Hindawi Publishing Corporation
International Journal of Geophysics
Volume 2014, Article ID 691521, 8 pages
http://dx.doi.org/10.1155/2014/691521

Research Article

Integrating Apparent Conductance in Resistivity Sounding to Constrain 2D Gravity Modeling for Subsurface Structure Associated with Uranium Mineralization across South Purulia Shear Zone, West Bengal, India

Arkoprovo Biswas, Animesh Mandal, Shashi Prakash Sharma, and William Kumar Mohanty

Department of Geology and Geophysics, Indian Institute of Technology Kharagpur, Kharagpur 721302, West Bengal, India

Correspondence should be addressed to Shashi Prakash Sharma; spsharma@gg.iitkgp.ernet.in

Received 29 May 2013; Revised 28 October 2013; Accepted 5 November 2013; Published 22 January 2014

Academic Editor: Ruey-Juin Rau

South Purulia Shear Zone (SPSZ) is an important area for the prospect of uranium mineralization and no detailed geophysical investigations have been carried out in this region. To delineate the subsurface structure in the present area, vertical electrical soundings using Schlumberger array and gravity survey were carried out along a profile perpendicular to the SPSZ. Apparent conductance in the subsurface revealed a possible connection from SPSZ to Raghunathpur. The gravity model reveals the presence of a northerly dipping low density zone (most likely the shear zone) extending up to Raghunathpur under a thin cover of granitic schist of Chotanagpur Granite Gneissic Complex (CGGC). The gravity model also depicts the depth of the zone of density low within this shear zone at ~400 m near Raghunathpur village and this zone truncates with a steep slope. Integration of resistivity and gravity study revealed two possible contact zones within this low density zone in the subsurface at depth of 40 m and 200 m. Our study reveals a good correlation with previous studies in Raghunathpur area characterized by medium to high hydro-uranium anomaly. Thus the conducting zone coinciding with the low gravity anomaly is inferred to be a possible uranium mineralized zone.

1. Introduction

Natural radioactive mineral deposits are found in suitable geological environment like shear zones [1–4], unconformity contacts, veins, and so forth [5, 6]. The mineralization may occur in vertical, dipping, and horizontal sheet-type structures. Uranium is highly conducting in nature and its presence in the subsurface provides good conductivity contrast between ore deposit and host rock [7, 8], making it possible to be delineated by electrical resistivity methods. Further, near surface structural features such as the shear zones can also be identified by detailed gravity measurements [9].

South Purulia Shear Zone (SPSZ) (Figure 1, after [10]) consists of mainly granite gneiss, amphibolites, phyllites, schist, carbonatite, and quartz-magnetite-apatite rocks and is of early mesoproterozoic age. Subsurface signature of uranium has been found in the existing apatite mine at Beldih but detailed geophysical activities are very limited in that area. Most of the previous studies deal with regional gravity and magnetic survey over the Eastern Indian Shield [11–13]. The Bouguer gravity anomaly map and magnetic data [14] suggest that there is a contrasting change from the Singhbhum Granite Craton in the south to the CGGC in the north but the detailed subsurface structure is little known in the present area. The gravity study shows a broad low anomaly zone [14]. There is a very good correlation with the nature of Uranium deposit in Beldih mine with the Uranium present in different locations of Singhbhum Shear Zone [15, 16]. Chemical analysis of water samples also shows presence of Uranium in the subsurface water (~40 m) collected from deep tube well [17]. All of these studies prompted us for further detailed subsurface investigation.

In the present study, deep resistivity sounding, apparent conductance, and gravity measurements were carried out

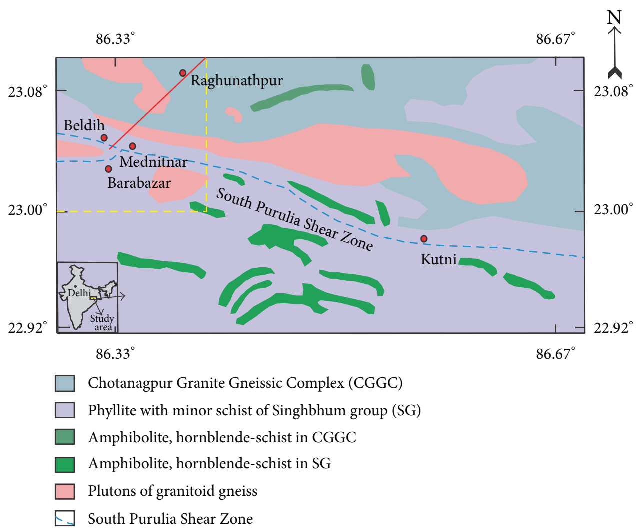


FIGURE 1: Geological map of the study area (after [10]) with gravity survey area (dotted yellow) and sounding profile line (red).

from SPSZ to Raghunathpur village (where high hydro-uranium anomaly was reported). Sometimes the possible thin mineralization zone may not be reflected in the conventional apparent resistivity measurement. Therefore, apparent conductance has also been studied simultaneously at all sounding locations. The variation in the apparent conductance suggests the presence of conductive formation at depth which helped in the correct interpretation of resistivity sounding data and sometimes to constrain the subsurface structure for 2D forward gravity data modeling.

2. Geology of the Study Area

The SPSZ (Figure 1) forms a part of the ENE-WSW to E-W to ESE-WNW trending curvilinear lineament which roughly marks the contact between North Singhbhum Mobile Belt (NSMB) in the south and the CGGC in the north [14, 15] (Figure 1). This lineament extends from Tamar, Ranchi district, Jharkhand, in the west to Porapahar, Bankura district, West Bengal, in the east. This lineament extends for a distance of nearly 150 km with width of 4-5 km affecting a very narrow part of CGGC and relatively broader part of Singhbhum group (reviewed in [15]). The major part of SPSZ is covered by felsic volcanics accompanied by mafic and ultramafic rocks with subordinate metapelites. Along the contact of SPSZ and CGGC, thin linear bands/lenses of tourmalinite, quartz reef, quartz breccias, ferruginous breccias, schroll, and mylonitic rocks are profusely developed. Quartz-magnetite-apatite rocks, carbonatite, and syenites are some of the other significant rocks reported along the SPSZ [18–21]. The general trend of the foliation along the shear zone is E-W to ESE-WNW with steep dip due north or south or vertical at places. The shear zone shows ductile to brittle-ductile deformational pattern [15] associated with intense brecciation, mylonitization, and hydrothermal alterations accompanied by development of apatite, magnetite, base metal, rare metals, rare earth, and uranium [14, 19, 21].

3. Geophysical Survey

3.1. Electrical Resistivity Sounding and Apparent Conductance. In electrical resistivity sounding, current is passed into the ground with a pair of metal electrodes and potential difference is measured with another pair of electrodes (copper rod dipped into $CuSO_4$ solution in a porous pot). The ratio of potential difference and current flow yields the apparent resistance of the ground. This apparent resistance is multiplied by the geometrical factor (depends on all electrode positions) of the array to get the apparent resistivity for a particular current electrode separation. Current electrode separations are gradually increased from a very small value (say 1.0 m to several km) to depict the vertical variation in the resistivity that reflects the variation in subsurface lithology. The number of layers is decided on the basis of variation in the apparent resistivity with electrode separation.

In spite of multidimensional development in the acquisition and interpretation of resistivity data, a problem exists in the conventional 1D electrical resistivity sounding to identify the actual number of layers in certain geological conditions. It is not possible to identify the actual number of layers when computed apparent resistivity increases continuously with increasing current electrode separation. To solve this problem, the amount of current flow at various current electrode separations can also monitored. The current flow is normalized with the applied external voltage and referred to as apparent conductance (C_A) [22, 23]. Lithological change in the subsurface is reflected in the C_A. Even though apparent resistivity is unable to reflect change in lithology, C_A depicts such changes and helps in the determination of actual number of layers present in the subsurface. We tried to analyze normalized C_A in the area to study its relationship with subsurface features or to get any additional information which might be helpful in qualitative or quantitative interpretation of conventional sounding data. To interpret the sounding data, some decisions about the number of layers and layer resistivities are also taken on the basis of C_A pattern revealed for each sounding.

3.2. Gravity. A total of nearly 175 gravity observations were recorded across the SPSZ along different approachable paths covering nearly 80 km^2 area. The survey was executed by a W. Sodin gravimeter (sensitivity 0.01 mGal) with a station spacing of nearly 200–250 m. The gravity measurements obtained from the study area were tied to the nearest absolute gravity base station at Purulia railway station (absolute gravity value (g_n) = 978796.73 mGal) [24].

The raw gravity data were reduced to mean sea level following the standard data reduction procedures (i.e., by employing instrumental drift correction, free-air correction, Bouguer correction, and terrain correction) to keep the effect of subsurface mass only. Base station was occupied at the beginning and end of each working day to remove the instrumental drift. Using linear interpolation between base station reoccupation, this temporal variation in the gravity field was estimated. Theoretical gravity value was calculated using the formula given on the 1967 Geodetic Reference System (GRS67). The free-air correction term was derived by the standard free-air gradient of 0.3086 mGal/m (neglecting higher order terms). To compute the Bouguer correction, the average crustal density was taken as 2.67 g/cm^3. Topographically, the study area was almost flat. Thus, the terrain effect as calculated from the mass integral method [25] was very small to affect the Bouguer anomaly significantly. Bouguer anomaly map after the data reduction is shown in Figure 2.

3.3. Regional-Residual Separation. The separation of the regional component from the Bouguer anomaly is a crucial step in subsurface gravity study for mineral exploration point of view as the residual part is contributed solely by the near surface density distribution. In the present study, the regional-residual separation was done using trend surface analysis method [26]. Third degree polynomial is used as the regional field for gravity anomaly (Figure 3). This polynomial gives the regional values at the analyzed points and the residual anomaly (Figure 4) values were obtained by direct subtraction of the regional values from the observed Bouguer anomaly values. The high residual anomaly on the north-east part (east of Raghunathpur village) and south-west (near Barabazar) are due to the high density metabasic rocks and compact granite intrusion within mica schist/phyllites, respectively. The highly altered rocks and brecciated granite in the middle part of the study area is depicted by a low gravity anomaly zone along the NW-SE trending shear zone. This also reveals the width of the shear zone. Thus, the residual gravity anomaly map shows a good correlation with the surface geology.

4. Results and Interpretations

4.1. Electrical Resistivity Sounding and Apparent Conductance. Schlumberger resistivity soundings were performed at 5 locations (Figure 1) along a profile perpendicular to the SPSZ. The spread of current electrodes was kept approximately parallel to the known geological strike (NW-SE direction) for smooth variation in the apparent resistivity. Current electrodes were expanded with AB/2 = 3 to 1000 m to delineate the structures extending to depth of 250 m. Since, the apparent resistivity data shows a continuously increasing trend with depth or current electrode spacing (AB/2), it was interpreted using 2-, 3-, 4-, and 5-layer model. However, the interpreted resistivity and thickness were erroneous and uncertainties in the model parameter were very high without considering C_A.

We have studied the C_A data for each sounding simultaneously with apparent resistivity data. First, the measured current flow at various current electrode spacings is normalized with the applied voltage to obtain the current flow for a unit applied voltage. Subsequently, each value is also normalized with the C_A computed at the first current electrode separation. Since the local condition varies at each sounding location we again normalized each data by the corresponding maximum value of C_A (Figure 5) for uniformity at various soundings. This shows a good correlation in the C_A at each sounding and depicts an increased C_A zone (Figure 5). Soundings S5, S4, S2, and S1 show a maximum C_A (Figure 5) at a deeper depth (current electrode spacing 250 m to 400 m, AB/2). C_A is also contoured taking all the

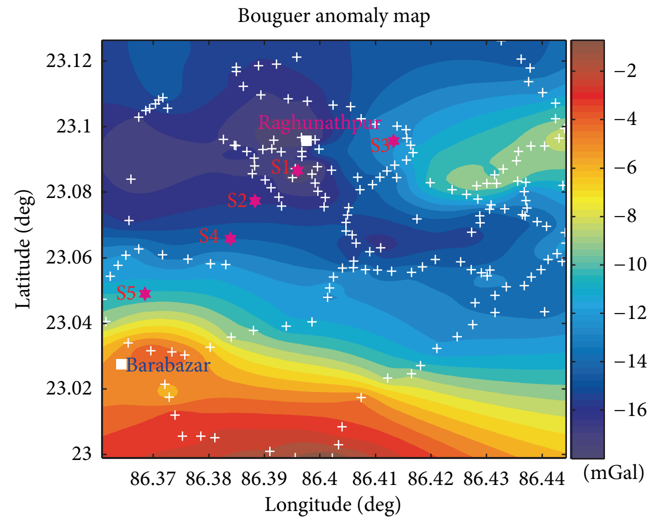


Figure 2: Bouguer anomaly map of the study area. Plus (+) symbols are the gravity survey locations.

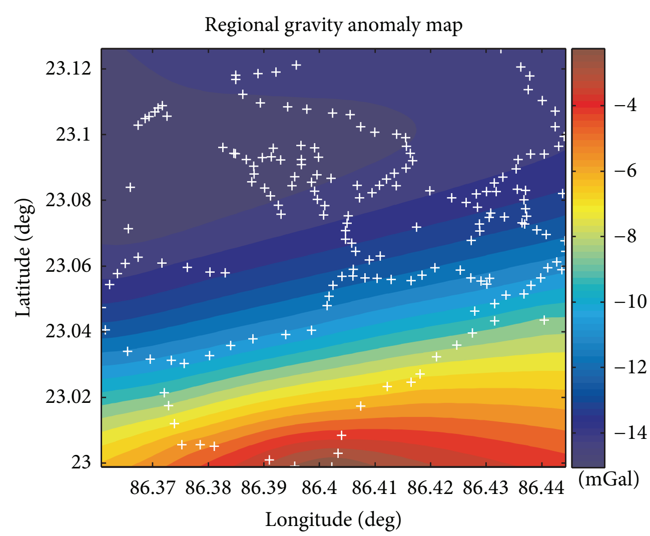


Figure 3: Regional gravity anomaly map of the study area after 3rd degree trend surface fitting to Bouguer anomaly. Plus (+) symbols are the gravity survey locations.

soundings into consideration. Figure 6 shows the contour map of normalized C_A which clearly depicts conducting layers at depth. The green dotted line demarcates (Figure 5) as the probable conducting zones which might be associated with uranium mineralized zone. Thus, such normalized C_A can be very effective in delineating the subsurface conductor where the formation is dipping and cannot be delineated using conventional resistivity data interpretation technique. This normalized C_A helps us to interpret the different layers in the sounding data and is very effective in delineating the subsurface layers accurately.

4.1.1. Interpretation of Resistivity Sounding Data. Resistivity sounding data is interpreted using 1D very fast simulated annealing global optimization inversion technique [27, 28].

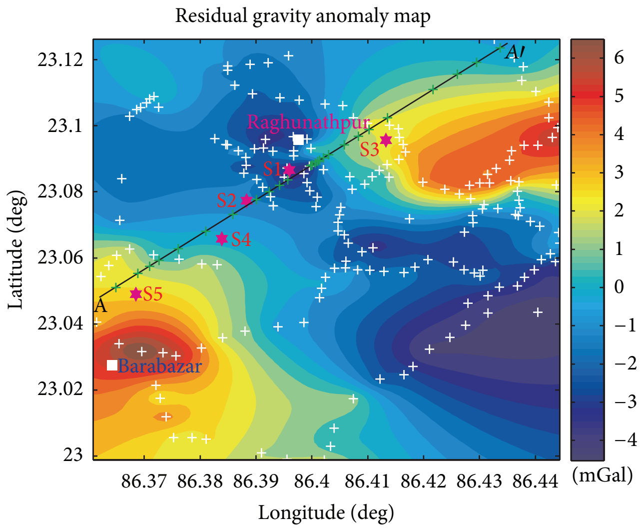


FIGURE 4: Residual gravity anomaly map of the study area after separation of 3rd degree trend surface polynomial from Bouguer anomaly. Plus (+) symbols are the gravity survey locations.

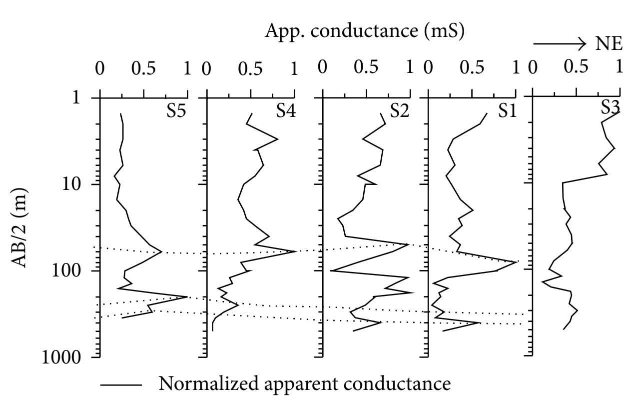


FIGURE 5: Normalized apparent conductance (C_A) for five soundings.

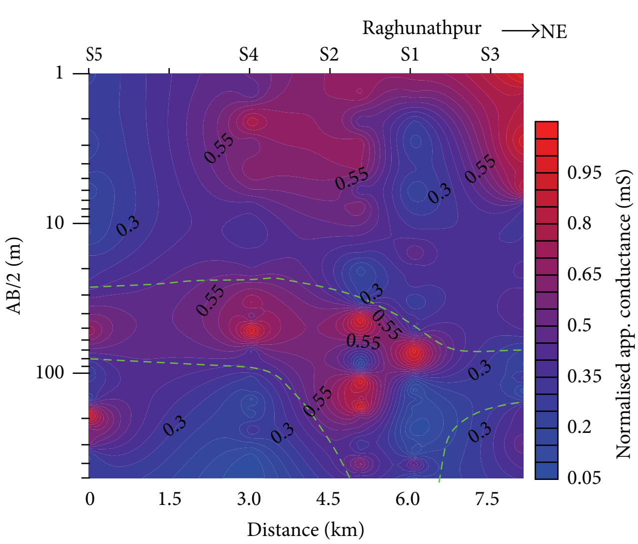


FIGURE 6: 2D Pseudo section contoured from normalized apparent conductance (C_A) of five soundings.

Interpretation of sounding data without considering the C_A may yield erroneous result and hence may not match with geologic section. Therefore, we present the interpretation of soundings using number of layers on the basis of C_A. Figure 7 presents the comparison between the observed and model data for all five soundings and their corresponding apparent conductance. Figure 7(a) shows that model data for soundings S1 and S3 could not fit precisely (especially the later part of the sounding data) due to fact that slope of soundings S1 and S3 is more than 45°. The resistivity sounding data shows that apparent resistivity is continuously increasing with depth after 10–20 m AB/2 values. Hence it can be understood that there is a massive resistive layer beneath the near surface conducting layer corresponding to AB/2 values of 10–20 m. However, this is not true; either there are different geological layers that are not seen in the C_A data or there are fractures in the massive resistive layer. Since the separation between S5 and S1 is 6 km, it is unlikely that there are only fractures which can cause such a correlatable C_A.

In principle only 3-layer models are sufficient to fit all resistivity sounding data. However such interpretation will be misleading. A multiple layer model is selected on the basis of C_A and interpreted the sounding data. However, such results have been arrived in a systematic manner after constraining some model parameters. If we allow all the model parameters to vary in the inversion process, a highly nonunique model will be obtained. To avoid this, we first tried to match limited data sets using 3-layer models. When model data exactly matches with limited observed data, the model parameters are very near to the actual resistivity and thickness indicating very small uncertainties in model parameters. In the next step, we fixed the model parameter for 3 layers and again interpreted the complete data set using multiple layer models. This approach was very much helpful in interpreting the resistivity sounding data where the formation of the subsurface layer is dipping. This yields very good results compared to the conventional method of resistivity data interpretation technique. Finally, we are able to interpret the sounding data with the help of this method. The interpreted model parameters are shown in Table 1.

4.2. Gravity Methods. At the middle portion of the Bouguer and residual gravity anomaly maps the ENE-WSW trending negative gravity anomaly zone is identified as the existing SPSZ (Figures 2 and 4). The intense brecciation, mylonitization, and ductile to brittle-ductile deformational pattern of the shear zone mixed with quartz breccias, ferruginous breccias, schroll, and mylonitic rocks cause this negative gravity anomaly zone. In the residual gravity anomaly map the closely spaced contour clearly indicates the existence of some shallow surface fractures/faults/contact along parallel as well as across the shear zone (Figure 4). To get better interpretation of the subsurface the residual gravity data modeling is performed.

4.2.1. 2D Forward Modeling of Residual Gravity Anomaly. In the present study, 2D forward modeling approach was employed along a profile AA' across the shear zone and passing through the south-east of Raghunathpur village

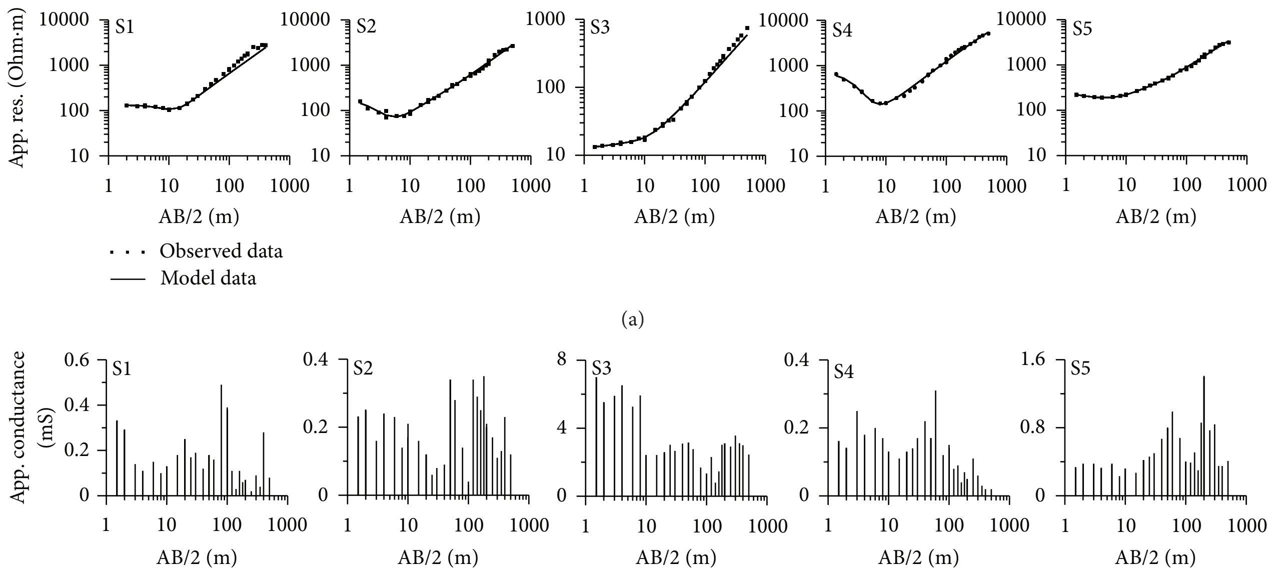


FIGURE 7: Fitting between the observed (solid dot) and calculated (continuous line) apparent resistivity of all soundings (S1–S5) and their corresponding apparent conductance (C_A).

TABLE 1: Interpreted model parameters for five soundings.

Parameters	S1	S2	S3	S4	S5
ρ_1 (Ωm)	131.3	169.1	12.8	680.1	252.2
ρ_2 (Ωm)	22.1	50.3	15.9	92.0	176.0
ρ_3 (Ωm)	9854	387.5	150.2	167.1	484.0
ρ_4 (Ωm)	198.0	846.2	97382	99756	2622
ρ_5 (Ωm)	94216	10116	858.8	169.5	95720
ρ_6 (Ωm)	795.6	936.0	99022	—	157.0
ρ_7 (Ωm)	99772	74155	—	—	—
h_1 (m)	5.1	1.2	1.2	1.5	0.7
h_2 (m)	2.3	4.3	8.8	4.2	5.9
h_3 (m)	74.8	9.2	28.9	5.3	24.9
h_4 (m)	1.0	33.1	99.7	198.0	95.4
h_5 (m)	99.7	61.8	10.1	—	87.4
h_6 (m)	10.0	7.9	—	—	—
Misfit	6.8×10^{-3}	1.3×10^{-2}	2.2×10^{-3}	1.2×10^{-3}	3.4×10^{-4}

(Figure 4). The study area mostly covered by weathered to compact schist and the density of this layer is modeled as 2650 kg/m^3 [29]. The existing brecciated quartz vein almost parallel to the SPSZ is modeled with a density of 2470 kg/m^3. Below these layers a 4-5 km wide highly sheared granite layer mixed with quartz breccias, ferruginous breccias, schroll, and mylonitic rocks (with assumed density 2270 kg/m^3) is identified as the surface extension of the SPSZ. The compact granite and amphibolite, hornblende-schist rocks as exposed on the north-east of Raghunathpur and over the southern side this shear zone are modeled with density varying from 2790 to 2970 kg/m^3 assuming a granitic basement of density 2670 kg/m^3 [29]. The 2-D forward models along these profiles were performed with the GRAVMAG software [30], keeping the above geological constraints in mind. The software calculates the gravity effect for structures of infinite strike length and polygonal cross-section using the solution of Hubbert [31] and Talwani et al. [32]. Modeling along profile AA' (Figure 8) shows the subsurface gravity structure without any resistivity constrain but only using the local geology. The estimated thickness of high density rocks on either side of the shear zone is quite large. The fitting between the observed and calculated anomaly gives an r.m.s misfit of 0.12 mGal. However, the interpreted apparent conductance from the resistivity data (from soundings S1 and S2) as collected along the same profile suggests the existence of two contact zones at ~40 m and ~200 m, near to Raghunathpur village. But the gravity model (Figure 8) does not reflect any contact zones on these depths. However, after constraining the thickness of high density layer and the depth of the contact zones (at about 40 m and 200 m) according to resistivity data, the gravity model shows a better match with the observed and calculated anomaly and gives an r.m.s misfit of 0.09 mGal. The width of the low gravity zone is nearly 5 km which is identified as the width of the existing shear zone. The conducting zones depicted in resistivity sounding are identified as the contact between compact granite and metabasic/mafic-ultramafic rocks (2790 kg/m^3) and low density material (2270 kg/m^3), possibly sheared granite, and mineralization (Figure 9). Figure 9 is more realistic and follows the local geology. The best fit 2-D models along the profile AA' (Figure 9) suggest the existence of mafic-ultramafic and metabasic volcanic rocks (of density 2790–2970 kg/m^3) on either side of the existing shear zone (of density 2270 kg/m^3) with granitic basement (of density 2670 kg/m^3). The gravity model along

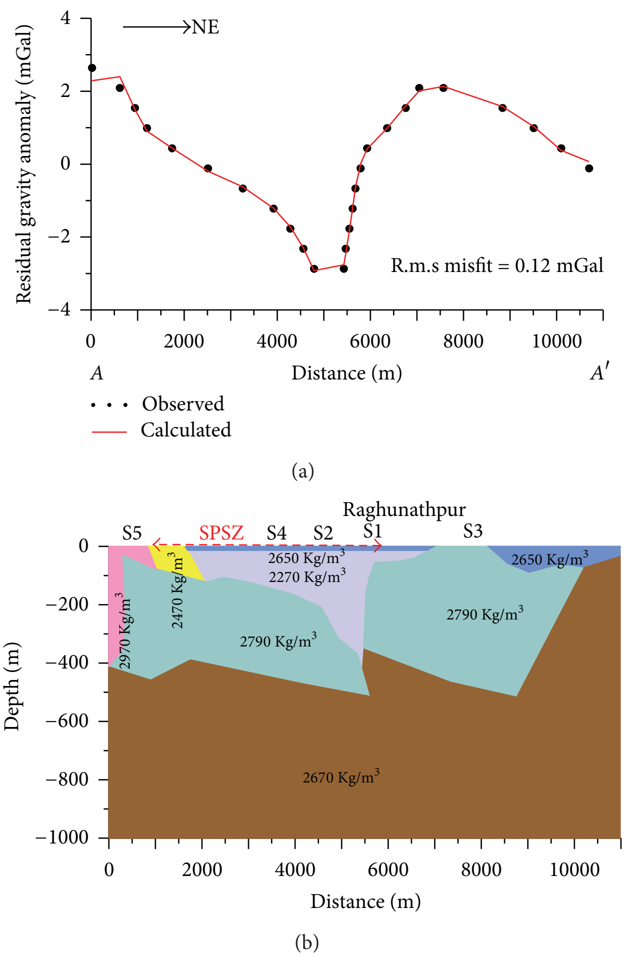


Figure 8: 2D model along AA' without resistivity constraints with r.m.s misfit 0.12 mGal. The red dashed line in the model section indicating the width of the South Purulia Shear Zone (SPSZ).

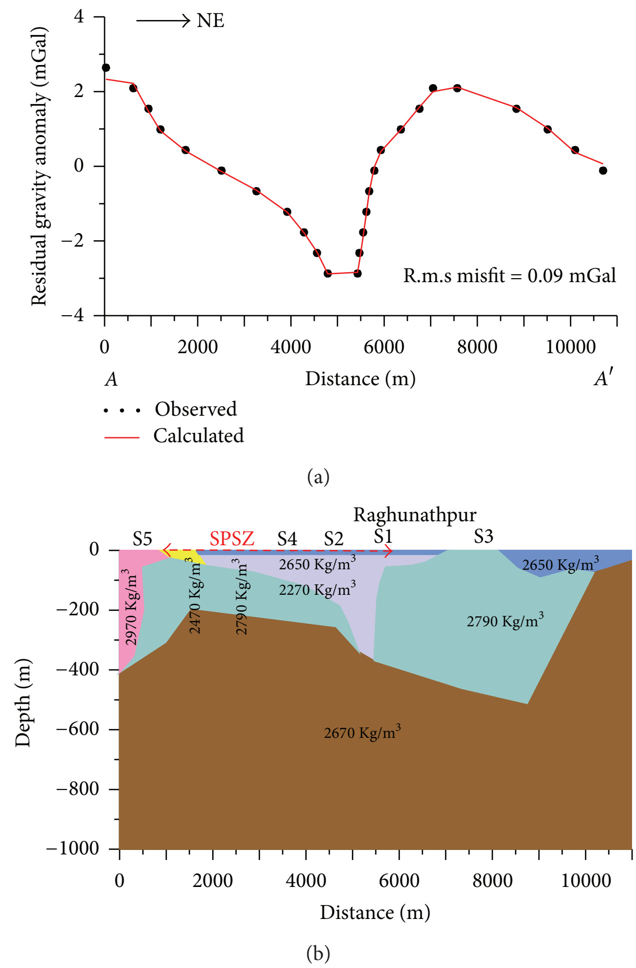


Figure 9: 2D model along AA' with resistivity constraint. The r.m.s misfit is 0.09 mGal. The red dashed line in the model section indicating the width of the South Purulia Shear Zone (SPSZ).

this profile also clearly suggests the existence of northerly dipping structure.

4.2.2. 2D Inverse Modeling of Residual Gravity Anomaly. The 2-D compact inversion approach [33] has also been employed along the same profile (AA') (Figure 4) with vertical layers at depths 1 m, 10 m, 40 m, 100 m, 200 m, 400 m, 600 m, 800 m, and 1000 m. The 40 m and 200 m layers were chosen as the resistivity results suggest the existence of contact zones at these depths. It is highlighted here that the cell size along the profile is taken as 100 m. Considering the surface geology, the density range was chosen as 2000–3000 kg/m^3 for inversion. This approach tries to fit the observed anomaly with minimum area of source density distribution keeping misfit as very low value [33, 34]. Modeling along profile AA' (SW-NE, Figure 10) shows the subsurface gravity structure mostly as vertical. The shear zone is identified as northerly dipping low density zones with nearly 5 km width (along AA', Figure 10). This is in well agreement with the existing literatures [17]. The estimated thickness of high density rocks on either side of the shear zone is quite large (going beyond 1000 m). Just south of Raghunathpur village the lowest density zone (density ≤ 2500 kg/m^3) within the above shear zone depicts some vertical layers with gradually decreasing of density from 2650 kg/m^3 at the surface to lower than 2400 kg/m^3 at the center of the lowest anomaly zone. The lowest density zone (density < 2500 kg/m^3) extends to a depth of 400 m, approximately. The interpreted apparent conductance from the resistivity data collected along the same profile also suggests the existence of conductive contact zones. The depth of these low density contact zones is shallower near Raghunathpur village and gradually increasing towards south.

5. Discussion

Gravity data suggest a low anomaly zone within the width of the shear zone. Resistivity soundings 1 and 2 carried out in this location show a high C_A at a depth of around 80 m AB/2 (~40 m) and 400 m AB/2 (~200 m) (current electrode spacing). It is also evident from the fact that, on that particular zone and at shallow depth, hydro-uranium anomaly has been reported at a depth of around 40 m [17],

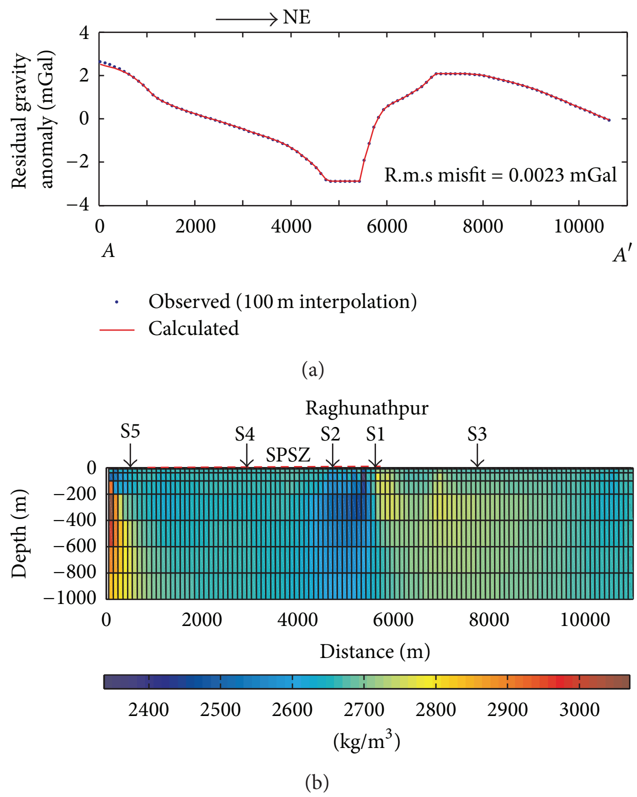


Figure 10: 2D residual gravity inverse model along profile AA' (Figure 4). The r.m.s misfit is 0.0023 mGal. The red dashed line in the model section indicating the width of the South Purulia Shear Zone (SPSZ).

particularly in sounding 1 which is exactly on the same location of high anomaly. The contact between schist and granite, at a depth below this region, appears to be the host of uranium mineralization. The updated gravity model after constraining with C_A and resistivity data are in agreement. The 2-D gravity inverse model is also in agreement with the integration of apparent conductance to constrain forward gravity modeling. In particular, the high to low density alteration zones (Figure 10) are also correlating well with the conducting layer at sounding locations (S1). Also, the coincidence of low gravity anomaly and a high conductive zone at around 200 m depth near to Raghunathpur village also indicates signature of possible uranium mineralization within the contact of sheared granite and mafic-ultramafic rocks. According to the model, the lowest density zone is extending up to ~400 m depth. Again, the 2-D model along the profile indicates the presence of almost vertical alteration zones near to the south of Raghunathpur village. Moreover, presence of uranium mineralization and its extension has also been confirmed from integrated geophysical studies around Beldih mine [35, 36] together with drilled bore-hole data [16].

6. Conclusions

Electrical resistivity and gravity surveys performed around SPSZ clearly revealed subsurface structure associated with uranium mineralization. A continuously increasing trend in apparent resistivity with depth and a wide low gravity anomaly zone has been observed along a NE-SW profile. Due to suppression problems in DC resistivity interpretation and dipping subsurface structures, it is difficult to determine the actual resistivity and thickness of the layer parameter using the conventional interpretation method. Apparent conductance plots help in identifying different subsurface layers and to interpret the resistivity data accordingly. The lithological boundaries interpreted from C_A data used to constrain the subsurface structure to model the gravity data revealed a good correlation with the local geology of the area. The constraints from resistivity data revealed efficacy of C_A in modeling gravity data from such complex region. Both forward and inverse gravity models revealed good correlation with the conducting structure. Therefore, the zones of low resistivity coinciding with low density (negative gravity anomaly) along the SPSZ are expected to be the possible zone of uranium mineralization.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

Gravity data is a part of the project work sponsored by the Atomic Mineral Directorates (AMD) and the BRNS under Department of Atomic Energy, Government of India. The authors gratefully acknowledge the financial assistance provided by the BRNS under Department of Atomic Energy, Government of India (Project no. *2007/36/85-BRNS*) in collaboration with Atomic Minerals Directorate for Exploration and Research (AMD), Eastern Region, Jamshedpur. They thank the anonymous reviewers for their comments and suggestions that have improved the paper. This paper is a part of collaborative Ph.D. work of Arkoprovo Biswas and Animesh Mandal, who thank IIT Kharagpur for Institute Research Fellowship to pursue their work.

References

[1] K. L. Bhola, Y. N. Rama Rao, C. S. Sastry, and N. R. Mehta, “Uranium mineralization in Singhbhum thrust belt, Bihar, India,” *Economic Geology*, vol. 61, no. 1, pp. 162–173, 1966.

[2] A. K. Saha, “Crustal evolution of Singhbhum—north Orissa, eastern India,” *Memoirs of the Geological Society of India*, vol. 27, p. 341, 1994.

[3] B. Kríbek, K. Žák, P. Dobeá et al., “The Rožná uranium deposit (Bohemian Massif, Czech Republic): shear zone-hosted, late Variscan and post-Variscan hydrothermal mineralization,” *Mineralium Deposita*, vol. 44, no. 1, pp. 99–128, 2009.

[4] S. I. Turchenko, A. B. Vrevsky, and V. B. Dagelaisky, “The precambrian metallogeny of India,” *Geology of Ore Deposits*, vol. 51, no. 4, pp. 317–329, 2009.

[5] D. S. Bhattacharyya, “Early proterozoic metallogeny, tectonics and geochronology of the singhbhum CuU belt, eastern India,” *Precambrian Research*, vol. 58, no. 1–4, pp. 71–83, 1992.

[6] V. Tuncer, M. J. Unsworth, W. Siripunvaraporn, and J. A. Craven, "Exploration for unconformity-type uranium deposits with audiomagnetotelluric data: a case study from the McArthur River mine, Saskatchewan, Canada," *Geophysics*, vol. 71, no. 6, pp. B201–B209, 2006.

[7] G. Nimeck and R. Koch, "A progressive geophysical exploration strategy at the Shea Creek uranium deposit," *Leading Edge*, vol. 27, no. 1, pp. 52–63, 2008.

[8] J. M. Legault, D. Carriere, and L. Petrie, "Synthetic model testing and distributed acquisition dc resistivity results over an unconformity uranium target from the Athabasca Basin, northern Saskatchewan," *Leading Edge*, vol. 27, no. 1, pp. 46–51, 2008.

[9] W. K. Mohanty, A. Mandal, S. P. Sharma, S. Gupta, and S. Misra, "Integrated geological and geophysical studies for delineation of chromite deposits: a case study from Tangarparha, Orissa, India," *Geophysics*, vol. 76, no. 5, pp. B173–B185, 2011.

[10] A. Chakrabarty, A. K. Sen, and T. K. Ghosh, "Amphibole—a key indicator mineral for petrogenesis of the Purulia carbonatite, West Bengal, India," *Mineralogy and Petrology*, vol. 95, no. 1-2, pp. 105–112, 2009.

[11] R. K. Verma, A. U. S. Sarma, and M. Mukhopadhyay, "Gravity field over Singhbhum, its relationship to geology and tectonic history," *Tectonophysics*, vol. 106, no. 1-2, pp. 87–93, 97–107, 1984.

[12] R. K. Verma, P. D. V. S. Rao, and M. Mukhopadhyay, "Analysis of gravity field over Singhbhum region and evolution of Singhbhum craton," in *Recent Researches in Geology*, A. K. Saha, Ed., vol. 16, pp. 123–133, Hindustan Publishing Corporation, New Delhi, India, 1996.

[13] L. K. Das, C. S. Pathak, N. P. Singh, D. K. Saha, M. K. Rai, and D. C. Naskar, "A look at the metallogeny of Singhbhum, India: a geophysical approach," *Indian Minerals*, vol. 51, no. 1-2, pp. 107–122, 1997.

[14] A. Gupta and A. Basu, "North Singhbhum Proterozoic mobile belt eastern India—a review," *Geological Survey of India*, vol. 55, pp. 195–226, 2000.

[15] A. Acharyya, S. Ray, B. K. Chaudhuri, S. K. Basu, S. K. Bhaduri, and A. K. Sanyal, "Proterozoic rock suites along south Purulia Shear Zone, eastern India: evidence for rift-related setting," *Journal of the Geological Society of India*, vol. 68, no. 6, pp. 1069–1086, 2006.

[16] V. J. Katti, J. Sen, and A. K. Bhatt, "Uranium potentiality of south Purulia Shear Zone, eastern India shield," in *Proceedings of the Technical Committee Meeting on Low Grade Uranium Deposits*, IAEA, Vienna, Austria, March 2010.

[17] A. K. Dwivedi, J. Sen, C. Murugan et al., "The application of hydrogeochemical method in uranium exploration—a case study from Barabazar-Manbazar area, Purulia district, West Bengal," *Journal of the Geological Society of India*, vol. 72, no. 4, pp. 561–570, 2008.

[18] T. K. Baidya, "Apatite-magnetite deposit in the chhotanagpur gneissic complex, Panrkidih area, Purulia District, West Bengal," *Indian Journal of Geology*, vol. 64, pp. 88–95, 1992.

[19] S. K. Basu, "Alkaline-carbonatite complex in Precambrian of south Purulia Shear Zone, eastern India: its characteristics and mineral potentialities," *Indian Minerals*, vol. 47, no. 3, pp. 179–194, 1993.

[20] A. K. G. Roy and P. R. Sengupta, "Alkalic-carbonatitic magmatism and associated mineralisation along the Porapahar-Tamar lineament in the Proterozoics of Purulia District, West Bengal," *Indian Journal of Earth Sciences*, vol. 20, no. 3-4, pp. 193–200, 1993.

[21] Y. Vapnik, S. Bushmin, A. Chattopadhyay, and D. Dolivo-Dobrovolsky, "Fluid inclusion and mineralogical study of vein-type apatite ores in shear zones from the Singhbhum metallogenetic province, West Bengal, India," *Ore Geology Reviews*, vol. 32, no. 1-2, pp. 412–430, 2007.

[22] A. Biswas and A. Mandal, "Current flow attribute in resistivity sounding to constrain gravity model around south Purulia Shear zone," in *Proceedings of the International Workshop on Recent Advances in Ground and Airborne Electromagnetic Methods—Innovations in Processing and Inversion Techniques*, pp. 65–67, AMD-NGRI-GSI, Hyderabad, India, September 2011.

[23] S. P. Sharma and A. Biswas, "A practical solution in delineating thin conducting structures and suppression problem in direct current resistivity sounding," *Journal of Earth System Science*, vol. 122, no. 4, pp. 1065–1080, 2013.

[24] M. N. Qureshy, D. V. S. Rao, S. C. Bhatia, P. S. Aravamadhu, and C. Subrahmanyam, "Gravity bases established in India by N.G.R.I.—part IV," *Geophysical Research Bulletin*, vol. 11, no. 2, pp. 136–152, 1973.

[25] H. Y. Yen, Y. H. Yeh, and C. H. Chen, "Gravity terrain correction of Taiwan, TAO," *Terrestrial, Atmospheric, and Oceanic Sciences*, vol. 5, no. 1, pp. 1–10, 1994.

[26] D. J. Unwin, "An introduction to trend surface analysis, concepts and techniques in modern geography," Geo Abstracts, University of East Anglia, Norwich, No. 5, NR4 7TJ, 1978.

[27] S. P. Sharma and S. K. Verma, "Solutions of the inherent problem of the equivalence in direct current resistivity and electromagnetic methods through global optimization and joint inversion by successive refinement of model space," *Geophysical Prospecting*, vol. 59, no. 4, pp. 760–776, 2011.

[28] S. P. Sharma, "VFSARES—a very fast simulated annealing FORTRAN program for interpretation of 1-D DC resistivity sounding data from various electrode arrays," *Computers and Geosciences*, vol. 42, pp. 177–188, 2012.

[29] W. M. Telford, L. P. Geldart, and R. E. Sheriff, *Applied Geophysics*, Cambridge University Press, New York, NY, USA, 2nd edition, 1990.

[30] H. R. Burger, A. F. Sheehan, and C. H. Jones, *Introduction to Applied Geophysics*, W. W. Norton & Company, 2006.

[31] M. K. Hubbert, "Line-integral method of computing the gravimetric effects of two dimensional masses," *Geophysics*, vol. 13, pp. 215–225, 1948.

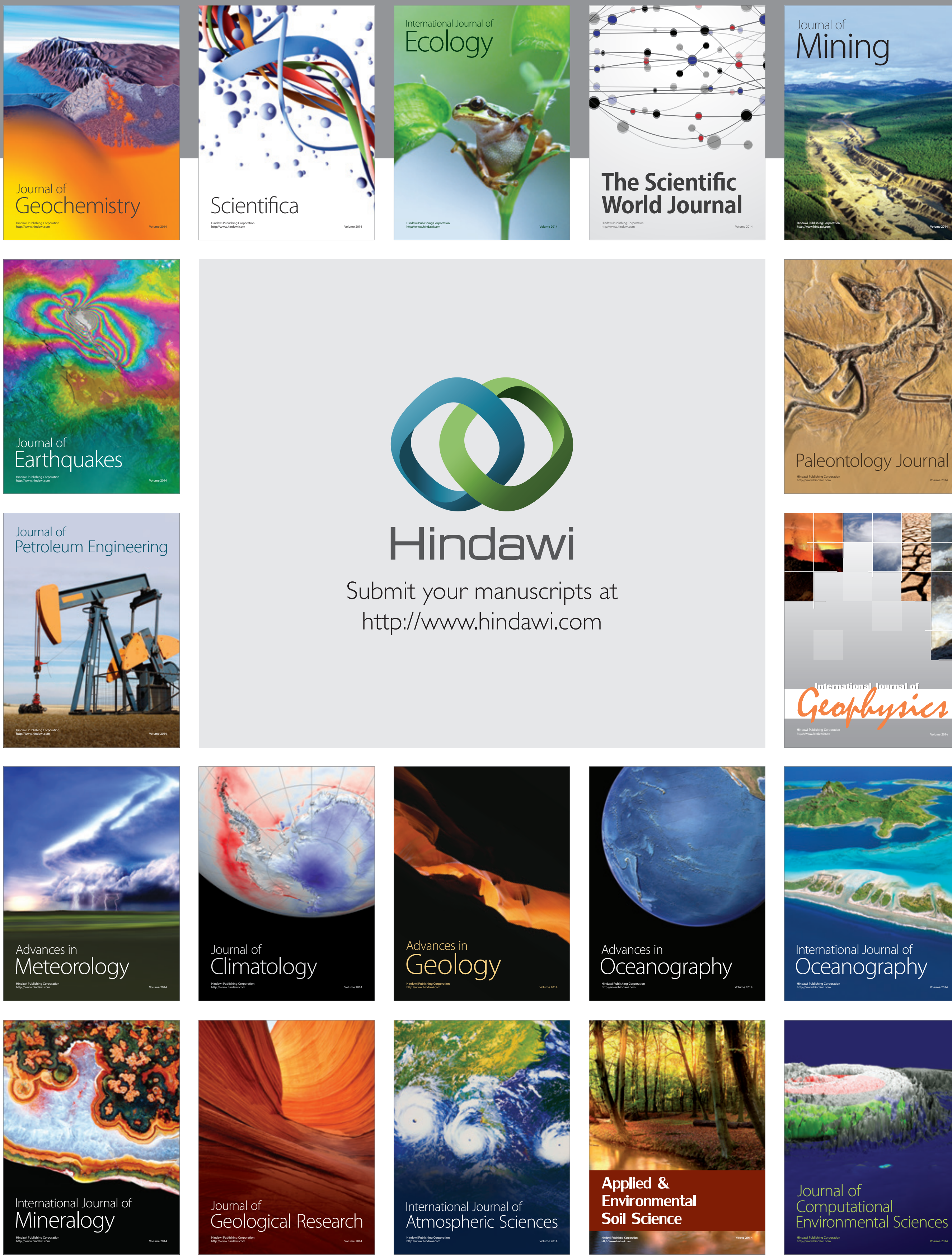
[32] M. Talwani, J. W. Worzel, and M. Landsman, "Rapid gravity computation of two-dimensional bodies with application to the Mendocino submarine fracture zone," *Journal of Geophysical Research*, vol. 64, pp. 49–59, 1959.

[33] B. J. Last and K. Kubik, "Compact gravity inversion," *Geophysics*, vol. 48, no. 6, pp. 713–721, 1983.

[34] Y. L. Ekinci, "2-D focusing inversion of gravity data with the use of parameter variation as stopping criterion," *Journal of the Balkan Geophysical Society*, vol. 11, no. 1, pp. 1–9, 2008.

[35] A. Mandal, A. Biswas, S. Mittal et al., "Geophysical anomalies associated with Uranium mineralization from Beldih mine, South Purulia Shear Zone, India," *Journal of the Geological Society of India*, vol. 82, no. 6, pp. 601–606, 2013.

[36] S. P. Sharma, A. Biswas, and S. Mittal, "Delineation of extension of Uranium mineralization zone using Resistivity and Very Low Frequency (VLF) Electromagnetic surveys around South Purulia Shear Zone (SPSZ), India," *Journal of the Geological Society of India*. In press.



Journal of Geochemistry
Scientifica
International Journal of Ecology
The Scientific World Journal
Journal of Mining
Journal of Earthquakes
Hindawi
Submit your manuscripts at
http://www.hindawi.com
Paleontology Journal
Journal of Petroleum Engineering
International Journal of Geophysics
Advances in Meteorology
Journal of Climatology
Advances in Geology
Advances in Oceanography
International Journal of Oceanography
International Journal of Mineralogy
Journal of Geological Research
International Journal of Atmospheric Sciences
Applied & Environmental Soil Science
Journal of Computational Environmental Sciences