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Inexpensive 3-D Visualization of Geothermal Well Targeting

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ABSTRACT

Faults in geothermal systems play an important role in the permeability conditions around geothermal wells. Drilling is often aimed toward fault zones, because the permeability of large production geothermal wells mostly results from such faulting systems. The authors have developed a free, user-friendly Windows-based program to simulate a well trajectory penetrating a fault. A simple code was also written in order to display the output in three dimensions using the anaglyph red-cyan method. In this method, a fault is taken as a plane structure, and the well track is taken as the summation of line segments in 3-D space. The fault and the well track are represented by a mathematical equation, and the intersection point can be simulated. The output of the program is then plotted in separate 3-D panels, where each panel has a different azimuth and latitude of view in order to give the left and right images, respectively. The images are then filtered using red and cyan filters and overlaid into a single frame. Using 3-D red-cyan glasses, this final image yields a three-dimensional view that is often very helpful when making important drilling decisions.

1. INTRODUCTION

The successfulness of drilling depends on good planning, including drilling prognosis that is eventually used as a drilling guidance. This prognosis contains subsurface information, especially about the existence of production targets. Faults are production targets of geothermal wells, because they play an important role as the feed zone of some reservoirs. Geothermal fluids can be easily exploited from these reservoirs because of the existence of faults that increase their permeability.

The intersection between fault and exploration/production wells can be predicted manually or by using software from directional drilling service companies. A freeware application called FaultWell that can help in planning the directional drilling is introduced in the present work.

2. BASIC CONCEPTS

In this paper, faults resulting from tectonic activity in the Earth's crust can be assumed as a plane structure, whereas exploration/production wells can be assumed as a line structure.

2.1 Plane Structure

The fault was usually presented as the direction and the slope (strike/dip) by directly plotting a topography map that referred to a certain location. Figure 1 shows an example of a normal fault. The strike is the imaginary horizontal line of the fault direction, and the dip is the deviation angle of the fault against the horizontal field that was measured perpendicular against the fault strike. Based on the "three fingers" formula, dip position was always on the right side of the strike.

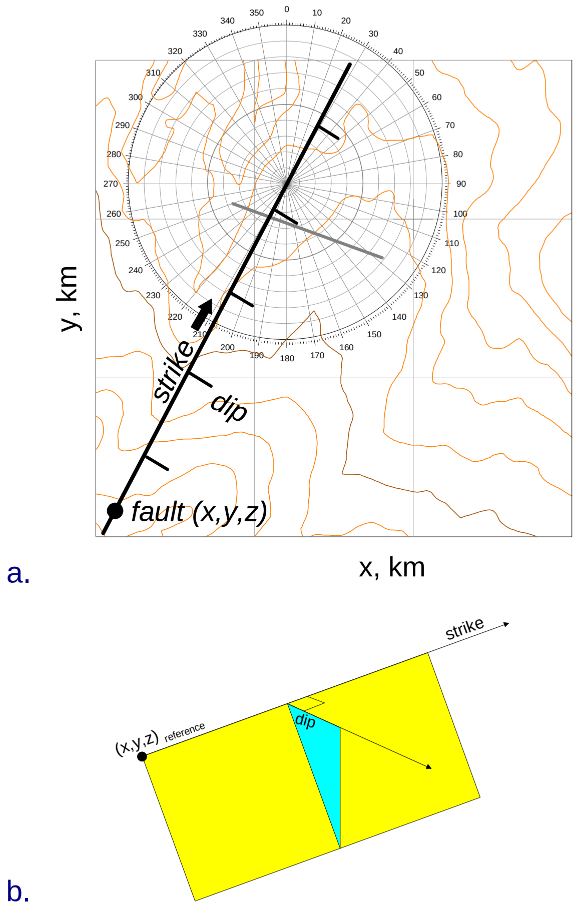

Figure 1: The representation of a fault on a topography map that contains a strike and a dip (a). 3D illustration of a fault with its measured parameters (b).

Faults can also be modeled as flat fields with Equation 1 (Henderson, 1995):

$$z = \alpha x + \beta y + \gamma \tag{1}$$

Where α is the coefficient indicating the slope in the x direction, β is the coefficient in the y direction, and γ is the displacement from the original point.

There are many methods that can be used to obtain α, β and γ. The easiest way is taking three coordinate samples from the fault plane, then form the normal equation and inverse it. Equation (2) and (3) show solutions using the approach of inversion:

$$\begin{bmatrix} x_1 & y_1 & 1 \\ x_2 & y_2 & 1 \\ x_3 & y_3 & 1 \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \\ \gamma \end{bmatrix} = \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} \qquad (2)$$

$$\begin{bmatrix} \alpha \\ \beta \\ \gamma \end{bmatrix} = \begin{bmatrix} x_1 & y_1 & 1 \\ x_2 & y_2 & 1 \\ x_3 & y_3 & 1 \end{bmatrix}^{-1} \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} \qquad (3)$$

By obtaining α, β and γ, the elevation of the Z plane can be determined at any coordinate (x,y), as easy as one-two-three.

2.2 Line Structure

In the geological view, a line structure could be represented in the form of a plunge (vertical deviation) and an azimuth, which is bound at a unique coordinate, e.g. N290E/35. Figure 2 shows a line structure, in the form of a deviation well, which generally consists of vertical sections, a build up, and directional sections. The presentation of a line structure in a topography map has sometimes constraints on interpretation, because a plain map can only accommodate flat elements (x,y).

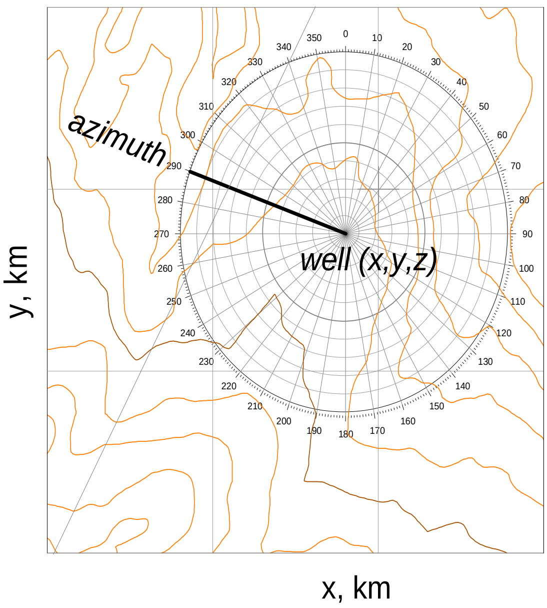

Figure 2: The representation of a well track with a vertical deviation angle and an azimuth.

In mathematical view, a line structure could be presented as a vector (Spiegel, 1974), which is recognized as (x1,y1,z1) and (x2,y2,z2). In the other method, we could see a line structure as an intersection of two plain fields: $(\alpha_1\beta_1\gamma_1)$ - $(\alpha_2\beta_2\gamma_2)$. The way of obtaining α, β and γ coefficients is as easy as before.

3. DISCUSSION

With understanding the behavior of plane and line coefficients, the intersection point between both structures becomes easy. Tracking a geothermal well to penetrate a fault plane is the application from this method. As illustration, plane structures have shape:

$$\alpha_1 X + \beta_1 Y - Z = -\gamma_1 \qquad (4)$$

while line structures have shape:

$$\alpha_2 x + \beta_2 y - z = -\gamma_2 \qquad (5)$$

$$\alpha_3 x + \beta_3 y - z = -\gamma_3 \qquad (6)$$

The position of intersection between the plane and the line could be obtained from normalizing equations (4), (5), and (6):

$$\begin{bmatrix} \alpha_1 & \beta_1 & -1 \\ \alpha_2 & \beta_2 & -1 \\ \alpha_3 & \beta_3 & -1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} -\gamma_1 \\ -\gamma_2 \\ -\gamma_3 \end{bmatrix} \qquad (7)$$

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} \alpha_1 & \beta_1 & -1 \\ \alpha_2 & \beta_2 & -1 \\ \alpha_3 & \beta_3 & -1 \end{bmatrix}^{-1} \begin{bmatrix} -\gamma_1 \\ -\gamma_2 \\ -\gamma_3 \end{bmatrix} \qquad (8)$$

Then the intersection point (x,y,z) is obtained.

When doing inversions, it is important to know the conditions of the matrices, in order to avoid singularity problems. One way to avoid this condition is avoiding the application from an extreme dip and a plunge: zero degree or 90 degree. One or two degrees can be utilized to represent zero degrees, while 88 or 89 degrees can be utilized as a "vertical angle".

It is unnecessary to be apprehensive about the inversion work because it has been taken over by FaultWell programs, shown by the windows in Figure 3. By one click execution, the position of intersection could be known or information if well design does not penetrate the fault. This Program can be run at Windows 98, 2000, XP, and Vista. If the icon of FaultWell.exe is clicked, a window at Figure 3 will appear on the screen.

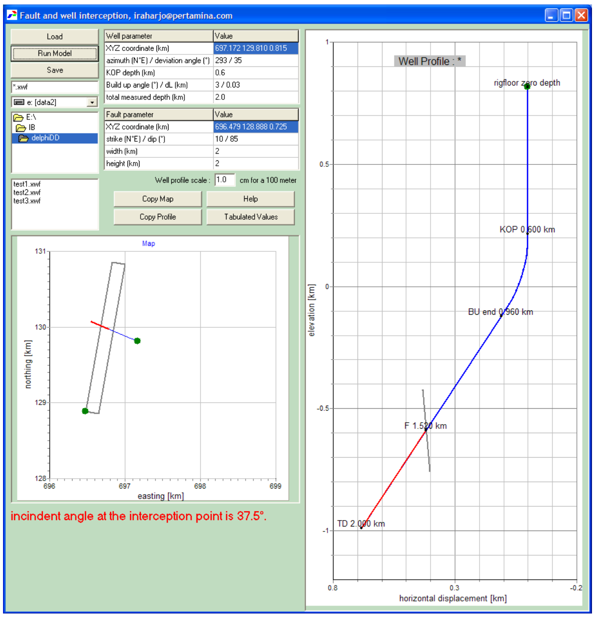

Figure 3: The windows of the FaultWell program for well targeting applications.

To run the program, the well design information is filled in:

- The surface coordinate (x,y,z) in km, written in a line with delimiter coma or space.
- The azimuth and vertical deviation angle, in degrees, written with delimiter space-slash-space, e.g. 293 / 35.
- The KOP, kick of point, in km.
- The build up angle in degrees/km, with delimiter space-slash-space. For example 3°/30 meters is written as 3 / 0.03.
- The total measured depth, in km.

Those parameters have to be specified in the program as shown in Figure 4.

Well parameter	Value
XYZ coordinate (km)	697.172 129.810 0.815
azimuth (N°E) / deviation angle (°)	293 / 35
KOP depth (km)	0.6
Build up angle (°) / dL (km)	3 / 0.03
total measured depth (km)	2.0

Figure 4: Input for representation of a deviation well.

Fault structures are represented with a coordinate point (x,y,z) in kilometers, a strike/dip, and structural dimensions, as shown in Figure 5. Delimiters used are space and space-slash-space.

Fault parameter	Value
XYZ coordinate (km)	696.479 128.888 0.725
strike (N°E) / dip (°)	10 / 85
width (km)	2
height (km)	2

Figure 5: Input for representation of a fault structure.

When all parameters have been specified, a button: **Run Model** is clicked and the calculation results are shown. In this example, a fault will be at 1520 meter depth. To see the detail calculations, e.g. fault corners, the well course, and the intersection position of x,y,z, a button: **tabulated values** should be clicked and a window as Figure 6 shows, will emerge. To collect the data, a cut/copy menu can be utilized.

The program looks for an intersection point in the interval between the coordinate end of the build up depth and the coordinate at the total depth. The intersection outside the interval would be rejected and reported according to the respective conditions, such as:

- The depth of the well is insufficient for the intersection point
- Intersection happened at elevation above KOP
- Intersection happened before the buildup section work was done

There is a minimum critical angle when the well trajectory penetrates the shear. If the incident angle is smaller the penetration would be progressively difficult. This program provides information of the incident angle as information for execution. The suited incident angle that is best for assorted conditions is 90°.

Tabulated Values

```
fault corners: X Y Z all in km
   696.479    128.888     0.725
   696.826    130.858     0.725
   696.998    130.827    -1.267
   696.651    128.858    -1.267
well course:  X  Y  Z  HorizDispl  MeasuredDepth, all in km
   697.172    129.810     0.815     0.000     0.000
   697.172    129.810     0.215     0.000     0.600
   697.171    129.810     0.185     0.001     0.630
   697.169    129.811     0.155     0.003     0.660
   697.166    129.813     0.125     0.007     0.690
   697.160    129.815     0.096     0.013     0.720
   697.154    129.818     0.067     0.020     0.750
   697.146    129.821     0.038     0.028     0.780
   697.137    129.825     0.010     0.038     0.810
   697.126    129.829    -0.018     0.050     0.840
   697.115    129.834    -0.045     0.062     0.870
   697.101    129.840    -0.072     0.077     0.900
   697.087    129.846    -0.097     0.092     0.930
   697.072    129.853    -0.122     0.109     0.960
   696.543    130.077    -0.989     0.683     2.000
fault encountered at:
   696.787    129.973    -0.589     0.418     1.520
```

Figure 6: Tabulated window values that contain ASCII text that can be cut/copied to be processed further by another program.

4. OTHERS

For other purposes like presentation figures and re-runs, other useful buttons are provided:

- Load: to take a fault model & a well from a disk, with file extension .xwf
- Save: to save a fault model & a well to a disk. Ensure that the button: **Run Model** has been clicked, before clicking Save
- Copy Map: to copy the Map Figure to the clipboard
- Copy Profile: to copy the Well-profile to the clipboard
- Help: to display by convention: strike/dip, plunge/azimuth

To alter a plot scale Well-Profile, edit the well profile scale, choose a scale which is convenient and re-click **Run Model**.

For 3-D visualization purpose, an alternative inexpensive method will be demonstrated. All the tabulated values from the program can be explored more. The fault corners will show a rectangle when plotted in a 3-D space, while the well trajectory will show a curve in the 3-D space.

The following Matlab codes (Raharjo, 2008) create left and right views as shown in Figure 7 and can be explored more to create a 3-D anaglyph image as shown in Figure 8. Usually a red filter is applied to the left image and a cyan filter to the right. The figures are then overlaid into the composite image.

```
% Imam Raharjo, university of utah 2008
% fraction of MT script to create 3-D view of geothermal wells
% Anaglyph software is needed. check www.stereoeye.jp
% Download also free faultwell.exe from www.pgeindonesia.com
clear all;closeall;clc
fault1=load('fault1.txt');
well1=load('well1.txt');
well2=load('well2.txt');
well3=load('well3.txt');
crosspoint1=load('crosspoint1.txt');
crosspoint2=load('crosspoint2.txt');
crosspoint3=load('crosspoint3.txt');
% save the first figure as left image, and apply red filter
figure
plot3 (fault1(:,1),fault1(:,2),fault1(:,3),'b-');hold on
```

```
x1=well1(:,1);y1=well1(:,2);z1=well1(:,3);
x2=well2(:,1);y2=well2(:,2);z2=well2(:,3);
x3=well3(:,1);y3=well3(:,2);z3=well3(:,3);
plot3(x1,y1,z1,'b','linewidth',1);
plot3(x2,y2,z2,'b','linewidth',1);
plot3(x3,y3,z3,'b','linewidth',1);
plot3(crosspoint1(1),crosspoint1(2),crosspoint1(3),'bo','markersize',5)
plot3(crosspoint2(1),crosspoint2(2),crosspoint2(3),'bo','markersize',5)
plot3(crosspoint3(1),crosspoint3(2),crosspoint3(3),'bo','markersize',5)
axis([695 698 128 131 -2 1]);
grid on
view(153,34); % azm and latitude to see a 3d world.
xlabel('easting,km');ylabel('northing,km');zlabel('elevation,km')
% save the second figure as right image, and apply cyan filter
figure
plot3 (fault1(:,1),fault1(:,2),fault1(:,3),'b-');hold on
x1=well1(:,1);y1=well1(:,2);z1=well1(:,3);
x2=well2(:,1);y2=well2(:,2);z2=well2(:,3);
x3=well3(:,1);y3=well3(:,2);z3=well3(:,3);
plot3(x1,y1,z1,'b','linewidth',1);
plot3(x2,y2,z2,'b','linewidth',1);
plot3(x3,y3,z3,'b','linewidth',1);
plot3(crosspoint1(1),crosspoint1(2),crosspoint1(3),'bo','markersize',5)
plot3(crosspoint2(1),crosspoint2(2),crosspoint2(3),'bo','markersize',5)
plot3(crosspoint3(1),crosspoint3(2),crosspoint3(3),'bo','markersize',5)
axis([695 698 128 131 -2 1]);
grid on
view(154,34); % azm and latitude to see a 3d world.
xlabel('easting,km');ylabel('northing,km');zlabel('elevation,km')
```

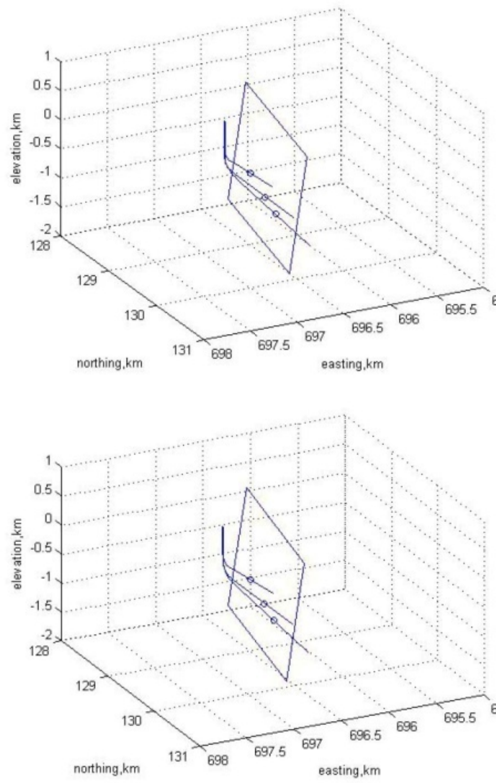

Figure 7: Filtered right and left images that are built from the MATLAB code.

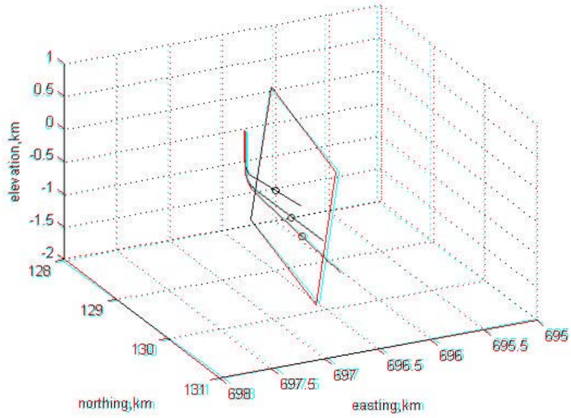

Figure 8: Composite images.

CONCLUSION

Software for geothermal well targeting, which included a deviated well and a planar fault configuration, has been developed. Furthermore, the software was dedicated for free to students and the public (this program could be downloaded for free at http://www.pgeindonesia.com/files/FaultWell.zip). It makes well targeting easier and has a repeatability point that is very useful for instant decisions. Modifying the result with a simple and an inexpensive way into a 3D view will help the interpreter to better imagine the angle of a well trajectory that penetrates faults. The software is free so users take the responsibilities for their use.

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