

RESISTIVITY METHODS APPLIED TO GEOTHERMAL EXPLORATION IN THE PHILIPPINES

Chris J. Bromley and Onofre S. Esparola

Kingston Reynolds Thom & Allardice (KRTA)
Philippine National Oil Company (Energy Development Corp.)

ABSTRACT

A number of resistivity methods have been used in the search for geothermal resources in the Philippines. The strengths and weaknesses of these methods are reviewed, using examples taken from surveys conducted in Tongonan, Southern Negros, Biliran, Mambucal, Davao and Bacon-Manito. Experience acquired from interpreting the substantial amount of resistivity data collected using Schlumberger-array traverses, vertical electrical soundings, and the dipole-dipole technique, suggests that maximum information can be gained from an integrated interpretation of these data. Dipole-dipole pseudo-sections should be modelled using soundings to define the near-surface layers. Both low and high resistivity anomalies delineated by traversing surveys should be checked by soundings to determine the vertical resistivity structure. Sounding sections are also useful to assist hydrological modelling in cases where the main resistivity anomalies are associated with extensive shallow outflows of geothermal fluid.

INTRODUCTION

The resistivity method is generally regarded to be the most useful geophysical technique for assessing a geothermal resource prior to drilling. The electrical conductivity of electrolytes increases rapidly with temperature. Hot geothermal fluids are also more saline, and hence more conductive, than cold meteoric fluids. Hydrothermally altered rocks associated with geothermal fluids also have lower resistivities. These factors combine to produce values typically less than 5 ohm meters in water-dominated geothermal systems. However, ambiguity can be introduced by the effect of steam zones (which have typically higher resistivities), sedimentary formations (which can have low resistivities), and the presence of highly altered conductive clays, which can be relatively impermeable and cold. Because of these ambiguities, temperature gradient measurements, geological, hydrological and geochemical surveys are often used to assist the interpretation of resistivity measurements.

The Schlumberger array traversing or mapping technique involves a series of measurements along profile lines at set electrode spacings (usually 250 and 500 m). It is a useful and rapid method for locating resistivity anomalies over a large area. A Schlumberger array sounding involves more

detailed measurements at one location to obtain a layered model of the vertical resistivity structure. Soundings must be located carefully to avoid vertical resistivity boundaries, because of the distortions they produce on sounding curves, which tend to invalidate the 1-dimensional layered interpretation. The dipole-dipole array is more difficult to interpret, but is often used to investigate the deeper 2-dimensional resistivity structure. The dipole-dipole field procedure is simpler, faster and safer than extended soundings, but a larger current is required. Soundings can be interpreted, while in the field, using curve matching procedures, and a programmable calculator. Dipole-dipole pseudo-sections, however, should be interpreted using 2-dimensional computer modelling taking into account terrain variations, and changes in near-surface resistivity.

SCHLUMBERGER ARRAY TRAVERSING INTERPRETATION

The simplistic approach of treating every low resistivity anomaly, identified by a regional traversing survey, as a potential geothermal resource can lead to serious errors in exploration strategy. It is important to consider possible hydrological models for subsurface fluid flow, and changes in lithology and rank of alteration of the near surface formations, before committing to drill an apparent resistivity anomaly. Apparent resistivities are strongly influenced by the near surface layers, and so a formation containing low resistivity fluids can be masked by a thin layer of fresh, dry, volcanic rock at the surface. Likewise, an area of shallow clays from a relict hydrothermal system can produce an anomaly with no present-day geothermal significance.

All of the geothermal fields considered here, exist near areas of quaternary volcanism, with prime resource areas at relatively high elevations. This setting is characterized by extensive subsurface outflows of geothermal fluid, travelling some tens of kilometers, and approaching the surface at low elevations only, where they form large resistivity anomalies. These skirt the area of prime interest (at high elevation), which is often masked by a thin, near-surface layer of fresh volcanics. Mambucal (Northern Negros), Bacon-Manito, and Southern Negros are good examples.

One technique which can be employed to help overcome the masking problem is to consider the ratio of apparent resistivities measured at 250

Bromley, Española

and 500 m spacings. Decreasing resistivity implies promising conditions at depth, whereas an increasing resistivity suggests that the anomaly is merely superficial.

SCHLUMBERGER ARRAY SOUNDINGS

Many of the interpretation problems associated with traversing anomalies can be resolved by a program of soundings. These rely on an assumption of uniform 1-dimensional layering, so the arrays should be carefully sited to avoid crossing resistivity contrasts (especially near surface) or excessive changes in topography. Where an anomaly can be related to a subsurface outflow of geothermal fluid, it is useful to draw two-dimensional sections through the soundings to trace the top surface (and sometimes the basement) of the outflow. By assuming a hydrological gradient from high to low elevation, the flow direction can be determined. Tracing back along the flow paths of several outflows will assist location of the primary high-temperature up-flow region, which may be too deep to be detected by standard resistivity methods. True resistivities from these sounding sections can also be correlated with hot spring chemistry to assist hydrological modelling. For example, in Burauen (Leyte) and Baslay-Dauin (Southern Negros), the top surface of a low resistivity anomaly ($<10 \Omega \text{m}$) can be associated with springs containing a chloride fluid component, while intermediate resistivity formations (20-80 Ωm), at higher elevation, correlate with steam-heated, acid-sulfate springs.

DIPOLE-DIPOLE INTERPRETATION

Interpretation of dipole-dipole data is limited by problems common to all potential methods, namely that, without realistic boundary conditions, numerous different models can fit the same set of data. Interpretation of pseudo-sections also suffers from additional problems in that the value of apparent resistivity is strongly affected by the resistivity beneath the current dipole (in contrast to Schlumberger arrays) and that in straddling a vertical boundary, the apparent resistivity obtained with a dipole-dipole array is not a simple function of the resistivity of the two media. Although, in the case of homogenous cover, it is possible to detect deeper resistivity structure with the dipole-dipole method, this becomes a difficult task if the cover is in-homogeneous. If no other data are available to define the gross structure of such in-homogeneous surface cover, interpretation of observed dipole-dipole data, in terms of a deeper structure, can be inaccurate and misleading. For this reason, it is important to use vertical soundings to provide realistic values for the near-surface resistivity structure (Hochstein, et al 1981). In addition, terrain can have a severe effect on dipole-dipole pseudo-sections. (Fox, et al 1980). Attempts to interpret pseudo-sections by neglecting topography and choosing a horizontal surface as upper boundary for the models, should be treated with suspicion unless the terrain is relatively level (slope angles less than 10°). Because of this sensitivity to topo-

graphy, dipole-dipole lines (and also Schlumberger soundings) should always follow the smoothest possible terrain. A grid pattern is not advisable in the mountainous regions of most Philippine geothermal fields.

Previous interpretation (Smith 1975, 1978) of Philippine dipole-dipole data from geothermal fields in Tongonan, Southern Negros, Davao, Mambucal and Bacon-Manito, is open to criticism, as it has involved little more than smoothing the data and increasing resistivity contrasts, while neglecting topographic and other distortions. Model studies show that computer-generated pseudo-sections often bear little resemblance to the true resistivity models. By using a finite element computer program, better use can be made of existing dipole-dipole data, and more refined interpretations prepared. In the following case studies, however, only qualitative interpretations have been used for comparison with results from the other resistivity methods.

CASE STUDIES

Tongonan

The role of resistivity in establishing a model for the Tongonan geothermal field was discussed by Whittome and Smith (1979). A dipole-dipole survey of the area was conducted in 1980 (Rian) to confirm the resistivity anomalies mapped from earlier Schlumberger traversing results and compare the methods. A grid of 12 lines revealed apparent resistivities of less than $100 \Omega \text{m}$ over most of the field. Near surface anomalies in the Mahiao, Sambaloran, Malitbog and Bao Valleys are similar to the traversing anomalies. However, there are some important dissimilarities at greater depth: the lateral resistivity contrasts are much less than the contrasts in the traversing survey. After careful interpretation of the pseudo-sections, it appeared that the dipole results showed an extension of low resistivity at depth, whereas the traversing 'boundaries' were strongly influenced by near surface high resistivities related to topographic highs. Two examples of this false boundary problem are the western edge of the Mahiao and Bao Valley anomalies, where there now appears to be a deep link with the lowland anomaly in the Ormoc-Kananga Valley, and also between Mahanagdong and Mamban, where dipole data predicts a connection, and traversing data suggests a high resistivity barrier. In 1981, soundings were sited to check these interpretations. They confirmed the existence of a deep low resistivity link ($30 \Omega \text{m}$ at sea level) removing the western 'boundary' of the Tongonan resistivity anomaly. This link is interpreted to be an outflow. Its existence is an important consideration for reinjection strategy. There is evidence from the traversing data to suggest that similar outflows exist to the northwest (Lemon) and northeast (Carigara). Another sounding on the small peak northwest of Mahanagdong confirmed the dipole-dipole model of continuous low resistivity, and showed the traversing data to be affected by 150 m of surface cover. Dipole lines through the Bao

Valley reveal increasing resistivity at depth, matching temperature reversals in nearby shallow TGE wells.

Reinterpretation of the Tongonan resistivity data shows that an integrated approach using soundings, traverse data and dipole-dipole sections, can provide much more information about the true nature of the resistivity anomalies than an interpretation based on just one technique.

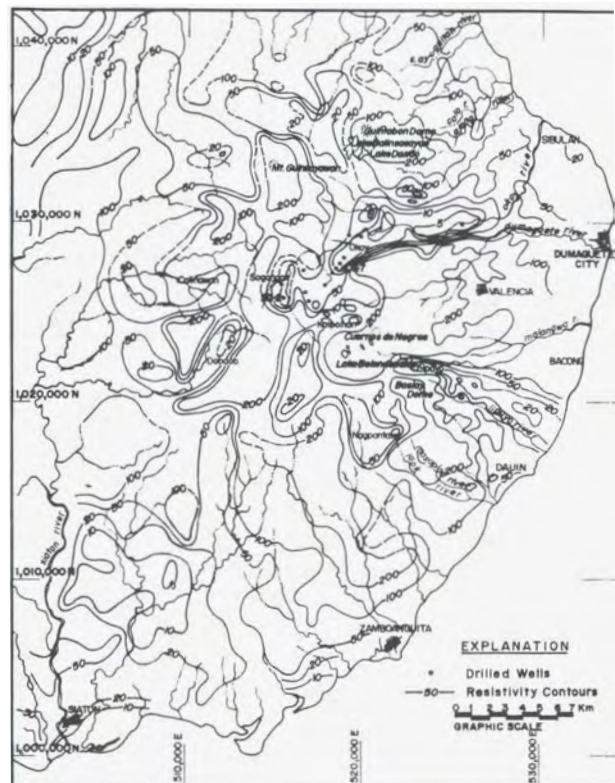


Southern Negros

Extensive resistivity surveys have been carried out over a decade of exploration in Southern Negros. Contour maps of the results from traversing surveys show widely scattered anomalies throughout the geothermal reservation (700 km²). These reflect near-surface flows of geothermal fluid and shallow zones of hydrothermal alteration. Recently, attention has focused on using dipole-dipole and sounding data to connect these anomalies and identify their origins. One of the earlier dipole-dipole surveys (Smith 1975) identified deep anomalies beneath the Kaipohan area south of the present development at Puhagan, east towards Valencia, and southeast towards Baslay. The interpretation suggests that the Okoy Valley and Baslay anomalies are connected to one deep system, centered beneath the Cuernos de Negros peak or Kaipohan. A program of soundings (Bromley 1982) further tested this postulate and deep drilling (3 exploration wells) is planned for the Baslay sector soon (see Harper, Arevalo - this publication). One sounding also supported the southerly extension of

the anomaly in Sogongon, connecting it to the anomaly west of Cuernos peak. Several soundings, and one dipole line in 1975, confirmed that the Lipayo and Nagpantaw anomalies are connected, and identified a very low resistivity anomaly (less than 10 Ω m), capped by a thin layer of high resistivity (5000 Ω m), within a 200 Ω m traversing contour south-east of the Baslay Dome.

Suggested connections between the Sogongon anomaly and Calinawan, Dobbob anomalies (further west and southwest) will also be tested by deep drilling in 1983. Interpretation of a dipole-dipole survey in the Valencia-Sibulan-Okoy area (Smith, 1978) suggests a southerly extension of the Okoy anomaly at depth. Macdonald (1978), challenged this conclusion, saying that the lack of contrast at depth could be a function of electrode configuration. He used contour maps of the dipole-dipole apparent resistivities at various spacings (N=1, 3, 5), to show that there was a correlation between the N=1 contours and Schlumberger traversing contours at AB/2=500m, but doubted the value of dipole-dipole data with N greater than 1 because the interpretation is confusing. However, subsequent directional drilling to the southeast of Puhagan substantiated the dipole-dipole model of a deep extension of the resource beyond the boundary that had been predicted from traversing contours. A recent sounding in this area confirmed the extension, showing a true resistivity of 25 Ω m, beneath a thick cap (420 m) of high resistivity. It is dangerous to use contour maps



APPARENT RESISTIVITY CONTOURS AT AB/2 = 500 M SOUTHERN NEGROS GEOTHERMAL PROJECT

Bromley, Esparola

of dipole-dipole pseudo-section data, without first interpreting the sections. Lateral variations in near-surface resistivity do have a marked effect on the deeper values in pseudo-sections, (as well as affecting the traversing apparent resistivities), causing them to differ significantly from the true resistivity values. However, computer modelling can readily solve this problem by enabling the interpreter to eliminate the effects of near surface changes in resistivity.

A large anomaly further south, near Siaton, was also investigated in detail using traversing and dipole-dipole surveys (Smith 1977), and began to look promising, until four shallow temperature gradient wells revealed disappointingly low temperature gradients (max 46°C, 10°C/100 m). A re-appraisal of the data suggests that the anomaly is mostly confined to shallow and intermediate levels, with a higher resistivity basement, except in localized areas (e.g. beneath the Siaton river), where the dipole survey could not penetrate beneath the anomaly. It is now interpreted to be an outflow from a source to the northeast, near Cuernos de Negros.

Mambucal (Northern Negros)

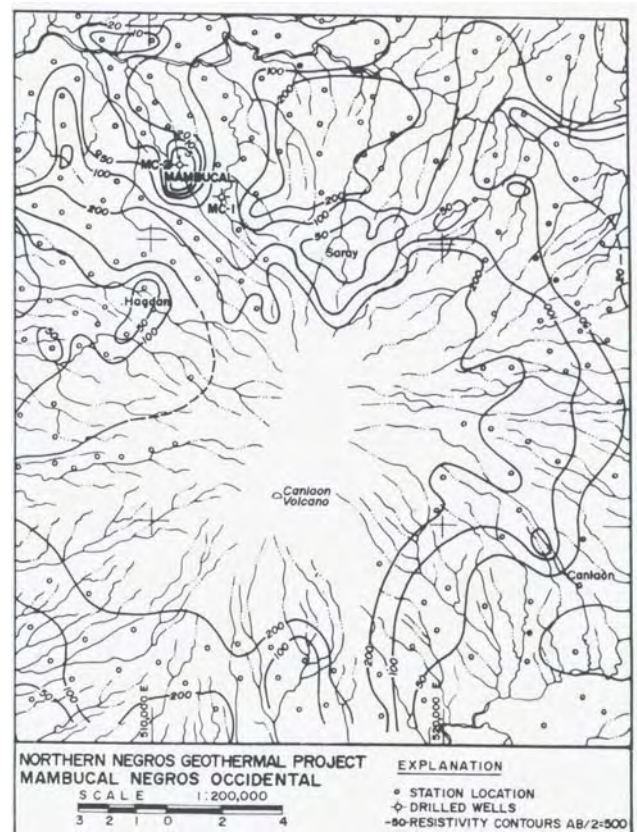
Resistivity surveys in Northern Negros have included: regional traversing at spacings of 250 m, 500 m (and 750 m over a smaller area), 5 soundings, and a dipole-dipole survey covering about 30 km², centered on Mambucal.

One justification used for selecting a resistivity anomaly at Mambucal for exploration drilling was the high lateral resistivity gradient (or contrast) along the southwestern side of the traversing anomaly which was considered to represent a well-defined geothermal boundary. A careful reconsideration of the data suggests there is no such boundary. Plotting the apparent resistivity values (at 3 different spacings) as miniature soundings, shows that the true deep resistivity to the southwest of Mambucal must be less than 50 Ωm and is probably less than 20 Ωm. Likewise, to the west, south and southeast of the Mambucal anomaly, there is no real evidence of a high resistivity boundary at depth. The top few hundred meters of high-resistivity volcanic tuffs and lavas appear to be crediting the apparent resistivity contrasts. This is more clearly demonstrated by dipole-dipole pseudo-sections, which show an extensive outflow throughout the area around Mambucal, with no evidence of lateral boundaries. However, there is a distinct high resistivity basement. (Two shallow exploration wells have intersected this outflow of about 160°C fluid, although no temperature reversals were observed). Previous reviews of the resistivity data have tended to ignore the dipole results because of the argument that they are severely distorted by near-surface anomalies. Interpretation, in this case, however, is relatively easy because the Mambucal pseudo-sections are uniformly layered.

A combined interpretation suggests that the three shallow traversing anomalies, Mambucal, Hag-

dan and Saray, are connected at depth and derive from a common source beneath high ground north of Canlaon (an active volcano). Resistivity anomalies around the eastern and western flanks of the volcano may also be connected to the same system. These predictions will be further tested by a program of soundings before targets for additional deeper drilling are considered.

This area illustrates, once again, the problems of the traversing method, where large vertical resistivity gradients exist. Lateral gradients implied from contouring the apparent resistivities can be misleading.



Davao

Recent reinterpretation of soundings and dipole-dipole data from this prospect (Layugan 1982), has shown that anomalies in Manat and Elizalde are shallow (100 to 200 m thick), with increasing resistivity at depth. Three medium-depth exploration wells were sited on these anomalies. The Manat wells encountered temperature inversions at shallow depth, with maximum temperatures below 100°C. Despite the existence of extensive relict alteration at depth (Arevalo 1979), which can reduce the resistivity contrast between hot fluid aquifers and cold impermeable ground, there is still a good correlation between the latest resistivity model and the observed temperature inversions.

Subsequent deep soundings (1982), in the Lake Leonard and Amacan areas (further south) have also revealed increasing resistivity at depth. It is presently thought that this high resistivity basement represents a quartz-diorite batholith.

Biliran

The island of Biliran has been well covered by a traversing survey (1978), supplemented by 45 soundings (1978, 1981) and 5 dipole-dipole lines. Where possible, the dipole-dipole pseudo-sections were interpreted in conjunction with models from nearby soundings so as to reduce the limitations caused by near-surface anomalies. The deeper resistivities of the sections were adjusted until a match with the observed pseudo-sections was obtained by using qualitative comparisons with computer generated pseudo-sections from model studies.

Several important features of the 2-dimensional resistivity structure were revealed by the dipole-dipole data but were not apparent in any of the soundings (Bromley, 1981). This illustrates the importance of the dipole-dipole technique as a back-up to the other resistivity methods when additional information at greater depth is required. For example, one line revealed extensive low resistivity at depth northwest of Kalam-bis. Also, a deep low resistivity body east of Vulcan (detected by soundings) is, according to the dipole-dipole sections, the result of an outflow. Likewise, it was demonstrated that a resistivity anomaly to the west of Mt. Sayao is an extensive outflow. Finally, a line through the Panamao anomaly, reveals increasing resistivity at depth along the entire section, implying that this anomaly is also an outflow from a displaced source (perhaps Mt. Panamao).

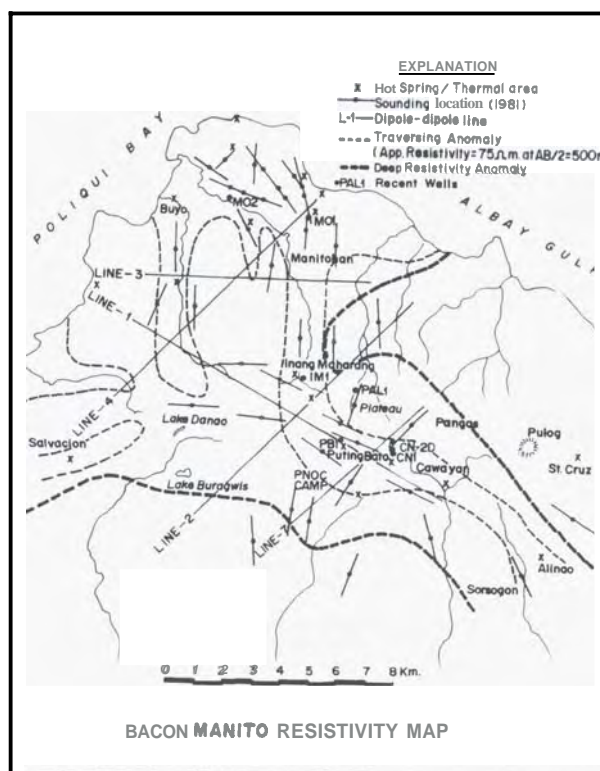
A combined interpretation of the main anomaly suggests a large active geothermal system centered near Vulcan, with outflows to the west and east and an extension towards Kalambis to the south-east. This is presently being tested with a three well exploration program (see Lawless, Gonzales - this publication).

Bacon-Manito

The Manito area (Southern Luzon) has been extensively surveyed with resistivity measurements, including traversing over about 270 km², 70 soundings, and 7 dipole-dipole lines. The results show narrow linear anomalies on the traversing contour map (mainly at low elevations where geothermal fluids are close to the surface); but a much larger resistivity anomaly at depth was deduced from sounding and dipole-dipole interpretations. The total anomalous area is now in excess of 160 km². The soundings show that the Palayang Bayan plateau area of high apparent resistivity north of Puting Bato is, in fact, underlain by very low resistivities. There also appears to be a hydrological gradient between the plateau and Inang Maharang, suggesting an outflow to the northwest. The soundings also indicate a connec-

tion between the Manito and Buayo river traversing anomalies suggesting that the northern outflow is continuous at depth. A deep outflow to the southeast (down the Cawayan valley, towards Sorsogon), has been confirmed by soundings and also a deep low resistivity body beneath Lake Danao, which extends the anomaly to the west. Soundings to the south of the PNOC camp, and east of Mt. Pulog indicate high resistivity boundaries in those directions.

Dipole-dipole lines, although concentrating mainly on the northern lowlands, provide some useful information on the deeper resistivity pattern within the area as well as confirming the shallow and intermediate depth anomalies detected using the Schlumberger array methods. Line 2, for example, suggests a deep southwest extension of the near-surface anomaly at Inang Maharang towards Lake Buragwis, and shows a boundary 3 km northeast of Inang Maharang. Lines 3 and 4 confirm the outflow to the north, linking Manito, Buayo and Salvacion rivers, and show a high resistivity basement at about 800 m depth. Lines 5 and 6 show some variations in the thickness of the outflow in the northern lowlands (also confirmed by a few soundings which penetrated through the outflow). Based on these conclusions, a geophysical prognosis of the northern lowland anomaly predicted a shallow outflow of hot chloride fluids associated with extensively altered rock (producing a true resistivity of 1 Ω m), and a basement at depths varying from 400 to 1200 m. Results from two



Bromley, EspaRola

recent exploration wells (M01, M02) confirmed this prediction, showing medium temperatures (about 200°C) at shallow levels, and a temperature inversion with depth has been determined in M01.

It can be seen that the more refined techniques of vertical sounding and dipole-dipole interpretation have greatly assisted the reservoir modeling process in Bacon-Manito. A final model, deduced from a combined interpretation, suggests a resource centered north of Cawayan, with a possible extension to the east. This model is presently being tested with a program of deep drilling on Palayang Bayan plateau. Extensively altered volcanics encountered below 330 m depth in PAL-1 correlate with a nearby sounding model which showed a layer of $17\Omega\text{m}$ at 370 m depth.

CONCLUSIONS

1. Lateral apparent resistivity gradients or contrasts from Schlumberger traversing contours, at set spacings, should not be used to define a geothermal anomaly without first checking the vertical resistivity structure, using soundings, in areas of both low and high apparent resistivity.
2. Sounding locations should be chosen after a traversing survey, and oriented to avoid crossing large contrasts in apparent resistivity and excessive changes in topography. Sections should be drawn from the interpreted sounding models (using true resistivities), to help produce a hydrological model for fluid outflows from the geothermal reservoir. This can then be correlated with a geochemical model, and assist in locating the prime up-flow region of the resource. Shallow outflows (with temperature reversals) can sometimes be successfully identified by noting increases in resistivity with depth.
3. Where dipole-dipole lines are warranted to investigate deeper resistivity anomalies, they should be accompanied by soundings to assist interpretation. Surface topography and accurate models of the shallow resistivity are necessary inputs for a reliable interpretation of pseudo-sections. To minimize distortions, dipole-dipole lines should also be sited carefully to avoid excessive changes in slope.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the assistance of PNOC-EDC geophysicists, especially D. B. Layugan, M. C. Vergara, O. R. Rian, N. A. Apuada and R. C. Rodriguez for their valuable contribution to the data collection and interpretation of these surveys.

BIBLIOGRAPHY

- Arevalo, E. M. 1979. "Evaluation of North Davao Geothermal Prospect, Mindanao". N.Z. Geothermal Institute Project
- Bromley, C. J. 1981. "Biliran Geophysics Resistivity Interpretation Report". KRTA Internal Report
- Bromley, C. J. 1981. "Baslay-Dauin Resistivity Surveys-VES Interpretation". KRTA Internal Report
- Fox, R. C., G. Hohmann, T. Killpacks, L. Rijo (1980). "Topographic Effects in Resistivity and Induced Polarization Surveys". Society of Exploration Geophysicists Journal, 1980.
- Hochstein, M. P., G. Caldwell, C. J. Bromley 1981. "Reinterpretation of Resistivity Data Over the Olkaria Geothermal Prospect". Proc. Geothermal Institute Workshop N.Z. 1981
- KRTA Report 1980 "Northern Negros Geothermal Exploration"
- KRTA Report 1978 "Evaluation of Geothermal Potential and Recommendations for Exploration Drilling, Northern Negros"
- Layugan, D. B. 1982. "Review of Geophysical Surveys in the North Davao Geothermal Area". 4th PNOC-EDC Geoscientific Conference
- Macdonald, W. J. P. 1978. "Comments on a Dipole-Dipole Survey of the Palinpinon Area, Southern Negros". DSIR-KRTA Internal Report
- Rian, O. R. 1980. "Phase I Dipole-Dipole Resistivity Survey Tongonan, Leyte Geothermal Project". PNOC-EDC Internal Report
- Smith, P. K. 1975. "Report on Reconnaissance Survey of Dumaguete Geothermal Project" for POGI (Philippines), by McPhar Geoservices
- Smith, P. K. 1978. "Report on Resistivity Survey (Dipole-Dipole) Mambucal, Negros Occidental" for PNOC-EDC, by McPhar Geoservices (Phil), Inc.
- Smith, P. K. 1978. "Report on Resistivity Surveys in Siaton and Valencia, Sibulan" for PNOC-EDC by McPhar Geoservices (Phil), Inc.
- Whittome, A. J., E. W. Smith. "A Model of the Tongonan Geothermal Field" Proc. N.Z. Geothermal Workshop 1979