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GRAVITY ANOMALIES, FLEXURE OF THE INDIAN PLATE, AND THE STRUCTURE, SUPPORT AND EVOLUTION OF THE HIMALAYA AND GANGA BASIN

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Abstract. Bouguer gravity anomalies along four profiles across the Western Himalaya and Ganga Basin show large deviations from local isostatic equilibrium. A deficit of mass characterizes the Ganga Basin, and an excess underlies the Lesser Himalaya. Both can be understood if the Indian plate is flexed down by the distributed load of part of the mountains. The cross sectional shape of the Ganga Basin seems to be controlled by the deflection of the Indian plate, which we compute assuming the Indian plate to overlie an inviscid fluid. From the shapes of both Bouguer anomaly profiles and the basement topography we place bounds on the flexural rigidity of such a plate. If the Ganga Basin is a steady state feature, then the age of the basal sediments in a given locality should be proportional to the distance of that locality from the southern edge of the basin. If the rate of convergence of India and the Himalaya were constant, that rate should equal the distance divided by the corresponding age. We find a rate of 10 to 15 mm/a for the last 15 to 20 Ma, which is consistent with a large part of the 50 mm/a rate of convergence between India and Eurasia being absorbed by the eastward extrusion of parts of Tibet. Profiles of Bouguer gravity anomalies show only a small peak or plateau over the southern edge of the Lesser Himalaya, implying that the boundary between the light sediments of the Ganga Basin and the heavier crustal rocks of the Lesser Himalaya is not sharp and that there exists some light material beneath the range. We infer that some sediment deposited in the Ganga Basin has been underthrust beneath the Lesser Himalaya, but the quantity is small; most of this sediment probably is scraped off the Indian plate to make the foothills of the range. We find that the load of the High Himalaya is too large to be supported solely by elastic stress in the Indian plate if the flexural rigidity of the plate is constant and if no other external forces act on the plate. The observed gradient in Bouguer gravity anomalies increases from an average of about 1 mGal/km over the Ganga Basin and Lesser Himalaya to about 2 mGal/km over the High Himalaya. This increase in the gravity gradient implies that the Moho dips more steeply (10°-15°) beneath the High Himalaya than beneath the Lesser Himalaya (2°-3°). We interpret this steepening of the Moho to be due to a weakening of the plate, which allows it to bend more sharply beneath the High Himalaya than farther south. With the inclusion of a weak

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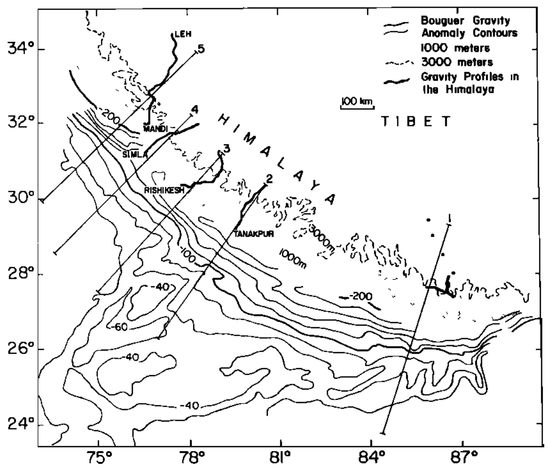

Fig. 1. Map of the Indo-Gangetic plains and the Himalaya with 1000 and 3000 m elevation contours and contours of Bouguer anomalies over the plains. For each of the profiles shown, the routes along which gravity measurements were made in the Himalaya are shown by a heavy line or by dots.

segment of Indian plate beneath the High Himalaya, calculated anomalies show a somewhat increased gradient beneath the High Himalaya, but when the weight of the entire Himalaya is used as a load on the plate, calculated anomalies are more negative than observed. Therefore an external force system is needed to support much of the weight of the High Himalaya, as well as to bend the plate sufficiently beneath the High Himalaya. The magnitudes of the bending moment and the force per unit length that must be applied to the end of the plate are compatible with their sources being gravity acting on a part of India's mantle lithosphere, stripped of its crust and underthrust beneath southern Tibet.

INTRODUCTION

Gravity anomalies over both the Himalaya and the Alps show large deviations from local isostatic equilibrium. Both ranges are associated with a local excess of mass, but adjacent to both are foredeep basins characterized by a deficit of mass. This undercompensation of the mountain ranges and overcompensation of the neighboring foredeeps can be understood if the continental lithosphere is flexed down by the load of the mountains and if its strength supports part of the mass of the mountain range [Gunn, 1943; Karner and Watts, 1983; Lyon-Caen and Molnar, 1983]. The deflection of the plate creates a foredeep basin in front of the load such that the depth and shape of the basin are directly related both to the strength of the plate and to the amount of load acting on it.

Various studies have assumed that, to a first approximation, the response of the lithosphere to such external loads can be treated as elastic and that of the asthenosphere as an inviscid fluid, at least for loads younger than about 100 Ma [e.g., Gunn, 1943; Hanks, 1971; Walcott, 1970; Watts and Talwani, 1974]. Both Karner and Watts [1983] and we [Lyon-Caen and Molnar, 1983] have used such a simple model to analyze gravity anomalies across the Himalaya, and in doing so we have tried to gain some insight into how the range is supported. Although the gravity field along at least one profile across the Ganga Basin and the Lesser Himalaya can be explained in the context of an elastic plate over an inviscid fluid, we found the load of the High Himalaya, at least in the Mount Everest region, to be too large to be supported solely by the strength of the Indian plate without additional forces applied to it [Lyon-Caen and Molnar, 1983]. A few gravity data in the area of Mount Everest and farther north suggest that the Moho steepens just south of the Mount Everest and reaches a depth of approximately 70 km at a position about 50 km south of the Indus-Tsangpo suture zone. New gravity data in this area [Van de Meulebrouck et al., 1983; Van de Meulebrouck, 1984] corroborate these inferences. We interpreted this steepening to be due to the weakening of the plate beneath the High Himalaya, probably at least in part, by detachment of the Indian crust during the collision process. We then found that the High Himalaya can be supported by the Indian plate if an external force or a moment is applied to the end of the plate, and we suggest that the source of this external force could be gravity acting on the cold mantle part of the Indian lithosphere detached from the crust [Lyon-Caen and Molnar, 1983].

The present paper describes a similar analysis of 4 gravity profiles across the western part of the Himalaya, in India, and across the Ganga Basin (Figure 1). These data are qualitatively consistent with the conclusions described above, but among them the profiles show differences in the various parameters controlling the shape of the flexed Indian plate. These data also allow a more detailed study of the structure of the Ganga Basin and Lesser Himalaya than was possible in our previous study, because the structure of these areas in western India is quite well known from deep wells, seismic reflection profiles, and detailed geological mapping.

After a brief review of the methods used to analyze the data, we show that the deviation from local isostatic equilibrium is large along all five profiles across the Himalaya. We then present an analysis of each profile separately, comparing inferences about the structure of the Ganga Basin and the Himalaya with geological observations when they are available. Finally, we discuss these inferences in light of the tectonic evolution of this region, and we use this inferred evolution of the Ganga Basin to place a constraint on the rate of convergence between India and the Himalaya.

DATA AND ANALYSIS

Gravity Anomalies

We obtained from the Defense Mapping Agency (DMA) a listing of gravity measurements made in the Ganga Basin. These measurements include simple Bouguer gravity anomalies, without terrain corrections, referenced to the 1971 Geodetic Reference System. Terrain corrections over the Ganga Basin are, indeed, small (a few milligals or less) and can be neglected here [e.g., Kono, 1974]. Bouguer anomalies over the Himalaya were taken from plots given by Das et al. [1979], who carefully made terrain corrections, some of which reach 100 mGals, but who reduced their measurements using the 1930 Reference System. Since the difference between the anomalies computed with the two reference systems is less than 1 mGal at the latitude of 30° [Woollard, 1979], however, we ignored this difference and simply connected the data presented by Das et al. [1979] with those from the DMA to obtain complete profiles across the Ganga Basin and the Himalaya.

A possibly important error in the Bouguer anomalies over the Himalaya could have been introduced by the way that we retrieved Das et al.'s [1979] data, because the profiles published by them show only relative variations of gravity. We obtained the absolute scale on their profiles by assigning to the southern end point of each profile the value given by the DMA for the closest point that we could find (Figure 1). Except for profile 5 the two points were within 2 or 3 km of one another. Verma and Subrahamanyam [1984], however, published plots of measurements for two of the profiles used here (profiles 3 and 5) with an absolute scale. Comparing the values of gravity given by Verma and Subrahamanyam [1984] for the end points with those from the DMA makes us confident that the errors involved in this process are less than 5 mGals at the northern edge of the Ganga Basin. For a given point, along each profile, however, the uncertainties probably increase proportionally to its distance from the edge of the Basin and may reach 25 mGals at the northern edge of each profile. In particular, the value of the Bouguer anomaly around Leh, at the northern end of profile 5, could have an error of 30 mGals attached to it, in part because the values given by Verma and Subrahamanyam [1984] and by Das et al. [1979] apparently disagree by about 25 mGals. Verma and Subrahamanyam [1984] do not specify that they included terrain corrections. This may be the source of the discrepancy, but their value is close to the one reported by Marussi [1964], who did make terrain corrections. Thus we do not know why the various values presented by different authors differ from one another, but we assume that the uncertainties in measurements over the Himalaya are no larger than 5 mGals near the Ganga Basin but could reach 25 mGals at the northern ends of the profiles.

We also reconsider the profile used in our previous study (profile 1 in Figure 1). At the time of that study we did not have the listing of data from the DMA, and instead we constructed a profile mostly from contours shown on published gravity maps for which variations in individual measurements had been smoothed. Although the scatter among measurements within a few tens of kilometers of one another along this profile is about 25 mGals, it turns out that there seems to be a resolvable relative gravity high about 20 km north of the edge of Ganga Basin. This high did not appear on the smoothed profile that we used, and the value that we used falls near the middle of these scattered values. We interpreted the absence of a gravity high as evidence that a substantial amount of low-density material

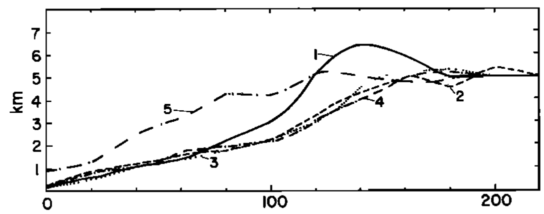

Fig. 2a

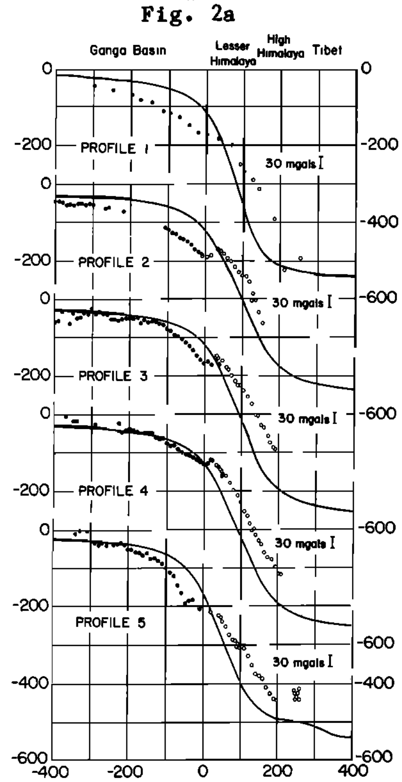

Fig. 2b

Fig. 2. (a) Mean topography along each profile in Figure 1. The northern edge of the Ganga Basin is at x=0. (b) Comparison of observed Bouguer gravity anomalies with anomalies computed assuming that the mean topography shown in Figure 2a is locally isostatically compensated by thickening of the crust from a reference thickness of 38 km beneath central India.

(sediments) had been underthrust beneath the range. The additional data that we have now seem to indicate that only about half of the amount of sediment that we suggested before may have been subducted.

Each of the four new profiles presented here also shows a plateau or a relative high from the edge of the basin to about 50 km north of it. In examining each profile, we will try to relate this feature in the gravity field to geological observations and to use it to place a constraint on the amount of underthrusting of sediment beneath the Lesser Himalaya.

Deviations From Local Isostatic Equilibrium

The Himalaya, at least in the areas south of Mount Everest [Kono, 1974] and near the Pakistan border [Marussi, 1964], is known to be largely undercompensated. We show here that the Lesser and High Himalaya are undercompensated on each profile in Figure 1, and therefore probably along the entire arc, and that this excess of mass is coupled with a deficit of mass beneath the Indo-Gangetic Plains.

Instead of computing standard isostatic anomalies, we computed the Bouguer anomaly that would result if the mean topography along each profile were locally compensated. For this purpose we obtained the mean elevation along each profile by averaging the elevations on the Aeronautical Navigation Charts (ONC charts) in a zone extending 100 km on each side of the profile (Figure 2a). We then computed the Bouguer anomalies assuming that compensation occurs locally solely by the thickening of the crust, which is assumed to have a normal thickness of 38 km under the Indian Shield [Kaila, 1982]. This value of 38 km, however, is not critical, and were values of 30 or 45 km used, the computed anomalies would differ by only a few mgals. The observed gravity data clearly show that large systematic deviations from local isostatic equilibrium are present (Figure 2b). The Ganga Basin is overcompensated, whereas the Himalaya are undercompensated by as much as 100 mGals.

This coupling of mass deficiency over the basin and mass excess over the mountains can be understood if isostasy occurs regionally with the strong Indian lithosphere being flexed down at the Himalayan front and extending beneath the range a certain amount. This would imply that the structure and the evolution of the Ganga Basin are essentially controlled by the flexure of the Indian plate.

Flexural Models

We analyze each of the profiles 2, 3, 4, and 5 using the method described in detail in Lyon-Caen and Molnar [1983] for profile 1. We treat the Indian lithosphere as an effectively elastic plate with a flexural rigidity D and that extends a certain distance X_0 beneath the

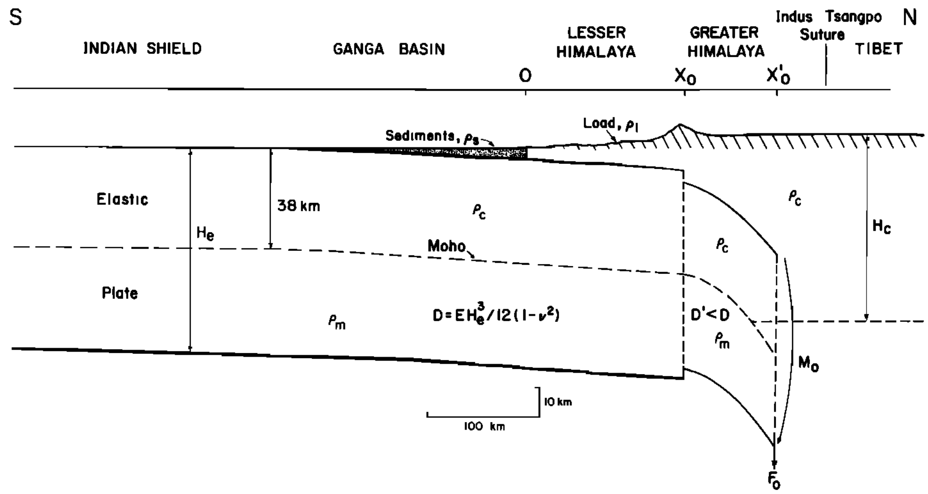

Fig. 3. Schematic cross section of the geometry used to calculate the shape of the flexed plate, and hence the shapes of the Ganga Basin and the Moho. In the first step, only a load between $0 < x < X_0$ is used and a straight line is drawn from the calculated depth of the Moho at $x = X_0$ to that beneath southern Tibet. In a second step, a short segment of plate is added, extending the plate to X_0'. The flexural rigidity D' of the segment between X_0 and X_0' is smaller than D. The load is the weight of the entire range between $0 < x < X_0'$. Values for X_0', and both a bending moment M_0, and an external force F_0 per unit length are then sought such that the computed and observed gravity anomalies match.

Himalaya (Figure 3). At first, we consider cases in which the plate has a constant flexural rigidity and the weight of the mountains is the only external force acting on the plate. In this first part of the analysis, only that part of the range with $x < X_0$ is used as a load acting on the plate. We calculate the deflection of the plate, and hence of the Moho, due to this distributed load, assuming that the trough created in front of the range is filled by sediments of lower density than crustal rock. To define the position of the Moho elsewhere, we assume that both the Tibetan Plateau [Amboldt, 1948] and the Indian Shield to the south of the Ganga Basin are in isostatic equilibrium. We then assume that the profile of the Moho is a straight line from X_0 to an arbitrarily chosen place beneath southern Tibet north of which isostatic equilibrium obtains. In doing so no specific mechanism is provided for the support of the Himalaya between X_0 and this place in southern Tibet. We consider this in a second step of the analysis described below.

We compute the resulting gravity anomalies assuming that they are due only to the density contrasts among crust, mantle, and sediments. The mean density of the sediments is chosen to be 2.4 g/cm^3, as suggested by measurements reported by Raiverman et al. [1983]. We used densities of 2.8 g/cm^3 and 3.35 g/cm^3 for the crust and mantle, respectively, and of 2.7 g/cm^3 for the load. In any case, Lyon-Caen and Molnar [1983] showed that density contrasts are not important parameters as far as the calculation of gravity anomalies is concerned. The least important difference is that between 2.7 g/cm^3 assumed for the load and 2.67 g/cm^3 for the Bouguer correction. A Bouguer correction of 2.67 g/cm^3 is the standard used by the DMA and in nearly all other studies, but for calculations of deflections we refrain from assigning a value with three significant figures to a density whose uncertainty affects the second significant figure. Had we used 2.67 g/cm^3 for the density of the load, the computed deflections would differ by less than 1%, an amount different from those calculated here comparable with the width of the lines in Figures 4-7.

For the gravity anomalies over the Ganga Basin and the Lesser Himalaya, the two essential parameters are the flexural rigidity D and the length that the elastic

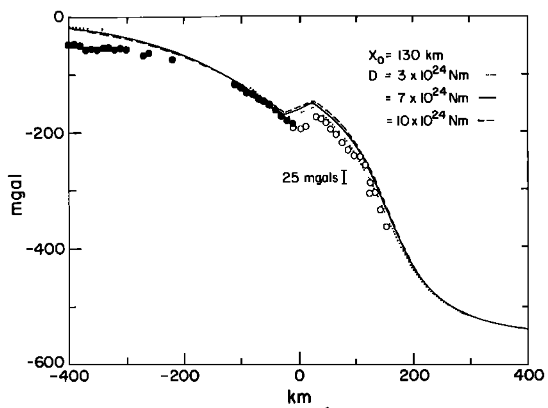

Fig. 4a

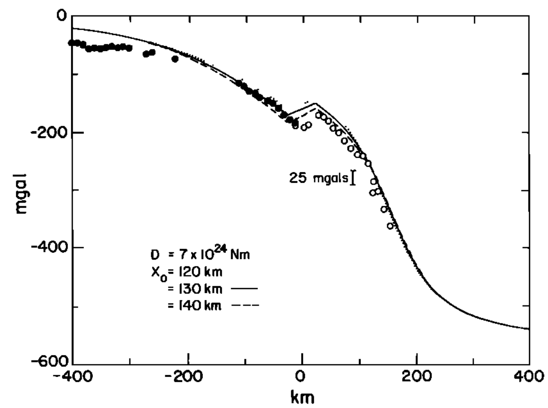

Fig. 4b

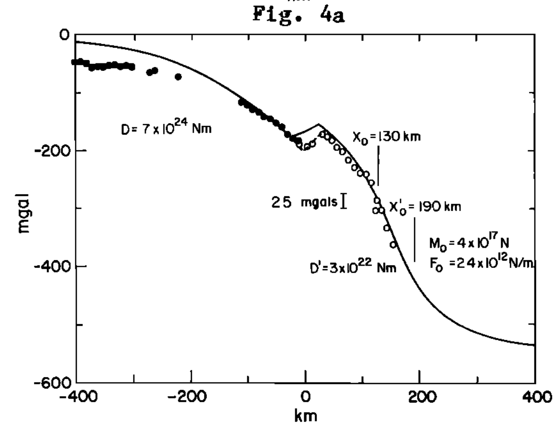

Fig. 4c

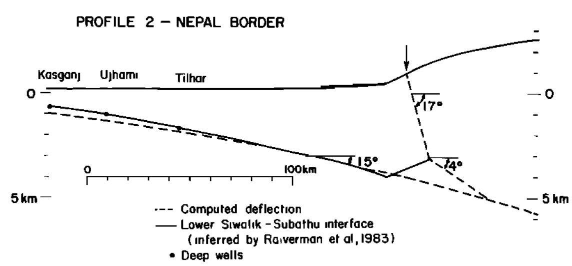

Fig. 4d

Fig. 4. Comparisons of observed and computed Bouguer anomalies and deflections of plates for profile 2. (a) A simple plate with a constant flexural rigidity is used here. X_0 is fixed and the computed anomalies for three different values of the flexural rigidity D are shown. (b) the configuration model as in Figure 4a is used, but D is fixed and the computed anomalies for three different values of X_0 are shown. (c) The flexural rigidity of the plate is D for $x < X_0$ and D' for $Xo < x < X_0'$ (see Figure 3). The bending moment M_0 and vertical force F_0 are applied at X_0'. The dashed line shows computed Bouguer anomalies for the case including a small wedge of underthrust sediments as shown in Figure 4d. (d) The computed deflection of the plate is compared with a profile of Ganga Basin inferred from deep wells near the profile. Positions of deep wells are shown in Figure 10. Vertical exaggeration is 10 times.

plate extends beneath the range, X_0. The wavelength of the anomaly over the Ganga Basin is mainly controlled by the value of D. Its amplitude depends on both the amount of the Himalayan mass that is supported, which is parameterized by X_0, and on D. Inferences of these two parameters can thus be made separately, using primarily the shape and amplitude of the gravity anomaly profile over the Ganga Basin.

In trying to account for the observed gravity profiles, we first infer values of X_0 and D, and then we try to deduce additional information about the structure beneath the Greater Himalaya. The four gravity profiles studied here show that the plate cannot extend more than 100 to 150 km beneath the Himalaya if its flexural rigidity remains constant and if no other forces act on it; the load of the entire High Himalaya is not supported solely by the strength of the flexed Indian plate, buoyed up by an inert asthenosphere beneath it. An additional force must contribute to the support of this mass. Moreover, as for profile 1, an increase in the gravity gradient beneath the High Himalaya implies that the Moho must

TABLE 1. Parameters Describing the Geometry and the Forces Acting on an Elastic Indian Plate, Inferred From the Gravity Anomalies

Profile	X_o, km	X_o', km	D, Nm	D', Nm*	M_o, N†	F_o, N/m†
1. Everest	130±10	200	$7(+13\ -4)\times10^{24}$	2×10^{22}	4.0×10^{17}	3.0×10^{12}
2 India Nepal Border	130±10	190	$7(\pm3)\times10^{24}$	3×10^{22}	4.0×10^{17}	2.4×10^{12}
3. Rishikesh	100±30	230	$1(+2\ -0.5)\times10^{24}$	3×10^{22}	4.0×10^{17}	4.0×10^{12}
4. Simla	70±20	240	$3(+4\ -2)\times10^{24}$	3×10^{22}	3.5×10^{17}	3.4×10^{12}
5. Mandi-Leh	100±20	200	$0.5(+0.5\ -0.3)\times10^{24}$	5×10^{22}	3.6×10^{17}	3.4×10^{12}

*Allowable values of D' probably lie within a factor 10 of those given here.
†Allowable values of Mo and Fo are probably within a factor of 2 of those given here.

steepen beneath this part of the range. We interpret this to be due to the weakening of the plate, and we analyze this situation by considering that a northern segment of plate, between $x=X_o$ and $x=X_o'$ (Figure 3) has a smaller flexural rigidity, D' than its remaining part. In all cases, however, we found that the inclusion of a weaker, northern edge of the plate alone, is not enough to explain the gravity anomalies as for profile 1 [Lyon-Caen and Molnar, 1983]; an external force system is necessary both to bend the plate down sharply beneath the High Himalaya and at the same time to support the heavy load of this part of the range. For each profile we found combinations of values for D' and for bending moments M_o and vertical shear forces F_o per unit length applied to the end of the plate that allow computed gravity anomalies to match those observed. These three parameters (D', M_o, and F_o), however, are coupled and cannot be determined uniquely [Lyon-Caen and Molnar, 1983]. Estimates of M_o and F_o increase with increasing values of D', but in general D' cannot be varied by more than a factor of 10 and M_o and F_o by a factor of 2. We give values for M_o, F_o, and D' here simply to provide estimates for the orders of magnitude of the required external forces. These values not only are uncertain by factors of 2 to 10, but also the physical reality of the simple model may make the values of the parameters only qualitatively important. The need for specifying them, however, attests to presence of dynamic mechanisms for supporting the load of the mountains.

ANALYSIS OF INDIVIDUAL PROFILES

Profile 2: (Nepal Border) (Figure 4)

Bouguer anomalies over the southern part of the Ganga Basin are nearly constant and equal to -50 mGal. Over the northern part of the Ganga Basin values become increasingly negative at about 0.75 mGal/km. Then the gradient steepens to 2.5 mGal/km over the High Himalaya. For a simple plate with a constant flexural rigidity extending a distance X_o beneath the range, the gradient over the northern part of the Ganga Basin constrains the flexural rigidity to be at least 3×10^{24} Nm (Figure 4a); a better fit is obtained for $D = 7 \times 10^{24}$ Nm. The values of gravity at the foot of the range constrain X_o to be 130 km ± 10 km (Figure 4b). Larger values of X_o, corresponding to heavier loads on the plate, yield poor fits. Thus an additional force must support this mass.

The computed Bouguer anomalies at the southern edge of the profile ($x \approx -200$ to -400 km) differ by about 25 mGals from the observed anomalies. We think that these more negative values of observed than computed anomalies may not be related to the flexure of the lithosphere. Instead they seem to be part of a regional low that extends farther south of the profile and can be seen on the Bouguer gravity map of India (Figure 1). The source of this low may be in the Indian crust and may reflect ancient sedimentary basins on the underlying Indian Shield or may be related to deeper density anomalies. Thus we do not try to fit these low values.

In order to compute the curves shown on Figures 4a and b, the Moho north of X_0 was assumed to dip at 17°, from its calculated depth of 45 km at X_0 to 63 km at x = 190 km. The Moho dips at an angle of about 2° beneath most of the Lesser Himalaya and thus steepens markedly beneath the Higher Himalaya. We inferred the place where this steepening occurs (x = 130 km) from the fit of the data only over the Ganga Basin, but notice that the increase of the gravity gradient occurs close to this point, near x = 110 km (Figure 4). The steepening of the Moho of course, need not be abrupt, as assumed in calculations here, but could take place over a few tens of kilometers.

As before, we explain the steepening of the Moho by assuming that the plate is weaker, and therefore its effective rigidity is smaller, beneath the Higher Himalaya than farther south [Lyon-Caen and Molnar, 1983]. Nevertheless, simply incorporating a segment of plate with a reduced flexural rigidity is not sufficient to provide a mechanism for both supporting the range and fitting these data. The additional load of the mountains that overlies the plate between x=130 and x=190 km would deflect the plate too much beneath the Indo-Gangetic plains. A bending moment per unit of length of 4×10^{17} N and a vertical force per unit of length of 2.4×10^{12} N/m applied to the edge of the plate at x = 190, however, are adequate to flex the plate up beneath the Ganga Basin sufficiently for the computed anomalies to match those observed (Figure 4c). The parameters used in the analysis of this profile (Table 1) are nearly identical to those used for profile 1 across the Mount Everest area [Lyon-Caen and Molnar, 1983].

The misfit between observed and computed gravity anomalies in the vicinity of x = 0 can be explained if we assume that sediments with a mean thickness of about 1 km over a length of 40 km have been underthrust with the Indian plate beneath the Lesser Himalaya (Figure 4c and 4d). Figure 4d shows the configuration of the wedge of sediment between 0 km < x < 40 km that yields the gravity profile shown by the dashed line in Figure 4c. This figure also compares the calculated position of the top of the Indian plate with, first, the depths of the pre-Tertiary basement obtained from three deep wells situated more than 130 km to the south of the Himalayan front and, second, the interface between the Lower Siwalik and the Subathu formations in the northern part of the basin inferred by Raiverman et al. [1983]. The Siwalik formation, of Miocene and Pliocence age, consists mainly of material eroded from the Himalaya and transported to the south. In contrast, the Eocene Subathu formation is older and was deposited in a shallow marine environment probably before the collision of India with Asia. Thus the depth of the interface between these two formations presumably represents the subsidence of the Ganga Basin since the collision. The agreement between the configuration of the basin calculated here and that inferred by Raiverman and his colleagues in the Oil and National Gas Commission of India give us confidence that the flexural model is applicable, even if the gravity anomalies are fit poorly over part of the profile.

The fault plane solutions of earthquakes that occur in western Nepal and near the area traversed by profile 2 between about 90 km < x < 130 km show thrust faulting with slip vectors plunging at 25° ± 10° [Baranowski et al., 1984; Ni and Barazangi, 1984]. Depths of foci are about 13 km ± 3 km below sea level [Baranowski et al., 1984]. These earthquakes may represent slip along the top part of the Indian plate where it dips more steeply than beneath the Lesser Himalaya [Baranowski et al., 1984; Ni and Barazangi, 1984]. The depth of the top of the plate, inferred here from gravity anomalies, is shallow (only about 8 km), but if the density contrast between the mantle and the crust were 0.45 g/cm^3 instead of 0.55 g/cm^3, as we assumed in this calculation, then the top of the steeply dipping part of the plate would be at a depth of 11 km and would be at a depth consistent with the earthquakes representing slip along the underthrust Indian plate. In any case, the earthquakes seem to be too deep to represent deformation of the overriding plate [Seeber et al., 1981], at least insofar as it is correct to assume that the Indian plate is flexed down by the weight of the Himalaya. Thus, both the inferred structure and the fault plane

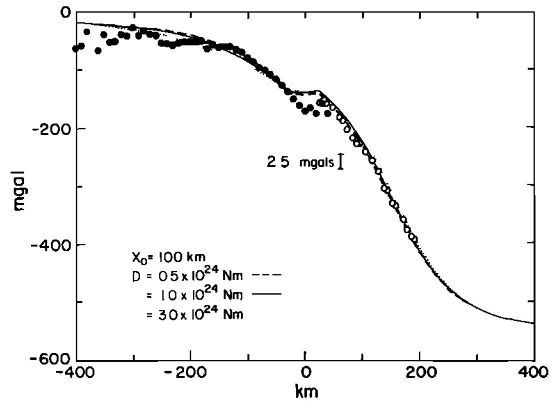

Fig. 5a

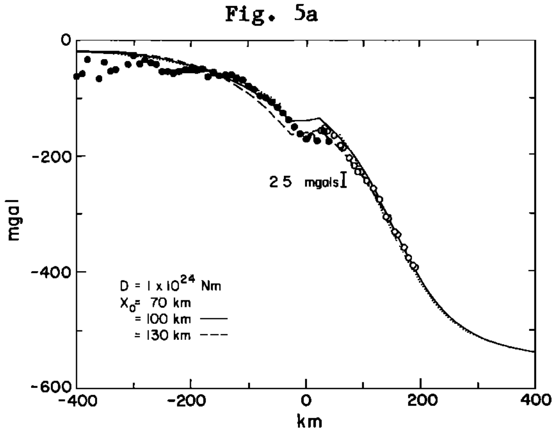

Fig. 5b

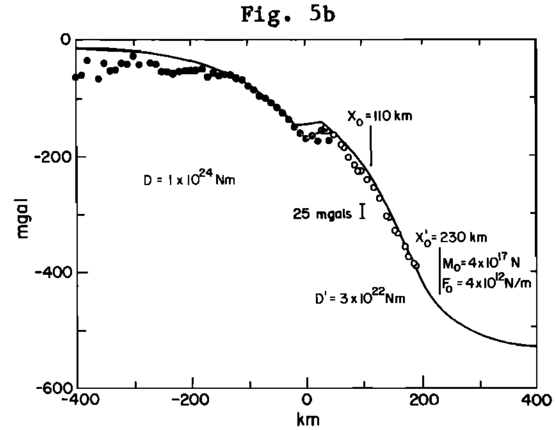

Fig. 5c

Fig. 5. Comparisons of observed and computed Bouguer anomalies for profile 3. (a) Format same as Figure 4a but for profile 3. (b) Format same as Figure 4b but for profile 3. (c) Format same as Figure 4c but for profile 3.

solutions and depths of the earthquakes are consistent with the earthquakes occurring on or very near the top surface of the Indian plate, but neither are well enough constrained to prove that this is the case.

Profile 3 (Rishikesh) (Figure 5)

Although the topographic profile, and hence the load, is almost the same as that along profile 2, the gravity gradient of about 1 mGal/km near the northern edge of the Ganga Basin is larger than that for profile 2, and the gradient over the High Himalaya of about 2 mGal/km is less than that of profile 2. For an Indian plate with a constant flexural rigidity, the values of the parameters that best fit the observations along profile 3 are a flexural rigidity between 0.5 and 3 x 10^{24} Nm (Figure 5a) and a value of X_0 of 100 ± 30 km (Figure 5b). The smaller value of the flexural rigidity than that obtained from profile 2 is required by the larger gravity gradient over this part of the basin than farther east.

To explain the steeper gravity gradient over the High Himalaya than over the Lesser Himalaya, the calculated dip of the Moho must increase from about 2.5° beneath the Lesser Himalaya to about 9° beneath the Higher Himalaya, with the depth of 63 km reached at x = 230 km. Note that the observed gravity gradient changes from about 1.3 to 2 mGal/km near x=100 km, approximately where an equivalent elastic plate of constant flexural rigidity might end. The change in curvature of the Moho can be matched if the flexural rigidity of the plate underlying the High Himalaya is about 3 x 10^{22} Nm and if a bending moment per unit of length of 4 x 10^{17} N and a vertical force of 4 x 10^{12} N/m are applied to the end of the plate at X = 230 km (Figure 5c).

A rectangular wedge of sediments between x = 0 and x = 20 km allows a slight improvement to the fit of the data near the front of the range (Figure 5c). These data may not require underthrust sediments, however, but rather may be unrepresentative of those along a typical profile because of variations in gravity along the front of the range. The area near Rishikesh, where most of the data between x = 0 and 20 km were obtained, lies in a reentrant of the Himalayan front, where the strike of the front is not perpendicular to the profile. Because of this possible three-dimensional effect, we are not confident of the existence of the sedimentary wedge used in Figure 5c.

The calculated maximum depth of the

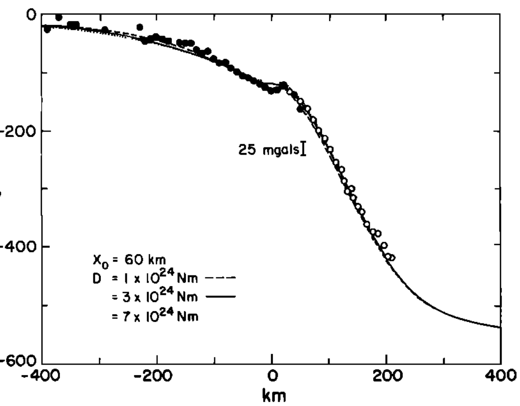

Fig. 6a

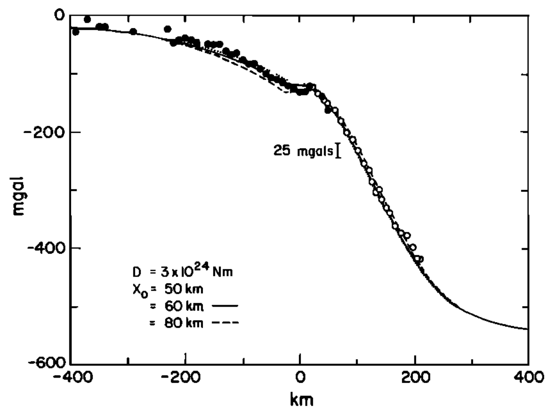

Fig. 6b

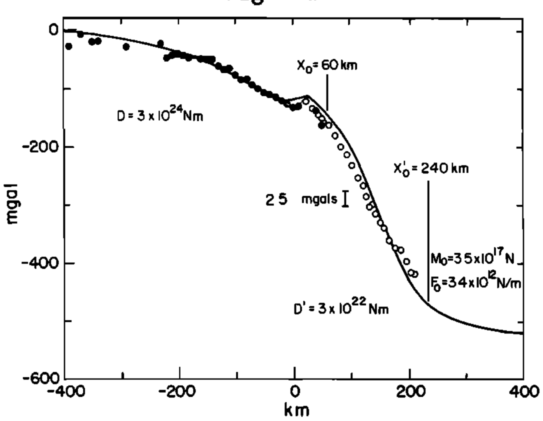

Fig. 6c

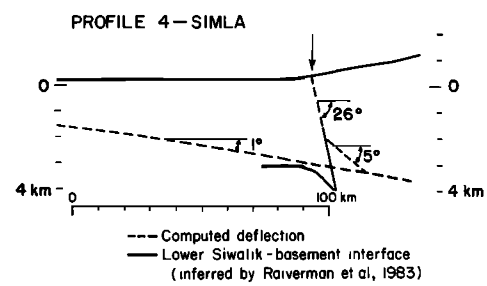

Fig. 6d

Fig. 6. Comparisons of observed and computed Bouguer anomalies and of deflections of the Indian plate for profile 4. (a) Format same as Figure 4a but for profile 4. (b) Format same as Figure 4b but for profile 4. (c) Format same as Figure 4c but for profile 4. (d) Comparison of the computed deflection with the depth of the basement inferred by Raiverman et al. [1983]. Vertical exaggeration is 10 times.

basin is 3.5 km. There are no direct measurements of the depth of the basin in this area, but the Mohand deep well, located 65 km to the west of this profile (see Figure 10 below), reached the basement at a depth of about 4 km below sea level. Approximately 400 m of the Subathu and Dharamsala (Oligocene-early Miocene) formations overlie the basement (see also Figure A1) [Sastri, 1979]. Much of this material was probably deposited before the Indian plate was flexed down. If projected onto this profile, the well would be located near x=0, and thus the calculated maximum depth of the basin due to flexure differs at most by only a couple of hundred meters from that reached in the deep well.

Profile 4 (Simla) (Figure 6)

The observed gravity gradient along this profile over the Ganga Basin is only 0.5 mGal/km, and X_0 need only be 70 ± 20 km for the plate to be flexed down sufficiently (Figure 6b). Consequently the flexural rigidity is very poorly constrained but probably lies between 1 x 10^{24} and 7 x 10^{24} Nm (Figure 6a). The observed gradient increases from about 1 mGal/km over the Lesser Himalaya to 1.9 mGal/km for x > 60 km. The values of gravity over the Higher Himalaya can be matched by including a segment of plate with a flexural rigidity of 3 x 10^{22} Nm between x=60 and 240 km and by applying a bending moment of 3.5 x 10^{17} N and a ver-

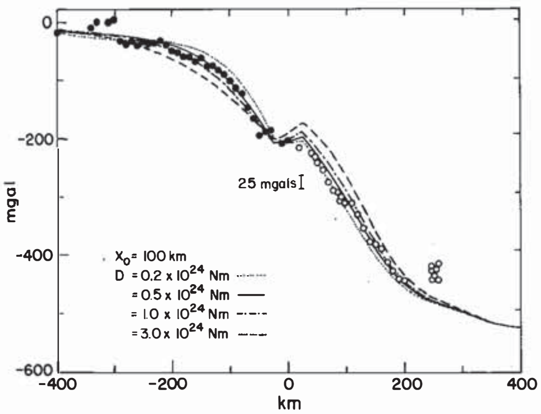

Fig. 7a

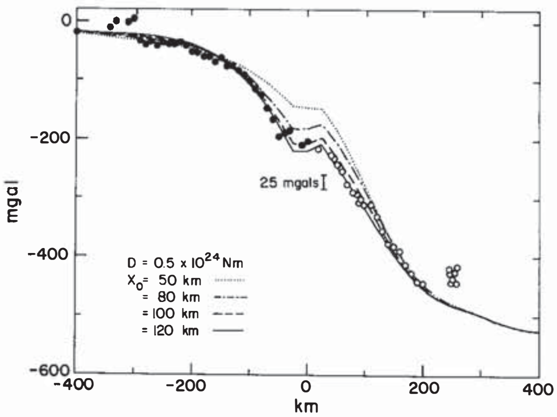

Fig. 7b

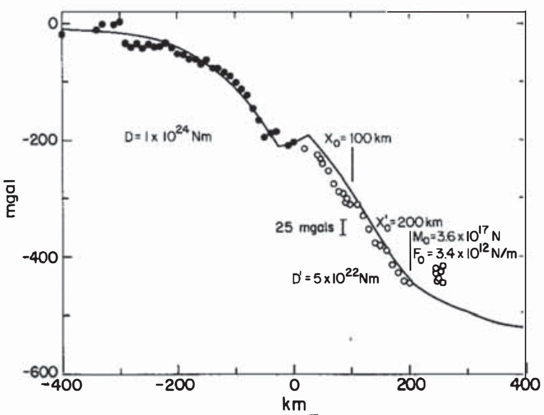

Fig. 7c

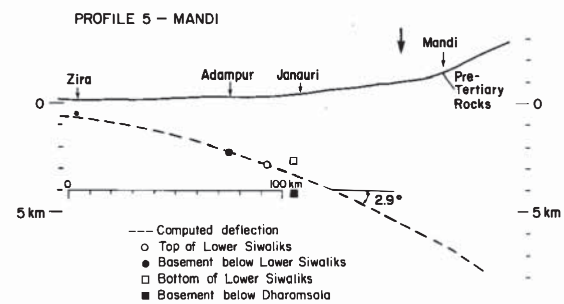

Fig. 7d

Fig. 7. Comparisons of computed and measured Bouguer gravity anomalies and of delfections of the Indian plate for profile 5. (a) Format same as Figure 4a but for profile 5. (b) Format same as Figure 4b but for profile 5. (c) Format same as Figure 4c but for profile 5.
(d) Comparison of the computed deflection of the plate using the parameters from Figure 7c with depths to various horizons obtained from deep wells. Vertical exaggeration is 10 times.

tical force of 3.4 x 10^{12} N/m to the end of the plate (X_0' = 240 km) where the Moho reaches a depth of 63 km (Figure 6c). Once again the inclusion of small wedge of sediments beneath the Lesser Himalaya (Figures 6c and 6d) improves the fit of the data near the front of the Lesser Himalaya. The calculated maximum depth of the basin is 3 km, compared to about 3.2 km inferred by Raiverman et al. [1983]. According to Raiverman et al. [1983], sediments from the Dharamsala formation are absent, and the basement is found directly below the Lower Siwalik group (Figure 6d).

Profile 5 Mandi-Leh (Figure 7)

The mean elevation, and therefore load along this profile, between x=0 and x=100 km is almost twice as large as those of profiles 2, 3, and 4 (Figure 2a), and the gravity gradient over the Ganga Basin is large, about 1.5 mGal/km. The flexural rigidity appears to be between 0.2 and 1 x 10^{24} Nm (Figure 7a), and X_0 is between 80 and 120 km (Figure 7b). Thus the large gravity gradient over the basin is a consequence of both the heavy load acting on the plate and the relatively small value of the flexural rigidity. The curves shown in Figure 7 are computed assuming a structure north of the edge of the plate, similar to the one deduced from the gravity data over the southern Tarim Basin and western Tibet [Lyon-Caen and Molnar, 1984]. The thickness of the crust is assumed to be 43 km beneath the northern part of the Tarim Basin and reaches about 50 km at its southern edge. It is 65 km beneath most of the Karakorum belt. Again, by introducing a plate with a reduced flexural rigidity ($D'=5\times10^{23}$ Nm) between x=100 and 200 km and by applying a bending moment of 3.6×10^{17} N and a vertical force of 3.4×10^{22} N/m, the mass of both the Lesser and the High Himalaya can be supported and a match of observed and computed anomalies is obtained (Figure 7c).

Figure 7d shows the calculated deflection of the plate in the basin along with depths to the basement and to the bottoms of the Lower Siwalik and Dharamsala formations obtained from deep wells. The calculated deflection passes through the middle of the Dharamsala formation in the Janauri deep well. This may, however, be a consequence of an unusually large thickness of the Dharamsala formation there, probably because of a doubling of the layer by thrust faulting (see the cross section near the Janauri well on Figure A2).

The underthrusting of a small amount of sediments beneath the Himalaya could improve the fit of calculated to observed anomalies, but it is not really required. This profile, like profile 3, lies in a reentrant of the Lesser Himalaya, and thus there is a three-dimensional effect that prevents us from giving a meaningful interpretation to subtleties of this part of the profile.

The computed gravity profile, however, does not predict the relatively small negative value of the anomaly at Leh. Although there is a wide range of values measured in this region, they all are at least 50 mGals less negative than what they would be if the area was in a state of local isostatic equilibrium (see Figure 2b also). A similar, but apparently less pronounced, relative high is present in profile 1 where it extends into southern Tibet. This high may reflect the presence of relative cold material of the mantle lithosphere of India that has been detached from the crust. This cold material might be supported dynamically by convective downwelling, and at the same time it might serve as an external force that applies a bending moment to the plate [Lyon-Caen and Molnar, 1983]. Neither the gravity anomalies nor the analysis given here prove the existence of such cold material there, but the occurrence of earthquakes at depths of at least 90 km in the mantle beneath the Karakorum belt and southern Tibet [Chen and Roecker, 1980; Chen et al., 1981; Molnar and Chen, 1983] is an indication of unusually strong, and thus probably colder, material than is usually present in this depth range.

DISCUSSION

The simple model that treats the Indian plate as an elastic plate over an inviscid fluid can be used to explain both the gravity field and the shape of the basement of the Ganga Basin quite well in the sense that few parameters are used and that sensible values for the flexural rigidities and for the external system of forces are obtained. Apart from the flexural rigidity that appears to vary by a factor of 10 or so along the arc, the other parameters involved in the calculations are quite stable from one profile to another despite variations in the topographic profiles and therefore in the applied loads.

Deep Structure

Although the Indian plate appears to be very strong (its equivalent elastic thickness is between 40 and 100 km), we found that the load of the entire Himalaya is too large to be supported by the elastic stresses in the Indian plate alone. When no additional forces are applied to the plate, the calculated deflection of the plate is too large, and the calculated Bouguer gravity anomalies are 100 mGals more negative than observed. Therefore, some additional force must contribute to the support of the Himalaya. The opposite situation apparently occurs in the Appenines and the Carpathians where the total load of the mountains creates a foredeep that is only half as deep as what is observed [Royden and Karner, 1984]. Thus clearly the simple model of a flexed elastic plate, by itself, is not adequate to account for how mountain ranges are supported or for the depths of neighboring foredeeps. A downward force applied to the end of India's equivalent elastic plate will help to bend the plate down steeply beneath the High Himalaya where it is presumed to be weak, while a bending moment can flex it up under the Lesser Himalaya where it is stronger. Thus the application of a bending moment can help the Indian plate to support the load of mountains.

The continuous underthrusting of India beneath the Himalaya probably prevents the portion of the Indian plate beneath the High Himalaya from becoming too weak or from being mechanically decoupled from the stronger part of the plate. One, but not the only, efficient and likely mechanism for weakening the plate is by detaching the crust, or at least part of it, from mantle portion the of the Indian lithosphere, as the mantle part slides beneath the Himalaya [Lyon-Caen and Molnar, 1983]. The mantle lithosphere with part or all of its crust removed could be negatively buoyant, and the gravitational force on it could then be transmitted to the rest of the plate. The magnitudes of the forces and moments used in the calculations are compatible with this interpretation.

We can represent the cold mantle part of the Indian lithosphere as a mass anomaly with a density contrast with the surrounding mantle $\Delta\rho$, with a constant thickness h, and with a down dip extent 2L. Then $F_o = 2 L \Delta\rho h g$, $M_o = 2 L^2 \Delta\rho h g$, and $L = M_o/F_o$. The calculations used here are consistent with L ≈ 100 km for profiles 3, 4, 5, and L ≈ 150 km for profiles 1 and 2. Given the non-uniqueness of the values of M_o and F_o, this difference is not required. Taking $\Delta\rho = 0.05$ g/cm^3 and L = 100 km, the values of M_o and F_o in Table 1 yield estimates of h that vary from about 25 to 40 km. Smaller values of $\Delta\rho$ yield larger values of h. Thus, for instance, a segment of mantle lithosphere extending 200 km beneath Tibet and 100 km thick, stripped of overlying crust, and more dense than the surrounding asthenosphere by 0.015-0.02 g/cm^3 would be adequate to account for the forces and bending moments needed. For a coefficient of thermal expansion of 3×10^{-5}°C^{-1}, these would correspond to a mean temperature difference of 150°-200°C, between the mantle lithosphere and asthenosphere, which certainly is reasonable. Thus we consider plausible the entire scenario that includes detachment of crust from mantle lithosphere, underthrusting the mantle lithosphere beneath Tibet, and then the gravitational force acting on this material to cause a bending moment that flexes the Indian plate up. This scenario is, however, not required by the data and is merely one special case in a family of dynamic processes for applying a force to the Indian plate and for supporting the range.

Variations in the Apparent Flexural Rigidity

We infer significant variations of the flexural rigidity of the Indian plate along the arc. The flexural rigidity for the westernmost part (profiles 3, 4, and 5) seems to be from 3 to more than 10 times smaller than that determined for profile 2 in the central part or profile 1 in the eastern part of the range. The trend is not systematic, and the flexural rigidity obtained for profile 4, although poorly constrained, seems to be about 3 times larger than that of the two surrounding profiles. In fact, profiles 2 and 3 are separated by only 200 km and over this distance the flexural rigidity apparently changes by a factor of 5 to 10. The differences in gravity anomalies requiring such differences in flexural rigidities are also apparent in the profiles shown by Karner and Watts [1983].

These large variations in flexural rigidity along the Himalaya are very difficult to reconcile with a model in which the flexural rigidity of the continental lithosphere depends only on its thermal structure at the time of loading [e.g., Karner et al, 1983]. These variations would imply very large lateral variations in the geotherm of the Indian plate, since a change by a factor of 5 in the flexural rigidity corresponds to a change of more then a factor of about 1.5 in the equivalent elastic thickness. If the elastic thickness were a measure of the depth to a particular isotherm, then these different flexural rigidities would imply differences in geothermal gradients of approximately the same factor of 1.5. Part of the observed variation in the apparent flexural rigidity could be due to small scale convection in the mantle that draws the the cold boundary layer at the bottom of the plate down into the asthenosphere in some places and injects heat in others. This process, if it occurs, should introduce lateral variations in the geothermal gradient, but differences as large as a factor of 1.5 over distances as short as 200 km probably are too large to explain in this way.

Differences in the creep strengths of

the crust and mantle may also affect the inferred flexural rigidity. Suppose that the crust, when hot enough, is much weaker than the neighboring mantle at nearly the same temperatures. A weak lower crust is suggested by depths of foci of earthquakes and by laboratory experiments, but neither are sufficient to prove this, to say nothing of quantifying it [e.g. Chen and Molnar, 1983]. Thus it is possible that when the temperature of the lower crust exceeds some value, the lower crust might deform rapidly by ductile deformation at relatively low stress. Were this to happen, the upper and middle crust might become partially decoupled from the uppermost mantle by rapid creep in the lower crust. The lithosphere might then flex as two parallel thin plates instead of as one thicker one, as would be the case when the temperature of the lower crust is too low for significant ductile creep to occur there. Thus one can imagine that for sufficiently cold geotherms, the flexural rigidity would be large. For somewhat warmer geotherms, it would be somewhat smaller, but when temperature in the lower crust became sufficiently high for ductile creep to be rapid there, the flexural rigidity might drop precipitously with a small increase in the geothermal gradient.

In any case, more work is needed to understand how the apparent flexural rigidity depends on rheological laws and rates of deformation, and we are puzzled by the variations along the Himalaya in the gravity profiles, the shape of the basement of the Ganga Basin, and in the flexural rigidities inferred from these.

Underthrusting and Deformation of the Siwalik Sediments

Both the computed and the measured depths of the basement beneath the Indo-Gangetic plains are 3 to 4 km. The absence of an increase in measured Bouguer gravity anomalies of 25-30 mGals from the plains to the Lesser Himalaya suggests that the boundary between the sedimentary fill in the Ganga Basin and the more dense rock of Lesser Himalaya is not sharp and not vertical. Instead, it appears that, for profiles 1, 2 and 4 at least, some relatively light sediment of the Ganga Basin has been underthrust beneath the Lesser Himalaya. The amount of light material beneath the Himalaya, however, does not appear to be very large; layers only 1 or 2 km in thickness extending 40 km or so under the range seem to be adequate to explain the observed gravity profiles. Thus probably large amounts of the sediment in the Ganga Basin have not been underthrust beneath the range.

Seeber et al. [1981] suggested that as the Indian shield slides beneath the Lesser Himalaya, the overlying sedimentary cover is scraped off the shield by a slip on a series of northward dipping, listric thrust faults. Near the Himalayan front, most exposures of the Siwalik group show steep dips and evidence of crustal shortening. In some areas, even tens of kilometers from the front, gentle folds in the Siwalik group break the otherwise featureless surface of the Indo-Gangetic plains. Published cross sections [e.g. Karunakaran and Ranga Rao, 1979; Mathur and Evans, 1964; Raiverman et al., 1983] often show basement involvement, but most such sections are not balanced. In order to examine whether or not geologic structures seen at the surface and stratigraphic divisions recognized in deep wells required that thrust faults penetrate the basement, we constructed balanced cross sections across two relatively simple anticlines south of the Himalayan front. The details are given in Appendix A. We simply note here that the information used to construct both cross sections seems to rule out any basement involvement. Instead they indicate that the Siwalik group detaches from the basement on listric faults much as Seeber et al. [1981] suggested. Thus we infer that the absence of large amounts of light material beneath the Lesser Himalaya is more consistent with detachment of these sediments and with crustal shortening by folding and faulting of them, than with subduction of the majority of this material.

Constraints on the Rate of the Convergence of India and the Himalaya

The Siwalik sequence of sediments, which are derived from erosion of the Himalaya, presumably record the existence and some aspects of the history of the Ganga Basin. Insofar as the Himalaya result from the underthrusting of the Indian plate beneath the range, a flexural basin should be a steady state feature that has lain in front of the Himalaya while such underthrusting has occurred. Its width should depend on the flexural rigidity of the Indian plate. We expect, and therefore assume, that the present

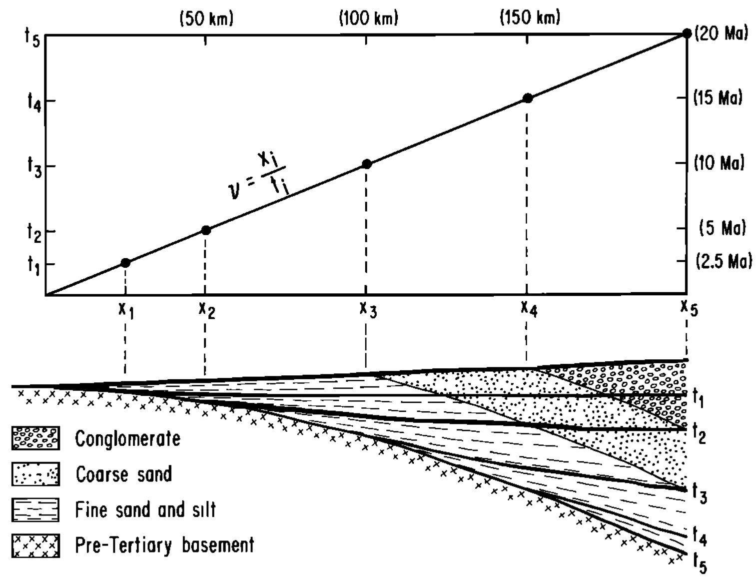

Fig. 8. Hypothetical, vertically exaggerated cross section of the Ganga Basin and (top) plot of expected basement ages vs. distance from the southwest edge of the basin. The Himalaya would be to the right of the drawing, and coarse debris are shed southward from the range. The basement bends down and moves to the right (northward) beneath the Himalaya. Sediment is presumed to be deposited on the basement when the basement is flexed below the level of the plains on the left. As the basement moves to the right, it is buried by younger, coarser material. Facies boundaries are time transgressive so that age horizons, given by t_1 to t_5, cross such boundaries. The rate of convergence can be obtained from the ratio given by the distance to the edge of the basin divided by the age of the oldest post-Himalayan sediment overlying the basement.

width of the Ganga Basin of 200-250 km is approximately the width of the basin that has existed since depostion of the Siwalik sediments began and perhaps for a longer period.

In an idealized evolution, a part of the shield would be emergent, as much of it is now in Central India, until it approached within 200-250 km of the range. Then relatively fine sediments from the distal edge of the Indo-Gangetic plains would be deposited onto the shield. As the shield moved north with respect to the Himalaya and flexed down, it would become buried in increasingly thicker sediments. Presumably, these sediments would be coarser, the closer that they were deposited to the mountain front. Thus, facies boundaries would be time-transgressive (Figure 8). Older, fine grained material would underlie younger, coarser material. The age of the oldest sediments deposited on the shield would increase northward from the edge of the Indo-Gangetic plains to the foot of the Himalaya, and a plot of the age of the basal sediment as a function of the distance from the southern edge of the Indo-Gangetic plains should define a monotonically increasing curve (Figure 8). If the basin were a steady state feature and the rate of convergence were constant then this curve should be a straight line with a slope inversely proportional to the convergence rate (Figure 8).

Thus we might expect measured ages of the Tertiary sedimentary cover to provide a constraint on the rate of convergence. Stratigraphic columns from northwest India (Figures 9 and 10), indeed, suggest both a northward, time transgressive coarsening of material and southward younging of the basal sediment [Karunakaran and Ranga Rao, 1979; Mathur and Evans, 1964; Sahni and Mathur, 1964]. Before examining data in detail, however, let us consider some simple cases. Assume that the basin is in steady state with a width of 200 km. If the convergence rate were 10 mm/a, the age of the oldest observable molasse deposited

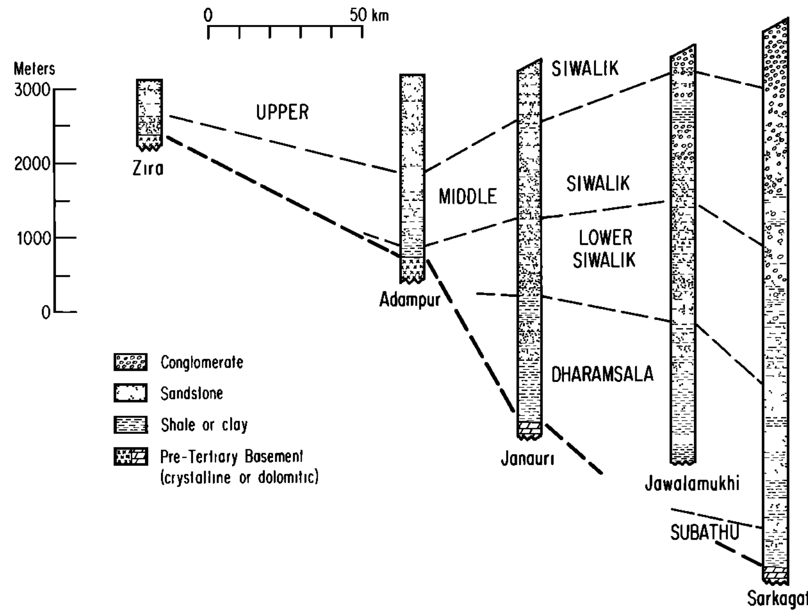

Fig. 9. Simplified stratigraphic columns from deep wells and surface outcrops in the northwest Himalaya (Figure 10). Horizontal scale gives rough distances between sites. Sloping top surfaces on columns indicate that erosion has removed the upper parts of the section. Wells only at Zira, Adampur, and Janauri reached basement. The column at Sarkagat is inferred only from surface exposures. Note the time transgressive nature of facies changes; conglomerates were deposited only relatively close to the Himalaya.

on the Indian Shield would be 20 Ma. Older sediments would have been detached from the basement or underthrusted beneath the range. If the rate were 20 mm/a, that maximum age would be 10 Ma. If molasse older than 20 Ma were to overlie the shield beneath the basin, then either the average convergence rate between India and the Himalaya would be less than 10 mm/a or the Indo-Gangetic plains would have been wider than 200 km when this material was deposited.

Stratigraphy of the Ganga Basin

The Oil and Natural Gas Commission of India has drilled a number of deep wells into the sediments of the Indo-Gangetic plains, and stratigraphic columns inferred from these wells provide data relevant for deducing the convergence rate between India and the Himalaya (Figures 9 and 10). The principal sources of error in deducing a rate are uncertainties in ages of the various formations, lack of numerous drill holes that reach basement, and difficulties defining the southern edge of the Ganga Basin.

Traditionally, the Siwalik sediments are subdivided into Upper, Middle, and Lower Siwalik. Virtually the entire sequence was deposited subaerially, and the provenance appears to be nearly entirely the Himalaya to the north of the Ganga Basin. Beneath the Siwalik sequence is the Dharamsala (or Murree) formation often treated as being quite distinct from the overlying Siwalik series, but we consider their origins probably to be similar. Paleocurrent directions suggest a northerly source for the Dharamsala formation [Raiverman, 1968].

The Subathu formation, which lies beneath the Dharamsala formation, however, is characterized by layers of nummulitic limestone among layers of shale, clay and fine sandstone. Therefore, this formation is very different from the overlying material. Whereas the Subathu formation was deposited in a shallow sea, the Dharamsala apparently was deposited subaerially or in fresh water [Karunakaran and Ranga Rao, 1979]. The Subathu formation overlies the pre-Tertiary basement of the Indo-Gangetic plains and is exposed in isolated patches in the Himalaya. It apparently was depo-

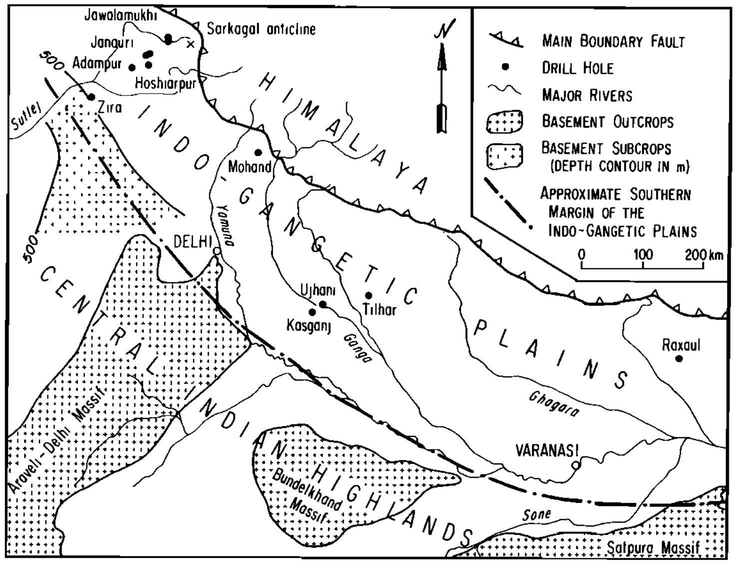

Fig. 10. Map showing locations of deep wells, basement outcrops, and the line used to define the edge of the Ganga Basin for constructing Figure 11.

sited before the collision of India with southern Tibet.

Ages of Cenozoic Sediments

The precise ages of most of the Tertiary sequence are difficult to determine because of the lack of fossils, and when dated in one locality, correlations with other areas are risky because of the likely time-transgressive nature of the facies boundaries. The nummulitic foraminifora require an Eocene age for the Subathu formation [e.g., Karunakaran and Ranga Rao, 1979]. The Dharamsala (or Murree) formation is usually assigned an Oligocene or early Miocene age, but it could be as old as the latest Eocene [e.g., Aditya et al., 1979; Karunakaran and Ranga Rao, 1979]. The Lower, Middle, and Upper Siwalik sequences are often assigned Middle Miocene, Late Miocene, and Plio-Pleistocene ages, respectively [e.g., Aditya et al, 1979; Karunakaran and Ranga Rao, 1979]. Studies of magneto-stratigraphy and fission track ages of bentonite layers, largely from Pakistan, corroborate these inferences and refine the ages for these formations in that region [e.g., Barry et al., 1982; N. Johnson et al., 1982; G.D. Johnson et al., 1982, 1983; Opdyke et al., 1979; Tauxe and Opdyke, 1982]. Nevertheless, given the lack of tight constraints for the ages of the particular formations at the bottoms of the various drill holes, we take the following ages (and allowable ranges of ages) for the bases of the following formations: Upper Siwalik, 5 Ma (between 3 and 7 Ma), Middle Siwalik, 11 Ma (between 9 and 12 Ma), Lower Siwalik, 15 Ma (between 12 and 18 Ma) and Dharamsala, 30 Ma (between 20 and 40 Ma). These ranges not only span the various ages proposed for the various sequences in particular areas but also allow for differences from place to place, given the expected time-transgressive nature of the group.

Using these ranges of ages and the stratigraphy reported from drill holes that reached basement in the Indo-Gangetic plains, we can construct a plot like that in Figure 8. In general, the reported thicknesses of Middle and Lower Siwalik sequences are similar from drill holes that are within 100 km of one another [Figure 9; Karunakaran and Ranga Rao, 1979; Sastri, 1979; Sastri et al., 1971]. Therefore, when the oldest sediments in a particular well were from either of these formations, we used the thickness from nearby wells penetrating older sequences as a reference. Then to obtain the age at the basement, we used these full thicknesses to interpolate between the ranges of ages of the top and bottom assuming the same constant rate of sedimentation for the Middle or Lower Siwalik sequence in both wells. For wells bottoming in the

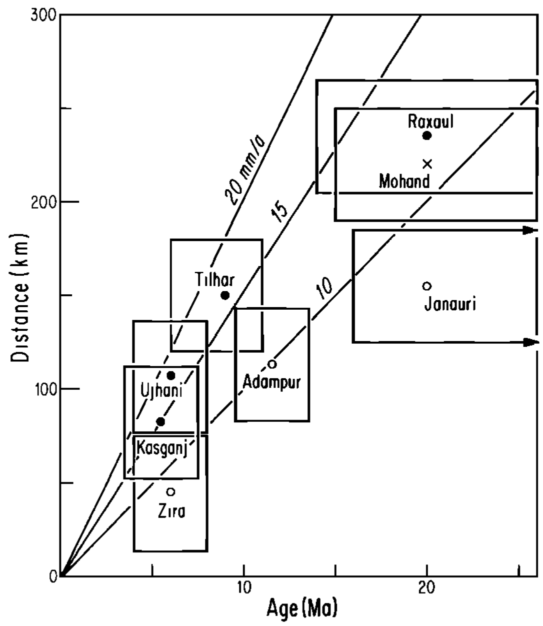

Fig. 11. Plot of inferred basement ages vs. distances from the edge of the Ganga Basin for deep wells in Figure 10. Uncertainties of 30 km are shown for all distances. Uncertainties in ages are discussed in the text. Solid circles, open circles, and the cross denote wells treated together as parts of profiles.

Dharamsala formation, we allowed wide ranges of ages for the basal sediment.

Finally, to obtain an estimate of the distance of the particular well site to the edge of the Indo-Gangetic plains, we drew a smooth curve through or near the edge of outcrops of the major Pre-Cambrian massifs of the Central Indian Highlands (Figure 10). The northwest part of the region is buried by recent sediments, and we drew the presumed former margin of the plains over the axis of a shallow basement high (Figure 10). Clearly, the edge of the Indo-Gangetic plains is not well defined, and we arbitrarily assigned an uncertainty of 30 km to each distance measured. From these ranges of distances to the edge of the Indo-Gangetic plains and ages of the oldest Tertiary sediments over the basement, we constructed a plot (Figure 11) like that in Figure 8.

Inferred Convergence Rates

Three widely spaced drill holes reached the Dharamsala formation before entering basement. In two wells, the thickness of the Dharamsala formation is thin: Raxaul, 65 m [Sastri et al., 1971] and Mohand, 246 m [Sastri, 1979]. In the third, Janauri, the Dharamsala formation is much thicker (Figure 9), which apparently is partly due to repetition in an overthrust section (see Appendix A). Nevertheless, half of the section of Dharamsala sediments is 1000 m, and we allowed a wider range of possible ages for its base than for those in the other two holes.

Notice that even if we underestimated the distance for Janauri to the edge of the Indo-Gangetic plains by 100 km, the occurrence of the Dharamsala formation over the pre-Tertiary basement limits the amount of convergence between India and the Himalaya during the last 15-25 Ma to about 200 km. Best fitting average convergence rates are near 10 mm/a and probably less than 15 mm/a. Even if Dharamsala formation were deposited before the Indian plate was flexed down, and the oldest sediment deposited in the Ganga Basin were the Lower Siwalik group, the rate would still be less than 20 mm/a. We conclude that the rate cannot be as high as 20 mm/a unless one of the basic assumptions used to construct Figure 11 is in error.

In five other wells, the oldest sediments overlying pre-Tertiary basement are either Middle or Lower Siwalik sequences. For the two wells in the northwest part of the Indo-Gangetic plains [Zira and Adampur, Figure 10], we used the thicknesses of Middle and Upper Siwalik sediments in the nearby Janauri deep well as reference thicknesses to assign ages to the oldest sediment. The distances vs. ages imply a rate of convergence of about 10 mm/a. Note, however, that an underestimate of 50 km in the distance to the edge of the Indo-Gangetic plains, an error that cannot be ruled out, would allow average convergence rates of 15-20 mm/a. At the same time, the rates obtained from the differences in basal ages and differences in distances among Zira, Adampur and Janauri, for which the uncertainty in the distance scale is only tens of meters (!), favor rates nearer 10 mm/a than 20 mm/a.

The other three deep holes, Kasganj, Ujhani, and Tilhar, lie in the central part of the Indo-Gangetic Plains (Figure 10). The oldest Tertiary sediment in each is from the Middle Siwalik formation (250 m in Kasganj, 330 m Ujhani, and 1090 m in Tilhar [Sastri, 1979; Sastri et al., 1971]). Although these localities are closer to Mohand than Raxaul, we use the thickness of 1500-1700 m for the Middle Siwalik in Raxaul for the reference thickness [Sastri, 19879; Sastri et al., 1979]. The Mohand deep well penetrates a thrust fault within or near the Middle Siwalik group [Appendix A; Raiverman et al., 1983; Rao et al., 1974], and therefore estimating the thickness of the Middle Siwalik formation in this well is problematic (see Appendix A). The basal ages and estimated distances of these three holes from the edge of the basin suggest rates of convergence of 15-20 mm/a (Figure 11). Note, however, that if the distance to the edge of the Indo-Gangetic plains were overestimated by 50 km, the inferred rate would be about 10 mm/a. Such an overestimate is quite possible given the exposures of the Aravali-Delhi massif near Delhi, some 50 km northeast of the line used for the edge of the Indo-Gangetic plains here (Figure 10).

Taken as a whole, the observations of distance vs. basal age show considerable scatter (Figure 11). Nevertheless, given the possible systematic overestimates of distance for Kasganj, Ujhani, and Tilhar and similarly possible underestimates for Zira, Adampur and Janauri, the data are consistent with an average rates of convergence between India and the Himalaya for the last 15-20 Ma of 10-15 mm/a. Average rates as high as 20 mm/a seem to be ruled out unless one of the basic assumptions used to construct Figure 11 is in error.

The rate of convergence between India and Eurasia ranges from about 40 mm/a at the western end of the Himalaya to 65 mm/a at the eastern end [Minster and Jordan, 1978]. Much of the convergence is known to be absorbed north of the Himalaya, both by crustal shortening and thickening and by translation of material eastward and out of India's northward path toward Eurasia [e.g., Molnar and Deng, 1984; Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1977]. How the roughly 50 mm/a of convergence is partitioned between underthrusting of India beneath the Himalaya and northward motion of the Himalaya and southernmost Tibet with respect to Eurasia is not well constrained. The results presented here, however, suggest that 10-15 mm/a are absorbed by underthrusting at the Himalaya. The rate of crustal shortening in the Tien Shan appears to be only 10 ± 5 mm/a [Molnar and Deng, 1984; Molnar and Tapponnier, 1975]. Thus half or more of the present convergence rate seems to occur by squeezing parts of Tibet and the areas north and east of it eastward [see also Tapponnier et al., 1982].

Note that if India were to have underthrust the whole of Tibet (~1000 km) in the last 50 ma, its average rate would have been higher than 15 mm/a (50 Ma x 15 mm/a = 750 km) and therefore its rate before 10 to 20 Ma would have to have been higher than since that time.

CONCLUSIONS

Gravity anomalies over the Himalaya and Ganga Basin show large deviations from isostatic equilibrium, which can be explained if a strong plate underthrusts the Himalaya. The weight of the mountains is supported in part by the strength of the plate, and the plate distributes the load by flexing down in front of the range to form a basin [e.g., Karner and Watts, 1983; Lyon-Caen and Molnar, 1983]. The Ganga Basin, which apparently formed by such a flexure, in turn is filled by sediment, the Siwalik group, derived largely by erosion of the Himalaya.

We analyzed the gravity anomalies in terms of the simple model of an elastic plate overlying an inviscid fluid, and we use gravity anomalies as well as profiles of the basement depth to constrain the flexural rigidity of the plate. Profiles of the basement inferred from gravity anomalies, via a flexural model, and those measured in deep wells or by seismic reflection agree within a few hundred meters, but both show variations along the Himalayan front. In terms of an elastic plate, these variations in gravity and basement shape imply a variation in the flexural rigidity of an order of magnitude along the Himalaya. The distance to which an elastic plate of constant flexural rigidity could reach beneath the Himalaya varies along the arc from about 70 to 130 km. Thus only a part of the weight of the range is needed to flex the Indian plate down, and a plate of constant flexural rigidity could not extend all the way beneath the Himalaya and Tibet unless forces other than the weight of the mountains and the buoyant response of the underlying asthenosphere act on it.

If the Ganga Basin is a consequence of the flexure of the Indian plate and if it is a steady state feature, then the age of the basal sediments should increase from very young ages at the southern edge of the basin to the older ages at the foot of the Lesser Himalaya where the basin is deepest. If convergence between India and the Himalaya has been steady, then a plot of the distance of a particular locality to the edge of the basin divided by the age of the basal sediment derived from the Himalaya should be equal to the rate. Results from deep wells drilled by the Oil and Natural Gas Commisssion of India indicate rates of 10-15 mm/a and almost surely less than 20 mm/a for the last 10 to 20 Ma.

The fit of computed and observed gravity anomalies over the southern edge of the Lesser Himalaya can be improved if some light material underlies the mountains [Lyon-Caen and Molnar, 1983]. We presume this to be sediment deposited in the Ganga Basin on the Indian plate and underthrust with it beneath the Lesser Himalaya. Not a lot of sediment need be underthrust; a layer 1-2 km in thickness extending 40 km beneath the range is sufficient to account for a slight gravity high or plateau over the Lesser Himalaya. Since the basin contains 3-4 km of Siwalik sediment, we conclude that most of it is scraped off the downgoing Indian plate by the overriding thrust sheets of the Lesser Himalaya [Seeber et al., 1981].

The gravity anomalies indicate that the Moho dips at a gentle angle of only a couple of degrees beneath the Lesser Himalaya but must steepen to 10°-15° beneath the Greater Himalaya [Kono, 1974; Lyon-Caen and Molnar, 1983; Warsi and Molnar, 1977]. We infer that this steepening occurs because the part of the Indian plate that has underthrust beneath the Greater Himalaya is much weaker and more flexible than that beneath the Lesser Himalaya or Ganga Basin.

To analyze this further we treat the Indian plate as consisting of two segments: one beneath the Ganga Basin and the Lesser Himalaya and a weaker one beneath the Greater Himalaya. Such a configuration alone, however, cannot support the Himalaya and allow a fit to the gravity anomalies. A plate strong enough to support the range is flexed down too much beneath the Ganga Basin and would create a much wider basin than exists. We conclude that an additional force system is needed to support the range. In a previous study [Lyon-Caen and Molnar, 1983], we examined in more detail than here the trade-offs among the flexural ridigity of the segment of plate beneath the Greater Himalaya and bending moments and forces applied to the end of the plate. Here we show that values for the moments and forces for each profile could be essentially the same for each profile. We then argue that the weakened plate, the bending moment, and the additional force could all arise if the Indian lithosphere, stripped of most or all of its crust, plunged into the asthenosphere and if this mantle lithosphere remained a few hundred degrees cooler than the asthenosphere. Then gravity acting on this segment of plate could generate the necessary bending moment. This explanation, however, is not unique and other dynamic mechanisms could contribute to the support of the Himalaya. Regardless, some dynamic mechanism seems to be required to support the range.

APPENDIX A: BALANCED CROSS SECTIONS ACROSS TWO STRUCTURES IN THE SUB-HIMALAYA

In order to place some constraints on amounts of shortening in the Siwalik sequence, we constructed balanced cross sections for two anticlines for which subsurface information is available. These results attest to several kilometers of crustal shortening across rather gentle anticlines that lie some tens of kilometers from the front of the Himalaya. The tighter folds and steeper dips of the Siwalik group closer to the Himalaya imply tens to several tens of km of crustal shortening within this group. This style of deformation corroborates Seeber et al.'s [1981] inference that the Siwalik sediments detach from the underlying basement along a series of listric thrust faults.

Mohand Anticline

South of the Himalayan front between the Yamuna and Ganga rivers (Figure 10) the Upper and Middle Siwalik formations emerge from the post-Siwalik cover and form a broad gentle anticline, which manifests itself topographically as the Siwalik Hills [e.g., Raiverman et al., 1983; Rao et al., 1974]. In the central and western part of the Siwalik Hills, the anticline is overturned and verges southward (Figure A1). Dips on the northern flank range from a maximum of 30° to about 20° (or rarely 15°) where recent, unconsolidated sediments bury the uppermost unit involved in the folding [Rao et al., 1974]. The crest of the anticline lies

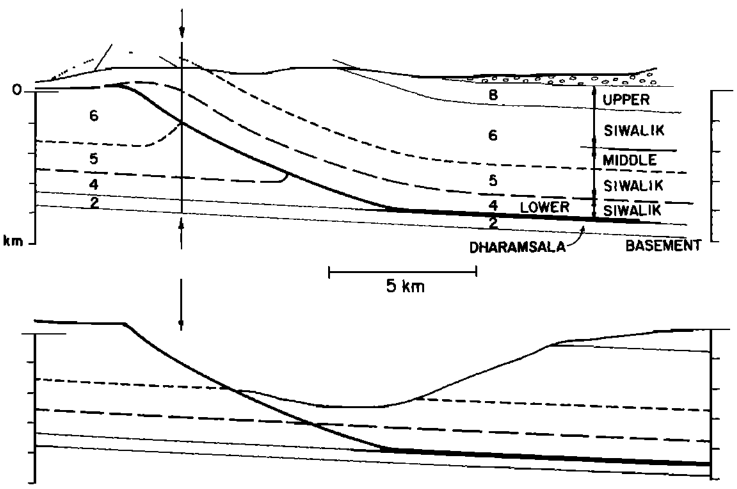

Fig. A1. Balanced cross section (top) and (bottom) palinspastically restored section across the Mohand anticline (see Figure 10 for approximate location). Following Raiverman et al. [1983], the stratigraphy is divided into layers according to grain size and heavy minerals. Strikes and dips given by Rao et al. [1974] were used to constrain the orientations at the surface.

south of the topographic axis, and the beds on the south flank dip steeply south (~50°).

Two drill holes corroborate the inference that a thrust fault dips northward beneath this portion of the Siwalik hills [Raiverman et al., 1983; Rao et al., 1974]. One shallow hole penetrated recent gravels below the Middle Siwalik formation on the south edge of the Siwalik Hills. The other, deeper hole was drilled south of the topographic axis of the Siwalik Hills, but north of the crest of the anticline (Figure A1). This hole penetrated the Middle and Lower Siwalik formations before intersecting the thrust fault and passing through another section of Middle and Lower Siwalik sediments and a thin layer of the Dharamsala formation. The Pre-Tertiary basement was reached at a depth of 4416 m below the surface [Sastri, 1979] or nearly 4000 m below sea level.

To construct a cross section, we use the reported results from the Mohand deep well and a profile of average dips of the various formations observed at the surface from Raiverman et al. [1983]. Raiverman et al [1983] used a slightly different stratigraphic column than is common for the Tertiary sedimentary sequence of the sub-Himalaya and Indo-Gangetic plains. They divided the column into nine units according to both grain size and distributions of heavy minerals. They consider their units 2 and 3 to include part of the Subathu formation and all of the Dharamsala formation. Unit 4 is essentially the same as the Lower Siwalik. The Middle Siwalik includes all of unit 5 and approximately the lower third of unit 6. The rest of unit 6 and units 7 and 8 together constitute the Upper Siwalik sequence.

To build a balanced cross section we assumed that the pre-Tertiary basement dips gently northeast beneath the Ganga Basin. We further assumed that thrust faults in the Tertiary formations do not cut the basement but instead detach the overriding formations from it. For the Mohand thrust we conclude that the sole of the detaching thrust fault is in the Dharamsala formation. The sole cannot be much above this depth because the thickness of unit 4 (Lower Siwalik) is the same above and below the thrust fault. The absence of the Dharamsala formation above the thrust fault suggests that detachment occurred above it. For units 4, 5, and 6, we used the thicknesses inferred by Raiverman et al. [1983] from the Mohand deep well and from the surface exposures north of it. The top and bottom of unit 6 crop out, and the nearly uniform dip of the formation leaves little room for controversy over its average thickness. The bottom of unit 5 is seen only in the Mohand deep well, but with the top exposed at the surface, a reliable estimate of the thickness can be obtained. The Mohand deep well penetrates approximately 800 m

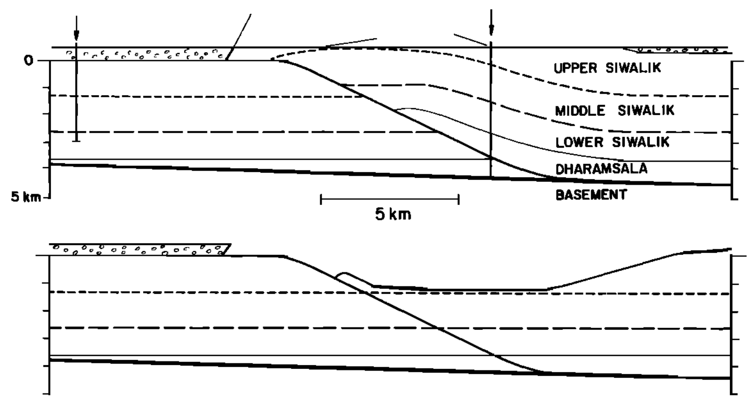

Fig. A2. (top) Balanced cross section and (bottom) palinspastically restored section for the Janauri anticline (see Figure 10 for the approximate location.) We used stratigraphic data given by Karunakaran and Ranga Rao [1979] and surface mapping reported by Mathur and Evans [1964] to constrain the thicknesses and dips of various layers.

of unit 4 beneath the thrust fault, and we take this value for its thickness. Approximately the same thickness overlies the fault. This drill hole did not penetrate unit 6 at all. For the thickness of all three units 4, 5, and 6 to be essentially the same on both sides of the faults, we, like Raiverman et al. [1983], are forced to assume that drag folding on the thrust fault has warped unit 5 up (see Figure A1).

In earlier cross sections [e.g., Rao et al., 1974], which were published at a smaller scale than Raiverman et al.'s, the Siwalik sequence was subdivided into the classical Lower, Middle and Upper divisions. On these cross sections the thicknesses of Middle and Upper Siwalik subgroups are nearly the same. Rao et al.'s cross section, however, shows the Mohand deep well penetrating only the Middle Siwalik portion of Raiverman et al.'s unit 6. We have used Raiverman et al.'s stratigraphy with the drag fold in unit 5, because their cross section was published at a much larger scale than Rao et al.'s. Were we to use Rao et al.'s, we would obtain essentially the same cross section, but without the drag fold in unit 5.

The vertical separation of the boundary between the Lower and Middle Siwalik (units 4 and 5) is nearly 3 km. This value, therefore, is a lower bound for the slip on the fault. The 30° dip of the beds near the well suggests that the dip of the fault must be at least 30° there. The gradual decrease northward to 20° where unit 8 crops out (Figure A1) suggests that the fault surface is listric and makes it very unlikely that the fault enters the basement in this region. The shape of the fault is then deduced by keeping the thickness of units 4, 5 and 6 constant, and a slip of 7.5 is obtained. This is probably close to an upper bound for the slip. Detachment could not have occurred at a much shallower depth, because the thickness of unit 4 is the same same above and below the fault. Detachment could have occurred within or at the base of the Dharamsala formation (units 2 and 3). If it did, however, then the fault would have to be steeper than is shown. If variations in thickness of the various units were 300 m, then the vertical separation could be in error by this much, and the estimated throw could be in error by 0.5-1 km. If the dip of the fault were 25° or 35° instead of 30° used here, then the slip could be in error by about 1 km. Thus we consider the slip to be between about 6 and 9 km.

Janauri Anticline

We have used much the same logic to construct a balanced cross section across the Janauri anticline. We used stratigraphic thicknesses reported for three drill holes: the Janauri deep well on the north slope of the anticline, the Hoshiarpur well about 6-7 km southwest of the edge of the anticline, and the Adampur deep well some 30 km southwest of the southwest edge (Figures 9 and 10). The first and third wells reached the basement, and all three penetrated comparable thicknesses of Middle Siwalik sediments (~1000-1400 m [Karunakaran and Ranga Rao, 1979; Sastri, 1979]). The top of the Upper Siwalik sequence is eroded from the Janauri anticline, but the gentle northward dip on the north flank and the mapped boundary between the Upper Siwlaik and Post-Siwalik formations indicate a thickness comparable to that observed in the Adampur and Hoshiarpur wells (1400-1600 m) (see Figure A2).

We have drawn the Middle and Upper Siwalik formations each with constant thickness, despite differences of 100-200 m in the drill holes. We also treat the thickness of the Lower Siwalik formation as constant (Figure A2). (The Hoshiarpur well did not penetrate the base of the Lower Siwalik sequence.) We assume that the pre-Tertiary basement slopes gently to the northeast and that Dharamsala sediments increase in thickness in that direction. This formation pinches out southwest of the Janauri well and is not exposed is the Adampur well, but it is particularly thick in the Janauri well.

To make the cross section, we took the dips at the surface on the north flank of the anticline and projected the various contacts downwards assuming constant thickness of the various units (Figure A2). We conclude that the thickness of the Dharamsala sequence in the Janauri well is roughly double that deposited on the basement, and that the deep well penetrated a northeast dipping thrust fault. If this is not so, then there must be very large lateral variations (>1000 m) in the thickness of the Dharamsala sequence over short distances (~10 km).

The Janauri anticline is a very gentle feature (Figure A2). On the northeast side, Upper Siwalik sediments generally dip 10° to 20° to the northeast, and the dip decreases smoothly towards the southwest [Mathur and Evans, 1964]. The crest of the anticline is broad with the Upper Siwalik sediments only gently warped. One the south edge of the anticline, dips become very steep (~80°) and even locally overturned [Mathur and Evans, 1964]. Thus the anticline is asymmetric, but the steep southwest side is a very local feature (Figure A2). The very steep dips are probably due to drag on the thrust fault where it approaches the surface at the southern edge of the anticline. In drawing a balanced cross section, we have not tried to match these steep dips.

The various units encountered in deep well are approximately 1000 m shallower in the Janauri well than in the Hoshiarpur or Adampur wells. Projecting the interfaces between units up dip to the south leads to approximately 1600 m of vertical separation. This value cannot be much larger; if larger vertical separation were to exist, then Middle Siwalik sediments would be exposed in the anticline. For instance, if detachment occurs within the Dharamsala formation, but if 8 km of thrust slip occurred on the fault shown, then even lower Siwalik sediments would be exposed in the anticline. Thus at least 1.6 km of slip must have occurred (if the fault were vertical), but regardless of the dip, the total slip probably does not exceed 5 km.

The dip of the fault is probably steeper than 20°, the maximum dip in the upper Siwalik sequence on the north flank. If the dip of the fault were only 20°, then the fault plane would project to the surface south of the south edge of the anticline. The fault surface could be listric between the Janauri deep well and the southern edge of the anticline, but if it is markedly listric, then the observed broad, gentle anticlinal cross section would not be matched. Therefore 20° is probably a lower bound for the average dip of the fault. We find that a dip of about 25° with a throw of 4 km allows a balanced cross section consistent with the measured dips at the surface and with the measured sections in the drill holes. If dip of the fault were as steep as 30° or 35°, then the throw could be less, but would still exceed 3 km. For steeper dips, however, the anticline would be much sharper, as it would be for a listric fault, and the broad, flat shape would not exist without introducing complexities at shallow depths. Allowing for lateral variations of 200-300 m in thicknesses of various units, ignored in drawing Figure A2, the uncertainty in the throw is probably 1 km. Hence we infer that the Janauri anticline formed by 4 ± 1 km of slip on a fault dipping north at 25° ± 5° and detaching the overlying sediments within the Dharamsala formation.

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