PROCEEDINGS, Twenty-Sixth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 29-31, 2001
SGP-TR-168

THREE DIMENSIONAL MODELING OF FRACTURE SYSTEMS USING IMAGES FROM BOREHOLES

Chitoshi Akasaka and Shigeo Tezuka

Electric Power Development Co., LTD
6-15-1, Ginza, Chuo-ku, Tokyo, 104-8165, Japan
e-mail: chitoshi_akasaka@epdc.co.jp

ABSTRACT

A *Fracture Modeling System* has been developed by Electric Power Development Company (EPDC) to facilitate the interpretation, display and analysis of fractures identified by borehole imaging tools. Borehole images of individual fractures provide understanding of the local properties of the fracture itself. If an integrated model of the field's large-scale fracture system could be developed, it would help optimize the further exploration and exploitation of the geothermal field. Such a representation would enhance the likelihood of penetrating permeable targets during drilling and aid in reservoir modeling and long-term field management.

Recently, numerous fractures have been detected and characterized using downhole electrical resistivity and/or ultrasonic imaging in EPDC's operating geothermal fields in Japan using Fullbore Formation MicroImager (FMI) logs and BoreHole TeleViewer (BHTV) logs. Integrated three-dimensional fracture modeling was then accomplished by extrapolating individual fracture properties (dip, azimuth and depth) from image data obtained in boreholes. As a result, 3-D trends of fracture orientation were successfully obtained which correlate with other data from nearby wells, such as lost circulation zones and mapped fracture distributions. The 3-D fracture system representations constructed using the Fracture Modeling System can provide useful information for geothermal reservoir characterization.

INTRODUCTION

In typical volcanic systems, geothermal reservoir characterization necessarily requires that the spatial distribution of fractures be understood. For reservoir evaluation, a macroscopic description of the fracture conglomerate and its influence on reservoir permeability and storativity will usually suffice. On the other hand, to plan make-up production (and injection) well drilling and to accurately locate promising drilling targets, a more detailed spatial description is required. Ordinarily, fracture positions are delineated by correlating drilling fluid loss records for adjacent wells with the help of geological logs and geochemical data, but this approach rarely provides sufficient orientation data to characterize the fracture distribution for these purposes. Therefore, we have developed new computer tools to help delineate the spatial properties of the reservoir's fracture system.

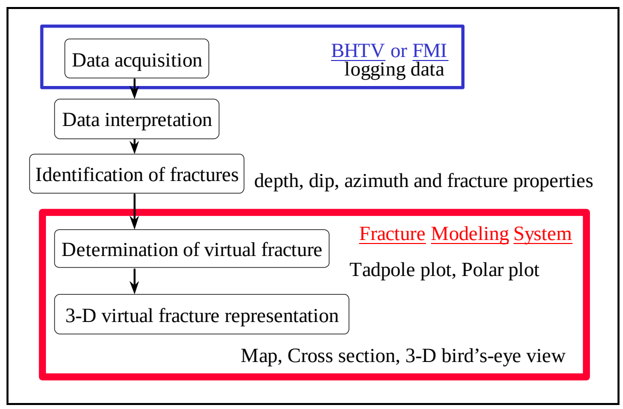

Figure 1. Schematic of 3-D Fracture Modeling System using borehole logging data. A "virtual fracture" is defined by the user to represent several real fractures.

The approach is outlined in Figure 1. Borehole imaging tools such as BHTV and FMI are now becoming practical for routine use in geothermal wells. These tools can detect the dip and azimuth of the fracture associated with a lost circulation horizon directly, so that the fracture orientation can be unambiguously established. A particular fracture will appear on the log as a sinusoidal feature on the "unrolled" rock-face image, which may be analyzed to yield both dip and azimuth (Figure 2.). Borehole images may also be used for fracture classification ("open", "sealed", "intermediate", etc.; Nagai et. al, 1998). Borehole imaging tools substantially increase both the quality and quantity of information available concerning reservoir fractures that intersect the wellbore.

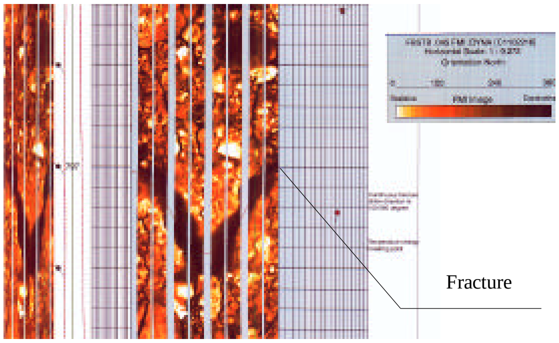

Figure 2. Fullbore Formation MicroImager data recorded about 797m deep in well I-4, located in the reinjection zone at the Onikobe Geothermal Field in Japan. Left: static normalized FMI image. Center: dynamic normalized FMI image. Right: orientation of selected fracture.

Downhole imaging techniques permit the absolute orientations of individual fractures to be determined, but complicated three-dimensional fracture structures constitute a severe visualization problem for reservoir engineers. The *Fracture Modeling System* was developed to help users delineate and visualize 3-D fracture distributions. “Polar plots” and “tadpole plots” may be used to identify trends in fracture orientation, and contouring tools for the “polar plots” are available to help evaluate statistical properties.

The user can choose the orientation of a specific fracture graphically (on the tadpole plot or the polar plot), and save the orientation information for this dominant fracture as an intermediate file on the hard disk drive. This specific fracture is called a “virtual fracture” in the system. The user can then visualize the virtual fracture using *Map*, *Cross Section* and *Birds-Eye View* images, and estimate the spatial extent of the fracture. In this paper, the system components and functions are described using data from the Onikobe geothermal field in Japan.

SYSTEM DESIGN

The three-dimensional fracture visualization system was developed to interpret fracture trends and to estimate fracture spatial extent. The system allows the user to analyze selected fractures and to visualize the dominant fractures as “virtual fractures” on 3-D images on the screen and/or hardcopy.

This system has been made possible by recent advances in hardware and software technology, and was developed using AVS/Express (AVS Inc, 1998b, 1998c). AVS/Express is a component-based software environment for visualizing complex data and for building applications with interactive visualization and graphics functions. It is supplied by Advanced Visual Systems Inc., a major worldwide visualization software supplier. The existing system is implemented on a Sun UNIX workstation, but AVS/Express is also available for Windows 95/NT. Therefore the system can easily be transferred to other platforms.

All user interactions take place through the graphical user interface (GUI). The GUI is designed to minimize the amount of keyboard entry required and to allow most selections to occur though mouse driven menus and displays. The GUI is also based on AVS/Express (AVS Inc, 1998a).

SYSTEM COMPONENTS

The system currently consists of seven modules:

Main Menu

This is the master program used to select data sets for analysis and to execute the other modules.

Polar Plot

Each fracture detected is plotted as a point in polar coordinates, with azimuth represented normally and radius proportional to dip angle (Figure 3). Fractures are each classified as one of several types (such as open, sealed, partially open and so on) and indicated by different colors on the plot. This plot allows the user to immediately recognize distributions of orientations and fracture properties. The depth interval for fracture inclusion in the plot is arbitrarily selected and can be moved both upward and downward at constant width. The user can designate the “virtual fracture” on this plot, but depth must be specified using the keyboard in a separate window.

Tadpole Plot

The tadpole plot shows all three fracture orientation parameters: depth, dip and azimuth (Figure 3). The horizontal axis represents the fracture dip and the vertical axis indicates depth in the well. The tail of the tadpole indicates the dip azimuth: an upward tail means dip to the north and a rightward tail means dip to the east. This plot also allows the user to recognize fracture distributions (especially dip) at a glance. Color indicates fracture type as in the polar plot (above). The vertical interval represented by the tadpole plot is user-designated in the same way as for the polar plot. The user can also designate the “virtual fracture” on this plot, but the direction of dip must be designated separately in a separate window.

The virtual fracture orientation is plotted on the tadpole plot, so the user can verify or modify his choice immediately. The depth interval may be made to coincide with that of the polar plot with a single mouse-click.

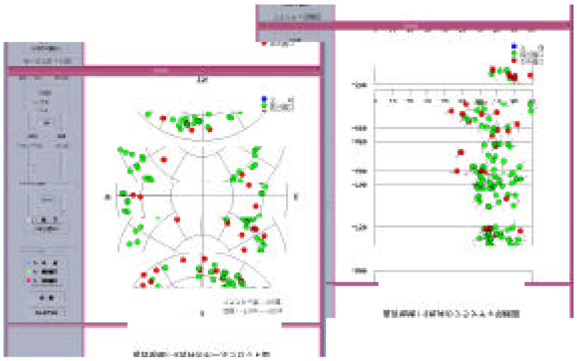

Figure 3. Polar plot (left) and tadpole plot (right) for reinjection well I-9, Onikobe geothermal field in Japan. Red circles indicate open fractures and green circles indicate relatively impermeable fractures.

Cross-Section

Subsurface cross-sections can be displayed by selecting any two points on the ground surface using the map module. Cross sections show subsurface topography together with well projections along the cross section. The virtual fracture is represented as a line. Well temperature and lost circulation logs can also be overlaid to permit the user to confirm that the virtual fracture selected is consistent with these data.

Combined Plot

This plot displays temperature logs and tadpole plots for the same well simultaneously, to help the engineer identify the dominant fractures and choose the "virtual fracture".

Map

The map module displays topographic contours. Other information may be overlaid on the image. Overlays include well locations, circulation losses and temperature logs along the well trace, and user-supplied bit-map images. Selecting any two points with the mouse will start the cross section module.

Birds-Eye View

In this plot, the designated virtual fracture is displayed on screen as a disc image (Figure 4.). The user can move his point of observation horizontally or vertically using the mouse in this 3-D birds-eye view. Well log data (temperature, lost circulation) may also be displayed on the 3-D well trace. In this way, the user can confirm spatial extrapolation of the virtual fracture and correlation with lost circulation points or fractures in other wells. The user may also adjust the orientation of the virtual fracture within this module, in light of the correlation (or lack thereof) observed with data from other wells.

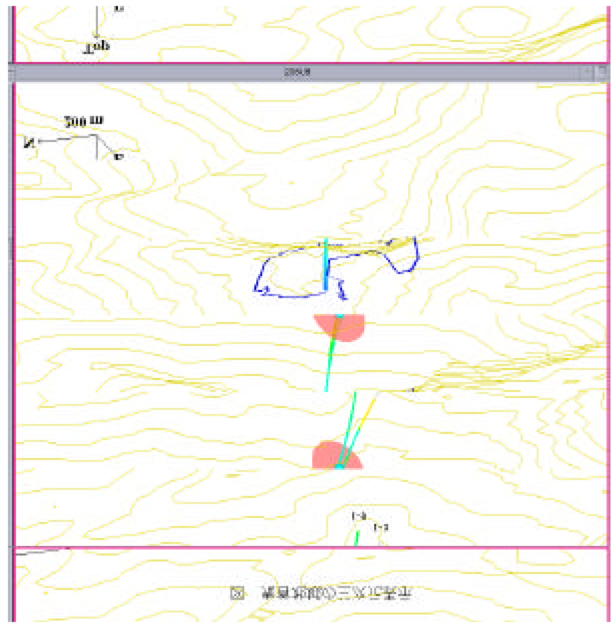

Figure 4. Birds-Eye View display of virtual fracture identified in reinjection wells I-9 and I-3 at Onikobe. Red disc indicates "virtual fracture". Small spheres indicate lost circulation points.

FRACTURE MODELING

Fracture modeling has been performed for the Onikobe geothermal field using the system. In production well 135, a fracture was identified by BHTV logging adjacent to a circulation loss point. Then, a virtual fracture was defined by the above procedure. Polar plots and tadpole plots were made based upon the inferred fracture at the fluid loss zone. In this case, the loss zone was of principal interest, so only "open" fractures were selected and plotted on both figures. The virtual fracture at the lost circulation zone is indicated as a disc on the 3-D birds-eye view shown in Figure 5. The extrapolated virtual fracture intersects circulation loss zones detected in adjacent wells, as shown. This figure implies that the virtual fracture disc is representative of the fracture system in this part of the field. Of course, the fracture system does not in reality consist of just a single plane, but the trend of the actual fractures may be represented reasonably well by that of the virtual fracture.

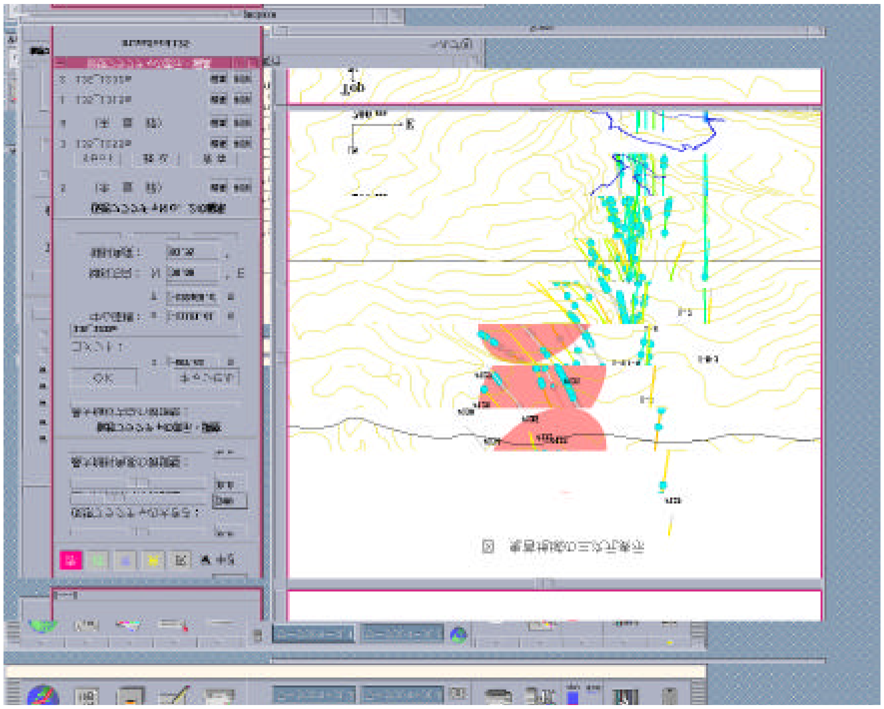

Figure 5. 3-D image of virtual fracture inferred from Well 135 data and intersections with other Onikobe wells. Virtual fracture indicated by a 600m diameter red disc. Small spheres indicate lost circulation zones.

CONCLUSIONS

Individual fractures characterized from borehole images reflect the distribution and dominant orientation of the local fracture system, and specific fractures can be identified as "virtual fractures" on polar plots and tadpole plots. In this way the user can estimate the spatial extent of specific fractures with confidence. By repeating this procedure, the user can gain a clearer understanding of the distribution of fractures in the field. It appears that the system can provide extremely useful insights concerning fracture spacing, which is one of the most important parameters in numerical reservoir simulation. It also can provide us greater chances of success when drilling make-up wells.

ACKNOWLEDGEMENTS

We thank H. Muratake and T. Hoshino of the Kaihatsu Computing Service Center for supporting the development of the Fracture Modeling System. FMI is a trademark of Schlumberger.

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