Interpretation of Gravity Data using 3D Euler Deconvolution, Tilt Angle, Horizontal Tilt Angle and Source Edge Approximation of the North-West Himalaya

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Abstract

The collision of the Indian plate and the Eurasian plate created shortening and imbrications with thrusting and faulting which influences northward tectonic movement. This plate movement has divided the Himalaya into four parts, *viz.* Outer Himalaya, Lesser Himalaya, Greater Himalaya, and Tethys Himalaya. The crystalline basement rock plays an imperative role for structural and tectonic association. The study has been carried out near Rishikesh-Badrinath neighborhood in the north-western part of the Himalayan girdle with multifarious tectonic set up with thrust and faulted geological setting. In this study area, 3D Euler deconvolution, horizontal gradient analysis, tilt angle (TILT) and horizontal tilt angle (TDX) analysis have been carried out using gravity data to delineate the subsurface geology and heterogeneity in the north-western part of Himalaya. The Euler depth solutions suggest the source depth of about 12 km and various derivative analyses suggest the trend of the delineation thrust-fault boundaries along with the dip and strike direction in the study area.

Key words: Euler deconvolution, tilt angle (TILT), horizontal tilt angle (TDX), gradient derivative, Indian Plate.

1. INTRODUCTION

The area of study, situated in the Rishikesh-Badrinath, extends from 30° N to 31.2° N and 78° E to 80° E (Fig. 1). The tectonic movements of the Indian plate and the Eurasian plate caused overlapping, shortening, stratigraphic changes, and tectonic setting in the north-western part of Himalayan belt (Leech *et al.* 2005). The Himalaya can be divided into four parts: Outer Himalaya, Lesser Himalaya, Greater or Higher Himalaya, and Tethys Himalaya (Gansser 1964). The Main Frontal Thrust (MFT) to the south and the Main Boundary Thrust (MBT) to the north are referred to as Outer Himalaya and have molassic Siwalik super-groups of Miocene and Pliocene ages. The Lesser Himalaya is also subdivided by the MBT to the south and the Main Central Thrust (MCT) to the north and a thick pile of highly folded Proterozoic sedimentary strata with older crystalline rocks (Gansser 1964). The Greater or Higher Himalaya is demarcated by the MCT to its south and the Dar-Martoli Fault or Tethys Fault or the South Tibetan Detachment (STD) to the north. The Tethys Himalaya includes thick pile of sedimentary rocks of Cambrian to lower Eocene ages. The structural and petrological aspects have been studied by Le Fort (1975). Structural and tectonic interpretations of parts of Himalaya have been carried out by Molnar *et al.* (1977) using some geophysical observations. The MCT and its quartz-rich tectonites in Central

Fig. 1. Computer generated map showing the topography of the study area and its surroundings.

Nepal have been studied by Bouchez and Pecher (1981). The deformation pattern of leucogranites of the Crystalline MCT (CMCT) sheet in southern Tibet was studied by Burg *et al.* (1984). Grasemann *et al.* (1999) represented kinematic flow of decelerating strain path analysis and extrusion of orogenic wedges from the MCT of north-west Himalaya. Beaumont *et al.* (2001) considered the extrusion of low-viscosity crustal channel in the Himalayan tectonics as coupled to focus surface denudation. Vannay and Grasemann (2001) made it clear that the Himalayan inverted metamorphism and sync-convergence extension are a consequence of a general shear extrusion. Bhattacharya and Weber (2004) elucidated the shear deformation in the MCT zone of north-western Himalaya region.

The crystalline basement rock plays a vital role for structural and tectonic involvement which is unperturbed with tectonic movement and deformation. In this text we have dealt with “basement rocks” or “crystalline basement rocks” which are basically of metamorphic or igneous origin and are termed “granitic basement”, generally covered by sedimentary rocks or sedimentary basin. Generally, *S*-wave velocity starts around 3500 m/s and *P*-wave velocity starts around 6000 m/s in this layer. This is the high velocity layer. It is generally described as the Indian Shield situated below the sedimentary layers and named the Indian Crystalline Basement.

The study area is located near Rishikesh-Badrinath neighborhood in the north-western part of the Himalayan girdle with multifarious tectonic set up with thrust and faulted geology. The estimation of crystalline basement depth in folded and thrust areas of such kind is very difficult. Different authors (Khattri *et al.* 1989, Reddy and Arora 1993, Bhattacharya and Weber 2004, Arora *et al.* 2007) worked for the estimation of basement depth, but the results are not very specific and clear.

Ghosh and Singh (2014) studied the Indian crystalline basement depth in the Dehradun-Badrinath area using spectral analysis and 2D Euler deconvolution technique of gravity data along the few selected profiles. The results are obtained using 2D approach and some geological models have been proposed for shallow crustal configuration based on the gravity data (Ghosh and Singh 2014). The average basement depth estimated was 11.27 km using 2D spectral analysis of gravity data. The 2D Euler deconvolution suggests basement depth varying from 10 to 15 km across the profile from SW to NE in the study area along the three selected profiles. The study suggests that most of the cluster points were located within 10 to 15 km depth range. However, the results provided do not meet in terms of holistic vision to get details in 3D interpretation.

In continuation, to study the area in terms of 3D depth investigation, we have used the published gravity data (Qureshy *et al.* 1974). The old gravity data have been digitized and re-interpreted in terms of geophysical conse-

Fig. 2. Bouguer gravity anomaly map (after Qureshy *et al.* 1974) digitized and replotted (Ghosh and Singh 2014). The colour bar denotes the Bouguer gravity anomaly values. Higher gravity value observed at Rishikesh, Srinagar, and Dehradun areas. Lower gravity values are observed at Badrinath, Harsil, and Joshimath areas. Moderate gravity value observed at Gwaldam in the central part orienting NW-SE trends.

quences. The contour maps have been generated using minimum curvature gridding with a grid spacing of 1000 m. The data has been further applied to 3×3 convolution matrix for better imaging. The different thrust locations (Ghosh and Singh 2014) are superimposed on the digitized gravity anomaly map (Fig. 2).

In the present study, various gravity gradients are interpreted and results are correlated. The horizontal gradient, tilt angle derivative (TILT), horizontal tilt angle derivative (TDX), and Euler deconvolution (ED) of gravity data have been used to delineate the subsurface geology, identifying the subsurface heterogeneity and crystalline basement depth in the study area. Apart from this, to locate the edges (*i.e.*, geological contacts) or peaks, deriving the source edge function have been estimated using gravity data. Source edge detection with dip and strike orientation have been derived from gravity grid data (Cordell and Grauch 1982, Blakely and Simpson 1986, Grauch and Cordell 1987).

2. GEOLOGY AND TECTONICS

The study area is enfolded with various kinds of geological formations with thrusting and faulting. It is covered by Ganga Basin, Sub Himalaya, Lesser Himalaya, Vaikrita Group, Higher Himalaya, and Tethys Himalaya. The Main Frontal Thrust (MFT) and Main Boundary Thrust (MBT) are located at the south-western part. South Almora Thrust (SAT) and North Almora Thrust are located in the southern part and mostly outside the study area. Main Central Thrust (MCT) divides into multi-faults/thrusts and prominently into two parts, Munsiyari Thrust (MT) and Vaikrita Thrust (VT), which are located at the central part of the study area oriented NW-SE. The MCT has played a role for the Himalayan mountain development. It connects the Greater Himalayan crystalline series over the Lesser Himalayan series. This MCT itself is a wide fault zone and coincides with several string faults.

The Southern Tibetan Detachment System (STDS) is situated in the north-eastern part of the map. The geologic and the tectonic map of the study area is shown in Fig. 3 (after Ghosh and Singh 2014). Patriat and Achache

Fig. 3. Geological and tectonic map of the study area (after Ghosh and Singh 2014).

(1984) observed shortening of continental crust in different incidents like subduction of continental crust, intra continental thrusting, internal deformation and lateral extrusion. Sinha (1987) studied the crustal evolution of collision and compressional belts and the tectonic zonation of Himalaya. The crustal movement of the Indian plate and the Eurasian plate causes the overlapping, shortening, and isostatic adjusted with the Tibetan Plateau. The details overall geological framework of the Himalaya have been provided by Heim and Gansser (1939) and Gansser (1964).

3. METHODOLOGY: 3D EULER DECONVOLUTION, TILT ANGLE AND TDX ANALYSIS

Euler deconvolution technique was used to estimate the source depth locations of the gravity or magnetic signature in a region; it was applied to profile or gridded data to solve the Euler's homogeneity equation (Thompson 1982) which states that:

$$(x - x_0) \frac{dF}{dx} + (y - y_0) \frac{dF}{dy} + (z - z_0) \frac{dF}{dz} = -N F, \quad (1)$$

where x_0 , y_0 , and z_0 are the source depth locations whose gravity field is F measured at x , y , z and N is the Euler's structural index (SI), which is a function of the source geometry of the causative bodies. Source depth has been estimated based on the Euler deconvolution technique applied to the gridded dataset by solving the Euler's homogeneity equation. Equation 1 in this text clearly explains the details of the theory. This depth estimation depends on the type of structural index (SI) which varies from -1 to 2 . In the case of gravity data set, $SI = -1$ denotes the contact type bodies, $SI = 0$ for thin sheet edge and thin sill dyke, $SI = 1$ for cylinder, thin bed and fault, and $SI = 2$ for point or spherical bodies. In this text, we have used $SI = 0$, which is theoretically not accurate but provides approximation of contact type bodies for depth calculation using the first vertical derivative of gravity data.

The Bouguer gravity anomaly across the south-western part to north-western part shows large deviation from local isostatic equilibrium. The mass deficiency characterizes the Ganga basin and the excess underlies the Lesser Himalaya. It is understood that the Ganga basin supposed to be overcompensated whereas the Himalayas are undercompensated by as much as 158 mGal (Fig. 2). This combination of mass deficiency over the Ganga basin and the excess mass over the Himalaya Mountains is due to isostatic occurrences within the strong Indian lithosphere being flexed down at the Himalayan front and extended beneath the Himalaya. The isostatic regional correction is applied to Bouguer gravity anomaly using Airy's isostasy model where 38 km crust thickness is considered. However, this 38 km depth

Fig. 4. Isostatic regional depths of the study area (calculated from topo-grid using Airy's isostasy model).

value is not critical and it is varying between 30 and 45 km (Kaila 1982). Bouguer density is considered to be $2.7 \times 10^3 \text{ kg/m}^3$ and Moho density contrast is $0.335 \times 10^3 \text{ kg/m}^3$ (Lyon-Caen and Molnar 1985, Qureshy 2004). Topographic grids are used to calculate the root depth grid below mean sea level by assuming Airy's isostasy for regional anomaly calculation at each grid point (Fig. 4). To calculate the isostatic residual grid, isostatic regional anomaly has been subtracted from the Bouguer gravity anomaly grid after applying upward continuation for 4 km (Fig. 5). The upward continuation has been studied from 1 to 4 km to reduce the short wavelength noise of the data and, finally, the 4 km upward continuation (4 grid cell points) has been applied in this study to smooth the data without changing the physical significance. This corrected isostatic residual anomaly (Fig. 5) is now used to calculate the first vertical gravity gradient (Fig. 6). This first vertical gravity gradient again breaks into three gradients viz. one vertical gravity gradient and others two numbers of horizontal gradient components in x and y directions, respectively.

Fig. 5. Isostatic residual map calculated after removing the isostatic regional depth from Bouguer gravity anomaly map and after applying upward continuation of 4000 m. The various thrusts/faults locations are superimposed on the Isostatic residual map.

Structural index (SI) needs to be carefully selected as per the expected geological bodies and structure. Euler depth calculation for fault/contact type bodies used Bouguer gravity anomaly using structural index $SI = -1$ (Stavrev and Reid 2007, 2010); however, we have used first vertical gravity gradient to calculate Euler depth for fault/contact type bodies using $SI = 0$, which is theoretically not accurate but provides approximated source depth calculation. As Euler deconvolution generates many solutions, so to accept the best results, the knowledge of the geology is very important. It has been observed that the source depth increases with increasing structural index. The Euler source depth solutions are shown by different symbols with color. In this study, we have used structural index $= 0$ with a combination of 12×12 window size (WS) for correlation purpose.

Reid *et al.* (1990, 2003), and Stavrev (1997) have explained the Euler deconvolution technique, more details in methodology and wider application regarding the Euler's source depth solutions. These Euler depth solutions are not

Fig. 6. Map of the first vertical gravity gradient of the study area (vertical gradient calculated from gravity residual isostatic map using Fig. 5).

only estimate the depth (z_0), but also delineate the horizontal boundaries (Wilsher 1987, Corner and Wilsher 1989, Klingele *et al.* 1991, Marson and Klingele 1993, Huang *et al.* 1995). In a general case, scattered data points cannot provide superior solutions (Mushayandebvu *et al.* 2004, Yaghoobian *et al.* 1993). Various researchers have used 3D Euler deconvolution technique for source depth estimations (Thompson 1982, Pilkington *et al.* 1995, Smith *et al.* 1998, Nabighian and Hansen 2001, Cooper 2002, Mikhailov *et al.* 2003, Milligan *et al.* 2003, Silva and Barbosa 2003, FitzGerald *et al.* 2004, Mushayandebvu *et al.* 2004, Fedi 2007, Melo *et al.* 2013, Reid and Thurston 2014, Reid *et al.* 2014).

The tilt angle defined by Miller and Singh (1994) and Verduzco *et al.* (2004) is as follows

$$\text{TDR} = \tan^{-1} \left(\frac{\partial g / \partial z}{\sqrt{(\partial g / \partial x)^2 + (\partial g / \partial y)^2}} \right), \quad (2)$$

where $\partial g/\partial z$ is the vertical gradient derivative and $\sqrt{(\partial g/\partial x)^2 + (\partial g/\partial y)^2}$ is the horizontal gradient derivative. Tilt angle (TDR) is varying within the range: $+\pi/2 > \text{tilt angle} > -\pi/2$.

The tilt angle is 0 radians at the measuring point ($x = x_0$) above the edges of the contact. It is evident that this property identifies the horizontal location of the source. In addition, one can determine the depth estimation since the tilt angle equals $\pi/4$ when $x - x_0 = z_0$ and $-\pi/4$ when $x - x_0 = -z_0$. Therefore, half the horizontal distance between the $\pm\pi/4$ radians contours of the tilt angle is the depth to source. In addition, the depth to source can be obtained from the distance between zero and $\pm\pi/4$ radians at the point $x = x_0$ over the vertical contact.

Cooper and Cowan (2006) studied the TDX (horizontal tilt angle) as

$$\text{TDX} = \tan^{-1} \left(\frac{\text{THDR}}{\text{VDR}} \right), \quad (3)$$

where VDR is the vertical gradient and THDR is the total horizontal gradient. TDX is varying between the $+\pi/2 > \text{TDX} > -\pi/2$, but has a much sharper gradient over the contrast than tilt angle derivatives.

The tilt angle and TDX analyses for thrust and fault locations have been carried out by many researchers (Blakely and Simpson 1986, Miller and Singh 1994, Hsu *et al.* 1996, Fedi and Florio 2001, Fedi 2002, Williams *et al.* 2005, Wijns *et al.* 2005, Phillips *et al.* 2007, Oruc 2010, Yuanyuan *et al.* 2010, Ansari and Alamdar 2011, Cascone and Campbell 2012, Fedi *et al.* 2012).

4. INTERPRETATION OF GRAVITY DATA

The present paper describes the analysis of source depth and thrust/fault locations using the gravity data (Qureshy *et al.* 1974). It has been observed that gradients of Bouguer anomalies increase from Ganga Basin to the Higher Himalaya, varying from 1 to 2 mGal/km. This increases the dipping of Moho rapidly, from 10° to 15° beneath the Higher Himalaya and 1° to 2° below the Lesser Himalaya (Lyon-Caen and Molnar 1985). The published gravity map of Qureshy *et al.* (1974) was further digitized with a grid spacing of 1000 m interval and re-interpreted in terms of geophysical consequences. The isostatic corrected residual anomaly has been calculated after removal of regional and upward continuation of 4 km from the Bouguer gravity data. The first vertical gradient of the isostatic residual anomaly corrected data is used for further 3D Euler deconvolution (ED), tilt angles, and TDX analysis for depths and horizontal boundary of faults or contact-like bodies. The study area comprises a continuous decreasing gravity anomaly

trend from south-west to north-east. The lower gravity anomaly is observed in the north-eastern part at Badrinath (−390 mGal), Harsil (−350 mGal), and Joshimath (−330 mGal) area. However, higher gravity anomaly has been observed at the south-western part near Rishikesh (−160 mGal), Dehradun (−160 mGal), and Srinagar (−185 mGal) area. Moderate gravity anomaly (−260 mGal) was observed at Karnaprayag and Matli areas. The Bouguer gravity anomaly decreases from −134 to −393 mGal while the elevation increases from −199 to 5960 m from south-western to north-eastern direction (Fig. 1). Bouguer gravity anomaly and the topography of the study area follow the opposite pattern due to isostatic adjustment (Qureshy 1981). Based on this observation, the area can be divided into three parts, viz. lower gravity anomaly in north-eastern part correlates with higher elevation; the higher gravity anomaly in the south-western part correlates with lower elevation, and the moderate gravity anomaly with moderate elevation is between these higher and lower gravity anomalies.

The gravity observations suggest that Bouguer gravity anomaly decreases rapidly from the Ganga Basin to the Greater Himalaya, causing isostatic adjustment and showing a decrease of crustal density. In various places, like Badrinath and Harsil areas, the crystalline rocks are exposed and might be due to the crustal intrusion, tectonic resettlement or movement process. It was suggested that crystalline rocks are uplifted over the sedimentary surfaces near to the thrust and faulted area. Hence, it is very difficult to find out the accurate thrust and fault locations through the geological studies accurately. The study suggests that these locations are fragmented in multiple locations.

Various authors (Tripathi *et al.* 2012, Chamoli *et al.* 2011, Arora *et al.* 2007, Gokarn *et al.* 2002) had carried out the depth estimation and provided their views. However, the present study provides better results and detailed information of source depth locations and structural boundaries with dip information. The results carried here are well corroborated with the available thrust fault boundaries, as shown in the tectonic maps of the area (Fig. 10).

Euler solutions are superimposed with the first vertical gradient of the Bouguer gravity map using $SI = 0$ and window size (WS) = 12×12 . Different source depth locations are marked with different color circles, which are varying from about 4 to 8 km (Fig. 7). The Euler deconvolution is also used to estimate the delineation of fault or contact at the different depth levels which corresponds to the fractures of basement. It is noted that upward continuation of 4 km has been applied to the gravity data, so the total depth of investigation can vary from approximately 8 km ($\leq 4 + 4$ km) up to 12 km (maximum depth $8 + 4$ km), where the isostatic regional root depth calculated from topo grid is more than 90 km.

Fig. 7. Map of the Euler source depth solutions superimposed on the geological thrust/fault locations of the Rishikesh-Badrinath area (Euler solutions calculated based on the vertical gravity gradients, SI = 0 (structural index), WS = 12×12 (window size)).

The various clusters points of the source bodies are evenly connected from shallow to deeper source depth and vary from about 4 to 8 km (alternatively adding 4 km due to upward continuation). It is suggested that the basement depths vary from shallow to the deeper crystalline rocks which are represented in the study. Euler depth solutions are studied from the cluster points located along the thrust boundaries at Main Boundary Thrust (MBT), South Almora Thrust (SAT), North Almora Thrust (NAT), Main Central Thrust (MCT), Munsiri Thrust (MT), Vaikrita Thrust (VT), and South Tibetan Detachment System (STDS). It has been noted that as MCT is a wide fault zone and has divided into several threads faults. However, in broad sense the MCT zone is basically divided into two faults, *i.e.*, upper bounding faults and lower bounding fault. The upper bounding fault is equated with Vaikrita Thrust (VT) and the lower bounding fault is equated as Munsiri Thrust (MT). For this reason, it may be assumed that the 3D Euler deconvolution results in terms of clustering are little scattered. This can also suggests that the thrust/fault boundaries are fragmented in nature, as suggested through Euler deconvolution. Hence, apart from these present thrust

Fig. 8. Map showing the total horizontal component superimposed with the Euler depth solution with SI = 0 and WS = 12 × 12.

locations (Fig. 3), more additional thrust/fault boundaries are acknowledged through cluster solutions (Fig. 7). In Badrinath area, shallow depth < 4000 m suggests the upwarpment of crystalline basement rocks, also observed at the Karnaprayag, Gwaldam, Rishikesh, and Harsil area (Fig. 7).

The horizontal gradient component superimposed with the Euler depth solution SI = 0 and WS = 12 × 12 are shown in Fig. 8. Cluster points are more prominent along the maximum and minimum gradients of gravity field. This horizontal gradient map analysis suggests the trends of major thrust locations and structural boundaries which are poorly exposed. These studies draw attention to weaker structures which can have major tectonic significance in this region. It has been suggested that horizontal gravity gradient analysis with the topography of the area have a strong correlation and need more attention for further study.

Tilt angle and TDX studies suggest the generalized local phase and enhance the weak gravity anomalies. Euler depth solution with structural index 0 and WS = 12 × 12 are superimposed on the tilt angle map (Fig. 9) and TDX map (Fig. 10). The tilt angle map is relatively smoother, with positive values over source and zero over the source edges at which the vertical derivatives is zero. TDX also showed the smoother contour along the peak val-

Fig. 9. Map showing the various thrust / fault locations, tilt angle map superimposed with Euler source depth solutions (using SI = 0 and WS = 12×12).

ues. However, in both the cases, tilt angle or TDX studies, the vertical contacts are more clearly defined by the zero contour map. The tilt angle map (Fig. 9) provides the source body boundaries elongated in the north-west to south-east direction, which is well correlated along the different known thrust/fault boundaries. The Source Edge Detection (SED) map was superimposed with dip direction and Euler depth solutions using SI = 0 and WS = 12×12 (Fig. 11).

The positive and the negative signatures of the gravity anomalies have been considered for processing to estimate in each grid points for calculating dip and strike direction. The map shows the dips of the source bodies with contact representing a symbol “ $\perp$ ”. The right hand is the dip direction standing on the strike direction (Fig. 11). The long axis represented the strike direction of the edge (contact) and the downward gradient directions are the dip directions as shown in Fig. 11. The map shows the four different strike directions varying from $0^\circ \leq \text{strike} \leq 90^\circ$, $90^\circ \leq \text{strike} \leq 180^\circ$, $180^\circ \leq \text{strike} \leq 270^\circ$ to $270^\circ \leq \text{strike} \leq 360^\circ$. This strike is measured in the clockwise direction varying from 0° to 360° , where the Y axis points to north. Dip can also be measured in degrees, varying from 0° - 180° relative to the direction perpendicular to the strike (Blakely and Simpson 1986).

Fig. 10. Map showing the various thrusts/faults locations, TDX (horizontal tilt angle map) superimposed with Euler source depth solutions (using $SI = 0$ and $WS = 12 \times 12$).

The tilt angle map, SED, Euler depth solution ($SI = 0$, $WS = 12 \times 12$) and identified thrust/fault boundaries are superimposed, as shown in Fig. 12. Similarly, the TDX analysis, SED, Euler depth solution ($SI = 0$, $WS = 12 \times 12$) and identified thrust/fault boundaries are superimposed, as shown in Fig. 13. These above studies suggest that the various results derived are well correlated.

Reddy and Arora (1993) reported basement depth from 10.0 to 15.0 km below the Himalayan collision region with a high conductivity layer embedded in the crust at using geomagnetic deep sounding (GDS). Gokarn *et al.* (2002) also observed the basement depth increases upto 15.0 km using magnetotelluric (MT) studies. Khattri *et al.* (1989) also suggested the depth of detachment of 15.0-18.0 km underneath the Lesser Himalaya of Garhwal. Bhattacharya (1999) suggested that during the collision of Indian and Eurasian plate, part of segment of the basement rocks were uplifted from the depth to the surface due to its buoyancy and the rock mass moved along the Main Central Thrust (MCT). It was recommended that most of the collisional stresses were compressive in nature which helped in stirring the mass up and about from the depth. The earthquake's hypocenters are between depths

Fig. 11. Map of the Source edge detection (SED) superimposed with dip direction and Euler source depth location (SI = 0 and WS = 12×12).

of 10.0 and 20.0 km, due to the under thrusting of Indian Plate and mass upliftment (Molnar and Chen 1982, Ni and Barazangi 1984). Chamoli *et al.* (2011) have studied the Himalayan detachment thrust to be 11.0 km in the north-western part of the present study area. Arora *et al.* (2007) also studied the Deep Resistivity Sounding (DRS) along the western part of the north-western Himalayas and suggest resistivity $> 300 \Omega\text{-m}$ up to depth of 15 km. Tripathi *et al.* (2012) suggested by coda wave attenuation analysis in the Garhwal region of north-western Himalaya that the earthquakes are mainly concentrated within depths from 10 to 15 km, which suggests that most of the crustal activation takes place within this particular depth. The coeval development of South Tibetan Detachment and the Main Central Thrust studies through simulation analysis and the thrusting dominating nature of Himalaya studies have been done by Shanker *et al.* (2002).

It can be concluded that the results obtained here are well correlated with the results of various scientists in this study area and neighboring areas (Tripathi *et al.* 2012, Chamoli *et al.* 2011, Arora *et al.* 2007, Gokarn *et al.* 2002).

The major thrust locations are identical as per the calculation of Source Edge Detection (SED) technique using the vertical gravity gradient data.

Fig. 12. Tilt angle, SED, Euler depth solution ($SI = 0$, $WS = 12 \times 12$) and thrust/fault location map are superimposed which looks a better correlation.

Fig. 13. Map of the Euler source depth solutions ($SI = 0$, $WS = 12 \times 12$) superimposed on the geological thrust-fault location of the Rishikesh-Badrinath area, horizontal tilt angle (TDX), and source edge detection (SED).

Fig. 14. Map shows the tectonic model (front view) using Euler deconvolution by plotting the cluster points and superimposed with the previously known identified thrust locations.

Fig. 15. Map shows the tectonic model (3D view) using Euler deconvolution by plotting the cluster points and superimposed with the previously known identified thrust locations.

Fig. 16. Map shows the 3D view of the cluster solutions indicating the extension of the cluster points along the thrust locations.

Most of the derived thrust boundaries are well correlated with the various well known thrust boundaries. However, this study provides more additional thrust boundaries, not noticeable earlier. The details identified automatic thrust locations and the dip directions are shown in Fig. 11. Tilt angle, SED and Euler source depth solutions are shown in Fig. 12, and TDX, SED, and Euler source depth solutions are shown in Fig. 13.

Fig. 17. Map shows the profile location oriented in SSE-NNW direction (profile A) across the area studied by Ni and Barazangi (1984) (a), depth section across the profile A and the relevant thrust locations Ni and Barazangi (1984) (b), and the derived solutions from the 3D Euler deconvolution in the present study(c).

Additionally, a 3D figure (tectonic model) has been developed showing the position of detachment surface with various thrusts like MFT, MBT, SAT, BT, MCT/MT, VT, and STDS. Figures 14 and 15 show the tectonic model using Euler deconvolution by plotting the cluster points and superimposed with the previously known identified thrust locations. Figure 16 shows the 3D view of the cluster solutions indicating the extension of the cluster points along the thrust locations. One of the tectonic profiles (Profile A) oriented SSE-NNW generated by Ni and Barazangi (1984), as shown in Fig. 17a, and the depth solutions model derived by Ni and Barazangi (1984), as shown in Fig. 17b, are correlated with the results derived from the 3D Euler deconvolution (Fig. 17c). The depths estimated along with the thrust locations are well correlated.

It is also to be noted that most of the thrust boundaries in the study area remain unidentified up to now. However, in the present study, additional information of thrust-fault boundaries has been provided. This additional information can be helpful for further detailed geo-scientific research work in the area.

5. DISCUSSION AND CONCLUSION

Automatic basement depth study has been carried out using 3D Euler deconvolution of gravity data. These cluster points derived from the Euler's source depth calculation suggest the shallower depth < 8 km and deeper depth > 12 km (as data is an upward continuation of 4 km). In addition, probable thrust and fault boundaries are identified using tilt angle analysis, TDX angle, and various horizontal gradient analyses of gravity data which have not been marked in the past studies. The Source Edge Detection (SED) technique has been applied and identified the thrust boundaries and dip direction. The various horizontal gradients indicate the structural boundaries in the study area. The information provided in this current study added more supplementary information which was not proposed by earlier study. The results shown here with different aspects are well correlated with the existing available information carried by the various potential workers. However, the present study, providing additional thrust/fault boundary information within Vaikrita Thrust (VT) and Southern Tibetan Detachment System (STDS), with source depth locations and dips directions, provided a need to carry further work with more attention. The gravity data interpretation provides a more reasonable explanation for the depth estimation, structural boundary, and source edge detection. The compilations of details of gravity analysis correlate with the depth and thrust boundaries of buried structures and also clarify the pattern of geological information in the north-western part of India.

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