PLATE TECTONICS AND THE HIMALAYAN OROGENY: A MODELLING STUDY BASED ON GRAVITY DATA

by

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ABSTRACT

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Submitted to the Department of Earth and Planetary Science
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Since the discovery of the theory of isostasy in 19th century, gravity data in Himalayas have been interpreted by assuming that some kind of equilibrium prevails in the mountain ranges and the topography is supported by forces acting in the vertical direction. Contrary to this, the plate theory of global tectonics attributes Himalayan orogeny to the collision of the Indian and the Eurasian plates. In the present study, an attempt has been made to analyse gravity data in Himalayan region, in conjunction with other geological and geophysical information available, using the concepts of rigid plate motions.

Several simple gravity models are constructed across the Himalayas where observed large negative Bouguer anomalies are reproduced by the underthrusting of continental crust along the Indus Suture Zone, the Main Central Thrust and the Main Boundary Fault. These models are conjectural as the data do not exist over the Tibetan Himalayas and the Tibetan plateau. It is, however, possible to infer with a fair degree of confidence that the continental underthrusting at the Main Central Thrust takes place at very shallow angles, around 15°. The total amount of underthrusting of the Indian shield across Himalayas may be about 375 Km. The models considered here imply an under-compensation or thinner 'roots' below the Lesser and the High or Great Himalayas. The Tibetan Himalayas and a part of the southern Tibetan plateau seem to be over compensated. A broad gravity high over Central India resembles the gravity highs observed over the outer rises on the seaward side of the oceanic trenches and may be due to a bending of the Indian shield. In conclusion, the present study indicates that the plate theory may be a plausible mechanism to account for the Himalayan orogeny.

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CHAPTER I

INTRODUCTION

Convergence zones of island arc and cordilleran type are now well understood and lend valuable support to the theory of 'plate tectonics'. In the continental convergence zones, of which Himalayas are considered to be the type example, the nature of subduction is, however, less clear. In Himalayas the seismicity is very shallow and diffused over a large region (Barazangi and Dorman, 1969) and it is difficult to delineate the underthrusting lithosphere beneath the mountains. Large scale vertical and horizontal movements, that took place during Himalayan orogeny, have obliterated many records of geologic and tectonic evolution of the region. Also, at places certain complexities such as reverse metamorphism in the normal geological sequence (Gansser, 1964) in the Himalayas may be due to such movements. Yet another handicap in studying Himalayas is the meagreness of the geological and geophysical data. Nevertheless, the available information permits us to at least understand the tectonics of the Himalayan region in a broad manner.

Among a wide variety of hypotheses about Himalayan orogeny, the major contestants have been the geosynclinal theory and the continental collision or the continental drift theory (Holmes, 1966). Increasing geological information has led many geologists to believe that the main Himalayan ranges are not made up of uplifted Tethyan geosynclinal rocks but were formed by an activation of the northern part of the Indian shield (Gansser, 1964; Wadia, 1966; Ahmad, 1968). Qureshy (1969) suggests that the large scale vertical movements due to phase changes in the upper mantle, dominate the scene of Himalayan uplift. He thinks that recumbent folding and nappe formation have been of secondary nature and are associated with the gravity gliding.

The concept of continental collision causing the uplift of the Himalayan mountains is not a new one and has existed for quite some time (Aragand, 1924 ; Holmes, 1966) but a new insight into the continent-continent collision was gained with the discovery of sea floor spreading which led Isacks et al (1968) to propose the theory of 'new global tectonics' based on rigid plate motions. They accepted, in principle, to describe the tectonics of Eurasia by the interaction of continental blocks. McKenzie (1969) calculated that the buoyancy effect of the light crust would resist the subduction of continental lithosphere and instead mountains would form by folding and faulting of the crust before the driving forces reorient themselves. Dewey and Bird (1970) suggested that Indus Suture Line in the north of the Great Himalayas is the relic of oceanic subduction before the continents collided. In their openion, crustal thickening in Tibet is a consequence of the continental collision. Earlier, Holmes (1966) postulated the underthrusting of the Indian crust beneath the Himalayas and Tibet due to some kind of current system in the mantle causing the great elevation of the region. Powell and Conaghan (1973) account for a presumed double crustal thickness and an uplift of 5 Km in Tibet by underthrusting Indian shield beneath the Tibetan plateau. They suggest that after suturing of the continents, Main Central Thrust formed and underthrusting took place along it. Dewey and Burke (1973) suggested that the widespread volcanic activity over the southern Tibetan plateau is a result of the thickening of crust after the collision, which gives rise to partial melting in the lower part of the crust. So far, no precise mechanism has been offered for the crustal thickening underneath Tibet. Moreover, the plate theory as applied to Himalayas has met with certain criticisms. According to Meyerhoff(1970), extension of Gondwana sediments into western Tibet contradicts the idea of subduction at the Indus Suture Zone. Crawford (1974) opined that the Himalayas are of intra-continental origin and the Tibetan plateau is the northern part of Gondwanic India. He suggested that the boundary of Indian plate lies further north , probably along Tien Shan mountains.

In the present study, an attempt is made to analyse some gravity data in the Himalayan and Indian shield regions along with other available information to see if the plate theory provides a viable mechanism to explain Himalayan tectonics. It seems plausible to account for the gravity anomalies over the Himalayas and the Indian shield in terms of continental underthrusting to shallow depths along the Himalayan axis. The plate models constructed here do not support the theory of thick 'roots' underneath all of the Himalayas. The Middle or Lesser and the High or Great Himalayas have relatively thinner 'roots' and are under compensated. The Tethyan or Tibetan Himalayas and southern Tibet plateau, on the other hand, may be over compensated.

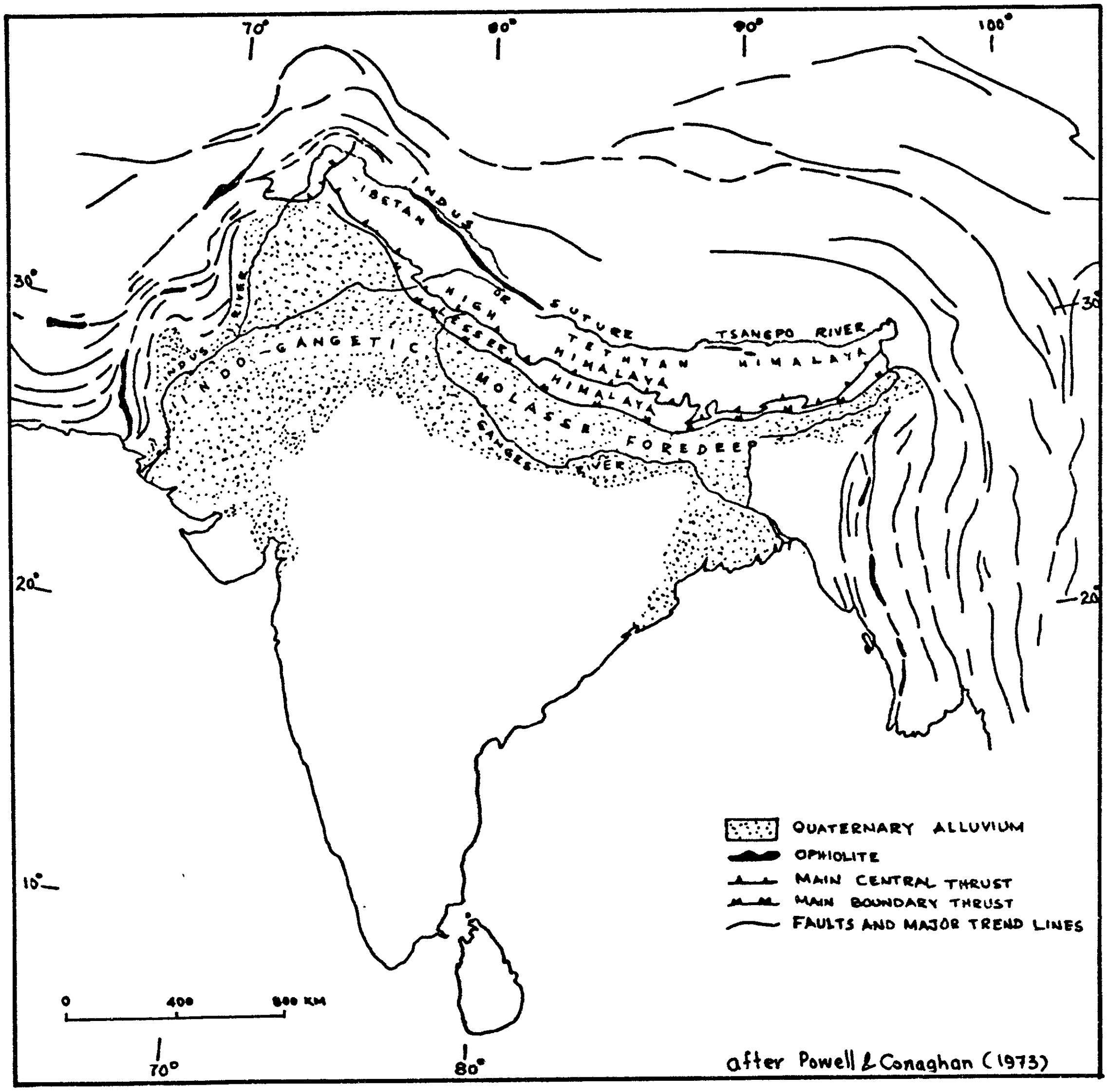
CHAPTER II

TECTONIC SETTING

The Himalayan range extends for about 2500 Km from Nanga Parbat in the northwest to Nemcha Barwa in the east. There are two syntaxial bends, one in the northwest around which mountain ranges swing sharply towards south and continue into the Kirthar-Sulaiman ranges which further connect with the Owen Fracture Zone through the Murray ridge (Nowroozi, 1972). The second knee bend is around 28°N , 97°E where commence the Arakan-Yoma ranges of Burma, which possibly continue into the Indonesian archipelago through Andaman-Nicobar islands (Krishnan, 1953). Le Pichon (1968) calculated that the Indian plate is moving in a northerly direction at a rate of about 5 cm/year and being underthrust beneath Himalayas. The western boundary of the plate is a transform fault and is marked by the Owen Fracture Zone and the Kirthar-Sulaiman ranges (Abdel Gawad, 1971).

Figure I shows the disposition of various tectonic features of the region of study. Geological mapping in the Himalayas has brought out three major tectonic elements :

1. Main Boundary Fault :- This is the youngest of the thrust fault systems. It passes along the foot hills of the Himalayas. South of it lie the low altitude and flat Gangetic basin filled with Tertiary to Recent molasse and the Siwalik hills. Further south of the Gangetic basin lie the plateaus of Central India and the



after Powell & Conaghan (1973)

Figure 1

stable land mass of the Indian shield. Gansser (1964) considers the Main Boundary Fault to be a very shallow dipping thrust which flattens at depth. Middlemiss (1919) mapped the thrust plane between the Murree and the Siwaliks and obtained dips of $10^\circ - 15^\circ$ to the north.

2. Main Central Thrust :- This thrust separates the crystalline rocks, mostly gneiss and granite, of the Great or the High Himalayas in the north from the Lesser or the Middle Himalayas characterized by exposures of unfossiliferous Precambrian and Palaeozoic sediments in the south. Geological mapping indicates a dip of about 30° of this thrust (Gansser, 1964; Powell and Conaghan, 1973).

3. Indus Suture Zone :- This zone comprises Cretaceous to Eocene radiolerites and ophiolite bearing flysch and separates the Tibetan plateau from the Tibetan or Tethyan Himalayas which are made up of Cambrian to Eocene fossiliferous sediments.

After the break-up of Gondwana, the Indian plate moved northward and it is believed that oceanic subduction took place at the Indus Suture Zone until the continental collision took place during the Eocene (Dewey and Bird, 1970; Powell and Conaghan, 1973; Molnar and Tapponnier, 1975). The suturing of the continents resulted presumably because the buoyancy of the continental crust did not permit much further subduction. Eventually the Main Central Thrust developed and underthrusting began again around mid-Miocene (~20 m.y.). The Main Boundary Fault seems to have developed later and probably displacement has not been much along it.

Gansser (1966) estimated a crustal shortening of the order of 500 Km due to the underthrusting in the Himalayas. On the other hand, Powell and Conaghan's model implies a crustal shortening of 1,500 Km in order to double the thickness of the crust underneath Tibet.

CHAPTER III

PREVIOUS GRAVITY AND OTHER GEOPHYSICAL INVESTIGATIONS IN HIMALAYAS

The first geophysical investigations in Himalayas date back to the Great Trigonometrical Survey by Sir G. Everest which led Pratt (1855) and Airy (1855) to propound the two theories of isostasy. Following this survey, a large number of plumb line deflection and the pendulum stations were observed over Himalayas and Gangetic basin in the late 19th and early 20th centuries. Burrard (1901, 1912, 1918) suggested the folding of the Himalayan belt due to a subcrustal flow of mass from underneath the Indian shield towards the Eurasian side which accompanied underthrusting of the Indian continent. He described the gravity low over Gangetic basin due to the light sediments deposited in a rift valley. According to him, the gravity high and the region of zero deflection over Central India is due to a subcrustal 'hidden range' of high density. Oldham (1917) found Burrard's idea of a rift valley unlikely and inferred a gradually northward sloping floor underneath the Gangetic basin. He estimated a maximum thickness of sediments of the order of 4.5 - 6.0 Km to lie along the foot hills. A similar figure of 6 Km was obtained by Cowie (1921) for the thickness of the sediments. Oldham also believed that the isostatic compensation prevailed in the mountain ranges. Burrard (1918), however, attributed the positive isostatic anomaly over the Great Himalayas to incomplete compensation. Glennie (1932) invoked the hypothesis of crustal upwarping and downwarping of the crust to account for the positive anamaly over Central India and negative anomaly over the Gangetic basin respectively.

After the beginning of the systematic gravitymeter observation in India, Gulatee (1958) investigated the isostatic equilibrium in Himalayas and found that the mountains had not yet reached the equilibrium. Qureshy (1969) and Qureshy et al (1974) suggested the Middle Himalayas to be in equilibrium and interpreted the positive isostatic anomaly in terms of a thick basaltic 'root' extending to a depth of 72 Km underneath. Kono (1974), after a gravity investigation in eastern Nepal Himalayas, suggested that the crust underneath is much thinner and as such the mountains are out of equilibrium. Choudhury (1975) obtained a crustal thickness of 72 Km underneath the Great Himalayas on the basis of gravity data.

There are several body wave and surface wave studies which indicate crustal thickness in the Indian shield region to be of the order of 30 - 35 Km. Crustal thickness increases underneath Himalayas and is often assumed to be of the order of 60 - 70 Km in the Tibet region. Tables I and II present a summary of the body wave and the surface wave studies respectively.

Some valuable information is now available from the focal mechanism studies of Himalayan earthquakes (Fitch, 1970 ; Tandon, 1972 ; Molnar et al, 1973 ; Rastogi et al, 1973). The dominant mechanism in the Himalayan region is thrusting along northerly to northeasterly dipping planes. Molnar et al (1973) inferred thrusting at shallow angles, less than 30°, for Himalayan earthquakes. There is some evidence that the Indian shield bends in front of the Himalayan arc as suggested by one mechanism south of the Main Boundary Fault. Tibet, however, is characterized

TABLE 1

thor(s)	Sedimentary Layer		Granite Layer 1		Granite Layer 2		Basalt Layer		Sub-Moho	Depth to Moho Km	Region	Source
	V_p	T	V_p	T	V_p	T	V_p	T	V_p			
y (1939)	-	-	5.26	14.8	-	-	6.21	25.4	7.80	40.2	Gangetic basin	Bihar earthquake(1934)
kravorty & osh(1960)	-	-	5.30	16.5	-	-	6.30	21.6	7.70	38.1	Himalayan region	near earthquakes
ouhan & ngh(1965)	-	-	5.50	26.0	-	-	6.60	26.0	7.80	52.0	Himalayan region	near earthquakes
ila et al 68)	2.70	6.0 ±1	6.20 ±.1	8.0 ±5	-	-	6.90 ±.1	14.0 ±7	8.20 ±.1	28.0 ±8	Himalayan foothills and Gangetic basin	Shallow earthquakes $\Delta < 650$ Km
ora(1971)	-	-	5.67 ±.1	16.0	-	-	6.51 ±.1	19.0	7.98 ±.1	34.7	South Indian shield (13° N, 77° E) around GBA array	Rock bursts and shallow earthquakes 25 Km $<$ $\Delta < 150$ Km
ndon and be(1973)	-	-	5.48 ±.02	23.1	6.0 ±.06	15.3	6.45 ±.02	18.4	8.07 ±.05	56.8	Himalayan region	Surface earthquakes $\Delta < 10^\circ$
rma(1974)	-	-	5.92 ±.03	12.8	-	-	6.80 ±.03	15.6	8.00 ±.03	30.1	Himalayan foothills and Gangetic basin	Shallow earthquakes in Himalayan foothills

= P wave velocity in Km / Sec.   T= Thickness of the layers in Km.

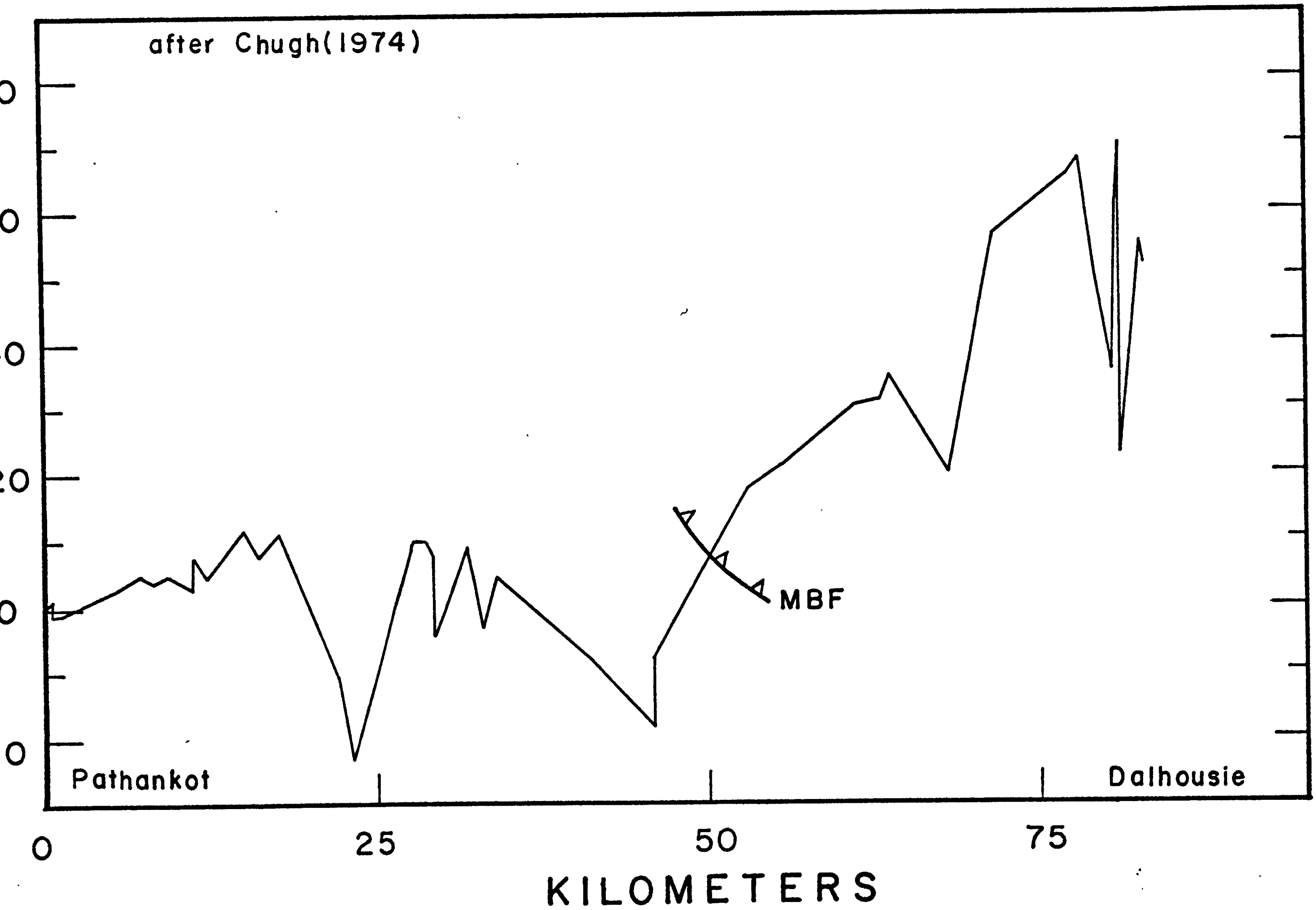
TABLE II

Author(s)	Crustal Thickness	Region	Source of data
Saha (1964)	45 Km	Novaya Zemlya-New Delhi path	Average crustal thickness using Rayleigh wave (M_2) dispersion from Soviet nuclear explosion of October 30, 1961
Gabriel and Kuo (1966)	38 Km	New Delhi-Lahore profile	Rayleigh wave phase velocity measurements using earthquakes in the Gulf of California and near Ecuador - Peru border
Gupta and Narain (1967)	65-70 Km	Himalayan and Tibet plateau region	Rayleigh wave group velocity measurements using Arctic region earthquake of August 25, 1964 recorded at Quetta, New Delhi, Shillong, Hong Kong and Seoul
Negi and Singh (1973)	50-55 Km	Himalayan and Tibet plateau region	Love wave group velocity measurements using Arctic region earthquake of August 25, 1964 recorded at New Delhi

by normal faulting along north-south oriented fault planes. These data are consistent with a northerly to northeasterly orientation of compression in the Himalayas and Tibet.

There has been some effort to measure the contemporaneous movements instrumentally along the thrust planes of Main Boundary Fault system. The studies are not conclusive as the data considered are for a very short interval (Agrawal and Gaur, 1972 ; Sinvhal et al, 1973). It may take a while before a significant trend is observed. However, the Survey of India has been carrying out levelling surveys for the past two centuries in the region and many lines have been repeated several times. Figure 2 shows a twelve year levelling data of a first order levelling line in northwestern Himalayas, running from Pathankot in the southwest to Dalhousie in the northeast (Chugh, 1974). A general increase in the elevations is seen to the north of the Main Boundary Fault whereas a sinkage is observed in Gangetic basin. The average uplift in the north of the Main Boundary Fault seems to be very large for a twelve year period (~ 0.4 to 0.5 cm/year) whereas the southern part has remained relatively stationary. Such an uplift along a shallow dipping thrust (10° - 15°) would imply a slip rate of the order of 2 cm/ year.

Figure 2



after Chugh(1974)
MBF
Pathankot
Dalhousie
0
25
50
75
KILOMETERS

CHAPTER IV

CONSTRUCTION OF TWO DIMENSIONAL CRUSTAL MODELS IN THE HIMALAYAS USING GRAVITY DATA

The Data :

During the past two decades, a large amount of gravity observations have been gathered in India, and an extensive gravity coverage is now available over the Indian shield and the Gangetic basin. A few traverses in the Himalayas are also available now. The Tibetan plateau, however, is not well surveyed. In the present study $1^\circ \times 1^\circ$ mean free air and Bouguer anomalies have been considered which are based on more than 31,000 observations made in 480 one degree squares. These observations were made by the Survey of India, Dehra Dun, the Geological Survey of India, National Geophysical Research Institute, Hyderabad and the Hawaii Institute of Geophysics. Some published data of Oldham (1918, 1923), Helbig and Thirlaway (1961), Farah and Ali (1964) and McGinnis (1971) have been incorporated in the northwest region of Hindu Kush, Afghanistan and Pakistan. A part of the gravity observations were made by the author while working with the National Geophysical Research Institute, Hyderabad, India. One degree mean anomaly values used in this study are tabulated in the Appendix.

Figure 3 shows the $1^\circ \times 1^\circ$ mean free air anomaly map of India and the contiguous region. The anomalies are based on the International Gravity Formula, 1930. The anomalies over the shield region are of the order of ± 40 mgals

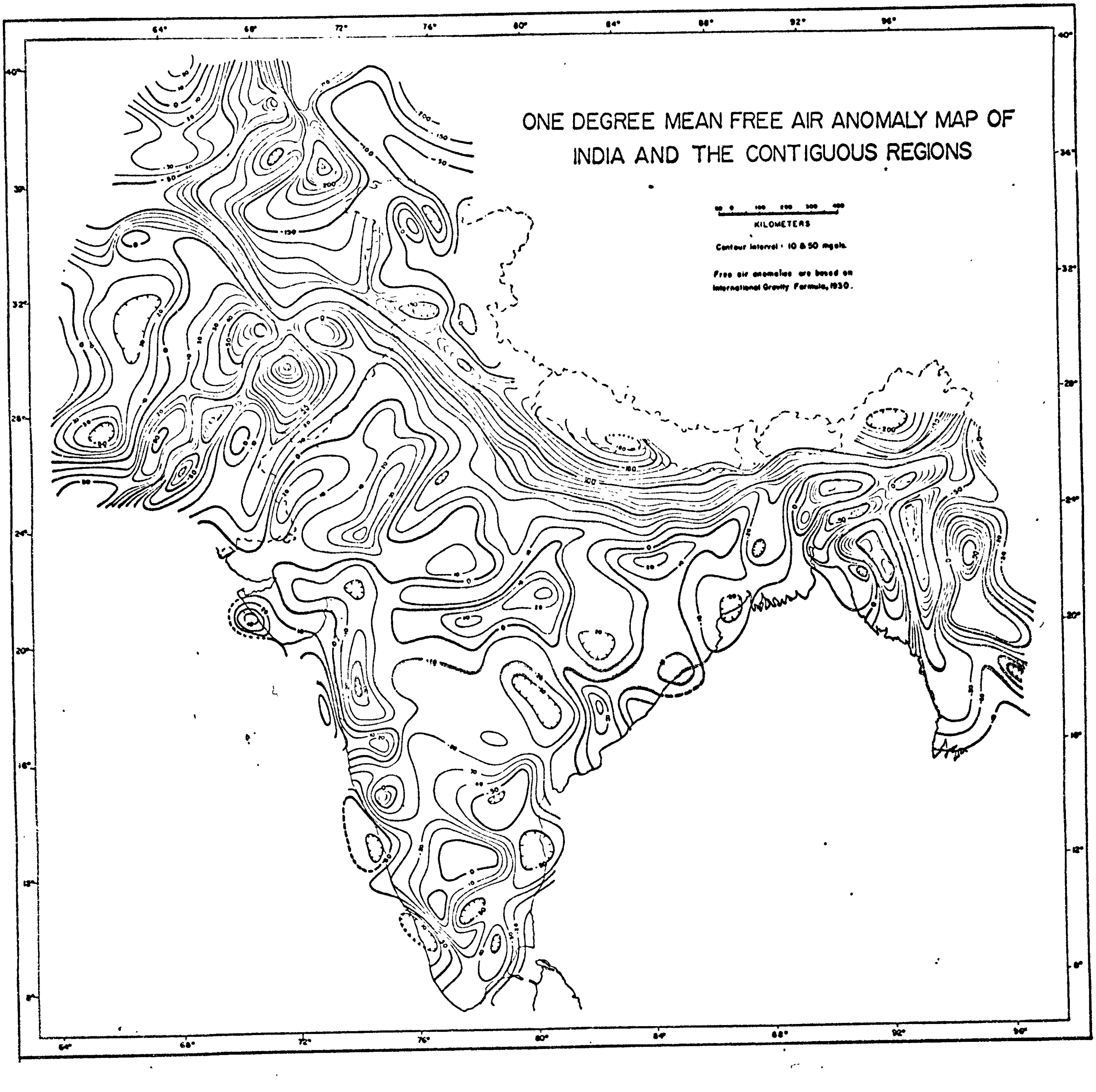

ONE DEGREE MEAN FREE AIR ANOMALY MAP OF INDIA AND THE CONTIGUOUS REGIONS
50 0 100 200 300 400
KILOMETERS
Contour Interval : 10 & 50 mgals.
Free air anomalies are based on International Gravity Formula, 1930.
64°
68°
72°
76°
80°
84°
88°
92°
96°
40°
36°
32°
28°
24°
20°
16°
12°
8°
200
150
100
50
0

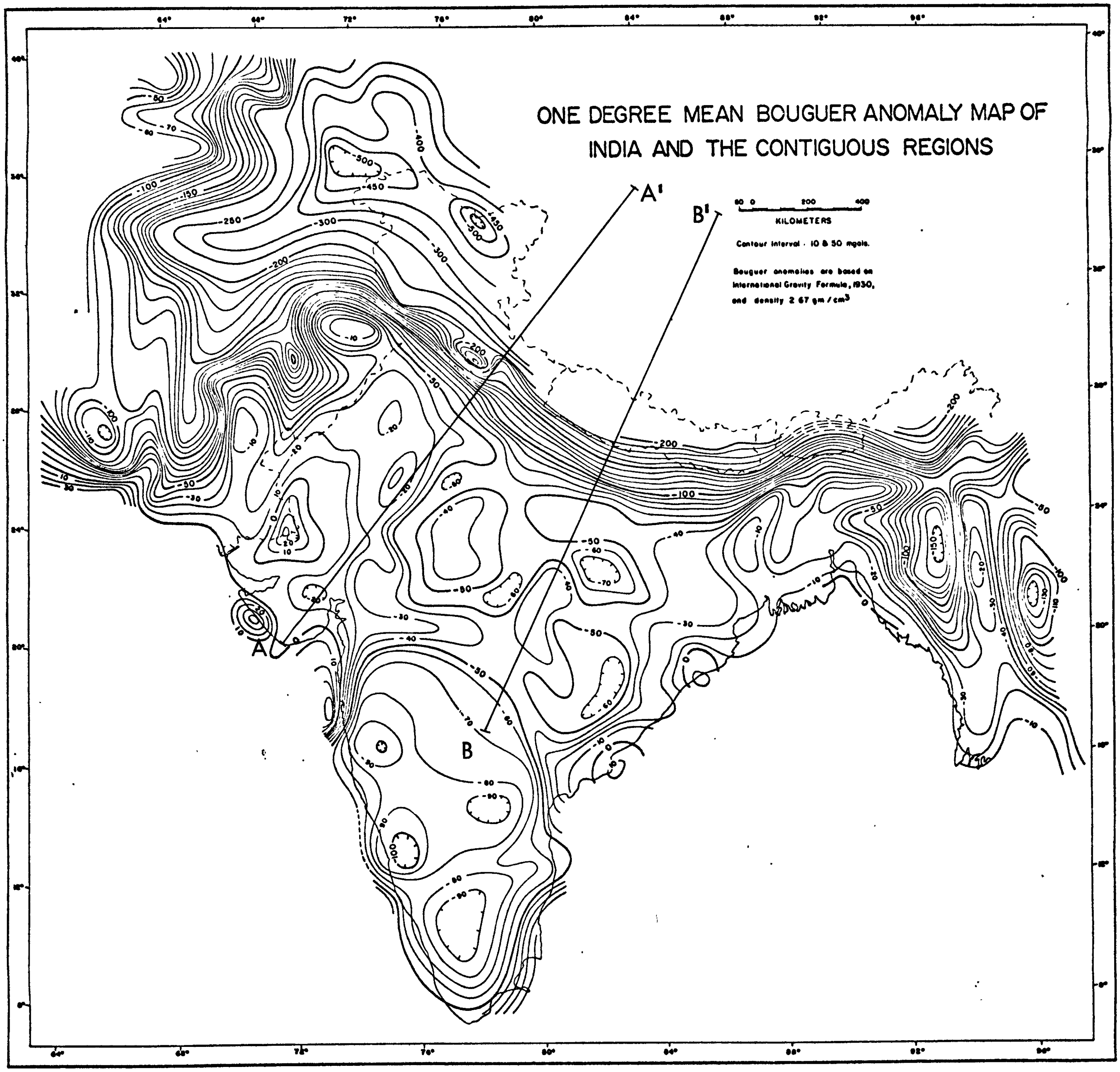
Figure 3

whereas extra-peninsular regions show large variation. The Gangetic basin and the southern part of the Indian shield are characterized by low free air anomalies and are separated by a zone 'high' anomalies which has an average relief of 50 mgals.

Figure 4 shows the 1° x 1° mean Bouguer anomaly map of the same region. The Bouguer anomalies were computed by assuming a correction density of 2.67 g/cm^3 for the Bouguer slab. Topographic corrections, which may be as high as 40 mgals in the Great Himalayas, have not been applied. Similar to the free air anomaly map, the Gangetic basin on the Bouguer anomaly map is characterized by northward decreasing anomalies which decrease further over the Himalayas and have a minimum of the order of - 575 mgals over the Tibetan plateau. Bouguer anomalies over the south Indian shield are also negative with a minimum of - 100 mgals and are separated from the Gangetic basin low by a 700 - 800 Km broad gravity high zone similar to the one seen on Figure 3. The average relief of this 'high' on Bouguer anomaly map is about 20 mgals. This gravity high may have some relevance to the convergence of the Indian and the Eurasian plates.

Crustal Structure and the Density value used in computing the models :

The crustal structure of the Indian shield is based on the body wave data as given in Table I in Chapter III. A two layer model with a total crustal thickness of 30 Km (13 + 17) has been adopted for the present analysis. The density



ONE DEGREE MEAN BOUGUER ANOMALY MAP OF INDIA AND THE CONTIGUOUS REGIONS

Contour Interval · 10 & 50 mgals.

Bouguer anomalies are based on International Gravity Formula, 1930, and density 2 67 gm / cm^3

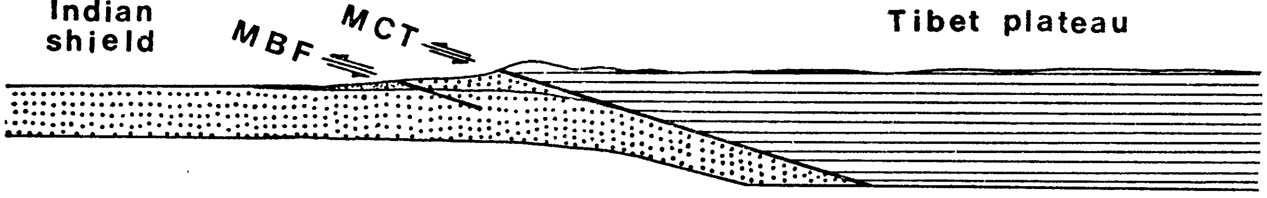
density values are obtained from seismic velocities using the Nafe - Drake experimental curve (Talwani et al, 1959). The crustal structure in the Tibet region is not very well known. Surface wave studies in Table II of the last chapter are consistent with a crustal thickness of the order of 60 - 70 Km . For the present study a 60 Km of thick crust has been assumed underneath Tibet with an average density of 2.80 g/cm^3 which makes the weight of the Tibetan standard column to a depth of 125 Km below mean sea level equal to the weight of Indian standard column extending to the same depth. The density values for the two crustal layers of Indian shield are 2.70 and 2.90 g/cm^3 respectively and a value of 3.35 g/cm^3 is adopted for the subcrustal material. As will be seen after the computations, neither the density nor the thickness of the Tibetan block is very critical for the present analysis. The gravity effect of this block on a point at the Great Himalayas, which is the northern limit of the observed data, does not exceed 15 - 20 mgals.

Underthrusting along the Main Boundary Fault is presumably much less as compared to that along the Main Central Thrust (Gansser, 1964). It is likely that the underthrusting along the Main Boundary Fault controlled the Pliestocene to Recent deposition in the Gangetic basin. Sastri et al (1971) studied the geological and geophysical data over the Gangetic basin, collected in connection with oil exploration, in great detail. A large part of the basin is very shallow and its floor slopes very gently (1° to 2°) towards north. A little south of the foot hills, the floor of the basin steepens further and the maximum thickness of sediments ~~lies~~

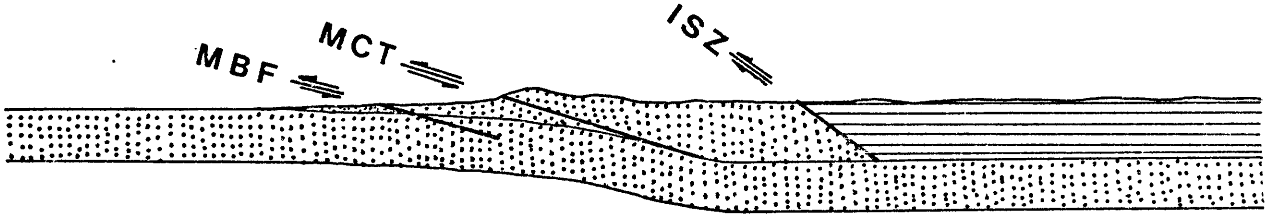
lies very close to the Main Boundary Fault. Several drill holes have confirmed that mainly post Miocene to Recent sediments were deposited on the Archean or perhaps Precambrian to Cambrian (Vindhyan) basement. The presence of Mesozoic sediments is not confirmed. In a deep bore hole close to India - Nepal border, a total thickness of about 4 Km sediments lying above the unconformity has been discovered (Mathur and Evans, 1964). For computational purposes the Vindhyan formation below the Gangetic alluvium is considered a part of the shield and not of the sediments. These are very old and compact sediments dating back to Precambrian age and comprise marine limestones, high density sandstones and quartzites. These sediments, possibly, do not contribute to the gravity effect significantly because the Vindhyan exposures in the south of the Gangetic basin show only a slightly negative anomaly (~20 - 25 mgals) along the synclinal axis of the deposition (Qureshy and Warsi, 1975). With a density contrast of 0.37 g/cm^3 with the upper crust, the sediments produce a negative anomaly of the order of - 60 mgals above the deepest part of the Gangetic basin whereas the observed anomaly is of the order of - 160 to - 180 mgals. The remaining effect of about - 100 mgals obviously comes from the underthrusting of the continental crust or the 'roots' of the Himalayas in the conventional sense.

The Gravity Models :

Four types of models, as sketched in Figure 5, have been considered for two dimensional gravity computations. These models are constructed along the


Indian shield
MBF
MCT
Tibet plateau

B.


MBF
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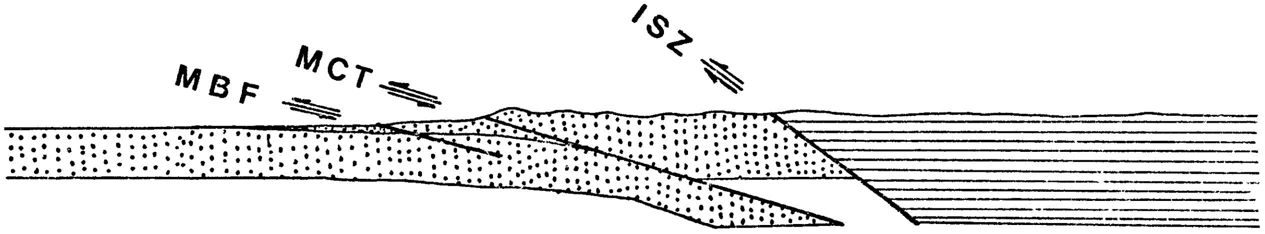
ISZ

C.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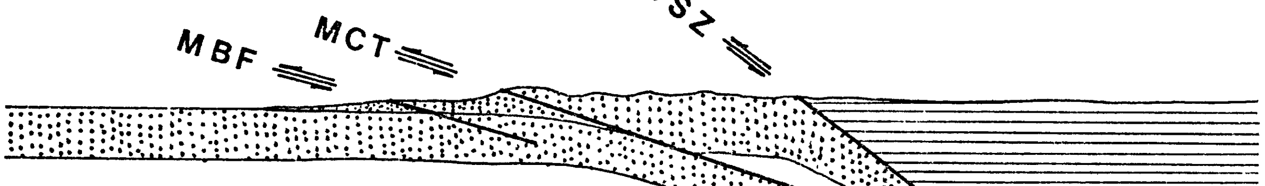
D.


MBF
MCT
ISZ

profile AA' shown in Figure 4. Bouguer anomalies have been considered for the modelling using one degree mean values up to the foot hills and published data of Qureshy et al (1974) in Garhwal - Kumaon Himalayas along this profile. However, further north over the Tibetan plateau, there exists a single station (Ambolt, 1948) which provides a valuable control. One degree averages were preferred for the shield region in order to get rid of the large scale variations due to suface geology. To construct these models, Talwani's method to compute the gravity effect of two dimensional polygons, was used. Also, the following assumptions were made to calculate these models :

1. The Indian shield and the Tibetan plateau, away from the mountains, are in isostatic equilibrium. The Indian shield, in general, appears to be in isostatic equilibrium as can be seen from the free air anomaly map in Figure 3. Most of these anomalies are of low relief and explainable in terms of surface geology and local elevations. Recent deep seismic sounding work in south India also supports this assumption (Anonymous, 1974). There are only two stations over the Tibetan plateau (Ambolt, 1948). These stations show near zero free air anomaly. The fact that a large flat region uplifted to a uniform height of 5 Km and characterized by near zero free air anomaly suggests that Tibet is probably in isostatic equilibrium.
2. The major part of the negative anomalies observed over the Gangetic basin and the Himalayas, comes from the upper part of the lithosphere, i.e. the crust. This seems to be a fair assumption. The continental crust is much thicker and

lighter compared with the oceanic crust and, if subducted, will produce large negative anomalies. The gravity anomalies observed over the oceanic trenches such as in the Aleutians (Grow, 1973) are of the order of - 200 mgals and over the cordilleran convergence zones such as the Andean trench (Grow and Bowin, 1975) are of the order of - 250 mgals as compared to - 500 to -600 mgals in the Himalayas. Subcrustal inhomogieties in Himalayan region, if they exist, will be of secondary nature and will not affect the magnitude of the negative anomaly significantly.

3. The isopiestic level was assumed to be at a depth of 125 Km below mean sea level.
4. Effects like density variations with depth and partial melting in the underthrusting slab have not been considered.

Model Type A:

This is the simplest model where the Indian lithosphere with a 30 Km thick continental crust is being underthrust beneath the Tibetan plateau along the Main Central Thrust. Figures 6, 7, 8, 9 and 10 show different models of this type based on dips of 5°, 10°, 15°, 20° and 30° respectively for the underthrusting zone. The purpose of constructing these simplified models was to see the effect of dip angle of the Main Central Thrust on the computed Bouguer anomalies. It is evident that a reasonable fit to the observed anomaly is obtained for thrust angles in the range of 10° to 15°.

ALAYAN PROFILE CSS-144 MODEL A10

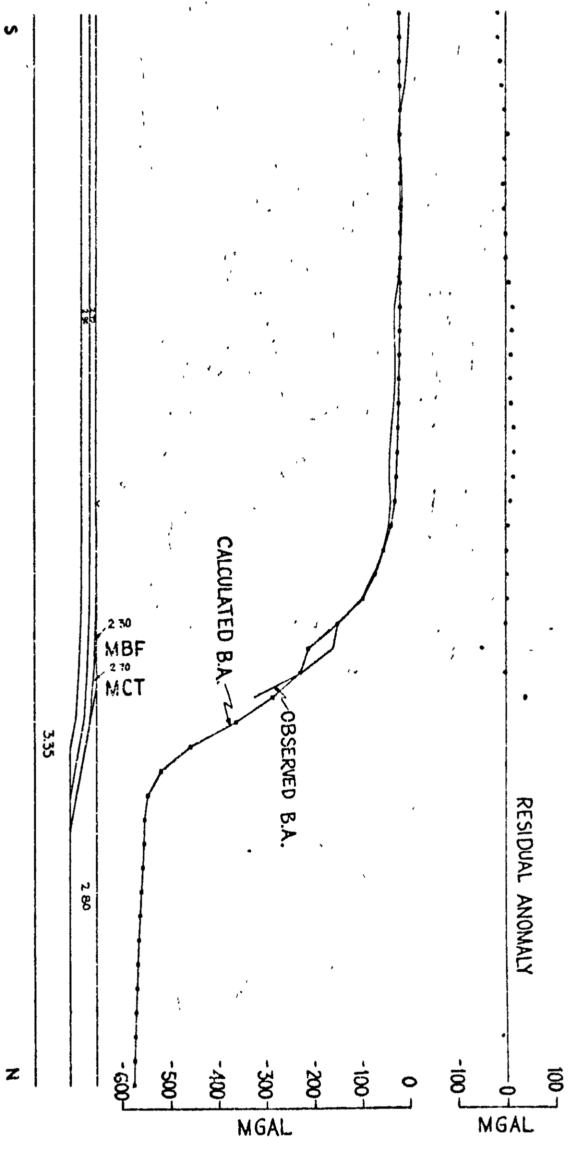
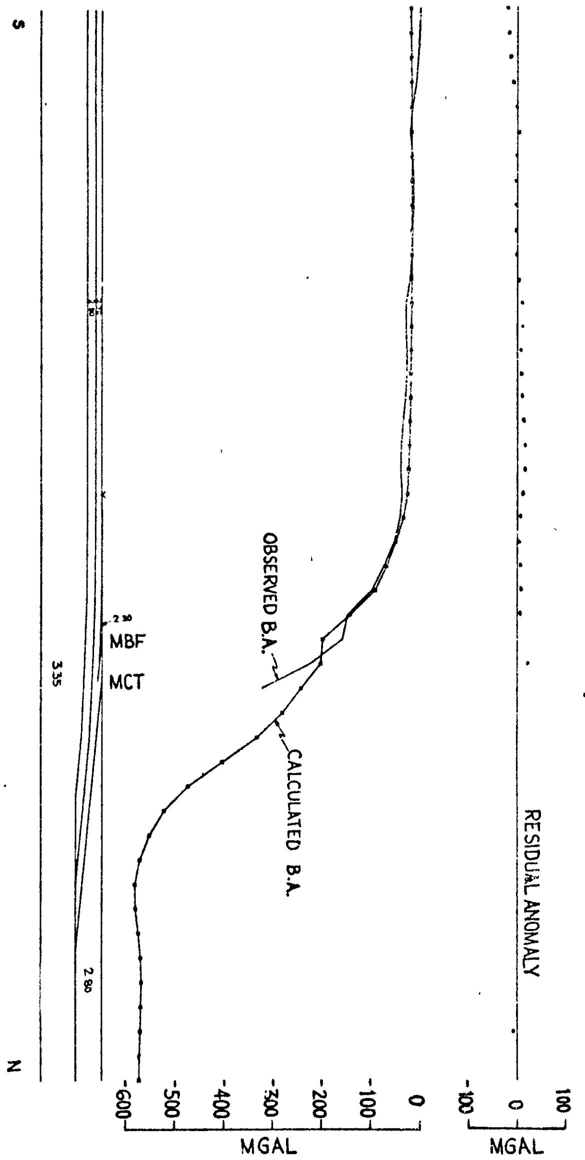


Figure 6

HIMALAYAN PROFILE CSS-144 MODEL A5



AN PROFILE CSS-144 MODEL A20

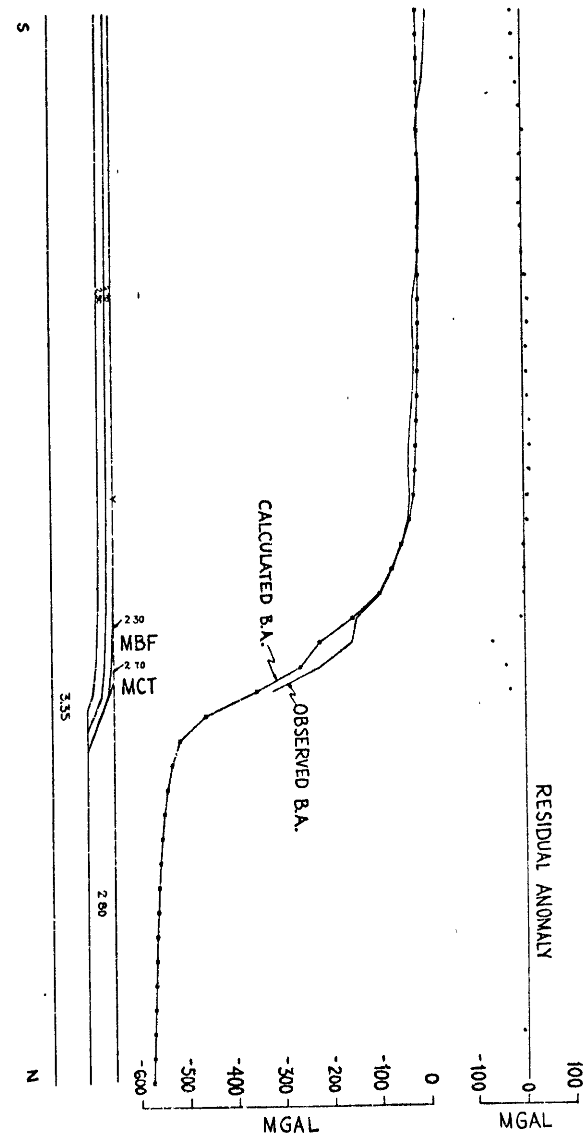
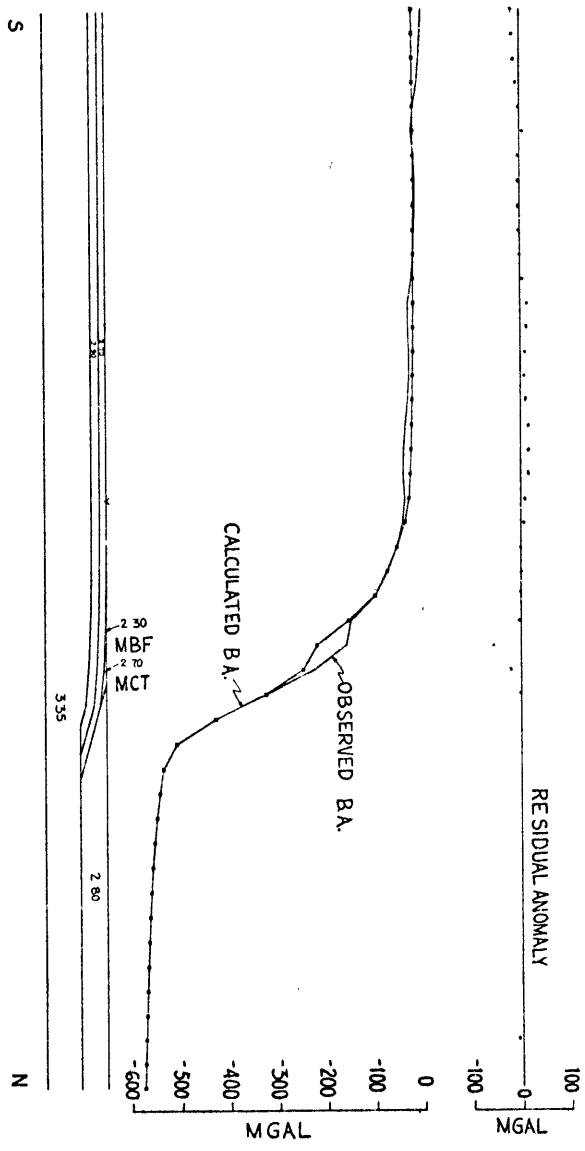


Figure 8

HIMALAYAN PROFILE CSS-144 MODEL A15



HIMALAYAN PROFILE CSS-144 MODEL PC

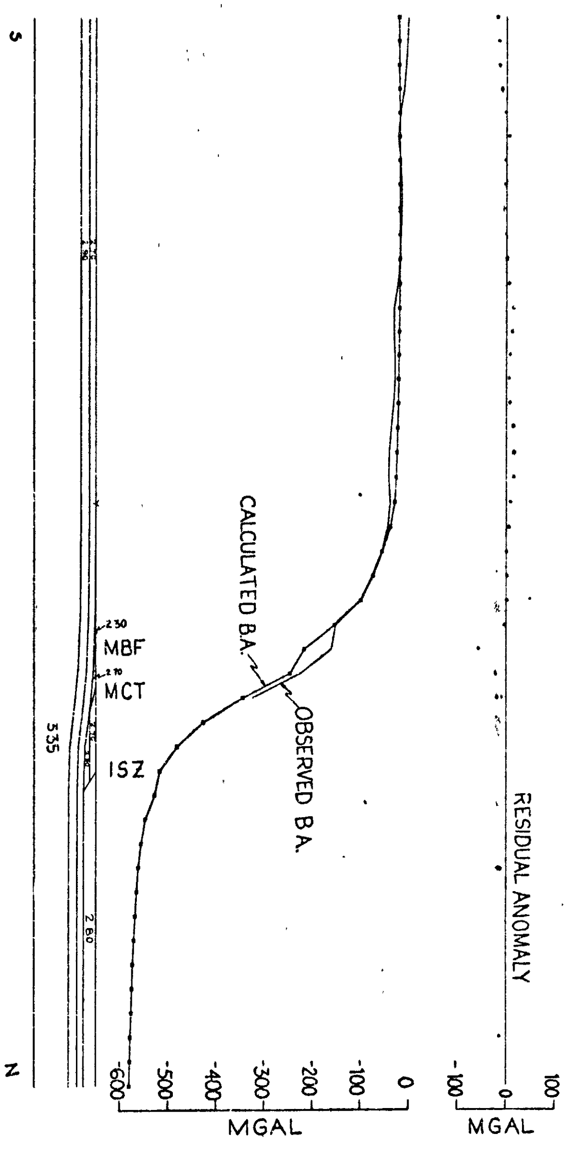


Figure 11

HIMALAYAN PROFILE CSS-144 MODEL A30

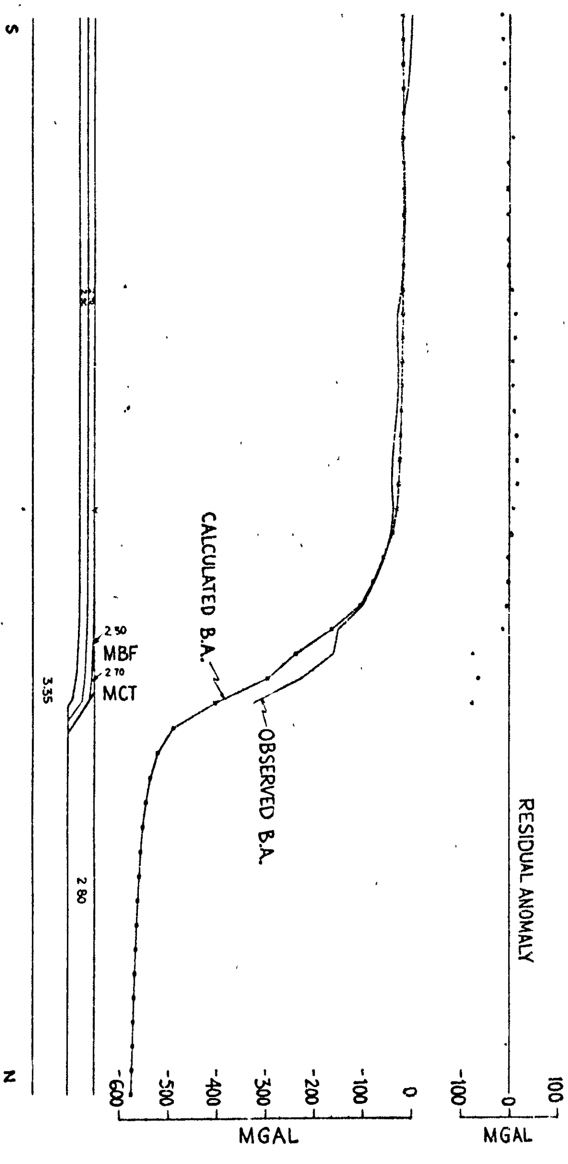


Figure 10

Model Type B :

Model B is the one suggested by Powell and Conaghan (1973) where Indian lithosphere is stacked underneath the normal crust (~30 Km) of Tibet by a mechanism that peels off the lower part of the Tibetan lithosphere as underthrusting of the Indian plate continues. This was basically motivated to account for the presumed double thickness of the crust under Tibet. This model implies a crustal shortening of 1,500 Km across the Himalayas. It is suggested that after suturing of the continents along the Indus Suture Zone, a continental piece broke off by the development of the Main Central Thrust which became the site of subsequent subduction. One of the models constructed by using this idea is shown in Figure 11. The Indian crust is underthrust at an angle of 15° at the Main Central Thrust which then underglides below the broken off fossil piece of the Indian continent and the whole of the Tibetan plateau. As can be seen on Figure 11, this model does reproduce the observed anomaly upto a point on the Main Central Thrust when underthrusting takes place at an angle of 15°. This model differs significantly in subsurface configuration underneath the Tibetan Himalayas and the southern Tibetan plateau as compared to models of the type C and D to be described later. This model, however, poses certain physical problems which cast doubts on the possibility of its existence. The horizontal stresses required to stack the Indian crust under Tibet, probably are very high and unrealistic. Also the isostatic uplift associated with horizontal undergliding, if accepted, would have produced a well developed drainage system over Tibet which is known to be absent.

Model Type C :

This model is constructed assuming that the Indus Suture Zone was the site of subduction before the continents collided. The continents sutured immediately after the collision without any subduction and underthrusting was subsequently resumed at the Main Central Thrust. Figures 12, 13 and 14 show three different models of this type constructed by using dip angles of 15°, 20° and 30° for the Main Central Thrust . The dip of the Indus Suture Zone is taken to be 30°. It is obvious that such a model where underthrusting of the continent takes place at angles 15° to 30° can account for the observed anomaly. However, underneath the Tibetan Himalayas and southern Tibet a high density block of subcrustal material lies at shallow depths between the decending Indian lithosphere and the Tibetan block. This subcrustal mass produces a pronounced gravity high anomaly in the north of the Great Himalayas. Such a pronounced gravity high does not seem probable in that region.

Model Type D :

This model is essentially similar to the type C with the only difference at the Indus Suture Zone. In this model it is assumed that a certain amount of continental underthrusting took place before the suturing of the continents. Figures 15, 16, 17 and 18 show four different models of the type D with the Main Central Thrust dipping at 10°, 15° , 20° and 30° respectively. In this case a better fit to the observed data is obtained when underthrusting takes

HIMALAYAN PROFILE CSS-144 MODEL B15

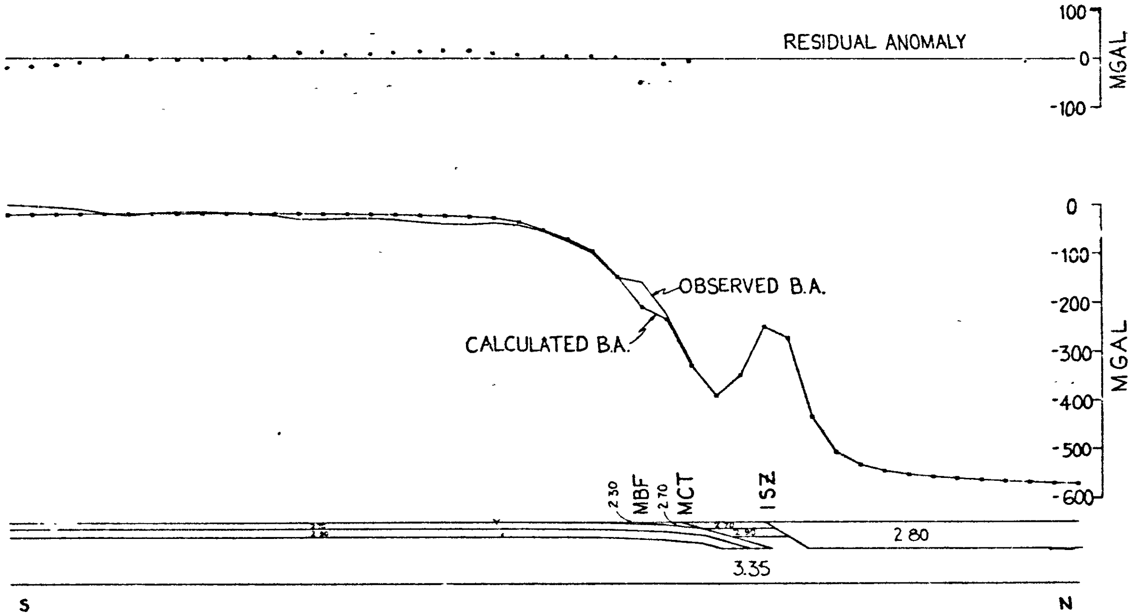


Figure 12

HIMALAYAN PROFILE CSS-144 MODEL B20

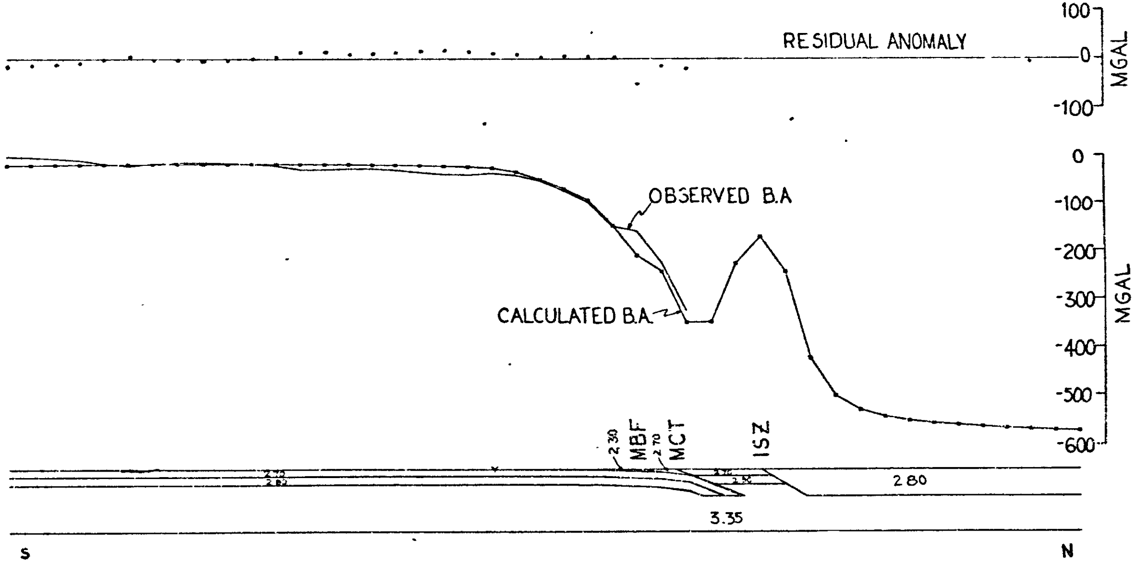


Figure 13

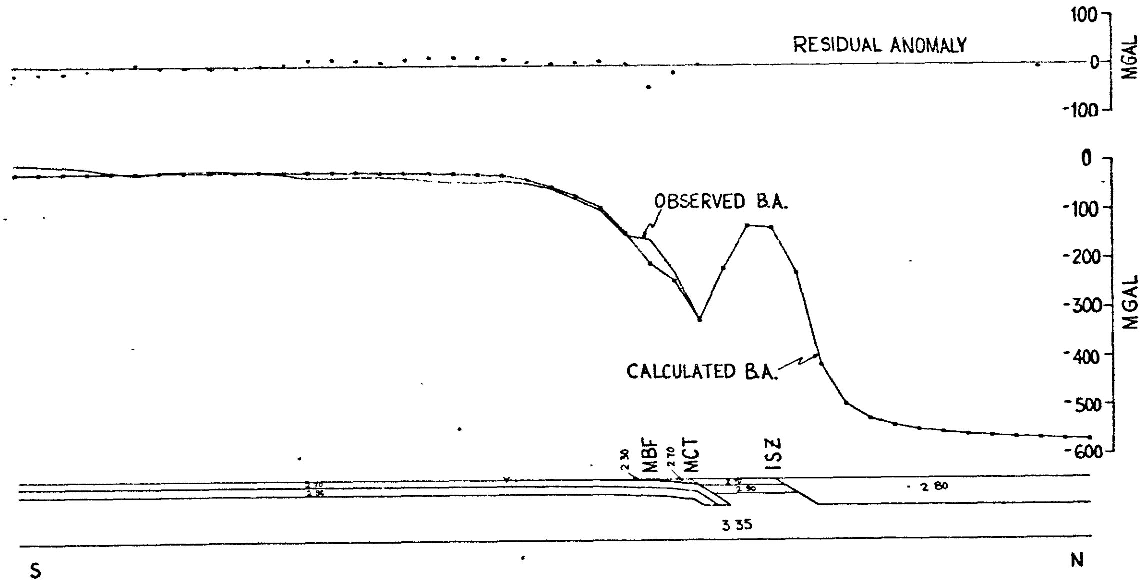


Figure 14

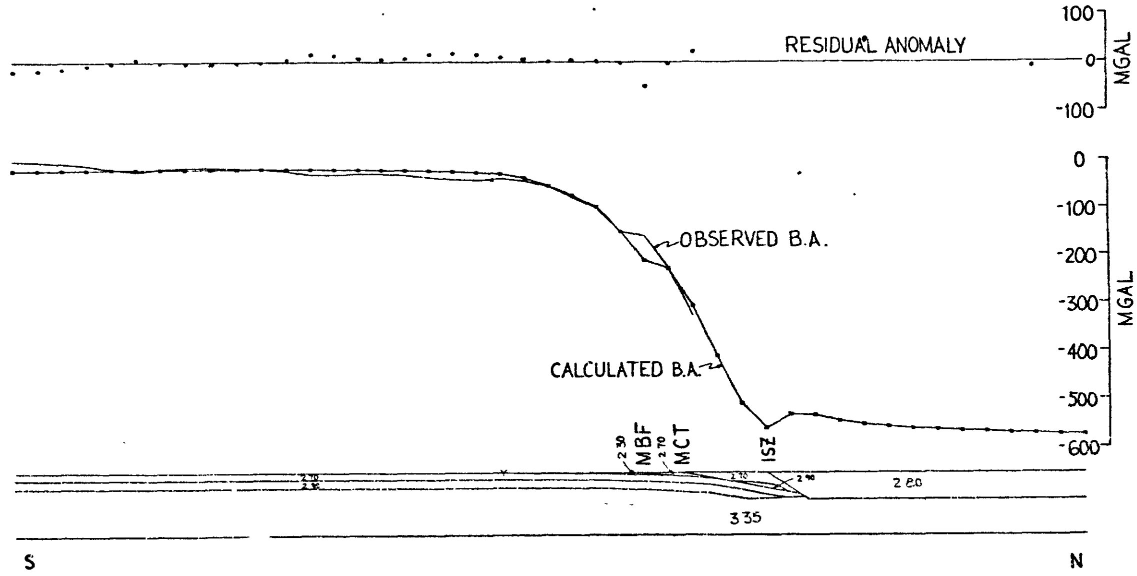


Figure 15

HIMALAYAN PROFILE CSS-144 MODEL C15A30

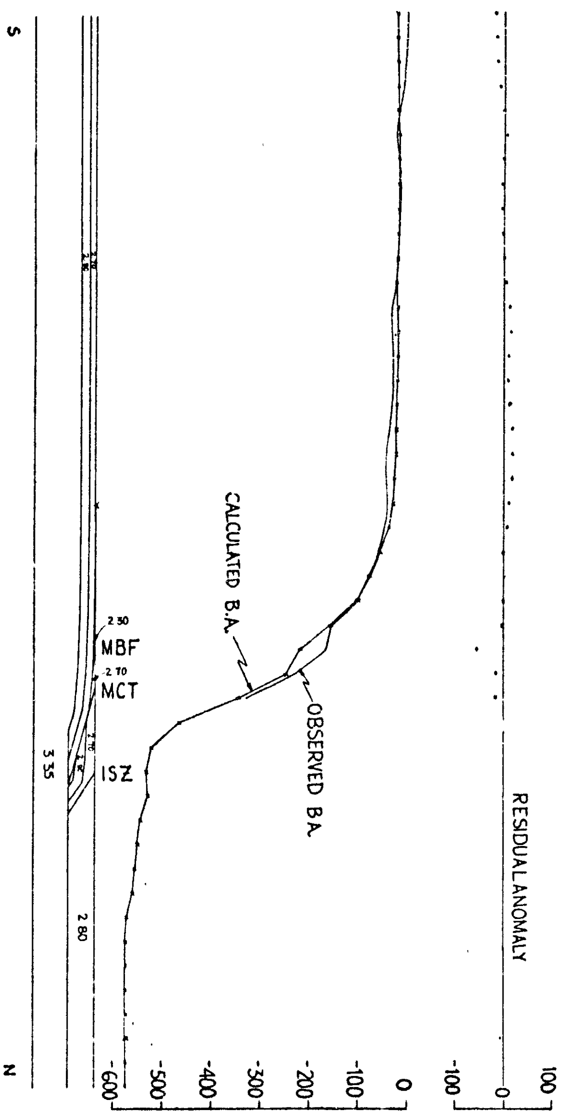


Figure 16

IMALAYAN PROFILE CSS-144 MDEL C20A30

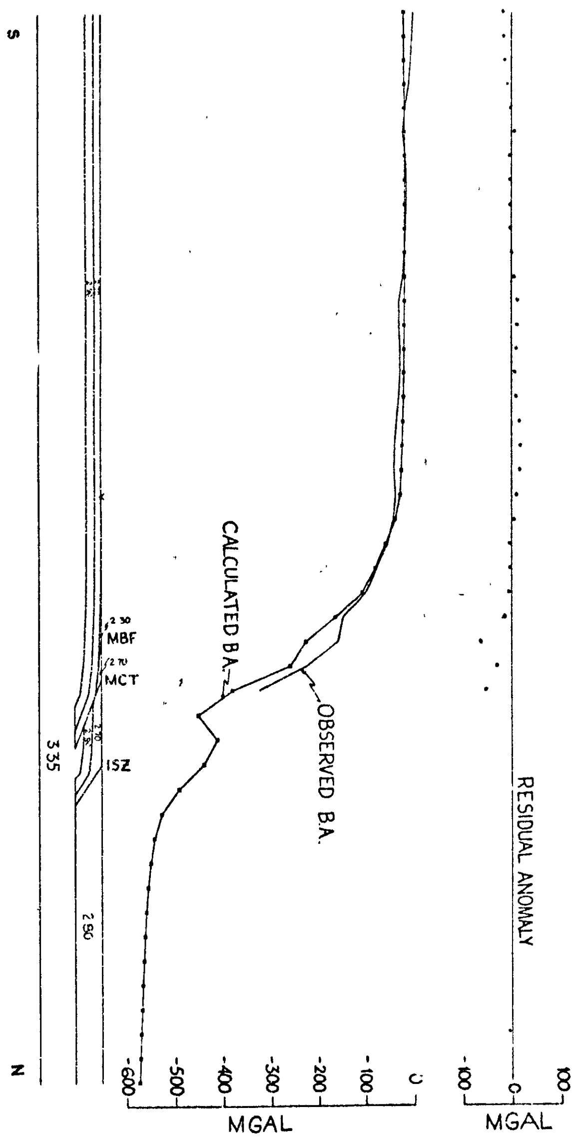


Figure 17

HIMALAYAN PROFILE CSS-144 MODEL C30A30

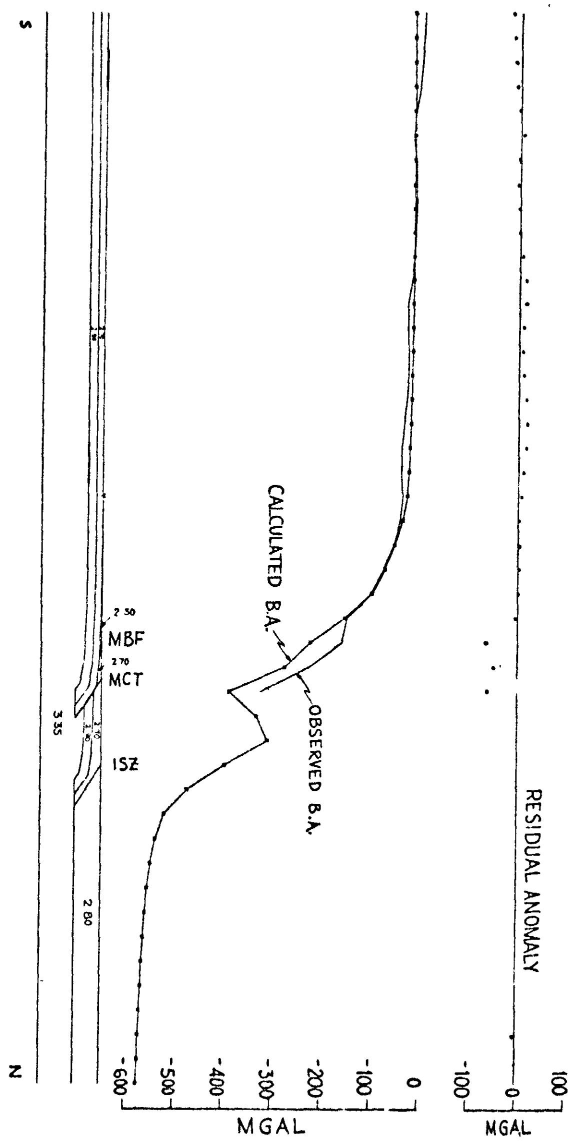
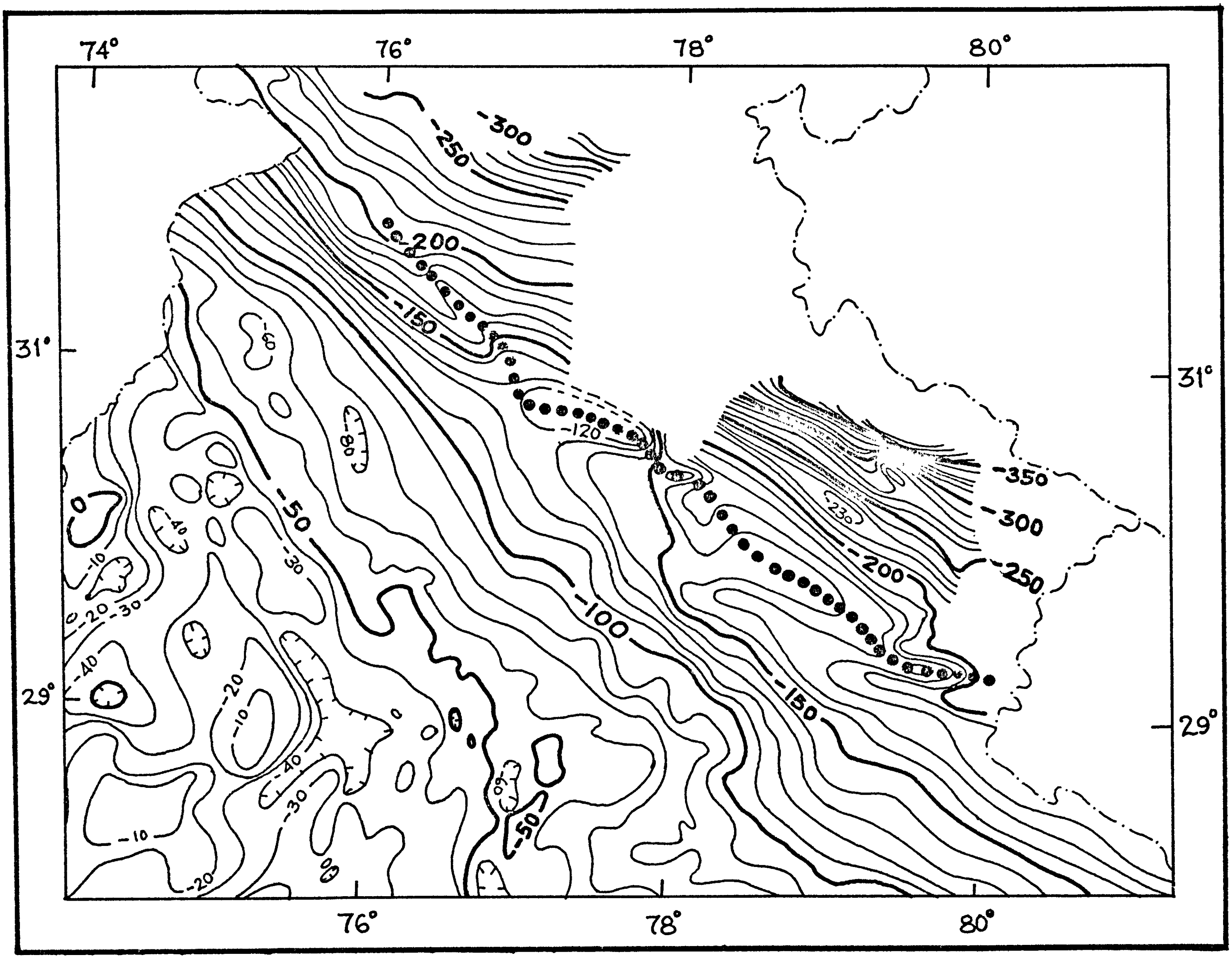


Figure 18

place at an angle of 15° at the Main Central Thrust. It may be noted here that the pronounced gravity high observed over the Tibetan Himalayas and the southern Tibetan plateau in models of the type C disappears in these models. For example, compare Figures 12 and 16. Continental underthrusting at the Indus Suture Zone in type D models does not permit us to have the high density subcrustal material at shallower depths to cause a broad gravity anomaly of large magnitude.

In the light of presently available geological and geophysical information, this model appears to be a reasonable approximation to the crustal structure in the Himalayas. In Figure 16, the continental crust of the Indian shield is underthrust along the Main Central Thrust to a depth of 55 Km below the mean sea level. The broken off fossil piece of the Indian plate is also moved down to a similar depth along the Indus Suture Zone at an angle ot 30°. The geometry of this model does not permit us to include a large block of subcrustal material in between the two underthrust pieces of the continental crust. This model reproduces the observed anomaly and the residual anomaly at all points lies within 20 mgals over the Himalayan region except for one point with - 58 mgals over the Middle or Lesser Himalayas. This is probably an intra-crustal anomaly lying at shallower depths. This falls over a region where some basic rocks outcrop on the surface. Rupke (1974) has found amphibolitic flows to lie very close to the surface and he correlates these masses with the pre-thrust uplift. An examination of the Bouguer anomaly map of the northwestern India, in Figure 19 taken from Qureshy (1970), shows that this 'high' is a typical feature which runs parallel to the

Figure 19


74°
76°
78°
80°
31°
31°
29°
29°
76°
78°
80°
-300
-250
-200
-150
-120
-350
-300
-230
-200
-250
-100
-150
-50
-50
-60
-80
0
-40
-10
-20
-30
-30
-40
-20
-10
-40
-30
-10
-20
-60

Himalayan axis and always lies in the north of the Main Boundary Fault. This may be a typical feature for the entire length of the Himalayan range as a similar'high' is observed on a profile in eastern Nepal (Qureshy, 1970). This gravity high may have some genetic relationship with the Himalayan orogeny and needs further investigations. It may be added here that Qureshy et al (1974) interpreted this'high' in terms of a thick basaltic 'root' under the Middle Himalayas.

If the validity of this model is accepted, a total crustal shortening of about 375 Km would have occurred by underthrusting along the Main Boundary Fault,the Main Central Thrust and the Indus Suture Zone since the collision of India with Eurasia. This figure is comparable to that of Gansser (1966) based on the geological observations.

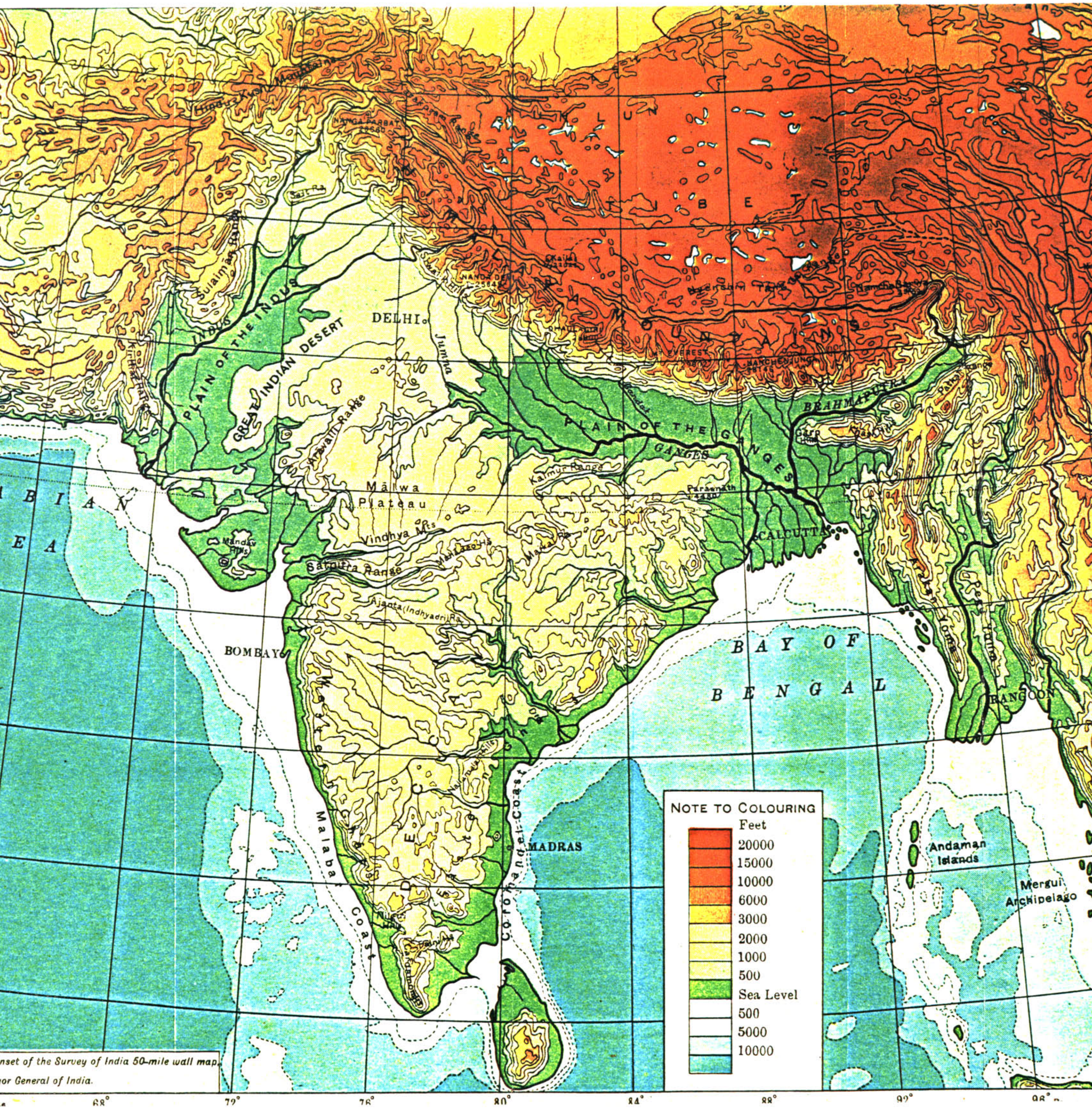
Isostatic Considerations :

The models presented here differ from earlier gravity models of Oldham (1917) and Qureshy et al (1974) that propose the Gangetic basin and the Himalayan region to be in near equilibrium. In the present model, the standard column under the deepest part of the Gangetic basin is in slight mass excess of the order of 50 Kg where the standard column extends to a depth of 125 Km below mean sea level. The Middle and the Great Himalayas, however, are largely under-compensated with a mass excess of 300 to 500 Kg in the standard column. The Tibetan Himalayas and a part of the southern Tibetan plateau may be over-compensated with a mass defect of about 200 to 400 Kg in the standard column. Kono (1974) suggests that the column under the Great Himalayas is 670 Kg heavier than the normal column down to a depth of 100 Km. It may, therefore, be said that the Himalayas are not in isostatic equilibrium and the tectonic forces associated with the plate motion are still active and supporting the topography.

The Outer Gravity High in Central India :

On the Bouguer anomaly and free air anomaly maps in Figures 3 and 4, a significant feature is a gravity high (F.A. relief ~ 40 mgals and B.A. relief ~ 20 mgals) which separates the gravity lows over the Gangetic basin and the south Indian shield. This 700 - 800 Km wide 'high' corresponds to an elevated plateau region of an average height of 0.5 - 1 Km (see Figure 20 taken from Pascoe, 1959) and resembles to the gravity highs observed over the outer rises on the seaward side of Pacific trenches (Watts and Talwani, 1974). This region is the same as that of the 'hidden range' of Burrard (1901) and shows up as a 'high' on the compensated geoid map of India shown in Figure 21. Oldham (1917) opined that it is probably a broad crustal upwarp that causes the 'high' anomaly rather than a sharp ridge as suggested by Burrard. In a recent study of the deflection of the plumb line in India, Chatterjee (1972) suggests that the 'high' may a virtual effect due to the mass deficiency in the Gangetic basin and the negative mass anomaly in the upper mantle in south India.

The correspondence between the free air and the Bouguer anomalies suggest that this 'high' is caused due to an excess mass at deeper levels, probably at the



nset of the Survey of India 50-mile wall map.
nor General of India.

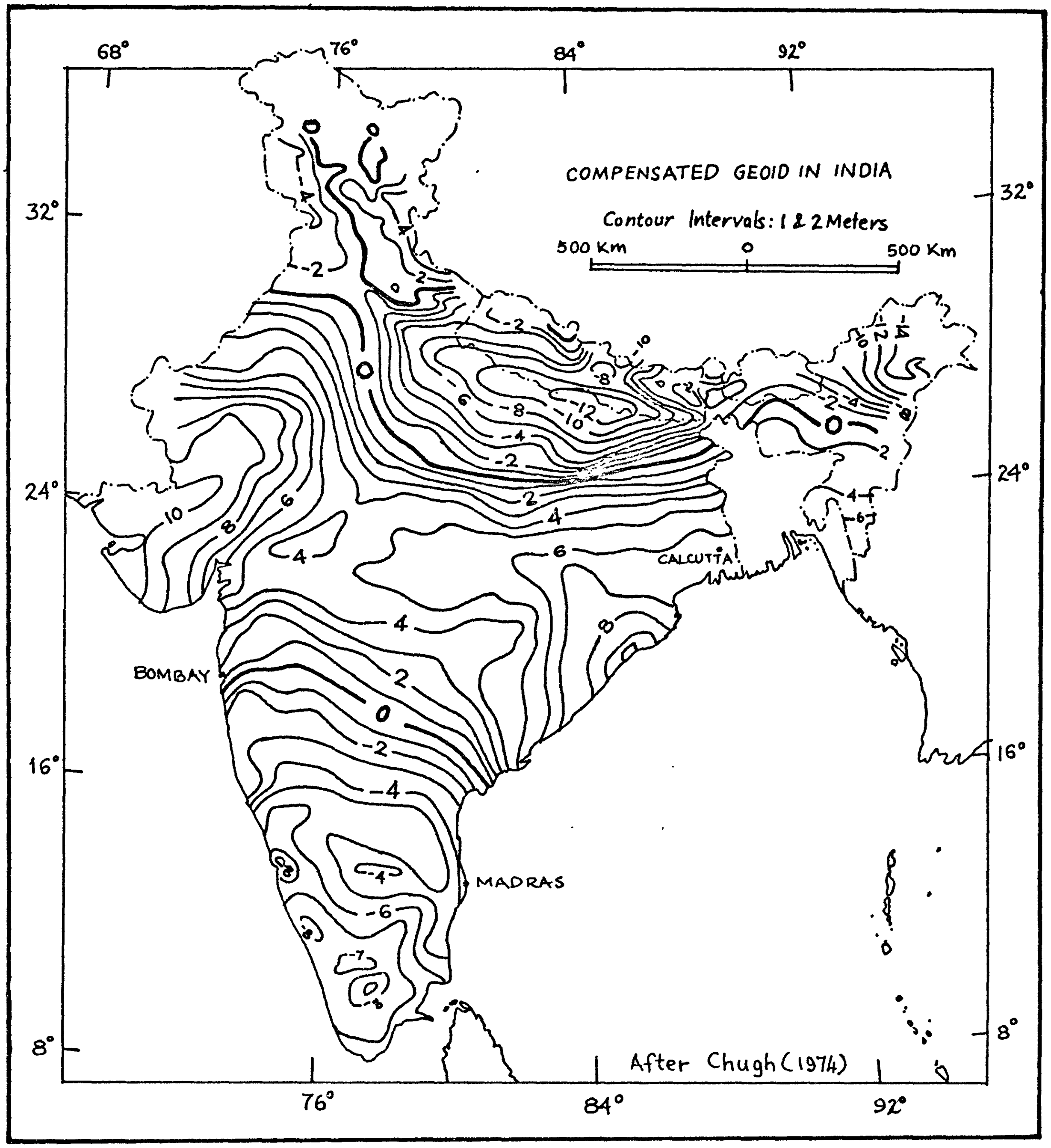

COMPENSATED GEOID IN INDIA
Contour Intervals: 1 & 2 Meters
500 Km
0
500 Km
68°
76°
84°
92°
32°
24°
16°
8°
BOMBAY
CALCUTTA
MADRAS
After Chugh (1974)
0
-4
-2
-12
-10
-8
-6
4
6
8
10
2
-7

Figure 21

crust mantle boundary. This may be a consequence of a bending of the lithosphere in front of a subduction zone similar to the periferal bulges seaward of many deep sea trenches. In the present case, a flexure of about I Km would account for the observed 'high' anomaly. Maximum contribution would come from the Moho where lies the maximum density contrast. Figure 22 shows a model of the type D constructed along a profile BB' marked on Figure 4 which passes over the outer 'high'. In this profile, the dips of the Main Central Thrust and the Indus Suture Zone are taken to be 15° and 30° respectively. The Bouguer anomaly 'high' on this profile over Central India was reproduced by a broad upwarp of the Moho having a maximum amplitude of 0.75 Km.

There is some evidence to support the crustal upwarping hypothesis. Figure 23 shows a plot of 1° x 1° mean Bouguer anomaly versus average elevation in Central India. The solid line shows the approximate straight line fit to the data whereas the broken line represents the Bouguer anomaly versus elevation relationship in an area of perfect isostatic equilibrium. As can be seen from this plot, the Bouguer anomaly falls off rather slowly with increasing elevations indicating the prevailance of some under compensation. In an ideal case, one would expect a positive slope for a region of crustal upwarping. The negative slope obtained in the present case may be an apparent effect caused by the surface geology. There are several Mesozoic basins in Central India filled with thick and very light sediments which have been uplifted upto a kilometer in many cases. These sediments can easily over shadow a + 30 to + 40 mgals anomaly arising due to the up-

HIMALAYAN PROFILE CSS-145 PASSING OVER THE OUTER HIGH

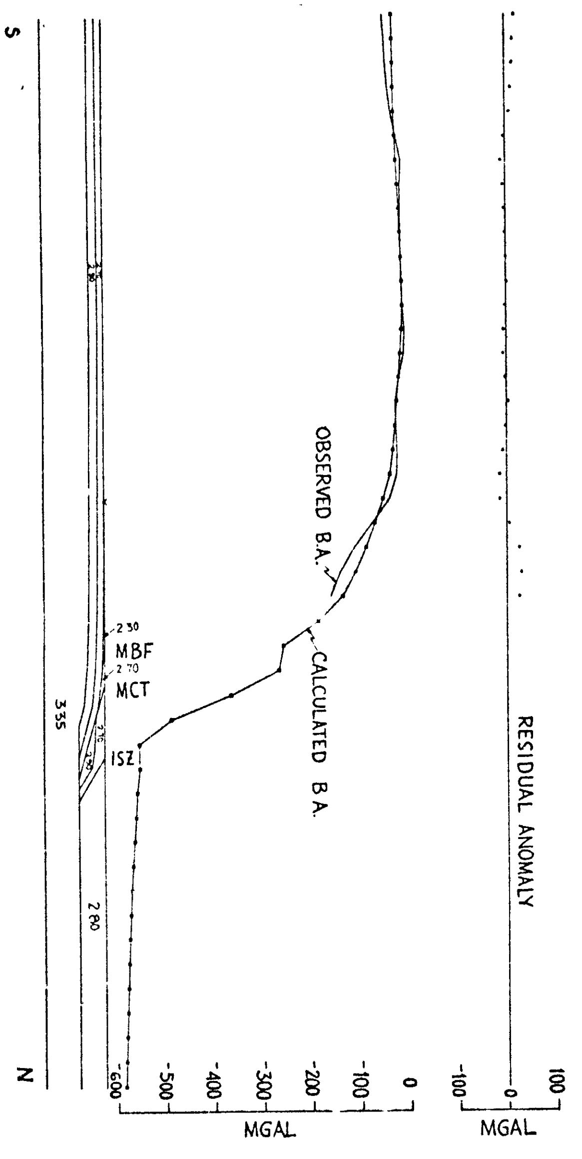
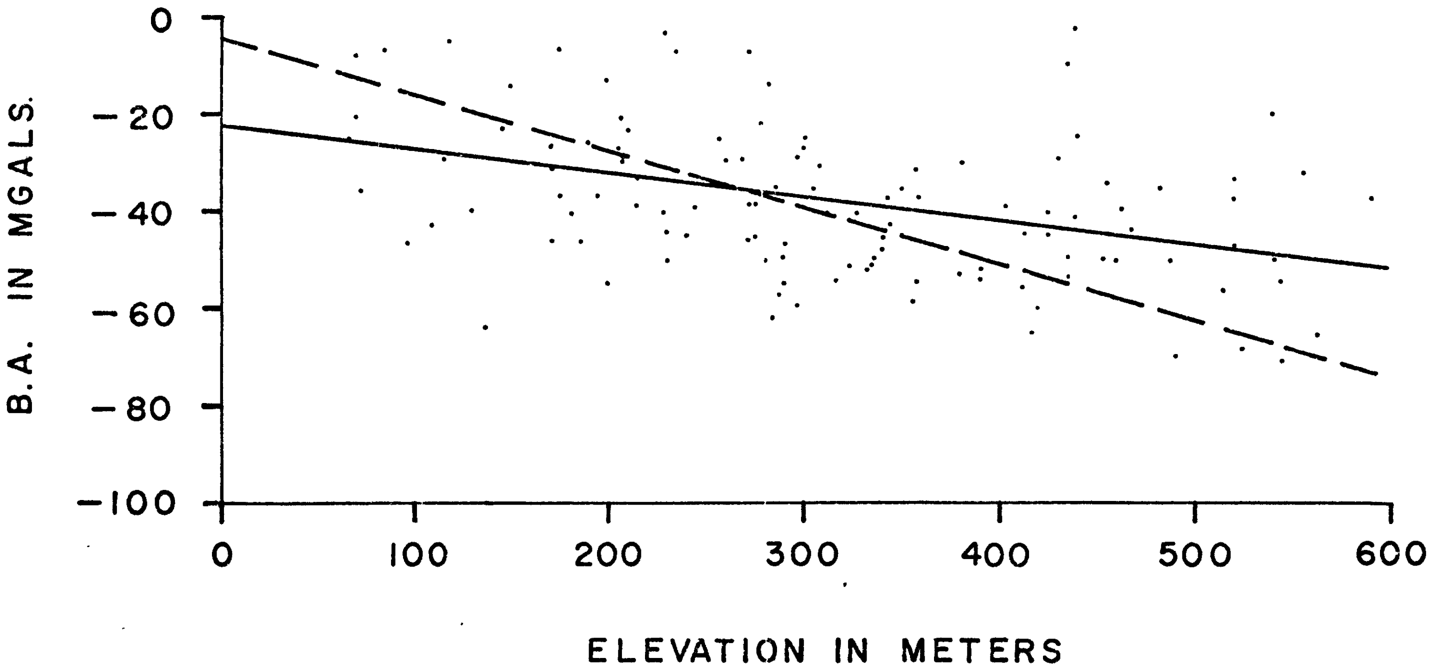


Figure 22

Figure 23



0
-20
-40
-60
-80
-100
B.A. IN MGALS.
0
100
200
300
400
500
600
ELEVATION IN METERS

warping at the Moho. Qureshy (1971) carried out the regression analysis of Bouguer anomaly and elevation data in Central India using only the selected stations falling on the outcrops of the Proterozoic formations and he obtained a slope of + 96.4 mgals/Km.

Also, there is evidence that the uplift has taken place after the mid-Miocene period, after the collision of India with Eurasia. The region of Central India was probably a flat land around Cretaceous - Eocene times as evidenced by large scale sub aerial volcanic flows of the Deccan Trap are found to cover about 500,000 Km^2 of area at present. There is evidence of marine transgression in the western part of Central India where the Bagh beds of Cretaceous age were deposited and elevated at a later date. Some Deccan Trap beds are found to lie at elevations of more than 1,000 meters which indicates uplift of the region at least of the order of one kilometer since their effusion. In the eastern part, Dunn (1939) recorded the uplift of the Chhota Nagpur and the Ranchi plateaus to be about 900 meters since the Lower Tertiary times.

It, therfore, seems reasonable that the 'high' over the region of Central may be due to a slight upwarping of the Moho caused by the bending of the Indian lithosphere.

CHAPTER V

DISCUSSION AND CONCLUSIONS

Gravity interpretation suffers from the problem of non-uniqueness which makes it necessary to consider and investigate all possible models that may exist in nature. Additional geological and geophysical controls help in selecting the most probable ones. Various models, considered in this study, are described in Chapter IV. All these models are conjectural beyond the Main Central Thrust as there are no data available from the Tibetan Himalayas or the Tibetan Plateau. From the foregoing discussion of the different models, it appears that an appropriate plate model for the Himalayas would be the one where underthrusting of continental crust takes place at shallow angles along the Main Central Thrust and the Indus Suture Zone.

The analysis of gravity data indicates the possibility of continental underthrusting which causes large negative anomalies in the Himalayan and the Tibetan region. This, however, is not in consonance with Airy's 'root hypothesis' which is believed by many to hold good in the Himalayas. The high ranges of the Middle and the Great Himalayas seem to be supported by underthrusting of the Indian shield instead of floatation of the crust over a fluid substratum. 'Roots' are not necessarily associated with every mountain range. In a recent compilation of gravity and deep seismic sounding data in the U.S.S.R., Belyaevski et al (1973) showed that the Kopet-Dagh and Lesser Caucasus mountains do not have 'roots'.

Doubts have been expressed about the compatibility of relatively large slip rates of 5 - 7 cm/year with the seismicity behind the Himalayan arc (Fitch, 1970). Molnar and Tapponnier (1975) have suggested that continental convergence is not confined only to Himalayan region but extends to the Pamir, Tien Shan, Nan Shan and other mountain ranges of Central Asia. In their opinion, continental convergence between the Indian and Eurasian plates pushes the intervening land mass in the east along large strike-slip faults which take up a major part of the present slip rate. The important point here is that it obviates the need of a 1500 Km of continental underthrusting below the Tibetan Plateau. The problem of the uplift of the Tibetan Plateau is one of the intricate puzzles in the Asian tectonics. Some thickening can be achieved by horizontal compression but a more subtle mechanism has to be found which can account for most of the problems of the Tibetan Plateau mentioned earlier.

As demonstrated by McKenzie (1969), continental subduction would come to a stop when the bouyancy force exceeds the forces pulling the slab downward. At present there is no evidence of a sinking slab underneath Himalayas and probably sufficient continental subduction has already taken place not to permit any further underthrusting of large dimensions. It, therefore, appears reasonable to attribute the tectonics of Central Asia to a reorientation of driving forces after the continental collision.

From the analysis and arguments presented before, it seems that the plate theory is a viable mechanism to account for the Himalayan orogeny. There is a distinct expression of underthrusting of the Indian shield on gravity anomalies and on source mechanisms of earthquakes. The plate theory suggests that the Gangetic basin should be regarded as a frontal molasse trough instead of an exogeosyncline. The 'outer gravity high' over Central India supports the idea of a bending of the Indian lithosphere similar to that observed in front of oceanic trenches. The model D presented in Figure 16 may, therefore, be a reasonable approximation to the actual tectonic situation in the Himalayas where underthrusting is supposed to have taken place mainly along the Main Central Thrust and the Indus Suture Zone with a little movement along the Main Boundary Fault. Underthrusting along the Indus Suture Zone is preferred because of the presence of some exotic blocks in the flysch zone. Such a model would account for a total amount of underthrusting or crustal shortening of about 375 Km across Himalayas. One of the important inferences drawn from this analysis is that the underthrusting of Indian lithosphere takes place at very shallow angles around 10° to 15° along the Main Central Thrust. It should be mentioned here that this is a very simple model and may not account for many of the complex situations met with in the Himalayas. However, it should be possible to work out a detailed mechanism for individual problems observed in the Himalayas within the broad frame work of the theory of plate tectonics.

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APPENDIX

ONE DEGREE MEAN ELEVATIONS, FREE AIR AND BOUGUER ANOMALIES IN INDIA AND CONTIGUOUS REGION

LAT NORTH	LONG EAST	NUMBER OF STATIONS	ELEV MTS	F.A. MGAL	B.A. MGAL	REF
34	61	2	745.0	-40.6	-124.0	
31	61	2	493.5	2.9	-52.2	
28	61	1	752.2	18.8	-65.3	
25	61	1	25.6	27.1	24.3	
39	62	1	225.0	5.1	-20.6	
34	62	1	933.0	-48.7	-153.1	
33	62	1	679.0	-18.6	-94.5	
32	62	2	727.5	-11.6	-93.0	
31	62	2	583.2	-22.4	-87.6	
27	62	1	535.5	-46.4	-106.3	
26	62	1	228.6	7.3	-18.2	
39	63	2	195.0	-12.8	-34.6	
38	63	1	188.0	-49.3	-70.3	
35	63	2	483.0	-59.2	-113.3	
34	63	2	1319.5	3.5	-144.1	
33	63	1	830.0	-13.6	-106.4	
28	63	3	569.2	-33.6	-97.3	
27	63	2	634.5	-55.6	-126.6	
26	63	1	914.4	12.6	-89.6	
25	63	2	71.3	34.2	26.2	
31	64	2	802.0	-35.6	-125.3	
28	64	1	849.1	-10.2	-105.2	
26	64	2	741.7	10.2	-72.6	
40	65	1	398.0	-26.1	-70.6	
37	65	1	262.0	-24.7	-54.1	
36	65	1	362.0	-60.5	-101.0	
34	65	1	2230.0	-.3	-249.8	
32	65	1	1053.0	-22.4	-140.2	
31	65	2	1012.5	2.0	-111.2	
27	65	2	1218.1	51.3	-84.8	
26	65	1	539.8	40.4	-19.9	
25	65	1	13.1	-41.5	-42.9	
39	66	3	614.0	-16.9	-85.6	
38	66	2	627.5	-46.2	-116.4	
37	66	1	290.0	-36.4	-68.8	
36	66	1	343.0	-101.4	-139.7	
34	66	1	2760.0	12.1	-296.6	
32	66	1	1571.0	5.2	-170.5	
30	66	2	1397.5	7.9	-148.4	
29	66	2	1392.7	15.1	-140.6	
28	66	2	1664.6	44.3	-141.9	

27	66	1	1247.2	3.8	-135.6	
26	66	1	88.3	-77.9	-87.8	
25	66	2	15.5	-25.2	-26.9	
40	67	1	386.0	-53.4	-96.6	
39	67	2	987.2	-65.7	-176.2	
38	67	4	1030.5	-47.5	-162.5	
37	67	2	412.5	-95.7	-141.8	
36	67	1	365.0	-104.5	-145.4	
34	67	1	2555.0	-25.5	-311.4	
30	67	6	1783.8	37.1	-162.3	
29	67	5	249.8	-28.9	-56.8	
28	67	1	73.1	-109.1	-117.3	
26	67	2	170.3	-27.6	-46.7	
25	67	1	138.6	-15.6	-31.1	
24	67	2	38.1	9.3	5.1	
40	68	1	360.0	-85.6	-125.9	
39	68	1	650.0	-81.2	-153.9	37A
38	68	2	870.0	-109.1	-206.4	37B
37	68	2	350.5	-129.0	-168.2	37C
36	68	4	573.2	-123.4	-187.6	37D
35	68	1	610.0	-153.5	-221.7	38A
30	68	2	1488.6	51.1	-115.3	39B
28	68	1	55.7	-2.4	-8.7	39D
27	68	6	56.5	1.5	-4.8	40A
26	68	4	33.4	-11.0	-14.8	40B
25	68	5	24.9	-12.2	-15.0	40C
24	68	2	12.1	-4.0	-5.3	40D
23	68	42	42.9	4.4	-.4	41A
22	68	3	36.3	4.5	.4	41B
40	69	2	367.5	-134.5	-175.6	
39	69	1	1025.0	-43.2	-157.8	37E
38	69	2	1050.0	-129.9	-247.3	37F
37	69	3	496.6	-159.7	-215.2	37G
31	69	2	1566.9	117.7	-57.5	39E
30	69	1	1536.1	73.0	-98.8	39F
28	69	2	72.1	-9.8	-17.9	39H
27	69	2	68.4	-6.9	-14.6	40E
26	69	31	63.9	-21.4	-28.5	40F
25	69	3	11.1	-22.4	-23.7	40G
24	69	1	19.8	-8.4	-10.6	40H
23	69	103	21.3	2.3	0.0	41E
22	69	58	48.1	1.9	-3.4	41F
21	69	7	49.9	47.3	41.7	41G
40	70	1	437.0	-177.8	-226.7	
39	70	2	1485.0	-172.2	-338.3	37I
38	70	4	1438.7	-132.9	-293.8	37J
37	70	1	1380.0	-120.5	-274.9	37K
33	70	4	536.1	-110.7	-170.7	38K
32	70	1	257.5	-105.2	-134.0	38L
31	70	2	551.0	-53.6	-115.2	39I
30	70	2	121.4	-139.0	-152.6	39J
28	70	7	85.1	-56.0	-65.6	39L
27	70	118	156.7	-16.0	-33.5	40I

26	70	172	182.6	7.1	-13.2	40J
25	70	21	147.1	29.9	13.5	40K
24	70	2	37.1	34.2	30.0	40L
23	70	33	11.1	-1.1	-2.3	41I
22	70	113	81.4	.7	-8.3	41J
21	70	68	121.2	11.6	-1.9	41K
20	70	46	37.6	-.1	-4.4	41L
40	71	3	553.3	-173.6	-235.5	
39	71	2	2087.5	-124.6	-358.2	37M
38	71	1	1795.0	-192.5	-393.3	37N
37	71	2	2045.0	-272.8	-501.6	37O
36	71	1	2460.0	-179.8	-455.0	37P
34	71	4	543.0	-135.4	-196.2	38F
33	71	1	498.9	-115.8	-171.6	38G
31	71	4	357.3	22.7	-17.2	39M
30	71	3	126.2	-60.9	-75.0	39N
29	71	6	113.9	-62.6	-75.4	39O
28	71	6	120.6	-11.6	-25.1	39P
27	71	215	153.3	2.6	-14.5	40M
26	71	99	231.3	22.7	-3.1	40N
25	71	118	85.5	2.9	-6.6	40O
24	71	210	41.4	12.1	7.4	40P
23	71	226	25.2	.7	-2.0	41M
22	71	177	84.9	-17.2	-26.7	41N
21	71	223	93.3	6.4	-3.9	41O
20	71	33	28.8	18.6	15.3	41P
40	72	3	950.3	-164.1	-270.4	
37	72	1	2915.0	-174.1	-500.2	42C
33	72	1	358.7	-131.8	-172.0	43C
32	72	4	281.2	-28.4	-59.8	43D
30	72	3	143.1	-27.5	-43.6	44B
28	72	141	145.7	-7.1	-23.4	44D
27	72	225	207.8	2.3	-20.9	45A
26	72	26	234.6	18.6	-7.5	45B
25	72	28	173.6	12.4	-6.9	45C
24	72	76	272.3	22.9	-7.5	45D
23	72	208	70.3	-2.6	-10.4	46A
22	72	175	17.6	-13.8	-15.8	46B
21	72	156	28.8	0.6	-2.5	46C
20	72	15	16.1	5.5	3.7	46D
19	72	41	11.8	26.5	25.2	47A
18	72	22	8.6	44.1	43.1	47B
5	72	2	1.3	15.4	15.2	
40	73	3	1794.3	-109.3	-310.1	
39	73	4	3278.7	-57.9	-424.7	42E
38	73	3	4000.0	56.5	-390.9	42F
34	73	2	882.2	-146.6	-245.3	43F
33	73	4	823.8	-83.7	-175.9	43G
32	73	6	206.8	-83.4	-106.5	43H
31	73	1	195.9	19.5	-2.4	44E
30	73	3	165.7	-28.8	-47.4	44F
29	73	9	169.7	-8.2	-27.2	44G
28	73	48	209.6	0.0	-23.4	44H

27	73	160	301.0	8.6	-24.9	45E
26	73	42	257.8	3.2	-25.5	45F
25	73	74	429.6	19.1	-28.9	45G
24	73	83	539.1	40.4	-19.8	45H
23	73	69	194.4	-14.8	-36.6	46E
22	73	159	72.4	-28.1	-36.2	46F
21	73	64	66.0	-17.8	-25.2	46G
20	73	11	171.7	-22.7	-41.9	46H
19	73	55	232.8	-42.1	-68.2	47E
18	73	79	552.1	-26.5	-88.3	47F
17	73	25	629.0	-27.9	-98.3	47G
15	73	20	84.8	-51.7	-61.2	48E
5	73	4	1.2	14.2	14.0	
34	74	1	1590.0	-102.3	-280.1	43J
33	74	51	1557.9	-79.3	-253.6	43K
32	74	53	470.8	-146.2	-198.9	43L
31	74	23	222.6	-35.2	-60.1	44I
30	74	93	201.3	-9.6	-32.2	44J
29	74	72	189.7	-5.0	-26.2	44K
28	74	36	283.1	17.6	-14.0	44L
27	74	23	380.5	12.6	-29.9	45I
26	74	84	433.5	38.9	-9.5	45J
25	74	98	437.8	27.2	-21.7	45K
24	74	119	460.3	.8	-50.6	45L
23	74	48	268.6	0.8	-29.2	46I
22	74	58	286.5	-3.3	-35.3	46J
21	74	46	206.0	-4.3	-27.4	46K
20	74	107	468.9	-12.0	-64.4	46L
19	74	107	615.6	-4.8	-73.7	47I
18	74	66	572.6	-24.3	-88.3	47J
17	74	59	650.9	-27.2	-100.0	47K
16	74	44	592.9	-17.9	-84.3	47L
15	74	62	582.0	-21.7	-86.8	48I
14	74	130	378.2	-50.4	-92.7	48J
13	74	81	214.6	-68.3	-92.3	48K
12	74	14	23.1	-36.0	-38.6	48L
39	75	1	1312.0	-207.3	-354.0	42M
35	75	3	3459.6	-6.3	-393.3	43M
34	75	17	2604.4	-34.9	-326.2	43N
33	75	70	1734.4	-69.9	-263.9	43O
32	75	249	431.3	-159.1	-207.3	43P
31	75	249	259.4	-107.0	-136.0	44M
30	75	148	230.0	-35.4	-61.1	44N
29	75	110	215.4	-9.6	-33.8	44O
28	75	46	260.5	-0.4	-29.6	44P
27	75	60	441.2	24.9	-24.4	45M
26	75	67	357.4	8.7	-31.2	45N
25	75	82	317.7	-18.7	-54.2	45O
24	75	76	434.4	-.2	-48.8	45P
23	75	115	486.9	3.9	-50.5	46M
22	75	159	412.3	-10.2	- 56.3	46N
21	75	43	299.0	6.2	-27.2	46O
20	75	65	558.0	-9.1	-71.5	46P

19	75	95	519.8	-14.4	-72.6	47M
18	75	91	629.1	-8.8	-79.2	47N
17	75	110	527.0	-20.5	-79.5	47O
16	75	108	594.0	-14.0	-80.5	47P
15	75	94	608.4	-19.4	-87.5	48M
14	75	521	641.1	-23.5	-95.2	48N
13	75	436	654.7	-29.4	-102.6	48O
12	75	94	471.2	-20.6	-73.3	48P
11	75	48	14.1	-70.1	-71.7	49M
35	76	1	2409.0	-167.9	-437.4	52A
34	76	2	3081.5	-52.0	-396.8	52B
32	76	37	780.9	-155.1	-242.5	52D
31	76	205	583.3	-116.6	-181.9	53A
30	76	140	307.5	-65.1	-99.5	53B
29	76	122	232.1	-31.5	-57.5	53C
28	76	144	230.2	-18.8	-44.5	53D
27	76	102	312.6	-5.5	-40.4	54A
26	76	30	284.2	-30.4	-62.2	54B
25	76	55	271.1	-7.8	-38.1	54C
24	76	57	343.8	1.6	-36.8	54D
23	76	46	456.3	16.7	-34.3	55A
22	76	34	280.1	-19.6	-51.0	55B
21	76	59	308.2	3.9	-30.5	55C
20	76	65	436.0	-4.5	-53.3	55D
19	76	45	444.5	-19.4	-69.2	56A
18	76	21	643.4	-11.3	-83.3	56B
17	76	88	519.9	-20.3	-78.4	56C
16	76	76	483.9	-27.0	-81.1	56D
15	76	83	480.3	-30.8	-84.5	57A
14	76	470	638.5	-11.7	-83.1	57B
13	76	589	697.0	-2.0	-80.0	57C
12	76	476	732.2	-1.8	-83.7	57D
11	76	138	915.8	8.5	-93.9	58A
10	76	74	112.5	-72.0	-84.6	58B
9	76	52	48.5	-51.7	-57.1	58C
8	76	26	32.8	-39.9	-43.6	58D
38	77	1	1200.0	-154.8	-289.0	51F
36	77	1	3658.0	-6.9	-416.2	51H
35	77	1	5359.0	33.2	-566.3	52E
34	77	1	3519.0	-76.3	-470.0	32M
32	77	11	3300.7	19.6	-394.6	52H
31	77	7	1711.3	-15.6	-207.0	53E
30	77	95	633.6	-161.3	-232.2	53F
29	77	66	241.8	-61.5	-88.5	53G
28	77	132	231.2	-27.2	-53.1	53H
27	77	148	182.4	-20.3	-40.7	54E
26	77	19	230.7	-25.8	-51.6	54F
25	77	104	402.5	5.7	-39.2	54G
24	77	196	468.7	8.5	-43.9	54H
23	77	117	462.0	12.0	-39.6	55E
22	77	37	356.6	-14.4	-54.3	55F
21	77	17	518.9	20.9	-37.1	55G
20	77	24	344.5	-4.6	-43.2	55H

19	77	25	417.9	-18.9	-65.7	56E
18	77	17	458.7	-16.8	-68.2	56F
17	77	54	565.1	-11.3	-74.6	56G
16	77	61	389.4	-31.5	-75.1	56H
15	77	85	394.7	-46.6	-90.8	57E
14	77	616	531.2	-23.2	-82.7	57F
13	77	720	777.1	10.2	-76.6	57G
12	77	88	759.8	-7.0	-92.0	57H
11	77	90	424.4	-46.6	-94.1	58E
10	77	99	676.2	-14.9	-90.5	58F
9	77	47	310.3	-39.5	-74.2	58G
8	77	58	74.2	-38.6	-46.9	58H
30	78	45	1032.7	-48.4	-163.9	53J
29	78	134	282.0	-100.2	-141.2	53K
28	78	272	203.2	-71.8	-103.4	53L
27	78	204	169.2	-36.5	-55.4	54I
26	78	85	189.3	-34.4	-55.6	54J
25	78	277	250.8	-16.7	-44.8	54K
24	78	158	379.2	-10.9	-53.3	54L
23	78	108	452.8	.7	-49.9	55I
22	78	68	523.0	-9.5	-68.1	55J
21	78	77	520.2	11.1	-47.1	55K
20	78	74	289.8	-14.8	-47.2	55L
19	78	66	336.2	-13.5	-51.1	56I
18	78	86	429.9	-14.3	-62.4	56J
17	78	91	535.9	-9.3	-69.3	56K
16	78	90	462.0	-21.2	-72.9	56L
15	78	174	288.9	-61.1	-93.5	57I
14	78	172	305.3	-52.4	-86.6	57J
13	78	118	621.8	1.4	-68.0	57K
12	78	82	461.8	-32.6	-84.2	57L
11	78	81	345.8	-32.7	-71.4	58I
10	78	37	145.9	-51.4	-67.8	58J
9	78	25	81.5	-40.5	-49.6	58K
8	78	10	11.1	-19.4	-20.7	58L
30	79	4	2225.3	-82.8	-331.7	53N
29	79	26	322.7	-142.8	-176.0	53O
28	79	209	180.7	-124.7	-129.7	53P
27	79	224	150.3	-68.4	-85.2	54M
26	79	109	137.4	-49.0	-64.4	54N
25	79	290	186.3	-25.3	-46.1	54O
24	79	128	287.4	-24.8	-57.0	54P
23	79	117	389.9	-10.7	-54.3	55M
22	79	71	520.6	25.0	-33.2	55N
21	79	70	306.8	-1.3	-35.6	55O
20	79	77	228.2	-14.6	-40.1	55P
19	79	67	198.7	-32.6	-54.8	56M
18	79	110	217.5	-20.2	-44.5	56N
16	79	123	143.6	-54.2	-70.3	56P
15	79	166	141.0	-55.0	-70.8	57M
14	79	210	83.8	-49.4	-58.7	57N
13	79	160	164.0	-53.3	-71.7	57O
12	79	146	128.9	-41.4	-55.8	57P

11	79	53	54.0	-15.1	-21.2	58M
10	79	7	31.3	-10.1	-13.6	58N
9	79	9	3.2	-9.2	-9.5	58O
8	79	2	1.8	-25.3	-25.5	58P
6	79	2	7.0	9.7	8.9	
28	80	190	158.8	-150.4		62D
27	80	240	157.4	-101.4	-117.5	63A
26	80	103	123.6	-73.4	-87.2	63B
25	80	102	131.7	-25.6	-40.3	63C
24	80	112	340.9	-7.4	-45.5	63D
23	80	75	438.6	8.4	-40.6	64A
22	80	52	556.4	30.8	-31.8	64B
21	80	51	333.0	-15.4	-52.6	64C
20	80	71	341.5	-10.1	-48.3	64D
18	80	49	164.2	-37.0	-55.4	65B
17	80	248	121.9	-23.0	-36.6	65C
16	80	756	41.7	-15.1	-19.8	65D
15	80	81	15.1	-12.7	-14.4	66A
14	80	5	9.3	-47.1	-48.1	66B
13	80	30	15.1	-54.3	-56.0	66C
12	80	13	18.0	-18.6	-20.6	66D
9	80	2	3.6	-40.9	-41.4	
8	80	1	87.7	-25.4	-35.2	
7	80	3	237.0	-7.6	-34.1	
6	80	4	632.3	40.1	-30.5	
5	80	1	3.0	39.7	39.3	
28	81	42	139.7	-159.6		62H
27	81	253	120.6	-137.4	-150.4	63E
26	81	69	107.9	-69.6	-81.6	63F
25	81	114	110.1	-30.8	-43.2	63G
24	81	106	327.0	-3.5	-40.1	63H
23	81	60	490.9	-18.1	-73.1	64E
22	81	101	515.5	1.4	-56.2	64F
21	81	176	288.3	-16.9	-49.1	64G
20	81	162	390.1	-8.6	-52.3	64H
19	81	56	543.3	5.9	-54.8	65E
18	81	55	367.0	-20.7	-61.8	65F
17	81	252	107.3	-1.9	-14.0	65G
16	81	174	29.4	-2.6	-5.9	65H
8	81	1	5.1	18.6	18.0	
7	81	2	122.2	5.3	-8.3	
6	81	3	230.7	24.4	-1.3	
27	82	156	110.6	-161.1	-173.0	63I
26	82	186	90.1	-115.1	-126.1	63J
25	82	94	96.3	-35.9	-46.7	63K
24	82	68	275.6	-14.6	-45.4	63L
23	82	48	545.8	-9.8	-70.8	64I
22	82	129	323.6	-15.0	-51.3	64J
21	82	68	273.6	-14.8	-45.5	64K
20	82	19	296.5	-26.3	-59.5	64L
19	82	5	562.4	-1.8	-64.7	65I
18	82	88	699.3	37.2	-40.9	65J
17	82	221	108.3	15.9	3.8	65K

16	82	48	3.9	13.0	12.6	65L
27	83	96	91.2	-180.1	-190.3	63M
26	83	204	81.9	-128.1	-136.6	63N
25	83	84	72.1	-54.3	62.4	63O
24	83	81	240.5	-17.9	-44.8	63P
23	83	53	541.1	10.3	-50.2	64M
22	83	56	419.3	-12.9	-59.8	64N
21	83	102	215.9	-14.3	-38.5	64O
20	83	43	175.1	-17.1	-36.7	64P
19	83	11	296.1	4.9	-28.1	65M
18	83	51	116.5	-12.5	-25.5	65N
17	83	71	45.7	3.5	-1.5	65O
27	84	45	96.3	-182.3	-193.1	72
26	84	254	66.6	-129.3	-136.8	72B
25	84	128	63.2	-72.2	-79.3	72C
24	84	81	171.3	-26.9	-46.1	72D
23	84	52	588.7	28.9	-36.9	73A
22	84	65	424.2	8.1	-39.3	73B
21	84	184	207.9	-5.9	-29.1	73C
20	84	182	277.2	9.1	-21.8	73D
19	84	112	197.3	8.9	-13.1	74A
18	84	36	88.0	-10.9	-20.8	74B
27	85	151	2017.6	0.9	-224.8	72I
26	85	88	53.4	-124.3	-130.3	72F
25	85	158	49.5	-73.6	-79.1	72G
24	85	80	274.8	-7.6	-38.4	72H
23	85	66	482.5	19.0	-34.9	73E
22	85	208	351.3	3.3	-35.9	73F
21	85	220	359.1	3.2	-36.9	73G
20	85	219	67.9	8.6	1.0	73H
19	85	42	5.7	14.7	14.1	74E
26	86	125	320.2	-116.5	-152.3	72J
25	86	207	39.7	-81.4	-85.9	72K
24	86	45	244.7	-11.7	-39.0	72L
23	86	98	206.7	-5.4	-28.5	73I
22	86	159	171.6	-12.4	-31.6	73J
21	86	244	114.0	-16.1	-28.9	73K
20	86	216	7.7	-11.4	-12.3	73L
19	86	13	2.7	-5.6	-5.9	74I
27	87	54	1368.8	-44.9	-198.1	72M
26	87	76	482.6	-106.8	-160.8	72N
25	87	178	57.6	-67.4	-73.9	72O
24	87	69	116.7	8.5	-4.5	72P
23	87	116	70.1	0.0	-7.9	73M
21	87	124	9.2	-20.8	-21.8	73O
27	88	2	2854.7	-109.8	-209.5	78A
26	88	62	117.1	-130.4	-143.2	78B
25	88	88	30.0	-12.3	-15.7	78C
24	88	8	23.3	-22.8	-25.5	78D
23	88	27	16.2	-30.8	-32.6	79A
22	88	30	5.4	-12.0	-12.6	79B
26	89	21	81.9	-87.8	-96.9	78F
25	89	15	47.9	-36.3	-41.7	78G

24	89	2	16.0	-25.3	-27.1	78H
23	89	3	9.3	-20.4	-21.4	79E
22	89	1	3.6	-10.5	-10.9	79F
26	90	49	50.1	-58.5	-64.1	78J
25	90	69	154.6	2.6	-14.6	78K
24	90	2	14.3	-20.4	-22.0	78L
23	90	1	7.9	-23.6	-24.5	79I
22	90	1	3.0	3.5	3.2	79J
26	91	123	66.5	-79.4	-86.9	78N
25	91	47	1026.6	95.7	-19.1	78O
24	91	2	11.1	-56.3	-57.6	78P
23	91	11	90.6	-5.9	-16.0	79M
22	91	2	7.4	-10.4	-11.2	79N
26	92	223	74.1	-97.7	-106.0	83B
25	92	29	768.9	74.6	-11.3	83C
24	92	36	21.5	-67.3	-69.7	83D
23	92	1	1148.4	78.7	-49.6	84A
22	92	1	30.4	-36.1	-39.5	84B
21	92	1	24.9	-12.6	-15.4	84C
20	92	1	3.0	13.4	13.1	84D
11	92	1	26.5	-8.7	-11.6	
27	93	18	101.0	-205.5	-214.8	83E
26	93	162	86.5	-137.0	-146.7	83F
25	93	26	367.1	-19.3	-60.4	83G
24	93	1	783.9	-28.3	-116.0	83H
22	93	1	1865.0	75.9	-132.7	84F
27	94	172	98.1	-202.9	-213.9	83I
26	94	142	105.0	-170.2	-182.0	83J
25	94	4	1244.4	39.7	-99.4	83K
24	94	1	131.9	-131.3	-146.0	83L
23	94	2	120.5	-141.4	-154.9	84I
22	94	2	159.7	-127.0	-144.9	84J
21	94	1	1884.5	115.6	-95.2	84K
20	94	2	132.4	-57.1	-72.0	84L
16	94	2	18.8	-17.2	-19.3	
15	94	1	15.5	6.0	4.3	
27	95	26	116.4	-175.7	-188.7	83M
26	95	1	151.1	-95.8	-112.7	83N
24	95	2	239.7	-7.8	-34.6	89P
23	95	1	586.0	110.9	45.4	84M
22	95	1	76.5	-10.6	-19.2	84N
21	95	1	75.5	-26.6	-35.1	84O
20	95	2	420.4	15.8	-31.2	84P
17	95	2	14.9	-38.0	-39.7	
25	96	1	172.8	-65.5	-84.9	
24	96	2	145.3	-36.7	-53.0	
22	96	2	1097.7	53.4	-69.3	
21	96	2	577.6	11.5	-53.1	
19	96	1	124.6	-21.2	-35.1	
18	96	1	48.4	-18.2	-23.6	
17	96	1	12.1	-11.3	-12.7	
16	96	1	16.7	-5.5	-7.0	

26	97	1	1105.5	3.5	-120.1
25	97	1	143.5	-33.3	-49.4
24	97	1	115.2	-44.4	-57.3
23	97	2	768.8	-12.9	-98.9
22	97	2	647.3	-29.1	-101.5
21	97	1	1056.7	-26.3	-144.5
19	97	1	899.7	10.4	-90.1
18	97	1	138.3	-48.9	-64.4
17	97	1	13.4	-12.5	-14.0
16	97	1	21.0	-6.9	-9.3
15	97	1	2.7	-5.1	-5.4
11	97	1	.9	1.3	1.2
21	98	1	300.2	-84.5	-118.1
20	98	1	680.6	-21.0	-97.1
16	98	1	16.1	-33.1	-34.9
14	98	1	34.4	-25.8	-29.6
13	98	1	10.0	-37.2	-38.3
12	98	1	28.9	-4.0	-7.2
11	98	1	3.0	-6.5	-6.8
10	98	2	26.3	-9.1	-12.0
21	99	1	833.3	-78.9	-172.1
20	99	1	391.3	-41.3	-85.1
12	99	1	12.8	-23.0	-24.4