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Gravity Inversion in Qinghai-Tibet Plateau

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Abstract. Due to its high elevation and high seismicity the Qinghai-Tibet plateau takes a primary position on the earth surface. The inaccessibility of the region makes geophysical studies difficult. Active seismic sounding is available along essentially one line crossing the eastern part of the plateau. In such a situation gravity is a powerful method to obtain information on the crustal structure. We apply an inversion of the gravity field throughout the entire plateau. The inversion is limited to the long-wavelength band of the field, which has been shown by spectral analysis to be generated at lower crustal levels. The field is inverted in terms of the oscillation of a boundary layer with strong density contrast. This boundary is identified with the crust-mantle discontinuity (Moho). A map of the 3D oscillations of the Moho is presented and the properties discussed along 4 profiles cutting the plateau longitudinally and transversally.

Keywords: Qinghai-Tibet Plateau, gravity methods, Moho

1. Introduction

In the present paper we aim at discussing the properties of the deep crustal structure throughout the area defined as the Qinghai-Tibet plateau, applying an inversion technique to the observed gravity field. In general terms the high elevation of the Tibet-Qinghai plateau and the Himalayan mountain chain is the product of the collision of the Indian and Eurasian tectonic plates. Different theories exist to explain details of the evolution of the thickened crust, as exposed e.g. in Keary and Vine (1996, p.180 ff.). It has been proposed that the thickened crust is the result of underthrusting of the Indian plate and a consequent doubling of the crustal thickness, the buoyant forces of which would explain the high elevations. An alternative theory proposes crustal thickening due to overthrusting of several crustal blocks along a series of thrust faults (Allègre et al., 1984). The results of Hirn et al. (1995) are consistent with the sequential crustal thrusting, as no evidence of Indian lithosphere beneath central Tibet could be found. Our interest is focussed on determining the depth of the crust-mantle boundary, or equivalently the Moho undulations from existent gravity data. As is known, constraints are necessary in the development of any gravity inversion. In a highly inaccessible area, as is the Tibet, it must be realized that results coming from active or passive seismic sounding are scarce. In fact the only seismic sounding investigations available run along essentially one profile (Yadong-Golmud), crossing the Eastern part of the plateau in a SW-NE direction (e.g. Wu et al., 1991 a,b). Any attempt of modeling the entire crust must thus be disregarded. In our study we attempt at modeling a limited wavelength band of the gravity values, which presumably in its greater part is generated at Moho level. The model consists of the undulations of a sheet demarcating a strong density contrast, identified as the crust-mantle boundary. The gravity contributions due to masses above the crust-mantle boundary are greatly eliminated by frequency filtering procedures. The contributions of masses below the boundary are modeled basing on a lithospheric thickness model obtained from the propagation of seismic surface waves.

The method used for inversion is a hybrid iterative inversion scheme, in which the downward continuation is alternated with the complete evaluation of the gravity field by approximations with right rectangular prisms. The inversion method is well established and has been tested on synthetic situations and applied to the modeling of the Moho in NE-Italy (Braitenberg et al., 1997; Zadro and

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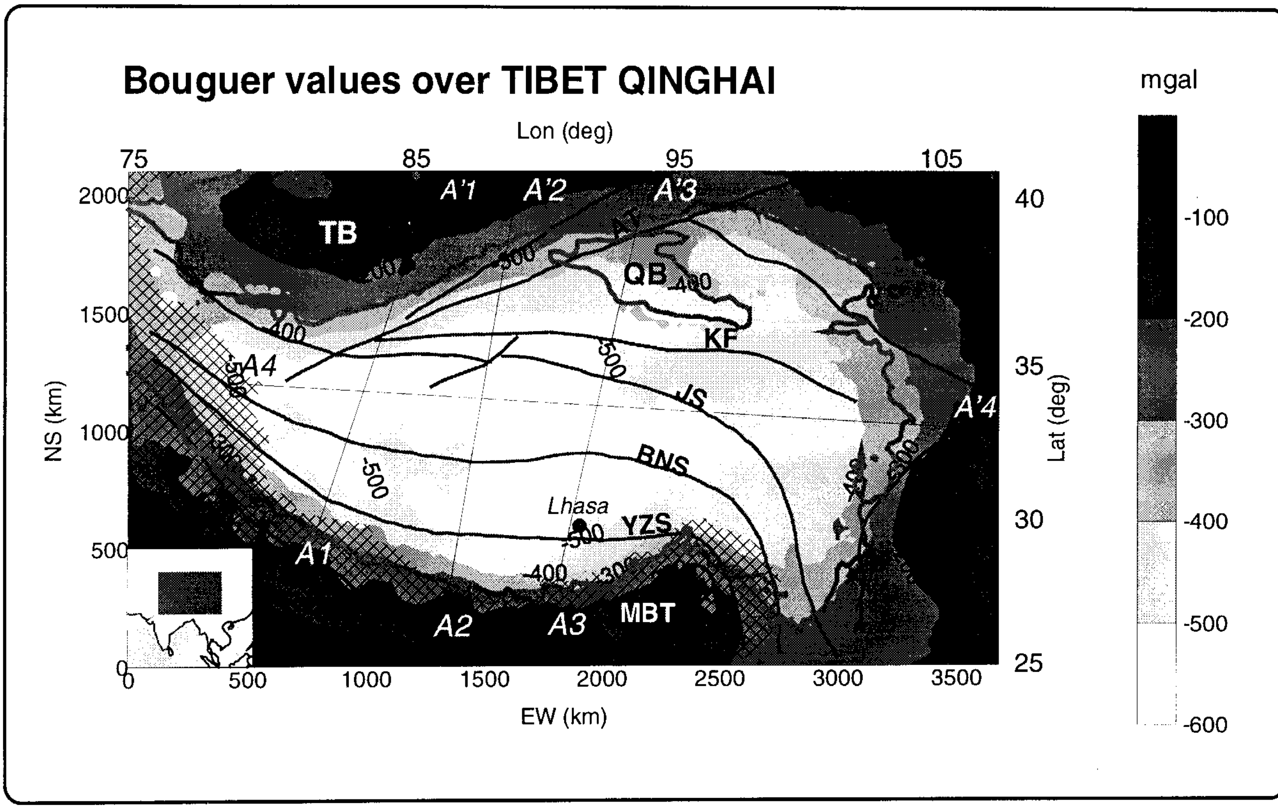

Fig. 1. Map of the Bouguer gravity field. Superposed as bold gray line is the outline of the Tibet-Qinghai plateau, defined as the 3000 m topographic isoline. The hatched area marks the region for which no detailed gravity data were available. Profiles 1 to 4 are identified as lines AA'1 to AA'4, respectively. Main tectonic lines are Main Boundary Thrust (MBT), the Yarlung Zangbo Suture (YZS), the Bangong Nujiang Suture (BNS), the Jinsha Suture (JS), the Kunlun Fault (KF) and the Altyn Tagh line (AT). The Tarim basin (TB) and Qaidam basin (QB) are marked. The inlay shows location of the studied area (grey rectangle).

Braitenberg, 1997; Braitenberg and Zadro, 1999) and in Kohistan (Braitenberg and Drigo, 1998). Previous studies of the gravity field over Tibet have been carried out by Jin et al., (1994; 1996). Jin et al. (1994) discuss the statistical properties of the gravity field. The analysis of the spectrum allowed them to conclude that essentially three depths can be distinguished at which the gravity field is caused: a mid-crust discontinuity is responsible for the gravity field with wavelengths less than 150-200 km. Lower wavelengths up to 500 km are seated at the Moho level, which for Tibet is at about 60-70 km depth; longer wavelengths should be ascribed to lithospheric thickening. In the later paper (Jin et al., 1996) six 2.5 D models are made along profiles crossing Tibet. The Bouguer values are modeled using a flexure model of the colliding Indian and Eurasian lithospheric plates and a prediction of the Moho depth based on the Airy linear relationship.

Another study of the gravity field was made by Wang and Hsu (1996) considering the admittance and coherence functions of topography and Bouguer gravity anomalies. Also they find that surface and subsurface loads are supported by a combined effect of the strength of the lithosphere and an Airy type local compensation.

2. Gravity inversion

The gravity data used for the inversion are 10'x10' gridded Bouguer anomalies. Resources were based on the Chinese gravity network 85, with height reference the Yellow Sea (Sun, 1989). The gravity data were reduced using the Helmert gravity formula. A complete terrain correction was made, with a maximim radius of 166.7 km and using a topographic density of 2.67 10^3 kg/m^3. In order to obtain data coverage over a rectangular grid, which necessarily goes beyond the Chinese border, the data were integrated with Bouguer gravity values derived from the IGG97L (Institute of Geodesy and Geophysics, CAS, Wuhan) earth gravity model (Hsu and Lu, 1995; Lu et al., 1998). This model is complete to degree and order 720 in China and available on a 30'x30' grid. The combined data set was interpolated on a grid of 20 km x 20 km spacing, extending over 2540 km in NS and 3900 km in EW direction (geographic window lon. 75°-105°, lat. 25°-43°). In **Fig. 1** a map of the Bouguer gravity field is given. Superposed as bold gray line is the outline of the Tibet-Qinghai plateau, defined as the 3000 m topographic isoline. The hatched area marks the region for which no detailed gravity data were available. The plateau, with its mean topographic height of 5000 m is characterized by low

Bouguer values ranging between -600 and -400 10^{-5} m/s^2. The smaller anomalies are found in the North-Eastern part of the plateau. The surrounding areas have much less negative Bouguer anomalies ranging between -250 and 0 10^{-5} m/s^2. The four profiles traced in the graph will be discussed in the sequel.

The Moho is modeled as the oscillations of the crust-mantle density discontinuity interface. The oscillations of the boundary are with respect to a reference depth (*d*), which is the depth of the crust-mantle interface of the reference earth model. The reference depth can also be interpreted as the depth of the Moho for zero Bouguer anomaly oscillations.

The inversion being limited to the Moho level, the gravity field must be freed from gravity contributions arising from masses above and below the Moho. Regarding the contribution of the deeper seated masses we adopt a lithospheric thickening model obtained from the study of surface wave propagation (Zhou et al., 1991). The reference model is a lithosphere of 90 km thickness, and deviations are approximated with rectangular prisms of 220 km x 220 km sides. The density contrast of lithosphere to asthenosphere is set to 0.04 10^3 kg/m^3. We obtain that the gravity effect is of very long wavelength and is nearly uniform over Tibet, amounting to about 50 10^{-5} m/s^2.

The contributions of masses above the Moho level are taken off by filtering processes, using the result of Jin et al. (1994) that the wavelength of 150 - 200 km separates the field generated at and above mid-crust from that generated at Moho level. The filter we use is a circularly symmetric modified Hamming frequency filter defined as:

$$\begin{aligned} H(s) &= 0.5(1+\cos(\pi s p_{\min})) && s \le 1/p_{\min} \\ H(s) &= 0 && s > 1/p_{\min} \end{aligned} \quad (1)$$

with p_{min} the cut-off wavelength. The cut-off wavelength (p_{min}) is set to 200 km.

At the first step of the inversion the gravity field is downward continued to a level *d* below the surface and the mass distribution of a flat sheet set at the same depth *d* is evaluated (Tsuboi, 1983, p. 114). The sheet mass is interpreted in terms of the oscillations of a density discontinuity surface with density contrast $\Delta\rho$. The gravity effect of the oscillating surface is evaluated by approximation with rectangular prisms (Nagy, 1966), and the residual gravity is obtained from the difference with the observed gravity. The residual gravity is then downward continued to calculate a correction to the sheet mass distribution. This sequence of operations defines the procedure of the inversion, which is repeated iteratively (Braitenberg et al., 1997; Zadro and Braitenberg, 1997). In the present case the inversion is made under the assumption of constant density contrast across the interface. The number of iterations is fixed to three in this case. It is found that in the first three iterations the gravity residual is reduced by 30%, but further iteration steps do not produce a further reduction.

Table 1. Root mean square error of the Moho depth obtained from gravity inversion and the constraining Moho depths from deep seismic sounding.

Depth (km)	*Density contrast (10^3 kg/m^3)*			
	0.50	***0.45***	***0.40***	***0.35***
45	6.2	8.2	12.8	17.4
40	4.7	4.5	7.2	12.1
35	8.0	5.5	4.2	7.2
30	12.7	9.9	6.4	4.2
25	17.8	14.9	10.7	6.4

The inverted Moho depends sensitively on the two parameters, the reference depth (*d*) and the density contrast ($\Delta\rho$). These two parameters are not known for the studied area, wherefore different geophysically plausible couples have been considered. In order to constrain the inversion we have used the results of the two existing seismic sounding investigations made in Tibet, the INDEPTH (Nelson et al., 1996) profile and the Yadong-Golmud profile (Hirn et al., 1984; Wu et al., 1991a,b). The INDEPTH profile covers in more detail a section of the older Yadong-Golmud profile. In **Table 1** the rms (root mean square) deviation of the seismic Moho from the gravity Moho for different couples of reference depth and density contrast is given. The seismic data do not constrain the possible couples of reference depth and density contrast univocally and compatible couples are d=35 km, $\Delta\rho$=0.40 10^3 kg/m^3 and d=30 km, $\Delta\rho$=0.35 10^3 kg/m^3. We have chosen the couple d=35 km, $\Delta\rho$=0.4 10^3 kg/m^3 for the remainder of the paper. A different couple, chosen among the couples with comparable rms deviation does not considerably alter the results. Rather, a nearly constant bias is produced, which defines the uncertainty with which we may determine the Moho. This uncertainty amounts to about 5 km, which is comparable to the uncertainty of the Moho determination by seismic sounding. The map of the Moho depths is shown in **Fig. 2**. The properties of the Moho are discussed along the four profiles shown, of which profiles 1 to 3 cut the plateau transversally, and the fourth runs along the plateau.

3. Discussion

Main features of the Moho depths underlying the Tibet-Qinghai plateau area are a thickened crust beneath the plateau of 70-75 km thickness. The Moho isolines reveal some correlation with the main tectonic lines, this observation being valid over the plateau as also along its borders. The Moho below the Tarim basin is at 40-45 km depth. Shallower values of Moho are also found in the NE part of the plateau, approximately in correspondence of the location of the Qaidam basin.

The **Figs. 3a, b, c, d** show the Bouguer values, the topography and the Moho along the profiles. The heavy lines show the weighted mean values at steps of 20km,

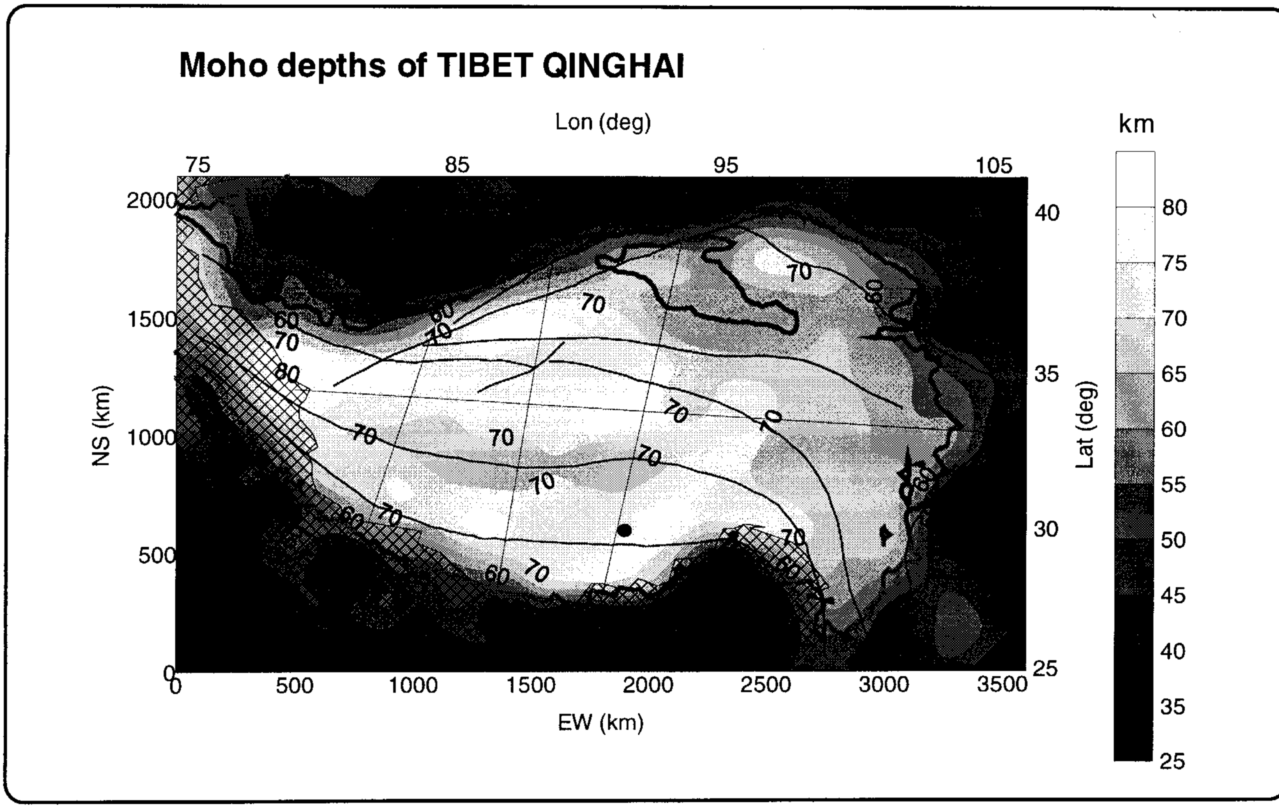

Fig. 2. Moho depths obtained from the gravity inversion (compare Fig. 1)

evaluated over a swath 100 km wide. The weights are inversely proportional to the distance of the data points from the profile. The thin lines give the maximum and minimum values found at each step over the swath. The comparison of the three transverse profiles (**Fig. 3a-c**) with the longitudinal profile (**Fig. 3d**) reveals the essentially flat nature of the plateau in the east-west direction. The small variation of the values is valid for the Bouguer anomalies, the topography and the Moho depth. The transverse profiles (**Fig. 3a-c**) show the sharp variation in topography, gravity values and Moho depth when approaching the plateau from North or South. On profiles 2 and 3 (**Fig. 3b, c**) it can be seen that the Northern flank is less steep than the Southern, which is found equivalently also in the variations of the Bouguer values and the Moho depth. The point at which the first derivative of the curves goes from a highly positive or negative value to zero in correspondence of the flanks is shifted plateau-inwards for the Bouguer anomalies, when compared to topography. This is observed also for the Moho depths. For what concerns the Moho, all three transverse profiles show that inwards from the border of the plateau the Moho presents a trough. The trough-axis is offset inwards by up to roughly 200 km from the border of the plateau.

Along the profiles the intersections with the major tectonic lines are marked. The shortcuts are YZS for Yarlung Zangbo suture, BNS for Bangong Nujiang suture, JS for Jinsha suture, KF for Kunlun fault, AT for the Altyn Tagh fault. In correspondence of the Bangong Nujiang (BNS) suture a Moho high is found on all three profiles. The Moho high along the Bangong Nujiang (BNS) suture is also evident in the map of the Moho depths (**Fig. 2**). Only in the central profile (profile 2) does the Yarlung Zangbo suture (YZS) coincide with the axis of a Moho trough. On the western and eastern profile the suture is shifted southwards of the trough axis. A less pronounced Moho high is seen on the two eastern profiles (**Fig. 3b, c**) at the approximate position of the Jinsha suture (JS).

4. Conclusion

The present work aims at constructing a model of the Moho undulations in the area of the Tibet-Qinghai plateau. The Moho is defined as the oscillating boundary of a strong density contrast, which is interpreted as the transition from lower crust to mantle. The density contrast across the boundary and the depth of the boundary in the case of undisturbed crust are obtained during the inversion process using the constraints of existing active seismic sounding profiles. The best fitting couples are 0.35 10^3 kg/m^3 and 30 km or 0.40 10^3 kg/m^3 and 35 km for density contrast and reference depth, respectively. The value of the best fitting density contrast is related to the depth of the crust-mantle boundary of the reference model, and vice-versa. The uncertainty in the couple of density contrast and reference

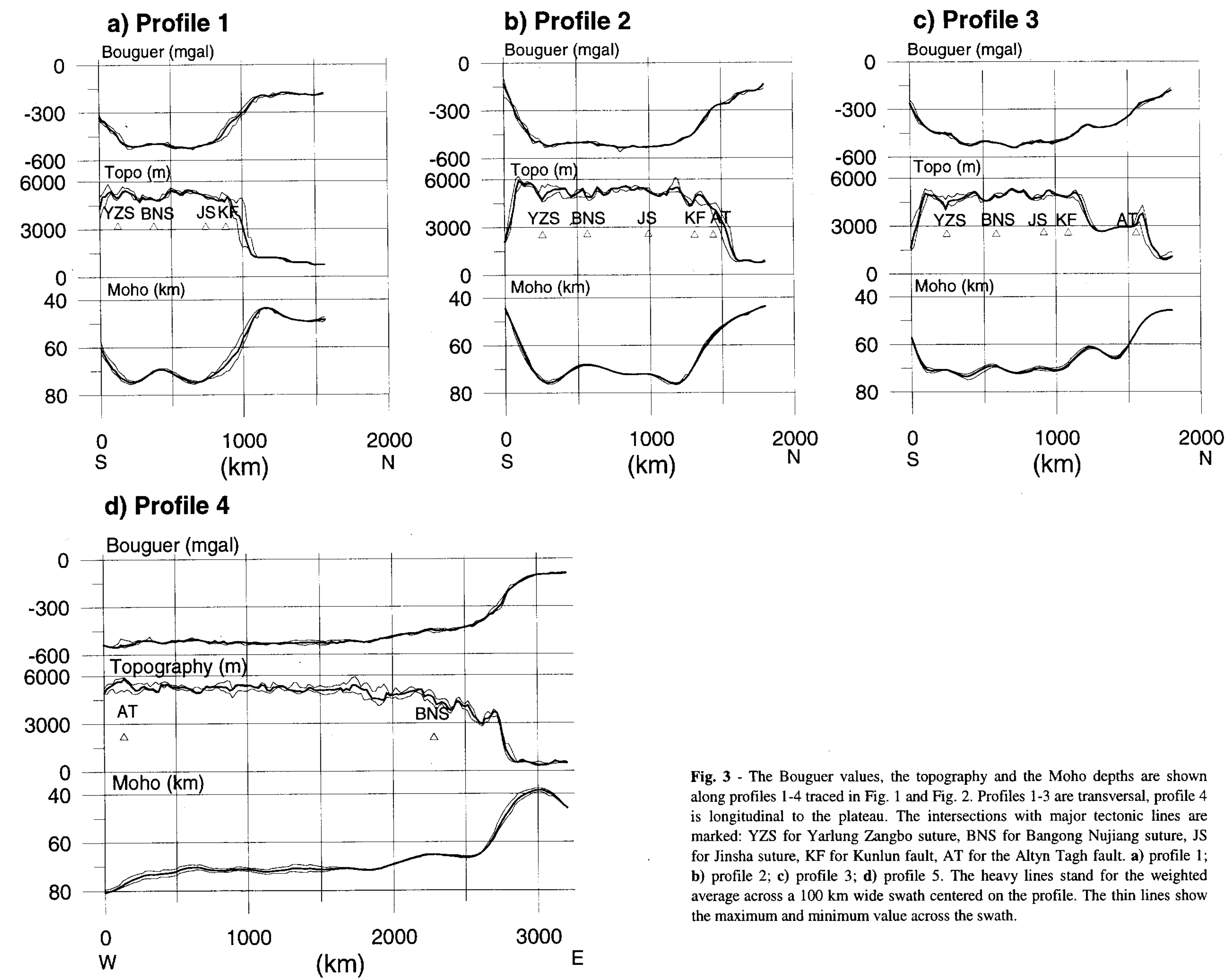

Fig. 3 - The Bouguer values, the topography and the Moho depths are shown along profiles 1-4 traced in Fig. 1 and Fig. 2. Profiles 1-3 are transversal, profile 4 is longitudinal to the plateau. The intersections with major tectonic lines are marked: YZS for Yarlung Zangbo suture, BNS for Bangong Nujiang suture, JS for Jinsha suture, KF for Kunlun fault, AT for the Altyn Tagh fault. **a)** profile 1; **b)** profile 2; **c)** profile 3; **d)** profile 5. The heavy lines stand for the weighted average across a 100 km wide swath centered on the profile. The thin lines show the maximum and minimum value across the swath.

depth can be reduced in the future, if more constraining values for the depth of the Moho will be available. Presently, with the seismic constraints being confined along only one profile, the uncertainty in the density contrast and reference depth translates to a possible bias of the Moho depths of about 5 km.

The Moho model accounts for most of the observed gravity signal with wavelengths greater than 200 km. The contribution of the lithospheric thickening is of about 50 10^{-5} m/s^2, and is an almost constant value over the Tibet-Qinghai plateau. The Moho-model explains the greater part of the Bouguer signal, the residual field having amplitudes of less than 10% of the observed field.

Our result assumes a constant density contrast throughout the area. The plateau being formed by suturing of different tectonic blocks, it cannot be excluded that lateral variations of density contrast are present. A Moho deepening could thus be substituted by a shallower Moho, overlain by a low-density lower crust. Analogously, a high density lower crust would show up in the inversion as a Moho high. At the present stage of knowledge it is not possible to introduce further details on the density structure of the crust, as sufficient further information is not available. In the future we intend to compare the Moho obtained from gravity inversion with the expected Moho from isostatic models.

Presently we may observe that the simple Airy isostatic model does not fit the observations, as the transverse profiles have shown that the Bouguer anomaly and the inverted Moho do not reveal the features of topography, which it would be in the Airy hypothesis. We have shown that the steepness of change of topography along the border of the plateau is much greater than that of the Bouguer anomaly and the Moho depth. Furthermore the Bouguer minimum values are shifted plateau-inwards with respect to the maximum topographic elevation. This indicates that the crustal flexural rigidity is different from zero, and that the plateau is partly sustained by flexural forces.

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