoclim., Palaeoecol., **37**, 17–42.

—, STIX, J., TAUXE, L., CERVENY, P. F. & TAHIRKHELI, R. A. K. (1985): Paleomagnetic chronology, fluvial processes and tectonic implications of the Siwalik deposits near Chinji village, Pakistan. – Jour. Geol., **93**, 27–40.

JORDAN, T. E., FLEMINGS, P. B. & BEER, J. A. (1988): Dating thrust-fault activity by use of foreland-basin strata. – In: Kleinspehn, K. L. & Paola, C. (eds.), New Perspectives in basin analysis, Springer-Verlag, 307–330.

KELLER, H. M., TAHIRKHELI, R. A. K., MIZRA, M. A., JOHNSON, G. D., JOHNSON, N. M. & OPDYKE, N. D. (1977): Magnetic polarity stratigraphy of the Upper Siwalik deposits, Pabbi Hills, Pakistan. – Earth Plan. Sci. Lett., **36**, 187–201.

LABREQUE, J. L., KENT, D. V. & CANDE, S. C. (1977): Revised magnetic-polarity time scale for Late Cretaceous and Cenozoic time. – Geology, **5**, 330–335.

MACKIN, J. H. (1948): The concept of a graded river. – Geol. Soc. Am Bull., **59**, 463–512.

MANKINEN, E. A. & DALRYMPLE, G. B. (1979): Revised geomagnetic polarity time scale for the interval 0–5 m.y. B. P. – J. Geophys. Res., **84**, 615–626.

MCGEE, V. E., JOHNSON, N. M. & NAESER, C. W. (1985): Simulated fissioning of uranium and testing of the fission track dating method. – Nucl. Tracks, **10**, 365–379.

OPDYKE, N. D., LINDSAY, E. H., JOHNSON, G. D., JOHNSON, N. M., TAHIRKHELI, R. A. K. & MIZRA, M. A. (1979): Magnetic polarity stratigraphy and vertebrate paleontology of the Upper Siwalik Subgroup of northern Pakistan. – Paleogeo., Paleoclim., Paleoecol., **27**, 1–34.

PAOLA, C. (1990): A simple basin-filling model for coarse-grained alluvium. – In: Cross, T. (ed.), Quantitative dynamic stratigraphy, Prentice Hall, 363–374.

ORI, G. G. & FRIEND, P. F. (1984): Sedimentary basins formed and carried piggyback on active thrust sheets: Geology, **12**, 475–478.

RAYNOLDS, R. G. H. (1980): The Plio-Pleistocene structural and stratigraphic evolution of the eastern Potwar Plateau, Pakistan [Ph. D. thesis]. – Hanover, New Hampshire, Dartmouth College, 256 p.

— (1981): Did the ancestral Indus flow into the Ganges drainage? Geol. Bull. Univ. Peshawar, **14**, 141–150.

— & JOHNSON, G. D. (1985): Rates of Neogene depositional processes, northwestern Himalayan foredeep margin, Pakistan. – In: Snelling, N. J. (ed.), The chronology of the geologic record, Geol. Soc. Lon. Mem., **10**, 297–311.

SCHUMM, S. A. (1968): River adjustment to altered hydrologic regimen – Murridge River and paleochannels, Australia. – U. S. G. S. Prof. Paper, **598**, 65 p.

— (1972): Fluvial paleochannels. – In: Rigby, J. K. & Hamblin, W. K. (eds.), Recognition of Ancient Sedimentary Environments, Soc. Econ. Paleon. & Min. Spec. Publ., **16**, p. 98–107.

SCLATER, J. G. & CHRISTIE, P. A. F. (1980): Continental stretching: An explanation of the post-mid-Cretaceous subsidence of the Central North Sea Basin. – J. Geophy. Res., **85**, 3711–3739.

SEEBER, L. & GORNITZ, V. (1983): River profiles along the Himalayan arc as indicators of active tectonics. – Tectonophy., **92**, 335–367.

STECKLER, M. S. & WATTS, A. B. (1978): Subsidence of the Atlantic-type continental margin off New York. – Earth & Plan. Sci. Lett., **41**, 1–13.

TAUXE, L. & OPDYKE, N. D. (1982): A time framework based on magnetostratigraphy for the Siwalik sediments of the Khaur area, northern Pakistan. – Paleogeo., Paleoclim., Paleoecol., **37**, 43–61.

VAN HINTE, J. E. (1978): Geohistory analysis – application of micropaleontology in exploration geology. – Am. Assoc. Petr. Geol. Bull., **62**, 201–222.

WELLS, N. A. & DORR, J. A., Jr. (1987): Shifting of the Kosi River, northern India. – Geology, **15**, 204–207.