Geological, isothermal, and isobaric 3-D model construction in early stage of geothermal exploration

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Abstract. Construction of geology, thermal anomaly and pressure distribution of a geothermal system in the early stage of exploration where data is limited is described using a 3-D software, Leapfrog Geothermal. The geological 3-D model was developed from a topographic map (derived from DEM data), geological map and literature studies reported in an early geological survey. The isothermal 3-D model was constructed using reservoir temperature estimation from geothermometry calculated from chemical analyses on surface manifestations, available shallow gradient temperature hole data and the normal gradient temperature (3°C/100m) for a non-thermal area. The isobaric 3-D model was built using hydrostatic pressure where the hydrostatic pressure is determined by the product of the fluid density, acceleration due to gravity, and depth. Fluid density is given by saturated liquid density as a function of temperature. There are some constraints on the modelling result such as (1) within the predicted reservoir, the geothermal gradient is not constant but continues to increase, thus, creating an anomalously high temperature at depth, and (2) the lithology model is made by interpolating and extrapolating cross-sections whereas usually only two to three geology sections were available for this study. Hence, the modeller must understand the geology. An additional cross section was developed by the modeller which may not be as suitable as the geologist constructed sections. The results of this study can be combined with geophysical data such as gravity, geomagnetic, micro-tremor and resistivity data. The combination of geological, geochemical, isothermal, isobaric and geophysical data could be used in (1) estimating the geometry and size of the geothermal reservoir, (2) predicting the depth of top reservoir, and (3) creating well prognosis for exploration and production wells.

1. Introduction
In the early stage of geothermal exploration, the surface and subsurface geological data are limited. Nevertheless, an interpretation of the subsurface condition and lateral extent of a geothermal area must be developed. This includes an interpretation of reservoir geometry, structural geology that may form permeability, lithology cover and reservoir depth. Such interpretation will encounter some difficulties due to the limited initial data and impact the accuracy of the interpreted model features such as the size of the geothermal system. Another problem encountered in developing a model is data integration of
disparate data sets. Typically, the data to be integrated consists of a variety of data types (such as geology, geochemistry and geophysics) from different previous workers and different years with possibly different degrees of accuracy. Disparate datasets cause confusion and is time consuming. Moreover an interpretation of geoscience data to develop geothermal conceptual model is usually conducted in 2-D models such as maps or cross-section but to better visualize and infer the size of the geothermal system, the interpretation must be conducted in a 3-D model. Hence, the geoscientist needs a tool for developing a geothermal conceptual model recognizing the limitations of the data being used.

The case study presented herein is for the Montelago geothermal prospect (Figure 1) which for the first time a 3-D subsurface model is attempted. Exploration was conducted from 1978 to 2016. The exploration survey consists of surface geologic mapping, geochemical sampling (water and soil-soil gas), and geophysics - gravity, geomagnetic, CSMT and MT surveys. Furthermore, eight shallow temperature holes (up to 300 m depth) were drilled in 1979-1980.

This paper only discusses the construction of 3-D geological and isothermal model. The input for the geological model is a surface geologic map, information on the thickness and basement depth is from published literature on gravity and geomagnetic survey results in this area. The isothermal model constructed by using surface temperature of hot and warm springs, geothermometry, and temperature gradients from shallow holes up to 300 m depth. The isobaric model constructed by using pressure as a function of temperature derived from the isothermal model. Geologic, isothermal and isobaric 3-D models were interpolated using Leapfrog Geothermal software [1].

2. Montelago Geothermal Prospect

The Montelago geothermal prospect is located in Oriental Mindoro, Philippines, situated between Naujan Lake and Tablas Strait (Figure 1). The area has low-lying to moderate elevation but sometimes rugged terrains.

![Figure 1. Location map for the Montelago geothermal prospect.](image)

In general, lithology in Montelago consists of basement rock, sedimentary rocks, and Quaternary volcanic rocks which are dominated by andesite, tuff, basalt, and volcanic breccia. Paleozoic metamorphic such as schists, slates, and amphibolites; Mesozoic diorites and ultramafics that compose the core of Mindoro and here are collectively referred to as basement rocks. Although this rock is not exposed in the prospect area, their subsurface presence is inferred on the basis of geophysical surveys and the presence of accidental xenoliths in Quaternary lavas [2].
Delfin and Zaiden-Delfin [2] reported on a PNOC-EDC 1986 aeromagnetic survey that mapped the top of the basement rock at a depth greater than 2,500 or at least 3,000 m-b.s.l [2]. Possibly this basement rock overlain by a thick pile of Tertiary (?) clastic sedimentary rocks of East Mindoro Basin (in which Naujan Lake occurs). The thickness of sedimentary rocks was believed to exceed 4,000 m based on seismic reflection data [3]. Sedimentary rocks are exposed in southern part of Naujan Lake and they are comprised of semi-consolidated conglomerates, pyroclastic, sandstones, and siltstones. Reyes [4] mentioned that basement of the geothermal system in Luzon-Mindoro segment is sedimentary rocks, intruded by an igneous plutonic rock [4].

Volcanism in Montelago was reported as starting in the Pliocene [2]. Eruptive centers in the prospect area consist of four small stratovolcanoes and three exogenous domes. The deposits of these centers dominate the entire prospect area. The stratovolcanoes are Mt. Montelago, Mt. Pola, Mt. Naujan, and Mt. Dumali. The domes are Matabang Bundok, Usuyan, and Dome Hill. As a unit, these volcanics have a minimum thickness of 700 m.

Regandara [5] divided the stratigraphy of the Montelago area into eight stratigraphic units: Bagaygay Andesite, Bungao Vulcanic-Andesite Breccia, Lugta Breccia Volcanic, Matabang Bundok Basalt, Pungao Volcanic-Andesite Breccia, Montelago Tuff, Buloc Andesite, and Bambang Tuff-Andesite (Figure 2) [5]. A total of 19 faults were identified in the prospect area and these are identified as F1 to F19 in Figure 3. The four eruptive centers that suggest intrusions at the depth. Those are Mt Montelago, Mt Pungao, Mt Buloc and Mt Matabang Bundok.

![Figure 2. Stratigraphy of Montelago. The left side based on PNOC-EDC research 1989 and the other side is from Regandara.](image)

Hydrothermal features in the Montelago geothermal prospect occur in three areas, Montelago-Pungao on the southern part (MP1 to MP9), Buloc-buloc on the northern part (BB), and Lugta (Montemayor) on the northeastern part (MM) (Figure 4). The Montelago-Pungao group of
manifestations comprises the most impressive hot spring occurrences at Montelago. The spring area is near the shore of Naujan Lake. Spring temperatures range from 40-77°C with a neutral pH [6]. The Buloc-buloc warm spring is subaqueous occurring in Buloc Bay. The springs are only observable during low tide. Buloc-buloc manifestation has a temperature 36°C with a neutral pH. Montemayor hot spring is located near the sea shore in Barangay-Lugta. The temperature of this spring is 58°C and a neutral pH.

Figure 3. Geological map and geological profile of the center part (section A-A’) and eastern part (section B-B’) of Montelago geothermal prospect [5].
The estimation of reservoir temperature using the Na-K geothermometer is about 180-200°C. Hochstein and Browne classified geothermal reservoirs with a temperature of 125-225°C as an intermediate temperature system [7]. Therefore, Montelago geothermal prospect classified as an intermediate temperature system.

Figure 4. Map of temperature distribution in thermal springs, shallow gradient temperature holes, and the non-thermal area in Montelago. This temperature data is used to construct the 3-D isothermal model reported herein.

3. 3-D Geological Model
The subsurface lithology model up to 5 km was constructed from topography data, a geologic map, geologic sections, surface structural data, and regional stratigraphy. Topography was used with a digital elevation model (DEM) data from the NASA shuttle radar topography mission (SRTM). Figure 5a shows DEM data from SRTM which has a 3 arc second (approx. 90 m) resolution.

Figure 5. (a) DEM data from SRTM with a resolution of 90m [8], (b) Topography interpolation for the 3-D model, (c) Montelago 3-D topography model.
Leapfrog Geothermal provided the interpolation methods such as linear and spheroidal interpolation. This interpolation could be used to make topography points denser than the original data (Figure 5b). Based on these points, the mesh of the 3-D topography models could be created. A 3-D topography model in Figure 5c can be combined with a 2-D geological map on Figure 3 to generate a 3-D surface geology map. To construct subsurface lithology, geologic cross-sections are needed. The north-trending geologic sections are C-C’, D-D’, and E-E’ (Figure 6). The structural model was constructed using strike and dip of a geologic structural measurement on the surface. The 3-D structural model illustrated in Figure 7.

![Combination of the geologic map and geologic sections in Leapfrog Geothermal. Section C-C’, D-D’, and E-E’ have a north-trend.](image)

**Figure 6.** Combination of the geologic map and geologic sections in Leapfrog Geothermal. Section C-C’, D-D’, and E-E’ have a north-trend.
Based on an interpretation of geologic sections A-A’ to E-E’, the geologic map, topography model, structural model, and stratigraphy of Montelago, a 3-D geological model was constructed by creating synthetic boreholes. There are 248 synthetic boreholes in this model. The vertical boundary for the geologic model is from an elevation of 312 m above sea level (m-a.s.l.) to 5,000 m-b.s.l.

![Figure 7. The structural model for 3-D geological model Montelago geothermal prospect.](image)

The Basement rocks, as mentioned previously, at least start from 2,500 meter b.s.l. on the northwestern part of model. Sedimentary Rock have thickness at least 2,000 meter start from 1,000 or 1,500 meter b.s.l. to 3,000 or 3,500 meter b.s.l. (Figure 8a). The Sedimentary Rock was intruded by Montelago Tuff, Buloc Andesite, Pungao Volcanic-Andesite Breccia, and Matabang Bundok Basalt (Figure 8b). Bambang Tuff-Andesite on the northwestern part of Montelago have thickness around 700 – 1,000 meter spreading toward southern part. Montelago Tuff and Buloc Andesite superimposed with Pungao Volcanic-Andesite Breccia have thickness at least 500 meter. On the upper part Lugta Breccia Volcanic superimposed with Bungao Volcanic Andesite Breccia and Bagaygay Andesite (Figure 8a).

![Figure 8. (a) 3-D Geological Model of Montelago geothermal prospect, (b) illustration models of volcanic rocks intruded sedimentary rocks.](image)
4. **3-D Isothermal Model**

The 3-D isothermal model was constructed using data from 11 surface manifestations, two shallow temperature gradient holes, and three non-thermal areas (Figure 4). The temperature gradient of the shallow holes was reported as approximately 23°C/100 m and 10°C/100 m (Figure 9). Where the shallow temperature gradient hole data is available, the reservoir temperature can be extrapolated to the depth by assuming conductive constant geothermal gradient (ΔG).

At -1000 m-b.s.l., the temperature of NGH-6 is 135.5°C while in NGH-4 is around 268°C. Based on ΔG, the NGH-4 temperature at -2000 m-b.s.l. is 498°C which is not reasonable. Therefore, the geothermal gradient from NGH-4 not applicable if temperature above the reservoir estimation (200°C).

![Figure 9. Illustration of gradient temperature vs depth in NGH-4 and NGH-6. ΔG is the geothermal gradient.](image)

In the area where shallow temperature gradient hole data is absent, the surface temperature of the springs and its geothermometer derived temperature is used to estimate the geothermal gradient from the surface to the top of the reservoir. The first step in constructing a 3-D isothermal model using surface manifestation data is to determine the temperature (T<sub>m</sub>) and the elevation (Z<sub>m</sub>) of thermal spring. The second step is to estimate the reservoir temperature (T<sub>Res</sub>) using the geothermometry of the thermal spring. In this model T<sub>Res</sub> is about 180-200°C [6]. The next step is to determine the depth of top reservoir (H<sub>Res</sub>). The depth of top reservoir is determined using linear interpolation from the graph of well depth (in meters) against bottom temperature (°C) developed by Hochstein and Sudarman, presented in Figure 10 [9].
Figure 10. Illustration of the correlation between temperatures with the depth of reservoir modified from Hochstein and Sudarman.

This graphic was made by plotting bottom temperature (x-axis) and depth (y-axis) of geothermal wells (both low and high temperature as well as productive and non-productive) in many Indonesian fields and prospects. The linear correlation of productive wells (solid circles in Figure 10) have a function as follow,

\[ H_{Res} = 8.2 T_{Res} - 390 \]  

(1)

Where \( H_{Res} \) is expected to be equal to the depth of top of the reservoir at any given reservoir temperature. Using this equation the top of the reservoir can be estimated.

Once the top of the geothermal reservoir has been determined, its depth must be converted to elevation to be able modelled in the Leapfrog Geothermal software. Input of elevation b.s.l. in Leapfrog Geothermal have negative values thus, the elevation of top reservoir \( (Z_{Res}) \) is \( Z_m \) minus \( H_{Res} \),

\[ Z_{Res} = Z_m - H_{Res} \]  

(2)

Where, \( Z_{Res} \) is an elevation of the top reservoir in meter.

\( H_{Res} \) is the depth of top reservoir in meter.

\( Z_m \) is an elevation of surface manifestation in meter.

Once \( Z_{Res} \) has been determined, the next step is to calculate temperature (T) distribution for the depth interval from the top of the reservoir to the surface manifestation by using following linear interpolation:

\[ T = T_m + \frac{(T_{Res} - T_m)}{(Z_{Res} - Z_m)}(Z - Z_m) \]  

(3)
Where,  \( T \) is temperatures in °C.
- \( T_m \) is a temperature of the surface manifestations in °C.
- \( T_{Res} \) is the estimate of top reservoir temperature from geothermometry in °C.
- \( Z \) is elevation in meter.
- \( Z_m \) is the elevation of surface manifestations in meter.
- \( Z_{Res} \) is elevation of the top reservoir in meter.

This procedure is illustrated in Figure 11. Applying this procedure to the calculation of temperature distribution above the reservoir assumes that the temperature in this interval is conductive and is dominated by a clay cap, thus, the gradient is considered linear.

![Figure 11. Illustration for determination of subsurface temperature using temperature from surface manifestation.](image)

Because the temperature model is calculated using linear interpolation, consequently, within the reservoir there is still temperature gradient causing unrealistic high temperature at depth greater than the reservoir. However, within reservoir zone, the temperature is affected by convective heat transfer causing a low geothermal gradient or in a steam reservoir the temperature is almost constant about 240°C causing a temperature gradient close to zero. Therefore, the isothermal model created in Leapfrog Software must be interpreted with caution. The isothermal model must be constructed up to the reliable reservoir temperature according to geothermometry data or the type of geothermal system. For example, Montelago is predicted as medium to the high-temperature reservoir system, thus, the maximum reservoir isothermal model that can be estimated is 250°C. The temperature cut-off about 250°C is taken from common geothermal reservoir temperature with high temperature worldwide. The last step is to input all the data such as coordinate, elevation, and temperature up to the depth of boundary condition in the model. The summary of the calculation from surface manifestations is shown in Table 1.

In areas where surface thermal manifestations are absent or in non-thermal areas, the normal geothermal gradient (3°C/100m) and surface temperature 26°C are used to estimate isothermal temperature model to depth. The distance between the thermal area and non-thermal area is at least 1 km and must be located outside the mapped low resistivity anomaly.
Table 1. Calculated reservoir elevation and associated reservoir depth based on the linear interpolation from the graph by Hochstein and Sudarman [9].

| No. | Manifestation | $T_m$ (in °C) | $T_{Res}$ | $Z_m$ (in meter) | $Z_{Res}$ | $H_{Res}$ |
|-----|---------------|---------------|-----------|------------------|-----------|-----------|
| 1.  | MP1           | 77            | 200       | 7                | -1239     | 1246      |
| 2.  | MP2           | 74            | 190       | 8                | -1156     | 1164      |
| 3.  | MP3           | 40            | 190       | 6                | -1158     | 1164      |
| 4.  | MP4           | 50            | 200       | 6                | -1240     | 1246      |
| 5.  | MP5           | 43            | 200       | 14               | -1232     | 1246      |
| 6.  | MP6           | 57            | 180       | 12               | -1070     | 1082      |
| 7.  | MP7           | 68            | 200       | 11               | -1235     | 1246      |
| 8.  | MP8           | 40            | 200       | 19               | -1227     | 1246      |
| 9.  | MP9           | 66            | 200       | 13               | -1233     | 1246      |
| 10. | BB            | 36            | 200       | 19               | -1227     | 1246      |
| 11. | MM            | 58            | 200       | 15               | -1231     | 1246      |

The isothermal model from shallow gradient hole, surface manifestations and non-thermal areas are presented in Figure 12. Based on this model, 200°C is at 1,100–1,200 m-b.s.l. in the central part of the prospect. In northwestern part of the prospect a temperature of 200°C is at 1,700–1,900 m-b.s.l. which is significantly deeper than the center part. The anomaly temperature 200°C occurs in NGH-4 at 700 m-b.s.l. The thermal model of NGH-4 is overestimated because the depth of shallow gradient hole is only 300 m.

Figure 12. Isothermal 3-D model.
5. 3-D Isobaric Model

The 3-D isobar model was constructed using pressure as a function of temperature derived from the isothermal model (Figure 12). In the area where shallow holes and surface manifestations are available, the pressure can be interpolated using depth by assuming hydrostatic pressure ($P_{hyd}$) [10]. Hydrostatic pressure is determined as a product of density, the acceleration due to gravity, and depth. The reservoir in Montelago is assumed to be a liquid dominated system thus density is given by saturated liquid density as a function of temperature. Temperature data was obtained from the 3-D isothermal model section. The equation to calculate hydrostatic pressure is as follows:

$$P_{hyd} = \rho_{liquid} (T) \cdot g \cdot h + P_0$$

Where, $P_{hyd}$ is hydrostatic pressure (bar).
- $\rho_{liquid} (T)$ is saturated liquid density as a function of temperature (kg/m$^3$).
- $T$ is temperature (°C).
- $g$ is acceleration due to gravity (9.8 m/s$^2$).
- $h$ is depth (m).
- $P_0$ is pressure at the surface (1.01325 bar)

In the area where any surface thermal manifestation is absent or in a non-thermal area, the hydrostatic pressure from equation (4) can be used. The non-thermal area is assumed as recharge area, hence, the density is still given by saturated liquid density. The distance between the thermal areas with non-thermal areas is at least 1 km and must be located outside the mapped low resistivity anomaly.

The isobaric model from shallow gradient hole, surface manifestation and non-thermal area are presented in Figure 13. Based on this model, a pressure 110 bar occurs at 1,100–1,300 m-b.s.l. in the central part of the prospect. In the northwestern part of the prospect, pressure 110 bar is at 1,000–1,100 m-b.s.l. which is shallower than the central part. In the southeastern part of the prospect, pressure 110 bar is at 900–1,100 m-b.s.l. The pressure 110 bar at NGH-4 occurs at 1,600 m-b.s.l.

![Figure 13. Isobaric 3-D Model.](image)
6. Discussion

A 3-D geological model and an isothermal model could be used to formulate a well prognosis for exploration and production wells. The geometry and size of the reservoir could be estimated using the isothermal model. The boundary of the top of the reservoir would be used layers from the isothermal model where in this case used geothermometry 200°C while the thickness of the reservoir is assuming with 1 or 2 km [11]. Based on the isothermal model, the depth to the top of the reservoir is 1,100–1,200 m-b.s.l in the central portion of the Montelago prospect. Furthermore, the depth of the lithology units between the volcanic rocks and sedimentary rocks in the project area could be used as a well target because these intervening units are assumed to be a permeable zone; continuity of the faults could be used as well for targeting purposes. However, the result of the 3-D geologic model may not suitable as it was not constructed by the original project geologist rather the software modeler made additional geological sections for the model which may or may not be accurate.

Any model, especially in the early stages of an exploration project has its positive and negative features. For example, one difficulty in constructing a 3-D geological model in a geothermal system in a volcanic environment is identifying the boundaries between the various stratigraphic units and their thicknesses. The lithology in geothermal systems in this type of setting generally has volcanic rocks in the upper part, not sedimentary rocks. If the lithology in a project area is volcanic then the model would generate subsurface intrusions. The gap between intrusions will be blank or interpreted as unknown lithology. Usually, this gap will be filled by sedimentary rocks, but this doesn’t happen if the models have all intrusion in their upper part. Additionally, the predicted temperature at depth using the geothermal gradient alone could generate anomalously high temperatures at depth. Therefore, the geothermal gradient in the model should be restricted based on the estimated temperature of the reservoir. The result of the 3-D isothermal model in the Montelago area could be used as an illustration of temperature distribution in a reservoir with a temperature of at least 200°C.

On the other hand, a 3-D geological model does begin to place constraints on the geothermal system and allow for a systematic determination of potential reservoir size among other factors. It provides an integrated, consistent summary of the relevant data and it can easily be updated with other or new data such as from geophysical model or data from temperature gradient holes and geothermal wells. It is a “living model” that allows planning for future exploration and development activities and updating as new data sets are generated.

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