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GEOPHYSICAL MODELLING AND RESERVOIR MONITORING STUDIES OF SOUTHERN NEGROS GEOTHERMAL FIELD

C.J. Bromley*, D.M. Rigor, Jr., R.C. Rodriguez, D.B. Layugan, C.P. Ignacio

*K.R.T.A. Ltd.
P.N.O.C. - Energy Development Corporation

ABSTRACT

In southern Negros, subsurface reservoir modelling using surface geophysical exploration methods, has involved two-dimensional interpretation of gravity and aero-magnetic surveys, and layered interpretation of vertical electrical soundings for hydrological modelling. Monitoring activities include the detection and location of induced microearthquakes, and the establishment of base-line gravity readings, on a network of accurately surveyed bench-marks, for future mass-withdrawal and subsidence studies. This paper presents some preliminary results from these modelling and monitoring activities.

GRAVITY SURVEY

Between July 1981, and April 1983, gravity readings were obtained from a total of 408 stations including 43 permanent benchmarks in Southern Negros. These benchmark readings form a precise gravity data base, for future monitoring of mass changes during the production history of the field. The bench marks have also been accurately surveyed (second-order precision) as a base-line for future deformation and subsidence studies. A "La Coste and Romberg" gravity meter was used throughout the survey, which spanned several field seasons. The Capitol Building of Dumaguete City was chosen as the reference station. Data reduction and interpretation involved the use of several customized programs on a portable computer. Instrument readings were corrected for tidal variations, using an algorithm by Longman (1959), with a phase lag of 1 hour and 'conformance factor' of 1.36 between the observed and calculated tidal response. Daily instrument drift was negligible. Corrections for latitude, elevation, Bouguer plate, and terrain were applied to calculate the Bouguer anomalies. Terrain corrections were computed using Hammer zones. Elevation differences for zones B and C were estimated in the field, and for zones D to F were obtained from a graticule overlay of 1:5000 scale maps. Zones G to M corrections were computed automatically from a data file that contains elevations on a 500 m grid covering the reservation. Sea level was chosen as the datum level elevation, and an average density of 2.67 gm/cc was used for the Bouguer plate and terrain corrections. This density is consistent with the reference basement density used in most New Zealand gravity studies, and also, closely approximates average saturated core densities from wells in the Okoy Valley, and Baslay-Daurn. (Average wet density of 55 deep core samples taken from the Southern Negros Formation, [predominantly altered andesites], is 2.76 gm/cc, while average wet density of 18 deep core samples from the Dauin volcanics is 2.56 gm/cc.)

The resulting Bouguer anomalies, calculated regional trend, and the final residual anomalies are contoured in figures 1, 2 and 3. The regional gravity trend was calculated using polynomial best-fit trend-analysis program applied to 96 regional Bouquer gravity values, (excluding a circular area of radius of 10.5 km, covering the central part of the field). A linear (first order) trend produced the best fit, with correlation trend, increasing from east to west, is also consistent with the regional trend observed in the free-air anomaly map of the Philippines (Bowen, 1982). The residual anomaly map (Bouguer-regional) reveals the following: a large positive anomaly centered between wells OK3 and OK1 in the Okoy Valley: a significant negative anomaly centered on the eastern peak of Cuernos de Negros volcano: a smaller negative anomaly over the Baslay Domes, with flanking positive anomalies. To check the reliability of the contour maps, an automatic contouring program was also applied to data from the 43 bench-marks. (Accurate elevations of these benchmarks are known, whereas elevations of the other stations were obtained, with less accuracy, from field altimeters.) Both Bouguer anomaly and residual anomaly contour maps, plotted from this reduced data set, reveal a pattern that is very similar to the hand-drawn contour maps.

Interpretation of the residual anomalies involved two-dimensional density-modelling, along three sections, using an interactive modelling program. The locations of these sections and a plan-view of the final density model is shown in figure 4. Two sections, through the Okoy Valley anomaly, are shown in figures 5 and 6. They illustrate the topography, density model, the observed gravity data, and the calculated fit. The modelling process included an initial attempt to fit the gravity data using the topography of the section (above sea-level) as the initial body. This helps remove any error in Bouguer plate or terrain correction caused by a poor selection of average terrain density. In fact, section 1, through Cuernos de Negros, shows that the negative anomaly, centered on its eastern peak, can largely be explained by low-density topography with a density contrast of -0.3 gms/cc. However, the topography associated with Mt. Guinsayawan, north of the Okoy Valley, has no density contrast. The largest high density body, interpreted from sections 1 and 2, is represented by a box, with dimensions of 6 km x 4.5 km x 1.5 km, a top surface at +500 m elevation, and an "outflow tongue" extending to the north-east. It has a density contrast of +0.3 gms/cc, and is interpreted to be caused by hydrothermal alteration and deposition produced by geothermal fluids passing through previously porous formations. The other three high density bodies are smaller (about 1 km wide and 0.5 km thick), shallower (close to the surface), and flank Cuernos de Negros volcano, One underlies the crater at Lake Belendepaldo. Another, underlying the Kaipohan cold gas discharges may be related to the pockets of hydrothermal alteration seen at the surface. The third body, on the eastern flanks of the volcano, could be related to a significant, but isolated, low resistivity anomaly recorded by a dipole-dipole line in this area. Severe three-dimensional effects around the volcano are expected, so more detailed two-dimensional modelling is probably not justified. It should also be noted that these density models are non-unique (depths and density contrasts can be adjusted slightly and still produce a similar match), however they provide a valuable insight into the most likely distribution of subsurface densities. Further support to the model is provided by the high average core density (2.76 gm/cc), and low porosity (1.6%) of Okoy Valley wells which pass through the largest high density body.

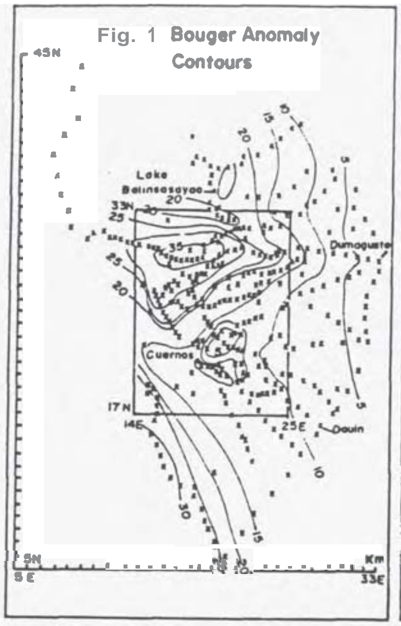


Fig. 1 Bouger Anomaly Contours

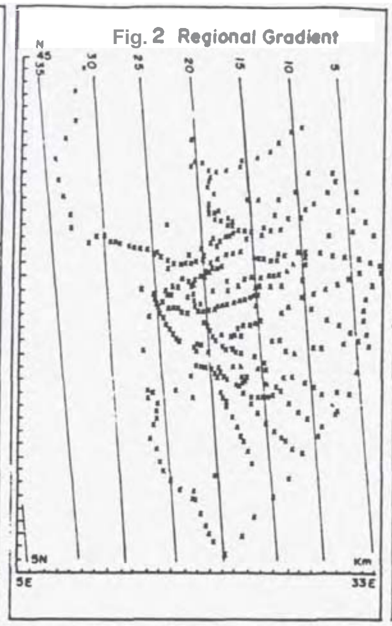


Fig. 2 Regional Gradient

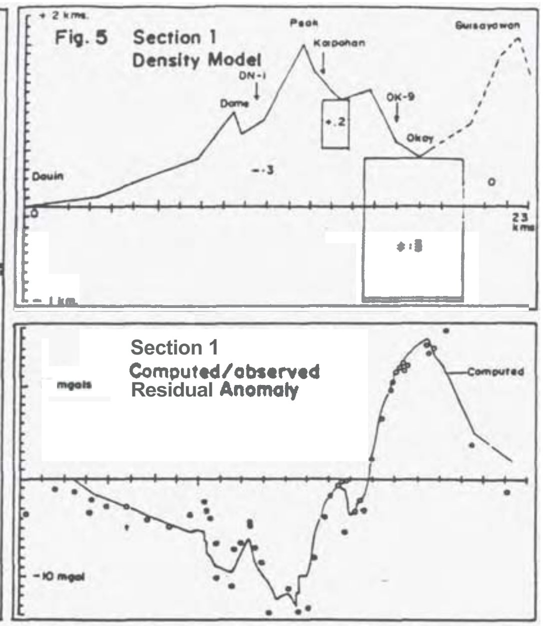


Fig. 5 Section 1 Density Model

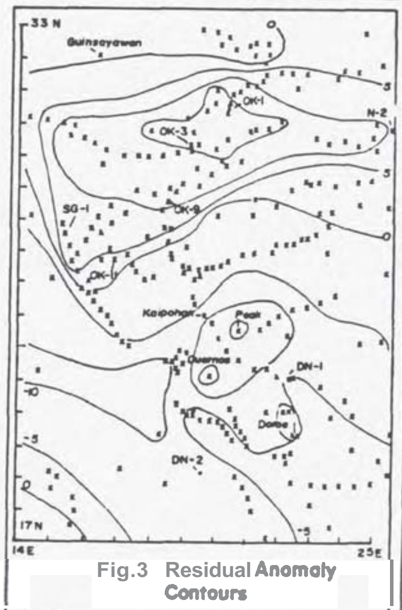


Fig.3 Residual Anomaly Contours

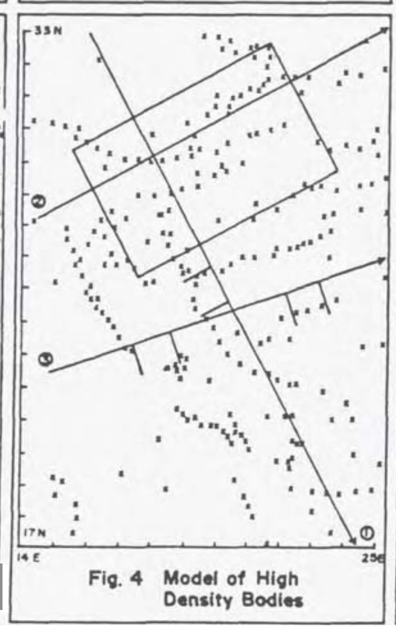


Fig. 4 Model of High Density Bodies

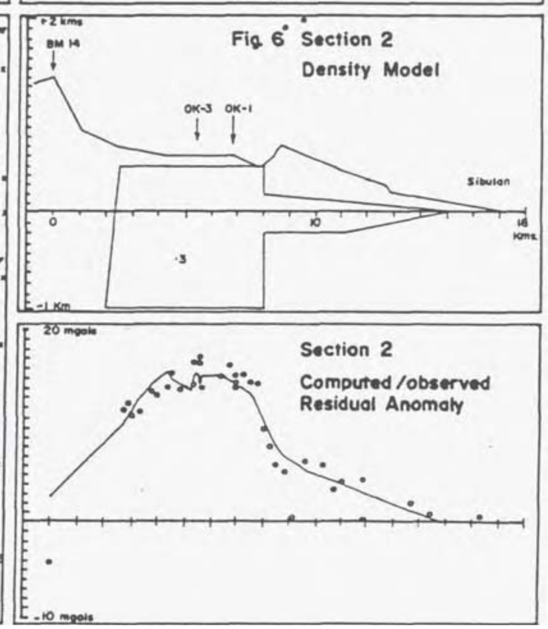


Fig. 6 Section 2 Density Model

density value for Cuernos volcano of only 2.16 gm/cc. Two of the wells closest to the volcano (Okoy 11 and Dauin 1) encountered molten sulphur (with a density of about *2.0* gm/cc), although the contribution of the sulphur to this low-density anomaly is not known. The Nasuji Pluton, to the west, does not appear as a gravity anomaly, whereas a similar survey in Tongonan (Ignacio and Bromley, 1982) successfully modelled the higher density Mahiao Pluton. This is explained by the lack of any density contrast for the Nasuji pluton, as revealed by core density measurements (average wet density of 2.73 gm/cc, compared to 2.76 gm/cc for the Southern Negros Volcanics).

AERO-MAGNETICS

Interpretation of aero-magnetic anomalies in Southern Negros, also using an interactive, two-dimensional, forward-modelling program, has contributed to a better understanding of the local geological setting. Magnetic anomalies can often be matched to formations of highly magnetized rock. However, intense hydrothermal alteration of volcanics, typical in geothermal systems, tends to convert magnetite into pyrite, and reduce the average magnetization. Therefore, anomalies of reduced magnetization are sometimes correlated with high temperature geothermal prospects (e.g. Layugan, 1981). At Southern Negros, the dip of the earth's normal magnetic-field vector is about 5°, the declination 0°, and the

(9000 ft). The vector addition of the anomalous dipole field associated with a positively magnetized body (assuming parallel induced magnetization) creates a negative anomaly directed above the body. Measurements of the magnetic susceptibility of deep cores, cuttings and surface samples, usually enhance the accuracy of the modelling process, assuming that induced magnetization is predominant. The possible effects of remanent magnetization are not considered, here, because of the lack of relevant data.

A zero-level regional magnetic field was assumed (B_o = 39280 nT), and magnetic anomalies calculated relative to this level from the total magnetic intensity contour map (Raymundo, 1978). Two north-south magnetic profiles have been drawn through the large negative anomaly overlying most of the geothermal prospect (see fig. 7). Interpreted 2-dimensional models are shown in figure 8, along with the computed and observed magnetic anomalies. Although 3-dimensional modelling has not been seriously attempted, it is recognized that severe east-west elongation of anomalies over isolated 3-dimensional bodies, can occur at these low magnetic latitudes. Therefore, the east/west location coordinates of anomalous bodies are not well constrained. Again, the procedure adopted in the modelling exercise, is to enter the topography above the reference level, and try to fit the observed magnetic profile by varying the average magnetic susceptibility of near-surface volcanics. Where this fit is

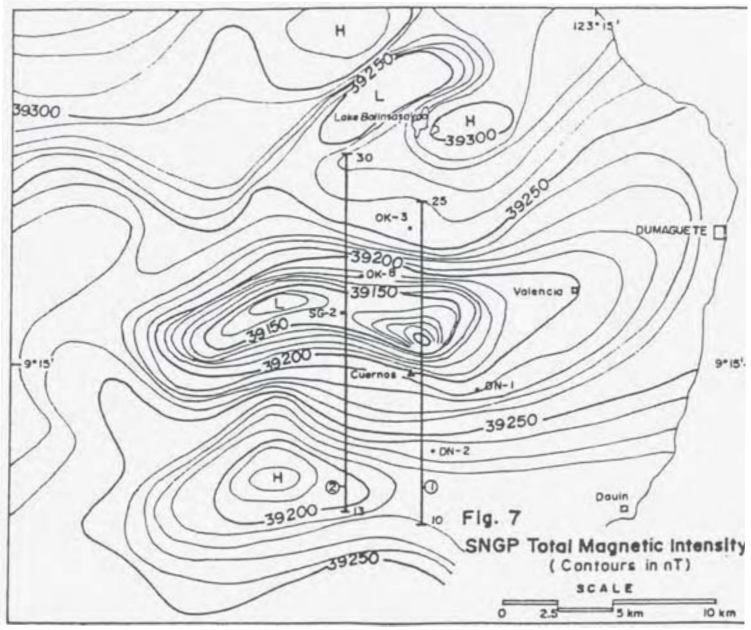
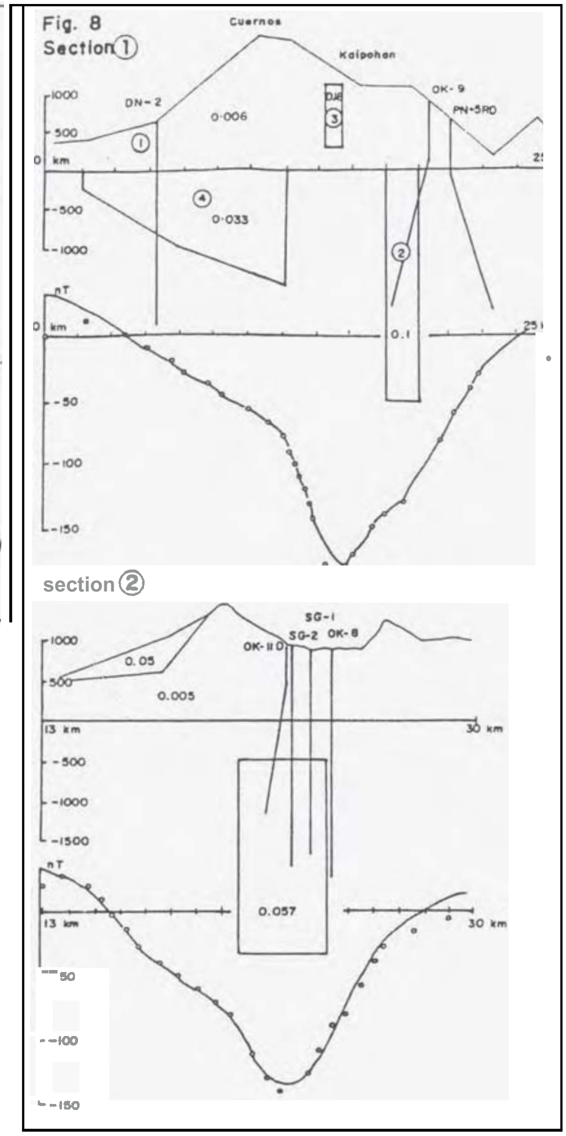


Fig. 7 SNGP Total Magnetic Intensity (Contours in nT)

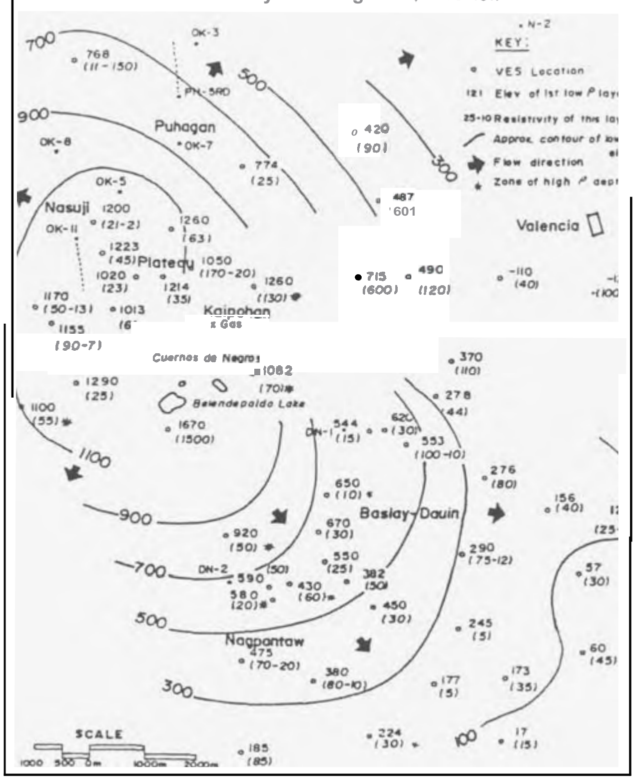


model, and varied in shape and magnetic susceptibility until a reasonable fit is obtained. The steepest negative anomaly is centered over the Kaipohan gas discharge, north of Cuernos, while a broader anomaly extends to the west, beyond Sogongon. A separate anomaly, north of Lake Balinsasayao, is also quite broad, but has steep sides, implying a relatively shallow origin. It has a distinct N.E./S.W. lineation, suggesting some structural control, and is centered over the headwaters of the Amlan river, There are no, obvious, surface geological explanations for either of these magnetic anomalies, since they occur in areas where intense hydrothermal alteration is exposed at the surface. Magnetic susceptibility measurements of cores and cuttings in Puhagan and Dauin show a wide range of values (e.g. 0.002 to 0.1 in OK9, and .005 to 0.1 in DN1). Layers in the volcanic pile have variable magnetization, and thin zones of reduced magnetization are caused by hydrothermal alteration along fractures. Aerial magnetics cannot resolve this fine detail, *So* the models shown should be treated as simply gross approximations of general trends in magnetic properties. Note, also, that the "magnetic basement", implied in the models, is not intended to represent the Curie-point isothermal depth, or even de-magnetized sedimentary basement, but merely a regional background against which the bodies in the model appear to have a positive magnetic susceptibility contrast.

Section 1, through Cuernos, has been modelled using four bodies, with magnetic susceptibilities, as shown, in S.I. units. Section 2 passes through Sogongon. It was modelled using a rectangular body which is probably the Nasuji pluton, with its contact skin. Although magnetic susceptibility measurements of core samples and cuttings from this fractured pluton are also scattered, because of variable alteration intensity, the average value of 0.051, Erom 34 samples, is close to that used in the model. *Two* important conclusions arise from the aero-magnetic interpretation: (a) there exists a hiqhly magnetized body at shallow depth beneath the Kaipohan gas discharges, north of Cuernos volcano, and (b) the Nasuji pluton, appears to extend to the west beyond Sogongon.

RESISTIVITY SOUNDINGS AND HYDROLOGY

Further insight into the regional hydrological model for this reservoir can be obtained from an interpretation of resistivity soundings. Early exploration commenced with a wide-ranging traversing survey to identify the main anomalies. This was followed by dipole-dipole surveys, and more recently, vertical soundings (Layugan, 1982). These soundings were originally programmed to test the Baslay-Dauin sector (south-east of Cuernos), prior to the drilling of two exploration wells. Later, however, the V.E.S. survey *was* expanded to cover the Valencia, Kaipohan, Puhagan and Nasuji areas, in order to investigate the pattern of separate resistivity anomalies, for connections at depth (Bromley, Española, 1982). Aside from the Okoy Valley anomaly (which includes Nasuji and Sogongon), these pockets of low apparent resistivity appear in the traversing map at: Kaipohan, Calinawan, Dobdob, upper Guinsuan (west of Cuernos), Siaton, Nagpantaw, Dauin, upper Amlan and upper Hinatongan (North Okoy). A few dipole-dipole lines hinted at connections between some of these anomalies, which were not obvious in the traversing contours, because of a thick mantle of high resistivity volcanics, at the surface, affecting some of the apparent resistivity readings. Interpretation of vertical electrical soundings helps solve this problem, by modelling the measured apparent resistivities in terms of resistivity layers. Given the elevations and interpreted models of the soundings, the top surface of a low resistivity layer can be shown in section, or contoured on a map, to illustrate the hydrology. This assumes that the low resistivity layer is created by a mineralized geothermal fluid. Other factors which complicate the interpretation, such as the effect on resistivity of alteration intensity and temperature, are not discussed here, The locations and elevations of mineralized springs are sometimes added to the map, or section, as a check on the contours, and to provide information on the chemical nature of the aquifer which is producing the resistivity anomaly (e.g. chloride or acid-sulphate fluid). In the Philippines, many of the geothermal prospects are located in recent volcanic terrain of hiqh elevation, where perched aquifers of steam/gas fed, acid-sulphate condensates are common. Southern Negros is no exception. So the hydrology inferred is that of the upper-most aquifer of geothermally fig. 9 SNGP Resistivity Sounding Interpretation



mineralized fluids. Assuming that these high-elevation aquifers are overlying the upwelling zone in the deeper (chloride fluid) hydrology, then this approach can be used to target the resource, and guide exploration drilling.

A total of 53 soundings have been interpreted, and the results are presented in figure 9 as elevations (contoured) of the top surface of the low-resistivity layer. The interpreted resistivities of this layer, are shown in brackets, and soundings with 'up-turns', indicating a possible high resistivity basement (but not A.C. effects), are labelled: "*". As expected, the Kaipohan plateau, between Cuernos and Nasuji, is underlain by low resistivities. Also, the traversing anomaly west of Cuernos is now linked to the Sogongon anomaly. However, high resistivities underlie two of the soundings near the eastern peak of Cuernos and the largest Kaipohan gas feature. They may be related to the shallow magnetic anomaly described earlier, Two main outflow directions are identified: to the north-east (the Okoy Valley outflow), and to the south-east (the Baslay-Dauin outflow). Both are associated with abundant hot springs and have been confirmed, by drilling, to have temperature inversions, or cooler temperatures for depth, relative to more central wells. Based on traversing anomalies, other outflows to the west, north-west and south are likely. There appears to be some variation in the surface of the low resistivity anomaly across the Kaipohan plateau, presumably as a result of localized fracture-controlled fluid feeding the Kaipohan features, and lateral contrasts in alteration. Some of the high-resistivity basements are also supported by deep dipole-dipole data, for example, near the eastern peak of Cuernos, and north of OK8. One sounding north of Puhagan has low resistivity at anomalously high elevation suggesting either a separate outflow from another source to the north, or relict, uplifted alteration. The Baslay-Dauin and Nagpantaw outflow anomalies are clearly linked. High resistivity basements in some soundings on the flanks of Cuernos may be caused by stratified impermeable formations (perhaps lava flows) separating the perched aquifers. Other evidence exists for the postulated outflow to the west: cooling subsurface temperatures and dilution of deep aquifer chloride concentrations from Puhagan through to Sogongon. At present, the highest temperatures in the field occur

lopments, and open-ended to the south (the Kaipohan plateau). This is consistent with the general hydrological model implied from the resistivity elevation contour map in figure 9.

MICROSEISMIC MONITORING

In keeping with field management policy, microseismic monitoring at Southern Negros commenced with the establishment of a permanent seismograph station, at OK3 well site, in February 1982. It was installed to record any changes in local microseismicity during the development and early production phases of this project. Previous experience in other geothermal fields, for example the Geysers (Eberhart-Phillips, et al, 1984), suggests that earthquakes can be induced by production or reinjection of geothermal fluids. Indeed, during the initial commissioning of the Palinpinon I, 112.5 MWe, power plant in Southern Negros, in April and May, 1983, there was a large increase in the level of local microseismicity (Bromley, Rigor, 1983). Prompted by this increase, four additional, temporary, seismograph stations were installed around the field in June (1983), and operated until March (1984). In this paper, we present the results of hypocenter calculations, using these records, and also some comments on: b-slope stability, first motion studies to determine fault plane solutions, temporal and spatial correlation of microearthquake swarms with reinjection and production well activity, a possible correlation with mass-flow and permeability improvements, and some postulated triggering mechanisms.

Hypocenters have been computed for 133 well recorded events occurring between July 20 and October 25. The results are plotted in figure 10. These events were selected from a resource base of several thousand similar microearthquakes (as recorded at OK3 station), on the basis of clear impulsive p-wave arrivals at 4 or 5 stations, accurately synchronized timing, and at least one good (S-P) time. The hypocenter program (designed for a portable computer) uses a single layer velocity model, which is considered appropriate for this small array (average spacing of 7 km). An average origin time for each event is calculated from the (S-P) and P-wave arrival times. The program then carries out a step-wise multiple regression, to minimize the RMS time residuals, by computing an adjustment vector, which shifts a trial hypocenter location. The iterations stop when the adjustment vector falls below 0.005 km. A uniform p-wave velocity of 4.1 km/s is used. This is based on laboratory sonic velocity measurements of 12 core samples from Puhagan wells (Pearson, 1984). Anomalously low velocities, measured on some samples from the Nasuji pluton, and also on some Dauin cores (average 3.3 km/s), have been excluded. Additional information includes a velocity log from OK11D, which reveals a velocity of approximately 4.3 km/s in the overlying volcanics, and 5.1 km/s in the diorite pluton. However, the calibration accuracy of this data is uncertain. A uniform velocity of 3.7 km/s was obtained from surface blasting at OK5 (1000 m elevation), as recorded by the microseismic array, but this value may be distorted by low-velocity near-surface formations. The core velocity measurements have not been corrected for the effects of water saturation and temperature, but it is expected that these effects will be reduced by mutual compensation. (Water saturation increases velocity, and high temperature decreases it.) The core velocities showed no correlation with depth (between -500 m and -1800 m, reduced level), supporting the use of a single layer velocity model, but showed a statistically significant linear relationship with density, supporting the use of Birch's Law: $V = 2.4 \ (\pm 0.5)\ \rho - 2.3 \ (\pm 1.3)$. Station corrections have not been applied to any of the arrival times used in the hypocenter calculations, although the low velocities and densities recorded in core samples from Dauin wells, suggest that corrections may be advisable for some of the southern stations. Nevertheless, uncertainty analysis of the Puhagan hypocenters reveals a very low median value for the average absolute time residuals, of 0.05 seconds. This is particularly reassuring, considering the chart speed of the portable seismograph recorders (1 mm/sec), which limits reading accuracy. The distribution of R.M.S. standard errors, which depend on station locations with respect reading accuracy of **0.05** seconds). To test the effect of a change in velocity on hypocenters, many of the locations were re-computed using a lower velocity of 3.9 km/s. This shifted the locations approximately **300** m to the south and about **300** m closer to the surface. Most of the located hypocenters are clustered within a small block of about 18 km^3, centered on the Puhagan production sector, at the intersection of the Lagunao and Ticala faults. Average focal depth of 2 km (± 1.5 km), below sea level, is consistent with the depth of major production zones in the Puhagan wells. Most of the larger, felt events (magnitude greater than 1.9) are located along a narrow elongated zone parallel to the Lagunao fault. No correlation was observed between hypocenter depth and magnitude, and there was no systematic variation of magnitude with time, during a swarm sequence.

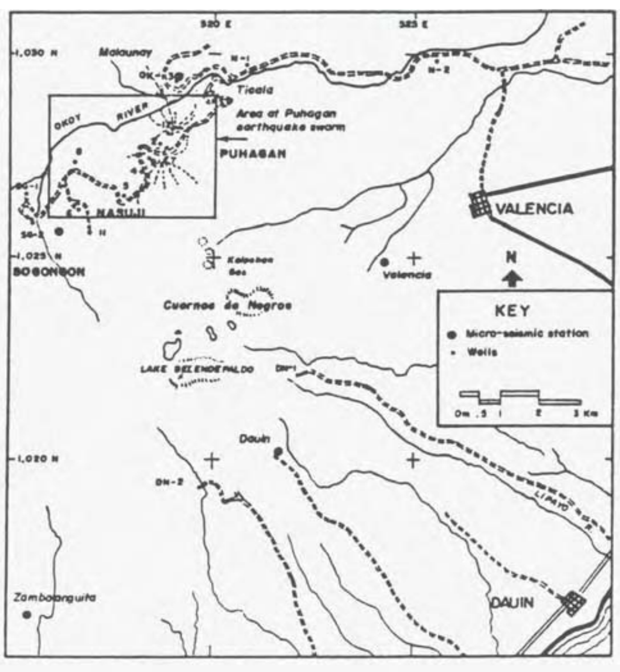
An initial b-slope calculation, from OK3 seismograms, for the Puhagan events was reported in 1983 (Bromley and Rigor). Subsequently, two more estimates have been calculated to investigate trends with time. The coda lengths (in seconds) are used to calculate the magnitudes, *by* applying formulas: $M(R) = 1.8 \log T - 1$, or $M(G) = 2 \log T - 0.87$. The b-slope is calculated using two separate techniques. The first involves regression analysis (R = correlation coefficient) to obtain the slope of the best fit line through the histogram of the log frequency/magnitude plot. The frequency of low magnitude events is often underestimated, so a cut-off magnitude of **0.5** is usually employed. The second calculation method (attributed to Aki), uses the equation $b = \log(e)/(\bar{m}-M_{min})$ where $\bar{m}$ is the average magnitude of all events above the cut-off minimum (also 0.5). Results are summarized in the following table:

Period (1983/84)	No. of Events	b-slope M(R) Histogram	R	b-slope M(G) Aki method
May 20→Aug 30	2832	1.27	0.999	1.27
Sept 1→Oct 30	1258	1.30	0.996	1.15
Nov 1→May 31	1151	1.32	0.998	1.24

It is concluded that there has been no significant change in b-slope with time. Using statistical predictions based on this stable b-slope, and the present level of activity, it can be concluded that, here, as in the Geysers field (Eberhard-Phillips, et al, 1984), the induced seismicity is "relatively benign..

An attempt has been made to derive fault plane solutions, using first motion directions, as recorded *on* seismograms during the epicenter study. The pattern of first motions can be used to determine the most likely active fault plane and slip vector directions, which may be very useful information for the structural geologists and reservoir engineers attempting to model the permeability of the reservoir. Unfortunately, with only **5** stations, the fault plane solutions of individual events are poorly constrained. However, composite fault plane solutions may be prepared from a number of events with similar fault plane mechanisms. The first motion patterns of Puhagan located events can be collected into four main groups: (1) d cccc **130 events),** (2) d ** cc (51 events), (3) c ** cc (23 events) and (4) mixed or undetermined pattern (29 events). Note that: d = dilatation, c = compression, • = either c or d or emergent (near a nodal plane), and stations are listed in clockwise order: - OK3, Val, Dau, Zam, Sgn. We plot these first motions ab equal area projections onto the upper hemisphere, assuming the rays will be 'up-going' for this small array. The first pattern (1) probably represents normal faulting along planes semi-parallel to the Ticala fault dipping steeply north-west. Events occurring on September 17, which haw a close temporal and spatial correlation with capacity reinjection into OK12 (which intersects the Ticala), also have this pattern of first motions. However, the solution is not unique: normal faulting along any azimuth between 55° and 115° would also fit the pattern. The second pattern (2) is consistent with predominantly normal faulting along the Lagunao or parallel fault planes with a north-west strike, a steep dip to the north-east, and a small amount of right-lateral strike-slip movement. Again, this solution is not unique, but it fits the observation that many of these events are located along the Lagunao fault zone. In conclusion, there are probably several different fault planes and slip vectors involved, so unique composite solutions may not be possible, however further investigations are anticipated.

Distribution of Puhagan events in time and space strongly suggests that most of the induced seismicity is caused *by* pressure drawdown due to mass withdrawal from production wells, while the remainder is due to hydraulic fracturing caused *by* large increases in pressure around reinjection wells. D.M. Rigor (1984) has listed the time correlations, for 17 swarms, in detail. In general, the onset of earthquake swarms follow, within a day or two, the discharge, or abrupt increase in flowrate of several production wells (particularly PN15/21/26/27/28, OK7/10). Likewise, many swarms occur within one day of the early capacity tasting, or maximizing of



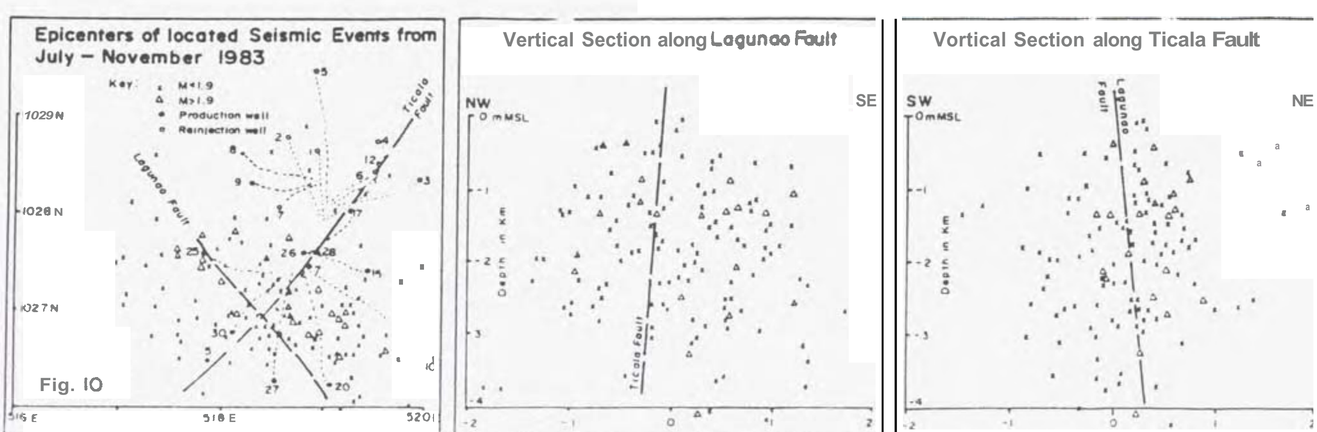


Fig. 10

gravity flow, into reinjection wells. Positive correlations with reinjection well-head pressure peaks were observed on 10 different occasions. C.F. Pearson (internal KRTA memo) used cross-correlation analysis to show that the well-head pressure history of PN2RD, for example, has a positive correlation (95% level of confidence) with the number of seismic events per day between May and October 1983. Some of the most obvious time correlations occur following plant start-up after several days shutdown (e.g. May 21, and Nov. 20, 1983), when several production and reinjection wells are brought on-line at the same time. Other major swarms (e.g. Oct. 14, 1983 and May 17, 1984) followed large step increases in production and reinjection flow rates as power demand increased. Attempts to match located earthquakes with well histories, have achieved several successes, notably: 6 events close to the Lagunao fault plane on July 20/21 which occurred shortly after PN28 (vertical well) was discharged; and also 4 events on September 17, which are located within 200 m of the OK12 and PN2RD well tracks, and followed injection capacity testing of these wells.

Given the large number of induced earthquakes (more than 5000 to date), originating from within the Puhagan reservoir, it is likely that some events have created additional permeability by extending existing fractures or re-fracturing sealed channels. In fact, there is some evidence for an overall improvement in reservoir permeability. Large increases in stable mass flowrates of many production wells have been measured. (Although several other factors, such as changing well head pressures, reservoir pressure interference, and enthalpy changes, complicate the interpretation of these mass flow changes.) In the reinjection sector, substantial improvements in permeability have also been measured, especially in the impermeable wells PN4/5/8RD. These wells all had predicted cold water injection capacities of less than 20 l/s, and transmissivities of less than 0.5 d-m, at well completion, but now accept hot water injection at capacities of 50 to 130 l/s. Injection capacities of the other wells have stayed relatively constant with time, despite large increases (more than 1 MPa) in reinjection sector pressures, as measured in monitor wells. This also suggests an improvement in permeability since the available injection head has declined (A.W. Clotworthy, personal comm.).

This leads to further consideration of mechanisms for the induced seismicity. Events originating in the reinjection sector, where zone pressures have increased more than 1 MPa, and pressure peaks of several megapascals are induced during capacity injection, are easy to explain in terms of hydraulically induced fault movement. A reduction in normal stress across faults, caused by the increase in pore pressure, reduces friction, and triggers failure of a stressed fracture system. Induced seismicity in the production sector, however, where pressure draw-down of about 1 MPa has been observed in monitor wells, is not so easily explained. Eberhart-Phillips, et al (1984), have discussed mechanisms for the Geysers seismicity, where similar pressure draw-down has occurred (about 1.5 MPa). They conclude that two mechanisms remain plausible: volumetric contraction due to mass withdrawal, or the conversion of steady state aseismic deformation to stick-slip deformation due to an increase in the coefficient of friction along fault surfaces (Allis, 1981). We favour the second mechanism. Laboratory studies have shown that rocks undergoing ductile creep, at conditions close to the brittle-ductile transition boundary, may cross the boundary and exhibit stick-slip movement, if the effective stress is increased by a reduction in pore pressure (Fyfe, et al, 1978). The observed pressure draw-down in Puhagan (a water dominated reservoir with isolated pockets of 2-phase fluids surrounding some producing wells) may be sufficient to cause this transition and trigger the earthquakes.

SUMMARY

Residual gravity anomalies are interpreted to indicate a Large volume of reservoir rock that has an increased density due to deposition of hydrothermal alteration minerals. Aero-magnetic anomalies are interpreted to indicate a magnetite-rich body, close to the surface, near the Kaipohan gas discharges, and also an extension, to the west, of the Nasuji pluton. Elevation contouring of low-resistivity layers from sounding interpretations implies an extensive geothermal hydrology with perched aquifers at high elevation, near Cuernos de Negros volcano. These aquifers are linked through radial outflows to large resistivity anomalies at lower elevation. Hypocenters have been determined, using a single layer velocity of 4.1 km/s, for 133 events chosen from the swarms of several thousand induced earthquakes detected at the Okoy 3 monitoring station. Correlations, in time and space, have been observed with production or reinjection well activities at Puhagan. The 'b-slope' of 1.3 has remained relatively stable. First motion directions can be related to possible fault plane solutions. Improvements in mass-flow and permeability may be related to this induced seismicity, and the favoured triggering mechanisms are: pressure draw-down in the production sector, and increased pressure in the reinjection rector.

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