Abstract. The intracontinental subduction of India beneath the Himalaya presents several similarities to that occurring at island arcs. We study one of those similarities by analyzing gravity anomalies across the Himalaya assuming that the topography is supported by the Indian elastic plate, flexed under the weight of both the overthrust mountains and the sediments in the Ganga Basin. We first examine in detail the effects of each of the following parameters on the configuration of the elastic plate and on the gravity anomalies: the flexural rigidity, the position of the northern end of the elastic plate (the amount of underthrusting of such a plate beneath the range), and the density contrasts between the crust and mantle and between the sediments and the crust. A plate with a constant flexural rigidity of about $0.7 \times 10^{25} \text{N m}$ (between 0.2 and 2.0 $\times 10^{25} \text{N m}$) allows a good fit to the data from the Lesser Himalaya and the Ganga Basin. Such a plate, however, cannot underthrust the entire Himalaya. Instead, the gravity anomalies show that the Moho steepens from only about 3° beneath the Lesser Himalaya to about 15° beneath the Greater Himalaya. This implies a smaller flexural rigidity beneath the Greater Himalaya (0.1 to 1.0 $\times 10^{23} \text{N m}$) than beneath the Ganga Basin and the Lesser Himalaya. Even with a thin, weak plate beneath the Greater Himalaya, the weight of the mountains depresses the plate too much unless an additional force or moment is applied to the plate. The application of a bending moment/unit length to the end of the plate of about $0.6 \times 10^{18} \text{N m}$ is adequate to elevate the Indian plate and to bring the calculated gravity anomalies in agreement with those observed. Both, the smaller flexural rigidity and the bending moment can be understood if we assume that part or all of the Indian crust has been detached from the lower lithosphere that underthrusts the Greater Himalaya. We study the tectonic implications of these results by means of a series of idealized balanced cross sections, from the collision to the present, that reproduce several important features of the geology of the Himalaya and predict an amount of eroded material comparable to that in the Ganga Basin and the Bay of Bengal. These cross sections include high-grade metamorphic rocks near the Main Central Thrust and a steeper dip of it there than in the Lesser Himalaya. They predict rapid uplift only in the Greater Himalaya and at the foot of the Lesser Himalaya.

Introduction

Geologic studies of the Himalaya suggest that the range was built by slivers of the Indian continent that successively overthrust the Indian shield to the south [e.g., Gansser, 1964, 1966; LeFort, 1975; Mattauer, 1975]. Following the closure of the Tethys Ocean at the Indus-Tsango suture zone, the northern margin of India was underthrust beneath southern Tibet an unknown amount. Later, probably during the Oligocene, convergence between India and southern Tibet apparently ceased at the Indus-Tsango suture, and slip began on the Main Central Thrust, the major fault within the Himalaya [e.g., Gansser, 1964, 1966] (Figure 1). More recently, the locus of underthrusting was again transferred southward to the presently active Main Boundary Fault. Both the Main Central Thrust and the Main Boundary Fault appear to the schuppen zones with slip on many separate, subparallel faults. Much of the present seismicity seems to occur on the Main Boundary Fault, which dips at a shallow angle beneath the Lesser Himalaya, and at present India seems to slide under the Himalaya on this fault [e.g., Molnar et al., 1977; Seeger and Arambruster, 1981; Seeger et al., 1981].

This description of the tectonic history in terms of successive southward jumps in the active underthrust zone is, of course, an oversimplification and ignores numerous less important thrust faults within the range [e.g., Valdiya, 1981]. Nevertheless, it provides a simple framework within which other aspects of the geologic history can be fit, and it serves as a reasonable working model with which geophysical observations can be compared [e.g., Molnar et al., 1977]. Specifically, fault plane solutions of earthquakes consistently show shallow north or northeast dipping nodal planes that probably are the fault planes [e.g., Fitch, 1970; Molnar et al., 1977]. Depths of foci of these events imply that many of these events lie on the Main Boundary Fault and therefore on the top surface of the Indian shield that presently underthrusts the Lesser Himalaya [Molnar and Chen, 1982]. Drilling of the sediments in the Ganga Basin [Sastri et al., 1971; Rao, 1973] and gravity anomalies [e.g., Choudhury, 1975; Wari and Molnar, 1977] show the existence of a deep basin south of the Himalaya, similar in shape and dimensions to deep-sea trenches at island arcs. Finally, gravity data imply that the crust gradually thickens northward beneath the Greater Himalaya [e.g., Choudhury, 1975; Vono, 1974; Wari and Molnar, 1977]. These observations suggest that this intracontinental subduction of India beneath the Himalaya is very similar to that occurring at island arcs, where oceanic lithosphere is being subducted. The essential difference comes from the underthrusting of thick buoyant continental crust instead of thin.
oceanic crust on top of cold mantle lithosphere.

In the present paper we examine one of the similarities of the Himalayan region to island arcs: that much of the topography owes its existence to the flexure of an elastic plate. Using such a simple mechanical model, we then use both the gravity anomalies over the Himalaya and the shape of the basinment of the Ganga Basin to place constraints on the mechanical properties of such a plate and on the forces that deform it. Several studies of gravity anomalies in the Himalayan region have estimated the crustal thickness or have addressed whether or not isostatic equilibrium prevails [e.g., Choudhury, 1975; Kono, 1974; Marius, 1964; Oureshy et al., 1974; Warsi and Molnar, 1977]. Although the inferred density models generally yield acceptable fits to the data, they are not constrained by assumptions of plausible mechanical behavior. Here we use the published data of Choudhury [1975], Kono [1974], and Warsi [1976] plus a few data in Greater Himalaya and Tibet [Tang et al., 1981].

We assume that the mass distribution results from the loading and flexure of an elastic continental lithosphere bent under the distributed load of Himalayan mass itself. The physical model is similar to those used for subduction of oceanic lithosphere at island arcs [e.g., Hanks, 1971; Watts and Talwani, 1974]. It differs principally by the trough (or trench) created by the flexure being filled by sediments and by the load being distributed and defined by the Himalayan topography. This is a simplistic model since elastic behavior is an idealization, but this will allow a test to be made of the simple hypothesis that the Indian (elastic) plate underthrusts the Himalaya and will provide a step toward a physical understanding of the structure and dynamics of the region. Instead of examining models with a large number of adjustable and arbitrary chosen locations of irregularly shaped bodies with different densities, we are free to vary only a few parameters, and the effects of each on the computed gravity anomalies may be studied independently. These parameters are the flexural rigidity of the
plate (defined below), density differences between the crust and mantle and between the crust and sediments in the Ganga Basin, the position of the northern end of the elastic plate, and the bending moment and the shear force applied at the end of the plate.

The final results of this study involve a sufficient number of modifications to the simple model of an underthrust elastic plate of constant flexural rigidity that we cannot expect the reader to believe them without a systematic analysis of each. Following both a brief discussion of the methods used to determine the shape of the plate and to calculate the gravity anomalies and a presentation of the gravity data, we begin by considering a simple plate with a constant flexural rigidity beneath the Ganga Basin, and we show that such a plate cannot underthrust the entire Himalaya. We then consider a plate with a smaller flexural rigidity in a short segment beneath the Greater Himalaya than that beneath the Lesser Himalaya, the Ganga Basin, and the Indian shield in order to examine the effect of a weak northern segment of plate. We show that regardless of the flexural rigidity, the weight of the material in the Greater Himalaya depresses the Moho too much to fit the observed gravity anomalies unless a bending moment is applied to the north end of the plate.

Finally, we discuss the possible physical mechanisms responsible for such a moment and the tectonic implications of the range of possible structures implied by the gravity and topographic data.

Basic Physical Model and its Mathematical Description

The Indian plate is treated as a two-dimensional thin plate. We analyze its elastic response to the loads of the Himalaya and of the sediments that fill the trough (Ganga Basin) created by the bending of the plate. The basic equation for two-dimensional bending of an elastic plate is [e.g. Hanks, 1971; Turcotte and Schubert, 1982]:

$$D \frac{d^2 y(x)}{dx^2} + g \rho y(x) = L(x)$$  (1)

where $y$ is the deflection at the abscissa $x$, $\Delta \rho$ is the density contrast between the two materials above and below the plate, $g$ is gravity, and $D = E t^3/12(1-\nu^2)$ is the flexural rigidity, $E$ is the Young’s modulus ($E = 1.6 \times 10^5$ N/m$^2$), $t$ is the thickness of the plate, and $\nu$ is Poisson’s ratio ($\nu = 0.25$). $L(x)$ is the weight/unit area of the topography at $x$. To obtain $L(x)$, we average the elevation within 100 km of either side of the profile. Below, we discuss the effects of errors in the observed load. We assume that the plate overlies an inviscid fluid with a density appropriate for mantle material. Above the plate, however, there are different segments with air, sediments, and rock of crustal density.

Accordingly, it is convenient to separate the plate into three domains (Figure 2). We then solve (1) in each domain and obtain the complete solution by matching boundary conditions where the segments are joined. For two dimensions and if we assume no shear stress at the base of the plate, the equation for a thick plate reduces to (1) [Parsons and Molnar, 1976]. Thus there is no problem in using the thin plate approximation for a series of short plate segments.

The first domain ($x < x_0$) includes the Indian shield where its surface is exposed. The equation to solve is (1) with $L(x) = 0$ and $\Delta \rho = \Delta \rho_1 = \rho_m$, where $\rho_m$ is the mantle density. The second domain ($0 < x < x_0$) spans the Ganga Basin. Here $L(x) = 0$ and the plate is overlain by sediments of density $\rho_s$; $\Delta \rho = \Delta \rho_2 = \rho_m - \rho_s$. Thus the sediment thickness is not assumed but is calculated. The third domain ($x > x_0$), where the load is applied, includes most of the Himalaya and possibly part of Tibet, depending on how far to the north the end of the plate, defined by $x_0$, is assumed to extend. Effectively, we assume that the plate is overlain by material of crustal density, with a load equal to the mass of rock above sea level; $\Delta \rho = \Delta \rho_3 = \rho_m - \rho_c$, where $\rho_c$ is the crustal density; $L(x) = \rho_g T(x)$ is calculated from the topographic profile $T(x)$, and $\rho_g$ is the assumed mean density for the mountains, $\rho_g = 2.7 \times 10^3$ kg/m$^3$. Note that we do not assume the thickness of the overthrust material but calculate it. Later we add a fourth domain ($x_0 < x < x_0'$), with a smaller flexural rigidity $D'$ but in which $L(x)$ and $\Delta \rho$ are defined in the same way as in the third domain. $x_0'$ will define the end of the elastic plate in this case.

The solution for (1) in domains 1 and 2 and for the homogeneous equation associated with (1) in domain 3 (and 4) is of the form

$$y_1(x) = e^{-\lambda x}[A_1 \cos \lambda x + B_1 \sin \lambda x] +$$

$$e^{\lambda x}[C_1 \cos \lambda x + D_1 \sin \lambda x]$$  (2)

with $\lambda_1 = (\Delta \rho g/4D)^{1/4}$, $i = 1, 4$. Solving (1) in domain 3 (and 4) requires the addition of a particular solution to the previous general solutions. This has been computed numerically by taking Fourier transforms of both sides of (1). Wavelengths ranging from $\pi$ to 2 km are considered in the computation. A check of the method has been made by comparing solutions with those obtained analytically for loads of rectangular and triangular shapes. Numerical and analytical solutions differ by less than 1%.

The following set of boundary conditions establishes a linear system of 10 (or 14) equations which may be solved for the 10 (or 14) remaining constants. At $x = 0$, $x = x_0$, and at $x = x_0'$, if a fourth domain is used, there must be continuity of the deflection of the plate $y$, of the slope of the plate dy/dx, of the bending moment $D(d^2 y/dx^2)$ and of the vertical shear stress $D(dy/dx)$ at $x = x_0$, or at $x = x_0'$, when there is a fourth domain, the bending moment and the vertical shear stress must be specified. In most calculations (but not the final ones) both are assumed to be zero, so that the end of the plate is free. An equilibrium of forces and moments results directly from (1) and from the specification of the boundary conditions.

We used the method described by Talwani et al. [1959] to compute the gravitational attractions of polygonal, two-dimensional bodies. We assume that the gravity anomalies of interest are caused by density contrasts between the crust and mantle and
between the sediments and mantle (Figure 2). Since both the bottom of the sedimentary basin and the Moho are parallel to y(x), which we calculate, we know the shapes of these two bodies for the region x>X₀ or (X₀'). We also assumed that the crust of Tibet (x<-250 km) is in isostatic equilibrium [Amboldt, 1948; Chang and Cheng, 1973; Tang et al., 1981], so that a column of its mass weighs the same as that to the same depth beneath the Indian shield. Assuming a crustal thickness of 35 km for the Indian shield, the depth of compensation Dc is given by

$$35\rho_c + (D_c-35)\rho_m = 5\rho_L + D_c\rho_c$$  (3)

With a mean elevation of 5 km and a mean density \(\rho_L = 2.7 \times 10^3 \text{ kg/m}^3\) of the material above sea level for Tibet, this yields a value of Dc between 60 and 70 km for \(\rho_L-\rho_c\) between 0.55 and 0.4 \times 10^3 \text{ kg/m}^3\). Although the crustal thickness Hc is difficult to resolve from surface waves data across Tibet, the more recent studies lead to estimates on crustal depth between 65 and 80 km [Chen and Molnar, 1981; Romanowicz, 1982] with a preference for Hc = 65 km = 5+Dc from pure paths across Tibet [Romanowicz, 1982]. A different assumed crustal thickness for India leads to a different one for Tibet, but such a change introduces a negligible perturbation in the calculated gravity anomalies. The assumed shape of the junction between the end of the elastic plate and the base of the crust in Tibet, however, does affect the calculated gravity anomalies and will be discussed later in more detail. At first we simply assume a smooth transition zone of the Moho from the end of the elastic plate to the position where local isostatic compensation obtains, near the suture at about x = -250 km, but this is an arbitrary choice.

Gravity Data


Wari's and Choudhury's contours generally agree within 0.15 mm/s² (15 mGal), but over a part of the Ganga Basin (100x<130) they disagree by about 0.30 mm/s². In this latter case we took the mean of the two values and assumed an uncertainty of ±0.25 mm/s² (±25 mGal). Elsewhere we assumed it to be ±0.15 mm/s² (±15 mGal). We averaged Kono's measurements in the Central Himalaya and assigned an uncertainty on the basis of the scatter; it varies from about 0.15 to 0.20 mm/s². Kono's data include terrain corrections, but Wari's do not. From Kono's calculation the terrain correction in the Lesser Himalaya is of the order of 0.10 to 0.15 mm/s². Wari's datum for x = -50 has been corrected on this basis. For the Greater Himalaya and Tibet we used four measurements (Table 1) that apparently include terrain corrections [Tang et al., 1981] and one measurement of Amboldt [1948] within the plateau (34°38.5'N, 84°50.3'E). It is reassuring that Kono's and Tang et al.'s anomalies agree in the Mount Everest region and that Kono's, Wari's, and
TABLE 1. Gravity Data From Tang et al. [1981]

<table>
<thead>
<tr>
<th>Latitude °N</th>
<th>Longitude °E</th>
<th>Bouguer, mm/s² or 10² mGal</th>
</tr>
</thead>
<tbody>
<tr>
<td>28°01.5'</td>
<td>86°56'</td>
<td>-3.04</td>
</tr>
<tr>
<td>28°33'</td>
<td>86°40'</td>
<td>-3.92</td>
</tr>
<tr>
<td>29°04.5'</td>
<td>86°17'</td>
<td>-5.23</td>
</tr>
<tr>
<td>29°28'</td>
<td>86°13'</td>
<td>-4.94</td>
</tr>
</tbody>
</table>

Choudhury's anomalies agree in the Lesser Himalaya.

From all of these data a profile was drawn, perpendicular to the trend of the Himalayan Mountains, in the Mount Everest area (Figure 1). We projected data measured within 60 km from the profile onto it.

Calculations of Flexure and Gravity Anomalies

Simple plate with a constant flexural rigidity. We calculated the shape of the top surface of the Indian plate and the corresponding gravity anomalies for a variety of assumed values for the flexural rigidity, density differences, and positions of the northern end of the plate. To some extent these series of calculations serve as numerical experiments to constrain the values of the parameters that are varied. The data are the gravity anomalies, the depth of the sediments in the Ganga Basin, and the width of the sediment-filled Ganga Basin. The sediment thickness is maximum at the foot of the range. There is no direct measurement of the sediment thickness where the profile crosses the basin, but the maximum thickness is probably between 4 and 5 km [Rao, 1973] and may reach 6 km farther west of the gravity profile in the Sarda depression (28°N, 80°E). The width of the basin is about 250 km. The top of the Central Indian Plateau, which may be analogous to an "outer topographic rise" at island arcs, is situated about 600 km from the foot of the range.

The calculations show that the flexural rigidity controls the dip of the plate, the width of the

TABLE 2. Calculated Maximum Thicknesses of Sediments in the Ganga Basin, Assuming That \( \rho_m - \rho_c = 0.55 \times 10^3 \) kg/m³ and \( \rho_c - \rho_s = 0.5 \times 10^3 \) kg/m³

<table>
<thead>
<tr>
<th>D,N m</th>
<th>2, ( \times 10^{25} )</th>
<th>0.7 ( \times 10^{25} )</th>
<th>0.2 ( \times 10^{25} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>X₀, km</td>
<td>-100 -125 -130 -150 -200 -400 -1000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2, ( \times 10^{25} )</td>
<td>1.8 3.15 3.5 4.7 6.55 7.85 7.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.7 ( \times 10^{25} )</td>
<td>2.25 3.8 4.2 5.5 7. 7.3 7.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.2 ( \times 10^{25} )</td>
<td>2.7 4.25 4.6 5.8 6.7 6.6 7.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In kilometers.

basin, and the position of an "outer topographic rise," whereas the thickness of the sediments at the foot of the range is controlled more by the position of the north end of the plate \( X₀ \), than by the flexural rigidity (Table 2). Values of \( D \) between 0.2 and 0.7 \( \times 10^{-2} \) N m and of \( X₀ \) between 125 and 130 km yield the closest matches to observed maximum thickness of the sediments and width of the Ganga Basin (Tables 2 and 3).

These ranges of values of \( X₀ \) (Figure 3) and \( D \) (Figure 4 and 5) also yield the most satisfactory fits to the gravity data over the Ganga Basin. Note that the position of the Moho between \( x = X₀ \), the northern end of the plate, and \( x = -250 \) km is arbitrarily drawn as a straight line. Therefore the fit of the observed and calculated gravity anomalies for \( x < X₀ \) is not a criterion for accepting or rejecting any of the parameters. The effects of different assumed values of the width \( X_s \) of the Ganga Basin are negligible. Assumed values of \( X_s \) between 200 and 300 km lead to very similar profiles. The effects of other parameters are now described in detail.

Constraints on the position of the northern end of the elastic plate (Figure 3). For a position of the northern end of the plate, \( X₀ \), closer than 120 km to the Himalayan front, the load is not sufficiently large to bend the plate enough: the calculated thickness of sediments is no more than 3.5 km (Table 2) and the computed gravity anomalies are less negative by 0.50 mm/s² (50 mGal) than those observed.

For \( X₀ \) between -150 and -200 km, the computed maximum thickness of the sediments is large (about 6.5 km) and the calculated gravity anomalies are large, with maximum residuals of the order of 1.00 mm/s² (100 mGal) in the Ganga Basin. Calculated gravity anomalies for profiles with \( X₀ \) between -200 and -1000 km are not very different one from another and can barely be distinguished. These results obtain for a wide range of acceptable flexural rigidities (Figure 4). An increase of the assumed density of the sediments from 2.3 to 2.5 \( \times 10^3 \) kg/m³ can halve the large residuals in the Ganga Basin, but nevertheless, nearly 0.5 mm/s² (50 mGal) cannot be explained, and 2.5 \( \times 10^3 \) kg/m³ is an upper limit for density of sediments.

For \( X₀ \) between -130 and -135 km, the maximum calculated depth of the sediments is between 4.2 and 5 km. As we discuss below, the fit of the gravity data can be improved by reducing \( \rho_c - \rho_s \)
Fig. 3. Comparison of calculated and measured Bouguer anomalies for different position of the northern end of the plate \(X_0\). The black dots are observed Bouguer anomalies (1 mm/s² is 100 mgal). Error bars represent assumed uncertainties, as discussed in the text. At the top, residuals of observed minus calculated anomalies are shown. In the lower right, configuration of the plate is sketched. Notice that the fit over the Ganga Basin implies a value of \(X_0\) between -125 and -135 km. The Moho between \(X_0\) and \(x=250\) km is arbitrarily drawn as a straight line, so the poor fit of calculated to the observed anomalies for \(x<100\) km is not significant.

(Figure 7). Thus the most likely value of \(X_0\) is between about -125 and -135 km.

Constraints on the flexural rigidity (Figures 4 and 5). The value of the flexural rigidity affects the curvature of the plate, while manifesting itself most clearly in the width (Table 3) and less obviously in the depth of the Ganga Basin (Table 2). Values of \(D\) as small as 0.2 \(10^{22}\) N m yield basins that are only 200-230 km in width, and values as large as 2.0 \(10^{22}\) N m yield basins wider than 350 km (Table 3). These results suggest that \(D\) is between these values and close to 0.7 \(10^{22}\) N m.

The gravity anomalies provide a weaker

Fig. 4. Comparison of calculated and measured Bouguer anomalies for different values of the flexural rigidity \(D\) when \(X_0 = -200\) km. Layout as in Figure 3. Note that there is no value of \(D\) that allows an acceptable fit of calculated to observed anomalies.
Fig. 5. Comparison of calculated and measured Bouger anomalies for different values of the flexural rigidity (a) for $X_0 = -125$ km and $\rho_c - \rho_S = 0.5 \times 10^3$ kg/m$^3$ and (b) for $X_0 = -130$ km and $\rho_c - \rho_S = 0.3 \times 10^3$ kg/m$^3$. Layout as in Figure 3. Note that in both cases the best fit of calculated to observed gravity anomalies over the Ganga Basin is obtained for $D = 0.7 \times 10^{25}$ N m but that values of $D$ of $0.2 \times 10^{25}$ or $2.0 \times 10^{25}$ N m may also be acceptable.

Effects of the density contrast between the mantle and crust (Figure 6). Results discussed above are based on calculations assuming that $\rho_m - \rho_c = 0.55 \times 10^3$ kg/m$^3$, which is a relatively large value. Calculations assuming that $\rho_m - \rho_c = 0.45$ and $0.4 \times 10^3$ kg/m$^3$ confirm that lowering this density contrast effectively increases the load by increasing crustal density relative to mantle density. Thus for $D = 0.7 \times 10^{25}$ N m and $X_0 = -130$ km, the maximum depth of the sediments increases from 4.2 ($\rho_m - \rho_c = 0.55 \times 10^3$ kg/m$^3$) to 4.75 km ($\rho_m - \rho_c = 0.45 \times 10^3$ kg/m$^3$) and 5 km ($\rho_m - \rho_c = 0.4 \times 10^3$ kg/m$^3$). If the relative density contrast between the mantle and sediments is
correspondingly reduced from 1.05 to 0.95 and 0.9 \times 10^3 \text{ kg/m}^3, calculated gravity anomalies in the Ganga Basin differ by a maximum of only 0.10 \text{ mm/s}^2 (10 \text{ mGal}) among the models with different density contrasts (Figure 6). Thus, although the density contrast between the mantle and crust affects the shape of the plate by depressing it about 10% more when \( \rho_m - \rho_c = 0.45 \times 10^3 \text{ kg/m}^3 \) and 20% more when \( 0.4 \times 10^3 \text{ kg/m}^3 \) than when it is \( 0.55 \times 10^3 \text{ kg/m}^3 \), it has almost no effect on the calculations of gravity anomalies. In our following calculations we will keep \( \rho_m - \rho_c = 0.55 \times 10^3 \text{ kg/m}^3 \), but even if \( \rho_m - \rho_c \) is actually closer from 0.4 than from 0.55 \times 10^3 \text{ kg/m}^3 \), this would not change our conclusions much.

**Effects of the density contrast between the crust and the sediments (Figure 7).** If the density contrast between the crust and the sediments is decreased from 0.5 \times 10^3 \text{ kg/m}^3, as assumed in most of the previous calculations, to 0.3 \times 10^3 \text{ kg/m}^3 and if the density contrast between mantle and crust is kept constant, the plate is depressed.

---

**Fig. 6.** Comparison of calculated and measured Bouger anomalies for two different values of the density contrast between the mantle and the crust \( (\rho_m - \rho_c) \). The density contrast between the crust and the sediments is kept constant and equal to 0.5 \times 10^3 \text{ kg/m}^3. Layout as in Figure 3.

**Fig. 7.** Comparison of calculated and measured Bouger anomalies for different values of the density contrast between the crust and the sediments. The density contrast between the mantle and the crust is kept constant and equal to 0.55 \times 10^3 \text{ kg/m}^3. Layout as in Figure 3.
Fig. 8. Comparison of different topographic profiles and their effects. (a) $L_1(x)$ is mean elevation within 100 km and $L_2(x)$ within 20 km of either side of the the gravity profile; $L_3(x)$ is Bird's [1978] average elevation over the entire width of the range. Comparison of calculated Bouguer anomalies for the different loads for $D = 0.7 \times 10^{25}$ N m and (b) for $X_0 = -200$ km and (c) for $X_0 = -130$ km.
more by only about 3%. Therefore, contrary to the density contrast between the mantle and the crust, the density contrast between the crust and the sediments has almost no effect on the shape of the plate but increases the gravity anomalies in the Ganga Basin by a maximum of about 0.25 mm/s² (25 mGals) at its deepest point. This is the reason why we cannot differentiate between the two profiles $X_o = -125$ km and $X_o = -130$ km with $D = 0.7 \times 10^{17}$ N m (Figure 7).

Sensitivity of the model to the choice of the load (Figure 8). Previous computations were performed using a load $L_1(x)$ obtained from mean elevation along a profile 200 km wide in the region where measurements were made (Figure 8a). The mean elevation reaches a maximum of about 6500 m at the abscissa of the Mount Everest. For comparison we also made computations with a load $L_2(x)$, obtained from mean elevations along a profile 40 km wide (Figure 8a), and a load $L_3(x)$ obtained from Bird's [1978] average elevation over the entire width of the range (Figure 8a). Elevations corresponding to $L_2(x)$ are higher than for $L_1(x)$ over the Greater Himalaya, but the maximum (8000 m) is reached at the same abscissa. The same holds for the Lesser Himalaya; the maximum elevation over the Lesser Himalaya are a little smaller than for $L_1(x)$. The profile corresponding to $L_3(x)$ is lower than $L_1(x)$ and $L_2(x)$ by about 2 and 3.5 km, respectively, over the Greater Himalaya and does not have a maximum elevation near the abscissa corresponding to the Mount Everest. This profile consists of an average elevation over various parts of the range that do not necessarily share the same tectonic evolution; therefore it is probably not the appropriate load to use in this study, but it provides an extreme with which to examine the uncertainties in the parameters that results from uncertainties in the load.

The differences among computed gravity anomalies for these three profiles can reach 0.50 mm/s² (50 mGals) for the case where the plate is assumed to underthrust the Greater Himalaya (i.e., $X_o = -120$ km). However, a plate with a constant flexural rigidity cannot underthrust the entire mountain range (Figure 8b). Differences among calculated anomalies are smaller for plates that underthrust only a fraction of the range (i.e., $X_o = -130$ km) (Figure 8c), and consequently, the uncertainty in the load increases the uncertainty in $X_o$ noted above. For instance, using Bird's [1978] profile, the data will be best fitted with $X_o = -140$ km instead of $X_o = -130$ km using $L_3(x)$ (Figure 8c) or $X_o = -125$ km using $L_1(x)$ (Figure 3). We present the following computations using only $L_1(x)$, but as we have shown here, using either a larger or a smaller load will only introduce small quantitative changes in our results.

Effect of a bending moment applied to the end of the plate. Below, we show that if a bending moment is applied at the end of the plate that underthrusts the entire range, the gravity anomalies cannot be fit well unless the flexural rigidity of the portion of the plate beneath the Greater Himalaya is considerably smaller than that beneath the Lesser Himalaya (Figure 13).

Summary. These calculations show clearly that a plate of constant flexural rigidity cannot underthrust even southernmost Tibet. Models that call for wholesale underthrusting of Tibet by the Indian shield [e.g., Argand, 1924; Powell and Conaghan, 1973] must do so only by allowing the Indian shield to lose a considerable amount of its strength approximately 120-140 km from the front of the Himalaya.

The calculations show that the flexural rigidity of the plate and the position of the end of the plate are constrained independently from one another. We have shown that the end of the elastic plate is between 120 and 140 km north of the Himalayan front and that a flexural rigidity of about 0.7±0.5 x 10^22 N m, corresponding to an elastic thickness of about 80±30 km, is necessary to explain the topographic features and the gravity field of the Ganga Basin. The fit north of the Ganga Basin, however, can be improved.

The dip of the Moho beneath the Greater Himalaya. The calculated anomalies over the Greater Himalaya and Tibet may be altered by arbitrarily changing the configuration of the Moho between the end of the elastic plate, $X_o$, and the southern margin of Tibet where isostatic equilibrium is assumed to prevail. If the crustal thickness of Tibet is reached 200 km from the foot of the range instead of 250 km, as assumed in Figures 3 to 8, the calculated and observed anomalies agree well (Figure 9). This corresponds to a dip of the Moho of about 5° beneath the Greater Himalaya (provided that $p_o = 5.5 \times 10^3$ kg/m³), compared with only about 3° beneath the Lesser Himalaya.

Possibility of subducted sediments beneath the Lesser Himalaya. In the Lesser Himalaya, calculated anomalies are consistently 0.25 to 0.50 mm/s² less negative than observed (Figures 5, 6, and 7). To eliminate this difference requires the introduction of material with low density beneath the Lesser Himalaya. The introduction of a thin wedge of material with a density $\rho = 2.5 \times 10^3$ kg/m³ beneath the Lesser Himalaya is adequate to eliminate this negative residual (Figure 9) and suggests that sediments were probably subducted along with the underthrust plate.

Plate with a reduced flexural rigidity beneath the Greater Himalaya. The steeper dip of the Moho beneath the Greater Himalaya suggests that the plate is flexed more and therefore that the flexural rigidity is less than beneath the Lesser Himalaya and farther south. To analyze quantitatively this change in dip, we studied the flexure of a plate consisting of two segments with different flexural rigidities (Figure 2). There are now two additional parameters that we can vary: the flexural rigidity of the northern segment $D'$ and the position of the junction between the two segments, now defined by $X_o'$. First, we fix the end of the elastic plate, $X_o'$, equal to -200 km in order to mimic the structure used in Figure 8. We seek values of $D'$ and $X_o'$ that will lead to a plate with a shape close to that used in the computation of Figure 9. We already know that $X_o'$ is between about -100 and -150 km. Although the purpose of adding another segment of plate is to fit the steepening of the Moho beneath the Greater Himalaya, the addition of this segment has a second important effect. The load of the Greater Himalaya on this additional segment must be supported by the elastic strength of the plate, and consequently, the plate is flexed down more than for the cases considered above that ignored the support of this mass. Even if $D'$ is small so that the northern segment bends
a great deal, the effect of this additional load is important. For a wide range of flexural rigidities of this segment (0.2 x 10^12 to 0.4 x 10^13 N m), and X0 = -130 km or -100 km, the plate is depressed about 50% more (Figure 10a) than for the case in Figure 9. The same effect is observed for other values of X0 between -100 and -150 km.

The corresponding gravity profiles (Figure 10b) show that it is not possible to match the gravity anomalies by just considering a plate with a variable flexural rigidity. If X0 is -130 km, values of D' from 0.2 x 10^12 to 0.4 x 10^13 N m allow the entire plate to be depressed too much, leading to an overall positive residual. If X0 is only -100 km, the entire plate is less depressed than in the case where X0 is -130 km, especially if D' is small (0.5 to 0.2 x 10^12 N m), but in this case the northern segment of the plate steepens too rapidly (Figure 10).

Profiles computed using other loads (L2(x) or L3(x)) show the same qualitative features, but the deflection of the plate is smaller when L2(x) is used and larger when L3(x) is used. For instance for profiles computed with L2(x) and with X0 = -130 km, X0' = -200 km, D = 0.7 x 10^22 N m and D' = 0.2 x 10^22 N m, the maximum depth of the basin at x = 0 km is only 5.2 km, compared with 6.5 km when L2(x) is used and 6.0 km when L1(x) is used (Figure 10).

The calculations discussed in the previous section implied that an elastic plate flexed by the load of the Lesser Himalaya could account for the gravity anomalies over that region and the Ganga Basin. The results of these calculations, however, show that if the load includes the Greater Himalaya, this additional load depresses the plate too much to allow a match of calculated and observed gravity anomalies. Either additional sources or deficits of mass are required or additional forces must operate on the plate.

Inclusion of a bending moment. Rather than appeal to additional and somewhat arbitrarily chosen excesses or deficiencies in mass, we examine the effects of other likely forces. We first investigate the effect of a bending moment applied at the end of the elastic plate. The moment both depresses the northern end of the plate and, in reaction, elevates a portion farther south. A sufficiently large moment can flex the plate up enough to overcome the subsidence created by the additional weight. An increase in the bending moment, however, causes the northern end of the plate to steepen. We found that a bending moment applied at the end of a plate with X0' = -200 km will not allow a satisfactory fit to the data. A bending moment of the order of 0.5 to 1.0 x 10^22 N m is needed to elevate the plate enough beneath the Lesser Himalaya and the Ganga Basin, but in this case the slope of the northern part becomes too large (-25°) (Figure 11). These calculations apply for values of D' between 8 x 10^12 and 1 x 10^22 N m. If D' is smaller than 10^22 N m, the contrast between the two flexural rigidities becomes too large, and the interaction between the two parts of the plate is very small. The bending moment will then bend the northern part of the plate a great deal but will have very little effect on the slope or position of the plate beneath the lesser Himalaya. On the other hand, if D' is larger than 10^22 N m, the difference between the two flexural rigidities is not sufficiently large to allow the steepening observed beneath the Greater Himalaya. We conclude that no bending moment applied 200 km north of the Himalayan front will allow a fit of observed and calculated gravity anomalies.

The position of the northern end of the plate, where the bending moment is applied, must be farther north. If the bending moment is applied at
X₀' < -270 km, it does not change the shape of the plate for x between -130 and -200 km enough, and if it is applied at X₀' > -230 km, it steepens the end of the plate (-200 < x < -130) too much and too quickly (Figure 12). Therefore if a bending moment is applied at the end of the elastic plate, this should be between 230 and 270 km from the Himalayan front.

If the moment is applied at the end of a plate where X₀' = -250 km, it is possible to find different combinations of D' and of the applied bending moment M₀ that will lead to acceptable fits of calculated and observed gravity anomalies (Figure 13). If D' is 0.7 x 10¹⁸ N m and X₀ = -125 km, M₀ must be about 0.85 x 10¹⁸ N m, but if D' = 0.2 x 10¹⁸ N m, M₀ need only be 0.55 x 10¹⁸ N. For the same value of D' the moment must be about 10% larger if X₀ = -150 km than if X₀ = -130 km. Again profiles computed with L₂(x) or L₁(x) show the same qualitative features as for L₁(x), but L₂(x) requires a larger bending moment (~0.65 x 10¹⁸ N) and L₃(x) a smaller one (~0.45 x 10¹⁸ N) than L₁(x) (0.55 x 10¹⁸ N).

One difficulty with applying a bending moment at x = -250 km is that although the calculated shape of the plate is fairly close to that used in Figure 9 for x > -200 km, the curvature of the plate continues to increase beyond this point, and the calculated depth of the Moho reaches 115 km at x = -250 km (Figure 11)! We do not believe that the Moho necessarily does reach such a depth. It would not be required, for instance, if we assumed that the decrease in flexural rigidity of the northern segment of the plate were accomplished by detaching the crust from the rest of the Indian lithosphere. In any case, the calculated gravity profiles obtained directly from the flexed plate with a Moho reaching 115 km and those obtained by arbitrarily assuming that the depth of the Moho does not exceed 65 km for x < -200 km differ primarily in the range -400 < x < -200 km (Figure 14). The data that we have are inadequate to eliminate one or the other extreme. It is interesting, however, that the profile given by Tang et al. [1981] for a portion of Tibet about 200 km farther east shows a minimum of about 0.30 mm/s² (30 mGal) near the Indus-Tsangpo suture, suggesting that the crust might be deeper there than farther north or south.

We conclude that to match the gravity anomalies with an elastic plate loaded by the weight of the overthrust mountains, there must be a bending moment applied to the end of the plate.

Origin of the bending moment. If a horizontal force/unit length F acts on the end of the plate that is bent down a distance y₀, then provided that this force is much less than critical buckling strength, it produces a bending moment M₀ = Fy₀/2 [Parsons and Molnar, 1976]. If we assume that this force is produced by a compressive stress σ acting on a plate of thickness h and depressed an amount y₀ at its end, then σ = 2M₀/My₀. If y₀ = 30 km, h = 50 km, and M₀ = 0.55 x 10¹⁸ N m, σ = 730 MPa (7.3 kbar). Since the horizontal compressive stress needed to maintain the high elevation and thick crustal root of Tibet is only 50 to 100 MPa [e.g., Frank, 1972; Tapponnier and Molnar, 1976], it does not seem possible to invoke a compressive stress as a mechanism to create the bending moment. We do not think that a large stress of 730 MPa can exist throughout the lithosphere.

---

**Fig. 10b.** Calculated Bouguer anomalies for the deflections shown in Figure 10a.
Layout as in Figure 3.
Another possible source of a large bending moment would be the torque applied to the Indian plate by gravity acting on a piece of relatively cold and dense material north of the range. If the mantle (elastic) lithosphere of India extended north of the Indus suture and were pulled down by gravity acting on it or by convective downwelling of the lower lithosphere, the force acting on this material would apply a torque to the portion of the plate beneath the Himalaya. We are not aware of evidence requiring such cold material beneath southern Tibet, but the downwelling of cold material beneath mountains is likely where crustal shortening has occurred [e.g., Fleitout and Froidevaux, 1982; Houseman et al., 1981]. If the center of gravity of this cold material is situated at a distance L from the end of the elastic plate beneath the Himalaya, the moment applied to it is

\[ M_0 = mgL, \text{ where } m = \Delta \rho S \text{ is the excess of mass per unit of length. Taking } \Delta \rho = 50 \text{ kg/m}^3 \text{, corresponding to material an average of } 500^\circ C \text{ colder than the asthenosphere, } S = 10^7 \text{ km}^2 \text{ and } L = 120 \text{ km, we obtain a moment per unit of length of } 0.5 \times 10^{15} \text{ N m. We must not neglect the additional force/unit length acting on the plate, } mg = 0.45 \times 10^{14} \text{ N m, caused by this excess mass. This represents 15-20% of the total force due to the weight of the mountains, and therefore its effects both on the size of the deflection of the plate and on the gravity anomalies are relatively small (Figure 14). In fact, the gravity anomaly caused by this additional mass improves the fit to the data from calculations in which the cause of the bending moment is unspecified (Figure 14). The contribution to the gravity anomalies depends on the position, depth, and amount of mass, which cannot be constrained independently of one another but whose contributions may be chosen somewhat arbitrarily. Therefore there is no unique configuration that can explain the gravity data. There are trade-offs among the bending moment, the position and amount of excess mass, and the flexural rigidity of the northern part of the plate. Without more information it is impossible to be more precise, but insofar as a bending moment must be applied to the Indian plate, the presence of relatively dense material beneath Tibet is a plausible cause of that bending moment.}

In summary, first, the flexural rigidity of the northern part of the plate beneath the Greater Himalaya must be less (0.1 to 1.0 \times 10^{13} \text{ N m}) than that of the rest of the plate (0.7 \times 10^{13} \text{ N m}) beneath the Lesser Himalaya, the Ganga Basin, and the Indian shield. Second, a bending moment/unit length, acting at the end of the plate (0.5 to 1.1 \times 10^{13} \text{ N m}) is necessary to support the mass of the mountains. Third, both to generate the moment and improve the fit to the gravity data in the Greater Himalaya, we suggest that there is cold dense material beneath southern Tibet that contributes a positive gravity anomaly over it.
Ganga Basin have been underthrust beneath the Lesser Himalaya may find analogy with the Siwaliks. The Siwaliks are clastic sedimentary rocks of Miocene age and derived from erosion of the Himalaya [e.g., Gansser, 1964]. They are overthrust and folded in a schuppenzone near the foot of the Lesser Himalaya. Older units of the Siwaliks may have been overthrust by the Main Central Thrust. The possibility that both the Siwaliks and the more recent sediments of the Ganga Basin have been overthrust by crystalline terrains of the Lesser Himalaya probably should not be overlooked in the consideration of the petroleum potential of the Himalaya.

The gravity anomalies as well as some of the fault plane solutions and focal depths of earthquakes in the Himalaya suggest that the Indian plate underthrusts the Lesser Himalaya coherently at least 100-150 km. The metamorphic terrains of the Lesser Himalaya would thus have been thrust on top of an effectively elastic plate whose flexural strength supports the mountain belt. Again, it seems likely that the same situation existed when the Main Central Thrust was the active northern boundary of the Indian plate.

We have ascribed the apparent steepening of the Moho from just a few degrees beneath the Lesser Himalaya to about 15° beneath the Greater Himalaya to a reduction in the flexural rigidity of the Indian plate at its northern extremity. If such a reduction in flexural rigidity has occurred, then two likely ways to accomplish this would be by warming, and hence weakening the plate, or by detachment of some of it. The top of the plate will warm much more rapidly than the interior or bottom [e.g., Molnar et al., 1983], and if the top weakens, it will detach from the deeper portions yet more easily than if it remained cold. Thus we think it likely that the decrease in flexural rigidity is a consequence of part or all of the crust being detached from the Indian lithosphere. Since the material below the Main Central Thrust and above the Main Boundary Fault was once part of

---

**Fig. 12.** Calculated deflections of the plate for different positions, $X_0$, where the bending moment is applied and for the combination of parameters shown.

pulls the Indian plate down slightly, but exerts a torque to the end of the plate so as to apply a bending moment.

**Implications for the Tectonic Evolution of the Himalaya**

Several aspects of the structures required by the gravity anomalies carry implications for the geologic evolution of the Himalaya. If the flexure of the Indian plate is an appropriate description of its present configuration, then it probably was also when slip occurred on the Main Central Thrust. Therefore it seems likely that the present structure serves as a reasonable model for that that existed while the Main Central Thrust was active.

The suggestion that sediments deposited in the

---

**Fig. 13.** Three different structures yielding similar Bouger anomalies. Plot in lower right shows the interdependence between the bending moment and the flexural rigidity.
the Indian subcontinent, detachment of it must have taken place sometime in the past. Associating the steepened dip of the Moho with the thinning of the crust on the Indian lithosphere implies a throw of 100–130 km on the Main Boundary Thrust. Similarly, because the material above the Main Central Thrust was once part of the Indian subcontinent, it probably was detached from the Indian lithosphere on the Main Central Thrust earlier. To present these inferences in an evolving scheme for the geologic history of the Himalaya, we constructed a series of idealized balanced cross sections from before the collision to the present (Figure 15). Several assumptions were used to construct these cross sections: first, we assume that prior to the collision subduction of oceanic lithosphere occurred beneath southern Tibet much as it does beneath the Andes (Figures 15a and 15b). We arbitrarily began with a crustal thickness of 65 km beneath the Kangdese granites of southern Tibet. We do not know when the crust beneath southwestern Tibet thickened, but clearly, this assumption is not critical for the cross sections shown here. Second, we assumed that continental crust was not carried to great depth in the asthenosphere, so that the cross-sectional area of the crust must be conserved. In fact, subduction of the lowermost crust is a reasonable possibility [e.g., Molnar and Gray, 1979], but its exclusion here will not affect the major features of the cross sections much. Third, we drew both the Main Central Thrust and the Main Boundary Fault initially as planar faults through the crust (Figures 15c and 15d). For the Main Central Thrust we arbitrarily detached the crust at the Moho (Figure 15c) in order to make conservation of crustal material easier. Clearly, these faults could have begun as listric faults detaching the upper crust along a subhorizontal zone in the crust. It is not our purpose, however, to examine all possibilities but only the gross implications of a few simple assumptions. Fourth, we assume that throughout the period the Indian plate is flexed in a manner analogous to that inferred from the gravity anomalies. Therefore while slip occurred on the Main Central Thrust, the Moho dipped at a shallow angle where coherent lithosphere was underthrust and more steeply farther north where crust had been detached (Figure 15d). Finally, to maintain balanced cross sections, because the position of the Moho is fixed, we stacked the overthrust material up on top of this underthrusting plate, paying no heed to the elevations that such material would reach if there were no erosion (Figures 15c, 15d, and 15e). Notice, however that at the toes of both the Main Central Thrust and the Main Boundary Fault, we have schematically allowed a small amount of underthrusting of sediments. Unlike the rest of the cross sections, however, we have not balanced this portion. To compare with a typical geologic cross section (Figure 1), we show the final cross section (Figure 15e) eroded appropriately to the level of the present topography (Figure 15f).

We show simple underthrusting of oceanic lithosphere (Figures 15a and 15b) followed by collision and underthrusting of Indian crust beneath southern Tibet (Figure 15c). After 100 km
Fig. 15. Sequence of idealized cross sections from before the collision to the present. (a) Subduction of oceanic lithosphere before collision. (b) Initial contact of Indian margin with the subduction zone on the southern edge of Tibet. (c) Formation of the Main Central Thrust (MCT) after 100 km of subduction of part of the northern margin of India. (d) Formation of the Main Boundary Fault (MBF) after 125 km of underthrusting of India along the MCT. Note the marked uplift of material over the MCT. (e) Underthrusting of 125 km of India along the MBF. Note that again pronounced uplift occurs where the MBF changes dip. (f) Same as Figure 15e but with material eroded to the level of the present topography. Note that many features of the present Himalaya are present (see Figure 1): the overthrust sediments are analogous to the Siwaliks, the klippe of crystalline rocks transported by the MCT to the south is present, the MCT dips at a gentle angle to the south but more steeply to the north, the metamorphosed sediments in the Lesser Himalaya are domed slightly, and high-grade metamorphic rocks are present above the MCT.
Underthrusting Along The MCT And Formation of The Main Boundary Fault

125 km of Underthrusting

Fig. 15d

Underthrusting Along The Main Boundary Fault

125 km of Underthrusting

Fig. 15e

Analogy With Present Geologic Structure

Fig. 15f
of convergence, we arbitrarily let slip begin on the Main Central Thrust (Figures 15c and 15d). By insisting that the shape of the Indian plate be similar to that inferred above from the gravity anomalies, both the slice of crust that once was the northern margin of the Indian subcontinent and part of accretionary prism are uplifted (Figure 15d) and presumably are eroded. After (an arbitrarily selected amount of) 125 km of underthrusting, we let slip begin on the Main Boundary Fault (Figures 15d and 15e). Again, requiring a shallow dip, this leads to a large uplift in the Central Himalaya (Figure 15e).

When we remove material that must be eroded in order to achieve a topographic profile similar to those across the Himalaya, several aspects of the hypothetical geologic structure are similar to those in the Himalaya today (Figure 15f). The klippe of crystalline rocks inferred to have been carried by the Main Central Thrust where it dips at a shallow angle southward into a gentle syncline is shown overthrust onto sediments analogous with the Siwaliks [e.g., Gansser, 1964; Heim and Gansser, 1939]. The gentle doming of metamorphosed sediments in the Midland terrain of the Lesser Himalaya [e.g., Hashimoto et al., 1973; Pecher, 1978] is present, underlying the Main Central Thrust where it dips steeply (30°) to the north. The high-grade terrain over the Main Central Thrust [e.g., Hashimoto et al., 1973; LeFort, 1975; Valdiya, 1981] is shown as material once buried about 30 km beneath the northern margin of the Indian subcontinent. If this interpretation were correct, the high metamorphic grades would not be due to heating during Tertiary orogenesis but would be simply due to transport of lower crustal material to the surface, as inferred by Bordet [1961] and Valdiya [1980]. (Such an inference is not inconsistent with the existence of the late Tertiary tourmaline granites in the Himalaya, if these granites formed below the Main Central Thrust or if the melting temperature in the crust is very low [Molnar et al., 1983].) Hence several aspects of the gross structure of the Himalaya are reproduced in Figure 15f.

Numerous palynological and paleontological studies by Chinese scientists in the Tibetan Himalaya have turned up evidence suggesting rapid uplift of this region [Quo, 1981; Li et al., 1981; Song and Liu, 1981; Xu, 1981; Zhang et al., 1981]. Such results are often generalized to include the whole of the Tibetan plateau, but it appears to us that the least equivocal data are from high altitudes on the north slope of the Greater Himalaya. Rapid uplift is also reported at the foot of the Lesser Himalaya (work of R.S. Chugh as cited by Molnar et al. [1977]). Chugh presented changes in elevation from relieving of one line from the Ganga Basin into the Lesser Himalaya in the northwestern Himalaya. The measured rate of uplift is a maximum of about 5 mm/yr at the crossing of the Main Boundary Fault and decreases both north and south. We are not aware of evidence for rapid uplift in most of the Lesser Himalaya, however.

Notice that the sequence of cross sections in Figures 15e and 15f imply that uplift of the Greater Himalaya should be large. If the dip of the top surface of the Indian plate beneath the Greater Himalaya is φ (=20-30°) and the rate of convergence in the Himalayas is v = 10 to 20 mm/yr, then the rate of uplift is v = v̇ sin φ = (5 to 12 mm/yr). Similarly, if the system of faults that compose the Main Boundary Fault at the foot of the Himalaya are listric [e.g., Seeba et al., 1981], then rapid uplift should occur there. The cross sections in Figures 15e and 15f, however, do not call for uplift in most of the Lesser Himalaya or of the Tibetan plateau.

Finally, we estimate the amount of material eroded from the cross section in Figure 15f to be 4.44 x 10^7 km^3. If this number were representative for the whole of the Himalaya, about 2000 km long, then this estimate implies that 8.88 x 10^7 km^3 of material have been eroded from the Himalaya. Let us compare this with some estimates of sediments nearby. If we assume a mean thickness of sediment in the Ganga Basin of 2 km, a width of 250 km, and a length of 2000 km, there are about 10^9 km^3. Curray and Moore [1971] estimated a volume of sediments above a well-defined horizon in the Bay of Bengal to be about 10.1 x 10^8 km^3. Later they assigned a Paleocene age to this horizon [Curray et al., 1982]. Therefore most of these sediments postdate the collision. The combination of the Ganga Basin and the Bengal fan contain 11.1 x 10^7 km^3. If we assume that the density of these sediments is 90% of the eroded crustal material, then this value should be reduced to 10 x 10^7 km^3, a value remarkably close to that estimated to have been eroded from the hypothetical cross section in Figures 15e and 15f, and that agreement certainly lends support to it.

Although we would have been satisfied with a greater difference between volumes of material eroded from the hypothetical cross sections and deposited in the Ganga and Bengal basins, it is worth noting some items that have been ignored. The Arabian Sea also contains sediments from the Himalaya, via the Indus River and its predecessors. The present transport of suspended material of the Indus River is about 1/5 that of the Ganga-Bramaputra [Curray and Moore, 1971] so that if this rate were representative of the entire history of the Himalaya, we might add about 2 x 10^7 km^3 to the value of sediments. At the same time, but choosing a length of 2000 km for the Himalaya, we have neglected about 500 km of the range now drained by the Indus River. Then ignoring the Indus River and the region that it drains might modify all of the agreement between hypothetical erosion and sediment volume. Finally, the slightly larger value of sediment than calculated erosion is consistent with a small amount of erosion of southern Tibet. Since we cannot estimate useful uncertainties in the amounts of sediment volume or the amounts of erosion and since the cross section in Figure 15f is only one among a large family of possibilities, these comparisons should be taken only as evidence supporting the general aspects of the cross sections and not the details.

The final cross section in Figure 15f is an oversimplification and is imperfect in many ways. It neglects numerous thrusts in the Lesser Himalaya [see Valdiya, 1981], and it does not portray the structure of Greater Himalaya and Indus-Tsangpo suture as it is shown in cross sections such as that of Bally et al. [1980]; Franke et al. [1977]; Gansser [1964, 1977]; and LeFort [1975]. We have not been concerned as much with this partly because of the variation along strike in the Himalaya and because of the clear evidence for northward reverse
or back thrusting in the Greater Himalaya. Finally, notice also that we have allowed for further detachment of deeply thrust crust by attaching the subducted crust beneath southern Tibet in Figure 15c to the base of the Moho in Figure 15f. The reader will probably note aspects of the cross sections that are artifacts of the simplistic and limited number of assumptions made. For instance, if we began in Figure 15a with a thinner crust beneath the Kandse geese granite in southern Tibet, we could underthrust more Indian crust beneath these than we did in Figure 15c. This addition of material could then cause an uplift and denudation of the cover. Clearly, numerous variations are possible. Moreover, the reader should not assume that 125 km of underthrusting along the Main Central Thrust is a precise estimate or that the equality of values used here for the Main Central Thrust and Main Boundary Fault implies that slip on the Main Boundary Fault will soon stop. These cross sections are meant to be cartoons drawn quantitatively accurately in order to explore qualitatively some aspects of the geology. Nevertheless, the rather small amount of material shown underthrusting southern Tibet and the Himalaya (350 km) compared with the total penetration of India into Eurasia since their collision (2000-3000 km) is consistent with most of this penetration being absorbed north of the Himalaya [Molnar and Tapponnier, 1975].

Summary

The flexure of the Indian plate is a plausible mechanism to support the mass of the Himalaya. The flexural rigidity of the plate beneath the Ganga Basin and the Lesser Himalaya is about 0.7 (±0.5) x 10^22 N m. A plate of constant flexural rigidity cannot underthrust the entire Himalaya. The plate must lose a considerable amount of its strength about 130 km north of the Himalayan front, where the Main Central Thrust crops out. Moreover, a bending moment must be applied to the end of the plate in order to compensate for the large weight of the Himalayan Mountains. These features are required by the gravity anomalies, which show that the dip of the Moho increases from about 3° beneath the Ganga Basin and the Lesser Himalaya to about 15° beneath the Greater Himalaya (for $\alpha = 0.55 \times 10^3$ kg/m^2).

Both the decrease in flexural rigidity at the Greater Himalaya and the bending moment can be understood if we assume that beneath the Greater Himalaya part or all of the Indian crust has been detached from the lower part of the Indian lithosphere, probably after warming and weakening of the plate during the collision process. Gravity acting on the cold sinking mantle material then is a possible cause of the bending moment. Although gravity anomalies allow this interpretation, the existence of such a cold material beneath the range is not demonstrated and is a possibility that needs further study.

Although the model studied here is simplistic in many ways, idealized balanced cross sections constrained by the above results reproduce various important aspects of the geology of the Himalaya. The estimated amount of eroded material is in good agreement with the volume of sediments that are thought to be derived from the Himalaya. The cross sections suggest that the high-grade metamorphic terrain over the Main Central Thrust is due to transport of lower crustal material to the surface and not to heating during the orogenesis. They also predict a large uplift only at the foot of the range and in the Greater Himalaya. The methods used here and the cross sections derived suggest that simple mechanical models coupled with classical techniques of structural geology can be combined to yield realistic models of the structure and dynamics of overthrust belts.

Acknowledgments. We thank B. G. Burchfiel for acquainting us with balanced cross sections and P. Bird for a thorough, constructive review. This research was supported by NSF grant EAR 8121184 and NASA grant NAG 5-41.

References

Amboldt, N., Relative schwerekraftsbestimmungen mit pendeln in Zentral Asien, 2 reports from scientific expedition to northwestern provinces of China under leadership of Dr. Sven Hedin, Publ. 30, II Geodes., Truckerf Aktiebolaget Thule, Stockholm, 1948.


Tang B., Liu Y., Zhang L., Zhou W. and Wang Q.,


(Received June 23, 1982; revised June 13, 1983; accepted June 16, 1983.)