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The Use of Non-Parametric Analysis of Subsoil Temperature Data at the Las Pailas Geothermal Field for Low Impact Geothermal Prospection

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ABSTRACT

Las Pailas geothermal field, located in northwestern Costa Rica and on the southwestern flank of the Quaternary Rincón de la Vieja volcano complex is adjacent to the Rincón de la Vieja National Park to the north and a non-governmental organization owned protected area to the west. These adjacent areas are within the extents of the area of geothermal interest, for which reason less invasive methods of prospection are required to evaluate the geothermal resource in these areas before new drilling exploration campaigns can begin.

1. INTRODUCTION

In Costa Rica, traditional geothermal prospection has been carried out since the first reconnaissance studies done in the late 1960's and have included:

- Geological mapping
- Mapping of thermal manifestations
- Geochemical Mapping
- Geophysical soundings (Electrical Resistivity, Magnetism, Gravity, Magneto Teluric soundings)
- Thermal gradient wells
- Deep exploration geothermal wells

Costa Rica has a total installed capacity of 204 MWe (Miravalles: 163 MWe; Las Pailas: 41 MWe). Unit 1 at the Las Pailas geothermal field, a 35 MWe binary plant, has been in operation since July of 2011. Currently there are 21 boreholes in the field (9 vertical and 12 deviated). Ever since 2009 only directional drilling has been undertaken and has made possible the commissioning of Unit 1 by increasing the radius of allowing exploration at depth and permitting the interception of fault zones at an oblique angle. A new drilling campaign is programmed to the east of the currently explored field at Las Pailas to tap a part of the reservoir that shall supply geothermal fluid to a second power plant to be constructed in the near future.

2. LOCAL GEOLOGY

The outcropping rock units range from late Miocene to Holocene in age. The older units are in the southwestern part of the field area and correspond to the dacitic lavas of the Alcántaro Formation and form the border of the Cañas Dulces caldera. Within the caldera rim are post Pleistocene pumitic to cristlao lithic pyroclastic flows of the Pital Formation covered by Quaternary andesitic lavas and the most recent deposit is a lahar / debris avalanche. Outside the caldera rim the Pleistocene Liberia Tuff crops out in the southeast and southern sectors of the field area. The shape of the caldera border can be recognized by the outcropping Alcántaro Formation and estimated by the contact between the Pital and Liberia Formations.

3. SHALLOW TEMPERATURE SURVEY FOR GEOTHERMAL PROSPECTION

Subsoil temperature measurements have proven a useful tool for geothermal prospection in geothermal fields located in other parts of the world (LeShack et al., 1983; Hersir & Bjornsson, 1991; Eneva et al., 2007; Coolbaugh et al., 2006a & b, 2007 & 2011, Sladek et al., 2009; Leaman, 1978; LeSchack & Lewis, 1983; Lechler P, 2004; Mongillo, 1992; Saba et al., 2007; Ehara, 2000) although in areas that are mostly desert regions and at different latitudes. This paper makes reference to the effectiveness of this prospection method in a tropical region. The minimum depth required for determining the mean annual soil temperature is that at which the oscilation of the anual temperature wave is reduced to approximately 37% (1/e) of its oscilation at the surface. That means that where there are larger seasonal temperature swings this depth will be greater.

4. FIELD AREA

In northwestern Costa Rica, specifically on the southern flank of the Rincón de la Vieja volcanic complex, the climate is tropical and surface temperatures oscilate between 20.5 and 30.4°C with a mean value of 25.8 +/- 2.03°C so therefore the minimum depth should be that at which the oscilation of the subsoil temperature is less than or equal to 3.66°C. The prevailing soil types are non-thermally active entisols and inceptisols with mean annual subsoil temperatures measured at an average depth of 1.2 meters of 24.69 +/- 1.4°C and 22.85 +/- 1.52°C, respectively and falling within the 3.66°C range (+/- SD) at 1.2 meters.

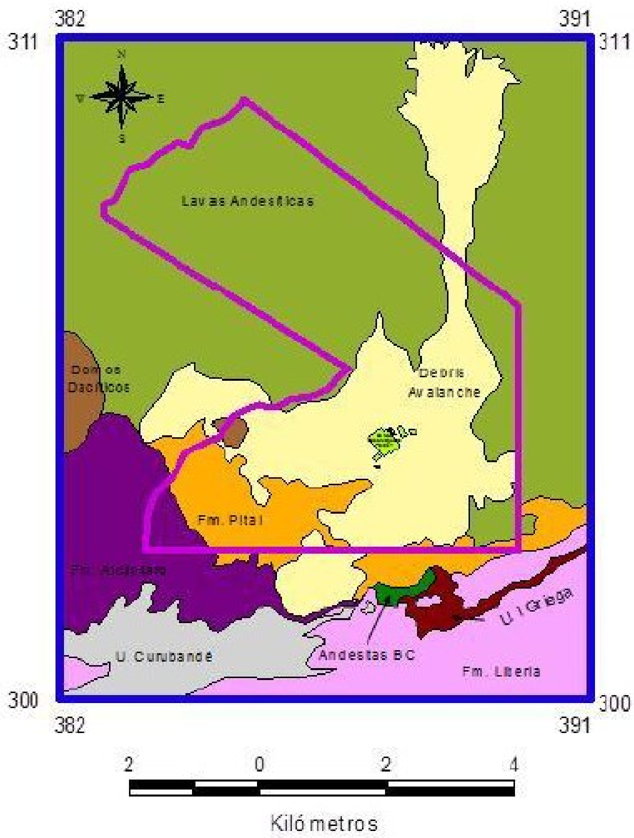

Figure 1: Local geologic map of the field area. Modified from Chavarría, et al. 2006

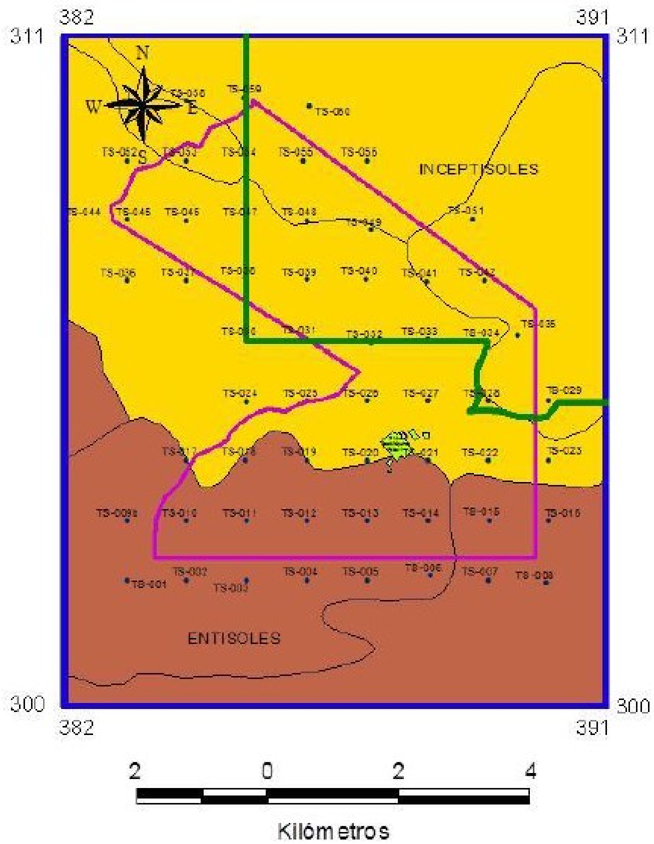

Figure 2: Distribution of the entisols and inceptisols in the field area. Personal compilation.

One tailed non parametric statistical analysis has shown that these subsoil temperatures may represent local subsoil thermal anomalies at a 95% confidence level where standard residuals are greater than Z = 1.645 ($p<0.05$). Although the Liliefors best fit curve shows that the data area normally distributed, Kruskal-Wallis and Mann-Whitney non-parametric methods were used to simplify data manipulation by eliminating the stricter requirements of their one-way ANOVA and Student's t parametric counterparts.

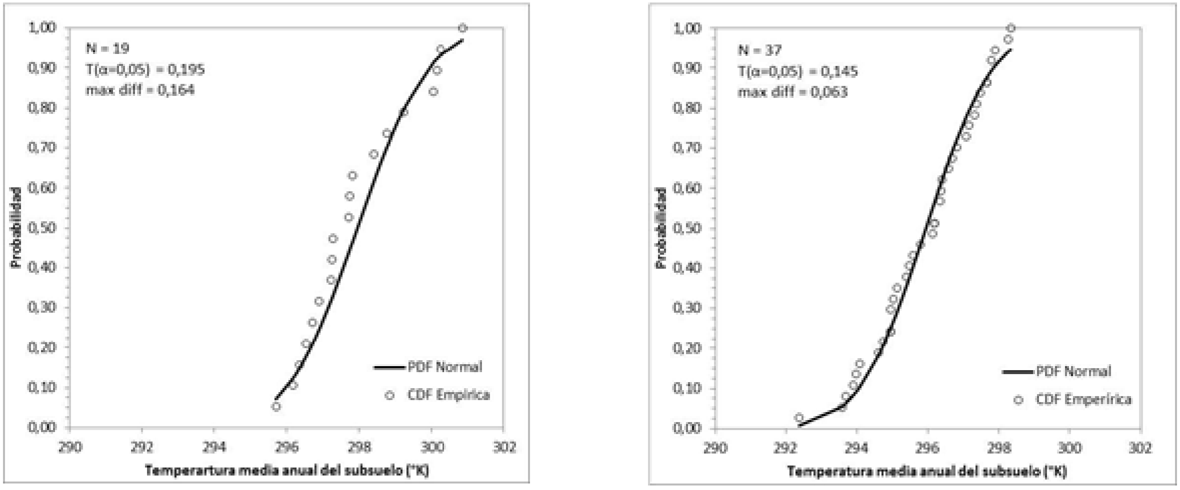

Figure 3: Lilifors best fit curve of mean annual subsoil data in entisols and inceptisols on the southern flank of the Rincón de la Vieja volcanic complex.

The variables taken into consideration for statistical analysis of the data were: soil type, elevation, mean air temperature, land use, geologic formation and geographic coordinates. The inceptisols are significantly cooler than the entisols (Kruskal-Wallis; N=56; H=14.23; $p<0.05$), and Spearman's rank coefficients show that the mean annual subsoil temperature in the inceptisols oscilates significantly in function of the measured variables, whereas in the entisols it does not.

Table 1: Kruskall-Wallis analysis of mean annual subsoil temperature data from entisoles and inceptisoles on the southern flank of the Rincón de la Vieja volcanic complex.

Grupo	n	ΣR	ΣR^2 / n	$SS_{bg(R)}$	Media	H	Valor p
Entisol	19	759,5	30360,01	3785,69559	266	14,23194	**$1,62 \times 10^{-04}$**
Inceptisol	37	836,5	18911.68				
Totales	56	1596	45486				

In the inceptisols there were significantly more observation points in forested areas than in open pastures (Chi squared; df=2; χ^2=19.51; p <0.05). Also, subsoil temperatures means are significantly different among the different types of land use (Kruskal-Wallis; H=7.348; p=2.537 x 10-2). It was found that the subsoil temperatures in open pastures are significantly higher than in other land uses (Mann-Whitney; U = 36; p=9,421 x 10-3) while in high meadows they are significantly less (Mann-Whitney; U = 53; p=4,966 x 10-2).

There were significantly more observation points over andesitic lavas than other underlying geologic units (Chi squared; df=2; χ^2=22.11; p <0.05). Additionally a significant difference in the subsoil temperatures was determined with respect to the underlying geologic unit (Kruskal-Wallis; H=13,127; p=1,411 x 10-3). The mean annual subsoil temperature in soils developed over lahar were significantly higher than over other lithologies (Mann-Whitney; U = 41; p=6,528 x 10-4).

A multiple linear regression of mean annual subsoil temperatures in the inceptisols taking into consideration only the variables that significantly affect the mean annual subsoil temperature (elevation, mean air temperature, land use and underlying geology) resulted in standard residuals higher than 1.645 at two observation holes (617 and 804 m s.n.m.), thereby possibly indicating a thermal anomaly at these locations with respect to a linear model.

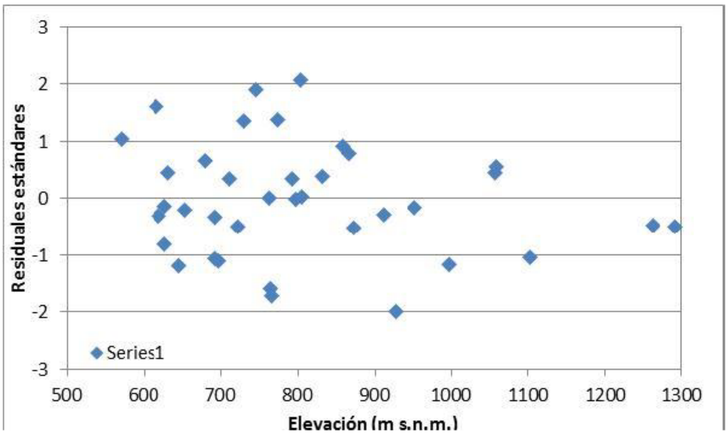

Figure 4: Standard residuals of measured subsoil temperatures in inceptisols plotted against elevation with respect to a multiple linear regression on statistically significant variables.

5. DISCUSSION

The use of statistical modeling is applicable to any area in which data are modeled to a known or expected behavior curve. What is crucial is the setting of a reasonable confidence level for error. The 95% confidence level is widely used in scientific analysis and ought to be employed in the recognition of anomalous results that may suggest that the data come from a different population than the one being modeled. The Kruskall-Wallis H statistic approximates a χ^2 distribution and the Mann-Whitney U approximates a normal distribution, both of which can be used to calculate a p value of 0.05 or less for formal statistical hypothesis testing, which in this case states a null hypothesis of the equality of means.

6. CONCLUSION

Background subsoil temperatures in the non-thermally active entisols and inceptisoles on the southern slope of the Rincon de la Vieja volcanic complex area normally distributed in the field area.

There is a significant difference in the mean annual subsoil temperature in the entisoles with respect to the inceptisols, the latter being warmer than the former. However, the subsoil temperatures in the inceptisols are more highly affected by differences in the measured variables than the entisoles are. For this reason it is suggested that greater depths for measuring subsoil temperates are required in the inceptisoles.

The analysis of standard residuals unveiled two observation holes where the subsoil temperature is more than 1.645 standard deviations higher than the multiple linear regression model. These access holes may be located near a latent heat source.

7. FINAL REMARKS

Other areas of geothermal prospecting where these methods can prove particularly useful are in the analysis of geophysical data (gravity residuals, resistivity curves from MT soundings, and magnetic surveys) and geochemical data.

During geothermal field production the reservoir response must be estimated by some curve just as characteristic production curves are routinely drawn for each well. Residuals should be compared against this curve to determine if it is representative of a modeled tendency. However it is important that the curve not be changed constantly to fit the data but rather determine what is causing the data to move away from the modeled curve. These differences may be due to changes in the production and reinjection scheme or simply evolution of the reservoir. For example, changes in cation concentration (Cl-) may be due to increased injection of geothermal brine in a certain sector of the field or the triggering of a new production zone in the well. Additionally fluctuations in the quantity of non-condensable gases in the steam can be modeled in this manner to determine if anomalously high or low concentrations of CO_2 or H_2S are being produced from wells.

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