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Model of Lasem Fault Inversion

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Abstract

The subsurface modeling of the Lasem area is to obtain a busted model in the Lasem fault zone is conducted by inversion method using gravity field data. The result of inversion modeling resulted in depression model in south and north of the research area, with density 2,1-2,8 gr/cm3. The depressed zone trending northeast-southwest. The modeling results correspond to the geological model. The depth of depression zone varies to a depth is 15 km.

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1. Introduction

One of the main objectives of the application of the geophysical method is to estimate the subsurface model based on observational data in the field. The field observation parameters obtained can be a gravitational field, magnetic field, and other physical observation parameters. The gravity method is one method in geophysics which is a response of density variations commonly used to estimate subsurface models for regional sources like estimate the faults presence or fractures.

In the field measurement activities/data collection in the field of geophysics is always conducted based on the procedures that have been determined. The result of the measurement obtained is recorded as observation data and in the interpretation process, the result of observation data processing will produce the subsurface model. In order to be able to necessary linkage model known physical properties with observed data obtained. The connector may be a mathematical equation or a mathematical model. There are two known mathematical models of forwarding and inversion modeling. In the forward modeling, the initial model is based on geological and geophysical intuition. The process conducted in the future modeling is to calculate the model anomaly and compare it with the measurement anomaly. The other modeling is the inversion modeling. Based on the mathematical model, the physical parameter values of the gravity field anomalies data (Hall, 2007, Candana, 2000, Suwarti, 1992; Chotin, 1984; Untung, 1978) were obtained.

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In this research, the inverse modeling as secondary data of gravity field data is used. The secondary data in the Lasem Fault area. Chotin et al (1984) are pointed out. The Lasem fault areas are located in three zones *i.e.,* Rembang Zone, Randublatung Depression Zone and Semarang-Rembang Depression Zone. Rembang Zone is a continuation anticlinorium path from Serayu Zone which is south of Semarang. Rembang Zone encompassed a row of not too high hills, with the east-west direction extending. Some of the hills are young anticline mountains and have not yet advanced erosion. Therefore, the convex shape of the anticline is still a height (ridge). In this zone there is a tendency toward a series of hills leading to the northeast-southwest, reflecting the shear of "*left lateral strike slip*" in the area basement. Regarding this research is expected to get the model of Lasem area fault in inversion.

2. Research Methods

The data used are secondary data of Bouguer anomaly complete taken in 2005 at Kudus, Pati and Grobogan area (Sigit, 2006). The study area geographically is located between 6° 41' 49,06" LS – 7° 07' 15,23" LS and 110° 48' 35,45" BT - 111° 06' 57,08" BT, 33.8 x 48) km2. The program simulation using forward method can generate data. It is then used as input inversion calculation. If the inverse calculation result is close to the parameter value used in the forward calculation then the matrix calculation process is correct. Thus, it can be calculated inversion by using field data.

Theory

Newton's pattern of attraction between the particles is the physical concept underlying the gravity method. It was stated that the attraction force between two mass particles m_0 and m the distance between them is from the center of mass whose magnitude is proportional to the multiplicity of the mass m_0 with m and inversely proportional to the distance squared. It can be formulated mathematically as follows.

$$\vec{F}(\vec{r}) = -G\frac{m_0\, m}{|\vec{r}-\vec{r}_0|^2} \times \frac{(\vec{r}-\vec{r}_0)}{|\vec{r}-\vec{r}_0|} \qquad 1$$

$\vec{F}(\vec{r})$ is a force acting on m that is due to m_0 and has a direction of force from m_0 toward m and G is the general constant of gravity $6{,}67428 \times 10^{-11}$ Nm^2kg^{-2} or $m^3kg^{-1}dt^{-2}$ (La Fehr, 2012). The change in the earth's gravitational field caused by these local anomalous bodies are called Gravity Field Anomalies and are denoted by Δg . The anomaly of the gravitational field can only be measured along with the earth's gravitational field in the same direction and when the magnitude of the earth's gravitational field is very small ($\Delta g << g$).

Grant and West (1965) described the gravitational field relationship with surface density on a horizontal field. It is assumed a horizontal field, $z = 0$ has surface density $\sigma(x, y)\ g/cm^3$ the gravitational potential at a point Q' as follows:

$$U_{Q'}{}' = -G\int_0^\infty\int_0^{2\pi} \frac{\sigma(r,\theta)}{\sqrt{r^2+z^2}}\, r\,\partial\theta\,\partial r \qquad 2$$

Since the gravitational potential U is due to the mass distributed locally in $z = 0$, therefore, the gravitational anomaly at point Q' as follows:

$$\Delta g_Q{}' = -\frac{\partial U_Q{}'}{\partial z} = G|z|\int_0^\infty\int_0^{2\pi} \frac{\sigma(r,\theta)}{(r^2+z^2)^{\frac{3}{2}}}\, r\,\partial\theta\,\partial r \quad z \le 0 \qquad 3$$

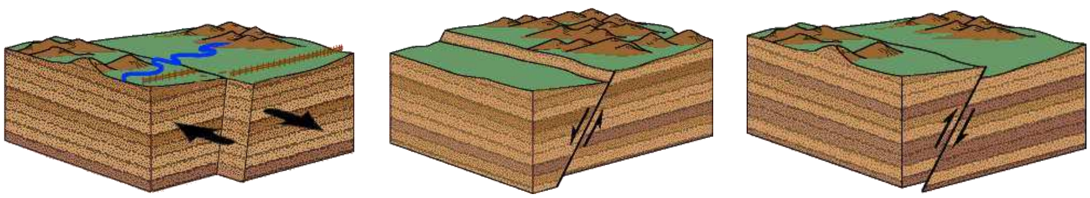
The negative sign in equation (3) is used because Δg . It is measured in the direction g . The physical mean of equation (3) is the gravitational field g on the surface of the earth varies and its value depends on the variation of density beneath the surface and its distance from the earth center (Balkely, 1995).

The gravitational response generally on the surface can be caused by a particular anomalous source. From the process of interpretation or modeling can be known form of anomalous source. However, the same gravity influence on the surface can be caused by different models. Therefore, the geological study is needed when determining the model.

Fault

In geology, there are known folds and broken rock layers. The folds or wrinkles are the movements of the earth's skin/layers of the earth horizontally which causes the crust of the earth to wrinkle. The folding occurs due to weakening pressure on a part in a long time and the rock layer is not fractured, while the fault occurs when there is strong and rapid pressure. Thus, the rock layers are separated from each other.

Horizontal fault or shear fracture is divided into two types, *i.e.,* dextral that is, if the block opposite wherein we stand to shift right and Cesare sinistral, that is, if on the contrary. The vertical shift shape which is the transition from a fold, the result of an increased endogenous power force called flexure. As a result of the endogenous forces formed many cracks in an area, some are up, some are down, some are sloping.



(a) (b) (c)

Figure 1. Fraction type a. Fault down b. Fault up c. Shear fracture (Link Source)

The fault area is generally the area that can be one source of tectonic earthquakes. The continuous movement of the plates of the Earth allows the activity of the fault movement also to continue even if it takes a long time to experience a shift back. At knowing the existence of a fault in one region hence mapping of earthquake-prone area can be conducted better. According to Telford (1999), the gravitational equation for layers with different angles of the fault slope can be written as follows:

$$g = 2\,G\,\rho\,t\,\left[\pi + tan^{-1}\left\{\left(\frac{x}{h_1}\right) + \cot\alpha\right\} - tan^{-1}\left\{\left(\frac{x}{h_2}\right) + \cot\alpha\right\}\right] \qquad 4$$

With h_1 is the depth of the fault right layer *i.e.,* from the surface to the middle layer, h_2 is the depth of the left fault layer *i.e.,* from the surface of the middle layer, α is the slope of the field and t is the layer thickness. Inversion Method (Grandis, H, 2009) stated that one of the bases of inversion is linear regression which is the relationship between model parameters and data linearly. Inversion is generally formulated in the form of vector or matrix notation. Unlike in the following formulation:

$$d = g\,(m) \qquad 5$$

Regarding $d = [d_1, d_2, d_3, \ldots, d_N]$ g is a common function and $m = [m_1, m_2, m_3, \ldots, m_M]$ = are model parameters. In guessing the data for a comparative model m is generally a forward function plays an important role in the inversion process because g can be called as a prediction function and g is the one that determines the data generated from a model.

$$\begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_N \end{bmatrix} = \begin{bmatrix} g_1\,(m_1, m_2, \ldots, m_M) \\ g_2\,(m_1, m_2, \ldots, m_M) \\ \vdots \\ g_N\,(m_1, m_2, \ldots, m_M) \end{bmatrix} \qquad 6$$

A linearly connecting function between a data set and a set of parameters can be written in matrix multiplication, where G is a kernel matrix.

$$d = G\,(m)$$

$$\begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_N \end{bmatrix} = \begin{bmatrix} G_{11} & \dots & G_{1M} \\ \vdots & \vdots & \vdots \\ G_{1N} & \dots & G_{NM} \end{bmatrix} \begin{bmatrix} m_1 \\ \vdots \\ m_M \end{bmatrix} \qquad 7$$

Towards a simple modeling as in 2D inversion modeling the cross-sectional shape of the anomalous object in the *x*-axis and the *z*-axis is considered fixed along the direction of the structure. The result of the model response, as well as measurement of data, is done along the cross-section. It is considered perpendicular to the direction of the structure. In simple 2D fault inversion modeling, it can be done by matching the curve. In the inversion process is done repeated calculations for a matching until obtained data inversion is close to or equal to the input data in this case gravity anomaly. In the case of the fracture model the general equation of the gravitational field with *d* is the data of the gravitational field value for the fracture model, the general inversion equation as follows:

$$d = g\,(m) \qquad 8$$

$$\begin{bmatrix} d_1 \\ \vdots \\ d_i \end{bmatrix} = \begin{bmatrix} g_1(t, h1, h2, \emptyset) \\ \vdots \\ g_n(t, h1, h2, \emptyset) \end{bmatrix} \qquad 9$$

$$\begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_N \end{bmatrix} = \begin{bmatrix} G_{11} & \dots & G_{1M} \\ \vdots & \vdots & \vdots \\ G_{1N} & \dots & G_{NM} \end{bmatrix} \begin{bmatrix} m_1 \\ \vdots \\ m_M \end{bmatrix} \qquad 10$$

$$\begin{bmatrix} d_1 \\ \vdots \\ d_i \end{bmatrix} = \begin{bmatrix} \frac{\partial G_{11}}{\partial t_{11}} & \dots & \frac{\partial G_{14}}{\partial \emptyset_{14}} \\ \vdots & \ddots & \vdots \\ \frac{\partial G_{n1}}{t_{n1}} & \dots & \frac{\partial G_{n4}}{\partial \emptyset_{n4}} \end{bmatrix} \cdot \begin{bmatrix} t \\ h1 \\ h2 \\ \emptyset \end{bmatrix} \qquad 11$$

$$m = inv\,(G^T.G)\,G^T.d \qquad 12$$

The case inversion generally in the geophysics field is a case of non-linear case. In nonlinear cases that are solved linearly, the kernel matrix which is a function of forwarding modeling no longer contains predicted model parameters. The kernel matrix is obtained by a differential process of each parameter searched for the purpose of showing a linear relationship between the data and the model parameters. This process also helps in the matching process. In the evaluation or matching process, the Kernel matrix is replaced by the Jacobi matrix. Jacobi matrix can be stated the relationship of predictive data changes with changes in model data or errors of modeling. The Jacobi method is one of the areas of numerical analysis used to solve the problem of linear equations. This method is one of the indirect methods. It starts from a convergent matching to the best matching and is generally used to solve large linear equations and the proportion of large zero coefficients. The matching method can be formulated as follows:

$$\Delta m = inv\,(G^T.G)\,G^T.(d-f) \qquad 13$$

$$\Delta m = inv\,(J^T.J)\,J^T.(d-f) \qquad 14$$

$$J = [\,j1^T \;\; j2^T \;\; j3^T \;\; j4^T\,] \qquad 15$$

J is a matrix Jacobi with j1 is a derivative h1, j2 is a derivative of h2, j3 is a derivative of *t* (thick), j4 is a derivative of angle (ϕ), J^T is a transpose matrix, *d* is a matrix of advanced model calculation and *f* is the inverse model calculation matrix.

3. Results and Analysis

In the process of the program test using synthetic data of advanced modeling results obtained with the result of modeling of the appropriate results between the forward model and its inversion model. The initial guess determines the number of iterations performed. In this programming obtained values for four parameters fault the layer thickness, the block depth one, the block depth 2 and the corner formed by both blocks. The corner will determine the type of fault.

The Jacobi matrix equation becomes an important part of the programming inversion. If the matrix equation is incorrect, it will produce an error or *Rar*, but even if the Jacob matrix is correct if the initial value of the initial model is too small. It will produce *NaN*. The result of the curve match inversion program as shown in Figure 1. The program can work as expected then it can be applied to the field data by changing the input data used.

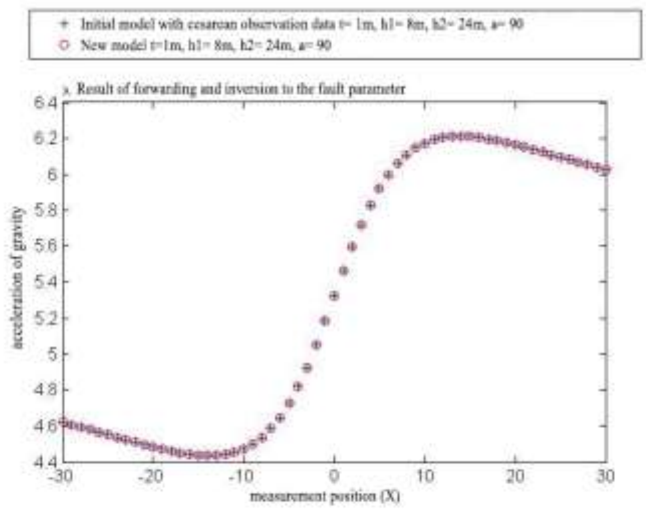


Figure 1. The calculations result of forwarding and inversion to the fault parameter

Regarding this inversion, the parameter value is searched, but the subsurface modeling has not been obtained yet. By adding a system block program to the curve-matching process, then, the sub-surface modeling can be illustrated more clearly. Many blocks can be determined by themselves as needed (Blakely, 1995). The created block will represent the contrast density of a block to the surrounding and initial blocks whose value is already specified. Towards the inverted contrast density inversion method, the subsurface model can be obtained. The test results of the synthetic data for the 1D subsurface inversion as in Figure 2.

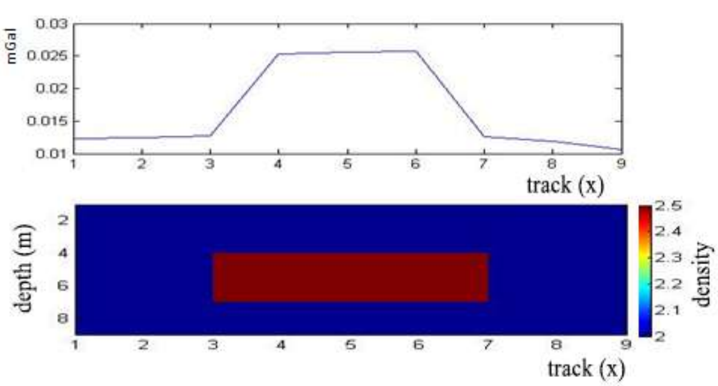


Figure 2. The calculations result of forwarding and inversion for the subsurface model

The Programming of subsurface inversion is as follows:

```
clc
Gg=6.67e-11;
faktor=1;
z=4; %kedalaman model
x=13; %lebar model
dx=10; %jarak spasial x
dz=10; %jarak spasial z
gridz=z/dz;
gridx=x/dx;
xi=1*dx:dx:x*dx;
zi=1*dx:dz:z*dz;
dens=zeros(z,x);
%dens(gridz/2-2:gridz/2-2,gridx/2+2:gridx/2+2)=10;
%BENTUK MODEL
aa=1;
for i=6:13
   for j=1:aa
      dens(j,i)=1000;
   end
   aa=aa+1;
end
%BENTUK MODEL
 for i=1:length(xi)
   for ii=1:length(xi)
   for jj=1:length(zi)
      A=xi(i)-xi(ii)+dx/2;
      B=xi(i)-(xi(ii)+dx/2);
      C=zi(1)-zi(jj)+dz/2;
      D=zi(1)-(zi(jj)+dz/2);
      a(jj,ii)=Gg*(A*log((A^2+D^2)/(A^2+C^2))-B*log((B^2+D^2)/(B^2+C^2))+2*D*(atan(A/D)-atan(B/D))-
2*C*(atan(A/C)-atan(B/C)));
   end
   end
   tot=0;
   for jm=1:length(zi)
      for im=1:length(xi)
      tot=tot+a(jm,im)*dens(jm,im);
      end
   end
   anom(i)=tot;
end
```

The development of basic programming blocks will be obtained the density values distribution. It can be known from the contrast observation of each block produced, whereas, the regular matching cannot be known the value of the density distribution. In the initial process parameter values can be calculated more easily because only through the curve matching process. However, the density is considered homogeneous, whereas, in block inversion process it can simulate the density distribution in more detail. But, it produces high model ambiguity. The ambiguity is one of the disadvantages of this method, unlimited modeling if relying on matching only. It needs to be given certain value limits on certain blocks based on existing geological reviews. If it is not done then it will be obtained as in figure 3. If it is geologically or another literature review, it can be shown the existence of Cesare then it is possible given a constraint to reduce ambiguities generated the model. By combining the method of matching with the block method, we obtain the modeling of the subsurface structure as shown in Figure 4 and 7. The result of the block system in Lasem fault field data, a model approaching 2 depression is found.

In this study, the analysis was conducted on 71 incisions with SN direction with a spacing of 475 m incision. The results show the same pattern of density contrast in southern and northern parts. The density values were 2.1 gr/cm^3 to 3 g/cm^3, with an average density of 2.67 g cm^3. The lowest density color contrast is 2.1 gr cm^3 and the highest density of black color with 3 gr/cm^3 density, the mean dark blue density is 2.67 gr/cm^3.

The contrast density varies to a depth of 20 km, contrasting colors that appear at a depth of 0-10 km with a density of 2,1-2,4 gr/cm^3. The resulting model depicts unlike a depression in the south and north, the southern depression zone is wider than the northern zone. The low density dept zones 2,1-2,4 gr/cm^3, while others density 2,67-2,8 gr/cm^3. In LANDSAT image interpretation results stated that the Lasem Fault is a wide horizontal fault. From the local anomalous forward incision modeling results, it appears that the subsurface geological condition of the Lasme Fault is controlled by the fault structure down which is interpreted as the appearance of the Lasem Fault with the strike direction ± N 255^0 E, the dip ± 45,8^0 (Sigit, 2006). Whereas, the inversion results describe the model as it is in the geological profile. The difference lies in the depth of the depression. In geological modeling, depression appears to be in the south and north with a depth of 500 m-1 km (Figure 5). Whereas, the inversion results vary to a depth of 15 km.

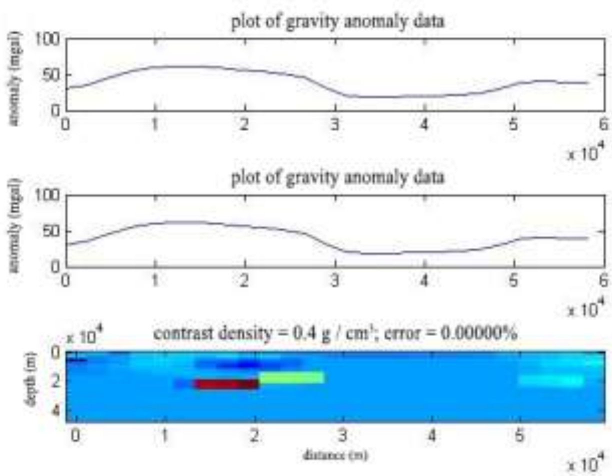


Figure 3. Inversion modeling without value constraints

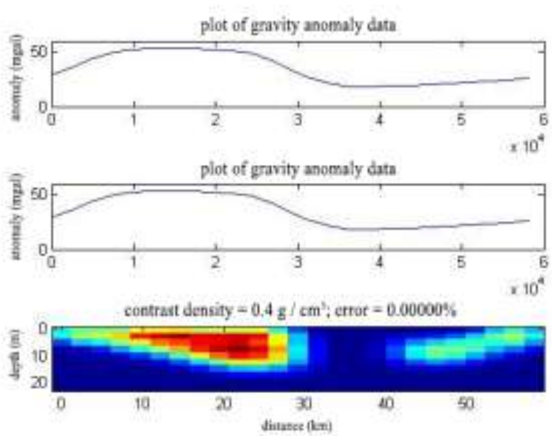


Figure 4. Lasem fault inversion modeling

Figure 5. Profile of the regional geological map of the Northern Kapur Mountains (Suwarti and Wikarno 1992)

Figure 6. Landsat image of the research area and modeling trajectory

Mastering the interpretation of aerial photographs and Landsat images can be recognized several straight and cesarean, the cesarean pattern at 110^0-111^0 northeast-southwest. Whereas, in 109^0-110^0 BT shows an almost pairwise pattern to the northeast-southwest direction. The result of inversion modeling resulted in the northeast-southwest alignment as generated from the Lansat image. The depressed zone in the western part of the land is cultivated and increasingly northward on the eastern incision. The depressed zone is less visible in the west, beginning to appear in the middle to the east (incisions to 17-71). The western geology is a zone of Depression Semarang-Rembang. Its appearance is alluvial sediment consisting of crude to clay spread in the middle and south of the research area. Geologically, it is developed structures in the study area are alignment, folding and fault structure, in both depressive zones (Semarang Rembang and Randublatung zone). There is not much geological structure. The structure of anticlines and *sinklin* generally leads west-east. The fault structure encountered in the form of normal faults, fault rises, and shear faults. Generally, the south-western trending fault with the main east-west fault direction, while the Rembang zone has a more complex geological structure. Semarang Rembang Zone is a density of 2,4-2,67 gr/cm^3. In the inversion results appear depressed areas that are widening to the north. Therefore, the northern depression narrows that when straightened then trending northeast-southwest.

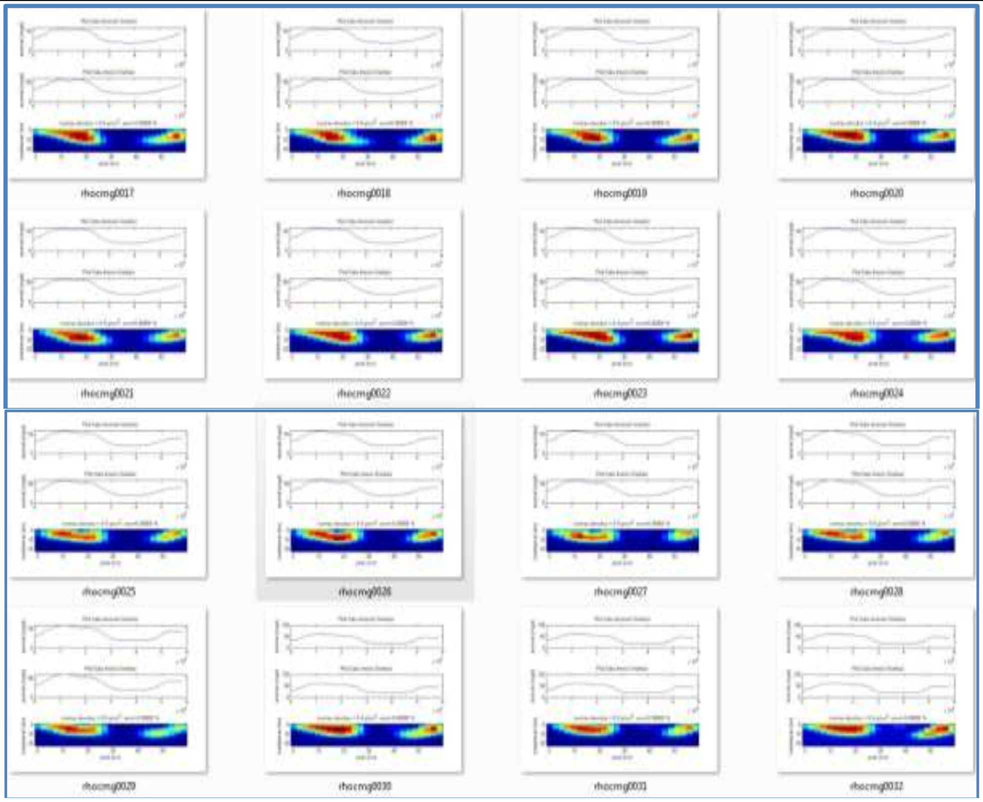


Figure 7. The sample for the result of Lasem fault inversion of SN incision from southwest to northeast

4. Conclusion

The result of inversion model is depression model in south and north of the research area, with density 2,1-2,8 gr/cm^3. The depressed zone trending northeast-southwest. The depth of depression zone varies is 15 km. The differences in depth values may be caused by less small block dimensions. In the method of block, dimension inversion determines the density distribution. Therefore, the result is more valid.

Conflict of interest statement and funding sources

The authors declared that they have no competing interest. The study was financed by personal funding.

Statement of authorship

The authors have a responsibility for the conception and design of the study. The authors have approved the final article.

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