Quantitative comparison of two 3-D resistivity models of the Montelago geothermal prospect

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Abstract. A combined TEM-MT survey was carried out in the Montelago geothermal prospect, situated on Mindoro Island, the Philippines, with the aim to obtain the dimensions and depth of the geothermal reservoir as well as to formulate the prospects’ conceptual model. The acquired MT data are static shift corrected using the TEM measurements. Two different 3-D inversion codes are used to create subsurface resistivity models of the corrected MT data set. The similarities and differences between the two resistivity models are quantitatively assessed using a set of structural metrics. Both resistivity models can be generalized by a three-layered model. The model consists of a thin heterogeneous, conductive layer overlying a thick resistive layer, while the basement has a decreased resistivity. Although this is a common characteristic resistivity response for the alteration mineralogy of a volcanic geothermal system, the temperatures at depth are lower than would be expected when interpreting the modelled resistivity model accordingly. Since the last volcanic activity in the area was about one million years ago, it is anticipated that the resolved resistivity structure is a remnant of a hydrothermal system associated with a volcanic heat source. This model interpretation is validated by the alteration minerals present in the exploration wells, where high temperature minerals such as epidote are present at depths with a lower temperature than epidote’s initial formation temperature. This generalized description of the resistivity model is confirmed by both resistivity models. In this paper the two inversion models are not only compared by assessing the inversion models, but also by reviewing a set of gradient based structural metrics. An attempt is made to improve the interpretation of the conceptual model by analyzing these structural metrics. Based on these analyses it is concluded that both inversions resolve similar resistivity structures and that the location of the two slim holes drilled are well chosen.

1. Introduction
The Montelago geothermal prospect on Mindoro Island, the Philippines, has been the target of development studies over a period spanning several decades. The prospect is situated in Oriental Mindoro Province along the east coast of Mindoro Island as illustrated in Figure 1. Despite the mountain range being situated along the north-western shoreline of Mindoro, the topography of the prospect area is locally very rugged. The prospect area is about 2 km wide and 3 km long, striking in a north-west south-east direction. In the north-east the prospect area is bounded by Tablas Strait and in the south-west it is adjacent to Lake Naujan.

One of the most prominent components of the geothermal exploration work carried out in the Montelago geothermal prospect is the resistivity survey, carried out in 2014 [1]. The TEM-MT survey was carried out to verify the existence of the inferred geothermal reservoir as well as to
determine its dimensions for a volumetric assessment and, in case of sufficient potential, the location of the exploration wells.

The acquired resistivity data were 1-D inverted [1] and later 3-D inverted using two different inversion codes ([2] and this paper). The inversion code used by Arnason and Hersir [2] is WSINV3DMT [3], while in this paper the MT data are inverted using ModEM [4]. The structural resistivity differences between the two 3-D inversion models are discussed and later analyzed using a set of gradient based structural metrics. The consequences of these differences for the geological interpretation and the definition of the conceptual model are discussed subsequently. Another aspect discussed is the placement of the exploration wells.

2. Geology
The geology, geochemistry and conceptual model of the Montelago geothermal prospect is extensively discussed by PT LAPI ITB [5] and summarized here.

The volcanism present in the prospect area are part of a narrow north-west trending volcanic chain of Pleistocene-Quaternary age. Locally, this volcanic range overlies Tertiary sediments as well as the Paleozoic-Mesozoic basement consisting of meta-sediments and amphibolites. There are currently no active volcanoes present on Mindoro Island, where the latest volcanic activity is dated between 1.6 and 0.8 Ma. Within the prospect area, the volcanic centres are eroded.

The dominant tectonic setting of the prospect area has a northwest-southeast striking direction. This orientation controls the structural geology on the island, which is dominated by strike-slip faulting. In the prospect area, geological structures are dominated by northeast and northwest trending faults. Since the locations of the geothermal manifestations at the surface coincide with northeast trending faults, it is believed that these faults act as fluid path-ways for geothermal flow to the surface.

Hydrothermal clay alteration mineralogy present at the surface in the prospect area comprises interlayered illite-smectite as well as quartz-epidote-calcite minerals. The former is formed at temperatures of at least 150 ̊C and is typically found at depths greater than 50 m. The latter is formed at much higher temperature (> 240 ̊C). The occurrence of these two alteration minerals at surface suggests that either erosion has occurred or that the materials are brought...
to the surface.

The geochemical analysis of sampled waters from the hot springs indicates that the system is water dominated. Furthermore, the magmatic component in the thermal water is very small, which implies that the geothermal system is not related to shallow magma or recent volcanic activity.

On basis of the findings summarized above, a conceptual model of the geothermal reservoir was defined [5]. The elements of the conceptual model are shown as a north-south orientated cross section of the geothermal system in Figure 2. The Buloc-Buloc bay hot springs with a temperature of 40 °C, possibly originating from another geothermal reservoir. Recharge of the geothermal system is believed to be from Lake Naujan, located southwest of the prospect area. Thermal gradient well NGH-4 measured a temperature of 94 °C at a depth of 305 m. As the thermal gradient in this well is linear the drilled formation is impermeable, possibility a clay cap.

Figure 2. Map of the prospect area of the Montelago geothermal prospect (upper) and a not to scale cross section of the geothermal prospect (lower). Indicated on the map are a gradient temperature well (NGH-4) and which revealed a temperature of 94 °C at a depth of 305 m, Mount Montelago and the location of the cross section. Also the location of the Pungao (PHS) and Buloc-Buloc (BHS) hot springs are given, as well as the faults in the prospect area. BHS is located in the Buloc-Buloc bay. The main road and the two main villages in the area are shown in purple. In the cross section the inferred isotherms are also given. Coordinates of this and all following maps, besides when specifically mentioned otherwise, in this paper are projected in UTM zone 51N using the WGS-84 datum. The cross section indicates inferred outflow areas, faults and recharge.
It is inferred that the heat source of the system is a very deep cooling pluton. Reservoir temperatures are estimated to be at least 200 °C.

Two slim holes down to 1,200 m depth below the surface were drilled to test the conceptual model of the Montelago geothermal prospect. Both wells were fully cored and the drill cuttings were described using hand lens and microscope. Methylene Blue (MeB) analysis was carried out on the cores and the cuttings of both wells to identify the clay type and identify the top of geothermal reservoir when drilled into.

Determination of the clay type can be carried out following a simplified relation between MeB-index and clay type. This relation states that a small MeB index value (< 10) corresponds to illite or kaolinite clay minerals, while a high MeB index value (> 10) indicates smectite, interlayered illite-smectite or interlayered chlorite-smectite clay minerals.

Based on core and cutting description, high temperature alteration clay minerals such as epidote occur in well SH-1 at 900-1,200 m below surface and between 600-1,000 m below surface in well SH-2. The temperature at the depth interval in which epidote is found is below 200 °C [6]. In contrast to the well temperature as shown in Figure 3, epidote is formed at temperatures above 230 °C. This suggests that the present day temperature is lower than the paleo temperature. In other words, the alteration mineralogy found in the present day geothermal system is the remnant of a former geothermal system.

The results of the MeB analysis suggests that at a depth of 500 m below surface the clay alteration type in the geothermal system is changing from interlayered illite-smectite (or smectite) to illite (or kaolinite). Interlayered illite-smectite usually is an indication of clay alteration above the geothermal reservoir, while illite is commonly related to clay minerals formed at higher temperatures near the top of the geothermal reservoir.

3. Data acquisition and processing

Resistivity data were acquired using both MT and time-domain electromagnetics (TEM). The TEM measurements are used to correct for the static shift effect in the MT data [1,7].

A total of 54 stations were recorded with a remote reference station simultaneously recording about 40 km away from the survey area. Each MT station collected data for approximately 20 hours. During data acquisition every third station was a telluric station. The survey layout is a semi-grid with an interstation spacing of approximately 500 m as shown in Figure 4.
Recorded MT data are processed using Phoenix Geophysics software. Telluric stations are processed with the simultaneously measured horizontal magnetic fields from the nearest station. The MT data are static shift corrected by an automated iterative process, simultaneously inverting the invariant of the MT response and shifting the invariant towards the coincident 1-D TEM response [8].

Despite the presence of elevated power lines and several villages in the survey area, as well as the rugged topography, the data quality is assessed as fairly good. Nevertheless all stations showed some problems around the MT dead-band.

**Figure 4.** Map of the Montelago geothermal prospect area showing the measuring grid of the MT-TEM survey. Black stations are full MT stations and blue stations are telluric stations. Mount Montelago and the main road are also shown.

**Figure 5.** XY-view of the central area of the model mesh used for the 3-D inversion of the MT data using WSINV3DMT and ModEM.

4. Data inversion

The resulting MT data set is inverted using two different 3-D inversion codes. The first code, WSINV3DMT, is developed by Siripunvaraporn et al. [3]. The results of that inversion, WSINV_10_mod, are presented in Árnason and Hersir [2]. The second code is ModEM, developed by Egbert and Kelbert [4]. The results of this inversion, ModEM_10_mod, are presented in this paper. Subsequently a comparison is made between the inversion results of the two models, WSINV_10_mod [2] and ModEM_10_mod (this paper).

To make a meaningful comparison, inversion mesh and inverted frequencies are chosen to be as similar as possible. As the MT data are already corrected for static shift, it is assumed by Árnason et al. [7] that inverting the model without topography, but including bathymetry, and applying a post-inversion correction for topography will deliver the most reliable resistivity model. To produce comparable models, the same inversion strategy was chosen for the ModEM inversion of the MT data.
The model mesh used for both models consists of 52x48x32 cells (x,y,z). The model mesh and the MT coordinate system are rotated to -46°. In Figure 5 the central area of the model mesh is shown, as well as the location of the recorded MT stations within the mesh. The central area of the model is 5.7 by 4.5 km, while the cell size is at 200 x 200 m. The horizontal cell size increases semi-logarithmically towards the model boundaries. The smallest vertical cell size is 2 meters increasing semi-logarithmically with depth, to a maximum dimension of 110 km at the base of the mesh.

The 2014 MT data are resampled to 31 periods with six values per decade covering the period range 0.01 s to 1,000 s for the inversion using WSINV3DMT. The inversion using the ModEM code uses MT data resampled to 28 periods with five values per decade covering the same range of periods.

In their 3-D inversion Árnason and Hersir [2] run three models using different initial models: a.) a homogeneous half-space of 10 m, b.) a homogeneous half-space of 100 m, and c.) the resistivity model compiled from joint 1-D inversion of individual TEM and MT sounding pairs. It is concluded by Árnason and Hersir [2] that the inversion model using the 10 Ωm initial model shows the best fit to the data and gives the most realistic image of the resistivity structure of the subsurface. Therefore, a 10 Ωm initial model is also used for the 3-D inversion using ModEM. Where the final rms misfit of WSINV_10_mod is 1.74, the final rms misfit of ModEM_10_mod is 1.92.

5. Inversion results

The results based on the two different inversions are shown in Figure 6 and 7, in which the resistivity maps at 500 and 1,000 m b.s.l. are given. As visible in Figure 6, both models show strongly heterogeneous conductivities at a depth of 500 m b.s.l. High conductivities are observed at the boundaries of the survey area. While the resistive anomaly in the south part of the survey area seems to be coincident in the two models, WSINV_10_mod also shows a resistive anomaly below Mount Montelago that is not present in ModEM_10_mod. This resistive anomaly is still visible at a depth of 1,000 m b.s.l., as observed in Figure 7. At this depth, the resistivity maps based on the two inversion models are in pretty good agreement. However, at 1,000 m b.s.l. (Figure 7) the resistive anomaly in the south part in ModEM_10_mod is apparent as a single coherent anomaly, while in WSINV_10_mod the resistive anomaly consists of two discrete parts. Again, beneath Mount Montelago a resistive anomaly is present in WSINV_10_mod.

To consider these observations further, the cross section in the model x-direction (see the model mesh in Figure 5) for both 3-D inversion models is given in Figure 8. See Figures 6 or 7 for the location of the cross section. In Figure 8 it is observed that there is a difference in character of the resistive anomaly at depth between the two models. Although both models require a conductive layer at shallow depth, the deep resistive anomaly is significantly smaller in ModEM_10_mod compared to WSINV_10_mod.

The location of the exploration slim holes SH-1 and SH-2 is based on the resistivity model and tectonics.

6. Quantitative comparison

The bulk of the resistivity structures in the two 3-D inversion models presented in the previous section are related to geological structures, particularly those anomalies consistent between both models. However, some of the features may be artefacts introduced by the inversions. To make a quantitative comparison between the two models, a set of structural metrics, considered to identify those resistivity structures which are required by the model, are computed. This means that in order for the modelled data to fit the observed data, the resolved resistivity structures need to be there. As the solution of a 3-D inversion is non-unique, an anomaly appearing in two different inversions is very reassuring. Those resistivity structures not appearing in both
Figure 6. 3-D inversion results presented as resistivity maps at an elevation of 500 m b.s.l. of (a) ModEM\textsubscript{10\_mod} and (b) WSINV\textsubscript{10\_mod}. Resistivity values are in $\Omega$m. Coastlines, faults, Mount Montelago (grey triangle) and main roads are shown as well. The location of slim holes SH-1 and SH-2 are indicated (grey stars). Diamond symbols are MT stations and the black line is the location of the resistivity cross section shown in Figure 8.

Figure 7. 3-D inversion results presented as resistivity maps at an elevation of 1,000 m b.s.l. of (a) ModEM\textsubscript{10\_mod} and (b) WSINV\textsubscript{10\_mod}. Resistivity values are in $\Omega$m. Coastlines, faults, Mount Montelago (grey triangle) and main roads are shown as well. The location of slim holes SH-1 and SH-2 are indicated (grey stars). Diamond symbols are MT stations and the black line is the location of the resistivity cross section shown in Figure 8.
Figure 8. 3-D inversion results presented as resistivity cross sections in the model X-direction at X = 100 m of (a) ModEM\_10\_mod and (b) WSINV\_10\_mod. Resistivity values are in Ωm. The location of slim holes SH-1 and SH-2 are indicated. For the location of the cross section, see Figures 6 and 7.

inversion models might be introduced by the code and not related to geological structures. The robust and required resistivity structures appearing in both models might then be regarded as related to geological structures and consequently suitable for the geothermal interpretation of the resistivity models.

6.1. Method
The structural metrics used in this section are derived from a joint inversion approach where they are used to compare the structural resemblance between models of different geophysical methods. An overview of the available metrics is given in a review paper by Gallardo and Meju [9]. Rosenkjaer et al. [10] experimented with several of these metrics. Here two structural metrics are used to compare the two inversion models.

(i) The difference between the normalized model gradients of the two resistivity models \(\delta\varphi\),

\[
\delta\varphi = \frac{\nabla m_1}{\|\nabla m_1\|} - \frac{\nabla m_2}{\|\nabla m_2\|}.
\]

(ii) The norm of the cross product of the two model gradients, the cross gradient \(\tau\), delivers a direct comparison between the two resistivity models:

\[
\tau = \nabla m_1 \times \nabla m_2.
\]

Here \(\mathbf{m}\) is the three-dimensional model matrix of the inversion model.

These structural metrics are computed for the WSINV\_10\_mod and ModEM\_10\_mod models. The results are presented for the resistivity maps and cross sections as shown in Figures 6, 7 and 8.

6.2. Discussion
The difference between the normalized model gradients of the two inversion models at an elevation of 500 and 1,000 m b.s.l., respectively, are given in Figure 9. At an elevation of 500 m b.s.l. the differences between the two model gradients are large, except for an area at the center of the models. The differences between the gradients are large at the locations of the
resistive anomalies and at the boundaries. Experiments with synthetic data showed that small differences in the exact locations of a resistive structure can lead to large differences between the model gradients. This is for example visible at an elevation of 1,000 m b.s.l. The difference between the two models in shape and location of the resistive anomaly in the south part of the area leads to large $\delta \varphi$ values. In this case, the large $\delta \varphi$ values might confirm the presence of the resistive anomaly in the south part of the prospect area and provide an indication of the actual boundaries of this anomaly. Here, it might be inferred that the minimum edge of the boundary is located at the east side of the corresponding large $\delta \varphi$ area. Beneath Mount Montelago the gradient of WSINV$_{10}$mod is variable while the gradient of ModEM$_{10}$mod at this location is relatively constant. This leads the large gradient difference below Mount Montelago.

![Figure 9](image)

**Figure 9.** Magnitude of the difference between the normalized model gradients of the inversion results of WSINV$_{10}$mod and ModEM$_{10}$mod at an elevation of (a) 500 m and (b) 1,000 m b.s.l., respectively. Red colors indicate those locations where the difference between the model gradients is relatively large and blue colors indicate those locations where the model gradients are relatively similar. The coastlines, faults, main roads, as well as the locations of Mount Montelago and the two slim holes drilled in 2015 are shown as well. In the map to the right the 70 Ωm resistivity contour of the two models (dotted line: ModEM$_{10}$mod; solid line: WSINV$_{10}$mod) is given. The black line is the location of cross section shown in Figure 11.

In Figure 10 the norm of the cross product of the model gradients at 500 and 1,000 m b.s.l., respectively, is plotted. Where the resistivity values of two models are significantly different, even when the structures are comparable, experiments with synthetic data showed that the cross gradient will show large differences between models. This is the case at an elevation of 500 m b.s.l. Similar shapes at different locations can be identified by a high cross gradient, while a low cross gradient indicates areas where the resistivity shows little variation in both models. At an elevation of 1,000 m b.s.l., the minimum area covered by the resistive structure in the south part of the survey area is indicated by the low cross gradient area. Although, resistivity values are significantly different, the resistive anomaly below Mount Montelago is present in both models, indicated by an area of "stable" resistivity.

In Figure 11 the difference between the model gradients and the norm of the cross product of the model gradients of the resistivity cross section as shown in Figure 8 is plotted. In the
Figure 10. Norm of the cross product of the model gradients of the inversion results of WSINV\textsubscript{10}mod and ModEM\textsubscript{10}mod at an elevation of (a) 500 m and (b) 1,000 m b.s.l., respectively. Red colors indicate those locations where the cross gradient of the models is relatively large and blue colors indicate those locations where the cross product of the model gradients is relatively small. The coastlines, faults, main roads, as well as the locations of Mount Montelago and the two slim holes drilled in 2015 are shown as well. In the map to the right the 70 \text{\Omega}m resistivity contour of the two models (dotted line: ModEM\textsubscript{10}mod; solid line: WSINV\textsubscript{10}mod) is given. The black line is the location of cross section shown in Figure 11.

Figure 11. Cross section of the magnitude of (a) the difference between the normalized model gradients and of (b) the norm of the cross product of the model gradients of the inversion results of WSINV\textsubscript{10}mod and ModEM\textsubscript{10}mod at X = 100 m. The location of wells SH-1 and SH-2 are indicated on the cross sections.

difference between the model gradients, the differences in the resistivity structures at a depth of 2,000 m are easily observed. On the other hand, the sharp boundary at Y = -300 m indicates the probable position of the resistive anomaly. The low cross gradient values below -1,000 m indicate that both models agree on the resistive structures at this depth. The resistive heterogeneity at
shallower depth is reflected in the high cross gradient values.

The anomalies in the resistivity models and the cross gradient structural metric at greater depths coincide with the location of the faults in the prospect area, indicating a certain degree of fault control of the geothermal prospect. This finding is confirmed by the structural geology data in the prospect area.

The analysis of these structural metrics becomes especially interesting when an attempt is made to interpret them in relation to the positioning of wells. Slim holes SH-1 and SH-2 were drilled in 2015 and proved the existence of the geothermal reservoir. Based on the structural metrics, the location of SH-1 is well chosen, drilling right by the structural metrics confirmed presence of the resistive anomaly. SH-1 reached the reservoir at a depth of 1,200 m b.s.l.

7. Conclusions
The two 3-D inversion models of the same MT data set from the Montelago geothermal prospect show roughly similar resistivity structures, although on a detailed scale differences are noticed. This gives a confidence in the present resistivity model.

Although having significantly different characteristics in both models, a resistive anomaly is present below Mount Montelago. The presence of the anomaly is confirmed by the analyses of the structural metrics. At this point it is unclear why this anomaly is relatively conductive in ModEM_10_mod and relatively resistive in WSINV_10_mod.

By evaluating the inversion models using two structural metrics, the existence of most of the main resistivity anomalies could be validated. The metrics presented here highlight other aspects of the similarities and differences between the two models.

Although a classic clay alteration resistivity profile is present, the actual temperatures are not matching with the clay alteration mineralogy found in the exploration wells. Consequently it can be concluded that the clay alteration of the Montelago geothermal system is the product of a paleo hydrothermal system.

Both resistivity models can be generalized by a three-layered model. This model consists of a thin heterogeneous, conductive layer overlying a thick resistive layer, while the basement has a decreased resistivity.

Based on the structural metrics, the location selected for slim hole SH-1 is well chosen.

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