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Subsurface geological model of sedimentary and metasedimentary wedge from Mansehra to Battal based on gravity data, Hazara area, Pakistan

Rizwan Sarwar Awan [a, b, c, *], Ashar Khan [d], Chenglin Liu [a, b, **], Shangfeng Yang [a, b], Qibiao Zang [a, b], Yuping Wu [a, b], Guoxiong Li [a, b], Khawaja Hasnain Iltaf [a, b], Muhammad Tahir [c, e], Sajjad Ali [a, b]

[a] College of Geosciences, China University of Petroleum, Beijing, 102249, China
[b] State Key Laboratory of Petroleum Resource and Prospecting, China University of Petroleum, Beijing, 102249, China
[c] The University of Azad Jammu and Kashmir Muzaffarabad, Pakistan
[d] Water and Power Development Authority, Pakistan
[e] Research Institute of Unconventional Petroleum, China University of Petroleum, Beijing, 102249, China

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A B S T R A C T

This study is aimed to delineate the subsurface structural elements using geophysical techniques in the Haraza area of Pakistan. We investigated the Oghi and Battal thrust faults, sedimentary and metasedimentary wedge, and the absolute crustal thickness based on terrestrial gravity data. Unlike seismic survey relying on wave propagation, magnetic survey is based on both attraction and repulsion, and electrical and electromagnetics on induction. The attractive gravity field produces relatively simpler patterns of anomalies, like a series of highs and lows over regions with undulating basements and buried structures. A qualitative interpretation of gravity data reveals a good deal of information. During the collision of Indian and Eurasian Plates, compressional structures were developed in the Lesser Himalayas or northwest of the Hazara Kashmir Syntaxis. The study mainly focuses on the western limb of the Hazara Kashmir Syntaxis. The regional and local Bouguer anomalies were incorporated to delineate the regional structural units. The gravity model is computed through geophysical technique along with profile A-A' from Mansehra to the Battal area that demarcates the blind Oghi Thrust and emergent Battal Thrust. Tanol Formation of Precambrian age demarcates the Oghi Thrust near Kotli Pine while the Battal Thrust is demarcated within the Mansehra Granite of Cambrian to Ordovician age near Battal. Along with the Battal Thrust, fault gouge and breccias have been observed during the field studies. The total thickness of the sedimentary/metasedimentary wedge in the Mansehra and Battal areas was estimated to be 13.6 km and 14.2 km. In comparison, the total thickness of crust in the Mansehra and Battal areas was 51.6 km and 52.2 km, respectively.

1. Introduction

The thickness of subsurface geological formations varies significantly across the continental margins and within the sedimentary basins. Mapping these variations is vital for understanding the processes of the continental rift, hydrocarbon habitats and subduction systems. Subsurface geological interfaces can be imaged precisely through exclusive deep seismic profiling. However, economic concerns make gravity modelling a more applied method for mapping crustal thickness over regional scales.

* Corresponding author. College of Geosciences, China University of Petroleum, Beijing, 102249, China.
** Corresponding author. College of Geosciences, China University of Petroleum, Beijing, 102249, China.
E-mail addresses: rsageche@gmail.com (R.S. Awan), liucl@cup.edu.cn (C. Liu).

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Regional gravity surveys have proved useful for the investigation of crustal structures, isostasy, underground mineral deposits, volcanic features, and tectonic structures (Nabighian et al., 2005). It has broad applications which investigate the variations from a normal background value caused by the changes in physical properties of subsurface materials and hence involve vitally the detailed interpretation techniques (Braitenberg et al., 2000). The geophysical exploration method (gravity) measures the differences in the strength of the geo-gravitational field at particular locations (Huang et al., 2001). It plays a vital role in imaging the subsurface geological objects and structures. The success rate of the gravity data depends on the variations in the measurement of operative parameter bulk densities (mass) of subsurface materials (Khan et al, 2016, 2018, 2020; Khan and Farooq, 2001; Özyalın et al., 2012; Rustam and Khan, 2003; Šumanovac, 2010). Hence the gravity methods provide the basis to model the thickening or thinning of continental crust (Kono, 1974). The accuracy of the subsurface modelling depends on how appropriately the eliminations of gravity anomaly sources may be carried out.

In northern Pakistan, numerous researchers typically performed gravity measurements under the direction of ArditoDesio and Antonio Marussi (Marussi (1976). Malinconico (1986) had conducted gravity and magnetic surveys across the Main Mantle Thrust (MMT) and Main Karakoram Thrust (MKT). He was the first worker who analyzed two-dimensionally the terrain-corrected gravity data. He suggested that the Indian Plate is being thrusted under Eurasian Plate and that the major structure in this region dips towards the north. Northern structures are older in age and have steeper dip than those of the south. Farah et al. (1977) analyzed the Precambrian basement of the Punjab Plain and Potwar Plateau by gravity modelling in the south. They suggested that the shield elements with the increasing sediment cover can be followed northward movement beneath the Himalayan southern thrust. The current study area is located in Mansehra of Hazara division, Pakistan, and covers nearly 30 km^2 comprising the villages of Faizabad, Hathimera, Shinai Bala, Tanda, Icherrian and Chinarkotand Battal. Fig. 1 indicates the locations of the study area and gravity base stations as well as gravity observation station layout. Previously performed gravity and magnetic surveys in the Hazara division and its adjacent areas of northern Pakistan indicate that the sedimentary and metasedimentary wedge in the form of Hazara-Kashmir Syntaxis (HKS) exists on the Precambrian crystalline crust of the Indian shield. But in the current scenario, the study to image the subsurface geology is focused specifically on a localized profile extending from Mansehra to Battal. In this specific area, no detailed geophysical work was carried out for the crustal study and/or for any other targets, e.g., exploration of ores. The main aims of this research are as follows:

1) To delineate the subsurface structural elements
2) To delineate the thickness of the sedimentary and metasedimentary wedge
3) To delineate the total thickness of the crust in the northwest of Hazara-Kashmir Syntaxis (HKS), Lesser Himalayas

2. Geological settings

2.1. Regional tectonics

With the breakup of Gondwana, the Indian Plate began to disintegrate into smaller parts. It was partially isolated during the Early Cretaceous Period. Indian Plate made the longest journey of all drifting continents, i.e., about 9000 km in 160 million years from Gondwana to Asia. The Late Cretaceous (~88 Ma) marked the rifting of the Indian Plate from the Madagascar block, and hence the movement of the Indian Plate began northward, isolated from other Gondwana continents. The Neotethyan ocean most likely disappeared completely around the latest Early Eocene (~50 Ma) when the Indian Plate was fully sutured to Eurasian Plate (Chatterjee et al., 2013). The collision between Indian and Eurasian Plates created the mountain range of the Himalayas (Gansser, 1964; Le Fort, 1975). The tectonic process is still ongoing, and the continuous northward drift of the Indian Plate is uprising the Himalayas. The Himalayan range is about 2500 km long and 160 to 400 km wide. To the north, an ophiolitic belt known as the Indus Tsangpo suture Zone (ITSZ) marks the boundary of the Eurasian and Indian Plates. This westward extending suture zone bifurcated into two major thrust faults and surrounded a sequence of rocks. These thrusts are Main Karakoram Thrust (MKT) and Main Mantle Thrust (MMT). Kohistan Island Arc (KIA) is present between these thrust faults. The northern suture zone, i.e., MKT, separates the intrusive high-grade metamorphic rocks of the Eurasian Plate from Kohistan terrain, while the southern suture, i.e., MMT, separates the KIA from the metasediments of the northern margin of the Indian Plate (Khan et al., 2020).

In the High Himalayas and Tibetan Plateau area, geophysical evidence shows that the continental crust was between 50 and 80 km thick, which is twice the normal crustal thickness (Molnar, 1984, 1986). Continuous underthrusting was attributed to this feature and underplating of the Indian Plate underneath the Eurasian. The collision of Eurasian and Indian Plates resulted in the development of the Hazara-Kashmir Syntax (HKS) and Nanga Parbat Syntax (NPS). The tectonic map of northern Pakistan is shown in Fig. 1. Southward migration of the sedimentary and metasedimentary wedge of the western limb of HKS developed the Jhelum strike-slip fault, which is the left-lateral strike-slip fault extending laterally towards the western boundary of the axial plane of HKS (Mehmood et al., 2019). The continued convergence of the Indian and Eurasian Plate has been accommodated by crustal shortening along with different thrusts, with an apparent progression of the thrusts from the north (Le Fort, 1975). Present shortening occurs through activation of shallow thrust faults within the Indian Plate along Main Boundary Thrust (MBT), Salt Range Thrust (SRT), and the Indian Plate thrusting beneath the Eurasian Plate.

Gansser (1964) and Powell (1979) divided the Himalayas into Tethyan, Higher, Lesser, and Sub Himalayas. The current study area is located in the extensions of Lesser Himalayas, northwest of the HKS, which is considered as a result of interaction between three tectonic elements, i.e. (a) the Indo-Pakistan shield, (b) the Himalayas, (c) the Salt Range, each of that are moving independently. Lesser Himalayas consist of folded and faulted rock formations ranging from Precambrian to Eocene (Ghazanfar et al., 1986). It is far delaminated to the south by the Tertiary molasses along with the MBT; locally called as Murree fault, and to the north by the Higher Himalayas crystalline rocks along the Main Central Thrust (MCT), a narrow southwestern region of the Lesser Himalayas has been termed as Para autochthonous belt (Wadia, 1930).

2.2. Regional and local geological units in Mansehra district

Regional geological units in the Mansehra district are ranging from Precambrian to Recent. Table 1 demonstrates a brief description of each particular geological unit present in the region of study. This depiction provided is endorsed by the Stratigraphic Committee of Pakistan (Iqbal and Shah, 1980). Localities where the gravity survey has been performed mainly contains Cambrian and Precambrian rocks. Alluvium and horizontally bedded clays and gravels of recent terrace deposits are also exposed. Alluvium in the region is loose sand, silt, and clay of yellowish to grey color.

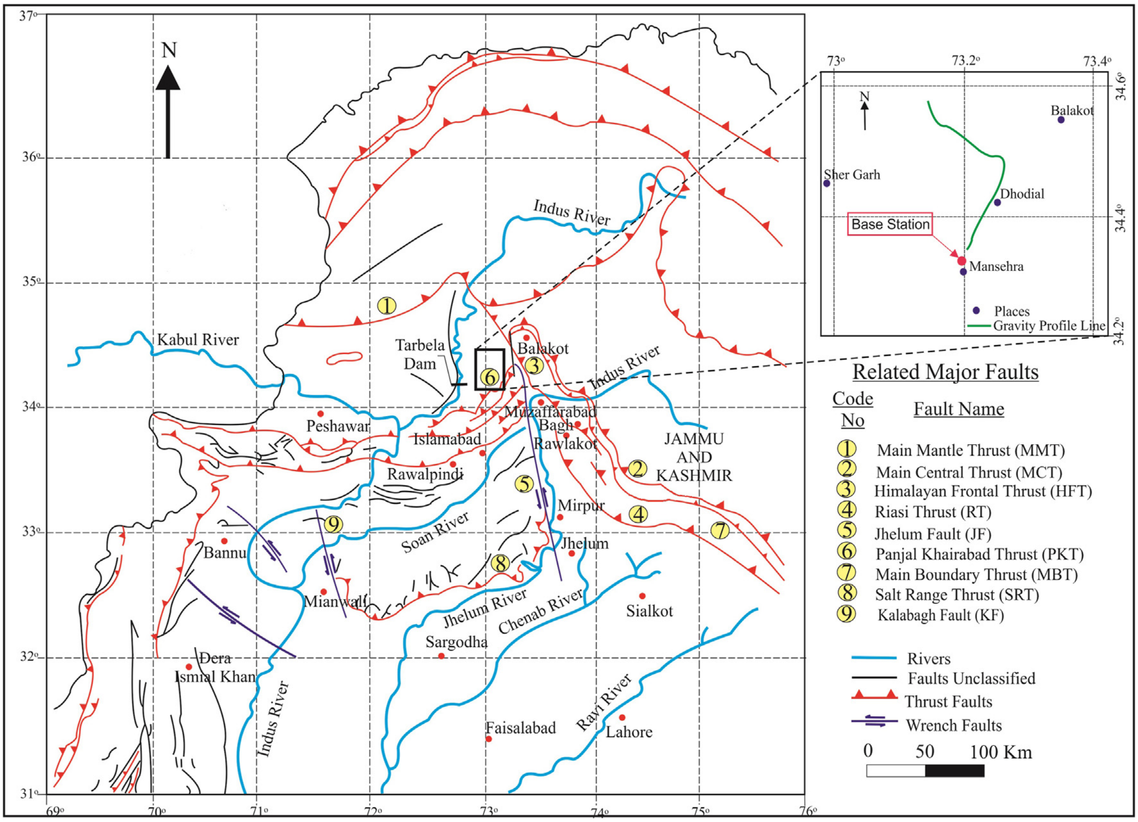

Fig. 1. The tectonic map of northern Pakistan with inset showing the base map of the study area.

Table 1
Regional stratigraphic and geological units of Mansehra.

Formation	Age	Description
Alluvium	Recent	Unconsolidated deposits of gravel, clay, and pebbles, etc
Siwaliks Group	Miocene to Pliocene	Sandstone, siltstone, clays, and conglomerates
Murree Formation	Early Miocene	Cyclic order of sandstone and shale with subordinate claystone and conglomerates
Kuldana Formation	Middle to Late Eocene	Siltstone and fine-grained sandstone
Chorgali Formation	Early Eocene	Siltstone and dolomitic limestone, calcareous shale
Margala Hill Limestone	Early Eocene	Limestone with subordinate greenish-grey shale
Patala Formation	Late Paleocene	Khaki shale and marl with subordinate sandstone and limestone
Lockhart Limestone	Early Paleocene	Massive, hard, and thick-bedded grey to medium grey nodular and flaggy limestone
Hangu Formation	Early Paleocene	Sandstone, laterite, bauxite, fireclay, and coal
Unconformity		
Mansehra Granite	Cambrian to Ordovician	Quartz alkali feldspar and sodium-rich plagioclase and accessory minerals are micas (muscovite and biotite). Xenolith present in some places.
Abbottabad Formation	Cambrian	Chiefly dolomite, limestone, chert bands, and black shale
Tanol Formation	Precambrian	Metasediments, phyllite, and quartzite schist
Hazara Formation	Precambrian	Slates with subordinate metasediments.

Mansehra Granite (Cambrian - Ordovician age) is a batholithic body that barges subconcordantly to discordantly into the neighboring rocks (Shams, 1961). Shear zones have been created in massive Mansehra Granite because of ductile deformation. These shear zones can be found in the Jhargali and Susalgali regions of the Mansehra district. Mansehra Granite is commonly foliated and gneissic with the irregular existence of massive variety in the Oghi-Battagram region. Mansehra Granite is abutted by Tanol formation of Pre-Cambrian age, which generally comprises the quartzite, quartzose schist, and schistose conglomerates. Rocks of Tanol formation have undergone Barrovian type regional metamorphism up to Kyanite grades (Le Fort, 1975; Shams, 1969). These rocks show recumbent folding, particularly in Jhargali and Darband areas.

3. Materials and methods

Scientific schemes of gravity survey can have serious effects on a highly prosperous interpretation tool or be a waste of resources. Station spacing, in regional surveys, is frequently determined from the area to be covered and divided by the number of stations that can be managed in the available budget (Alice S Murray, Ray M. Tracey; Best Practice In Gravity Surveying). The current project was planned to conduct the profile pattern of gravity studies on the region bounded by latitude 34° 21′ 38″ and 34° 34′ 64″ N and longitude 73° 12′ 38″ and 73° 08′ 60″ E. Availability of exposed geological structures was also considered while selecting the profile pattern. CG-5 Autograv was used to make gravity measurements, while Global Positioning System (GPS) was utilized to accomplish the elevation estimations. Survey for estimating the thickness of sedimentary and metasedimentary cover over the basement was to be performed by choosing the suitable station intervals with closely spaced ranges across the access road since no previous or indicative gravity data was available for our particular zone of interest. An evenly spaced coverage of 2 km was surveyed throughout the profile. Before performing the gravity survey, it was essential to establish a base station network. There are two reasons for setting a base station. Firstly, in order to monitor the drift of the gravity meter, it is necessary to revisit a site of known gravity (a gravity base station) at regular intervals. Secondly, the gravity values measured during the survey are relative to the base station, and hence the base station needs to be linked to internationally accepted absolute values. Detailed information of various parameters of the Main, National, and Auxiliary Base Stations is shown in Table 2. Base station located in Mansehra city (lat. 34° 20′ 30″ N, long 73° 12′ 25″ E) (Helbig and Thirlaway, 1961) in the current study lies just outside the surveyed area about 2 km away from the jeepable track. Its location was such that it could be repeated at the start and end of everyday coverage. Observation stations were selected sensibly to avoid the data being influenced by physical properties that are difficult to measure. The standard formulae for the estimation of gravity anomalies adopt a flat earth surface at the observation point. Any deviation from a flat surface needs to be compensated by a terrain correction. Printed topographic maps were made available to cope with expected terrain corrections. As terrain corrections are hard to compute precisely for the features close to the station, it is better to pick the station point that diminishes this issue (Leaman, 1998). The general workflow of this research is illustrated in Fig. 2.

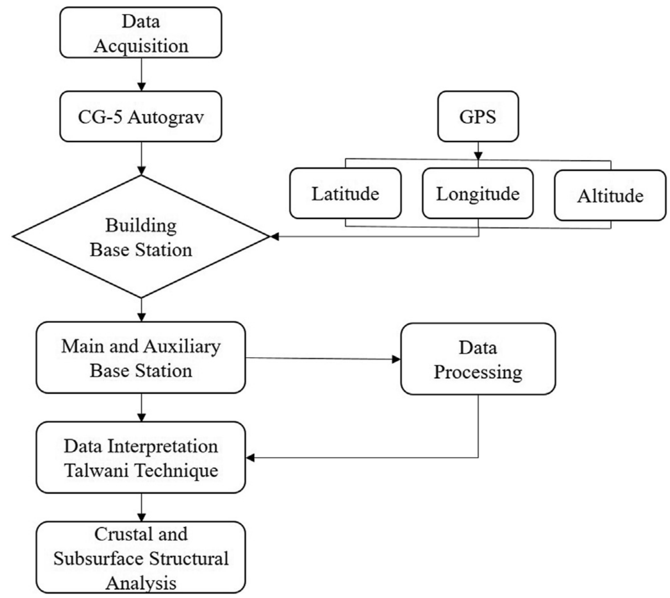

Fig. 2. The general workflow of this research.

3.1. *Gravity measurements*

Gravity measurements are used at a wide range of scales and for a wide range of purposes (Nabighian et al., 2005). They involve sensitive consideration of details in order to achieve precise measurements. To start the survey, there should be an assessment of the objectives to be estimated for the identification of the finest survey to cover the region and decide a path or grid at points where gravity values are to be acquired. Gravity attraction is not dependent on the absolute densities of subsurface materials. It just depends on the density contrast amongst the subsurface lithologies. Gravity field data (acceleration) is linked directly to the mass (density) of the earth under the gravity observation station. Highs and lows in the variation of gravity data most possibly show where the basement rocks are shallower or deeper from the surface (Sultan and Ahmed, 2014, 3:6).

CG-5 Autograv (Scintrix, Canada) was utilized for gravity data acquisition in the current project area. CG-5 Autograv has a preference as compared to other gravimeters in a context that it is proficient in applying drift correction with respect to the time and elastic expansion in its interior components because of temperature and heat index. Likewise, automatic free air correction can be applied as CG-5 Autograv considers the curved ground height with its built-in Garmin Global Positioning System. The instrument demonstrated a consistent drift, which had a rate for the most part of about 0.001–0.002 mGal per minute during the coverage. It was supposed that the gravimeter would indicate a similar behavior throughout the field investigation.

While surveying along with the targeted pattern of regional profile line, i.e., from Faizabad (close to Mansehra city) to Battal, the accuracy of observed data was kept constantly under consideration because even a minute error in the gravity observations can possibly lead to serious inaccuracies in the geological interpretation of gravity anomalies. Errors regarding observation, heights, position, or density were considered to calculate the precision of data. A survey was conducted along with the profile that was most of the time access road from Mansehra city to the Battal village to delineate subsurface geological structures more clearly, and most importantly the depth of basement rocks in the project area.

3.2. *Gravity data processing*

Gravity survey is comprised of making numerous mathematical corrections to the acquired data to improve the signal-to-noise ratio. These corrections are to be performed for the elevation of data acquisition point, the spatial position of the instrument with respect to the earth, density of the material between observation station and datum plan, tides, and the encompassing topography, all of which involve specific data processing techniques. Traditional data processing consists of a series of steps, each designed to remove a gravitational effect that can be calculated with well-

Table 2
Detailed information of various parameters of the Main, National, and Auxiliary Base Stations.

Stations	Gravity (mGals)	Elevation (meters)	Latitude	Longitude
National Base Station (Rawalpindi, Pakistan)	979,286.43	511	33° 58′ 36″ N	73° 03′ 34″ E
Main Base Station (University city campus Muzaffarabad, Azad Kashmir)	979,282.38	728	34° 22′ 26″ N	73° 28′ 10″ E
Auxiliary Base Station (Mansehra, Pakistan)	979,258.65	994	34° 21′ 38″ N	73° 12′ 38″ E

constrained assumptions.

First of all, corrections regarding the instrumental drift and tilt are to be settled. CG-5 delivers a software-based automatic technique to find the drift constant and update the internal correction information spontaneously. This technique gives an appropriate approach to define the drift constant, which is precise for most applications. Actually, measured gravity is termed “observed gravity,” ranging from about 9.78 to 9.83 m/s^2 over the earth. The primary reason for the variation in observed gravity is the shape and rotational velocity of the earth, which can be calculated as a latitude function. A secondary cause for variation in gravity is elevation. These effects of elevation and latitude are calculated and removed from the observed gravity to obtain “free-air gravity.”

The next step in traditional gravity data reduction is to calculate and remove the effect of topographic mass (above sea level) from free-air gravity to obtain Bouguer gravity. Most gravity studies employ Bouguer gravity for modelling on land; many studies employ free-air gravity for modelling offshore. Studies that span onshore and offshore areas often employ hybrid maps with Bouguer gravity on land and free-air gravity offshore. Bouguer gravity is generally low over high mountains and high over the ocean basins (Blakely et al., 1999). These corrections were applied relative to datum plan, i.e., sea-level as;

$$E.C = F.A.C \pm B.C$$

Bouguer Correction here is $B.C = 0.04193 x \delta x h$, where 'δ' is the density of material in height ‘h’.

While Free-Air Correction $F.A.C = 0.3086 x h$, where ‘h’ is height (meter).

For the next step in gravity data reduction, a correction is made to calculate and remove gravity's effect due to the non-spherical shape and rotation of the earth. Gravitational attraction increases with increasing latitudes. Correction is performed while moving from pole to equator. Correction is done only for relative movement in the N–S direction. Correction for a particular latitude is linear over approximately 1 km. The current project area is located in the northern hemisphere, and the observation stations northward of the base station. So the correction is made by subtracting $0.811\sin(2\phi)$ mGal/Km while moving northward. The base of this correction is the international gravity formula, which is given below;

$$\text{International gravity formula} = g = 978.049\,(1 + 0.0052884\,\mathrm{Sin}^2\phi - 0.0000059\,\mathrm{Sin}^2 2\phi)$$

where ‘g’ indicates the value of gravity in gals at latitude 'ϕ' of the observed stations on the ellipsoid. The following formula is used for latitude correction;

$$L.C = 0.8122\ \mathrm{Sin}2\phi\ (\text{N–S distance/Km})$$

The standard formulae for the computation of gravity anomalies assume a horizontal earth surface at the observation station. Since our project area is located in the Lesser Himalayan orogenic belt, where variation in relief is constantly observed, our processing also included the application of terrain correction. This correction considers the fact that a close vicinity mountain attracts upwards on the gravimeter, hence reducing the estimated values. Likewise, a close vicinity basin fails to pull downwards on the instrument, again dropping the gravity values. A positive terrain correction should be introduced to the observed anomaly in both cases to normalize the values. This correction relies upon the density of the surface layers (Leaman, 1998). Numerous geophysical processing packages presently contain automatic terrain correction tools. In the current project, terrain correction is performed by making use of Hammer charts, which extend out to a radius of about 25 km. The Hammer net method involves compartmentalizing the area surrounding the measurement point using a template, i.e., the Hammer net. The net was utilized with available printed topographic maps. Radial lines from the gravity station extend from the center of the net, and the concentric circles are drawn at explicit distances from the gravity station. Consistent with the scale of the topographic map. An average altitude above or beneath the station elevation within each compartment was assessed.

$$gcomp = G\delta\Delta\theta R^{\circ} - R' + \sqrt{R\prime^2 + h^2} - \sqrt{R^{\circ}2 + h^2}$$

‘G’ is the universal gravitational constant, $\prime\delta'$ is bulk density, ‘h’ is the height difference of compartments, $\prime\Delta\theta'$ is the angle subtended by two radial lines bounding the segment, R° and R' are inner and outer radii bounding the compartment. Gravitational impact of each compartment is then added to measure the terrain correction;

$$gterr = \sum_{k=1}^{n} gomp$$

‘n’ is the total number of compartments.

Station elevation was obtained by placing the center of the net on the gravity station. The elevation difference with each compartment was then estimated.

After making all the necessary corrections to the observed gravity, the Bouguer anomaly is calculated as given by;

$$B.A = (g_{obs} - g_{base}) \pm D.C \pm F.A.C \pm B.C \pm L.C + T.C$$

3.3. 2D gravity modeling

Geophysical data modelling keeps a very significant role in direct interpretation. Gravity modelling involves computing the gravity effects of a given density model (Huang et al., 2001; Mehmood et al., 2019). Observed gravity anomaly provided us with the general trend of gravity along nearly 30 km length of the profile A–A'. Once the observed measurements were reduced to Bouguer anomaly, forward modelling technique, i.e., Talwani method (Talwani et al., 1959), following the Malinconico Jr (1986) software was used for gravity modelling. Two-dimensional gravity modelling was carried out to a depth of about 53 km. Consequently, the gravity models were constructed, which revealed that the thickness of the crust increases to the northwestern end of the study area. The modelling process generated a model anomaly or calculated gravity. The shape and density of the subsurface bodies were changed in such a way that the model anomaly matches the observed anomaly. Previously this was done manually through a tedious process, but currently, interactive applications are available that can quickly create and fit the model. For the tectonic study of the present project area, quantitative analysis has been done a lot with the help of formerly acknowledged structural and geological data of Greco (1989); Khan and Farooq (2001); Latif (1973), (1970); Rustam and Ali (1994); Rustam and Khan (2003); Seeber et al. (1981); Valdiya (1980); Wadia (1928), (1931), (1930). Profile A − A' from Mansehra to Battal has been selected across the different lithological units for this purpose. Geological structures with finite length and polygonal cross-section have been estimated as a horizontal prism in the gravity model. The model takes into account the constraints provided by deep-source gravity anomalies. According to the literature, density values have been assigned to non-survey parts of the subsurface. The density distribution is gradually altered to achieve the best fit between the observed gravity and calculated gravity (Bernabini et al., 1996; Khan et al., 2020). As shown in Fig. 3 and Fig. 4, the generated gravity model demonstrates the distribution of the surface and subsurface structural components such as Oghi and Battal Thrusts, thickness of sedimentary and metasedimentary wedges, and the total thickness of the crust. The gravity model is calculated with previous geological data (Rustam and Ali, 1994).

Geological units encountered in the current project region are categorized as the Hazara Formation and Tanol Formation of Precambrian, Granites of Cambrian to Ordovician, and Alluvium of recent age. The density contrast of subsurface layers varies. Density contrast assigned to these geological units with respect to the crystalline crust (2.95 gm/cc) are −0.50, −0.47, −0.90 and −0.70 gm/cc, respectively. This gravity model has been created among the observed gravity, calculated gravity, and geology to show a suitable relation among them. The calculated gravity of this model indicates reasonably the observed gravity effect. This gravity model computed by geophysical experiments along with the profile A-A' from Mansehra to Battal areas demarcated the Oghi and Battal Thrust faults. Oghi Thrust is demarcated within the Tanol Formation of Precambrian age near Kotli Pine. The fault dips 43° towards the northeast and penetrates 13.7 km deep in the sedimentary and metasedimentary wedge in the research area. Modern Alluvium has covered Oghi Thrust, i.e., its tip has not been exposed on the surface. So in terms of structural geology, it is called a blind fault. In contrast, the other structural element was noted as Battal Thrust, which is demarcated within the Mansehra Granite of Cambrian to Ordovician age near Battal village. This emergent faultdips 32° towards the northeast and penetrates 13.74 km deep within the sedimentary and metasedimentary wedges. Battal Thrust joins the Oghi Thrust at a depth of 13 km. Along the Battal Thrust, fault gouge and breccias have been observed during the field excursion. The total thickness of the sedimentary and metasedimentary wedge in the Mansehra and Battal areas is 13.6 and 14.2 km, while the total thickness of the crust is 51.6 and 52.2 km, respectively (Figs. 3 and 4). These results also conclude that basement is deepening northward, which is already known as the hinterland zone.

4. Results and discussion

Projected gravity data were employed for our research area in Lesser Himalayas to generate a gravity model to illustrate the relationship of known geology with the gravity anomaly. The model parameters (e.g., dimensions, density, and depth) are adjusted until the best fit between the calculated gravity and observed anomalies were achieved. Seismic data has suggested the tectonic complexity in this area that actually lies northwest of Hazara-Kashmir Syntaxis (Seeber, 1979). Several regional-scale gravity studies (A Caporali, 2000; Alessandro Caporali, 2000; Caporali, 1995; Das et al., 1979; Duroy, 1986; Malinconico Jr, 1986; Marussi, 1976) were performed in different areas of northern Pakistan with the objectives of delineating crustal structures and flexural rigidity. Rustam and Ali (1994) concluded that the average thickness of the crust varies from 46 km at Fatehjang to 59 km at Kundal Shahi in close vicinity areas in northern Pakistan, giving as the average dip of Moho 4.75° towards the northeast. Mishra and Rajasekhar (2006), based on gravity profile across this area, suggested a crustal thickness of 40 km south of Lahore–Sargodha ridge to about 70 km under the Karakoram range. The geological structures are approximated as a horizontal prism with finite length and polygonal cross-section in the gravity model. For the alteration of calculated and observed gravity data, modelling was based on three steps: the effects of sediments/meta-sediments, Moho, and the combined effect of Moho and sediments/meta-sediments with respect to nearly 40 km thick crystalline crust of northern Pakistan. Density contrast assigned to these geological units with respect to the crystalline crust (2.95 gm/cc) are −0.50, −0.47, −0.90 and −0.70 gm/cc, respectively. The model considers the constraints delivered by

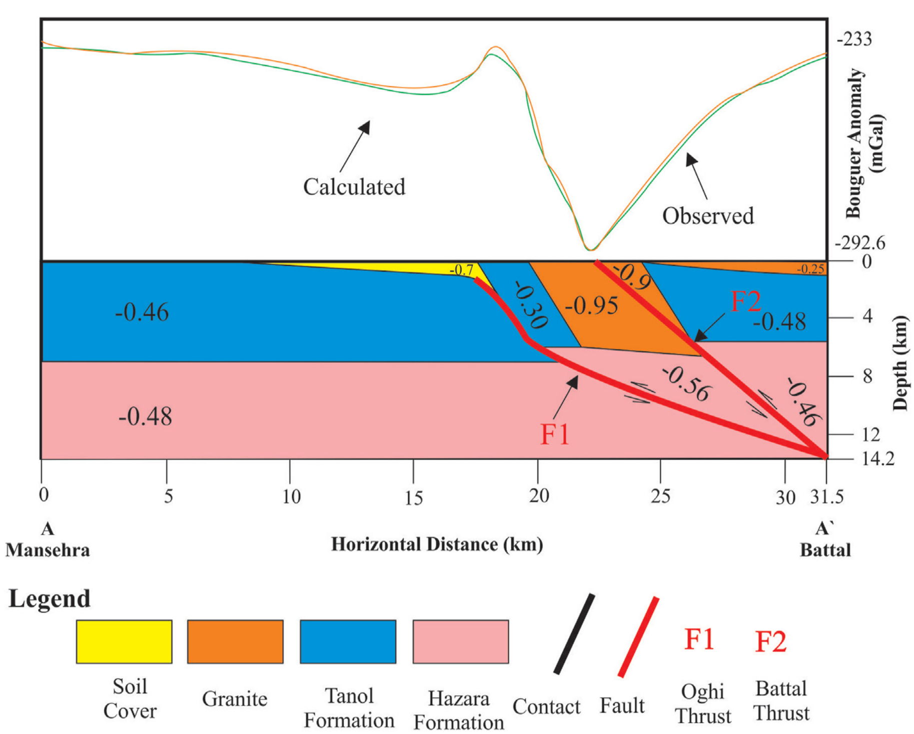

Fig. 3. Geological model of the sedimentary, meta-sedimentary wedge along with the profile A-A' from Mansehra to Battal.

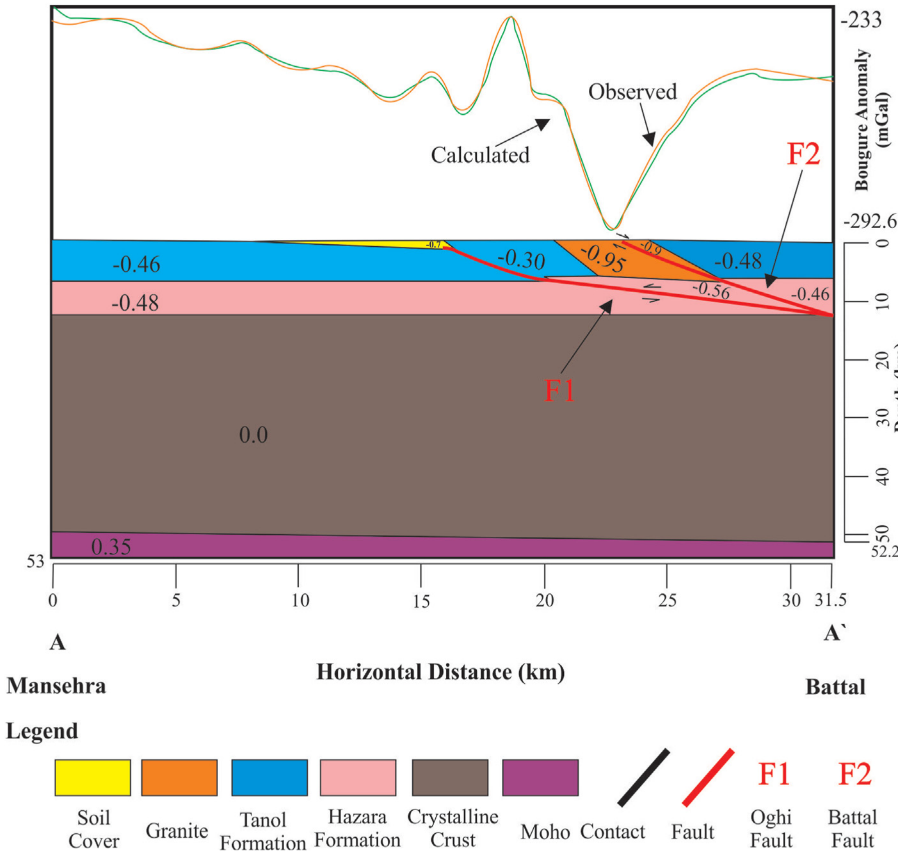

Fig. 4. Geological model of the crust along the profile A-A' from Mansehra to Battal.

deep-source gravity anomalies. According to the literature, density values have been given to non-survey parts of the subsurface. The density distribution is gradually altered to achieve the best fit between the observed gravity and calculated gravity (Bernabini et al., 1996). The density contrast consigned to the mantle and geological bodies is relative to the average density of crystalline basement, which is taken as 2.95 g/cm3 (Khan and Ali, 1997), while the density consigned to the mantle is 3.30 g/cm3 (Khan et al., 2016; Leathers, 1987). This geological model has been computed under constraint of formerly known geological and structural information (Latif, 1970, 1973; Rustam and Ali, 1994; Rustam and Khan, 2003; Wadia, 1928, 1930, 1931).

The spatial variations of the gravity field recorded at the earth surface depend on the bodily structure of the earth ranging from a very small scale to thousands of kilometers. The current study demonstrates the recorded effect of gravity from different sources stretching from the earth surface downward up to Moho. 2D gravity modelling was performed to a depth of about 53 km. As a result, the gravity model was generated, which revealed that the thickness of the crust increases to the northwestern end of the study area. Fig. 4 shows that the Moho dips shallowly towards the northwest in the particular case study. Following the gravity model, the above part shows a graph between the observed gravity values (green) and the calculated gravity values (red). Y-axis shows the gravity in mGal and the X-axis surface distance in kilometers. Following the results of 2D gravity modelling, it is suggested that the normal crustal thickness in the southmost part of the study area has been assumed to be nearly 51 km. Thickness increases slowly to the northeastern and then northwestern part of the study area (Figs. 1 and 3), and then finally, it is estimated to be maximum at the northern extreme with the value of 52.2 km.

The current research was planned to be conducted in the profile pattern of gravity studies from Mansehra city to the Battal area by keeping in view to study the available exposed geological structures along with the profile. Since our area of interest is located close to the highly deformed Hinterland zone, the main tectonic components are often found exposed here. The location of the study area, in terms of tectonic features, falls between MBT and MMT. The border between Kohistan Island Arc and Indian Plate is called the Indus Tsangpo Suture Zone or MMT (Baig and Lawrence, 1987), as shown in Fig. 1. Rustam and Ali (1994) suggested that the Jhelum left-lateral strike-slip fault cuts the Punjal and Main Boundary Thrusts near the tip of the Hazara Kashmir Syntaxis. Moreover, Murree, Abbottabad, and Hazara formations are greatly distorted amongst the Muzaffarabad and Balakot areas. Results from this study chiefly include the presence of shallow northward dipping blind thrust named Oghi Thrust, which is demarcated within the Tanol Formation of Precambrian age near Kotli Pine. This fault dips at an angle of 43° northeast and penetrates up to a depth of 13.7 km in the sedimentary/metasedimentary wedge (Fig. 3). It is the first detailed research in northern Pakistan, so it is expected that advanced investigations of the Oghi Thrust in surrounding outcrops may bring knowledge about its extensions in the further surrounding areas. The tip of the Battal Thrust pierces out of the Mansehra granite (Cambrian - Ordovician age). It has been confirmed during the field excursion that the same profile location was found with the presence of fault rocks, i.e., fault gouge and breccia. Its location, orientation, and fault type on field site and section A-A' ties the results. This fault dips at an angle of 32° northeast while penetrates up to a depth of 13.74 km in a sedimentary and metasedimentary wedge of the project location. The total thickness of the sedimentary and meta-sedimentary wedge in the Mansehra area is estimated to be 13.6 km, while the Battal area is 14.2 km. The basement dips shallowly northward due to flexure caused by the Himalayan orogenic belt. This shallow dip can be locally seen in Fig. 4. Moving approximately 30 km northward from Mansehra to Battal, the crust thickens. It is estimated that the crustal thickness varies from 51.6 km to 52.2 km.

5. Conclusion

In this study, the detailed information regarding the crustal variations of the study area is determined by incorporating the applications of the gravity technique. The regional Bouguer anomaly, along with the local Bouguer anomaly, was incorporated to delineate the regional structural units. The results bring out new subsurface images and provide more evidences to connect the information on local and regional tectonics and thickness variations of crust towards the hinterland zone. Following conclusions are drawn based on gravity observations:

1. Oghi Thrust has been drawn within the Tanol Formation of Precambrian age near Kotli Pine in the research area. This fault dips 43° towards the northeast and penetrates 13.7 km deep in the sedimentary, metasedimentary wedge.
2. Modern Alluvium covers the Oghi Thrust. As a blind thrust, and its tip has not yet been exposed on the surface.
3. Battal Thrust is demarcated within the Mansehra Granite of Cambrian to Ordovician age near Battal. This fault dips 32° towards the northeast and penetrates 13.74 km deep in the sedimentary and metasedimentary wedge.
4. Battal Thrust joins the Oghi Thrust at a depth of about 13 km.
5. The total thickness of the sedimentary and metasedimentary wedge increases to 13.6 km in the Mansehra and to 14.2 km in the Battal area. In the Mansehra and Battal areas, the total thickness of the crust is 51.6 and 52.2 km, respectively.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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