Identification of intraterrane dislocation zones and associated mineralized bodies is of immense importance in exploration geophysics. Understanding such structures from geophysical anomalies is challenging and cumbersome. In the present study, we present a fast and competent algorithm for interpreting magnetic anomalies from such dislocation and mineralized zones. Such dislocation and mineralized zones are well explained from 2D fault and sheet-type structures. The different parameters from 2D fault and sheet-type structures such as the intensity of magnetization \((k)\), depth to the top \((z_1)\), depth to the bottom \((z_2)\), origin location \((x_0)\), and dip angle \((\theta)\) of the fault and sheet from magnetic anomalies are interpreted. The interpretation suggests that there is uncertainty in defining the model parameters \(z_1\) and \(z_2\) for the 2D inclined fault; \(k\), \(z_1\), and \(z_2\) for the 2D vertical fault and finite sheet-type structure; and \(k\) and \(z\) for the infinite sheet-type structure. Here, it shows a wide range of solutions depicting an equivalent model with smaller misfits. However, the final interpreted mean model is close to the actual model with the least uncertainty. Histograms and crossplots for 2D fault and sheet-type structures also reveal the same. The present algorithm is demonstrated with four theoretical models, including the effect of noises. Furthermore, the investigation of magnetic data was also applied from three field examples from intraterrane dislocation zones (Australia), deep-seated dislocation zones (India) as a 2D fault plane, and mineralized zones (Canada) as sheet-type structures. The final estimated model parameters are in good agreement with the earlier methods applied for these field examples with a priori information wherever available in the literature. However, the present method can simultaneously interpret all model parameters without a priori information.

1. Introduction

Geophysical exploration employing magnetic data helps study the subsurface properties by measuring the variation of the geomagnetic field primarily caused due to the presence of mineral bodies and different geological structures [1]. Such variation of magnetic field intensity formed due to contrast of magnetic susceptibility between the host rocks and the target mineralized bodies or the structures and can be used to limit the depth, location, orientation, geometry, and magnetic moment of the subsurface structure [2–5]. Magnetic data has also been used for various applications such as oil-bearing zone detection [6], dike location [7], buried metallic objects [8], archeological investigation [9–11], geotechnical engineering [12, 13], cave detection [14–16], geothermal exploration [17–19], solid waste landfill [20], basement depth [21], and buried igneous intrusions [22]. Inversion of magnetic data for a complex subsurface structure is ill-posed and so inherently tough to clarify as they do not have a unique solution and might be erroneous
In such cases, the problem of various types of uncertainty, data density, noises, etc., is inherent and could not be well determined [27] and hence leads to misinformation about the model parameter estimation, and the uncertainty remains in the final model parameters. Thus, simple geometric or idealized structures reduce the uncertainty and give the best results [5, 28, 29].

Various interpretation techniques have been developed for magnetic data interpretation considering the idealized structures such as a sphere, cylinder, and dike. Such methods include monograms [30], theoretical curve matching techniques [31, 32], characteristic curve approaches [33–37], least-squares means [38], Hilbert transforms [39], Euler deconvolution [40–43] derivatives from analytic signals [44], Werner deconvolution [45, 46], and fair function minimization approaches [47]. Other derivative-based approaches, including the steepest descent, Gauss–Newton, and Levenberg–Marquardt, are commonly used to interpret magnetic data [48–54]. However, this interpretation needs some required knowledge about the different variables and geological information to give a reliable estimate of the model parameters [55]. Hence, the conventional method needs some a priori knowledge, without which the final solutions often get trapped in local minima than global minima.

Due to its limitations in delineating an effective solution, global optimization or metaheuristic optimization is necessary for finding an optimal solution that does not need an initial guess of the model parameters and can give the best result. Global optimization such as the genetic algorithm (GA), particle swarm optimization (PSO), differential evolution (DE) algorithm, very fast simulated annealing (VFSA), genetic-price algorithm (GPO), and whale optimization algorithm (WOA) has been applied to numerous geophysical applications such as seismic data [56–58], self-potential data [59–73], and also in the interpretation of gravity and magnetic data [3, 74–92].

In exploration or crustal studies, fault and sheet-type structures are an essential feature that has been extensively interpreted for mineral, oil, and gas exploration and crustal modeling. Magnetic interpretation of a fault is usually measured as a 2D semi-infinite horizontal slab completed by either a vertical or dipping structure [34]. The magnetic anomaly over a thin sheet with finite and infinite extent is usually applied for mineral exploration studies. However, both the 2D fault and the thin sheet are very close in terms of structure and presence of mineralized bodies as the thin sheet and mineralized deposition in the fault or dislocation zones are similar. Delineation of the depth, depth extent,
and the angle of the plane of a fault and sheet-type structure from magnetic data have given strong attention. However, in many cases, the parameters are not well resolved, which leads to uncertainty in final model estimation (fault or sheet), and are not well studied. Hence, the present work is focused on interpreting the different parameters from 2D input magnetic data.

**Flowchart for the VFSA algorithm.**

---

**Figure 2: Flowchart for the VFSA algorithm.**

- **Start**
- Input magnetic data
- Define the search space (min. and max) for every model parameter (Fault/Sheet)
  - Select a random model $P_i$ in the search space and compute the model response and misfit error ($\phi$)
    - $P_i^{(i+1)} = P_i^{(i)} + y_i (P_{i}^{\text{max}} - P_{i}^{\text{min}})$
  - Move in the model space ‘nv’ times by updating model parameters by $y_i$ at one temperature level, compute misfit, select or reject the new model and store selected models in the memory
    - $y_i = \text{sgn}(u_i - 0.5) T_i [(1+1/T_i)|u_i-i]-1]
  - Decrease the temperature using the eq.
    - $T_i(j) = T_{0i} \exp(-c_{i}j/|T_i|)$
  - If the lowest temperature level achieved
    - Write model parameters and misfit error for $i$th run
  - 10 number of runs completed
    - Within all selected models, select models that have misfit error less ($\phi$) than pre-defined threshold (10^{-4} for noise free and 0.01/0.02 for noisy data)
    - Plot histogram of models selected above
  - Compute Gaussian PDF of above models
    - $f(y, \mu, \sigma^2) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{1}{2} \left( \frac{y - \mu}{\sigma} \right)^2}$
  - Select models whose every parameter has PDF>60.65%
    - $P_i = \frac{1}{NM} \sum_{n=1}^{NM} P_{i,n}$
  - Compute mean model, covariance and correlation
    - $CovP(i,j) = \frac{1}{NM} \sum_{n=1}^{NM} (P_{i,n} - \bar{P}_i) (P_{j,n} - \bar{P}_j)$
    - $CovP(i,j) = \frac{\text{CovP}(i,j)}{\sqrt{\text{CovP}(i,i) \times \text{CovP}(j,j)}}$

**Stop**
fault and sheet-type structures from magnetic anomalies and the uncertainty estimation for every model parameter for finding reliable results and slightest uncertainty. As discussed in [92], we have applied the very fast simulated annealing (VFSA) inversion technique to model 2D fault and sheet-type structures. It has been theoretically proved that the algorithm must be applied in noise-free synthetic data with different degrees of noise for such studies. The uncertainty of all model parameters is also studied using the histogram analysis, 2D and 3D crossplots, and three field examples from intracontinental vis-à-vis intraterrane dislocation zones from Australia, deep-seated dislocation zones from India, and mineralized zones from Canada.

2. Methodology

2.1. Forward Technique. The following forward equations give the measured magnetic anomalies over 2D fault and sheet-type structures.

2.1.1. 2D Fault. The magnetic effect for a 2D fault (Figure 1(a)) is given by the following equation [36, 93]:

\[
g(x) = 2k \left[ \sin \theta \left( \tan^{-1} \frac{x-x_0}{z_1} - \tan^{-1} \frac{x-x_0}{z_2} \right) + \frac{\cos \theta}{2} \ln \left( \frac{(x-x_0)^2 + z_2^2}{(x-x_0)^2 + z_1^2} \right) \right],
\]

where \( k \) is the intensity of magnetization, \( z_1 \) is the depth to the top, \( z_2 \) is the depth to the bottom of the fault, \( x_0 \) is the origin location, and \( \theta \) is the dip angle of the fault. For the vertical fault, the dip angle will be 90°.

2.1.2. 2D Sheet with Finite Depth Extent. Following [34], the magnetic effect of a 2D sheet with finite depth extent

---

**Figure 3:** Convergence pattern for every model parameter and misfit error.
extending infinitely in the horizontal direction (Figure 1(b)) is given as

\[
g(x) = k \left[ \frac{x_0 \sin \theta - z_2 \cos \theta}{x_0^2 + z_2^2} - \frac{x_0 \sin \theta - z_1 \cos \theta}{x_0^2 + z_1^2} \right],
\]

where \(k\) is the magnetic constant of the sheet, \(x_0\) is the location, \(z_1\) is the depth to the top, \(z_2\) is the depth to the bottom of the sheet, and \(\theta\) is the polarization angle.

2.1.3. 2D Sheet with Infinite Depth Extent. Following [34], the vertical magnetic effect of a 2D sheet with infinite depth extent extending infinitely in the horizontal direction (Figure 1(c)) is given as

\[
g(x) = k \left[ \frac{z \cos \theta - x_0 \sin \theta}{x_0^2 + z^2} \right],
\]

where \(k\) is the magnetic constant of the sheet, \(x_0\) is the location, \(z\) is the depth to the top, and \(\theta\) is the polarization angle.

2.2. Inversion Technique. Inversion of geophysical data needs a globally best solution within several local optima. Hence, to achieve the best solution, the global search algorithm is the best to find out the optimized solutions in a controlled manner. Geophysical data inversion is ill-posed, and nonlinear models are persistent in numerous studies, and their results always require a global search process. Many global optimization methods such as the simulated annealing (SA), genetic algorithm (GA), artificial neural network (ANN), particle swarm optimization (PSO), differential evolution (DE), whale optimization algorithm (WOA), and hybrid optimization algorithm such as genetic-price algorithm (GPA) have been successfully applied in the interpretation of various geophysical data [1, 29, 89, 90]. In the present work, a modified version of the SA named the very fast simulated annealing (VFSA) global optimization algorithm has been used to interpret the magnetic anomalies over 2D fault and sheet-type structures. The fundamental idea behind this algorithm comes from the analogy of chemical thermodynamics or the heat bath algorithm [94]. VFSA has been applied in numerous geophysical interpretations, and the detailed process of the technique can be well understood after [74, 95]. Since the details are available in such literature, for brevity, it is not explained here and can be seen in detail after [95]. The significant advantage of VFSA is that it can negate the problem of linear inversion and the stability and robustness of the method. It can also help resolve the issue of nonuniqueness of different parameters and have a good resolution of the data. Moreover, it takes a minute time to complete the inversion process even if there are more than \(10^6\) models, less CPU time, and less memory and gives a high-resolution data interpretation [96].
Every inversion technique needs to find out the error in the final interpretation. Hence, for this inversion technique, the error estimation is taken after [62].

\[
\varphi = \frac{1}{N} \sum_{i=1}^{N} \left( \frac{M_i^0 - M_i^c}{[M_i^0 + (M_{\text{max}}^0 - M_{\text{min}}^0)/2]} \right)^2,
\]

where \( N \) is the number of data, \( M_i^0 \) and \( M_i^c \) are the \( i \)th observed and model responses for magnetic data, and \( M_{\text{max}}^0 \) and \( M_{\text{min}}^0 \) are the maximum and minimum values of the magnetic data.

The global solution is always necessary to interpret any geophysical data [1, 29, 97]. Hence, the procedure developed by [98, 99] is used for the present study. A detail of these techniques can also be found in various literature [62, 95]. Also, to see the uncertainty behind the interpretation of every model parameter, the correlation between each parameter, and the probability density function (PDF), we followed the work of [83, 100]. For brevity, it is not discussed here. These ideas are well explained in the above literature and were applied in many geophysical data such as gravity, magnetic, and self-potential data [29, 72, 91, 92]. The algorithm was developed in the Windows 10 operating system using the MS Fortran Developer Studio on a desktop PC with an i7 Intel Pentium Processor (9th Generation) and 16GB RAM. The computation time (not CPU) for a single run is 3 seconds, and for 10 runs, it is 22 seconds. A flowchart for the entire VFSA optimization process is shown in Figure 2.

### 3. Results and Discussion

#### 3.1. Synthetic Example

3.1.1. Search Space and Fine-Tuning of Parameters. Finding a globally best-fit model or solution requires an initial search space for all model parameters. In the present study, initially, the search space is defined, and a single run for the inversion process is completed. After studying the interpreted model parameters, whether it has been computed within the search space, the search space is again reduced within a probable range to get the best-fit models with less uncertainty in model parameters. Next, the convergence pattern for all parameters is studied to see whether all the model parameters are close to the actual value and the error minimization process in the final interpretation (Figure 3). Finally, ten runs are performed to delineate the mean model. Next, the interpreted data for all parameters whose errors are below 10^{-4} are taken for statistical investigation, which falls inside one standard deviation. Different models and actual values were selected, and the inversion process was repeated with the help of noise-free data and different degrees of Gaussian noise (with mean 1 and standard deviation 0.2).

3.1.2. Model 1 (Inclined Fault). The initial model for a 2D inclined fault-type structure \((k = 100 \text{ nT}, x_0 = 75 \text{ m}, z_1 = 10 \text{ m}, z_2 = 30 \text{ m}, \text{ and } \theta = 60^\circ)\) was formed using Equation (1) (Figure 4(a)). The inversion process discussed above was executed, and the parameters for such model \((k, x_0, z_1, z_2, \text{ and } \theta)\) were interpreted (Table 1). Next, histograms were prepared from the analyzed data to understand that every parameter is interpreted precisely (Figure 5(a)). Subsequently,
10% noise was corrupted in the noise-free data, and the inversion technique was repeated. Histograms were also set for noisy data (Figure 5(b)). From the interpretation of this data, it is visualized that the VFSA inversion can precisely delineate all the model parameters. Figures 4(a) and 4(b) illustrate the observed and model responses for both the noise-free and noisy data.

3.1.3. Model 2 (Vertical Fault). A different model for a vertical fault-type structure (\( k = 50 \text{ nT}, x_0 = 80 \text{ m}, z_1 = 15 \text{ m}, z_2 = 40 \text{ m}, \) and \( \theta = 90^\circ \)) was taken, and the inversion process is repeated considering noise-free and noisy data (10%)

### Table 2: Results from synthetic noise-free and noisy data for Model 2.

| Parameters | True value | Search space | Inversion results |
|------------|------------|--------------|-------------------|
| \( k \) (nT) | 50 | 0–100 | 50.3 ± 0.6 | 49.8 ± 1.5 |
| \( x_0 \) (m) | 80 | 0–100 | 80.0 ± 0.0 | 80.0 ± 0.1 |
| \( z_1 \) (m) | 15 | 0–20 | 15.0 ± 0.1 | 14.9 ± 0.2 |
| \( z_2 \) (m) | 40 | 0–50 | 39.9 ± 0.3 | 39.1 ± 0.7 |
| \( \theta \) (°) | 90 | 0–180 | 90.0 ± 0.1 | 90.3 ± 0.3 |
| Error | \( 3.1 \times 10^{-8} \) | \( 2.4 \times 10^{-4} \) |
3.1.4. **Model 3 (Finite Sheet).** This sheet-type model ($k = 100$ nT, $x_0 = 250$ m, $z_1 = 10$ m, $z_2 = 20$ m, and $\theta = 60^\circ$) was taken where both the top and the bottom of the sheet can be interpreted, and the model was prepared using Equation (2). The inversion method was implemented for these sheet-type models. It can be understood from the histogram analysis that the inversion process can precisely delineate every model parameter (Figures 7(a) and 7(b)). Figures 6(a) and 6(b) demonstrate the observed and model responses for both the noise-free and noisy data. The final interpreted parameters are given in Table 2.

(Figures 6(a) and 6(b)). It can be understood from the histogram analysis that the inversion process can precisely delineate every model parameter (Figures 7(a) and 7(b)). Figures 6(a) and 6(b) demonstrate the observed and model responses for both the noise-free and noisy data. The final interpreted parameters are given in Table 2.

### Table 3: Results from synthetic noise-free and noisy data for Model 3.

| Parameters | True value | Search space | Inversion results |
|------------|------------|--------------|------------------|
| $k$ (nT)   | 100        | 0–200        | Noise-free: 99.1 ± 6.5 | Noisy: 92.7 ± 6.3 |
| $x_0$ (m)  | 250        | 0–500        | 250.0 ± 0.0 | 250.9 ± 0.2 |
| $z_1$ (m)  | 10         | 0–20         | 9.9 ± 0.2 | 10.2 ± 0.3 |
| $z_2$ (m)  | 20         | 0–30         | 20.2 ± 0.5 | 20.4 ± 0.6 |
| $\theta$ (°) | 60 | 0–90         | 59.9 ± 0.2 | 63.7 ± 0.9 |
| Error      | $3.0 \times 10^{-7}$ | $1.4 \times 10^{-4}$ |

Figure 8: Observed and model responses for Model 3 (thin sheet with finite extent).

Figure 9: Histogram for Model 3: (a) noise-free and (b) noisy data.
model parameters \((k, x_0, z_1, z_2, \text{ and } \theta)\), and the model responses for noise-free and noisy data (10%) are demonstrated in Figures 8(a) and 8(b). The histogram for this type of structure was also achieved, and the interpreted data show that it can delineate the model parameters correctly (Figures 9(a) and 9(b)). The final elucidated model parameters are shown in Table 3, and the observed and model responses are illustrated in Figures 8(a) and 8(b).

3.1.5. Model 4 (Infinite Sheet). The alternate sheet-type model \((k = 10 \text{ nT, } x_0 = 250 \text{ m, } z = 10 \text{ m, and } \theta = 60°)\) was
taken where the depth to the end of the sheet is at infinity using Equation (3). This infinite-depth extent of the sheet-type model is also interpreted using the inversion process considering both the noise-free and noisy data (20%) (Figures 10(a) and 10(b)). Additionally, the histogram of all model parameters was also interpreted to see that the model parameters are close to the initial value (Figures 11(a) and 11(b)). The final fittings between the observed and model responses for noise-free and noisy synthetic data are shown in Figures 10(a) and 10(b), and the elucidated model parameters are shown in Table 4.

3.1.6. Uncertainty Analysis. To comprehend the relation between the model parameters, its uncertainty in explaining the precise parameters, and how various models come near to the initial (actual) value, a 2D crossplot investigation was designed for all models. For the 2D inclined fault, parameters such as $k$, $z_1$, $z_2$, and $\theta$ were taken for such analysis. Figure 12(a) shows the various plots between $k$, $z_1$, $z_2$, and $\theta$, and the parameters are near their actual value for noise-free data (Model 1). However, from the crossplots, the parameters such as $z_1$ and $z_2$ show a small wide range in the plots. From these crossplot data, the parameters for this model are close to the actual data (blue), and the final mean model parameters are within the uncertainty value and lie within the high PDF (red). Figure 12(b) shows the same for noisy data as discussed above for noise-free synthetic data, suggesting that the parameters $z_1$ and $z_2$ show some uncertainty in the final interpretation.

For the 2D vertical fault model (Model 2), all the parameters ($k$, $z_1$, $z_2$, and $\theta$) were selected to perceive the connection between them. Figure 13(a) demonstrates the relationship between parameters $k$, $z_1$, $z_2$, and $\theta$ for noise-free data, and Figure 13(b) reflects the relationship between $k$, $z_1$, $z_2$, and $\theta$.
for noisy data. In both cases, it can be well understood that the parameters \( k \), \( z_1 \), and \( z_2 \) show a broad distribution (blue), but the final mean model is in the high PDF zone (red) with minimum uncertainty.

Hence, from the study of crossplot analysis for 2D inclined and vertical faults, it can be understood that the depth to the top of the fault and bottom end of the fault plane provides some uncertainty for the inclined fault plane. The intensity of magnetization and the depth to the top and bottom show some uncertainty for the 2D inclined fault.

As discussed above for the 2D fault plane, crossplots for the 2D sheet-type structure with finite depth extent (\( k \), \( z_1 \), \( z_1 \), and \( z_2 \)) are also studied for noise-free data and noisy synthetic data (Model 3). Figure 14(a) shows the crossplots for noise-free data, and Figure 14(b) shows those for noisy data. Here also, it can be seen from the crossplots that the parameters \( k \), \( z_1 \), and \( z_2 \), show a widespread solution, but the final estimated parameters are within the expected uncertainty.

As discussed above that for the 2D vertical fault plane, three parameters show some uncertainty; hence, we have carried out a study to see a 3D crossplot for the parameters \( k \), \( z_1 \), and \( z_2 \). Figures 15(a) and 15(b) show the 3D crossplots for noise-free and noisy data for the 2D vertical fault plane. It can be understood from the crossplot that all three parameters show some uncertainty (yellow) which are equivalent models with lower misfits. However, the final mean model is near the actual value and within the high PDF (red) but with a slightly wide range of solutions. This advocates that a small uncertainty prevails between these parameters, although the final mean model is near the actual value.

Finally, to understand any uncertainty related to the 2D sheet-type structure with infinite depth extent (\( k \), \( z \), and \( \theta \))
(Model 4), all parameters \((k, z, \text{ and } \theta)\) were selected for this study. Figure 16(a) demonstrates the 3D crossplot for noise-free data, and it can be seen that the parameters \((k \text{ and } z)\) show some widespread solutions (yellow) and are equivalent models with lower misfits. The final mean model parameters are within expected uncertainty and in the area of the high PDF (red). Figure 16(b) displays the noisy data where the results are the same.

3.2. Field Example. For theoretical modeling of geophysical data, it must be confirmed using field data for such types of structures to show the efficacy of the inversion method to delineate the model parameter estimation and further the uncertainty in such parameters. Field examples are always linked with different types of noises [24, 25]. To validate the theoretical models, three field data were taken from various literature, and the inversion procedure was carried out and compared with the previous results and drilling data.

It must be mentioned that without prior geological knowledge of the subsurface structure, interpretation of the subsurface structure from geophysical data would lead to erroneous results. For example, the presence of mineralized zones within the subsurface structure such as fault/dislocation/fracture zones or sheet-type structures cannot be well delineated if the geological understanding is poor. In such a case, mineralized bodies present in the fault or simple sheet-type mineralized bodies cannot be well determined and can lead to wrong information of the subsurface. Hence, it is recommended that with a priori knowledge of the local geology, it will clarify the subsurface structure and help determine the structure precisely. Though assessment and possibility in magnetic data interpretation are generally acknowledged, the idea behind the interpretation of the field data is to visualize the subsurface structure related to 2D inclined and vertical and 2D finite and infinite sheet-type structures and their geological implications.
3.2.1. **Perth Basin, Australia.** The field case was taken from the total field magnetic anomaly data from the Perth basin in Australia (Figure 17(a)). It is an elongated northwestern basin which is a rift structure formed during intracontinental setting lying in the southwestern margin part of the Carnarvon Basin [101]. This basin is well known for hydrocarbon exploration, where more than twenty oil fields are found. Based on the geological information and borehole
data, the magnetic anomaly was observed as a deep-seated N-S striking fault-like structure [101]. The length of the profile is 40 km, and it was digitized with an interval of 1 km. The magnetic anomaly was interpreted using the inversion procedure, and the parameters such as $k$, $x_0$, $z_1$, $z_2$, and $\theta$ were interpreted. The earlier investigation advises that the fault plane is inclined; however, to confirm the same, the data was analyzed considering both the inclined and vertical faults (using Equation (1)). The results from the inversion suggest that the fault plane is an inclined fault plane with the parameters estimated as $k = 184.3 \text{nT}$, $x_0 = 20.7 \text{ km}$, $z_1 = 7.8 \text{ km}$, $z_2 = 11.8 \text{ km}$, and $\theta = 36.2^\circ$. Uncertainty analysis was also carried out in this field example (Figure 18), and it also shows that there is a small, varied solution for the parameters $k$, $z_1$, and $z_2$; however, the estimated mean model is within the limits of uncertainty. This field anomaly was also interpreted by different methods [29, 47, 70, 89, 101–104], and the results are summarized in Table 5. The observed and model responses and the subsurface structure are shown in Figure 17(a).

3.2.2. Dehri Aeromagnetic Anomaly, Bihar, India. The field example was taken from a deep-seated fault from the southwest part of Dehri, Bihar, India (Figure 17(b)). The area is enveloped by the Vindhyan group of rocks and is connected to the Bijawar group of rocks. The anomaly was digitized, and 17 data points were taken for the inversion. Earlier literature suggests that the fault plane is an example of a vertical fault [32, 47, 101, 104]. The present inversion technique was applied to interpret the magnetic anomaly data, and the parameters are estimated as $k = 283.0 \text{nT}$, $x_0 = 32.0 \text{ km}$, $z_1 = 10.9 \text{ km}$, $z_2 = 27.2 \text{ km}$, and $\theta = 40.3^\circ$. The interpretations from other techniques are summarized in Table 6, and the observed and model responses are illustrated in Figure 17(b).

3.2.3. Pishabo Lake Anomaly, Ontario, Canada. The total magnetic anomaly data as a field example (Figure 19) was taken over an outcropping olivine diabase dike of gabbric composition from Pishabo lake, Ontario, Canada [105]. The field anomaly was digitized at an interval of...
The estimated parameters from this field data are $k = 140563.2 \text{nT}$, $x_0 = 1.6 \text{ m}$, $z = 324.2 \text{ m}$, and $\theta = 37.9^\circ$. The field data was also interpreted by different forward equations [3] and different interpretation and inversion techniques [4, 105, 106]. The estimated parameters are in good agreement with the other results and are summarized in Table 7. Uncertainty analysis was also carried out for this field example, and it also shows that the parameters $k$ and $z$ show some uncertainty, but the estimated final model is within the limits of uncertainty (Figure 20). The field data and the model responses are shown in Figure 19.

4. Conclusion

Interpretation of magnetic anomalies has a vast range of utility, from crustal studies such as intraterrane dislocation zones to mineral exploration. The choice of specific methods in the interpretation of magnetic anomalies is vital for such studies. However, the understanding of different parameters for magnetic data is also crucial to delineate accurate subsurface information. In the present study, magnetic anomalies from 2D inclined and vertical faults, as well as the 2D thin sheet with finite and infinite depth extent, have been studied. The parameters such as
the depth to the top and bottom of the fault and sheet ($z_1$ and $z_2$), location ($x_0$), magnetic intensity/constant ($k$), and dip angle ($\theta$) have been studied, and the uncertainty estimation has also been studied for each parameter. The results show that the magnetic intensity ($k$) and depth from the top and bottom ($z_1$ and $z_2$) show some uncertainty for the 2D fault-type structure, and the magnetic constant ($k$) and depth to the top ($z_0$) offer a broad solution for the sheet-type structure with infinite extent.

Although these parameters ($z_1$ and $z_2$) are vital for the delineation of subsurface structures, the final model is close to the actual values. The inversion results are shown with noise-free data and noisy Gaussian data with validation from three field examples from intracontinental/intraterrane dislocation zones (Australia), deep-seated dislocation planes (India), and mineralized zones (Canada). The results are in Table 5: VFSA optimization and other results from Perth basin, Australia.

| Parameters | Search space | Present method (VFSA) | Qureshi and Nalaye (1978) | Rao and Babu (1983) | Asfahani and Tlas (2007) | Tlas and Asfahani (2011) | Radhakrishna Murthy et al. (2001) | Ekinci et al. (2019) (DE) | Ekinci et al. (2019) (PSO) | Di Maio et al. (2020) (GPA) | Gobashy et al. (2020) (WOA) |
|------------|--------------|-----------------------|--------------------------|---------------------|-------------------------|--------------------------|----------------------------|-----------------------|-----------------------|-------------------------|-------------------------|
| $k$ (nT)   | 0–1000       | 184.3 ± 68.7          | —                        | —                   | 200.30                  | 200.56                   | —                         | 78.53                 | 104.46                | 169.4                   | 213.16                  |
| $x_0$ (km) | 10–30        | 20.7 ± 0.1            | —                        | —                   | —                       | —                        | —                         | 17.16                 | 17.93                 | 0.80                    | -1.731                  |
| $z_1$ (km) | 0–20         | 7.8 ± 0.5             | 6.30–6.85                | 6.26                | 7.50                    | 7.22                     | 6.21                      | 5.10                  | 5.62                  | 8.50                    | 6.032                   |
| $z_2$ (km) | 0–50         | 11.8 ± 0.6            | 15.55–16.50              | 15.45               | 14.00                   | 13.72                    | 15.07                     | 13.76                 | 10.49                 | 12.00                   | 13.036                  |
| $\theta$ (°) | 0–90         | 36.2 ± 0.3            | —                        | 40.0                | 39.80                   | 35.54                    | —                         | -14.93                | 12.90                 | 35.86                   | 48.092                  |
| Error      | $2.8 \times 10^{-3}$ | —                     | —                        | —                   | —                       | —                        | —                         | —                     | —                     | —                       | —                       |

Table 6: VFSA optimization and other results from Dehri, India.

| Parameters | Search space | Present method (VFSA) | Qureshi and Nalaye (1978) | Rao and Babu (1983) | Asfahani and Tlas (2007) | Tlas and Asfahani (2011) | Gobashy et al. (2020) (WOA) |
|------------|--------------|-----------------------|--------------------------|---------------------|-------------------------|--------------------------|-------------------------|
| $k$ (nT)   | 0–1000       | 283.0 ± 105.5         | —                        | —                   | 815                     | 789.38                   | 856.40                  |
| $x_0$ (km) | 20–50        | 32.0 ± 0.2            | —                        | —                   | —                       | —                        | 0.04                    | -2                    | 9.235                   |
| $z_1$ (km) | 0–20         | 10.9 ± 1.2            | 7.5                      | 8                   | 10.2                    | 10.54                    | 25.5                    | 25.22                 | 24.538                  |
| $z_2$ (km) | 0–50         | 27.2 ± 3.2            | 30                       | 32                  | 25.5                    | 25.22                    | 24.538                  |
| $\theta$ (°) | 0–90         | 40.3 ± 1.0            | -133                     | -130                | -141.6                  | -141.6                   | -131.813                |
| Error      | $2.3 \times 10^{-3}$ | —                     | —                        | —                   | —                       | —                        | —                       |

Figure 19: Observed and model responses from Pishabo lake anomaly, Ontario, Canada.
Table 7: VFSA optimization and other results from Pishabo lake anomaly, Canada.

| Parameters | Search space | Present method | McGrath and Hood (1970) | Abdelrahman et al. (2012) | Biswas (2016) | Essa and Elhussein (2017) | Singh and Biswas (2021) |
|------------|--------------|----------------|--------------------------|---------------------------|---------------|---------------------------|--------------------------|
| $k$ (nT)   | 1000–1000000 | 140563.2 ± 1181.2 | —                        | 1429                      | 141187.3      | 1547.1                     | 769000                   |
| $x_0$ (m)  | -10–10       | 1.6 ± 1.4       | —                        | —                         | 1.7           | —                         | 0.48                     |
| $z$ (m)    | 0–500        | 324.2 ± 3.3     | 301.5                    | 320                       | 324.0         | 311.5                     | 374.65                   |
| $\theta$ (°) | 0–90       | 37.9 ± 0.3      | 54                       | 37.3                      | -37.9         | 53.5                      | 42.17                    |
| Error      | $2.5 \times 10^{-3}$ | —                | —                        | $2.5 \times 10^{-3}$     | —             | 0.03                      |

Calculated value

$k = 140563.2$

$z = 324.2$

$\theta (°) = 37.9$

Figure 20: 3D crossplot for Pishabo lake anomaly, Ontario, Canada.
good agreement with other interpretation methods. The efficiency of this method is that it can be used to interpret all parameters of subsurface structures and can be well applied in a multifaceted geological environment. Furthermore, the present inversion does not require prerequisite information such as geology and structures within the subsurface. However, it would be better to resolve the subsurface structure if a priori information is available for all inversion/optimization methods.

**Data Availability**

The data will be available upon request.

**Additional Points**

**Highlights.** The global optimization algorithm examines magnetic anomalies. Model parameter estimation of synthetic and noisy data for 2D fault and sheet-type structures is demonstrated. 2D magnetic fault and sheet-type structures are well demarcated by inversion of field data. Uncertainty estimation for model parameters is well demonstrated. Interpretation of magnetic anomalies from intraterrane zones and exploration is presented.

**Disclosure**

This work forms a part of the Ph.D. thesis of KR.

**Conflicts of Interest**

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.

**Authors’ Contributions**

The entire work has been carried out by both authors.

**Acknowledgments**

KR would like to thank the Council of Scientific and Industrial Research (CSIR), New Delhi, for the research fellowship. AB would like to thank the Institution of Eminence (IoE), Banaras Hindu University, Varanasi, for the seed grant to pursue this work.

**References**

[1] Y. L. Ekinci, A. Buyuksarac, O. Bektas, and C. Ertekin, “Geophysical investigation of Mount Nemrut Stratovolcano (Biflis, Eastern Turkey) through aeromagnetic anomaly analyses,” *Pure and Applied Geophysics*, vol. 177, no. 7, pp. 3243–3264, 2020.

[2] P. V. Sharma, “Magnetic method applied to mineral exploration,” *Ore Geology Reviews*, vol. 2, no. 4, pp. 323–357, 1987.

[3] A. Biswas and T. Acharya, “A very fast simulated annealing method for inversion of magnetic anomaly over semi-infinite vertical rod-type structure,” *Modeling Earth System and Environment*, vol. 2, no. 4, pp. 1–10, 2016.

[4] A. Singh and A. Biswas, “Global particle swarm optimisation technique in the interpretation of residual magnetic anomalies due to simple geo-bodies with idealised structure,” in *Basics of Computational Geophysics*, P. Samui, B. Dixon, and T. Bui, Eds., pp. 13–32, Elsevier, 2021.

[5] Ç. Balkaya and I. Kafıtan, “Inverse modelling via differential search algorithm for interpreting magnetic anomalies caused by 2D dyke-shaped bodies,” *Journal of Earth System Sciences*, vol. 130, no. 3, pp. 1–23, 2021.

[6] L. Eventov, “Applications of magnetic methods in oil and gas exploration,” *Leading Edge*, vol. 16, no. 5, pp. 489–492, 1997.

[7] W. T. C. Sowerbutts, “Magnetic mapping of the Butterton Dyke: an example of detailed geophysical surveying,” *The Journal of Geological Society*, vol. 144, no. 1, pp. 29–35, 1987.

[8] L. Barrows and J. E. Rocchio, “Magnetic surveying for buried metallic objects,” *Ground Water Monitoring and Remediation*, vol. 10, no. 3, pp. 204–211, 1990.

[9] A. J. Powell, J. G. McDonnell, C. M. Batt, and R. M. Vernon, “An assessment of the magnetic response of an iron-smelting site,” *Archaeometry*, vol. 44, no. 4, pp. 651–665, 2002.

[10] Y. L. Ekinci, C. Balkaya, A. Seren, M. A. Kaya, and C. S. Lightfoot, “Geomagnetic and geoelectrical prospection for buried archaeological remains on the upper city of Amorium, a Byzantine city in midwestern Turkey,” *Journal of Geophysics and Engineering*, vol. 11, no. 1, article 015012, 2014.

[11] M. Pisz, A. Tomas, and A. Hegyi, “Non-destructive research in the surroundings of the Roman Fort Tibiscum (today Romania),” *Archaeological Prospection*, vol. 27, no. 3, pp. 219–238, 2020.

[12] M. Hasan, Y. Shang, W. Jin, and G. Akhter, “An engineering site investigation using non-invasive geophysical approach,” *Environmental Earth Science*, vol. 79, no. 11, p. 15, 2020.

[13] O. Igwe and A. A. Umbugadu, “Characterization of structural failure soils found in panning of Mangu, Central Nigeria,” *Geoenvironmental Disasters*, vol. 7, no. 7, 2020.

[14] T. Mochales, A. M. Casas, E. L. Pueyo et al., “Detection of underground cavities by combining gravity, magnetic and ground penetrating radar surveys: a case study from the Zaragoza area, NE Spain,” *Environmental Geology*, vol. 53, no. 5, pp. 1067–1077, 2008.

[15] C. Orfanos and G. Apostolopoulos, “Analysis of different geophysical methods in the detection of an underground opening at a controlled test site,” *Journal of the Balkan Physical Society*, vol. 15, pp. 7–18, 2020.

[16] C. Balkaya, G. Göktürkler, Z. Erhan, and Y. Levent Ekinci, “Exploration for a cave by magnetic and electrical resistivity surveys: Ayvacik Sinkhole example, Bozdağ, Izmir (western Turkey),” *Geophysics*, vol. 77, no. 3, pp. B135–B146, 2012.

[17] M. Abdel Zaher, H. Saib, K. Mansour, A. Khalil, and M. Soliman, “Geothermal exploration using airborne gravity and magnetic data at Siwa Oasis, Western Desert, Egypt,” *Renewable and Sustainable Energy Review*, vol. 82, pp. 3824–3832, 2018.

[18] E. M. Abraham and O. M. Aliie, “Modelling subsurface geological structures at the Ikogosi geothermal field, southwestern Nigeria, using gravity, magnetics and seismic interferometry techniques,” *Journal of Geophysics and Engineering*, vol. 16, no. 4, pp. 729–741, 2019.

[19] X. Zhao, Z. Zeng, Y. Wu, R. He, Q. Wu, and S. Zhang, “Interpretation of gravity and magnetic data on the hot dry rocks
(HDR) delineation for the enhanced geothermal system (EGS) in Gonghe town, China,” Environmental Earth Science, vol. 79, no. 16, p. 13, 2020.

[20] C. Prezzi, M. J. Orgeira, H. Osteria, and C. A. Vasquez, “Ground magnetic survey of a municipal solid waste landfill: pilot study in Argentina,” Environmental Geology, vol. 47, no. 7, pp. 889–897, 2005.

[21] R. Kumar, A. R. Bansal, S. P. Anand, V. K. Rao, and U. K. Singh, “Mapping of magnetic basement in Central India from aeromagnetic data for scaling geography,” Geophysical Prospecting, vol. 66, no. 1, pp. 226–239, 2018.

[22] Y. L. Ekinci and E. Yigitbas, “A geophysical approach to the igneous rocks in the Biga Peninsula (NW Turkey) based on airborne magnetic anomalies: geological implications,” Geodinamica Acta, vol. 25, no. 3-4, pp. 267–285, 2012.

[23] W. J. Hinze, R. R. B. von Frese, and A. H. Saad, Gravity and Magnetic Exploration: Principles, Practices, and Applications, Cambridge University Press, 2013.

[24] S. A. Mehanee, “Accurate and efficient Regularized inversion approach for the interpretation of isolated gravity anomalies,” Pure and Applied Geophysics, vol. 171, no. 8, pp. 1897–1937, 2014.

[25] S. Mehanee and K. S. Essa, “2.5D regularized inversion for the interpretation of residual gravity data by a dipping thin sheet: numerical examples and case studies with an insight on sensitivity and non-uniqueness,” Earth, Planets and Space, vol. 67, no. 1, p. 26, 2015.

[26] M. Utsugi, “3-D inversion of magnetic data based on the L1–L2 norm regularization,” Earth Planets and Space, vol. 71, no. 1, p. 19, 2019.

[27] M. Fedi, P. C. Hansen, and V. Paoletti, “Analysis of depth resolution in potential-field inversion,” Geophysics, vol. 70, no. 6, pp. A1–A11, 2005.

[28] M. Tlas and J. Asfahani, “A new best-estimate methodology for determining magnetic parameters related to field anomalies produced by buried thin dikes and horizontal cylinder-like structures,” Pure and Applied Geophysics, vol. 168, no. 5, pp. 861–870, 2011.

[29] Y. L. Ekinci, C. Balkaya, and G. Gokturkler, “Parameter estimations from gravity and magnetic anomalies due to deep-seated faults: differential evolution particle swarm optimisation,” Turkish Journal of Earth Sciences, vol. 28, pp. 860–881, 2019.

[30] T. Prakasa Rao, M. Subrahmanyam, and A. Srikrishna Murthy, “Nomogram for the direct interpretation of magnetic anomalies due to long horizontal cylinders,” Geophysics, vol. 51, pp. 2156–2159, 1986.

[31] S. P. Gay, “Standard curves for interpretation of magnetic anomalies over long tabular bodies,” Geophysics, vol. 28, no. 2, pp. 161–200, 1963.

[32] D. Atchuta Rao and H. V. Ram Babu, “Quantitative interpretation of self-potential anomalies due to two-dimensional sheet-like bodies,” Geophysics, vol. 48, pp. 1659–1664, 1983.

[33] J. M. Bruckshaw and K. Kunaratnam, “The interpretation of magnetic anomalies due to dykes,” Geophysical Prospecting, vol. 11, no. 4, pp. 509–522, 1963.

[34] F. S. Grant and G. F. West, Interpretation Theory in Applied Geophysics, McGraw-Hill Book Co., New York, 1965.

[35] T. Koulomznne, Y. Lamontagne, and A. Nadeau, “New methods for the direct interpretation of magnetic anomalies caused by inclined dikes of infinite length,” Geophysics, vol. 35, no. 5, pp. 812–830, 1970.

[36] B. S. R. Rao and I. V. R. Murthy, Gravity and Magnetic Methods of Prospecting, Arnold-Heinemann, New Delhi, India, 1978.

[37] W. M. Telford, L. P. Geldart, and R. E. Sheriff, Applied Geophysics, Cambridge University Press, 2nd edition, 1990.

[38] E. M. Abdelrahman, A. I. Bayoumi, Y. E. Abdelhady, M. M. Gobashy, and H. M. el-Araby, “Gravity interpretation using correlation factors between successive least-squares residual anomalies,” Geophysics, vol. 54, no. 12, pp. 1614–1621, 1989.

[39] N. L. Mohan, N. Sundararajan, and S. V. Seshagiri Rao, “Interpretation of some two-dimensional magnetic bodies using Hilbert transforms,” Geophysics, vol. 47, no. 3, pp. 376–387, 1982.

[40] A. B. Reid, J. M. Allsop, H. Granser, A. J. Millett, and I. W. Somerton, “Magnetic interpretation in three dimensions using Euler deconvolution,” Geophysics, vol. 55, no. 1, pp. 80–91, 1990.

[41] D. Gerovska and M. J. Araúzo-Bravo, “Automatic interpretation of magnetic data based on Euler deconvolution with unprescribed structural index,” Computers & Geosciences, vol. 29, no. 8, pp. 949–960, 2003.

[42] A. Salem and D. Ravat, “A combined analytic signal and Euler method (AN-EUL) for automatic interpretation of magnetic data,” Geophysics, vol. 68, no. 6, pp. 1952–1961, 2003.

[43] R. Pasteka, “The role of the interference polynomial in the Euler deconvolution algorithm,” Bollettino di Geofisica Teorica ed Applicata, vol. 47, no. 1-2, pp. 171–180, 2006.

[44] A. Salem, “Interpretation of magnetic data using analytic signal derivatives,” Geophysical Prospecting, vol. 53, no. 1, pp. 75–82, 2005.

[45] R. R. Hartman, D. J. Teskey, and J. L. Friedberg, “A system for rapid digital aeromagnetic interpretation,” Geophysics, vol. 36, no. 5, pp. 891–918, 1971.

[46] C. Ku and J. Sharp, “Werner deconvolution for automated magnetic interpretation and its refinement using Marquardt’s inverse modeling,” Geophysics, vol. 48, no. 6, pp. 754–774, 1983.

[47] M. Tlas and J. Asfahani, “Fair function minimization for interpretation of magnetic anomalies due to thin dikes, spheres and faults,” Journal of Applied Geophysics, vol. 75, no. 2, pp. 237–243, 2011.

[48] I. V. R. Murthy, “A gradient method for interpreting magnetic anomalies due to horizontal circular cylinders, infinite dykes and vertical steps,” Proceedings of the Indian Academy of Sciences, vol. 89, no. 1, pp. 31–42, 1980.

[49] K. K. Khurana, “Frequency domain least squares inversion of thick dike magnetic anomalies using Marquardt algorithm,” Geophysics, vol. 46, no. 12, pp. 1745–1748, 1981.

[50] I. J. Won, “Application of Gauss’s method to magnetic anomalies of dipping dikes,” Geophysics, vol. 46, no. 2, pp. 211–215, 1981.

[51] H. V. Ram Babu, A. S. Subrahmanyam, and D. Atchuta Rao, “A comparative study of the relation figures of magnetic anomalies due to two-dimensional dike and vertical step models,” Geophysics, vol. 47, no. 6, pp. 926–931, 1982.

[52] D. Atchuta Rao, H. V. Ram Babu, and D. C. Venkata Raju, “Inversion of gravity and magnetic anomalies over some...
bodies of simple geometric shape,” *Pure and Applied Geophysics*, vol. 123, no. 2, pp. 239–249, 1985.

[53] I. V. Radhakrishna Murthy, “Magnetic anomalies of two-dimensional bodies and algorithms for magnetic inversion of dykes and basement topographies,” *Proceedings of the Indian Academy of Sciences*, vol. 99, no. 4, pp. 549–579, 1990.

[54] M. Beiki and L. B. Pedersen, “Estimating magnetic dike parameters using a non-linear constrained inversion technique: an example from the Särna area, west central Sweden,” *Geophysical Prospecting*, vol. 60, no. 3, pp. 526–538, 2012.

[55] Y. Li and D. W. Oldenburg, “3-D inversion of magnetic data,” *Geophysics*, vol. 61, no. 2, pp. 394–408, 1996.

[56] G. Göktürkler, “A hybrid approach for tomographic inversion of crosshole seismic first-arrival times,” *Journal of Geophysics and Engineering*, vol. 8, no. 1, pp. 99–108, 2011.

[57] P. Soupios, I. Akca, P. Mlpogiatis, A. T. Basokur, and C. Papazachos, “Applications of hybrid genetic algorithms in seismic tomography,” *Journal of Applied Geophysics*, vol. 75, no. 3, pp. 479–489, 2011.

[58] C. Caylak, G. Göktürkler, and C. Sarı, “Inversion of multi-channel surface wave data using a sequential hybrid approach,” *Journal of Geophysics and Engineering*, vol. 9, no. 1, pp. 19–28, 2012.

[59] E. Peksen, T. Yas, A. Y. Kayman, and C. Özkan, “Application of particle swarm optimization on self-potential data,” *Journal of Applied Geophysics*, vol. 75, no. 2, pp. 305–318, 2011.

[60] G. Göktürkler and C. Balkaya, “Inversion of self-potential anomalies caused by simple-geometry bodies using global optimization algorithms,” *Journal of Geophysics and Engineering*, vol. 9, no. 5, pp. 498–507, 2012.

[61] C. Balkaya, “An implementation of differential evolution algorithm for inversion of geoelectrical data,” *Journal of Applied Geophysics*, vol. 98, pp. 160–175, 2013.

[62] S. P. Sharma and A. Biswas, “Interpretation of self-potential anomaly over a 2D inclined structure using very fast simulated-annealing global optimization - an insight about ambiguity,” *Geophysics*, vol. 78, no. 3, pp. WB3–WB15, 2013.

[63] A. Biswas and S. P. Sharma, “Optimization of self-potential interpretation of 2-D inclined sheet-type structures based on very fast simulated annealing and analysis of ambiguity,” *Journal of Applied Geophysics*, vol. 105, pp. 235–247, 2014.

[64] A. Biswas and S. P. Sharma, “Interpretation of self-potential anomaly over idealized bodies and analysis of ambiguity using very fast simulated annealing global optimization technique,” *Near Surface Geophysics*, vol. 13, no. 2, pp. 179–195, 2015.

[65] R. Di Maio, P. Rani, E. Piegari, and L. Milano, “Self-potential data inversion through a genetic-price algorithm,” *Computers & Geosciences*, vol. 94, pp. 86–95, 2016.

[66] R. Di Maio, E. Piegari, P. Rani, R. Carbonari, E. Vitagliano, and L. Milano, “Quantitative interpretation of multiple self-potential anomaly sources by a global optimization approach,” *Journal of Applied Geophysics*, vol. 162, pp. 152–163, 2019.

[67] A. Biswas and S. P. Sharma, “Interpretation of self-potential anomaly over 2-D inclined thick sheet structures and analysis of uncertainty using very fast simulated annealing global optimization,” *Acta Geodaetica et Geophysica*, vol. 52, no. 4, pp. 439–455, 2017.

[68] A. Biswas, “Inversion of source parameters from magnetic anomalies for mineral/ore deposits exploration using global optimization technique and analysis of uncertainty,” *Natural Resources Research*, vol. 27, no. 1, pp. 77–107, 2018.

[69] Y. L. Ekinci, C. Balkaya, and G. Göktürkler, “Global optimisation of near-surface potential field anomalies through meta-heuristics,” in *Advances in Modelling and Interpretation in Near Surface Geophysics*, Series of Springer Geophysics, A. Biswas and S. P. Sharma, Eds., pp. 155–188, Springer, Cham, 2020.

[70] M. Gobashy, M. Abdelazeem, M. Abdarabou, and M. H. Khalil, “Estimating model parameters from self-potential anomaly of 2D inclined sheet using whale Optimization algorithm: applications to mineral exploration and tracing shear zones,” *Natural Resources Research*, vol. 29, no. 1, pp. 499–519, 2020.

[71] Sungkono, “An efficient global optimization method for self-potential data inversion using micro-differential evolution,” *Journal of Earth System Science*, vol. 129, no. 1, pp. 1–22, 2020.

[72] K. Rao, S. Jain, and A. Biswas, “Global Optimization for delineation of self-potential anomaly of a 2D inclined plate,” *Natural Resources Research*, vol. 30, no. 1, pp. 175–189, 2021.

[73] A. Biswas, *Self-potential method: theoretical modeling and applications in geosciences*, 1, Springer, Cham, 2021.

[74] A. Biswas, “Interpretation of residual gravity anomaly caused by simple shaped bodies using very fast simulated annealing global optimization,” *Geoscience Frontiers*, vol. 6, no. 6, pp. 875–893, 2015.

[75] A. Biswas, “Interpretation of gravity and magnetic anomaly over thin sheet-type structure using very fast simulated annealing global optimization technique,” *Modeling Earth Systems and Environment*, vol. 2, no. 1, p. 30, 2016.

[76] Y. L. Ekinci, “MATLAB-based algorithm to estimate depths of isolated thin dike-like sources using higher-order horizontal derivatives of magnetic anomalies,” *SpringerPlus*, vol. 5, no. 1, p. 1384, 2016.

[77] Y. L. Ekinci, C. Balkaya, G. Göktürkler, and S. Turan, “Model parameter estimations from residual gravity anomalies due to simple-shaped sources using Differential Evolution Algorithm,” *Journal of Applied Geophysics*, vol. 129, pp. 133–147, 2016.

[78] Y. L. Ekinci, S. Ozyalin, P. Sndir, C. Balkaya, and G. Gokturkler, “Amplitude inversion of the 2D analytic signal of magnetic anomalies through the differential evolution algorithm,” *Journal of Geophysics and Engineering*, vol. 14, no. 6, pp. 1492–1508, 2017.

[79] Y. L. Ekinci, C. Balkaya, G. Göktürkler, and Ş. Özyalın, “Gravity data inversion for the basement relief delineation through global optimization: a case study from the Aegean Graben System, western Anatolia, Turkey,” *Geophysical Journal International*, vol. 224, no. 2, pp. 923–944, 2020.

[80] A. Singh and A. Biswas, “Application of global particle swarm optimization for inversion of residual gravity anomalies over geological bodies with idealized geometries,” *Natural Resources Research*, vol. 25, no. 3, pp. 297–314, 2016.

[81] A. Singh and A. Biswas, “Global particle swarm optimization technique in the interpretation of residual magnetic anomalies due to simple geo-bodies with idealized structure,” *Basis of Computational Geophysics*, vol. 1, pp. 13–32, 2021.
prismatic bodies using differential evolution algorithm,” *Journal of Applied Geophysics*, vol. 136, pp. 372–386, 2017.

[83] A. Biswas, M. P. Parija, and S. Kumar, “Global nonlinear optimization for the interpretation of source parameters from total gradient of gravity and magnetic anomalies caused by thin dyke,” *Annals of Geophysics*, vol. 60, no. 2, pp. 1–17, 2017.

[84] A. Biswas, “A review on modeling, inversion and interpretation of self-potential in mineral exploration and tracing paleo-shear zones,” *Ore Geology Reviews*, vol. 91, pp. 21–56, 2017.

[85] I. Kaftan, “Interpretation of magnetic anomalies using a genetic algorithm,” *Acta Geophysica*, vol. 65, no. 4, pp. 627–634, 2017.

[86] K. S. Essa and M. Elhussein, “PSO (particle swarm optimization) for interpretation of magnetic anomalies caused by simple geometrical structures,” *Pure and Applied Geophysics*, vol. 175, no. 10, pp. 3539–3553, 2018.

[87] K. S. Essa and M. Elhussein, “Interpretation of magnetic data through particle swarm optimization: mineral exploration cases studies,” *Natural Resources Research*, vol. 29, no. 1, pp. 521–537, 2020.

[88] N. L. Anderson, K. S. Essa, and M. Elhussein, “A comparison study using particle swarm optimization inversion algorithm for gravity anomaly interpretation due to a 2D vertical fault structure,” *Journal of Applied Geophysics*, vol. 179, article 104120, 2020.

[89] R. Di Maio, L. Milano, and E. Piegarì, “Modeling of magnetic anomalies generated by simple geological structures through Genetic-Price inversion algorithm,” *Physics of Earth and Planetary Interiors*, vol. 305, article 106520, 2020.

[90] M. Gobashy, M. Abdelazeem, and M. Abdrabou, “Minerals and ore deposits exploration using meta-heuristic based optimization on magnetic data,” *Contributions to Geophysics and Geodesy*, vol. 50, no. 2, pp. 161–199, 2020.

[91] A. Biswas, “Interpretation of gravity anomaly over 2D vertical and horizontal thin sheet with finite length and width,” *Acta Geophysica*, vol. 68, no. 4, pp. 1083–1096, 2020.

[92] K. Rao and A. Biswas, “Modeling and uncertainty estimation of gravity anomaly over 2D fault using very fast simulated annealing global optimization,” *Acta Geophysica*, vol. 69, no. 5, pp. 1735–1751, 2021.

[93] M. A. al-Garni, Y. Srinivas, and N. Sundararajan, “Sundararajan transform—an application to geophysical data analysis,” *Arabian Journal of Geosciences*, vol. 3, no. 1, pp. 27–32, 2010.

[94] M. Sen and P. Stoffa, *Global Optimization Methods in Geophysical Inversion*, Cambridge University Press, Cambridge, 2013.

[95] A. Biswas, *Identification and resolution of ambiguities in interpretation of self-potential data: analysis and integrated study around South Purulia Shear Zone, India*, [Ph. D. thesis], 2013.

[96] L. Ingber and B. Rosen, “Genetic algorithms and very fast simulated reannealing: a comparison,” *Mathematical and Computer Modelling*, vol. 33, no. 1, p. 523, 1992.

[97] Z. Fernández-Muñiz, J. L. G. Pallero, and J. L. Fernández-Martínez, “Anomaly shape inversion via model reduction and PSO,” *Computers & Geosciences*, vol. 140, article 104492, 2020.

[98] K. Mosegaard and A. Tarantola, “Monte Carlo sampling of solutions to inverse problems,” *Journal of Geophysical Research*, vol. 100, no. B7, pp. 12431–12447, 1995.