PROCEEDINGS, 25th Annual PNOC-EDC Geothermal Conference
Manila Diamond Hotel, Philippines, March 10-11, 2004

DATABASE SYSTEM AND APPLICATIONS DEVELOPED FOR RESERVOIR MODELLING AND MONITORING OF GEOTHERMAL FIELDS IN THE PHILIPPINES

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ABSTRACT

The present database system of PNOC Energy Development Corporation for reservoir engineering is improved to support rapid correlation of diverse sets of reservoir data for model conceptualization and reservoir modelling. Simple application programs for data visualization were created to show how database functionality could be enhanced from mere data storage into a useful tool for reservoir simulation and monitoring.

Logical data blocks are drawn from an Oracle database on the fly within a UNIX shell script to create dynamic line graphs and contour planes of temperature and pressure providing basic graphic representation of the reservoir. Developer forms are created for graphical retrieval and handling of data.

1.0 INTRODUCTION

Management of a geothermal reservoir relies on adequate information on the geothermal system (Stefánsson and Steingrímsson, 1980). The prediction of the behaviour of a reservoir during the production stage depends on the conceptual model of that reservoir, the governing physical processes, and the quality of data used in the interpretation. Good quality of data is not an assurance of a perfect conceptual model but is important in realizing that goal (Grant *et al.*, 1982).

The study deals with the optimization of the design of and inclusion of new application tools to the present database system of the Reservoir and Resource Management Department (RRMD) of PNOC Energy Development Corporation (PNOC-EDC). The RRMD database has been redesigned to capture more accurate information on geothermal systems and to support the data requirements of reservoir modelling and field monitoring.

At present, the database contains information from close to 350 wells that have been drilled into the geothermal fields of Bacon-Manito, Palinpinon, Tongonan, and Mindanao and into exploration areas of Northern Negros, Mt. Labo, Central Leyte, and Southern Leyte. The data in all geothermal fields are contained in spreadsheets with a file-based structure. In 1997, a decision was made to create a data management system for geothermal data for all project locations to improve the quality of data used for managing the reservoir. Web-based database set-up using thin-client architecture was chosen to be ideal for the collection of data from remote locations (Zapanta *et al.*, 1999). As a result, a geothermal database management system broadcasted on the web was adopted for RRMD.

Geothermal data from different areas are standardized and collected in a central database in Fort Bonifacio, Makati. Collection of data includes contextual information such as wellhead and well track coordinates, and boundaries of pads, sectors and projects. Numerical data from temperature, pressure, spinner, calliper, and sonic logs can be downloaded and used to create graphs. Maps of well locations of different geothermal projects are available in static hypertext mark-up language (HTML) format. Well test interpretations provide information regarding feed zone locations, injectivity indices, permeability thickness and skin values.

Access to the database is comprehensive as it allows personnel, with an approved Internet protocol (IP) address and valid user ID, to view and update information as needed by using only their web browsers.

The study includes a review of the current reservoir engineering database setup for PNOC-EDC against a data management model for reservoir simulation. The database has application forms to perform basic calculations like data interpolation for temperature and pressure. The database management system also has basic computational tools but its architecture, however, has to be refined to provide better collection of data for reservoir conceptualization and modelling. Moreover, database application programs need to be developed to provide a basic graphical representation of the reservoir data.

The database and applications were developed using the software installed on the UNIX server, called Strokkur, of Orkustofnun. These UNIX-based programs were accessed from a personal computer operating on Windows XP 2000 by installing an X-windows terminal on the PC to emulate the UNIX environment.

2.0 BACKGROUND OF STUDY

2.1 Current Web-Based Database System of PNOC-EDC for Reservoir Engineering

In 1997, the Reservoir and Resource Management Department of PNOC-EDC, developed a web-based geothermal database management system using thin-client architecture to handle large volumes of data coming from remote and geographically diffuse project locations. Data from these sources come in heterogeneous types and formats.

Database management systems using thin-client architecture operate like a corporate intranet with database connectivity. Transmission control protocol / Internet protocol (TCP/IP) is used as a communications protocol by the intranet to provide hypertext transfer protocol (HTTP) services containing information from the database to users.

Thin-client architecture is a multi-level architecture with distributed computing power. Thin-client architecture has a web-browser client on the front-end, an application server in the middle, and a database server on the back-end. The client portion, as shown in Figure 1, is an entry screen for making requests and receiving services, such as a web page, from a computer functioning as an application server in the network.

Figure 1. User interface for RRMD web-based database.

2.2 Web-Based Database Architecture and Its Advantages

The first tier in a multi-tier web-based database system is the user interface. In the RRMD configuration, a web browser that comes bundled with preinstalled application programs in desktops and mobile computers is used as a user interface. Computer users from Fort Bonifacio, Makati central office and from satellite offices in Tongonan, Palinpinon, Bacon-Manito and Mindanao geothermal projects can access data using the web browsers on their computers as long as they are connected to the LAN and WAN.

The second tier is an application server containing application programs and forms. An application server may be any server supporting web services and web scripting languages like HTML and JavaScript. In the RRMD configuration, the second tier is a Microsoft NT computer running Internet Information Server (IIS). The data entry and retrieval forms are designed using Microsoft FrontPage and JavaScript.

The third tier is a web server, which is an HTTP server that has object database connectivity (ODBC). ODBC allows creation of HTML documents using data from a relational database. In the RRMD set-up, Oracle Webserver's Listener triggers the Oracle web agent when a database connection is requested, to make a connection to the Oracle database. Stored procedures written in procedural language / structured query language (PL/SQL), which provide program logic, are compiled in an Oracle 8.05 server to create dynamic HTML

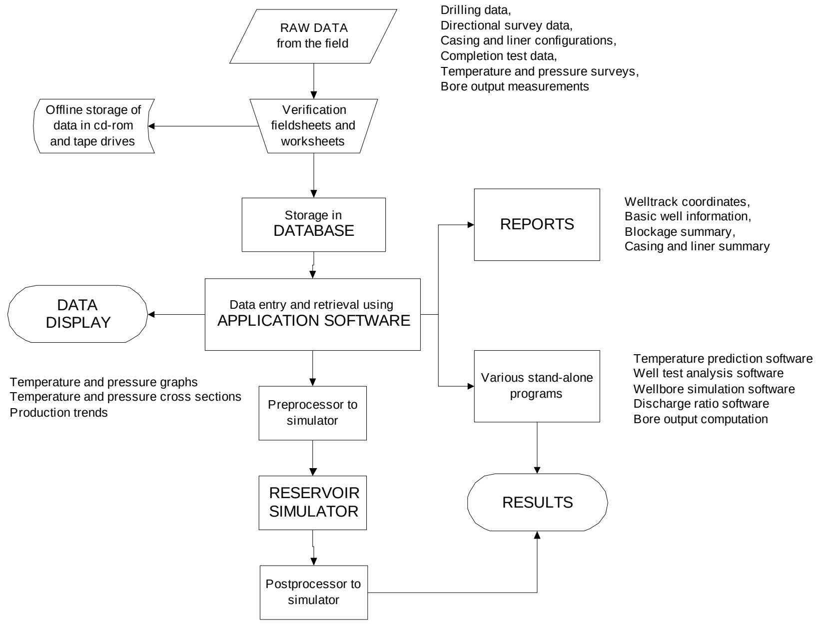

Figure 2. Role of data management and related software in reservoir simulation patterned after GeothermEx Inc., 1995.

pages, and storage for dynamic data in relational tables.

The fourth tier that completes the architecture is the geothermal data, which is stored in an Oracle relational database management system (RDBMS). The Oracle RDBMS runs on SUN's Solaris platform.

The main advantage of a web-based database system is the database and analysis modules are stored in a centralized system. Updates to programming applications only have to be made on the server. No additional programs are needed at remote client desktop computers. Changes, whether in the data, forms, or application programs, are dynamically made available to all users at their web browsers without having any need to install additional programs.

3.0 DEVELOPMENT OF GEOTHERMAL DATABASE

3.1 Objective of the Study

This project, done primarily in fulfilment of the course requirement of the 25th UNU geothermal training programme in Reykjavik, Iceland, deals mainly with the improvement of the present RRMD database system to extend its function as storage of archival geothermal data into an effective tool for reservoir conceptualization and modelling. The database was restructured to be more fitting for database application programs that were developed to facilitate the rapid correlation of different sets of reservoir data and provide visualization of different reservoir parameters.

3.2 Effective Geothermal Database Design

A systematic collection of data is important in understanding a geothermal resource in its natural state and in monitoring changes of the resource during exploitation. The database provides a structure for systematic gathering of information. By placing data in a database, standards are imposed on data that improve the quality of data and make data easily accessible in the future.

Data modelling is used to define areas where the present data management system is adequate and areas where it needs improvement. The reservoir simulation experience of PNOC-EDC is evaluated against the data flow diagram showing how data management and related software is used in reservoir simulation (Fig. 2).

Batches of raw data verified to be correct are sent from field offices to the Makati head office by electronic mail for uploading to the database. The architecture of the database allows for interactive updating from remote locations using the web browser. However, due to bandwidth limitation from the central office to remote locations, this method is slow and is not practical. Data from the field offices, in file-based spreadsheets format and in flat file databases, are recorded in recordable compact discs for archival purposes. Meanwhile, electronic logging data are stored in tape cartridges.

Data viewing is done using the RRMD web page interface. After data are uploaded to the database, users with a proper IP and authorized user ID can view a web report from computers that are part of the LAN and WAN. The reports can be saved directly as HTML or can be copied and pasted into a text editor.

The database, ideally, is linked seamlessly to various stand-alone reservoir engineering programs used to determine stable formation temperature, interpret well tests, and simulate wellbore conditions. However, the current reservoir database is not linked seamlessly to any stand-alone reservoir application software. Data is searched from the database and downloaded before it can be used as an input for a well test analysis, wellbore modelling, or other software.

The database, ideally, is linked seamlessly to a reservoir simulator pre-processor via the application software. In this manner, the database is able to supply information required for a numerical simulation model which is nearly the entire database collected in the course of exploration, drilling, well logging, well testing and production/injection operations over the life of the project. In this aspect, the RRMD database is being updated to enable it to generate sufficient data for reservoir model conceptualization and perhaps create a preliminary input deck for the simulator.

The reservoir simulator should be able to pass simulated data to a postprocessor for model calibration. TETRAD, the reservoir simulator currently being used, has a postprocessor that allow results of modelling to be viewed graphically and calibrated against measured data. The database should be able to display graphics on the fly using data from the database.

3.3 Tools Used for Database and Applications

Assortments of programming languages and graphing tools are used to develop the database and the applications. These include SQL+, Oracle SQL* Loader, UNIX shell scripting, AWK, Oracle Developer, GNUPLOT, and GMT.

The database engine used is Oracle8i Enterprise Edition Release 8.1.7.3.0. Being a relational database, information is stored into Oracle's tables with the ability to link data between tables at the record level. SQL+, or Structured Query Language Plus, the language used for relational database development is used to create the database.

SQL+ statements are embedded in simple programs written using UNIX shell scripts. The shell scripts run embedded SQL+ statements to query the database and spool selected data into a file. The shell script automates the plotting program to use the input data and to display the data in graphical form. Data files from the Oracle database are formatted into the desired data input structure using AWK. AWK, named after its developers Aho, Weinberger, and Kernighan, is a UNIX utility that uses regular expression for pattern matching. An AWK program searches a set of patterns and actions that tell what to look for in the input data and what to do when it is found (Aho *et al.*, 1988; Dougherty, 1992).

Forms and reports interface applications are created using Oracle Developer. Oracle Forms can be used to view, insert, and edit data while Oracle Reports allows the user to access data and to publish it (Lakshman, 2000).

For the X-Y plots, GNUPLOT is used to create the graphs using input data from the database. GNUPLOT is a command-line driven interactive plotting utility that runs on UNIX, MSDOS, and VMS platforms. The software is copyrighted but is freely distributed. GNUPLOT can handle both curves (2 dimensions) and surfaces (3 dimensions).

Generic Mapping Tools (GMT) is used to generate the contours. GMT is a free software package, with General Public License, that can be used to manipulate columns of tabular data,

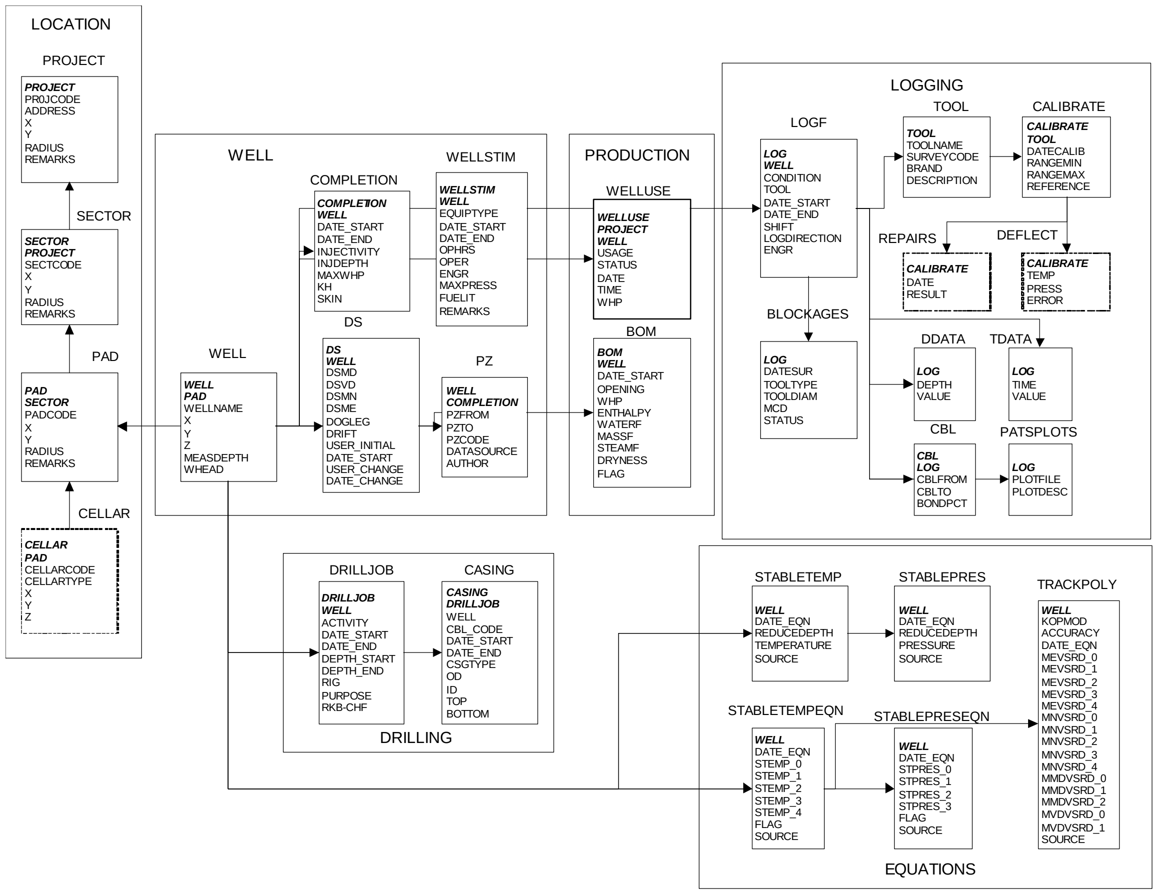

Figure 3. Entity-relationship diagram for reservoir engineering database.

time-series, and gridded data-sets, and display these data in a variety of forms ranging from simple X-Y plots to maps and colour, perspective and shaded-relief illustrations (Wessel and Smith, 1998).

All of the software used are installed on the Strokkur server of Orkustofnun. To run these UNIX-based programs on a personal computer operating on Windows XP 2000, an X-windows terminal is installed first on the PC to emulate the UNIX environment.

3.4 Database Design and Creation

In designing the database, key information required for successful resource management as described by Stefanson and Steingrímsson (1980) is considered. These include:

- Knowledge on the volume, geometry, and boundary conditions of a reservoir;
- Knowledge on the properties of the reservoir rock, i.e. permeability, porosity, density, heat capacity and heat conductivity; and
- Knowledge on the physical conditions in a reservoir, which are determined by temperature and pressure distribution.

There is a conscious effort to separate original data from derived data, to include the source of interpretations, and indicate the accuracy of measurements. The improved design also used strictly ID numbers as the primary key instead of wellnames to describe relationships between different data sets.

3.4.1 Well Location Module

The Location module includes tables for pad, sector, project, and cellar that describe the geographical location of a well by area (Fig. 3). The tables in the Location module describe the location of a well by giving its rough centre and radius.

PAD table contains ID of pad and sector where pad belongs, name of pad, easting (x) and northing (y) coordinates of pad, and a remarks column describing the pad location.

SECTOR table contains ID of sector and project where sector belongs, easting (x) and northing (y) coordinates of centre of sector area, radius of sector area, and a remarks column for the official name of the sector.

PROJECT table contains ID of project, official name of project, mailing address of project, easting (x) and northing (y) coordinates of centre of project area, estimated radius of project area, and a remarks column for the official name of the project.

CELLAR table contains ID of cellar and pad where cellar belongs, name or code of the cellar, easting (x) and northing (y) coordinates of centre of cellar, and estimated radius of cellar area.

3.4.2 Drilling Module

The drilling module contains information about the drilling activity and the casing configuration of a well (Fig. 3).

DRILLJOB table contains drilling ID, well ID, name of well, type of drilling activity, date of start and finish of drilling activity, final depth of drilling, name of rig used for the activity, reason for activity, and distance from rotary table to wellhead.

CASING table contains casing ID, ID of drill job, well ID, sonic log ID, date of start and finish of setting of casing, type of casing, outer diameter of casing or slotted liner, inner diameter of casing or slotted liner, top of casing, and bottom of casing.

3.4.3 Well Module

The Well module has information about the wellhead coordinates, well track coordinates, results of well tests and stimulation activities done on a well (Fig. 3).

WELL table contains ID of well and pad record where well belongs, nickname of well, easting (x), northing (y), and elevation (z) wellhead coordinates. Well coordinates are based on National Mapping and Resource Information Authority (NAMRIA) maps with a scale of 1:50,000 and use the Clarke 1866 spheroid and Transverse Mercator projection as coordinates (Los Banos *pers. comm.*, 2003). WELL is a central table to which all other tables are linked. Several views can be created to link WELL with tables describing location to speed up searches for a well by pad, sector, or project.

COMPLETION table contains the interpreted results of a well completion test. A well completion includes several tests like waterloss, injectivity, and pressure transients. COMPLETION stores the ID of the completion test and well, date of start and finish of well tests, injectivity index of well computed from injectivity tests, depth of setting of the pressure tool during injection test, maximum wellhead pressure during injection test, computed permeability thickness and skin, and name of person who analyzed the data.

DS table contains results of directional surveys. DS is widely used in mapping applications when projections of well track of deviated wells are made on different surfaces and cross-sections. Entities in this table include the ID of the well where the survey was done, measured length along the casing and vertical depth where a directional survey point was taken, easting (x) and northing (y) coordinates of the point where the survey is taken, dogleg severity, names of encoder or personnel who made changes to the record, and dates when record was inputted or changed.

PZ table includes permeable zones of a well interpreted from temperature, and in some cases, spinner logs. PZ contains the ID of the well where the log was done, completion ID when the permeable zone is identified from a log during well completion, interval of permeable zones, rough classification of the permeable zone as major or minor, data source such as logs performed to identify a permeable zone or a wellbore simulation, and author of interpretation.

WELLSTIM table covers parameters measured when a well is initiated to discharge by air compression. WELLSTIM contains the ID of well stimulation activity, the ID of the well being discharged, the type of equipment used to discharge the well, date of start and finish of well activity, total hours of operation, maximum pressure reached during compression, volume of fuel consumed by equipment, names of engineers and operators who carried out the project, and comments on how to improve the next discharge stimulation activity.

3.4.4 Production Module

The Production module contains tables that describe the production history of wells, utilization of production and reinjection wells, and measurements of well output (Fig. 3).

WELLUSE table contains the ID record of well utilization, present use of the well (e.g. used for production, reinjection, or monitoring), status of the well (e.g. shut, in use for power plant, flowing, on bleed off), date and time of start of utilization, and wellhead pressure while being used.

BOM table or bore output measurement table contains ID of bore output records and well, date of start of output measurement test, wellhead condition, computed enthalpy, water flow, mass flow, steam flow, and power output, and a flag for stable outputs that can be used for generating bore output curves.

3.4.5 Logging Module

Logs give information on well performance and design. This information is necessary during drilling to avoid anticipated drilling difficulties, and to estimate success. Logs give information on structure, physical properties and performance penetrated by wells (Stefansson and Steingrímsson, 1980).

The Logs module contains information about geophysical logs such as temperature, pressure, spinner, sonic, calliper, blockage detection, and flow. The Logs module also contains a description of the tools used for logging, results of calibration performed on a tool to keep it accurate, and records of repairs done on tools. The modules for logging are designed to allow tracking the number of times a tool has been used and the wells where it has been used. This feature is very important in tracing all the wells logged by a tool that is giving wrong readings due to an off-calibration (Fig. 3).

LOGF table contains the ID of the log and well, the condition of the well while it is being logged (e.g. shut, flowing, on-bleed), tool used for logging well, date of start and finish of logging activity, shift value to correct for errors in zeroing to the reference point during logging, direction of log (e.g. log is made going up, going down or stationary), and names of loggers.

DDATA table contains logging data against depth. Data from moving logs of temperature, pressure, and spinner against depth are stored in this table.

TDATA table includes logging data against time or time series data. Data from stationary logs of pressure like those performed during multi-rate injection and pressure transient tests are stored in this table.

TOOL table contains the ID of the tool, name of the tool, kind of tool (e.g. temperature, pressure, spinner, flow meter, neutron, gamma, resistivity, X-Y calliper, casing inspection or multifinger calliper), brand or manufacturer of the tool, and general description of the tool.

BLOCKAGES table contains records of all blockages detected during a Go-devil, lead impression block, and sinker bar survey. BLOCKAGES contains the ID of the log, date of the log, outside diameter of the tool used, and depth where the blockage is detected. This table can be a part of the LOG table.

CBL table contains data on cement bond logs. CBL includes the ID of the log, the casing interval where CBL is performed, and the quality of cement bond or percent bond index. This table can also be a part of the LOG table.

PATSPLOTS table contains previous plots of logs performed on wells in HTML format.

CALIBRATE, REPAIRS and **DEFLECT** tables contain information about calibration of tools, equations used in the calibration of tools, and details of repairs done on tools.

3.4.6 Equations Module

The Equations module contains interpreted stable formation temperature and pressure from downhole logs and polynomial equations describing the stable profiles. There is also a table describing the well tracks using polynomial equations. The equations module is mostly used for finding temperature and pressure of wells at different depths in the reservoir (Fig. 3).

STABLETEMP and **STABLEPRES** tables contain stable formation temperature and

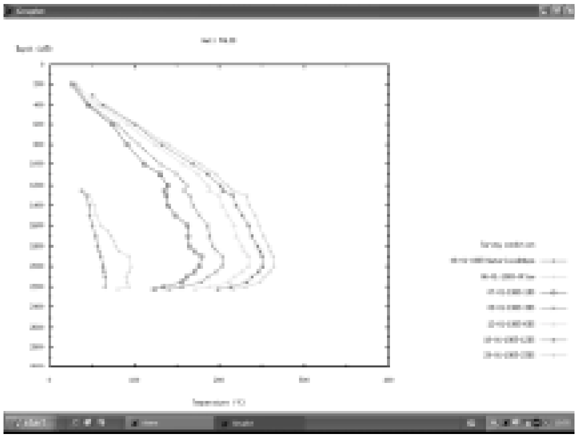

Figure 4. TPLOT showing temperature profile during heat-up of well PAL3D in the Bacon-Manito geothermal production field.

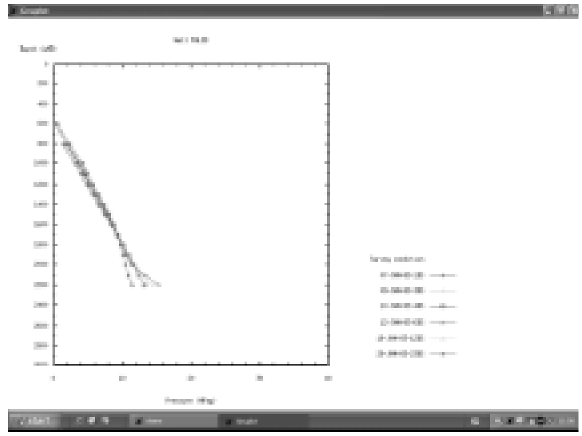

Figure 5. PPLOT showing pressure profiles of well PAL3D in the Bacon-Manito geothermal production field.

pressure. The table has interpreted stable formation temperatures and pressures, depth where measurements are taken, and the name of the person who made the interpretation.

STABLETEMPEQN and **STABLEPRESEQN** tables contain equations of the polynomial fit line to the interpreted stable formation temperature and pressure plots.

TRACKPOLY table contains polynomial equations describing the welltrack. The polynomial equations relate easting, northing, measured depth, and vertical depth to absolute depth. The table also stores the name of the person who created the polynomial fit.

4.0 DEVELOPMENT OF SIMPLE DATABASE APPLICATIONS

4.1 Development of Temperature and Pressure Program

Graphing modules **TPLOT** and **PPLOT** are developed to give reservoir analysts a quick view of the plot of all available temperature and pressure data for all wells in the database. These modules display dynamic two-dimensional plots of temperature and pressure for any given well within a given time frame. Updated temperature and pressure data are readily seen on the graphs when the graphs are refreshed after the changes are made.

The **TPLOT** program is capable of extracting temperature data from the database and generating a plot of temperature against depth. The **PPLOT** program, on the other hand, can produce a plot of pressure against depth (Figs. 4 and 5).

The basic algorithm calls for a UNIX kornshell script to run an embedded SQL+ statement to retrieve temperature values against measured depth and spool it into an initial input file. The same kshell script contains an AWK string used to filter the initial input file and create a file in a format readable by plotting software. The kshell script automates the plotting program, which is in this case GNUPLOT, to generate a graph with the desired features.

TPLOT and **PPLOT** programs can display temperature and pressure logs taken at specified inclusive range of dates. The temperature logs taken at different dates are displayed in various line colours and symbols for distinction. The condition at the time when the log is taken is also displayed along side the data as a guide for analysis.

Both programs run under a UNIX environment. They can also be used on Windows platform provided there is an X-Window that emulates a UNIX environment. To run the program, the user is prompted to enter a well ID, and the range of the dates of the survey to generate the desired plots. The simple programs TPLOT and PPLOT can be very useful tools for analyzing downhole logs and in visualizing well behaviour.

4.2 Forms Development

Oracle Forms are used to create a graphic interface for retrieval, review and modification of data from the database. With these forms, the user does not need to learn how to use the SQL+ language to retrieve, update, and save changes to the database. One or more tables can be used to create Oracle Forms as the design and contents of Oracle Forms can be customized depending on the data requirements of the user (Lakshman, 2000).

Oracle Forms designer is run from the Strokkur server through an X-Windows terminal emulating the UNIX environment. The command **f60desm**, which stands for Forms 6.0 design mode, is issued to invoke Oracle Forms Designer. Several tools are available for forms development under Forms Designer, such as the layout editor and property palette

A form can be designed to view or update any table or view in the database. The form shown in Figure 6 can be used to search for interpreted stable temperature for any well in the database and the polynomial equations describing these temperature and pressure profiles.

The coefficients for these polynomial equations can be changed using this form when there are new interpretations. The author of the new interpretation will be recorded and a flag can be used to group these polynomial equations according to the model being developed by the author.

To run these forms, the command **f60runm <name of file>**, is issued to invoke the forms run mode. At the moment, these forms are run under the UNIX environment, but they can be viewed like a web page under the web-enabled database version with the corresponding http server.

4.3 Development of Time Series Plots

A module for graphing data in time series is developed to give the reservoir analyst a quick view of the bore output measurements with time. This program called **TSERIES** has the option of displaying wellhead pressure, massflow, and enthalpy trends of all production wells in the database that have bore output measurements. To create the TSERIES module, UNIX shell scripting and GNUPLOT are used.

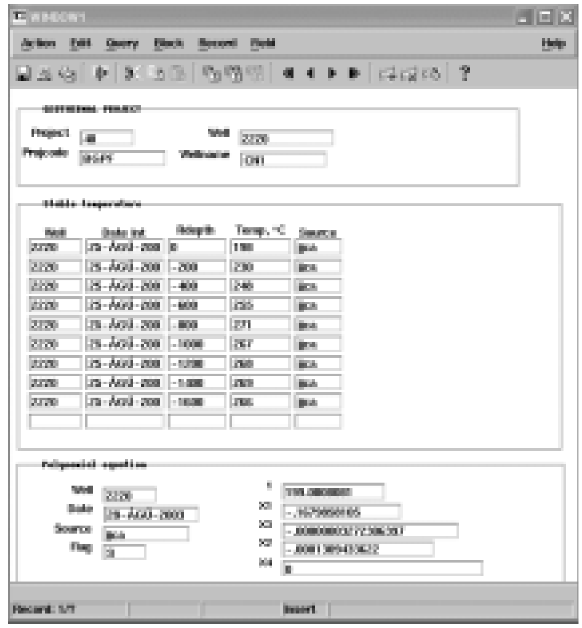

Figure 6. A form that displays interpreted stable well temperature and polynomial equations describing stable profile.

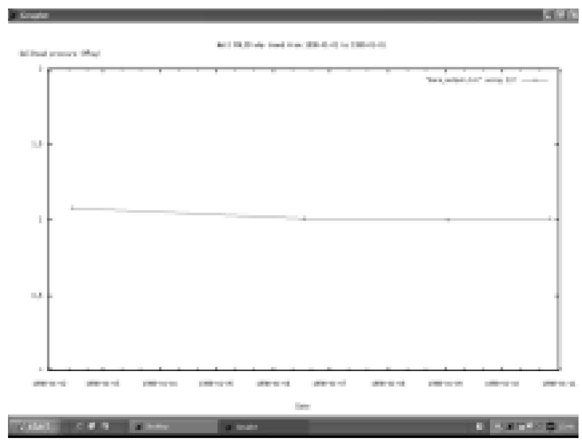

Figure 7. Wellhead pressure trend of well PAL3D in the Bacon-Manito geothermal production field.

The program provides a menu from which the user can select the well output parameter the user wants to view. Depending on the parameter chosen by the user, the UNIX script extracts wellhead pressure, massflow, or enthalpy data from a BOM table from the database and generates an input file called bore_output.lst. GNUPLOT is then automated to plot the bore_output.lst file using a time format axis. Bore output data is plotted on the y-axis while the date of measurement is plotted on the x-axis. Shown in Figure 7 is the wellhead pressure trend with time of a well in Bacon-Manito geothermal production field.

Time series plots are very useful for monitoring individual well output. Monitoring of individual well extraction through periodic output measurement and well utilization monitoring provides useful data on well performance. Close monitoring of well performance is necessary to ensure a steady supply of steam for the power plant. Corrective measures, like drillout of blockage and/ or acidizing, can be undertaken on wells with declining output to clean the feed zones by removing mineral deposition. Well output monitoring is used also to identify wells suffering from drawdown or to indicate reservoir changes like cooling due to pressure changes or due to inflow of natural recharge or injection returns (Sarmiento, 2000).

4.4 Development of Contouring Application

A contour map is a two-dimensional representation of three-dimensional data. The first two dimensions are the XY coordinates, and the third dimension (Z) is represented by lines of equal value. The relative spacing of contour lines indicates the relative slope of the surface. The area between two contour lines contains only grid nodes having Z values within the limits defined by the two enclosing contours. The difference between two contour lines is defined as the contour interval.

Temperature and pressure contours provide an important picture of the temperature and pressure distribution at different levels of the reservoir. From contours, a general pattern of flow can be inferred and used in assigning the heat source and the outflow crop in the reservoir.

Plots of temperature and pressure are analyzed to estimate the stable formation temperature and pressure. Relevant portions of temperature and pressure surveys are chosen to give a best approximation of formation temperature into an estimated temperature profile, which is plotted against elevation. Temperature and pressure points selected by reservoir engineers to establish a stable well profile is inputted to the Oracle database.

The polynomial equations describing these stable temperature and pressure profiles are also loaded into the Oracle database. Polynomial equations are used to allow interpolation between points of the log where there is no data. Such is the case when a mechanical gauge is used for logging, resulting in gaps in the logged depths. Polynomial equations for stable temperature and pressure, in conjunction with polynomial equations describing the track of vertical and deviated wells are used to obtain welltrack coordinates and temperature and pressure values at any given depth. In turn, these estimated stable temperature and pressure values are used to generate contours.

A simple contouring program called **CONTOUR** was developed to retrieve data from the database and generate dynamic contour plots. The program basically has two major parts: data retrieval and data display. The first part is an embedded SQL+ script in UNIX that is used to select welltrack coordinates, temperature, and pressure values for any project location at any depth of interest from the table of polynomial equations and generate an input file named xyztemp. The second part is a GMT manipulation kshell script that is used to generate contours. The kshell script looks for the input file xyztemp, grids the input file, and contours the gridded file. The script also sets the color scheme, puts the name of the wells and the values of prominent contour lines.

The program **CONTOUR** can create temperature and pressure distribution for any project location at any given depth. The **CONTOUR** program can display dynamic data. Any changes made on the data using the forms editor or SQL+ commands are automatically reflected in the contour plots. The program is very scalable, in the sense that, any reservoir parameter can be contoured by updating the *Select statement* in the program code to select other reservoir parameters.

The program **CONTOUR** is used to create temperature contours at different elevations for the Bacon-Manito geothermal production field. These contours can be improved further by masking areas where there are no wells and therefore no temperature data, and by including the complete tracks of wells instead of only the point in the track of the well at the given elevation (Fig. 8).

4.5 Scripts to Generate Data File for Vertical Slice

After creating surface contours, temperature of the wells at different elevations can be used to

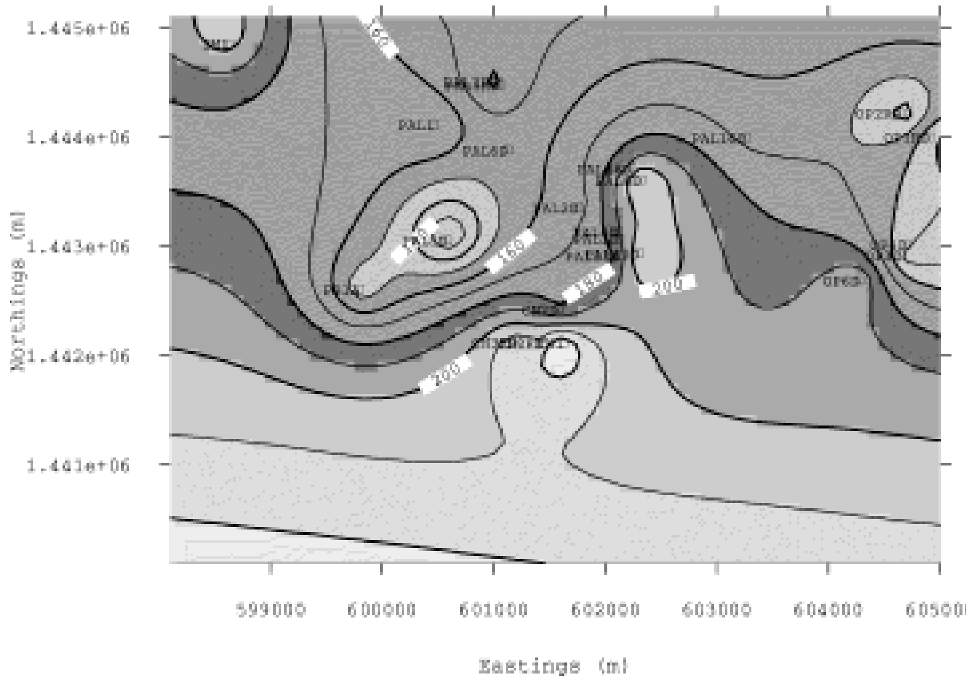

Figure 8. Temperature contour of the Bacon-Manito geothermal production field at 200 m b.s.l.

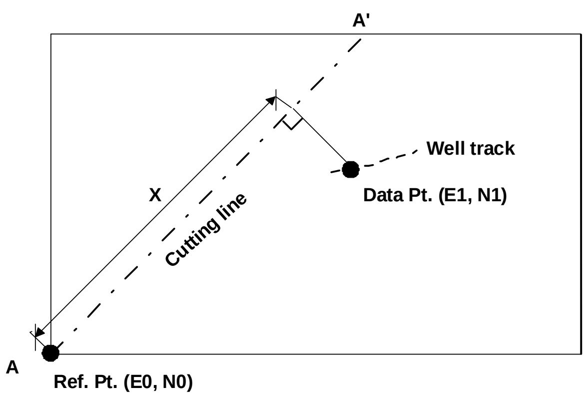

Figure 9. Surface map

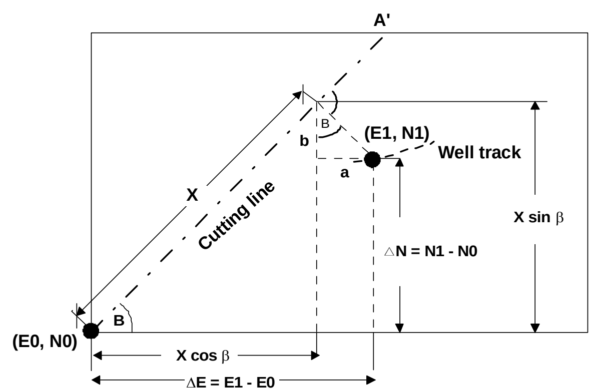

Figure 10. Solution by triangulation

create vertical sections. Temperature and pressure can be projected at a given cross sectional cut to generate a vertical section. A SQL+ script is written to select the data points to plot well tracks and contours in a vertical slice. The same SQL+ script used in program CONTOUR is used to get easting, northing, and temperature data. Then a simple triangulation procedure is used to project these data points to a cutting plane from a reference point (Figs. 9 and 10). Vertical cross-sections of temperature and pressure are very useful in analyzing the fluid movement in the reservoir and in making a conceptual model of the reservoir. Figure 11 shows how a vertical section is used to visualize the direction of fluid flow in the reservoir.

4.6 Mesh Creation for Numerical Simulation

Modelling constitutes the most powerful tool available to the reservoir engineer, and is applied to various management purposes. Modelling needs lots of data and in this regard, mathematical models are developed on the basis of the historical data stored in the Oracle database and data visualization tools. Through modelling, the nature and properties of the system can be estimated and its behaviour understood.

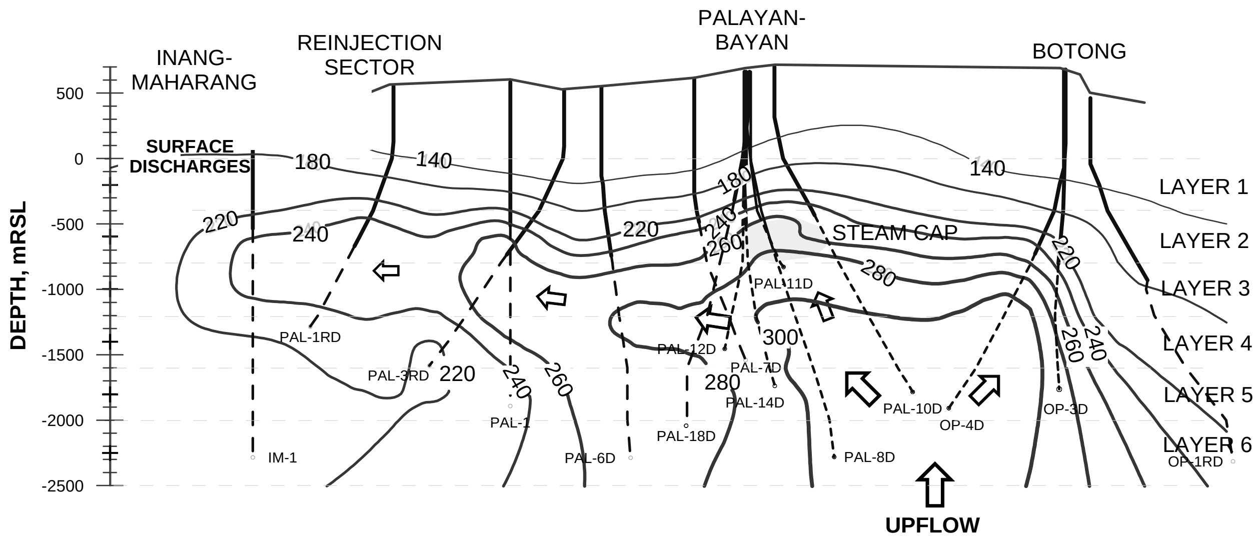

Figure 11. Bacon-Manito geothermal production field vertical section showing temperature contours, welltracks, upflow and outflow areas, grid layers, and centers of layers for numerical simulation.

The mesh grid shown in Figure 12 is produced using Grapher and a simple macro written in Excel to draw the grid lines. The mesh grid shows the model layer from 1.2 km. to 1.6 km. below sea level. It contains well tracks, coordinates of the well track at this elevation, and the grid blocks. Block properties for the input deck are stored in tables in the Oracle database. These include properties of the reservoir rocks and model volume, geometry, and boundary conditions, which were interpreted using data collected over time from surface exploration, exploration drilling, logging, and well testing.

5.0 CONCLUSIONS

Database tables were normalized during the development process with the objective of separating original data from derived data, and including author of interpretations and accuracy of measurements. The improved design used strictly ID numbers as primary keys to relate attributes from different tables. A number of simple database applications for data visualization using data dynamically from the database were developed. These database applications include:

- **TPLOT** and **PPLOT** programs for generating dynamic X-Y plots of temperature and pressure against depth;
- **CONTOUR** program for generating dynamic temperature and pressure contours at different elevations;
- **TSERIES** program for monitoring wellhead pressure, massflow, and enthalpy trends of individual wells;
- Algorithms for projecting temperature, pressure, and well track to a given cross-sectional cut which are used to generate vertical sections;
- Simple Excel macro program to create a mesh for numerical modelling.

Oracle Developer forms for viewing welltest, temperature, and pressure data were created for graphical retrieval, review, and modification of data from the database. With these forms, the user does not need to learn how to use SQL+ programming language to retrieve, update, and save changes to the database.

The data visualization programs that were developed are very scalable. The embedded SQL+ statement in these programs can be easily modified for visualization of other reservoir data of interest. Generic mapping packages like GNUPLOT and GMT were used in the program to minimize the amount of code development.

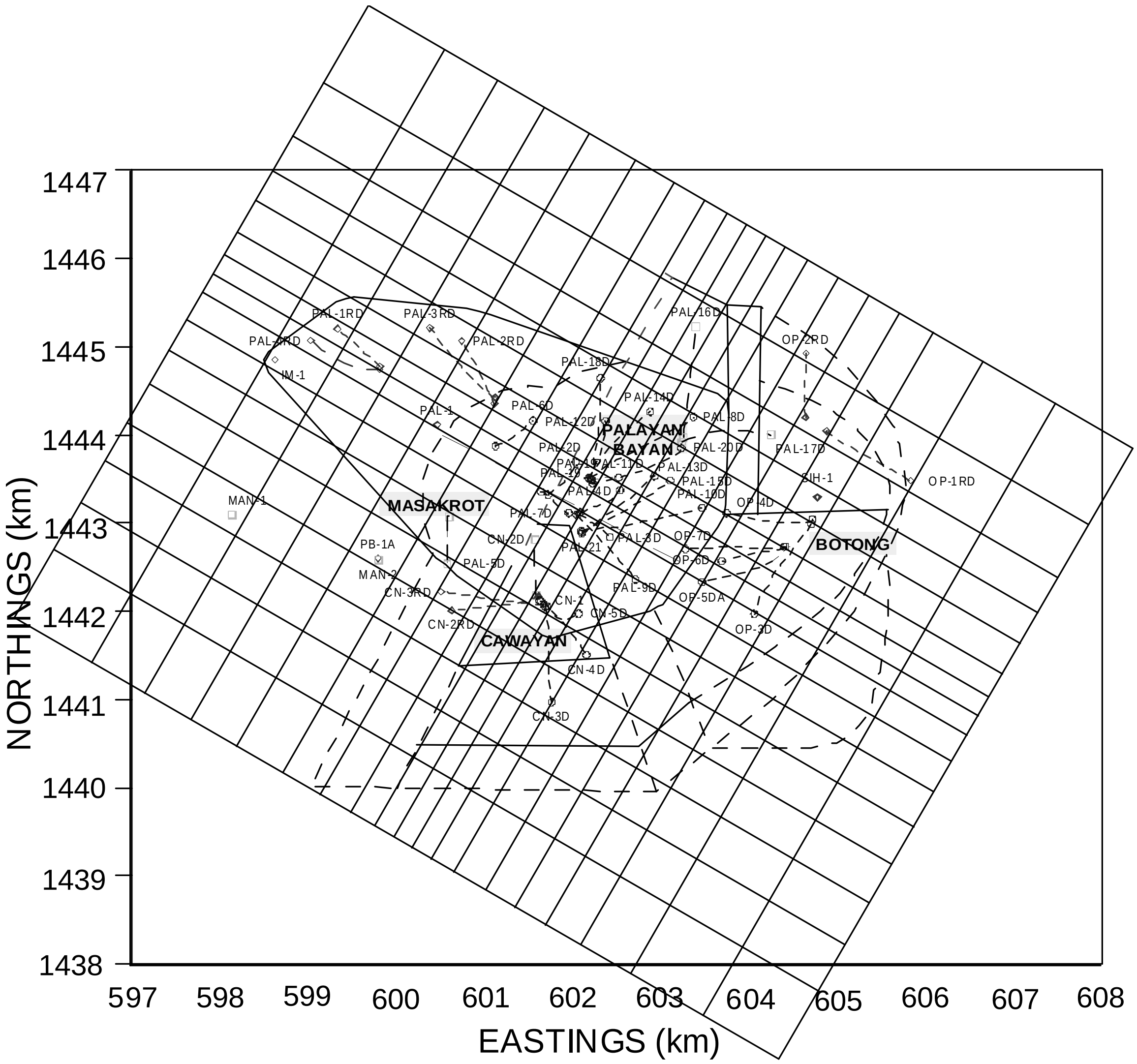

Figure 12. Bacon-Manito geothermal production field plan map showing welltracks and grid blocks for numerical simulation.

The database system and applications developed to retrieve data blocks from the Oracle database to create dynamic line graphs and contour planes, Developer forms, and projection algorithms from within a UNIX shell script, are very useful tools in providing a basic graphic representation of the reservoir. With the database system and visualization tools, the interpretation time during data analysis can be increased by reducing wasted time spent in looking for, loading, and editing data.

This project focused on the development of the database and database applications for data visualizations. The next phase will focus on the integration of data visualization modules developed in this project to the existing reservoir engineering database of PNOC-EDC; the linkage of reservoir engineering database with other geothermal databases to obtain a more comprehensive collection of data for model conceptualization; and the development of more graphical visualization tools possibly for the Windows platform.

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