Los Humeros superhot and Acoculco EGS: distribution of rock modulus and correlation with temperature

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Abstract

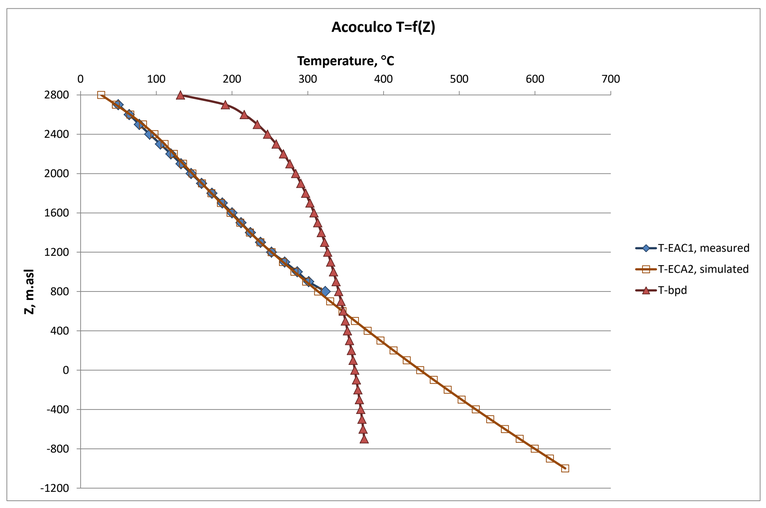
Temperature measurements are available within geothermal wells down to circa 2 km depth or ~800 m asl elevation in Acoculco enhanced geothermal system (EGS), and down to circa 3 km depth or ~300 m bsl elevation in Los Humeros super-hot geothermal system. A constant temperature gradient is evident in Acoculco and a close to boiling-point-to-depth temperature pattern in Los Humeros.

In Acoculco EGS, one dimensional S-wave elastic modulus, calculated from ambient seismic noise analysis and local gravity survey, is related to measure temperature with a logarithmic function. This relationship may be also valid at deeper elevations below well bottom, down to the elevation where a local maximum elastic modulus is observed, as indicated when comparing S-wave modulus with extrapolated temperature calculated by the reservoir computer model of the field, which was developed within the GEMex project.

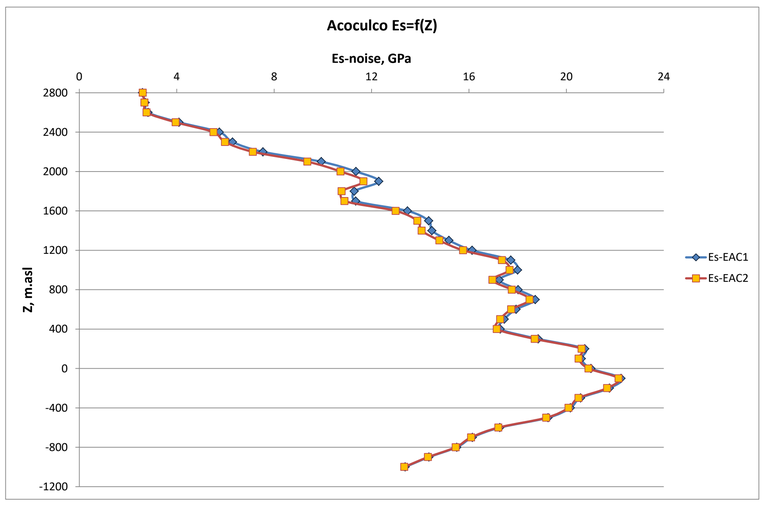
As an approximation, in Los Humeros super-hot geothermal system, P-wave elastic modulus, which was estimated from both legacy active (1998) and recent passive seismic 3-D surveys coupled to a regional gravity survey, increases almost linearly with depth down to 100m above sea level. S-wave elastic modulus, which was estimated by 1-D ambient seismic noise analysis and 3-D passive seismic survey coupled to a regional gravity survey, follows a similar pattern down to 500 m asl approximately, where its value stabilizes with depth. At deeper levels, S-wave modulus shows variations not shown by P-wave modulus.

In Los Humeros super-hot geothermal system, where 3-D data are available, seismic velocities and elastic moduli are correlated to temperature in the vertical direction by exponential functions, while no such statistically significant correlation is evident in the horizontal direction. This implies that an indirect relation may exist between seismic velocities and elastic moduli with temperature, e.g., through their dependence on common independent variables such as rock matrix pressure and/or pore pressure and fluid saturation. The weak correlations observed indicate that local anisotropy is also important.

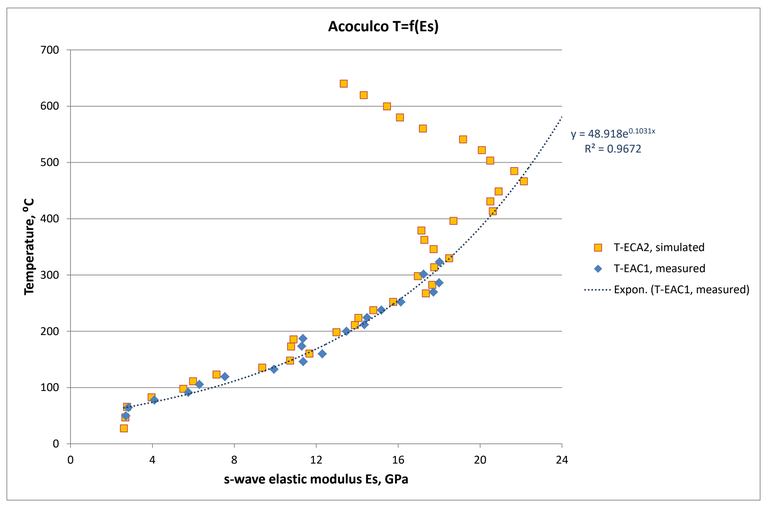
Acoculco



.Steady state temperature profiles in Acoculco, as measured in well EAC-1 and as simulated by the reservoir model in well EAC-2 in comparison with the boiling point to depth (bpd) model.

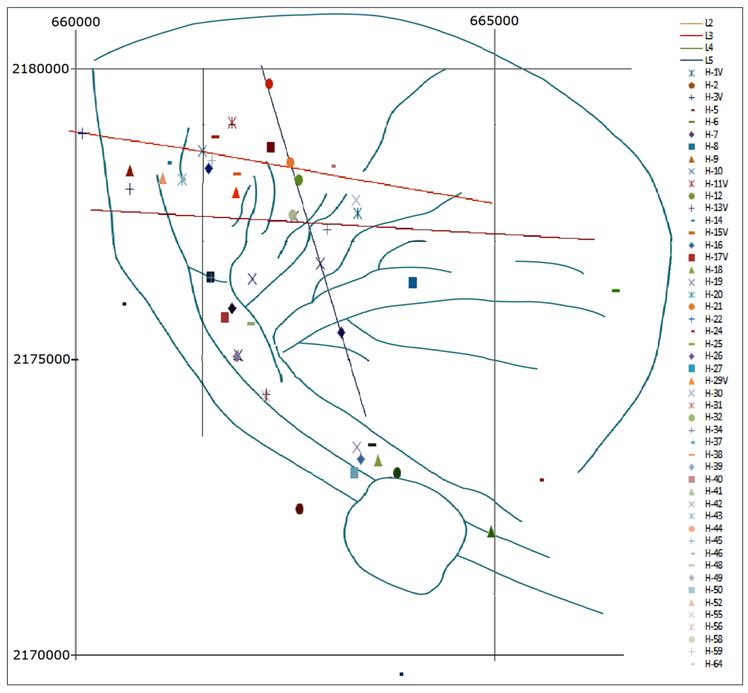


Profile of S-wave elastic modulus at the locations of wells EAC1 and EAC2

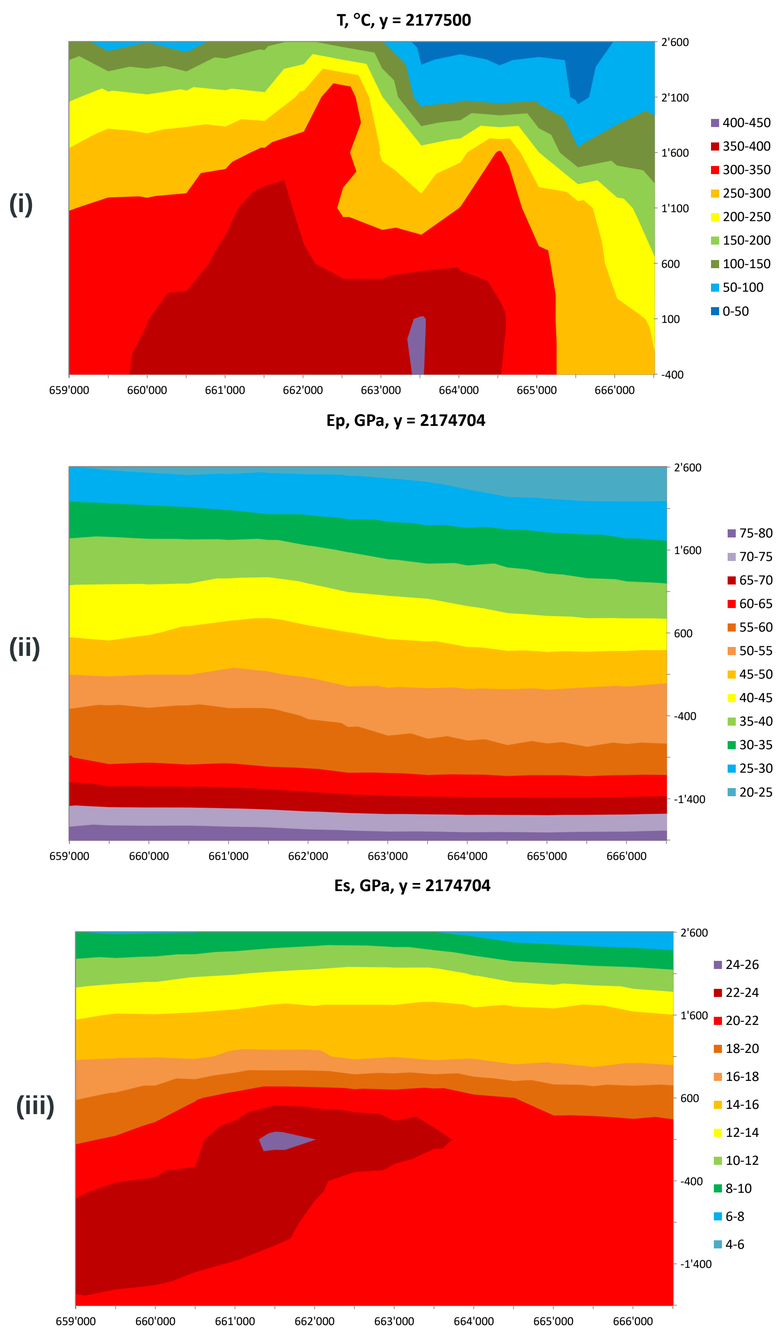


Measured & simulated temperature as a function of S-wave modulus in Acoculco and extrapolation of measured values using the best fit exponential function.

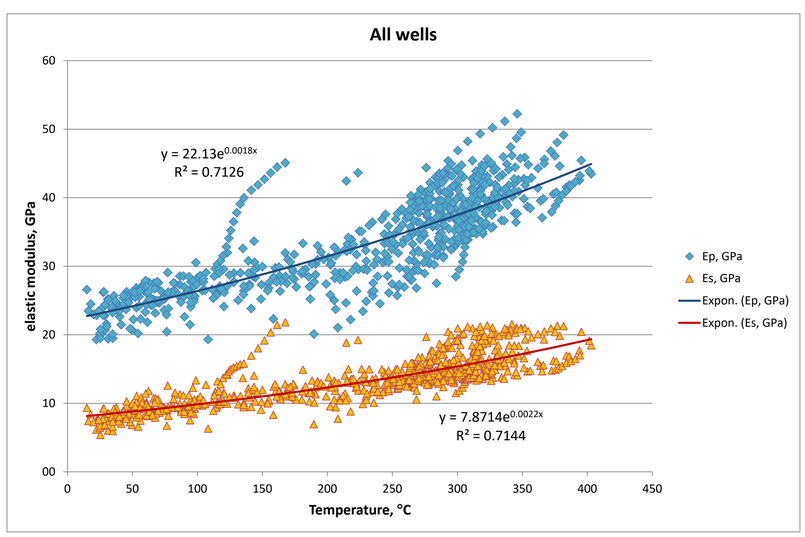
Los Humeros



Well locations (H-n) and seismic lines (Ln) of the legacy CFE active seismic survey carried our during 1998, in comparison to main fault structures (green lines) at Los Humeros in the UTM coordinate system



Temperature (i), P-wave modulus (ii) and S-wave modulus (iii) distribution along a vertical cross section in the direction West (left) -East (right) at y=2177500, or 2174704 of the UTM coordinate system; the vertical axis is the z-coordinate in m.asl.



P-wave and S-wave rock modulus derived by 3-D passive seismic & gravity surveys as a function of temperature

Multiple parameter linear regression analysis

For each one of the two seismic surveys performed in Los Humeros, a series of multiple linear regression analyses were run using the SPSS package taking as independent variables temperature and elevation, or temperature and the logarithm of elevation and seeking potential correlations with one of the quantities P-wave velocity Vp, its logarithm Ln(Vp), S-wave velocity Vs, its logarithm Ln(Vs), P-wave modulus Ep, its logarithm Ln(Ep), S-wave modulus Es and its logarithm Ln(Es) as dependent variable.

The validity of specific assumptions was checked in each case, which are critical when performing multiple linear regression analysis in order to accept the derived correlations. These assumptions are linearity between each independent variable and the dependent variable, linearity between independent variables collectively and the dependent variable (by checking studentized residuals against the unstandardized predicted values), homoscedasticity, absence of multicollinearity and normality of the residuals.

In all cases, there was no linearity between each independent variable and the dependent variable, as assessed by partial regression plots, or linearity between independent variables collectively and the dependent variable, as assessed by a plot of studentized residuals against the predicted values for each case. With two exceptions, where the test was marginally passed, there was heteroscedasticity, as assessed by visual inspection of a plot of studentized residuals versus unstandardized predicted values.

Therefore, assumptions met were the “no multicollinearity” and “normality of the results”, while assumptions not met were linearity (single and collective) and homoscedasticity. As all five assumptions must be met, in order to run a multiple linear regression model that provides valid results, we conclude that since the specific variables do not meet the required assumptions, we cannot properly examine if statistically significant relations occur between dependent variables Vp, Vs, Ep, Es, ln(Vp), ln(Vs), ln(Ep) and ln(Es) neither with T and Z, nor with T and ln(Z), on the basis of a multiple linear regression model.

Main conclusions

Both Acoculco (EGS) and Los Humeros (superhot) are high-elevation geothermal systems with wellheads located at 2700-2800 m asl altitude.

In Acoculco, the temperature increases linearly with depth down to well bottom, which is located at 800 m asl elevation, trend typical of conductive geothermal systems of almost zero permeability. 1-D S-wave modulus values, derived from ambient seismic noise and gravity surveys carried out in the field, indicate that S-wave formation modulus increases with depth down to around 0 m asl elevation, where a local maximum value is observed.

In Acoculco, a statistically significant correlation exists between 1-D S-wave modulus and temperature, which corresponds to second order polynomial or logarithmic functions down to 0 m asl.

In Los Humeros, the temperature down to -300 m asl increases with depth approaching the boiling point to depth model, which is typical for convective hydrothermal systems of high permeability, including the upper part of a superhot convective system. The P-wave formation modulus of elasticity, as derived from past active seismic and recent 3-D passive seismic surveys, increases more or less with depth, with minor horizontal variations. The S-wave formation modulus, as derived by 1-D ambient seismic noise and past active seismic and recent 3-D passive seismic surveys increases with depth down to elevation level of around 500 m asl, also depending on location, and remains approximately constant at deeper levels. Variation in the horizontal direction is more pronounced in S-wave elastic modulus than in P-wave one.

In Los Humeros, a weak statistically significant relation exists between both P-wave and S-wave elastic moduli with temperature in the vertical direction, which can be expressed as exponential and second order polynomial functions. No such statistically significant correlation is evident in the horizontal direction.

Further research in this direction should include the field investigation of seismic properties and rock moduli and their relation to pressure and temperature at both the upper 3 km of Los Humeros where rock behaves as an elastic medium, and at the deeper part of the system where inelasticity prevails, seismic frequency becomes important and variations of seismic velocities and rock moduli with temperature are sharp.

Acknowledgements

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