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CRUSTAL SHORTENING IN THE WEST HIMALAYA

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ABSTRACT

The main collision between the Indian and Asian lithospheric plates occurred during the late Eocene (40 million years ago) and continued closure at the rate of 5 cm/yr has resulted in approximately 2000 km of crustal shortening between the two plates (Molnar and Tapponnier, 1975; Molnar, 1984). In northern India it has been suggested that while some of the shortening is by underthrusting (Molnar and Tapponnier, 1975) much may be the result of diffuse deformation in China (Tapponnier, 1982). However, in northern Pakistan the problem is complicated because there is no Tibetan plateau analog and no evidence of strike-slip structures that could have removed significant amounts of crustal material.

In order to place tighter constraints on tectonic models for the Indian-Asian collision in the western Himalaya it is important to be able to estimate the amount of crustal shortening that has occurred. Current estimates of 500 of 700 km of convergence in northwestern Pakistan (Butler, 1986), are calculated from balanced cross section methods. This is significantly less than the 2000 km required by closure models based on paleomagnetic data (Powell, 1979; Molnar and Tapponnier, 1975; Molnar, 1984).

An important step in estimating the amount of shortening that has occurred is to determine the volume of crust that remains in the orogen. The crustal models based upon observed gravity profiles presented in this paper suggest that there may be enough crustal volume to account for between 550–1100 km of shortening. This is still significantly less than the 2000 km of closure that has presumably occurred. The balance of the closure might be accounted for by erosion and/or diffuse deformation or it might suggest that less than 2000 km of closure has occured in the northwestern Himalaya.

INTRODUCTION

The northward migration of the Indian lithospheric plate and its subsequent collision with the Eurasian plate has been well documented by magnetic reversals on the floor of the Indian ocean (Powell, 1979). The main collision occurred during the late Eocene (40 million years ago). At that time the rate of migration of the Indian plate dropped from 10 cm/yr to 5 cm/yr (Molnar and Tapponnier, 1975) and continued closure at the rate of 5 cm/yr may have resulted in approximately 2000 km of crustal shortening (Molnar and Tapponnier, 1975; Molnar, 1984). A major unanswered question is, "How has this shortening been accommodated?" While a large portion of the convergence in northern India, perhaps as much as 1500 km, has been taken up by either thrusting of Indian lithosphere beneath Asia (Barazangi and Ni, 1983) or diffuse deformation within Asia (Molnar and Tapponnier, 1975; Tapponnier et al., 1982), in northern Pakistan the mechanism for crustal shortening is less clear.

The amount of convergence accommodated by deformation along the Himalayan front has been estimated for rocks both in northern India (Gansser, 1964; Burg and Chen, 1984) and northern Pakistan (Coward and Butler, 1985; Butler, 1986). However, the shortening estimates in these two areas are considerably different. In northern Pakistan 500 to 700 km of convergence, calculated from balanced cross section methods, is thought to be taken up along thrust faults (Butler 1986). While in India thrusting accounts for only 200 km of shortening (Burg and Chen, 1984). Because of the discrepancy in shortening estimates different tectonic models have been proposed for these two regions. One model, for northern Pakistan, suggests that large amounts of convergence (150 of the 700 km) are accommodated by thrusting of unimbricated Indian crust under Asia (Butler, 1986). An alternative tectonic model, involving whole crustal imbrication with little overriding of Asia over Indian crust, is proposed to explain the 200 km of shortening observed in northern India (Mattauer, 1985). However, at present, there are insufficient quantitative constraints to determine if the differences in convergence observed in these two regions are due to different tectonic processes or an artifact of the methods used to estimate horizontal shortening.

This study attempts to place quantitative constraints on the amount of convergence taken up by crustal thickening in northern Pakistan using two-dimensional modeling of gravity data to estimate the amount of crustal material that remains within the orogenic belt. For example, if all of the 2000 km of convergence between the Indian and Asian plates were accommodated by crustal thickening, then we should be able to account for 60,000 km^2 of crust in the Pakistan Himalaya (2000 km length X 30 km average crustal thickness before collision). The balanced cross section studies (Butler, 1986) estimate that approximately 470 kilometers of shortening has occurred between the Punjab foreland and the MMT (Coward and Bulter, 1985) and that up to 200 kilometers more may exist intact beneath the Kohistan Arc terrane and the Karakoram (Butler, 1986, figure 10). This would suggest a total shortening of almost 700 kilometers across the orogen. However, if the 2000 km closure number is correct, then 1300 km still must be accounted for. Some of this material may have been eroded off and some of it may remain in the orogen. Modeling of the gravity data provides an estimate of how much remains in the orogen.

GEOLOGIC AND TECTONIC SETTING OF THE STUDY AREA

Greatly simplified, the tectonic history of the northwest Himalaya involved: 1) pre- and early Tertiary accretion of Gondwanan fragments, 2) Eocene collision with Gondwana proper, and 3) continued post collisional deformation by underthrusting, imbrication and uplift. During the accretionary events, arc magmatism occurred, resulting in large igneous complexes.

The geology and structure of the area (Fig. 1) has been well documented by several investigators. Tahirkheli (1979a, 1979b, 1982, 1983) has shown that in northern Pakistan, the Indus Suture Zone bifurcates into two structural zones, the Main Mantle Thrust (MMT) and the Main Karakoram Thrust (MKT) (Fig. 1). These structures are sutures that surround the Kohistan Arc terrane which has been interpreted as an obducted island arc (Coward et al., 1982a,

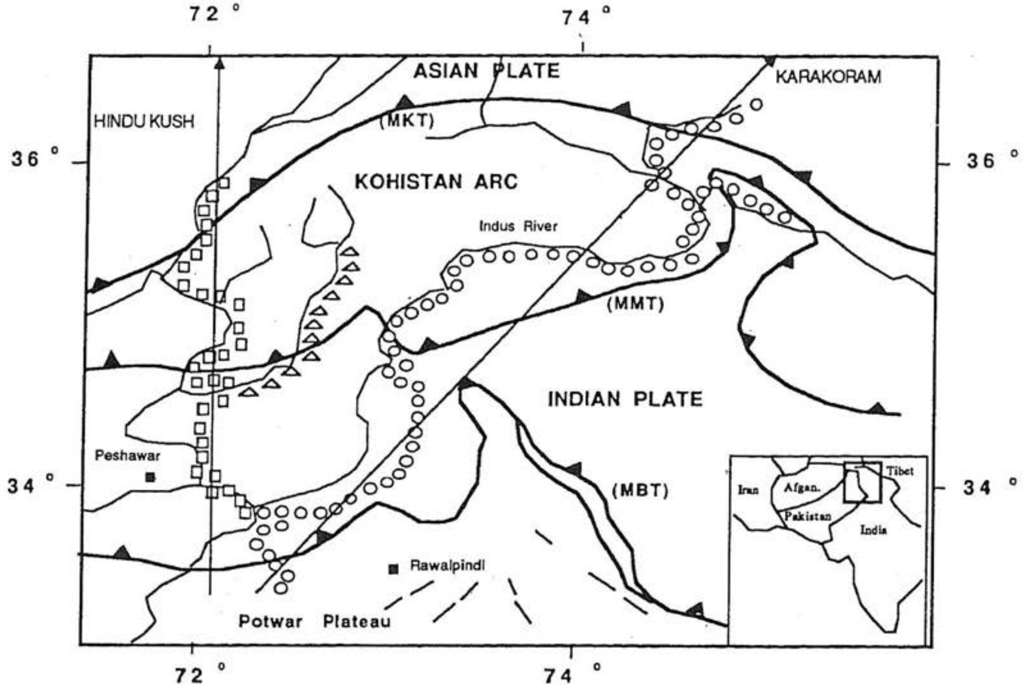

Fig.1. Structural trends in northern Pakistan. The open squares, circles and triangles show the location of the recently aquired gravity data in northern Pakistan (Malinconico and Adams, 1986).

1982b). The northern suture, the Main Karakoram Thrust (MKT), separates the intrusive and high-grade metamorphic rocks of the Eurasian plate from the Kohistan Arc terrane. The Kohistan Arc terrane has, on the northern edge, deformed gabbros, volcanics and greywackes (Rakaposhi Volcanic Complex) that are intruded by tonalites, diorites and pegmatites. To the south, the rocks are composed of a deformed, layered igneous complex metamorphosed to granulite facies (Jan, 1979). The southernmost rocks of the Kohistan Arc are metasediments, amphibolites and granites. The southern suture, the Main Mantle Thrust (MMT), separates the Kohistan Arc from the metasediments on the northern edge of the Indian plate. The northern edge of the MMT is marked by sporadic occurrences of ultramafic rocks (Tahirkheli, 1979a, 1979b, 1982). The Indian plate rocks are late Precambrian to early Paleozoic schists, marbles, gneisses and granitic gneisses that have been thrust southward over younger sediments. In turn, these have been thrust southward over the Tertiary molasse sediments of the Rawalpindi and Siwalik Groups. Southward thrusting continues within the molasse sediments and evidences the continued convergence of the Indian and Asian plates.

PREVIOUS STUDIES

Geophysics

From an historical point of view, some of the earliest studies of deep crustal structure were first conducted in the Himalaya in an attempt to explain the deflections of a plumb bob (from the vertical) observed by the British survey teams in northern India (Pratt, 1855). Two different proposals were made (Airy, 1855; Pratt, 1859) to explain the observed deflections which subsequently led to the development of the concept of isostacy (Dutton, 1889).

More recently, Lyon-Caen and Molnar (1983), in northern India, and Duroy (1986), Duroy et al. (1989), in the foreland of Pakistan, have used observed gravity data and flexural models to constrain the crustal structure.

In northern Pakistan, much of the early gravity studies were conducted by A. Marussi (1976, 1980) and his colleagues (Ebblin et al., 1983). These compiled gravity data were used to produce generalized Free-Air and Isostatic anomaly maps of the Hindu-Kush and Karakoram and to estimate the crustal thickness at certain locations.

Just to the south of the orogenic belt, Farah et al. (1977) and more recently Duroy (1986) and Duroy et al. (1989) have used gravity data to model the structure beneath the Punjab Plain. These gravity models have been correlated with seismic reflection profiles and in this region show a gently dipping Moho 35 kilometers deep (Lillie and Yousef, 1985; Lillie et al. 1985, 1986).

Malinconico (1986) has collected new, higher resolution gravity data that were then used to model the shallow crustal structure of the Kohistan Arc terrane in northern Pakistan. These results showed that the structures (MMT and MKT) bounding the Kohistan terrane were both dipping northward at angle between 35 to 50° and that the Arc terrane was 8 to 10 kilometers thick.

In addition to determinig crustal structure, gravity data have also been used to determine crustal thickness in Pakistan. For example, using a maximum gravity anomaly value of -450 mgals and the empirical relationships worked out by several investigators (Worzel and Shurbet, 1955; Demenitskaya, 1958; Andreev, 1958; Wollard, 1959; Wollard and Strange, 1962; Choudhury, 1975) the average crust in the Hindu Kush/Karakoram in northern Pakistan was estimated to be 67 km (±6). However, this yields only a spot estimate of the crustal thickness in the Pakistan Himalaya. What is needed is a series of crustal thickness profiles across the whole of the orogen. Some of these data have already been collected (Malinconico, 1986; Malinconico and Adams, 1986) along traverses that run normal to the strike of the orogenic belt. When these data are combined with the data compiled by Marussi (1976) and others (Ebblin et al., 1983; McGinnis, 1971; Defense Mapping Agency - Bouguer Gravity Map of Asia, 1973), it is possible to construct extremely long gravity profiles that cross the whole of the orogenic belt.

RESULTS

Figures 2 and 3 show preliminary results from two of the gravity profiles. The locations of these two traverses are shown on Figure 1. The symbols on the map are the same as the symbols in Figures 2 and 3, and they represent the locations where new gravity readings were made (circles and squares for the eastern traverse and circles for the western traverse). Each symbol actually represents five to six measurements. This resulted in a spacing of approximately 2 km between readings. All of the new gravity values have been corrected for drift, elevation and terrain and reduced to the IGSN71 reference plane.

While the newly acquired data stop at the northern political boundaries in Pakistan, the

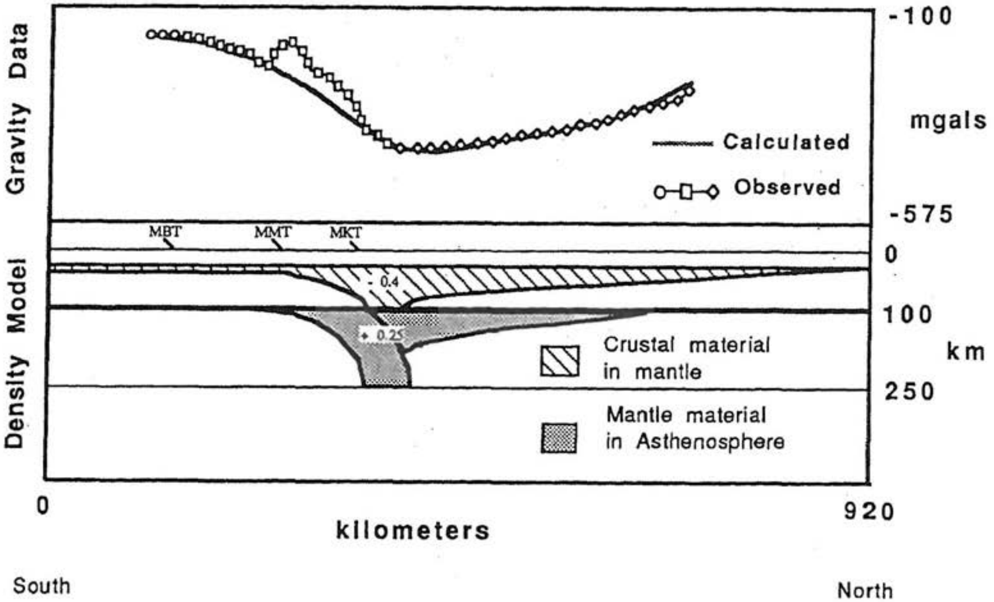

Fig. 2. Density model of the deep crustal structure across the Karakoram in northern Pakistan along the western traverse. Each symbol in the upper window represents approximately five gravity observations. The symbols correspond to those in Fig. 1. Note that the horizontal distance for this traverse is 920 km. There is no vertical exaggeration in the density model

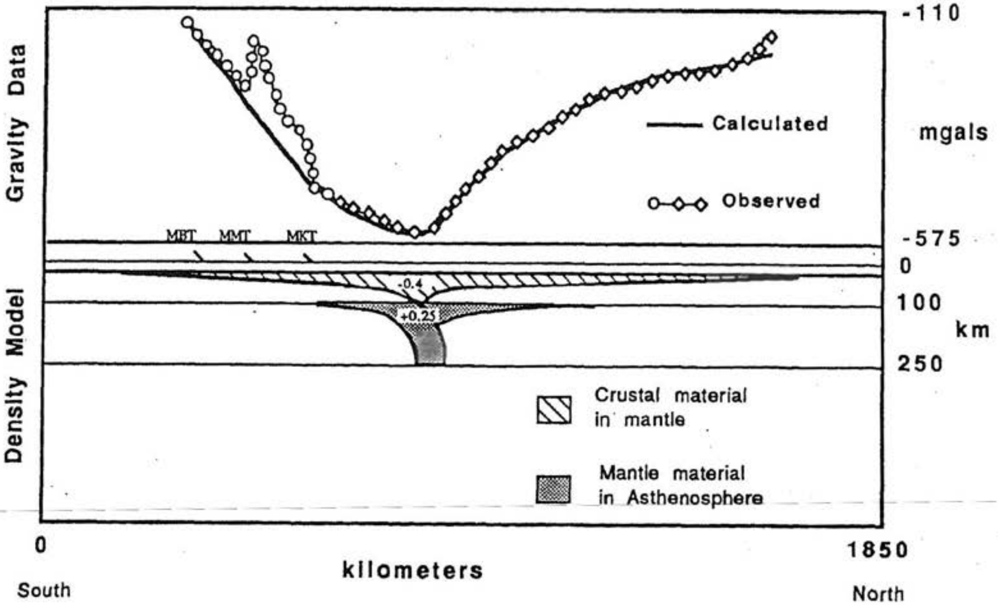

Fig. 3. Density model of the deep crustal structure across the Karakoram in northern Pakistan along the eastern traverse. Each symbol in the upper window represents approximately five gravity observations. The symbols also correspond to those in Fig. 1. Note that the horizontal distance for this traverse is 1850 km, twice as long as in Fig. 2. There is no vertical exaggeration in the density model.

gravity anomaly continues to the north. In order to adequately model the deep crustal structure it was necessary to obtain a complete picture of the shape of the anomaly. This was done by compiling data available from a variety of sources (Marussi, 1976; Ebblin et al., 1983; McGinnis, 1971; Defence Mapping Agency-Bouguer Gravity Map of Asia, 1973). The observed lines in Pakistan were then extended to the north (western line) and north-northeast (eastern line) using these compiled data. These data are shown as triangles in Figures 2 and 3.

While there are short wavelength variations in the gravity anomalies, the long wavelength -450 mgal and -550 mgal anomalies are the dominant features. These large negative anomalies are the result of the increased crustal thickness caused by the underthrusting (or imbrication) of the Indian plate beneath the Asian plate. Using techniques developed by Talwani et al. (1959) and modified by Malinconico et al. (1986) two-dimensional models have been constructed to determine the crustal structure beneath the two profiles (Figs. 2 and 3). Three major anomalous density areas are used in the models. The first is the region where crustal material resides in the mantle (below 30 kilometers). A negative density contrast of approximately -0.4 was assigned to this polygon. No attempt has been made to differentiate between crust from the Indian or Asion plates. The second and third polygons represent mantle material from the lower lithosphere which is now located in the asthenosphere. These polygons were given a density contrast of +0. 25 and they extend to a maximum depth of 250 km. The shape and depth of the models were constrained by structural interpretations based on seismicity in western Pakistan and eastern Afghanistan made by Tapponnier et al. (1981).

OBSERVATIONS

There are two important observations that can be made from the density models shown in Figures 2 and 3. These models allow us to estimate the amount of crustal material that remains in the orogenic belt in the northwestern Hiamalaya. This is done simply by measuring the cross-sectional area of crust below a depth of 30 kilometers for each of the traverses. For the western traverse this amount is equal to approximately 16,300 km^2 while the amount for the eastern traverse is 32,400 km^2. If we now presume that the crust of the Indian plate averaged 30 kilometers in thickness, it is possible to calculate the amount of closure that the accumulated crustal material represents. For the western traverse this is approximately 550 km (16,300 km^2/30) and for the eastern traverse approximately 1100 km (32,400 km^2/30 km). Both of these values are significantly less than the 2000 km (60,000km^2) required by a 5 cm/yr migration over 40 my, but are equal to or greater than the amount estimate by Butler (1986). If these numbers are valid, there appears to be a difference between the amount of underthrusting, or at least the amount of crustal material accumulated, as one progresses from west to east. This may reflect some change in tectonic style as one approaches the rapidly uplifting Nanga Parbat massif (Zeitler, 1985; Zeitler et al., 1982, 1986).

These estimates of 550 to 1100 km of crustal thickening do not help to settle the question of mechanism of thickening, i.e. crustal imbrication versus unimbricated underthrusting, however, it does help place constraints on how much material still has to be accounted for. In the case of the higher value (1100 km), 900 km is still unaccounted for. There are three possibilities for the missing material:

1) As has been suggested for the Himalaya of northern India (Molnar and Tapponnier, 1975; Tapponnier et al., 1982), diffuse deformation has occurred.

2) Erosion has removed some of the material.

3) 2000 km worth of closure have not occurred in this region.

The second observation that can be made from these models concerns the nature of the underthrusting that may be occurring in the northwestern Himalaya. Models for the Himalaya in northern India have suggested that underthrusting is occurring at a very shallow angle. However, the models shown in Figures 2 and 3 suggest that this may not be the case for the Himalaya of northwestern Pakistan. Under the Potwar Plateau (see Figure 1) the Indian plate is underthrusting at a very shallow angle, in a fashion similar to the flexure models presented by Duroy (1986) and Duroy et al. (1989). However, this situation changes very rapidly just north of the Kohistan Arc terrane where the gravity anomaly reaches the maximum negative values. At those points, the Indian plate is deflected very steeply downward and is underthrusting at nearly vertical attitudes. As was the case with the crustal structure models presented by Tapponnier et al. (1981), it is not possible to determine the direction of underthrusting uniquely. Especially with the eastern traverse, it is possible to model the gravity data with an Asian plate underthrusting the Indian plate. However, even this model (not shown) suggests that underthrusting is occurring at a very steep angle.

SUMMARY

In order to place tighter constraints on tectonic models for the Indian-Asian collision in the western Himalaya it is important to be able to estimate the amount of crustal shortening that has occurred. Current estimates for shortening in northwest Pakistan (Butler, 1986), based on balanced cross sections, predict amounts that are significantly less than the 2000 km required by closure models (Molnar and Tapponnier, 1975; Molnar, 1984).

An important step in estimating the amount of shortening that has occurred is to determine the volume of crust that remains in the orogen. The crustal profiles based upon models of the observed gravity data presented in this paper suggest that there may be enough crustal volume to account for between 550—1100 km of shortening. This is still significantly less than the 2000 km of closure that has presumably occurred. The balance of the closure might be accounted for the erosion and/or diffuse deformation or it might suggest that less than 2,000 km of closure have not occurred in the northwestern Himalaya.

The crustal models also suggest that the style of underthrusting in the northwestern Himalaya may be significantly different than that proposed for the Himalaya of northern India. Here the underthrusting seems to be occurring at a very steep angle when compared to the shallow underthrusting proposed for India.

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