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Abstract	The Kohistan Ladakh area in northeastern Pakistan is an exposed top to bottom crustal section, implying that high density rocks of the lower crust are at the surface. The new GOCE satellite observations improve the gravity field in this remote area, giving a new dataset for geophysical interpretation. We use the new data to determine the crustal thickness variations and to define the geometry of the overturned crustal columns constituting the base of the former island arc. For the first time the entire extension of the arc is traced with the help of the gravity field observed by GOCE. The entire arc generates a positive gravity signal up to 180 mGal, limited by two geological boundaries, the Main Karakorum Thrust at north, and the Main Mantle Thrust at south. The Main Karakorum thrust marks the transition from the Indian to the Eurasian plate. The crustal thickness varies here between 40 and 70 km. The three geologic units that define the Kohistan arc, the South Plutonic Complex, the Chilas and Gilgit Complexes, occupy the upper crust, with depths increasing northwards between 14 and 44 km. There are not enough constraints to model the eastern part of the arc, the Ladakh, but the similarity of the gravity signal suggests that the thickness of the upper dense crustal units is similar.

Keywords (separated by "-")	Crustal thickness - Gravimetry - Satellite GOCE - Himalaya - Kohistan-Ladakh arc

Detecting the Elevated Crust to Mantle Section in the Kohistan-Ladakh Arc, Himalaya, from GOCE Observations

Daniele Tenze, Carla Braitenberg, Eva Sincich, and Patrizia Mariani

Abstract

The Kohistan Ladakh area in northeastern Pakistan is an exposed top to bottom crustal section, implying that high density rocks of the lower crust are at the surface. The new GOCE satellite observations improve the gravity field in this remote area, giving a new dataset for geophysical interpretation. We use the new data to determine the crustal thickness variations and to define the geometry of the overturned crustal columns constituting the base of the former island arc. For the first time the entire extension of the arc is traced with the help of the gravity field observed by GOCE. The entire arc generates a positive gravity signal up to 180 mGal, limited by two geological boundaries, the Main Karakorum Thrust at north, and the Main Mantle Thrust at south. The Main Karakorum thrust marks the transition from the Indian to the Eurasian plate. The crustal thickness varies here between 40 and 70 km. The three geologic units that define the Kohistan arc, the South Plutonic Complex, the Chilas and Gilgit Complexes, occupy the upper crust, with depths increasing northwards between 14 and 44 km. There are not enough constraints to model the eastern part of the arc, the Ladakh, but the similarity of the gravity signal suggests that the thickness of the upper dense crustal units is similar.

Keywords

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1 Introduction

The aim of this work is to use the gravity observations of the GOCE satellite mission ~~(Pail et al. 2011)~~ in a geologically unique part of the Himalayan orogen, which is the Kohistan-Ladakh arc. In the Kohistan the entire section of the crust from the mantle-crust transition, to the volcanic deposits in the upper crust is exposed (Fig. 1b, c) (Ahmad et al. 2008; Bard 1983; Dhuime et al. 2007, 2009; Garrido et al. 2007; Jagoutz and Schmidt 2012; Jagoutz et al. 2006, 2007, 2009, 2011; Mahéo et al. 2004; Petterson 2010; Rolland et al. 2002). The arc is located at the western syntaxis of the Himalayan belt. In analogy to the horizontal GPS velocities observed surrounding the eastern syntaxis (Jin and Zhu 2003; Jin et al. 2007) it can be expected that the horizontal velocities rotate anti-clockwise around the syntaxis. During geological evolution the Kohistan-Ladakh arc evolved from a volcanic island arc to an overturned piece of crustal section, where rocks formed at great crustal depth have been brought to the surface. The presence of these rocks is interesting for gravity studies, because they have relatively high density, and therefore generate a positive gravity signal. Only with the advent of the GOCE satellite gravity mission can the entire extent of the arc be studied. This gives a unique opportunity to study the arc and determine the density anomaly.

The Kohistan-Ladakh arc is at the limit of resolution of the GOCE gravity field, due to its relatively small dimensions, as it is 180 km wide and 800 km long. The GOCE data give

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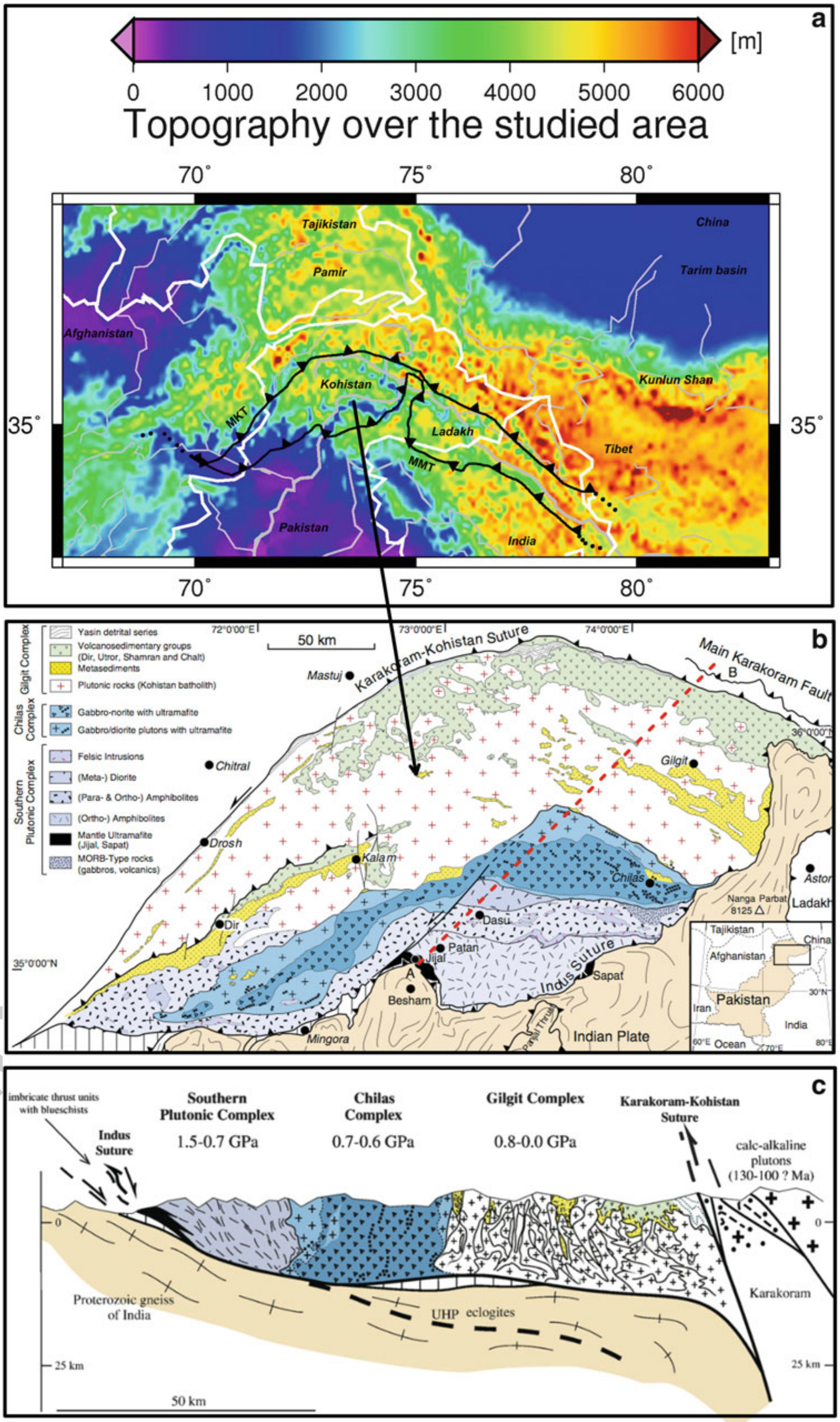

Fig. 1 (**a**) Topography of western Himalaya, centered on the Kohistan-Ladakh arc. *MKT* Main Karakorum Thrust, *MMT* Main Mantle Thrust. *White lines*: national borders, *grey lines*: rivers. (**b**) Geologic map of the Kohistan arc (Jagoutz and Schmidt 2012), the *red ~~dotted~~ line* ~~represent~~ the geologic section shown in (**c**) (Jagoutz et al. 2011)

the first comprehensive gravity field over this complex, as terrestrial gravity data exist (Ebblin et al. 1983), but do not cover the entire regional extent. The questions that are to be solved are the entire extent of the arc, the thickness of the units formed by the high density rocks and the evolution of the arc in the framework of plate tectonics.

The GOCE satellite mission has measured the gravity gradient tensor at a height of 250 km ~~since March 2009,~~ producing a much higher resolution and precision of the gravity field with respect to previous satellites (Floberghagen et al. 2011; Rummel et al. 2011). The improvement of the gravity field is particularly evident in remote mountain areas of difficult access, where terrestrial gravity data are sparse. The time-wise geopotential gravity model (Pail et al. 2011) processes the GOCE satellite observations and reproduces them in spherical harmonic expansion up to degree and order 250, which corresponds to a resolution of 80 km. A first study using the GOCE field in the Himalayas is by Basuyau et al. (2013), where a joint inversion of teleseismic and GOCE gravity data is fulfilled. Shin et al. (2007) use the GRACE satellite to infer the Moho over the entire Tibetan plateau. To the north of Tibet and our study area, Steffen et al. (2011) undertook a study of the isostatic state and crustal thickness variations. In the present paper we have searched a relation between the GOCE satellite gravity signal and the geological information related to the high density units outcropping in the Kohistan region. The results confirm that the GOCE data resolve this structure and give a comprehensive field with which we improve the knowledge of the density units.

2 Regional Geology of the Kohistan-Ladakh Arc and Geodynamic Context

The Kohistan-Ladakh region is situated in north-east Pakistan, Himalaya, and its terrane is one of the best examples of a complete exposed section of an island arc type crust extending from the rocks relative to the uppermost crust to the crust-mantle transition (Petterson 2010). Moreover these formations are totally separated from the rocks deriving from a different geological history separated from the arc by two big fault systems (Fig. 1a): the Shyok Suture known also as Northern Suture or Main Karakorum Thrust (MKT) to the north, and the Indus-Tsangpo Suture known as the Main Mantle Thrust (MMT) to the south. The Kohistan Arc Complex represents the units relative to a fossil Cretaceous to Tertiary arc complex (Bard 1983) now entrapped between the Eurasian and the Indian plates within that collisional environment which created the Himalaya orogen.

The intra-oceanic subduction process which accreted the Kohistan island arc began around 117 Ma within the Tethyan oceanic plate (Dhuime et al. 2009) and then collided with the Indian and the Eurasian plate. Many papers have catalogued the different units outcropping in the Kohistan region (Dhuime et al. 2007, 2009; Garrido et al. 2007; Khan et al. 2009) and related these with the formations outcropping in the Ladakh region (Ahmad et al. 2008; Mahéo et al. 2004; Rolland et al. 2002). In the following we concentrate our detailed study on the Kohistan arc, the western part of the Kohistan-Ladakh arc. In accordance with Jagoutz and Schmidt (2012) the present work will consider three main formations: the Southern Plutonic Complex, the Chilas Complex and the Gilgit Complex (Fig. 1b). Burg et al. (2006) and Jagoutz et al. (2011) present a section of the crust crossing the Kohistan arc, red ~~dotted~~ line in Fig. 1b, in which the thickness of the different units is estimated along a generic profile (Fig. 1c). The geological model assumes the crust to have been segmented and trapped between the converging Indian and Eurasian plates, and tilted by 90°. The thickness of the units should be equal to the width of this piece of crust.

The Southern Plutonic Complex represents the lowermost ultramafic-mafic units outcropping in the area. It contains the Jijal Complex, a series of ultramafic-mafic metamorphosed igneous complexes representing the transition between the upper mantle and the lower crust (Dhuime et al. 2007, 2009; Garrido et al. 2006, 2007) and the Kamila Amphibolites, a unit characterized by metavolcanic and metapluntonic rocks (Dhuime et al. 2009; Petterson 2010).

The Chilas Complex is a large-volume, mafic-ultramafic plutonic body composed of gabbro norite, minor diorites and subordinate tonalites (Jagoutz et al. 2006, 2007).

The Gilgit Complex is dominated by the Kohistan batholith and its calc-alkaline domain. It represents the mid and upper arc crust of the island arc (Jagoutz and Schmidt 2012). Within this complex the rocks have predominantly quartz-, quartzmonzo- and granodiorites composition with intrusions of picro-basaltic dykes to leucogranites stocks and sheets (Petterson and Windley 1985).

3 Methodology

We use two methodological approaches for gravity inversion that are tuned to the scale of the investigation. In the first part, with the spectral inversion (Braitenberg and Zadro 1999; Braitenberg et al. 2000) and the flexural model (Braitenberg et al. 2002, 2003), the crustal thickness variation and the rigidity of the crust is determined. Then tightening the studied area to the Kohistan region, we use a prisms model (Nagy et al. 2000) to solve the forward and the inverse problem for estimating the thickness of the three main outcropping geological units of the Kohistan arc. The gravity field model is the GOCE geopotential *time-wise* model GO_CONS_GCF_2_TIM_R3 published in 2011 complete to

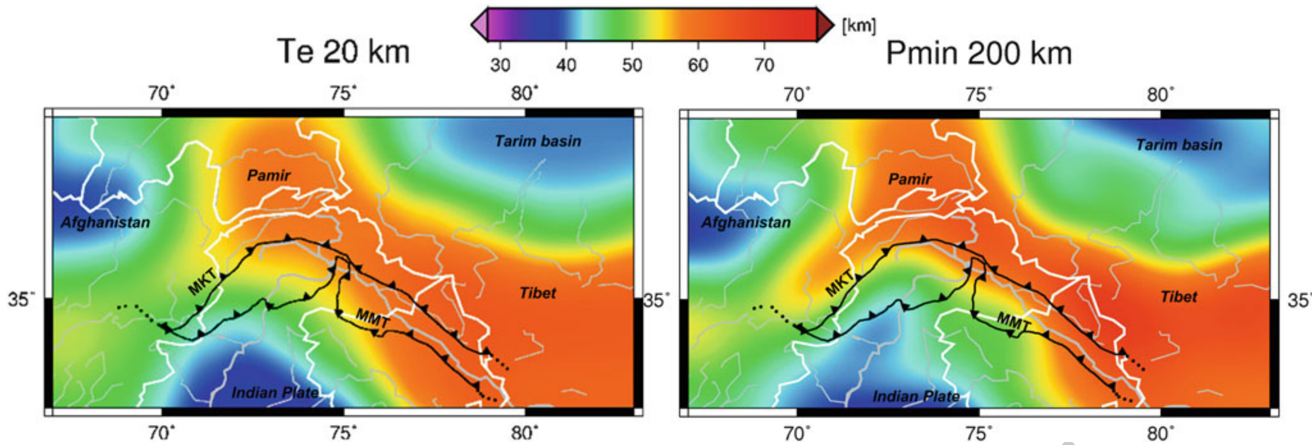

Fig. 2 The two Mohos obtained with the spectral inversion with low pass filter of 200 km and with the Flexural Model with an elastic thickness of 20 km. Even if the two methods are different the images looks similar

degree and order 250 (Pail et al. 2011), (http://icgem.gfz-potsdam.de/ICGEM/). The gravity anomaly is calculated at a height of 8,900 m and successively reduced by the effect of topography using the algorithm proposed by (Forsberg 1985) obtaining the Bouguer gravity anomaly. The height of 8,900 m is chosen to be above the regional topography to allow a reduction of the observations for the topographic effect.

The main goal of the regional gravity spectral inversion and of the isostatic analysis is to remove the regional gravity signal and enhance the signal of the Kohistan-Ladakh arc.

The spectral inversion is an iterative method which is based on the Parker series expansion of the gravity field of a boundary separating layers of different density (Blakely 1996; Braitenberg and Zadro 1999; Braitenberg et al. 2000; Parker 1972), the results depend on the reference depth and the cut-off wavelength of the filter, that limits the frequencies entering the inversion (Braitenberg et al. 2008). Due to the properties of the earth filter (Blakely 1996) high wave number signals of the gravity field are not generated at Moho level, so the components of the Bouguer gravity anomalies with short wavelength are eliminated. We test different cutoff frequencies of the filter in the frame of this study, seeking the best agreement with the isostatic model. The cut-off frequencies range between 1/100 1/km and 1/400 1/km. The lower cut-off frequency produces a flatter Moho. Increasing the frequency too much results in unrealistic high amplitude oscillations in the Moho. We use the criterion of making the flexure Moho and the gravity Moho match to find the most adequate filter-frequency and elastic thickness.

The isostatic flexure model (Watts 2001) is an independent means to model the crustal thickness variations, starting with the topographic load (Braitenberg et al. 2002, 2003, 2007). Here the fundamental parameter is the elastic thickness: the greater the elastic thickness is, the more rigid the lithosphere and hence the smaller the oscillations of the crustal thickness generated by the load will be. The gravity field of the isostatic crustal thickness is calculated assuming a constant density contrast (300 kg/m^3) across the crust-mantle boundary ~~(Mohorovicic~~ Discontinuity, Moho) using the spectral method (Parker 1972). We adopt the digital terrain model ETOPO1 of the *National Geophysical Data Center, ~~national~~ Oceanic and ~~Atmosphere~~ Administration* (NGDC, NOAA) (Amante and Eakins 2008) [http://www.ngdc.noaa.gov/ngdc.html]. The spectral and isostatic studies were principally made to obtain the regional gravity field and separate it from the local field generated by the crustal density inhomogeneities of the Kohistan Arc Complex. We make tests for the different filters, using the cut-off frequencies of 1/400, 1/300, 1/250, 1/200 and 1/100 1/km. We find a good agreement between the isostatic and the gravity Moho when eliminating wavelengths smaller than 200 km from the Bouguer gravity anomalies and for an equivalent elastic thickness of Te = 20 km. These values are also very similar to the ones that were found by Shin et al. (2007) and Braitenberg et al. (2000) for the Tibetan plateau. The agreement between the isostatic and the spectral Moho shows that there is full isostatic compensation in the area. This agrees to Steffen et al. (2011) who define isostatic compensation in terms of the ratio between Moho from gravity inversion and the isostatic Moho. Their analysis includes the Pamir Mountains where they find compensation between 90 and 110 %. The gravity and isostatic Moho depths are shown in Fig. 2. The Moho deepens sharply at the transition from the Indian plate across the Main Mantle Thrust reflecting the geometry of the thrust. The Moho is deep below the Tibet plateau, over 70 km, and shallow towards the Tarim Basin, between 35 and 47 km. The Pamir mountains have deep Moho values, around 60 km. These values agree well with the previous studies (Bassin et al. 2000; Shin et al. 2007; Steffen

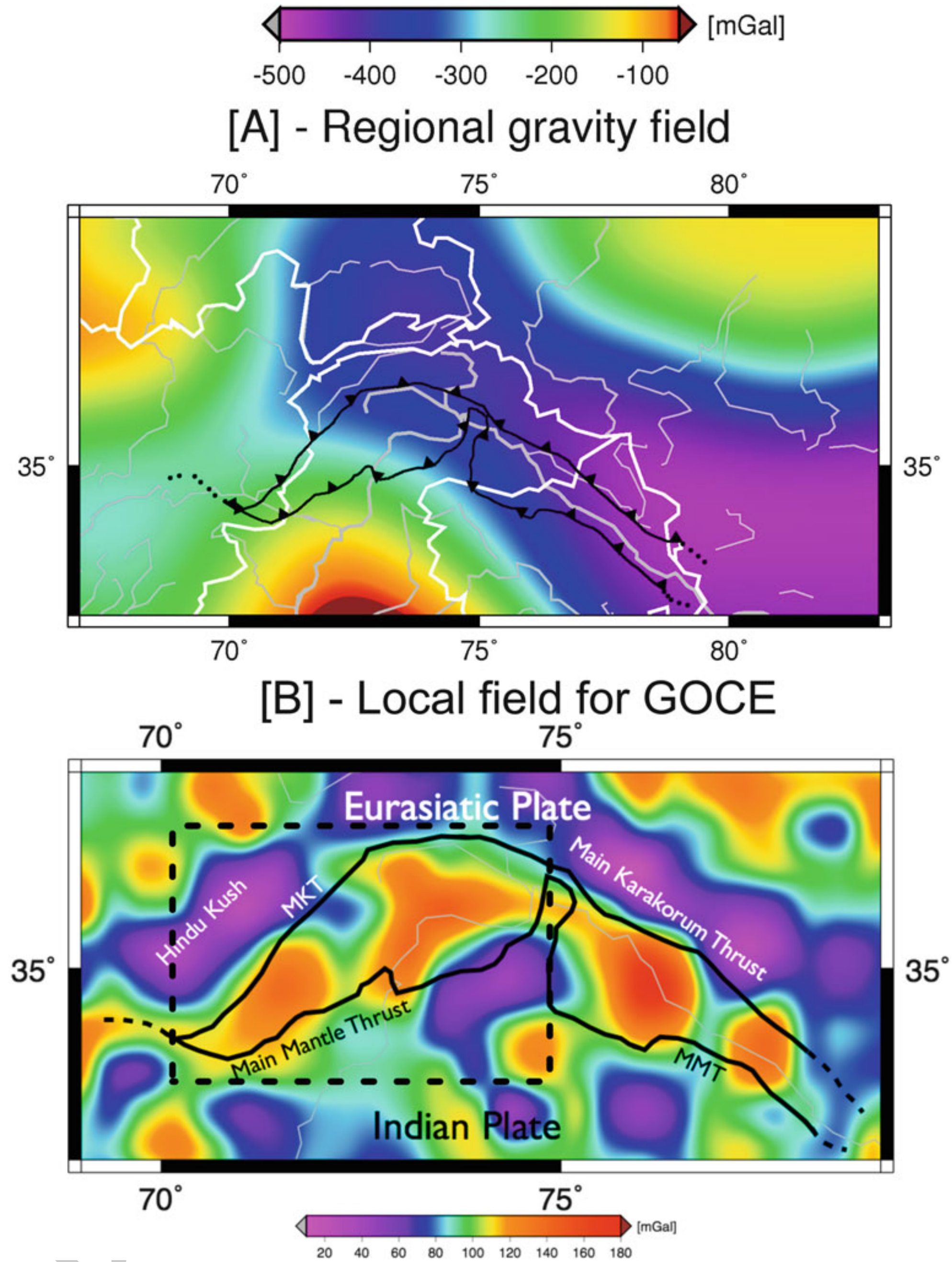

Fig. 3 (**a**) Regional gravity field calculated from the isostatic Moho with elastic thickness of 20 km, and density contrast of 300 kg/m^3. (**b**) The residual Bouguer gravity field, calculated at 8,900 m, which remains after subtracting the isostatic Moho. The signal is well correlated with the Main Karakoram Thrust, that delineates the Kohistan and Ladakh units to the North

et al. 2011). In the Kohistan area the value around 50 km agrees also with the CRUST2.0 model, although he latter has a smaller resolution of 2° (Bassin et al. 2000). The Moho depth follows the topography because the elastic thickness is relatively low.

The Bouguer gravity field which remains after subtracting the gravity field of the isostatic Moho (Fig. 3a) is given in Fig. 3b. The residual is well correlated with the Main Karakoram Thrust, that delineates the Kohistan and Ladakh units to the North. Both Kohistan and Ladakh generate a continuous relative increase in the gravity value, which we define a gravity high. The indentation separating the two arcs is associated to a decrease in the gravity value.

4 Gravity Model of the Kohistan Arc Complex

Once the Moho gravity effect has been estimated (Fig. 3a), we used the gravity residual (Fig. 3b) to analyze the Kohistan region. Our goal is to obtain a density model of the three main units based on the geological model that explains this residual gravity field. We adopt the geological map of Jagoutz and Schmidt (2012) and the cross section Jagoutz et al. (2011) and Burg et al. (2006) presented in Fig. 1, and create a forward prisms model of the three main formations: the Southern plutonic Complex, the Chilas Complex and the Gilgit Complex, each one with its own densities. The density values have been taken from the published ones (Miller and Christensen 1994) and are as follows. The Southern Plutonic Complex has a bulk density of 3,055 kg/m^3 and a thickness of 11 km, the Chilas Complex a bulk density of 2,965 kg/m^3 and a thickness of 11–17 km and the Gilgit Complex a bulk density of 2,789 kg/m^3 and a thickness of 11–21 km. The thickness of the units is based on the geologic section, extrapolating the depths from the section to the remainder of the arc. This model, which we term the forward model, is the starting point for the gravity inversion, that aims to optimize the thickness of the three geologic units and to obtain a best fit to the gravity observations. The gravity of the Kohistan Arc Complex is obtained from the sum of the gravity of the three units and is shown in Fig. 4a. The forward model has been used as first guess for the prisms inversion which refines the thickness of the prisms during the inversion process. The densities are not touched during the inversion, as it is not possible to invert for the geometry and the densities at the same time.

The inversion procedure is based on a Tikhonov regularization approach (Engl et al. 1996; Kügler and Sincich 2009). However, as is well known, because of the inherent ambiguity of the gravimetric data interpretation, any depth estimate relying exclusively on gravity data might be non unique and highly unstable. We overcome such a difficulty by integrating a priori information which acts as physical constraints within our inversion technique, which is in turn based on a minimization argument. In particular, we consider a total variation (TV) stabilizing function which favors solutions with controlled oscillation. The relevance of such a smoothness constraint is tuned by the choice of a weight parameter which is a multiplicative constant of the stabilizing function. Moreover such a parameter acts as a balance between accuracy and stability of the corresponding regularized solution. We shall outline in the following our interpretation model and discuss our parameter choices as well as the error propagation issue. In detail, the three main formations are approximated by a model with M vertical prisms. From a set of N gravity anomaly observations $g^0 = [g_1{}^0, \ldots, g_N{}^0]$ we compute a vector $Z = [z_1, \ldots, z_M]$ of prisms height of each prismatic cell of the given model. The prisms heights represent the thickness of the complex we are considering and are related with the observed gravity anomaly $g_j{}^0, j = 1, \ldots, N$ by a closed formula (Blakely 1996). In order to overcome the ill-posedness of the problem, we combine the gravimetric data misfit with TV regularization term which favors solutions with controlled oscillations. In such a way we reformulate our problems in the minimization of a Tikhonov type function, whose minimization was realized by the MATLAB routine fmincon which in turn is partly based on first order optimization procedure, as the quasi Newton method for non-linear equations (Hanke 1995). This is a well known iteration method looking for the steepest descent of the function which requires the computation of first order partial derivatives. The implemented stopping rule is either an upper bound on the threshold on the gap between two consecutive iterations output or a fixed maximum number of iterations. As soon as one of these two criteria is satisfied the procedure stops. In most of the cases the iteration stops, because the maximum number of iterations has been exceeded. The typical number of iteration steps is about 10–15. Among many performed choices of the regularization parameter α, we select a close to optimal situation tuning $\alpha = 0.01$, which gives a satisfactory result in term of small gravity residuals. Such a choice for the regularization parameter α has been performed also by considering it as a rescaling factor between the gravimetric data misfits and the total variation term. Higher values of α tend to flatten the solution, lower values are also acceptable. Increasing the number of iterations does not appreciable alter the results, as already a good fit to the gravity values is achieved during the 15 iterations. The inversion starts from a first-guess prisms distribution that was built on the basis of the Kohistan geologic units. The inversion process refines this model to obtain a better fit to the gravity data. The algorithm is allowed to change only the lower extent of the prisms, the upper border being kept constant. The density of the prisms is constant and is that of the rocks of the geologic units. We have studied the influence of the data noise. For that purpose we perturbed a synthetic gravity anomaly by adding a pseudo-random Gaussian noise with zero mean and standard deviation 1 mGal. As a result, we obtain a standard deviation of the prism thickness residual of about 300–400 m.

The inversion process has given the three refined units shown in Fig. 4b with the respective gravity signal. The correction of the prisms through the inversion is up to 20 km, with the values increasing northwards, Fig. 4b. The inverse model assigns to the Southern Plutonic Complex a thickness which varies from 14 km to 17 km, to the Chilas Complex a thickness variable from 15 km to 22 km, to the Gilgit Complex a bulk density of 2,789 kg/m^3 and a thickness variable from 24 km to 44 km. These numbers reproduce the

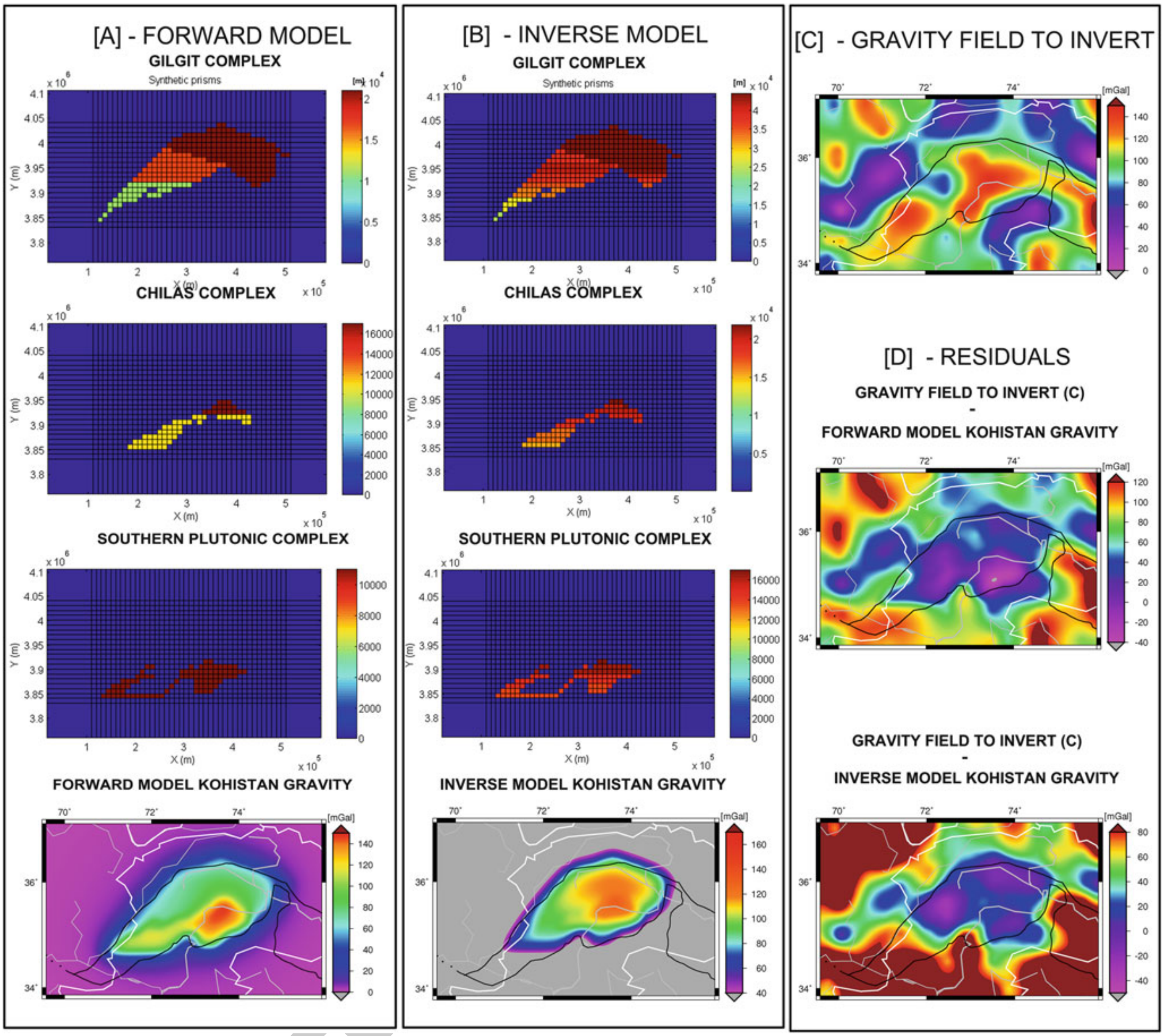

Fig. 4 The gravity model of the Kohistan Arc Complex: (**a**) The forward models of the three main geological units and the forward gravity signal calculated from them. (**b**) The inverse models of the three main geological units obtained with the inversion and the gravity signal calculated from them. (**c**) The field to invert, obtained from the spectral inversion with cutoff wavelength of 200 km. (**d**) The two final residuals obtained: one from the forward model and one from the inverse model

geologic-geophysical section of the Kohistan arc published by Jagoutz et al. (2011) shown in Fig. 1b and used for the forward model of the previous chapter. The correction in terms of the gravity effect reaches 170 mGal. The final gravity residual is shown in Fig. 4d and for the modeled region of the Kohistan varies between −30 and 10 mGal. The inversion process has definitely improved the initial forward models of the three units: The Southern Plutonic Complex is thinner in the south part with respect to the initial information, for the Chilas Complex there is a more gradual thickening toward north and finally, for the eastern part of the Gilgit Complex the inversion model gives a lower depth of the units, (compare Fig. 4a to b). The residuals show that the full modeling of the Kohistan arc requires further geologic units that are not considered in the present model. This will be part of the future study. For instance the presence of an eclogite layer (bulk density of 3,455 kg/m^3) has been proposed to reside beneath the Gilgit units, just above the subducting Indian plate. The effect of this unit would be to decrease the inverted prisms thickness in the northernmost part of our model. There are though too many uncertainties yet to include this unit in our modeling.

Conclusion

Our work shows that the GOCE gravity anomalies derived from the spherical harmonic expansion have sufficient resolution and precision to resolve the geologically important Kohistan-Ladakh arc, characterized by high density rocks from the lower crust reaching the surface. The correlation with the geology is enhanced, after separation of the regional gravity field. As crustal thickness variations from independent geophysical sources are not available, we use the isostatic model to make a first order Moho model and to estimate the regional gravity field. We find a good agreement between the flexural Moho with a Te value of 20 km and the gravity Moho obtained from inverting the long-wavelength part of the Bouguer gravity anomalies limited to a wavelength of 200 km. We find that the area is in isostatic equilibrium due to the fact that isostatic and gravity Moho are in good agreement.

Our findings are made possible only with the comprehensive field obtained from GOCE that allows us to homogeneously map the gravity field over the entire area and surrounding regions. Finally we use the gravity residual to test whether the existing geologic model of the Kohistan arc, which explains it being a crustal section extending from lower crust to the surface magmatic deposits, is compatible with the gravity field. The gravity residual is positive over the entire Kohistan-Ladakh arc, demonstrating its continuity and full east-west extension. The depth development of the units is only partially known from previous investigations, and only along one profile the depth extent of the units is known. We therefore could use the gravity inversion to estimate the thickness of the units over the whole arc, starting from the known information. Our final model explains the gravity signal better, as the residual is reduced from a starting value of 50 to 170 mGal to a final residual between −30 mGal and 10 mGal, when considering the modeled area of the Kohistan.

In future, a refinement of the inversion process is planned, with a greater variability of the prism densities and the extension of our study to the east, for a better understanding of the Ladakh province, which we expect to have high density superficial rocks as well judging from the gravity signal which is very similar to the one of the Kohistan.

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