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DEVELOPMENT OF A GEOTHERMAL DATABASE AND RESOURCE ASSESSMENT OF MT. NATIB GEOTHERMAL PROSPECT, PHILIPPINES

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ABSTRACT

A geothermal database mainly storing information gathered from geothermal wells was created using Microsoft ACCESS. To make the database user friendly, a menu-driven navigation was included in the design. It is envisioned that the database will be expanded in the future to include other information derived from geothermal exploration, development and exploitation.

Review and analyses of existing exploration data from Mt. Natib geothermal prospect reveals that it has very low potential for electricity generation. According to Monte Carlo volumetric assessment, the field can only supply the steam requirement of 10 to 15 MW_e power plant for twenty years. However, with the high temperature (>260°C) intercepted by the exploratory wells, the area warrants additional exploration to possibly identify areas of higher permeabilities.

1. INTRODUCTION

As part of the United Nations University (UNU) Geothermal Training Programme, the Fellows are required to write a report presenting the results of their research work while on training. This report is the fulfilment of such requirement which deals with the development of a geothermal database and resource assessment of Mt. Natib geothermal prospect, Philippines.

The author is employed by the Philippines' Department Of Energy (DOE). Among others, the DOE is the government agency mandated to administer the overall programme for exploration and development of indigenous energy resources including oil, natural gas, coal, geothermal and small-hydro power. Parties who want to engage in the above said activities must enter into a service contract agreement with the government through the DOE. One of the service contractor obligations is to provide the Department with geological, geophysical and other information resulting from their operations. Aside from this information the Geothermal Division of DOE's Energy Resource Development Bureau also generates exploration data by conducting geoscientific investigation on various geothermal prospects in the country. To date DOE manages voluminous amounts of data derived from geothermal operations since the start of exploration in the early 1970's.

In recognition to the importance of a computerized database the author decided to undertake a project study on the development of a geothermal database suitable to DOE's functions. It is anticipated that the result of this work will be used to start the systematic computerization of existing and incoming data derived from exploration, development and exploitation of geothermal resources in the Philippines. It should not be overlooked that a comprehensive database for DOE can only be made by an experienced system analyst. The experience and expertise of Orkustofnun, the National Energy Authority of Iceland in developing and maintaining a comprehensive geothermal database management system has undeniably helped the author in this endeavour.

Philippine National Oil Company-Energy Development Corporation (PNOC-EDC), a government owned and controlled corporation conducted the exploration of Mt. Natib geothermal prospect. Exploration works in the area led to the drilling of two exploratory wells in 1989. Both wells intercepted high temperatures (>260°C) at depth but with relatively poor permeability. Attempts to discharge the wells by stimulation were unsuccessful. This study tries to evaluate the resource potential of Mt. Natib based on the exploration data made available to the author.

2. DEVELOPMENT OF GEOTHERMAL DATABASE

2.1 Rationale

The Philippines being situated in the so-called "circum-pacific belt of fire" was endowed by nature with abundant geothermal resources that are economically exploitable for electricity generation. Since the first commercial operation of a 3 MW_e pilot plant in Tongonan, Leyte in 1977, geothermal energy has proven to be a dependable source of clean and cheap energy. The Philippines remains the second largest world user of geothermal energy for electricity generation with a total installed capacity of 1114 MW_e as of September 1995 (Table 1).

TABLE 1: Geothermal power generation statistics (mod. after Huttrer, 1995)

Country	Installed capacity (MW_e)	
	1990	1995
USA	2775	2817
Philippines	888	1114
Mexico	700	753
Italy	545	632
Japan	215	414
Indonesia	145	310
New Zealand	283	286
El Salvador	95	105
Costa Rica	0	55
Iceland	45	49
Kenya	45	45

As energy self-reliance becomes a continuing objective of the government, development of the country's geothermal resources has always been a part of the power development programme. These apparently never ending explorations, development and exploitations of geothermal energy constitute the generation of large volume of data which is under the management of DOE. It is essential that a computerized database will be developed for the efficient storage and retrieval of this valuable information. An integrated computerized database will not only provide a coherent way of storing data but also give centralized control of all geothermal operational data. Among others, a centralized controlled data is standardized and can be shared with minimum amount of redundancy and inconsistency. Aside from the data management function, DOE also supervises the management of the resource. The department sees to it that geothermal service contractors do not over-exploit the resource. It is viewed that this resource is renewable and that sustainable development can be realized through judicious and efficient management of the resource (Geothermal Division, 1995). Maximum benefit from its utilization can be achieved not only for the company but also for the country as a whole. A database can be of help in the fulfilment of this objective through the provision of quick, accurate and reliable information.

2.2 Scope of study

In general a database is an integrated collection of stored data where data and/or combinations of data can be stored, retrieved, updated, added or deleted quite quickly and easily. A complete geothermal database can take several months or even years to be fully developed. A database system flow chart is presented in Figure 1. As to what the time permits, it has been decided that the database to be designed should at least manage to store most of the information gathered from geothermal wells. In anticipation that other information may later on be added, the database was designed to have the flexibility to incorporate additional tables. At its present form it can accept data resulting from drilling, production, injection, well logging, analyses of water from well discharges, downhole or surface spring samples and specific locations of any mappable geothermal features such as wells, hot/warm springs, resistivity soundings, gravity and/or magnetic stations, etc.

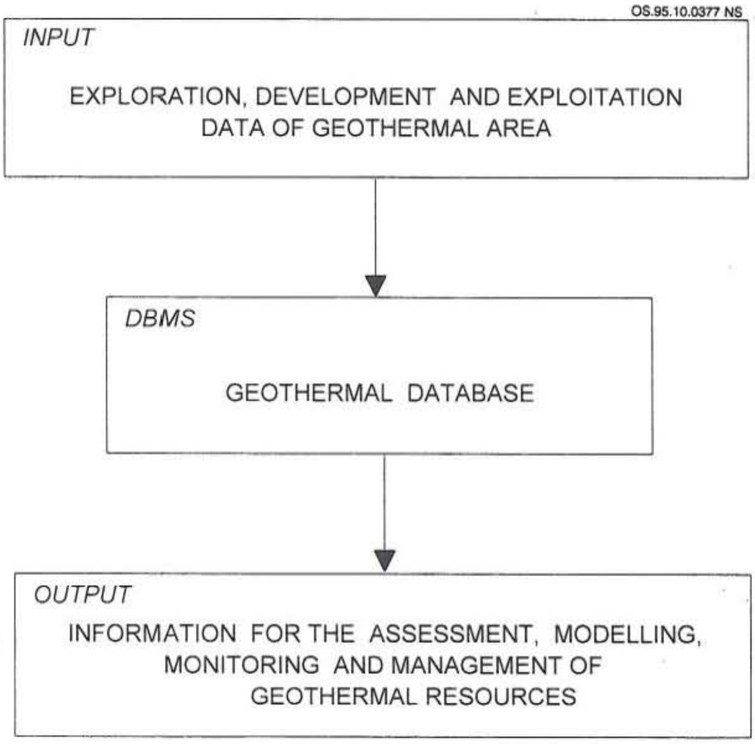

FIGURE 1: Database system flow chart

2.3 Selecting the appropriate database management system

Today, a number of the so-called relational database management systems (RDMS) has been made available on the market by the ever-advancing computer technology. Choosing the appropriate system may not be difficult as it largely depends on the available hardware as well as on the objective of the database. Future hardware upgrading should also be considered in the selection. Considering the above parameters it is believed that Microsoft ACCESS database system can easily and efficiently handle the envisioned geothermal database.

Microsoft Access (1994a; 1994b; 1994c) is a window based interactive relational database management system that also works in a multi-user environment. It runs on IBM or IBM compatible personal computers with 80386 or higher processors with random access memory (RAM) of at least 6 megabytes (MB). It requires 17 MB hard disk space for typical installation, however, 5 MB space is sufficient to use the system. Since Microsoft ACCESS is a window based software package, mouse, EGA or VGA monitor and MS-DOS 3.1 or higher are needed.

Microsoft ACCESS can import data from any database format and application of PARADOX 3.x and 4.x, Microsoft FOXPRO 2.0 and 2.5, DBASE III, DBASE IV, BTRIEVE (with data define files FILE.DDF and FIELD.DDF), SQL databases (including Microsoft SQL server, Sybase SQL server and Oracle server) and Microsoft ACCESS databases other than the open database. It can export and import data from spreadsheet (Microsoft EXCEL and LOTUS 123) and Text files (delimited and fixed-width).

2.4 Designing and creating the database

Hursch and Hursch (1987) and Microsoft Access User's guide (1994b) offer a comprehensive guide in designing a database. Generally those recommendations were observed in the design. Test runs were made to ensure that the database will work according to what it was intended for, to provide quick, accurate and reliable information. Available data from wells drilled in Mt. Natib, Mahanagdong geothermal area and production and injection data from operating geothermal fields were used to determine the information usually available from wells. Other information that was perceived to be necessary to be part of the database were also included.

2.4.1 Creating tables, forms and queries

As provided in the guidelines, information was grouped into separate subjects to form tables. A table is equivalent to a file in common computer terminology. It is called a table because relational database stores data in rows (records) and columns. Information that describe or characterize a specific subject were put together in a table. Grouping of information to construct a table is not as easy as it sounds. A good understanding of geothermal operations and computer programming concept is necessary. The tables were named according to how they best described their contents. The tables were created, field properties were defined and relationships among tables were set in accordance with the steps provided by Microsoft ACCESS manuals. A brief description of tables and fields is presented in Appendix I.

To uniquely identify each record, primary key(s) were selected. For easy identification of the key whenever possible it has the same name as the table. Figures 2 and 3 show the database structure where the table names are in bold and primary key(s) in bold italics. Primary keys may be comprised of several columns. This is to prevent any record from storing similar and/or inaccurate redundant information (e.g. a well at certain depth must have only one coordinate at that depth). The key is also used to relate or connect information from one table to another. Redundancy of data to be stored was also avoided by ensuring that no tables contain similar information. Rolland's (1991) recommendation to ensure that the values found in the intersection of row and column cannot be further subdivided into subsets was observed in the design.

As tables display data in a spreadsheet like view, forms were created to facilitate the viewing and editing of data per record. Forms is a versatile object that can display data the way the user likes. Macro and command buttons were used to customize the forms. Through the command button available in any given form, related information stored in other tables/forms can be obtained.

Sample queries were devised to test whether the created database can provide the required information. ACCESS has a special query window which is the graphical query-by-example (QBE) tool. Because of its graphical feature a mouse can be used to select, drag and otherwise manipulate objects in the window to specify the fields and records to be displayed (Microsoft Access, 1994b). Tables with the desired information are selected and the field containing the data needed is dragged to the QBE grid one by one to complete the query. A complicated query may require the writing of structured query language (SQL) statement specifying the tables and fields containing the information as well as the criteria to be satisfied by the information being sought (Van Der Lans, 1988).

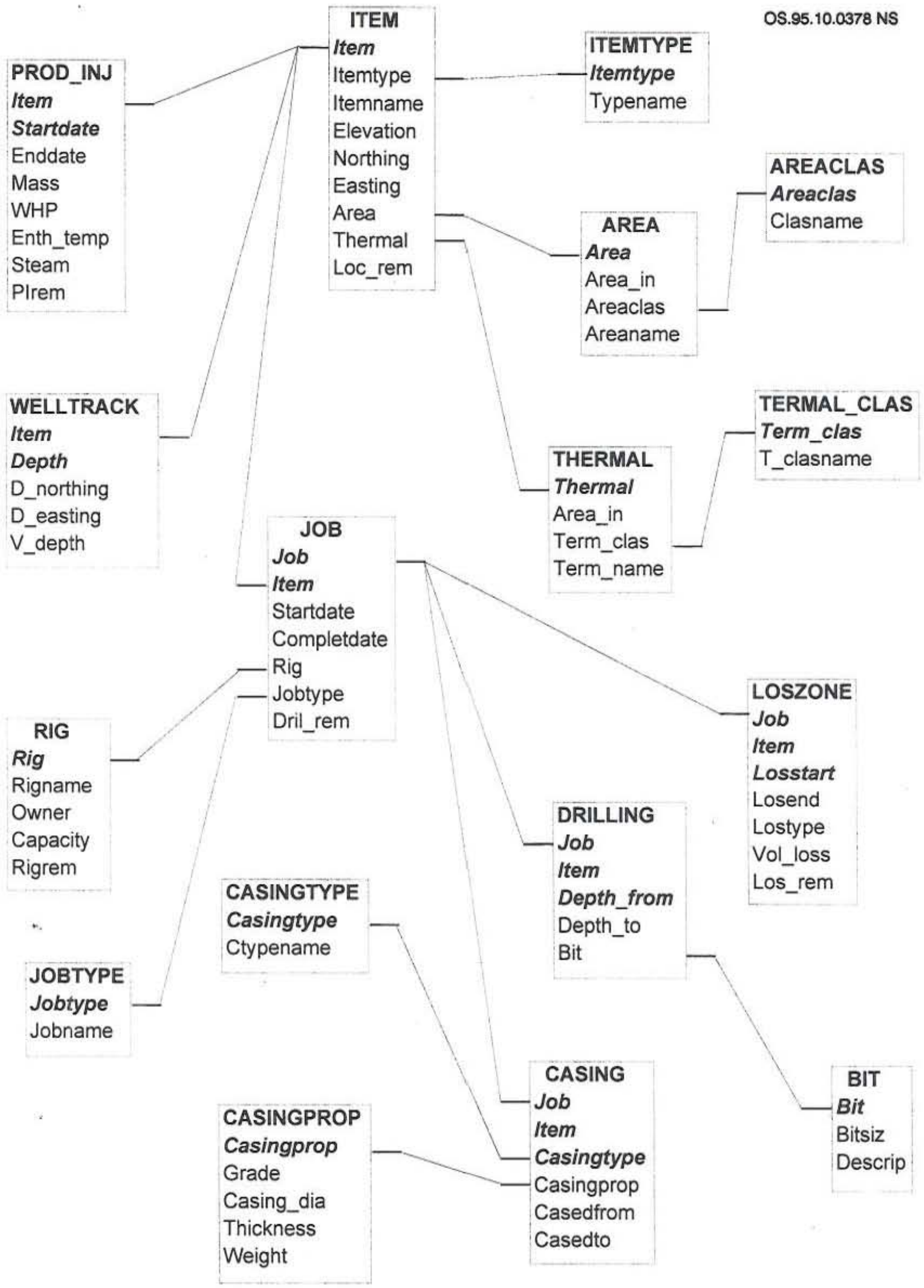

FIGURE 2: Database structure showing relationships between tables

2.4.2 Database navigational aid

Forms and command buttons responding to macro were used to create menus that will facilitate the guided use of the database. The menus were developed to organize, control and manage the addition, editing and viewing of records. Figures 4 and 5 display the sample menu and flow chart indicating the navigational route within the database, respectively. Below is a brief description of the menu:

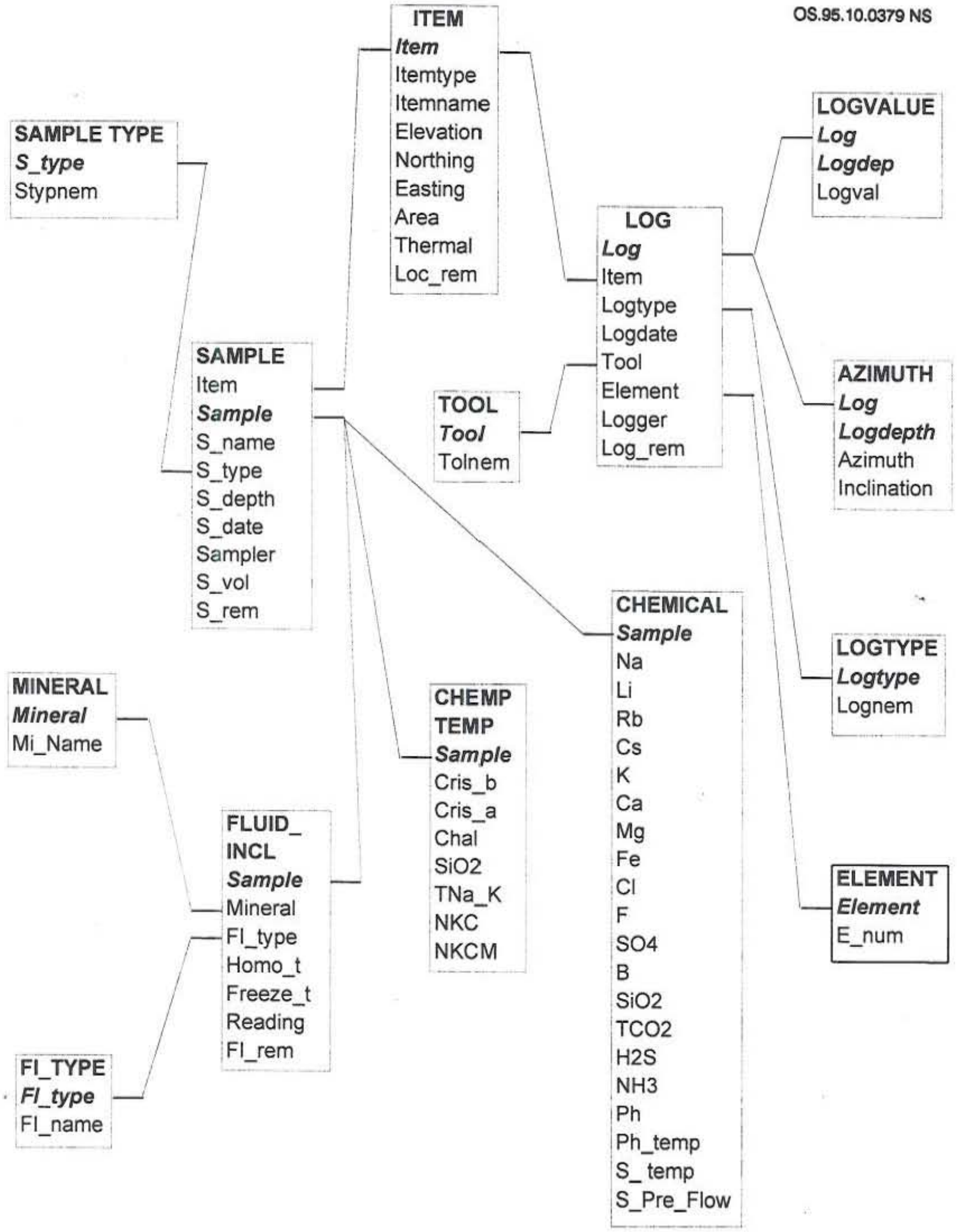

FIGURE 3: Database structure showing relationships between tables

Main Menu organizes and controls the navigation within the database. It provides access to all forms, queries, database windows or to quit ACCESS. The database window is a display in the screen layout when a database is open and hidden (at the back of the active menu) when the main menu is in use.

Forms (Main Forms) administers the general groupings of forms according to the stored information. This is the main gateway to the customized display of records of any specified table that allows addition, editing and deleting of records.

Query deals with the showing of ready made inquiries in spreadsheet view. Usually it is a combination

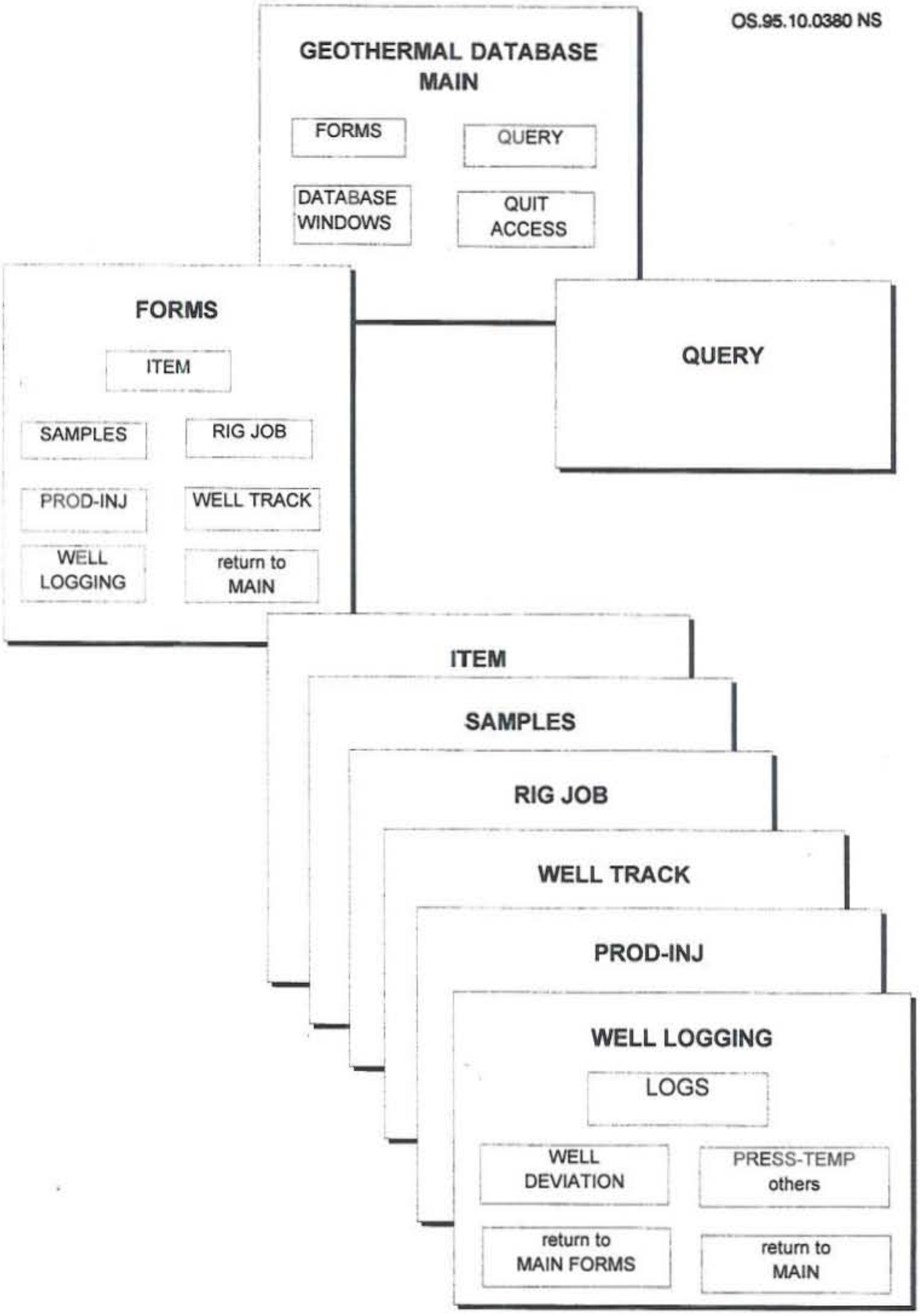

FIGURE 4: Sample menu within the database

of data from several tables.

Samples manages the forms that relate to the result of sample analyses particularly water chemistry, solute and fluid inclusion geothermometry.

Well logging controls the forms that hold well logging information on the well deviation, temperature, pressure and other logs.

Rig job handles drilling and other rig related statistics such as casings and bits with their corresponding sizes or weight.

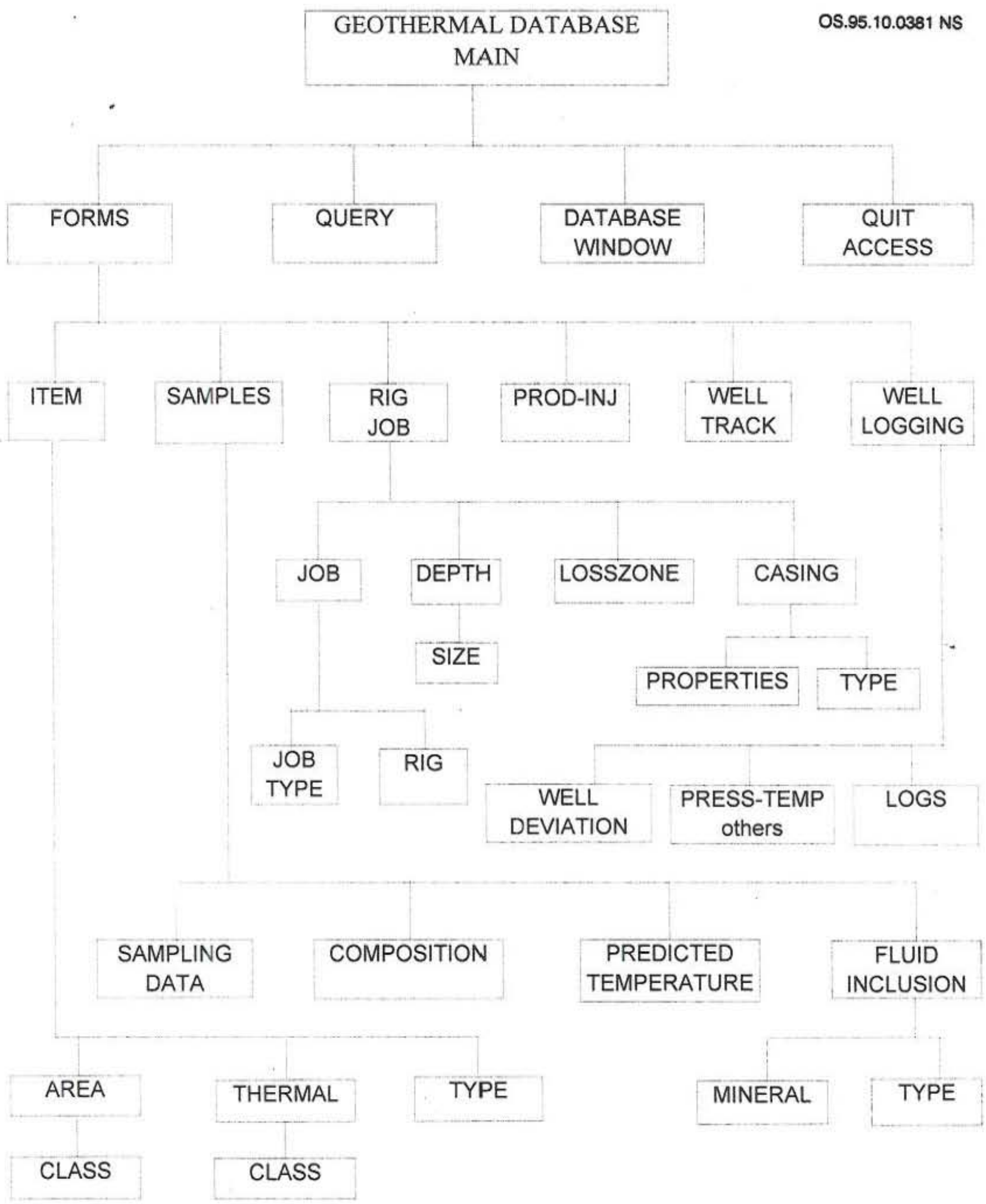

FIGURE 5: Database navigation guide

2.5 Using the database

As shown in Figures 2 and 3 the table "ITEM" is the focal point of the database. All data that will be stored must originate from this table except for tables that act as reference tables such as ITEMTYPE, AREA, THERMAL, BIT, CASINGPROP, RIG, etc. These tables contain fixed information that seldom needs updating. Examples of these are the size of bits, weight and size of casings, name of towns, provinces and geothermal fields, rigs used for drilling, tool and element used for logging. This is to say that a well can only be drilled by a rig that exists at the "RIG" table and be located in an area known to the database. Moreover the bit and casing used to drill and case the well must be present in their respective tables. Just like in well logging, the tool and element must be available before it can be used for the said purpose. These tables are sources of data and also validate the information being saved so that they should be accomplished first before putting any data resulting from geothermal operations.

The field "Item" is the key not only to the specific location of any geothermal entity/item as regards to barangay, town, province, etc. and thermal area (sector, field and reservation) but also to the other data contained in other tables. "Item" can be wells, hot springs, resistivity soundings, gravity or any other geophysical stations or features found in geothermal areas. These were already defined in the "ITEMTYPE" table.

The "JOB" table specifically handles the start and completion of a rig job and is connected with other tables that hold information related to rig activities. As the name implies the "LOG" and "SAMPLE" tables deal with statistics involving well logging and sampling activities, respectively.

There are several ways to open the geothermal database from the Microsoft ACCESS start up window. It can be opened either through the open database command from the file menu or open database button on the tool bar or by choosing the file if displayed at the bottom of the file menu.

Once the database has been opened, run the macro "MAIN" either from the File pull-down menu of ACCESS startup window or database window. The database main menu will be displayed and by a single click on the available options other menus will be displayed in lieu of the first screen layout.

Addition and editing of records can be done in the forms or tables as they are all in edit mode. Any record that is to be added should start at the item table or form. Closing of forms, tables or queries can be done through the control-menu box at the upper left corner of any particular window or through the close button (if available). At any given form, moving from record to record can be done by using the command button or scroll box.

3. RESOURCE ASSESSMENT OF MT. NATIB GEOTHERMAL PROSPECT

3.1 Background

The Mt. Natib geothermal prospect is a part of the 850 km^2 Natib-Mariveles geothermal prospect investigated by Philippine National Oil Company-Energy Development Corporation (PNOC-EDC) in the late 80's. It is located at the Bataan Peninsula, west-northwest of Manila (Figure 6). Presence of relatively impressive thermal manifestations and low resistivity anomaly led to the conduction of semi-detailed geoscientific investigations and the subsequent drilling of two exploratory wells (basic well information is presented in Appendix II). Below is a summary of the existing information of the area with emphasis on results significant for resource assessment.

Geology, structures and thermal manifestations

Mt. Natib is one of the andesitic strato volcanoes responsible for the widespread deposition of Late Pliocene to Pleistocene volcanic rocks in the Bataan Peninsula. On the basis of lithology and apparent age, Panem (1988) grouped the lithology into recent deposits and Natib volcanics. The Natib volcanics are subdivided into old, middle and young volcanics. The old Natib volcanics consist of basaltic and andesitic lavas intercalated with tuff and volcanic breccia, and interlayer volcanic breccia, tuff and laharic deposits. Pyroxene-hornblende andesite to hornblende andesite characterized the middle Natib volcanics. The young Natib volcanics are composed of hornblende andesite lava domes and weakly consolidated andesitic lithic tuff with fragments of basalt and pumice. Recent deposits include alluvial deposits, unconsolidated sedimentary rocks and andesitic laharic flows.

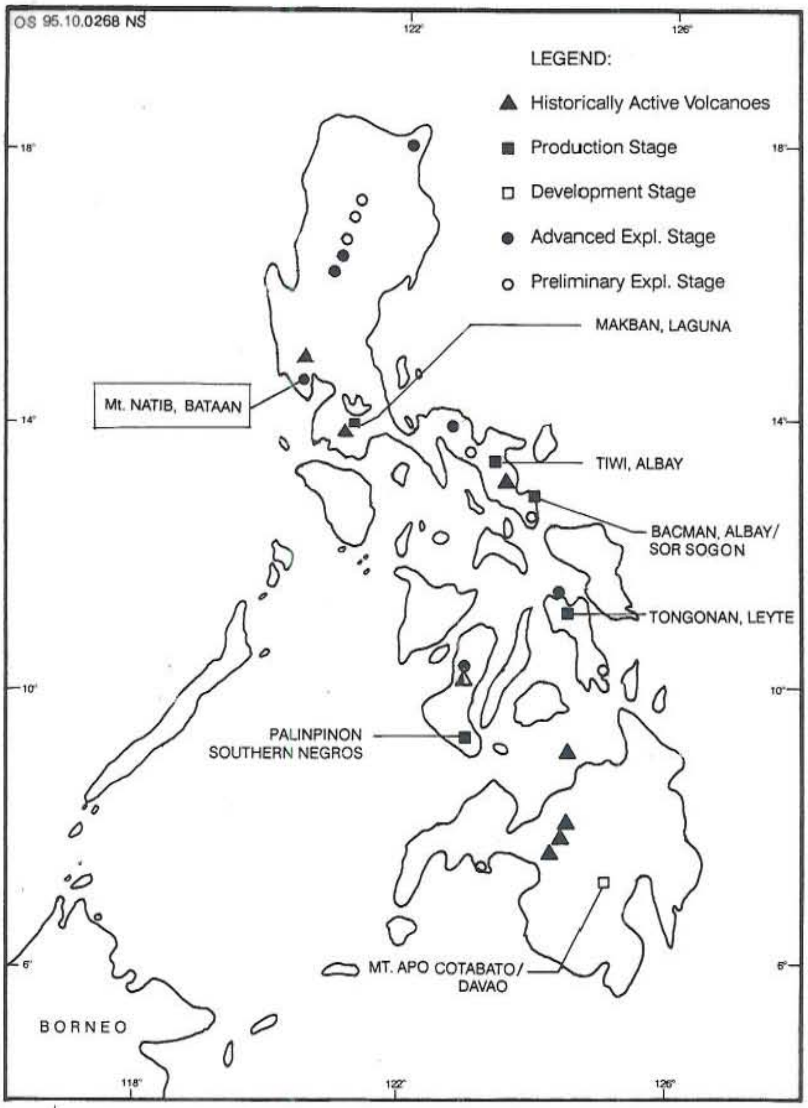

FIGURE 6: Location map of Mt. Natib geothermal prospect

Several structural features suggesting active volcanism through geologic time were found to exist in the area. The most conspicuous structural feature identified is the Natib caldera structure which is estimated to have an area of 38 km^2 (Figure 7). Several faults and lineaments mostly trending NW-SE and E-W with dominant dip slip movements were also recognized.

Thermal manifestations found in the area are limited to warm/hot springs and altered ground. The thermal springs exhibited low flow rate ($\leq$ 1 l/s) with neutral pH (7.5-8.0) were found to be associated with the NW-SE and E-W faults and confined within the caldera structure. Travertine and limonite were noted to be deposited around the springs.

Geochemistry and geophysical studies

Analyses of thermal water reveals that they are of the secondary neutral to slightly alkaline SO_4-HCO_3-Cl and HCO_3-Cl type. Silica and Na-K-Ca geothermometry predicts subsurface temperature of 168 and 189°C, respectively. On the other hand the Chloride -Enthalpy plots provide a relatively higher estimate of 210°C (PNOC-EDC, 1990).

Geophysical studies conducted are direct-current Schlumberger traversing (SRT) and vertical electrical soundings (VES). Figure 7 shows the apparent resistivity values at 500 m depth. The resistivity anomaly roughly follows the configuration of the Natib caldera structure.

Subsurface geology and downhole chemistry

The two directional wells, NA-1D and NA-2D intercepted rock formation mostly belonging to the Natib volcanics. Several quartz monzodiorite to diorite dikes were also encountered with the Bakyas intrusive complex being intercepted only by NA-2D. The drilled formation appears to be tight as no circulation losses were noted during drilling. The presence of gypsum associated with sphene and epidote suggest that the hydrothermal system has cooled down by as much as 130°C from the temperature indicated by epidote and sphene.

Silica geothermometry of downhole samples reveals an average temperature of 288 and 276°C for NA-1D and NA-2D, respectively (Mesquite Group Inc. et al., 1990). On several occasions while drilling between 2400 to 2780 mVD, gas kicks were experienced. Downhole samples reveal that this gas is CO_2. Chloride-enthalpy diagrams do not show apparent dilution or the possible relationship that is between surface springs and downhole samples (PNOC-EDC, 1990).

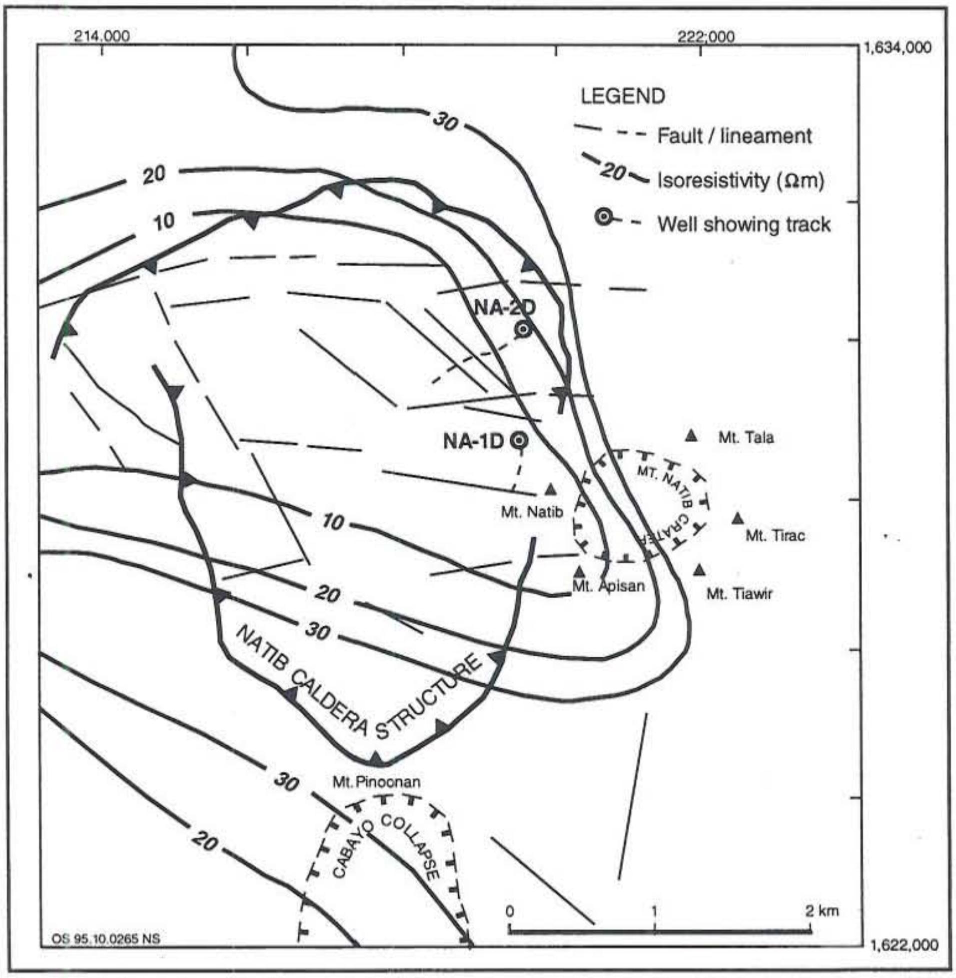

FIGURE 7: Mt. Natib tectonic lineaments and iso-resistivity contours at 500 m below surface (modified from PNOC-EDC, 1990)

3.2 Previous assessment

Following are the highlights of the post-drilling evaluation conducted by PNOC-EDC in 1990. Absence of outflow tongues in the resistivity anomaly pattern and low flows of thermal springs indicate that the area has low permeability. The thermal gradient ranges from 3 to 3.6 times normal. The postulated upflow zone where the wells were drilled does not exist. Alteration minerals and fluid inclusion studies suggest that limited amount of meteoric water may percolate down through faults. Drilling results such as low injectivity, very low transmissivitites, poor response to hydro-fracturing and inability to discharge despite stimulation have verified the limited permeabilities of the formation and structures intercepted by the wells. Considering the area blocked by the two wells a reserve of 170 MW_t energy for 25 years was estimated (PNOC-EDC, 1990). The area is not suitable to generate electricity in commercial scale.

A consultant team from Mesquite Group Inc., Harding Lawson Associates and Dames and Moore (1990) conducted a review on the assessment of Mt. Natib. Given the available data to date, they agree with PNOC's assessment, however they believed that since only a small portion of the prospect has been drilled, prospective drilling targets within and/or on the flank of the volcanic complex could still have high permeabilities and temperatures which can be developed for power generation. The team also suggests a hydrologic model wherein the volcanic highlands including the flanks are recharged areas and lateral flow paths of hot geothermal water may exist at depth beneath and on the flanks of the volcanic centre. Moreover, a major upflow or outflow zone is not necessarily essential requirements of an exploitable geothermal system (Mesquite Group Inc. et al., 1990)

3.3 Analyses of well completion test and heat-up surveys data

3.3.1 Types and objectives of completion test and heat-up surveys

To gain information on the physical properties that can characterize the reservoir several downhole measurements are usually conducted in newly drilled wells. Among others it includes water loss surveys, heat-up surveys, and pressure transient tests (injectivity and pressure fall-off). Hydro-fracturing operations and discharge stimulation of wells are also conducted whenever necessary.

Water loss surveys are employed to estimate the location of permeable zones. They are carried out by measuring the downhole temperature while pumping water at a constant rate. An increase in the temperature can be observed as the water gets lost in the formation (most likely in permeable zones).

Pressure transient test. Injectivity test and pressure fall-off test were used to assess the well permeability. The injectivity test is conducted by measuring the downhole pressure close to the best feedzone of the well at different pumping rates. The slope of the plot of injection rate versus pressure give injectivity index, a measure of the well over-all permeability. Pressure fall-off test is the continuation of the injectivity test conducted by monitoring the pressure response after stopping water injection (Sarmiento, 1993). From the data the transmissivity can be estimated by semi-log plot analysis. Semi-log analysis is based on the reservoir transient pressure responses that fall on a straight line when pressure versus time (log-scale) is plotted. Both the Horner or Miller-Dyes-Hutchinson (MDH) method were used in the study. In the semi-log plot the slope m is given by

$$m = 0.1832 \frac{q\mu}{kh} \quad ; \quad T = \frac{kh}{\mu} = 0.1832\, q \qquad (1)$$

where

m	= Slope of the semi-log straight line (Pa/cycle)
q	= Flow rate (m^3/s)
μ	= Dynamic viscosity (Pa s)
k	= Permeability (m^2)
h	= Reservoir thickness (m)
T	= Transmissivity (m^3/Pa s)

The start of the semi-log straight line was determined by using log-log plot (ΔP vs. time) and the rule of thumb described by Economides and Fehlberg (1979) as follows: In the absence of a fracture the start of the semi-log straight line is approximately 1.5 log cycles after the well bore effect which is reflected by a unit slope; In the presence of a fracture the "double ΔP" rule can be used which states that the semi-log straight line starts at a point where the pressure difference is twice ΔP at the deviation from the ½ slope. Horne (1995) stated that finite and infinite conductivity fracture has a straight line slope of 1/4 and ½, respectively in the log ΔP vs. log Δt plot. It should be noted that in well test analyses, the ambiguity of the data leads to several interpretations which must be compared with the results of other studies for consistency of interpretation.

Heat-up surveys (temperature and pressure) are conducted after the completion test. They are conducted to have an estimate on the stable formation temperature and pressure that has been substantially affected by cold fluids during drilling and completion test. As an example temperature profiles suggest location of permeable zone(s) as they either warm up more slowly than impermeable rocks or flow of hot water into the wellbore, resulting in a temperature peak or even internal flow. They may confirm or belie the zone(s) identified by the water loss survey. Moreover, it detects flow between aquifer and boiling as manifested by fairly constant temperature at depth and emulating the boiling point profile, respectively. Pressure surveys help to locate aquifers that accept/contribute fluid from/into the well and, furthermore, the depth of the best feedzone of the well by using the pivot-point concept. Plots of the measurements indicate the formation temperature and pressure recovery rate. Fast thermal recovery connote high permeability.

Formation temperature every 200 m was estimated by using the programme BERGHITI (Helgason, 1993), however, before using BERGHITI well measurement data were interpolated and organized as a function of time by employing the programme WELLTIME (Arason and Björnsson, 1994). A sample plot of temperature recovery data at 2200 mVD in well NA-1D is presented in Figure 8.

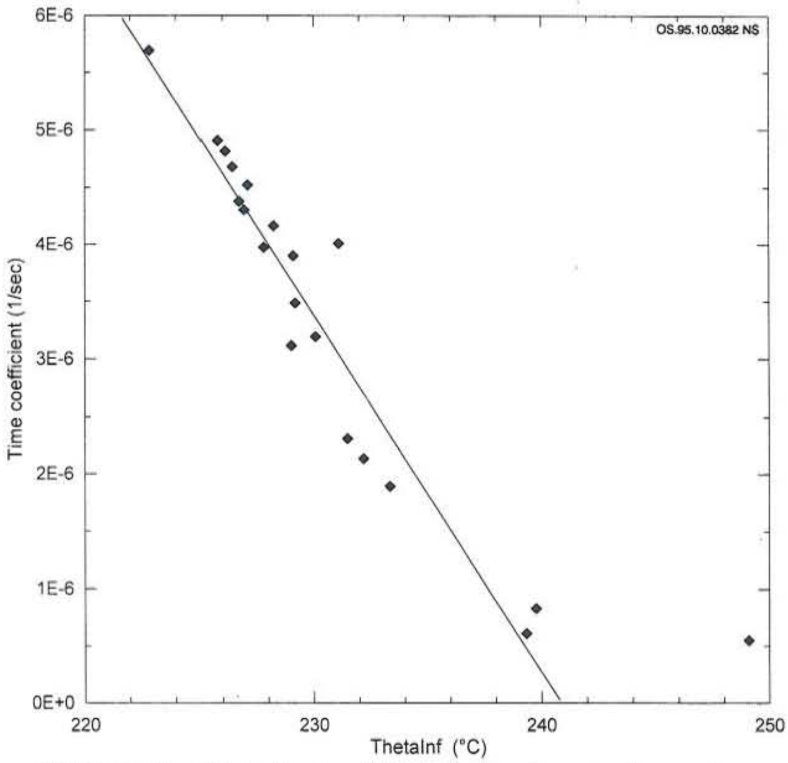

FIGURE 8: Plot of estimated formation temperature using Albright method of BERGHITI at 2200 mVD of NA-1D

3.3.2 Water loss and heat-up surveys

Well NA-1D. The water loss survey and heat up surveys indicate the possible existence of a permeable zone at 1800 to 1970 mVD. Figures 9 and 10 present the collected downhole pressure and temperature data. Generally the temperature profiles are a typical conductive heat type suggesting no or negligible permeability. The maximum temperature measured is 282°C at the bottom of the well. The temperatures at the production casing shoe (PCS) and bottom are estimated to rise up to 200 and 296°C, respectively. Based on the estimated formation temperature, average thermal gradient is about 96°C/km. The pivot point was not

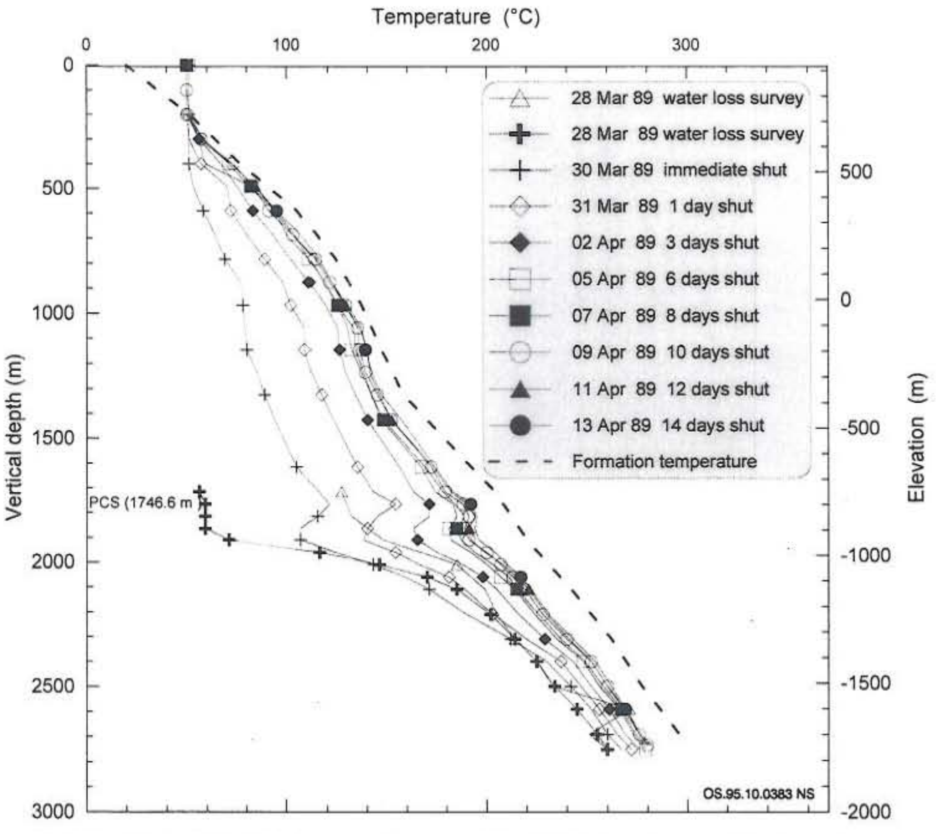

FIGURE 9: NA-1D temperature profile, PCS denotes production shoe

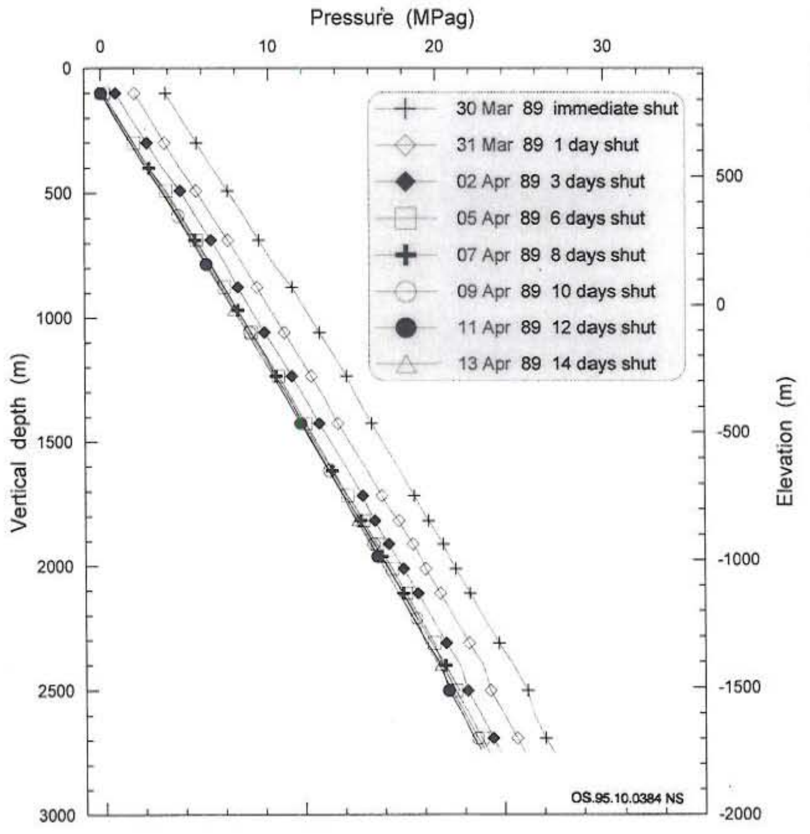

FIGURE 10: NA-1D pressure profiles

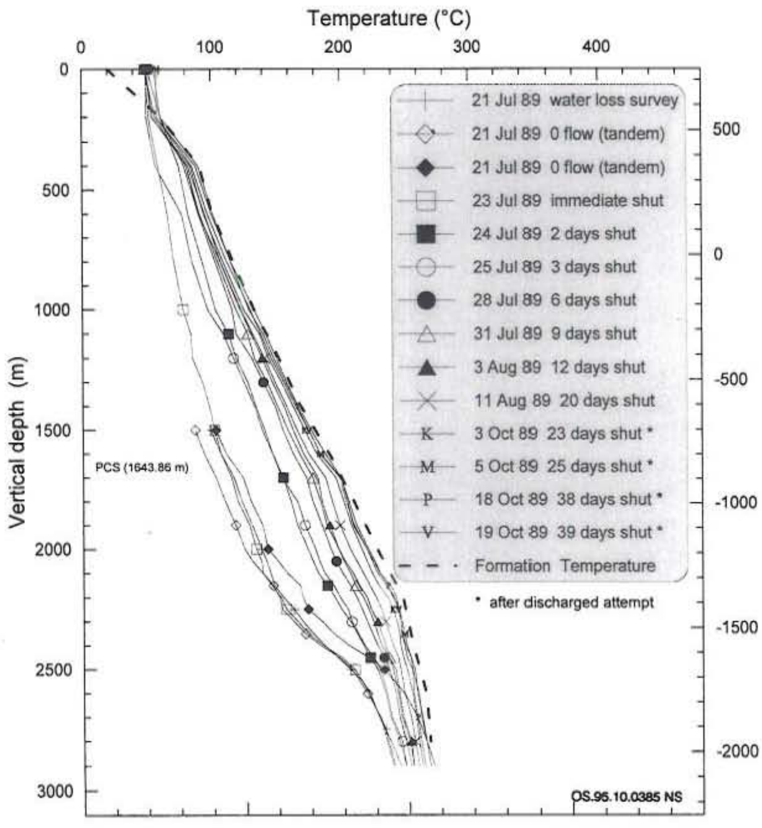

FIGURE 11: NA-2D temperature profiles, PCS denotes production casing shoe.

evident in the pressure data. The pressure profiles suggest low permeability as indicated by the apparently slow rate of stabilization after the completion test. The water level stabilized at 75 m below the casing head flange (CHF).

Well NA-2D. The temperature and pressure profiles collected in well NA-2D are shown in Figures 11 and 12. The water loss survey suggests a minor permeable zone at 2000 m, 2200 mVD and at the bottom, however heat-up surveys indicate a permeable zone only at the bottom. It is indicated by a convective profile below 2200 mVD. The maximum temperature measured is 269°C. Temperatures at PCS and bottom are estimated to reach about 195 and 269°C, respectively. An average thermal gradient of 96°C/km was implied by estimated formation temperature. The pivot point is not reflected by the pressure graph. The static water level is estimated to be at 300 m below CHF.

3.3.3 Injectivity test

Based on the best fit line on the injection rate versus pressure graphs in Figures 13 and 14, Table 2 presents the calculated injectivity index. The initial pressure was not always considered in determining the best fit line as downhole and well head pressure have been already affected by preceding injection activities. Both wells have low injectivity indices and exhibit positive well head pressure during the test. In an attempt to increase the permeability of the wells hydro-fracturing operation was conducted. It may have improved the permeability (higher injectivity index after hydro-fracturing) but still not enough to make the wells productive. Little improvement is indicated by the lowering of well head pressures while injecting water at the same pumping rate. Both wells have low injectivity indices suggesting low permeability.

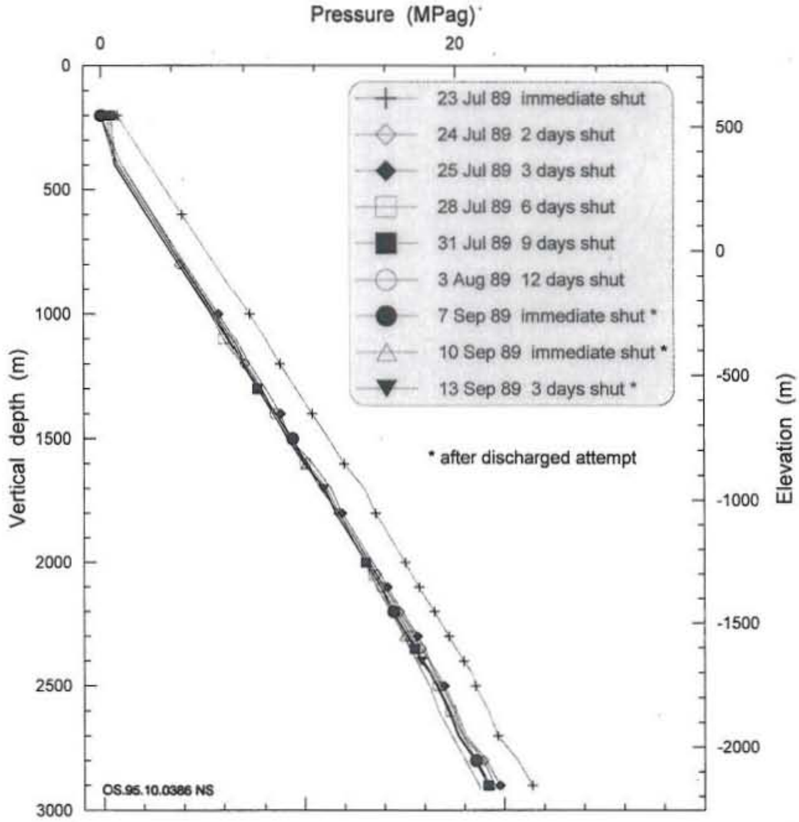

FIGURE 12: NA-2D pressure profiles

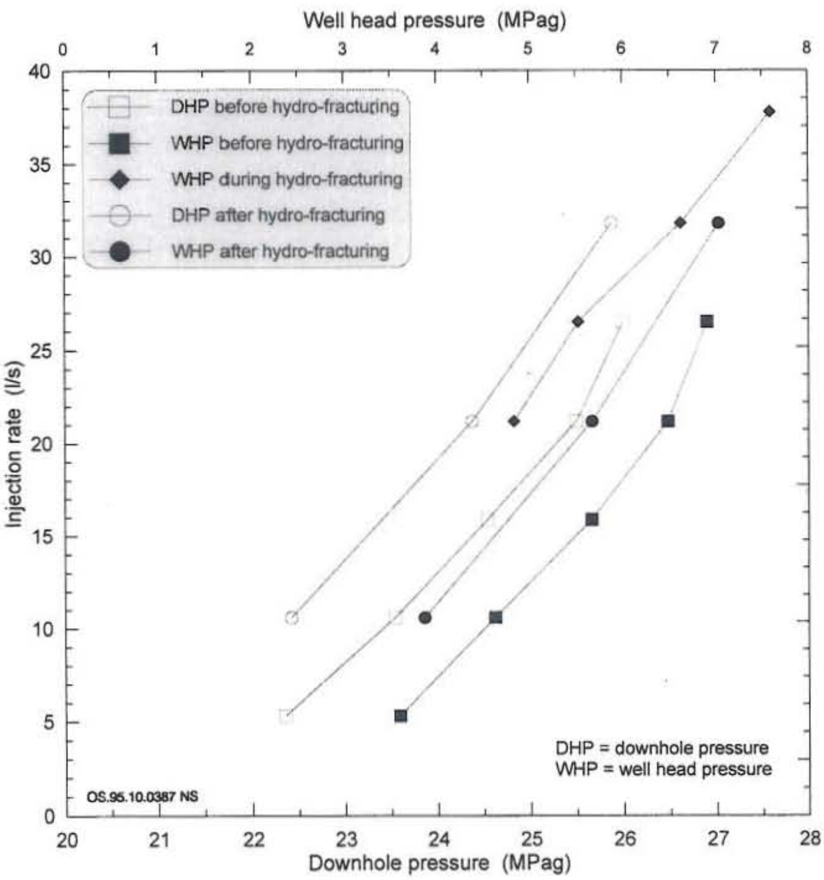

FIGURE 13: Plot of NA-1D injectivity test at 2100 mMD (2010 mVD)

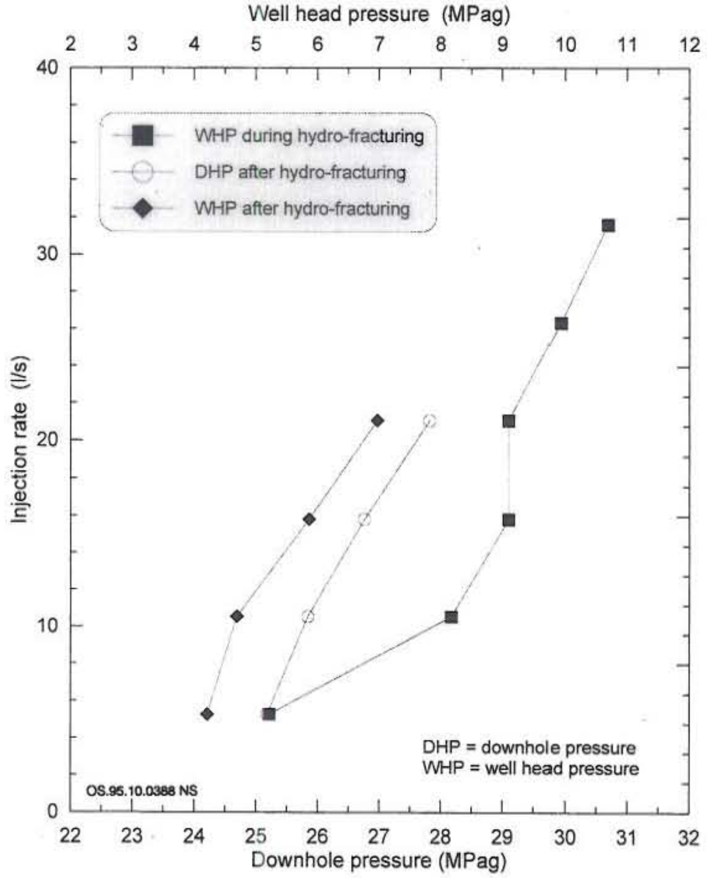

FIGURE 14: Plot of NA-2D injectivity test at 2507 mMD (2250 mVD)

TABLE 2: Results of injectivity tests

Well	Injectivity index (l/s MPa)		
	Based on well head pressure		Based on downhole pressure
	During hydro-fracturing	During injectivity test	
NA-1D	5.9	6.0* 6.8**	5.8* 6.1**
NA-2D	5.3	4.7**	5.3**

* Before hydro-fracturing; ** after hydro-fracturing

3.3.4 Pressure fall-off test

The existence of the semi-log straight line is not evident for both wells (or it really does not exist at all), however, by using the rule of thumb described above, the point exists at a late time of the test (Figures 15 and 16). Figures 17 and 18 present the semi-log plot of the test for NA-1D and NA-2D, respectively. For NA-2D it is assumed that the completion test programme has been carried out as planned to have a total injection time of 480 minutes. This time is used for the semi-log (Horner plot) analysis of the test. Table 3 shows the calculated transmissivity values indicating very low permeability. It is more likely that the low permeability is the main cause for the failure for the wells to discharge. Except for 45 minutes natural discharge of NA-2D, the wells never did discharge despite stimulation. Assuming fluid viscosity of 1.07×10^{-4} Pa s the permeability thickness (kh) ranges from 0.05 to 0.14 Dm.

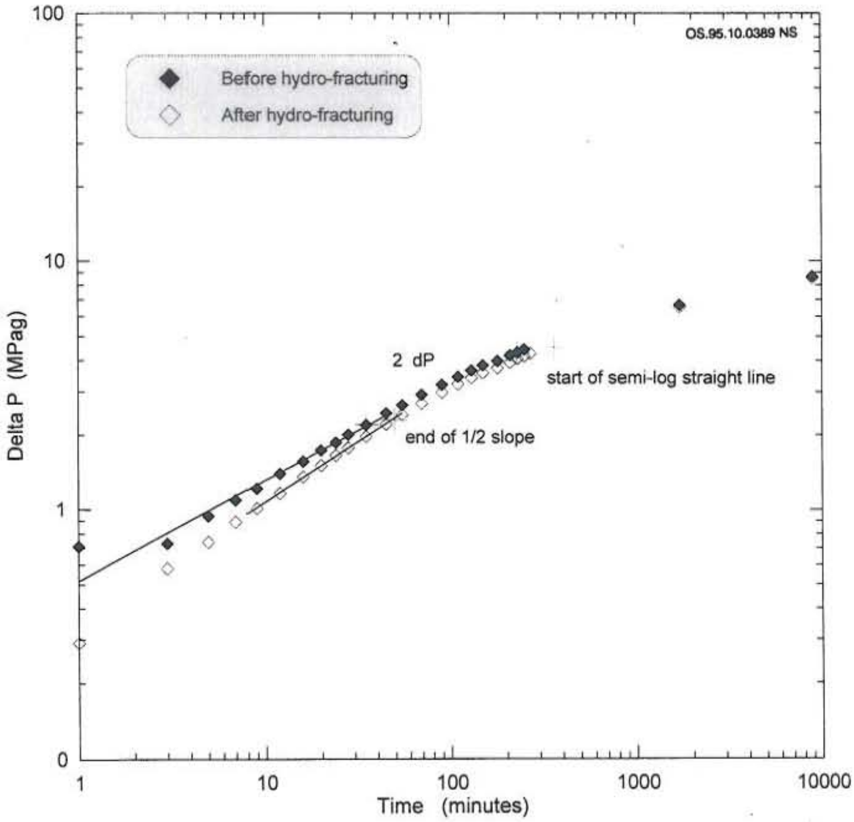

FIGURE 15: Log-log plot of NA-1D pressure fall-off test at 2010 mVD

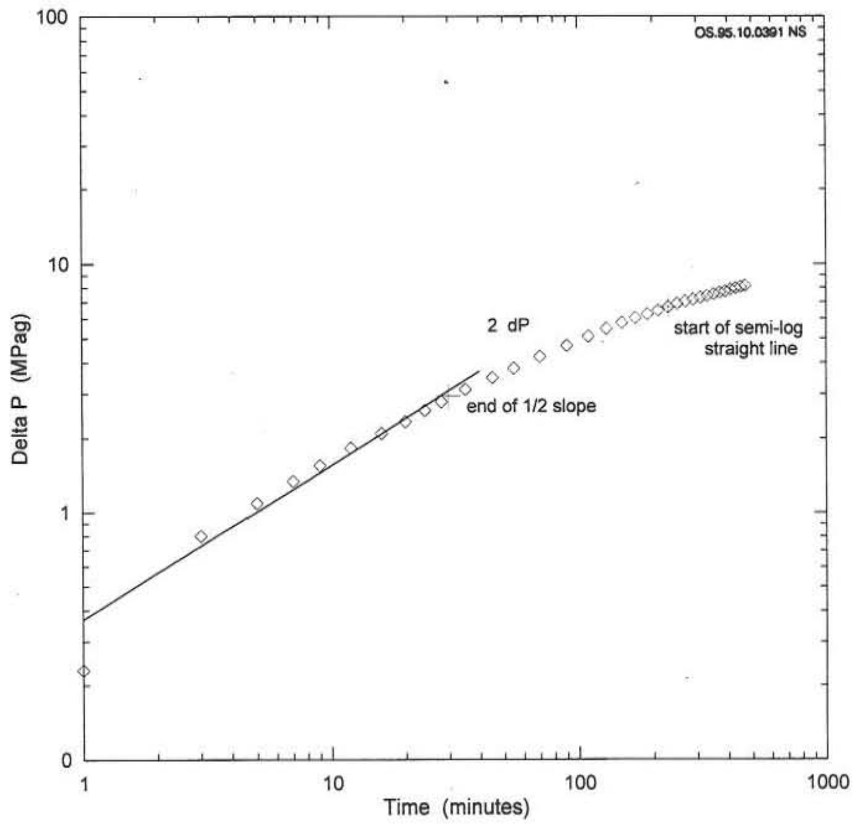

FIGURE 16: Log-log plot of NA-2D pressure fall-off test at 2250 mVD

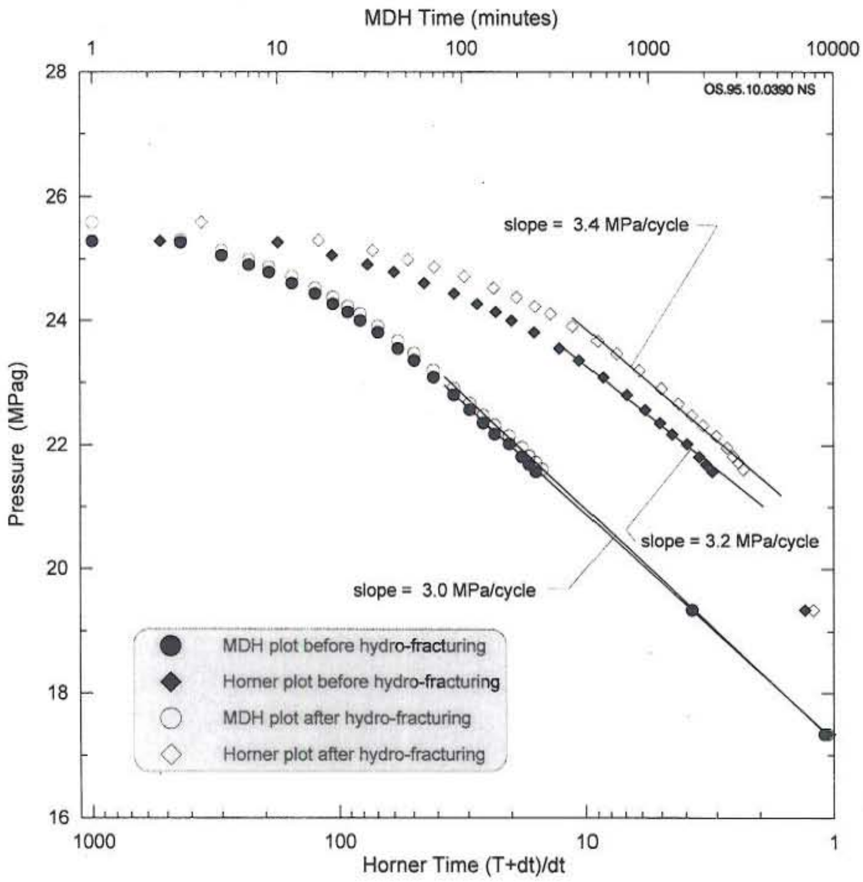

FIGURE 17: Semi-log plot of NA-1D pressure fall-off test at 2010 mVD

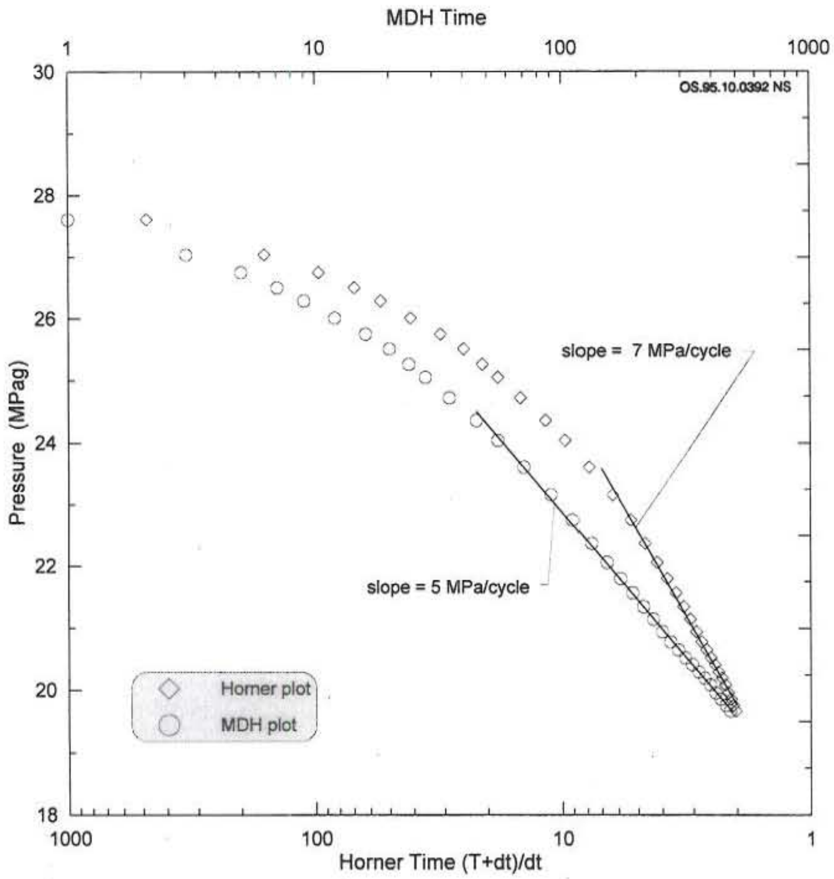

FIGURE 18: Semi-log plot of NA-2D pressure fall-off test

TABLE 3: Results of the pressure fall-off tests

Well	MDH		Horner	
	Slope (MPa/cycle)	**Transmissivity kh/μ (m^3/Pa s)**	**Slope (MPa/cycle)**	**Transmissivity kh/μ (m^3/Pa s)**
NA-1D	3	1.29×10^{-9}	3.2	9.04×10^{-10}
	3	1.02×10^{-9}	3.4	1.29×10^{-9}
NA-2D	5	3.02×10^{-10}	7	4.83×10^{-10}

3.4 Initiation of discharge

Aside from low permeability, both wells exhibit low temperature at the upper portion that impede them to discharge naturally, thus, requiring stimulation. NA-1D and NA-2D were stimulated by two-phase injection using a portable boiler (Clayton E-500). The aim of injecting hot fluid is to pressurize the well and heat up the casing in order to attain the energies required to overcome heat losses from the well to the cold formation. Several attempts to discharge the wells were unsuccessful, primarily because of poor permeability, failure to heat up the upper portion of the casing and not attaining sufficient pressure to stimulate the discharge (Sarmiento, 1993).

3.5 Conceptual model

Results of two exploratory wells have provided considerable information to further understand the Natib geothermal system. Even though the wells were drilled in a virtually impermeable formation it confirms the presence of a high-temperature reservoir (>260°C) with apparently very little fluid at depth (Figure 19). It indicated that the area may not be a classical geothermal system where major upflow and outflow zones exist. It is rather a conductive system where the temperature gradient is not very high at only about 3.2 times the normal gradient for the region. The relatively higher temperature encountered by NA-1D

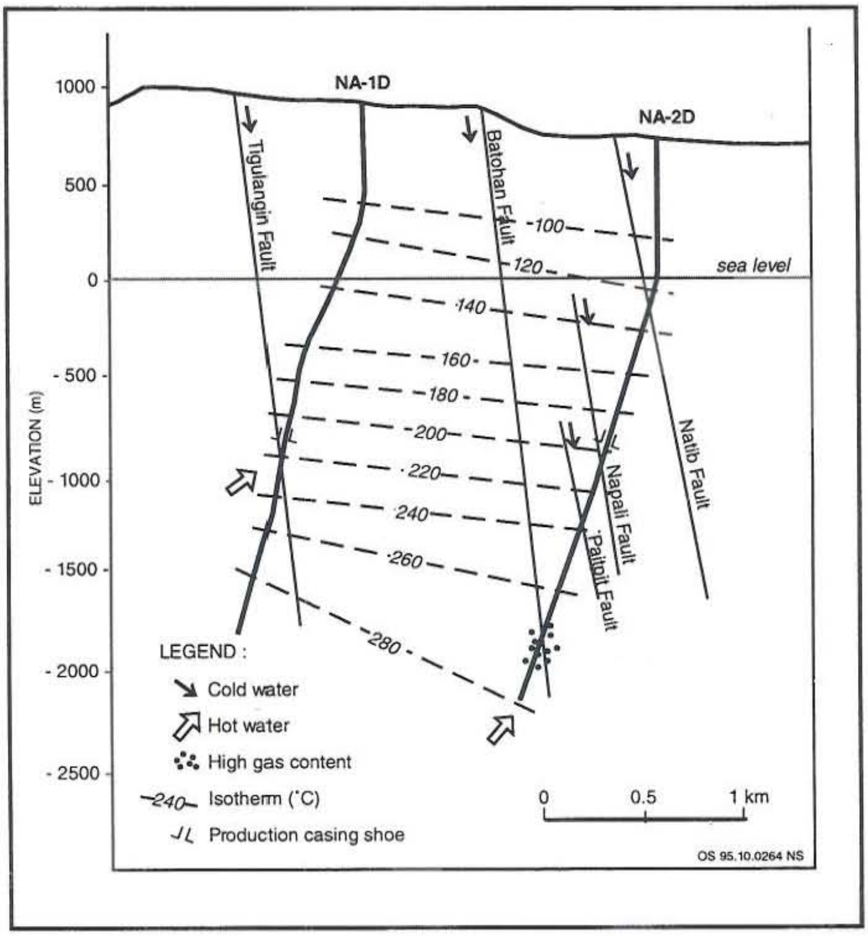

FIGURE 19: Cross-section through wells NA-1D and NA-2D facing west (modified from PNOC-EDC, 1990)

suggests its proximity to a heat source. Alteration mineralogy suggests a cooling system and limited downward percolation of meteoric water through faults (PNOC-EDC, 1990). As the chloride-enthalpy diagram does not indicate relationship between the reservoir and spring samples and the structures appear to have limited permeability, no clear fluid flow path can be deduced. It is possible that a convective system may exist within the 20 km^2 area delineated by the VES measurements but outside the drilled area or beyond the drilled depth.

3.6 Reserve estimate

With the available information it seems that only the volume method can be used to estimate the available heat that can be economically utilized with present technology. It is calculated by the following equation:

$$E = E_r + E_f = V\rho_r(1-\phi)C_r(T-T_r) + V\rho_f\phi C_f(T-T_r) \qquad (2)$$

where

- E = Total energy available for utilization;
- E_r = Energy contained in the rock;
- E_f = Energy contained in the fluid;
- C_r = Rock specific heat (kJ/kg°C);
- C_f = Fluid specific heat (kJ/kg°C);
- ρ_r = Density of rock (kg/m^3);
- ρ_f = Density of fluid (kg/m^3);
- ϕ = Porosity;
- T = Rock and fluid temperature (°C);
- T_r = Reference (abandonment) temperature (°C);
- V = Reservoir volume (m^3).

The reserve potential is estimated by:

$$Reserve\ (MW_e) = \frac{Energy\ available\ *\ Recovery\ factor\ *\ Conversion\ efficiency}{Plant\ life\ *\ Load\ factor} \qquad (3)$$

To cover the uncertainties involved in the conversion efficiency, recovery factor and determination of reservoir properties, the Monte Carlo simulation was used (Sarmiento, 1993). Monte Carlo simulation is made possible by using Microsoft Excel spreadsheet and several built-in functions such as rand (to generate random number), frequency, normdist and lognormdist. The frequency function is used to count the distribution of values in each pre-determined interval while the normdist and lognormdist is used to return the cumulative normal and lognormal distribution, respectively for the specified mean and standard deviation. Random numbers generated follow a uniform distribution, on the other hand triangular distribution is engendered by the products of two columns of random numbers (Grímur Björnsson, pers. comm.). To build confidence in the results of simulation a sample population of 1000 random numbers was used for each parameter. Table 4 shows the best guess value and the probability distribution used in the stored heat and reserve estimate calculation. The simulation shows that Mt. Natib can adequately supply the steam requirements of 10 to 15 MW$_e$ power plant for at least 20 years, a very conservative estimate (Figure 20). The very low power potential is mainly due to a low porosity and recovery factor used in the simulation.

TABLE 4: Best guess values and probability distribution input for Monte Carlo analysis of Mt. Natib reserve estimates

Parameter	Best guess (model)	Probability distribution		
		Type	Minimum	Maximum
Area (km^2)	8	Triangular	4	20
Reservoir thickness (m)	750	Triangular	500	1000
Porosity (%)	5	Log normal	2	15
Rock density (kg/m^3)	2700	Constant	---	---
Rock specific heat (kJ/kg°C)	0.9	Constant	---	---
Fluid density (kg/m^3)	792	Constant	---	---
Fluid specific heat (kJ/kg°C)	4.185	Constant	---	---
Aver. reservoir temperature (°C)	255	Normal	220	290
Abandonment temperature (°C)	180	Constant	---	---
Recovery factor (%)	7	Triangular	5	20
Conversion efficiency (%)	12	Triangular	9	15
Plant life (years)	25	Triangular	20	30
Load factor (%)	75	Triangular	65	90

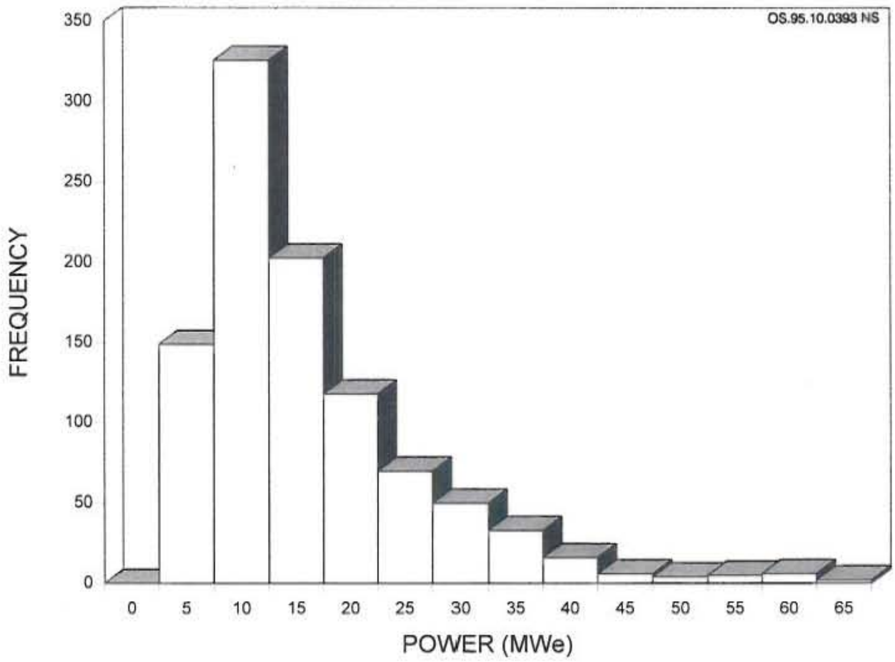

FIGURE 20: Frequency distribution of Mt. Natib reserve estimates

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Geothermal database

It is believed that the created database will pave the way for the start of the systematic computerization of available data at the Geothermal Division of the Philippines´ Department of Energy. The database must be expanded to store other information that was not considered in the design. Additional study on

Microsoft ACCESS and SQL must be undertaken to fully utilize its capability and to further enhance the performance of the database.

4.2 Resource assessment

Review and analyses of existing exploration data from Mt. Natib reveal that the area delineated by drilling has very low permeability. It is a conductive system with a thermal gradient of about 96°C/km. Monte Carlo simulation shows that the area can adequately supply the steam requirement of 10 to 15 MW_e power plant for 20 years. The high temperature (>260°C) encountered by drilling is enough to encourage additional exploration in the prospect. Gradient holes with depth no less than 500 m may be drilled to locate zones with abnormally high thermal gradient (>100°C/km) which may indicate the presence of convective zones below.

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I also would like to express my thanks to Ms. Griselda J.G. Bausa and Mr. Francisco A. Benito for giving me the opportunity to participate in this training; Geothermal Division staff for their continuous support and PNOC-EDC for allowing me to use the data from Mt. Natib. Thanks is also due to my family (Ditas, Carlo and Paulo) for bearing all the inconveniences of having me away for long six months.

Glory be to GOD for giving me the strength and will to succeed in this endeavour.

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APPENDIX I: A brief description of the database tables and fields

Table/Fields	Data type	Field size	Description

ITEM

general information about an object (wells, hot/warm springs) found in geothermal areas.

Item	number	integer	item identification number
Item type	text	1	item identification code
Itemname	text	10	name of the item
Elevation	number	single	elevation of the item from mean sea level (metre)
Northing	number	single	coordinates, northing (metre)
Easting	number	single	coordinates, easting (metre)
Area	number	integer	area code of an entity/item
Thermal	number	integer	geothermal area identification code
Loc_rem	memo	description of an item location	

ITEMTYPE

description of the types of items/entity stored in the database.

Itemtype	text	1	item type identification code
Typename	text	20	name of item/entity-type

AREA

area used to localize an item/entity as regards to sitio, barangay, town, etc.

Area	number	integer	code of an area
Area_in	number	integer	area code of a parent-area
Areaclas	text	1	area classification code
Areaname	text	15	the name of an area

AREACLAS

area/locality classification table.

Areaclas	text	1	area classification code
Clasname	text	8	name of area class (i.e. barangay, town, province, etc.)

THERMAL

location of an item with regard to geothermal area/reservation, field and sector.

Thermal	number	integer	geothermal area identification code
Termal_in	number	integer	geothermal area code of parent geothermal area
Termal_clas	text	1	thermal area classification code
Term_name	text	15	name of geothermal area

TERMAL_CLAS

thermal area classification table.

Termal_clas	text	1	thermal area classification code
T_clasname	text	11	thermal area classification name

JOB

commencement and completion of a rig activity and the type of job it undertakes.

Job	number	integer	job identification number
Item	number	integer	item identification number
Startdate	date		date the job commences
Completdate	date		date of job completion
Rig	number	integer	rig identification number
Jobtype	number	byte	job type identification code
Dril_rem	memo		drillers notes

DRILLING

information on the depth where a rig job has been undertaken.

Job	number	integer	job identification number
Item	number	integer	item identification number
Depth_from	number	single	depth (metre) at start of job from casing head flange (CHF)
Depth_to	number	single	depth at end of job from CHF (metre)
Bit	number	byte	bit code

JOBTYPE

type of job a rig usually does.

Jobtype	number	byte	job type identification code
Jobname	text	12	name of work undertaken

BIT

size and type of bit available for drilling.

Bit	number	byte	bit code
Bitsiz	number	single	bit size
Descrip	text	50	notes about the bit

WELLTRACK

information on well coordinates at any given depth.

Item	number	integer	item identification number
Depth	number	single	well measured depth from CHF (metre)
D_northing	number	single	well coordinates (y) from CHF at a given depth (metre)
D_easting	number	single	well coordinates (x) from CHF at a given depth (metre)
V_depth	number	single	vertical depth (z) from CHF (metre)

CASING

casing configuration of cased wells.

Job	number	integer	job identification number
Item	number	integer	item identification number
Casingtype	number	byte	casing type code
Casingprop	number	byte	casing property code
Casedfrom	number	single	measured depth at start of casing from CHF (metre)
Casedto	number	single	measured depth at end of casing from CHF (metre)

CASINGTYPE

casing type name used in geothermal wells.

Casingtype	number	byte	casing type code
Ctypename	text	13	casing type name

CASINGPROP

weight of a casing with reference to its grade and diameter.

Casingprop	number	byte	casing property code
Grade	text	4	grade/class of casing
Casing_dia	number	single	casing outside diameter (millimetre)
Thickness	number	single	casing wall thickness (millimetre)
Weight	number	single	weight of casing (pounds/foot)

RIG

name, owner and capacity of rigs.

Rig	number	integer	rig identification number
Rigname	text	15	name of the rig
Owner	text	20	rig owner/operator
Capacity	number	integer	rated capacity of the rig (metre)
Rigrem	text	50	other information about the rig

LOSS_ZONE

depth and degree of circulation loss encountered during drilling.

Job	number	integer	job identification number
Item	number	integer	item identification number
Losstart	number	single	measured depth at start of circulation loss from CHF (metre)
Losend	number	single	measured depth at end of circulation loss from CHF (metre)
Losstype	text	3	degree of circulation loss (partial, total)
Vol_loss	number	single	volume of fluid loss in litres per minute
Los_rem	memo		drillers remarks

LOG

information on logs, date conducted, instrument used and logger name.

Log	number	integer	log identification number
Item	number	integer	item identification number
Logtype	text	1	log type code
Logdate	date		date when log was conducted
Tool	number	integer	tool/instrument code
Element	number	integer	element code
Logger	text	4	initial of logger
Log_rem	memo		logger remark

LOGTYPE

types of logs conducted in Philippine geothermal field.

Logtype	text	1	log type code
Lognem	text	11	name of log conducted

TOOL

instrument available for logging.

Tool	number	integer	tool/instrument code
Tolnem	text	10	name of instrument

ELEMENT

element (sensor) available for logging.

Element	number	integer	element code
E_num	text	10	instrument element number

LOGVALUE

result of logs conducted other than deviation survey.

Log	number	integer	log identification number
Logdep	number	single	measured depth from CHF (metre)
Logval	number	single	logging measured value

AZIMUTH

results of well deviation survey.

Log	number	integer	log identification number
Logdepth	number	single	log depth from CHF (metre)
Azimuth	number	single	throw azimuth, clockwise from north (degrees)
Inclination	number	single	inclination of well (degrees)

SAMPLE

sample description.

Sample	number	integer	sample identification number
Item	number	integer	item identification number
S_name	text	10	sample name
S_type	text	1	type of sample
S_depth	number	single	sampling depth from CHF (metre)
S_vol	number	integer	volume of sample (millilitre)
S_date	date		sampling date
Sampler	text	4	initial of sampler
S_rem	memo		sampler remark

SAMPLETYPE

type of samples collected during geothermal operations.

S_type	text	1	sample type code
Stypnem	text	10	sample type name

CHEMICAL

chemical composition of a sample.

Sample	number	integer	sample identification number
Na	number	single	sodium concentration (ppm)
Li	number	single	lithium concentration (ppm)
Rb	number	single	rubidium concentration (ppm)
K	number	single	potassium concentration (ppm)
Ca	number	single	calcium concentration (ppm)
Mg	number	single	magnesium concentration (ppm)
Fe	number	single	iron concentration (ppm)
Cl	number	single	chloride concentration (ppm)
SO4	number	single	sulphate concentration (ppm)
B	number	single	boron concentration (ppm)
Cs	number	single	cesium concentration (ppm)
F	number	single	fluorine concentration (ppm)
SiO2	number	single	silica concentration (ppm)
TCO2	number	single	total carbon dioxide concentration (ppm)
H2S	number	single	hydrogen sulfide concentration (ppm)
NH3	number	single	ammonia concentration (ppm)
pH	number	byte	sample pH at given temperature
pH_temp	number	integer	temperature when pH was measured
S_Temp	number	integer	sample temperature (°C)
S_Pre_Flow	number	single	"+" sampling pressure (MPa); "-" flow rate (l/s)

CHEMTEMP

calculated temperature of geothermal reservoir based on solute geothermometry.

Sample	number	integer	sample identification number
Cris_b	number	integer	cristobalite-beta predicted temperature (°C)
Cris_a	number	integer	cristobalite-alpha predicted temperature (°C)
Chal	number	integer	chalcedony predicted temperature (°C)
SiO2	number	integer	silica predicted temperature (°C)
TNa_K	number	integer	sodium potassium predicted temperature (°C)
NKC	number	integer	sodium potassium calcium predicted temperature (°C)
NKCM	number	integer	Na-K-Ca-Mg predicted temperature (°C)

FLUID_INCL

homogenization and freezing temperature of an inclusion.

Sample	number	integer	sample identification number
Mineral	number	integer	mineral name code
FI_type	text	1	fluid inclusion type code
Homo_t	number	byte	homogenization temperature (°C)
Freez_t	number	byte	freezing temperature (°C)
Reading	number	byte	number of readings per temperature
FI_rem	memo		remark

MINERAL

minerals found in geothermal area.

Mineral	number	integer	mineral code name
Mi_name	text	15	name of mineral

FI_TYPE

type of fluid inclusion

FI_type	text	1	fluid inclusion type code
FI_name	text	10	fluid inclusion type name

PROD_INJ

well production/injection capacity, well head pressure and enthalpy/temperature

Item	number	integer	item identification number
Startdate	date		date at start of production
Enddate	date		date at end of production
Mass	number	single	aver. mass flow rate (tons per hour), "+" production; "-" injection
WHP	number	single	well head pressure (MPa)
Enth_temp	number	single	"+" discharge enthalpy (kJ/kg); "-" injection temperature (°C)
Steam	number	single	average steam flow rate (tons per hour)
PIrem	memo		production-injection remark

APPENDIX II: Mt. Natib, basic well information

Well name		**NA-1D**				**NA-2D**			
Objective		Exploratory				Exploratory			
Location		Nagsiete, Orani, Bataan				Bakyas, Orani, Bataan			
Wellhead coordinates	**North**	1,628,760 m				1,630,220 m			
	East	219,600 m				219,662 m			
Cellar elevation (m a.s.l.)		922				745.55			
Date spudded		27 January 1989				23 April 1989			
Date completed		30 March 1989				23 July 1989			
Kick-off point (m)		441				491.72			
Build-up angle (average)		1.7°/30 m				1.99°/30 m			
Measured depth (m)		2859.0				3353.72			
Vertical depth (m)		2751.5				2916.12			
Throw (m)		660.7				1443.9			
Bottom coordinates	**North**	1,628,105 m				1,629,527.49 m			
	East	219,510 m				218,395 m			
Casing type		**Size (mm)**		**Depth (mVD)**		**Size (mm)**		**Depth (mVD)**	
		Casing	**Hole**	**Casing**	**Hole**	**Casing**	**Hole**	**Casing**	**Hole**
Surface		508	660	84	97	508	660	93	96
Anchor		340	445	389	393	340	445	396	406
Production		244	311	1748	1753	244	311	1645	1653
Liner: Top		194	216	1702		194	216	1621	2919
Bottom				2737	2751			2916	