Thrusting and gravel progradation in foreland basins: A test of post-thrusting gravel dispersal

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ABSTRACT

The use of gravels as syntectonic indicators of thrusting has recently been questioned by foreland-basin models that assign gravels to a post-thrusting interval of progradation, except in very proximal areas. On the basis of precise temporal control provided by magnetostratigraphically dated sections, the history of gravel progradation after a major thrusting and uplift event in the northwestern Himalaya is shown to be a virtually syntectonic phenomenon. Despite considerable crustal subsidence driven by a thick-skinned thrust, gravels prograded ~70 km during a 1.5-m.y.-long thrusting event. By 3 m.y. after the start of thrusting, gravels extended more than 110 km into the basin. Although delayed gravel progradation appears appropriate for many Rocky Mountain foreland basins, it is clearly not valid for the Himalaya. We attribute the difference in depositional response between these basins to differences in the quantity of sediment supplied to them (sediment starved vs. overfilled), the availability of resistates in the source area, and the size of the antecedent drainage.

INTRODUCTION

Reconstructions of the absolute and relative timing of thrusting events along the margins of foreland basins have frequently been based on interpretations of the stratigraphic record. Progradation of conglomeratic facies from a thrust-bounded source terrain has often been cited as an indicator of an episode of thrusting (e.g., Armstrong and Oriel, 1965; Wiltschko and Dorr, 1983; Heller et al., 1986). In the proximal regions of foreland basins where conglomerates may be in intimate association with adjacent thrusts (e.g., Riba, 1976), it is reasonable to tie conglomeratic packages, especially syntectonically deformed ones, to thrusting events. In many basins, however, subsequent deformation and erosion have removed this very proximal record of thrusting, and so the most proximal strata preserved may be tens of kilometres from their source terrains. Because facies progradation is time transgressive, the ages of influx of a conglomeratic sequence will vary between locations, and none will provide a precise age for the causative thrusting event (Jordan et al., 1988); therefore, other approaches to dating thrust activity must be considered.

In foreland basins where very precise time constraints are available on facies migration, such as in northern Pakistan (Raynolds and Johnson, 1985), it may be possible to extrapolate an observed rate of gravel progradation backward in time and space toward the thrust front in order to estimate the time of initial progradation (Burbank and Raynolds, 1988). The accuracy of such an estimate is dependent on the frequently untestable assumption of a steady rate of progradation through time. When a thrust elevates a new, lithologically distinct source terrain, sandstone compositions across a broad part of the foreland basin may record this change almost immediately (Jordan et al., 1988). Analyses of provenance variations are only useful the first time a new lithologic component is introduced by thrusting and therefore are not applicable to many thrusted foreland sequences that repeatedly expose lithologically similar source areas.

The concept of conglomeratic facies as reliable indicators of thrusting events has recently been questioned. Beck (1985) pointed out that in some of the Rocky Mountain foreland basins, thrusting was associated with subsidence-induced, fine-grained sedimentation in much of the proximal part of the basin, except immediately adjacent to the thrust shelf itself. Significant parts of the distal foreland were dominated by fluvial systems flowing *toward* the thrust front, and lacustrine facies occasionally spread across the medial part of the basin (Beck, 1985; Beck et al., 1988). The conglomeratic sheets that prograded across the basins and that had formerly been interpreted as indicators of thrusting events (Wiltschko and Dorr, 1983; Armstrong and Oriel, 1965) were described as primarily postorogenic facies related to cessation of thrusting (Beck and Vondra, 1985).

These interpretations of Cretaceous and Tertiary sedimentation in the Rockies have provided a basis for conceptual models that attempt to link thrusting, crustal flexure, subsidence histories, and facies geometries in foreland basins (Beck et al., 1988; Kvale and Beck, 1985; Heller et al., 1988; Blair and Bilodeau, 1988). According to these models, thrust loading induces a predominantly elastic crustal response in which the maximum basin subsidence is localized adjacent to the thrust. Because the rate of subsidence frequently outpaces the rate of gravel supply, the coarse-grained facies derived from the uplifted terrain are confined to a narrow belt adjacent to the thrust. The depositional axis of the basin is displaced toward the thrust belt and is often dominated by fine-grained sedimentation. Moreover, the major tributaries to the foredeep are rivers flowing toward the zone of maximum subsidence from the distal margin. Consequently, throughout much of the foreland basin, episodes of thrusting will be recorded by either low-energy axial deposition or by rivers flowing toward the thrust belt. When thrusting ceases and erosion reduces the thrust load, these models predict that thrust-induced subsidence will slow or cease and conglomeratic facies will prograde extensively across the basin (Beck and Vondra, 1985; Kvale and Beck, 1985; Heller et al., 1988). Furthermore, Heller et al. (1988) suggested that, after a thrusting event, erosion of the thrust sheet will cause isostatic rebound, generating widespread proximal unconformities.

Can these proposed interpretations of conglomeratic facies and their relation to thrusting be tested against existing data sets? In order to evaluate the model rigorously, stratigraphic data with high-resolution time control and also independent evidence of the initiation and cessation of thrust activity are needed. This paper describes such a data set from the northwestern Himalaya—probably the most precisely dated terrestrial foreland basin succession in the world. Interpretation of the local deformational and depositional history suggests that the models for delayed gravel progradation are not applicable to the thick-skinned thrusts in the northwest Himalaya.

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STRUCTURAL GEOLOGY AND THRUST CHRONOLOGIES IN THE NORTHWEST HIMALAYA FORELAND

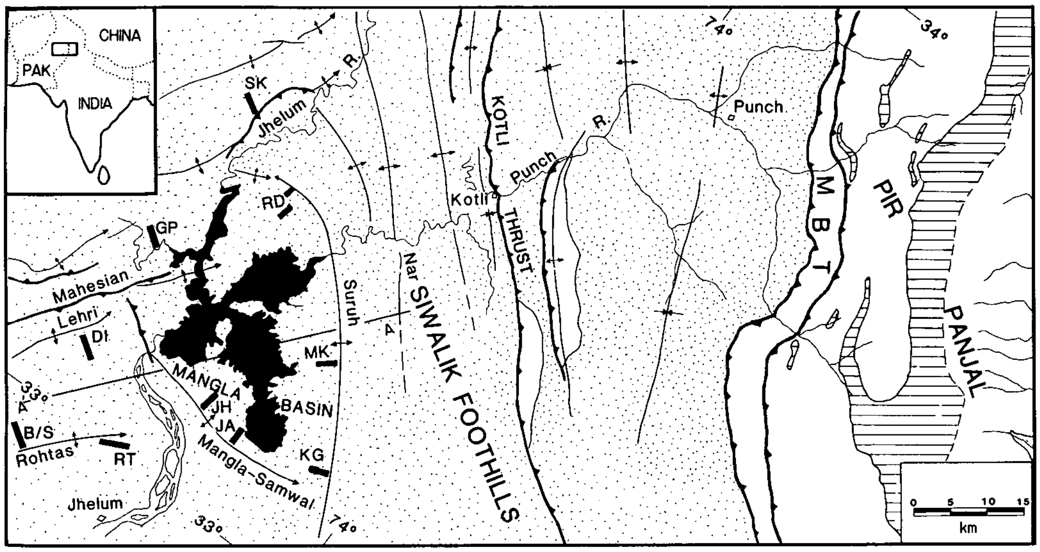
The Himalayan foreland basin accommodates more than 10 km of terrestrial sediments that accumulated during the Cenozoic collision of the Indian subcontinent with Asia. The Miocene and younger part of this sequence, known as the Siwalik Group, have been dated through numerous magnetostratigraphic studies (e.g., Opdyke et al., 1979; Johnson et al., 1979, 1982, 1985; Raynolds, 1980; Raynolds and Johnson, 1985). In this study we focus on the record southwest of the Kashmir Basin and Pir Panjal Range (Fig. 1) where two thrust systems appear to have controlled the pattern of Pliocene-Pleistocene deposition and deformation along the east limb of a major structural reentrant. The Main Boundary thrust (MBT) system is the forward edge of a thick allochthon comprising the entire Pir Panjal Range and the Kashmir Basin (Fig. 1). Few subsurface data are available to constrain the geometry of the thrust at depth. Conservative reconstructions indicate a likely thrust-plate thickness of at least 10 km. The Kotli thrust (Fig. 1) is located between the MBT proper and the present foreland basin. It juxtaposes pre-Miocene molasse strata over younger molasse sediments.

The timing of initiation of motion on the MBT has been constrained through previous studies of facies, provenance, and paleocurrent changes (Burbank and Raynolds, 1984, 1988). Major reorganization of drainage systems within the proximal foreland, the first influx of volumetrically significant sediments from the Pir Panjal, and the commencement of lacustrine deposition in the Kashmir piggyback basin all indicate that MBT thrusting began between 4 and 5 Ma. A later interval of major movement on the MBT system occurred ~0.4 Ma (Burbank and Raynolds, 1984, 1988). The timing of movement on the Kotli thrust is not well constrained, but facies patterns and the history of folding in the reentrant suggest that it became active after 2 Ma.

GRAVEL PROGRADATION AND SEDIMENT ACCUMULATION

Along the limbs of folds in the proximal foreland, ten sections (Fig. 1) have been dated by using magnetostratigraphy (Johnson et al., 1979; Opdyke et al., 1979; Raynolds, 1980).

Figure 1. Simplified geologic map of study area adjacent to Main Boundary thrust (MBT). Section locations: Basawa/Sanghoi Kas (B/S); Dina (DI); Ganda Paik (GP); Jari (JA); Jhel Kas (JH); Kas Guma (KG); Mawa Kaneli (MK); Rata-Dadial (RD); Rohtas (RT); Sakrana (SK).



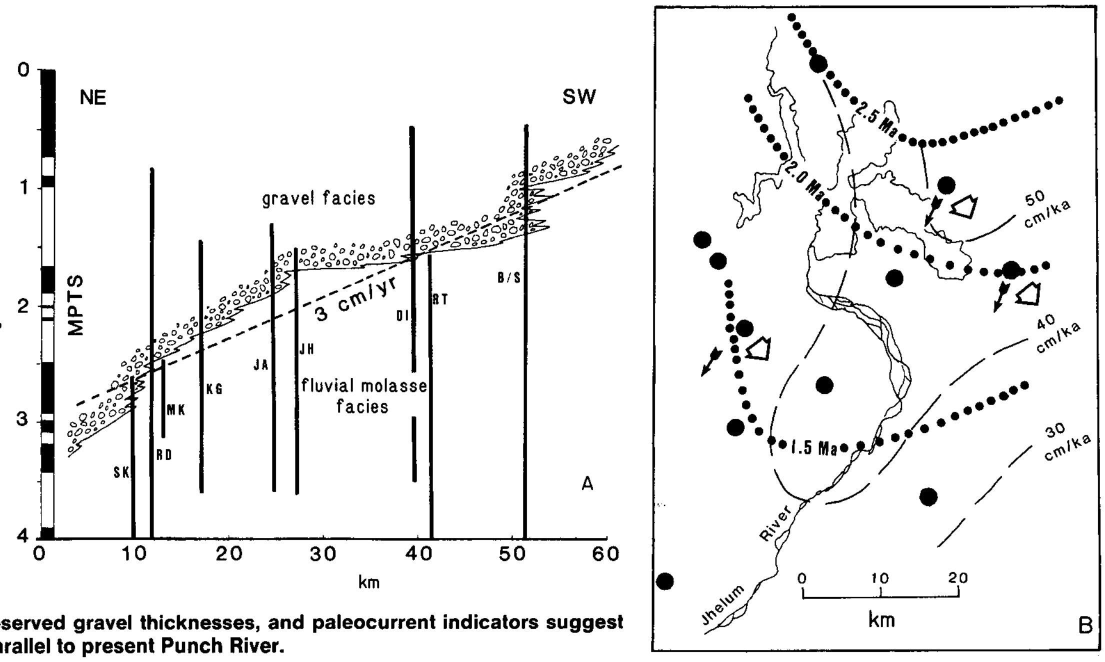


Figure 2. A: Gravel progradation plotted on northeast-southwest transect perpendicular to Main Boundary thrust (MBT) (see Fig. 1 for location: A-A'). Solid vertical lines indicate magnetostratigraphically dated part of each section. MPTS = magnetic polarity time scale. Abbreviations as in Figure 1. B: Sediment-accumulation rates (dashed contours), Gauss chron (3.4–2.48 Ma); approximate position of distal margin of gravels (dotted isochrons); and paleocurrent directions in gravel facies (filled arrows) and in pre-gravel sandstones (open arrows). Axis of maximum accumulation, preserved gravel thicknesses, and paleocurrent indicators suggest progradation along pathway parallel to present Punch River.

The resultant chronologies span an interval from ~5.5 to ~0.4 Ma, and they provide an extensive temporal framework within which to define gravel progradation and its relation to thrusting. Two facets of the available data are particularly relevant to this study: (1) the specific timing of deposition of conglomerates with a Pir Panjal provenance at various sites across the foreland basin, and (2) the record of changes of sediment accumulation rates and subsidence at these same sites.

The conglomerates derived from the Pir Panjal are dominated by Paleozoic quartzite clasts with subordinate quantities of distinctive Permian-Triassic Panjal volcanics. The first appearance of these Pir Panjal–derived conglomerates is a time-transgressive event that sweeps from northeast to southwest across the foreland (Raynolds, 1980). When the temporally defined position of the first conglomeratic influx at each section is projected onto a transect (Fig. 1) that is perpendicular to the thrust front, gravel progradation is seen to have commenced in the north between 3.1 and 2.5 Ma and to have migrated southward at a mean rate of ~3 cm/yr (Fig. 2). At present, there are no dated sections farther north and closer to the thrusts that provide data on earlier conglomeratic sedimentation.

Sediment accumulation rates in terrestrial basins with an abundant sediment supply are, to a large extent, a proxy for basin subsidence rates because load-induced crustal depressions will be rapidly filled with sediments up to the regional base level. In order to examine the history of sediment accumulation in the Himalayan foreland, each dated section has been decompacted as a function of burial depth and lithologic characteristics (Sclater and Christie, 1980). When sediment accumulation is plotted as decompacted thicknesses vs. time, the results (Fig. 3) reveal two important aspects of the sediment accumulation history. First, for all those sections encompassing the earlier part (3–5 Ma) of the record, there is a nearly synchronous increase in rates of accumulation beginning between 4 and 4.5 Ma. Second, virtually all of the sections show a tendency toward decreasing sediment accumulation rates beginning at ~3.0 Ma. This change is generally more pronounced in the proximal sections, i.e., those closest to the thrust front.

In order to convert sediment accumulation curves into basement subsidence curves, an external frame of reference is useful. In the studied area, axially southeast flowing rivers, coupled with an abundant sediment supply, appear to have maintained a subhorizontal surface until the conglomeratic facies prograded transversely across the region. Where data are available, the shift from axially to transversely directed paleocurrents (Fig. 2B) occurs slightly before the first conglomeratic influx. Therefore, during the time in which the two accumulation rate changes are observed (Fig. 3), the subhorizontal depositional surface can serve as a reference frame for assessing basement subsidence.

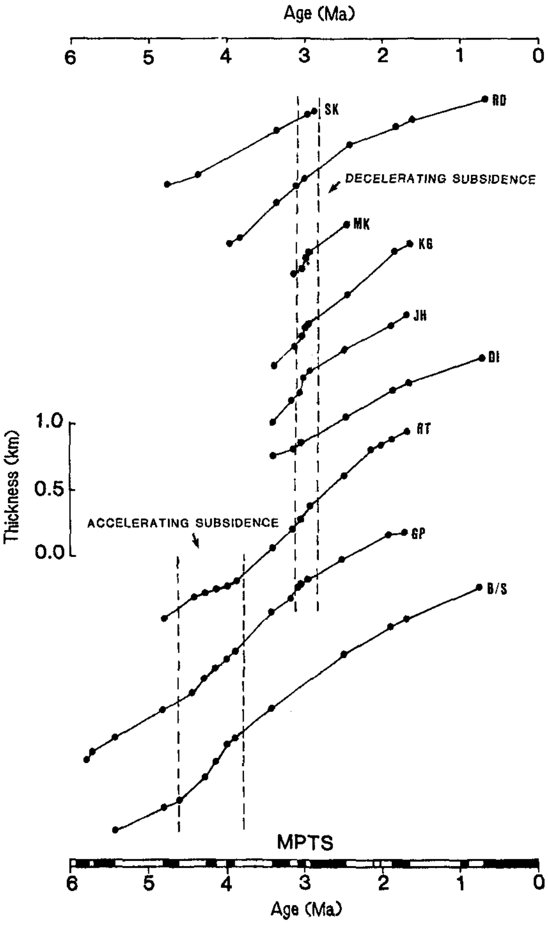


Figure 3. Decompacted sediment accumulation at nine sections. Shaded regions indicate two intervals of changing rates of sediment accumulation. MPTS = magnetic polarity time scale.

SUBSIDENCE AND THE TIMING OF GRAVEL PROGRADATION

The data presented above can be used to evaluate the conflicting models of synthrusting vs. post-thrusting gravel progradation. The synchronous increases in sediment accumulation and subsidence at 4.5–4 Ma (Fig. 3) coincide in time with the initiation of thrusting along the MBT that has been inferred from provenance, paleocurrent, and facies data (Burbank and Raynolds, 1984, 1988). Because of the high-quality time resolution available here, this example provides some of the most unequivocal support for the concept that thrust loading causes enhanced subsidence in foreland basins (e.g., Beaumont, 1981; Jordan, 1981). The observation of accelerated subsidence at sites >100 km away from the active thrust indicates at least a short-term elastic crustal response to imposed loads (Jordan, 1981; Hagen et al., 1985).

What is the significance of the rate decreases beginning at ~3 Ma? We interpret these as representing either the cessation or deceleration of this interval of thrusting or the transition point where the rate of erosion of the thrust sheet significantly exceeds the rate of addition of new material through thrusting. In either case, the rate of loading of the crust will diminish, as will sediment accumulation and subsidence rates. Whereas the Heller et al. (1988) model predicted uplift in the proximal foreland at this time, our data suggest continued subsidence, but at a slower pace. This continued subsidence may result from (1) the more continuous regional load of the still-deforming Greater Himalaya; (2) a subsidiary, viscous component within the predominantly elastic crustal flexure; or (3) continued thrust loading, but at a lower rate along the MBT. The rate changes at 4.5 and 3 Ma would then represent responses to the local load of the ancestral Pir Panjal Range superimposed on the regional (Himalayan thrust belt) loading.

The relation of gravel progradation to the termination of thrusting may now be examined. Whereas the northernmost study sites lie many kilometres south of the MBT, the coincidence in time at ~3 Ma of decreasing sediment accumulation and subsidence rates (Fig. 3) with the beginning of advance of the conglomerates from northeast to southwest across the study area appears to support the idea that gravel progradation is primarily a post-tectonic phenomenon. However, the northernmost sites at Rata-Dadial and Sakrana (Fig. 1) are currently situated >60 km from the thrust front. In order to begin prograding across the studied area by 3 Ma, the conglomerate facies would have had to traverse the intervening distance after thrusting began ~4.5 Ma. The rate of gravel progradation across the 60 km of "proximal" foreland would have occurred at a mean rate of 4 cm/yr. This rate ignores shortening across the Kotli thrust which, if included, would increase the mean rates. This early rate of progradation is more than 30% greater than the later (<3 Ma) rate, and it argues strongly against any discernible ponding of the coarse-grained facies adjacent to the active thrust front. Within 1.5 m.y. of the start of thrusting, conglomerates extended >60 km from the thrust, and within 3 m.y., they were out >110 km into the basin. Rather than accelerating (Heller et al., 1988), the mean rate of progradation apparently slowed as thrusting waned. It is also interesting to note the reconstructed geometry of the gravel body. As opposed to a coarse apron shed uniformly into the foreland, it appears as a broad tongue, lensoid in cross section and elongated perpendicular to the thrust front (Fig. 2B). The axis of gravel progradation during the late Pliocene follows the axis of maximum accumulation during the middle Pliocene and is nearly coincident with the path of the modern Punch River. This trend is at an acute angle to the axis of the present structural reentrant and the course of the Jhelum River, suggesting that Pleistocene deformation in the proximal foreland may have shifted the focus of deposition from the Punch area to its present position.

CONCLUSIONS

In recent years, the traditional interpretation of prograding gravels as indicators of thrust activity has been challenged in models which predict that, except in the most proximal areas of the foreland basin, progradation will be delayed until subsidence and thrusting wane or cease (Beck et al., 1988; Heller et al., 1988). Data related to the thrusting and uplift of the Pir Panjal Range in the northwestern Himalaya provide perhaps the most detailed and precise record of foreland deformation and deposition available. These data are incompatible with the recently proposed models. Despite the presence of a thick-skinned thrust, which would be expected to induce greater asymmetric subsidence than a thin-skinned thrust, gravels prograded >110 km into the basin in the 3 m.y. after the initiation of thrusting. In contrast to post-thrust gravel progradation models for the Rocky Mountains, major gravel progradation in the northwestern Himalaya was certainly not delayed until thrusting ceased.

The model for delayed gravel progradation appears appropriate for the latest Cretaceous to Eocene foreland basins of the northern Rockies (Beck et al., 1988). The cause of its inapplicability to the Himalayan foreland basin may lie in several factors, including the presence of major antecedent rivers that provided voluminous sediments to the Himalayan foreland (i.e., high rates of erosion and transport); highly resistant rocks, particularly quartzites, in the uplifted Pir Panjal source area; possible focusing of gravel progradation along a depositional axis defined by enhanced subsidence (Fig. 2B); and the rigidity of the underlying crust which did not sag appreciably during loading. A sediment-filled basin is a prerequisite for extensive transverse gravel progradation. In contrast to the underfilled and partially sediment-starved basins of the Rockies, the Himalayan foreland basin was filled to near capacity for most of its history, and considerable sediment was transported out of the basin. In similar sediment-filled foreland basins, thrusting events may be directly linked to extensive gravel progradation. We conclude that a synthrusting vs. post-thrusting origin for transversely prograding gravel sheets in foreland basins is strongly dependent on rates of sediment erosion and transport, of thrusting, and of subsidence, and that neither model is universally applicable.

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