Complex 3-D Geological Model Construction for Volcanic Geothermal Area in North Taiwan

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ABSTRACT

This paper describes the 3-D geological concept model as a construction tool (GeoModelBuilder-3D), developed by the author. This tool is then used to build the conceptual model from a candidate geothermal site around the Tatun Volcanic Group (TVO) and Huang-Zuei Volcano (HZV). With the established preliminary models, the geothermal heat source model thereby can be effectively evaluated at two different local scales, including the large model (TVO area) and small model (HZV site) respectively. For engineering application, they can serve as a good tool for engineering management of the thermal reservoirs and reach sustainable operation. Prior to commercial power generation, current results of model studies should be regarded as the initial guess. Subsequent modifications are taken for granted to cope with new additional geological data, including new finding on supplementary drilling, geophysical survey, geochemical analysis, etc. According to the current conceptual model assessment on HZV site, the geothermal heat source model at north HZV should be the residual heat flow of later stage magma activity of TVO. The high steam content heat flow derived from deep seated magma chamber at HZV, which went through some Neo-tectonic structures near crater, and finally migrated into shallow ground surface. There are many obvious volcanic heat signatures and geothermal manifestations in the surrounding area, including many hot springs, fumaroles, and widely distributed areas of metasomatism. All of these constituted an excellent geothermal site for engineering development.

I. INTRODUCTION

Geothermal development can be dated back to 1970s when global oil crisis endangered energy supply in Taiwan. First geothermal power plant in Ching Shui was constructed using wet steam as heat source in slate formation near northeast Taiwan. This plant began power generation in a single-flash designed, 3-MWe capacity scale in early 1981. Unfortunately, the generated thermal power declined rapidly within five years and was therefore decommissioned in 1993. Due to government policy to close all nuclear power plants and replace them with developing renewable power, the return of geothermal power is highly encouraged, and new investment projects from private sector have been booming in recent years. Such domestic investment was more or less accelerated by the governmental certificated FIT (Feed-in-Tariff) system, in parallel with an exemption of EIA (Environmental Impact Assessment) under 10 MW announced in 2018. Currently, according to the Renewable Energy Purchasing Rate set by Taiwan’s Bureau of Energy (BOE, 2019), the purchase price per kilowatt hour is set at NT$5.1956.

Among recent major investment projects, geothermal development at Tatun Volcanic Group (TVO) is regarded as most promising site and attracts most attention to potential investors. The heat generating capacity is estimated to reach 514 MWe (ITRI, 1994) by the area exploration review. It has been also pictured that inside the TVO covering area, there is a SW–NE trending geothermal belt, with a stretch length about 10 kilometers and a width about 3.5 kilometers. This belt extending from Pei-Tou to Ken-Tze-Ping and with Ma–Tzao as a center as shown in Fig. 1. Near TVO’s center, at least tens of high geothermal outcrops with vast metasomatism areas can be observed in the field. According to early exploration and literature review, the reservoir volume in TVO is at least 40 cubic kilometers, and the reservoir temperature is found to be about 200-290 °C. As highlighted in Fig.1, almost entire high geothermal potential zone (HGPZ marked area in red) is situated inside the Yang-Ming-Shan National Park (marked area in green).

Although TVO’s power generation potential is very high, but due to the current National Park Act, geothermal development within national park is strictly prohibited by law. However, in northeast HGPZ and north Huang-Zuei Volcano (HZV), very high potential geothermal resources are still identified recently and become a feasible candidate site attracting geothermal power investors. This is because of the benefits of its location being outside the National Park. An at least 1-MW geothermal power generation demonstration project supported by BOE is now underway at the area.

At the early phase of the geothermal development, geothermal potential of the development zone must be confirmed through geological exploration on various scales (Yu, et al., 2018a, 2018b). Exploration methods may include appraisal drilling, geophysical survey, geochemistry, etc. The results of geological exploration are commonly used to build a geological conceptual model, and to effectively and specifically evaluate the migration path of geothermal heat source. Hence, a rational geological conceptual model is very important to subsequent engineering management of thermal reservoir and to achieve sustainable operation of a successful plant. Taking TVO as a geothermal development target area, and select north HZV as an example site, this paper uses the 3-D geological model as a construction tool (GeoModelBuilder-3D, developed by the author) to explain how to build geological concept mode needed to cope with project planning, and how the model can be used to support drilling decision if required. It should be noted that the model is based just on a preliminary assessment data, and the geothermal heat source model exhibit here may be to change with new exploration findings whatsoever.

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2. GEOLOGICAL BACKGROUND

TVO in northern Taiwan is the largest volcanic body on the island. The volcanic body includes four volcanic subgroups, namely: Qixing-Shan, Tatun-Shan, Zhuzi-Shan, and Huangzuei-Shan. In general, each subgroup is composed of a combination of conical volcanic bodies and volcanic mounds. Most identified craters of TVO is roughly distributed on the northwest side of the NE-SW running thrust fault (K-Fault), and also the southeast side of a parallel thrust fault (G-Fault). During the Quaternary Period, Neotectonic extensional expanding movement is not only the formation of the Okinawa Trough in Japan, but also extended to Northern Taiwan. It has been discovered that this tectonic movement has close relationship with the active episode of TVO, accompanied by formation of some extinct normal fault on the preexisting K- and G-Fault. One well know normal fault is called San-Giao Fault (SG-Fault) along the old path of G-Fault, and is an active fault recognized by the Taiwanese government.

TVO’s volcanic activity was reported to begin about 2.8-2.5 million years ago, and the most vigorous volcanic episode may occur around 800,000 years ago. The activity did not stop until about 10,000 years ago, forming the landscape and topographic feature as seen today (Song et al., 2000; Wang et al., 1999). The main body of the volcanic group is composed of volcanic rocks dominated by andesite or subdivided into tuff breccia (T), andesite (A), and basalt (B) according to type and age of magma eruption. From the LiDAR topographic survey conducted by the Central Geological Survey (CGS, 2005), TVO may have a total of 43 distinct and speculative craters. An earlier study (Chen, et al., 2003) had pointed out that at least 29 volcano craters can be identified and named, using an old version and lower resolution digital terrain model (DTM), as depicted in Fig. 2.

Fig. 3 shows the landform of HZV’s main volcanic crater viewed from its north. The hydrothermal reforming zone activity of volcanic activity in the north side of the volcano is still visible, accompanied by many geothermal signatures, including steaming ground, hot spring, fumaroles, and metasomatic zones. On the right side of the photo you can see a hat like volcano called Sha-Mao-Shan.
3. MODEL CONSTRUCTION

3.1 Model Scale Selection

Both the TVO target area and the HZV geothermal development site are taken as examples for study with respect to two model scale in this paper. Each scope area for the geological concept model is illustrated by the block indicator shown in Fig. 4. For readers to easily understand, model scopes are named as “TVO area” and “HZS site” respectively for large and small targeting areas. Some alluvium deposits will be ignored due to their limited cover and depth within the model. The default upper boundary of the two model ranges is 1,000 meters above sea level, while the lower boundary of the model is 1,000 meters below the sea surface.

The model area of the TVO area is about 18.6 x 15.6 square kilometers. The geologic formations entering the model are basically Tertiary Formations, including the Wuchishan (Wc) of Oligocene, and the Mushan (Ms), Taliao (Tl), and Shiti (St), the Nankang (Nk), the Nanchuang (Nc), and the Keichulin (Kcl) of Miocene. Within the model covers two major thrust faults, including K-fault and G-fault (or SG-Fault) and some intermittent faults. The overlying volcanic formations including HZV and other neighboring volcanos. It should be noted that too many geological units used in a model can cause excessive complexities in constituting 3-D model, and hence, sometimes, a compromise to leave out some unit become a crucial steps.

Model area for the HZV site is about 2.62 x 2.76 square kilometers. Due to the small model size, the formation entering the model is only the Wuzhishan (Wc), and the volcanic formation is exclusively in the HZV, with some post-volcano tuffs. As a consequence, in model construction process, the key point is emphasizing geological structures including the intervening faults, fractures, and their intersections, for these would provide prevailing path to control the migration of geothermal heat flow upward to the ground outcrop.

Figure 3: Global view of north Huang-Zuei Volcano (HZV).

Figure 4: Two different model scales of interested model zones.
3.2 Tools for Model Construction

In this paper, due to space limitations, the integrated program (GeoModelBuilder-3D), and its related interface tool or modules for input and output can only be briefly described as follows:

- **Interface modules [.exe] developed using VB6.0**
  - [Starter.exe] for defining model scale or window scope (E_start, N_start, E_end, N_end) and for creating dtm files (*.dtm); either the TWD97 or TWD67 coordinate system can be used.
  - [Editor.exe] for editing dtm files (*.dtm)
    - Grid-based (Xzone_no, Yzone_no, Xzone_width, Yzone_width)
    - Xgrid_no=Xzone_no+1; Ygrid_no=Yzone_no+1
    - Resolution can be selected and self-defined (best resolution from 2~40m for single grid zone)
  - [Builder.exe] for creating and editing model files (*.dtm)
    - Regular planes
      - [Run strike/dip at X,Y,Z]
      - [Run 3-points]
      - [Run ...]
    - Irregular planes (using spatial Kriging method)

- **Integrated model files (Case_now.xxx)**
  - Input z_top (model top elevation) and z_bot (model bottom elevation)
  - Define Geo-Formation sequences using designated relevant “dtm boundary” such as topographic surface, geologic formations, boundary fault, etc.
  - Define episode of geologic event using “zone boundary”, one set of “zone boundary” contain several “dtm boundary”
  - Auxiliary coordinate information (drillings, volcanos, contour lines, points, lines, polygons, etc.)
  - Create surface geological map corresponding to the input “dtm boundary” and “zone boundary”

- **Output 3-D Models (combine output files of with VRML2 format, Ames et al., 1997)**
  - 3-D Block Diagram (*.bmp, *.wrl)
  - 3-D Cut Block Diagram (*.bmp, *.wrl)
  - 3-D Profile Diagram (*.bmp, *.wrl)
  - 3-D Fence Diagram (*.bmp, *.wrl)
  - 3-D Diagram with defined designated zonal windows (*.bmp, *.wrl)
  - [Viewer.exe] for scripting VRML2 files (*.wrl)

4. RESULTS AND APPLICATIONS

4.1 TVO Areal Model (Large Scale Model)

Full 2-D range of the “TVO areal” model is shown in Figure 5(a). In which the DTM grid network (Xzone_no, Yzone_no) used is (369, 311) and the grid width (m) of each zone (Xzone_width, Yzone_width) is (50.47, 50.25). Under such high grid densities, the resolution of 2-D surface topography zoning and geological feature can be shown better. The input 2-D geological model for our 3-D construction work is borrowed from a regional geological map provided by the Central Geological Survey (unpublished data). It can be replaced by the digital geological map calculated from the 3-D model construction, or any other relevant geological map with same coordinate range. The model covers 27 geological units (X1 ~ X27) with several main episodes of geological event cutting through earlier geologic formations in sequence, as those described in previous Sections.

Corresponding to the 2-D range shown in Fig. 5(a), the results of a 3-D model with a form of block diagram is shown in Fig. 5(b) in a VRML2 format (.wrl). Such block diagram is commonly used for general 3-D display. To view the model in a more flexible manner, user can also define his own output type such as selecting multiple fence diagram along the selected grid position and direction (see Fig. 6), or arbitrarily defined profile diagram by choosing single or multiple linear coordinates within the model. In such a way, users can easily apply the model to do geological analysis for the engineering planning and design work. Fig. 7, shows profile diagrams or the cross-sectional output from the model built. Fig. 7(a) shows the position of the section line (NW-SE trending), while Fig. 7(b) shows the 3-D model view.

In the larger model scale, the more complex the geological formation, the higher the model construction difficulty. The results of geological profile sketch had been published by a local research institute (BOE, 2014) on the same profile location as shown in Fig. 7(a). The reader can see how the complexity of geological model is along the profile. In this study, to check current developed model’s relevancy and capability, a comparison is made by the author, and the results are illustrated in Fig. 8. It shows almost identical results between the two. With our model, the existing geological map and profile data can be used as input and duplicated in a rational 3-D reconstruction work. It is also proven that using the developed computer program with enough geological knowledge toward the model domain, even in such a complex situation as the TVO area, the relevancy and capability of the GeoModelBuilder-3D can be validated.

However, from the engineering point of view, it is worth emphasizing that for geothermal development, 3-D model re-construction of the large-area model can only provide rough and descriptive geological conceptual model, mainly to help the engineer to judge the theoretical volume or capacity of potential geothermal resource for public communication purpose. In the volcanic geothermal area, most valuable outcome will come from examining the geologic evolution or history from a 3-D manner, discover types of thermal reservoirs, and cap rocks, re-evaluate the geothermal gradient distribution by integrating other exploration data, etc. It should be also aimed at constructing the heat flow migration mechanism and try to pictureize them by 3-D model construction.
Figure 5: Large scale models (Block Diagram).

(a) 2-D block view (geologic map of CGS, unpublished)
(b) 3-D block view

Figure 6: Large scale models (Fence Diagram)

(a) 2-D fence view (with Fences-1,2,3,4)
(b) 3-D fence view (Fences-1,2,3,4)

Figure 7: Large scale models (Profile Diagram)

(a) 2-D view with profile line (NW-SE)
(b) 3-D profile view
4.2 HZV Site Model (Small Scale Model)

Full 2-D “HAV site” model is shown in Figure 9(a), where the DTM grid network (Xzone_no, Yzone_no) used is (52, 55) and the grid width (m) of each zone (Xzone_width, Yzone_width) is (50.47, 50.25). The grid width (m) is identical to that used in the “TVO area” model, since the small scale model is an orthogonal window cut from the large scale model (369, 311). The grid densities is much less, thereby resolution of 2-D surface topography zoning and geological feature is concurrently reduced yet still acceptable for the model study. In contrast to the large scale model, the small scale model covers only 5 geological units (X1 ~ X5) with episodes of volcanic layer and some speculative structural features to be confirmed. Fig. 9(b) shows the corresponding results of a 3-D model counterpart with a form of block diagram in a VRML2 format (.wrl). Fig. 10 shows the profile diagram cutting across the HZV at due NS section in 2-D (Fig. 10a) and 3-D (Fig. 10b) views. There are two rectangular area shows the steaming grounds where two high geothermal resources (Site-1, and Site-2, see Fig. 11) have been identified to the north of the HAV crater.

Small scale model often covers limited stratigraphic formation and shows only monotonic model content as in the case of “HAV site”. It is more a site-specific scale than large scale model, hence the additional input of geological structures such as faults, fractures, and their intersections would be more important. Normally, detailed supplementary investigation data (drilling and downhole measurements, geo-physics, etc.) are often available and can be used to delineate structure locations and should be adopted as major model input for engineering applications, particularly in a geothermal site where fault intersections are generally regarded as major heat source migration path.

5. APPLICATIONS

HZV site model can be a good base to build more rational geothermal conceptual model for engineering applications. Although many existing investigation data surrounding the site are available, most cannot provide exact location of critical fault structures so as to allocating the optimal drilling and uncover the underground heat source economically.

Due to heavy tropical plant coverage and no outcrop of faults is observed in HAV site, it is noted that recent LiDAR images (2 meter resolution) may provide an excellent tool to examine the structure pattern by carefully examining volcanic remains and topographic characteristics. According to preliminary survey study, the area may be dominated by two major fractures (F1, F2), and their attitudes are found to strike in NW-SE (F1) and NE-SW (F2) direction with speculative scenarios of dip directions and angles as shown in Fig. 13.
Figure 9: Small scale models (Block Diagram).

(a) 2-D view (with satellite image)  
(b) 3-D block view

Figure 10: Small scale models (Profile Diagram).

(a) 2-D view with profile line (N-S direction)  
(b) 3-D profile view

Figure 11: Steaming grounds outcrop within small scale model.

(a) Field view of Site-1  
(b) Field view of Site-2
Due to difficulties in determining dip direction and angle, two scenarios (A, B) are assumed with a deterministic values as can be noted in Fig 13. To be simple, both fault planes of F1 and F2 are respectively assumed to be regular planes. All model elements are editable and subject to change when more accurate data are available, wherever necessary. In each scenario, the two faults (F1, F2) will intersect with each other, and a linear path will be created. Surrounding this path is a possible migration channel of the underground heat source, as illustrated in Fig. 14(a) for Scenarios-A and Fig. 14(b) for Scenarios-B respectively in a 2-D model view. Here the heat source path projection is in north of the intersection for Scenarios-A, and in south of the intersection for Scenarios-B. The situation in Scenarios-B is noted to be more accurate because the heat source pointing to the bottom of HZV, and heat source. Fig. 15 shows the 3-D model view of the situation on par with Fig. 14. The funnel-shaped HAV is picturized with two heat source paths (the red spheres) respectively for of the Scenarios A and B.

To study the drilling strategy with an established conceptual geological model, a profiling line in Fig. 14(b) for Scenarios-B is generated. It cuts through the heat source path shown for Scenarios-B in a perpendicular direction. Location of the profiling line and corresponding geologic profile are respectively shown in Fig. 16. In Fig. 16(a), the selected profile line cuts the intersecting axes of F1 and F2, the resulting geological section model as shown in Fig. 16(b). Where all the dots indicating projection of the intersected path, and blue dots represent those nearest to the profile section. This figure can be an important reference for studying optimal drilling direction and length. For instance, if the user chooses two points for well head and well bottom respectively, i.e. the colored symbols shown in Fig. 16(b), it is easy to know what kind of geological features will be encountered, and an optimal drilling length can be predicted. In this example, the drill length in between the two selected points (e.g., well head and bottom) is about 477 meters in order to touch the heat source along F1, F2 Intersection.

Figure 13: Possible fault patterns in the HAV site.
Figure 14: Estimated heat flow paths (Scenario-A, B) in small scale models.

Figure 15: 3-D view of heat flow scenarios (A, B) due to fault Intersection in small scale models.

Figure 16: Strategic evaluation to optimizing a drilling location use model profile.
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6. CONCLUSIONS

This paper illustrates the use of 3-D model construction tool (GeoModelBuilder-3D) developed by the author to generate two geological conceptual models with different scales. One is building geological conceptual model in the Tatun Volcanic Group (TVO area). The other is a candidate geothermal site near the north slope of Huang-Zuei Volcano (HZV site) within TVO.

The large scale TVO area model is a complex 3-D model and covers 18.6 x 15.6 km², which is successfully constructed with 27 entered relevant geological units. Comparing with published geological profile, both relevancy and capability of the GeoModelBuilder-3D are validated. The 3-D model output can be selected as block diagram, fence diagram, and profile diagram. These templates can be integrated in to a VRML2 formatted file to be visualized in 3-D manner.

In the small scale HZV site model, only an area about 2.62 x 2.76 km² is studied with much less geological formations within the model. More structural elements like faults can be used as input to study fault influences in a geothermal area and the possible heat source path along the fault intersections.

Applications following the results of small scale model show that a relevant fault scenario study can predict what kind of geological features will be encountered and how an optimal drilling direction and length can be predicted. The construction of 3-D model can be very useful in engineering decision making, if and only the geological data are relevant.

REFERENCES


