New Workflow for Characterizing a Geothermal Resource and Potential for HFR Alternative Energy at the Momotombo Field

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Summary

With the worldwide desire to cut CO2 emissions, geothermal energy and it's less technically mature cousin, Hot Fractured Rock (HFR), are sure to play an increasingly important role in the global energy mix. As geothermal/HFR is new to Shell, an integrated workflow was developed to model the sub-surface and assess new business opportunities worldwide. The case study here is from the Momotombo field in Nicaragua, for which we characterized the structural, temperature and permeability anisotropy. Faults were mapped from Landsat data/aerial photographs; *in-situ* stress was deduced from earthquake focal mechanisms; aeromagnetic data suggested the existence of steam caps related to bodies of hydrothermal alteration, and the thermal evolution of the field was constructed from temperature logs. Stress perturbations were calculated around the faults and fault slips were resolved to highlight prospective geothermal areas and HFR potential.

HFR potential

Whereas geothermal (or hydrothermal) is the production of hot water from an existing naturally fractured reservoir and using steam to drive a turbine, the HFR (or Enhanced Geothermal Systems [EGS]) concept is the creation of a heat exchanger by hydraulically fracturing the sub-surface, ideally connecting to an existing natural fracture network and drilling into the stimulated zone. Cold water is then pumped through the system and hot water/steam is produced at surface. The Momotombo geothermal field (figure 1), operated by Ormat TECHNOLOGIES Inc. has been producing electricity since 1983 and has an installed capacity of 77 MW and current output of 32 MW (Porras *et al*., 2007; Bjornsson, 2008). The Momotombo power plant therefore has the potential to exploit heat transferred by HFR, but the question remains if this concept is feasible?

The synergies between oil and gas and the geothermal businesses are well established, but have they been fully exploited? Over 10 years ago Shell started investigating an emerging concept to produce alternative energy from HFR. Since then the team has monitored HFR initiatives around the world, investigated the commerciality of HFR projects and assessed the feasibility of applying technology available to Shell to solve the key technical hurdles facing the HFR energy concept.

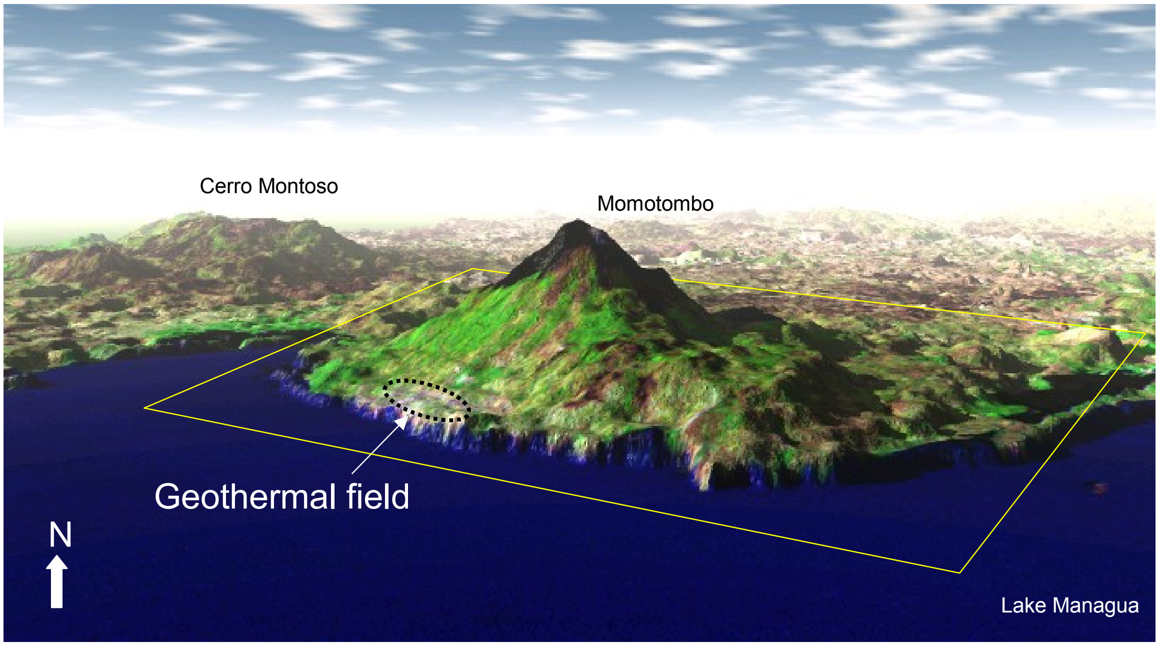

Figure 1: Virtual image of Momotombo compiled from Landsat data draped over a DEM used for structural interpretation. X3 vertical exaggeration. Yellow box shows approximate coverage of aeromagnetic survey.

Remote-sensing, faults, and a 4D Temp. cube

Interference tests between Momotombo wells indicate fracture dominated flow (Porras *et al.*, 2007) and early studies postulated a correlation between zones of high permeability deduced from lost circulation and fractures related to faulting (Moore *et al.,* 1981). The technical objectives of this study were to assess the state of stress in the region of the Momotombo field, develop some structural scenarios that could account for the fault and fracture network, and understand the distribution of permeability. Momotombo is a suitable field to study the geothermal sub-surface, because it has been producing power for over 25 years, has more than 30 wells, and hence is data-rich.

Airborne techniques allow geophysical data collection over areas where surface access is difficult, such as Momotombo. Residual anomalies were modeled on a number of lines across the field and different scenarios were envisaged to investigate their origin, such as fault displacements or steam caps related to hydrothermal alteration.

Evidence for the state of stress is obtained from earthquake focal mechanisms and interpretation of neo-tectonic structures, which show that the maximum horizontal stress direction ($\sigma_{H.max}$) is NNW-SSE in a strike-slip setting. Lineaments were interpreted from satellite images and aerial photos, correlated with lineaments from Grav-Mag data and validated as faults from outcrop work. The surface expression of the faults is typically a linear zone of hydrothermally altered ground ± sulphur ± silica deposits and steam, providing proof that these structures act as flow conduits.

Without seismic, a temperature (T) survey containing spot measurements from over 30 wells over the last 25 years offers an important control on sub-surface structure and flow (figure 2). These data were interpolated inside *gOcad* to create a 4D T-cube, from which the development of anisotropy in the thermal structure of the reservoir could be visualized. The NW-SE and NNE-SSW faults are thought to act as the primary flow conduits in the sub-surface at the shallow feed-zone (or aquifer) level (figure 2C) and furthermore, both sets are optimally oriented to slip in the present-day stress field.

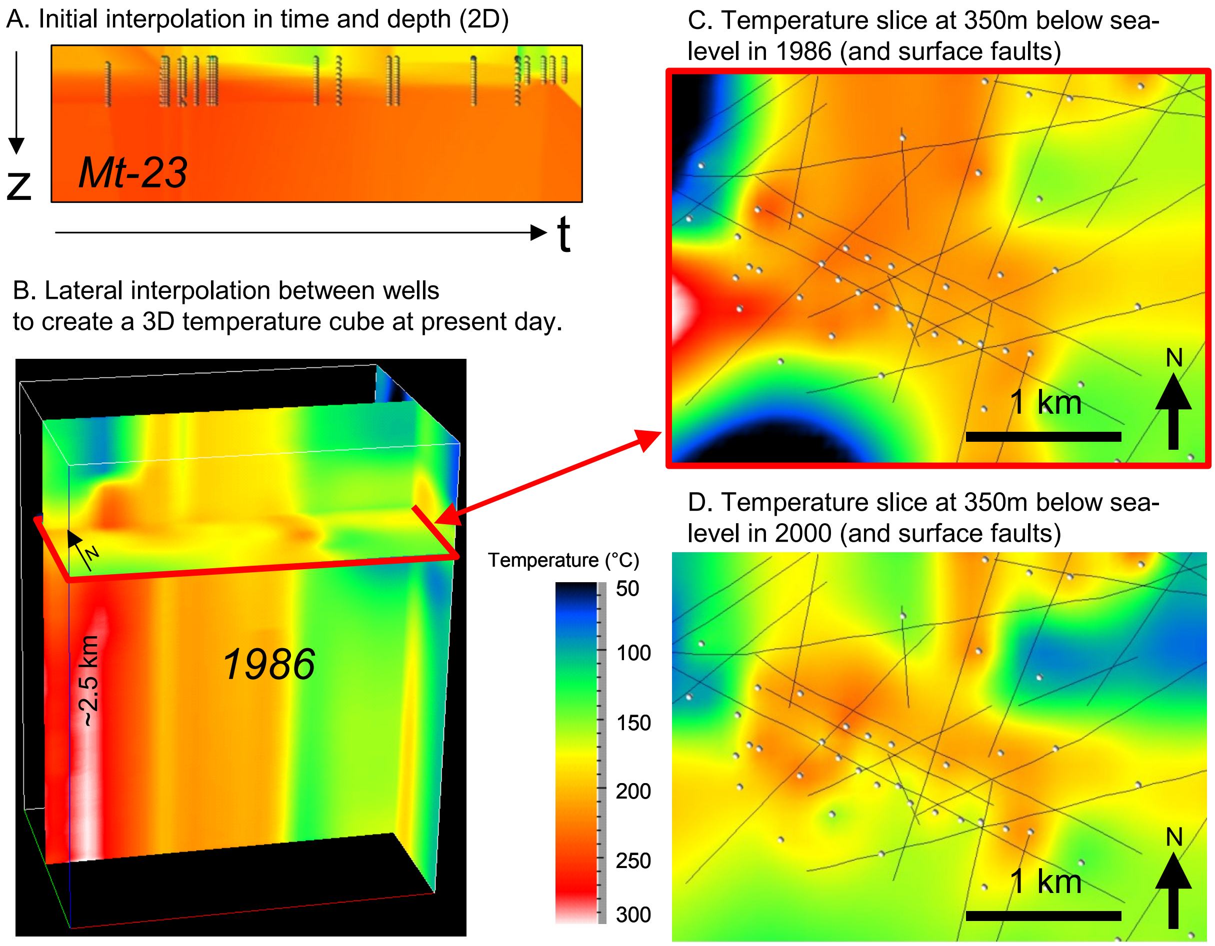

Figure 2: Temperature modeling in the Momotombo reservoir. Interpolation is: A) in 2D, for Mt-23 well through time, B) in 3D, between all the wells in the field, and C, D) in 4D, in the reservoir at different times in the past. Lines in C and D show surface lineaments, mapped from Landsat data. Circles in C & D show well locations.

Stress modeling & fault slip

We investigated the possible effect of fault-related deformation in the Momotombo field using the boundary element code, *Poly3D* (Thomas, 1993) and a Shell proprietary software package, *SVS Fracture Solutions*, with which the stress changes in and around the fault network were calculated. Figure 3A shows a map of calculated mean stress at the level of the highest feed-zone for a scenario where the in-situ stress field is strike-slip with $\sigma_{H.max}$ = 165° (NNW-SSE). Areas in green are in effective tension and are more likely to be regions of natural fracturing, and hence enhanced permeability.

The tendency to slip, defined as a ratio of shear stress to normal stress, was also calculated and displayed as a property on the fault surfaces (figure 3B) with hot colours indicating more slip. With $\sigma_{H.max}$ = 165°, the NW-SE and NNE-SSW faults are both optimally oriented to slip with a right lateral and left-lateral shear-sense respectively.

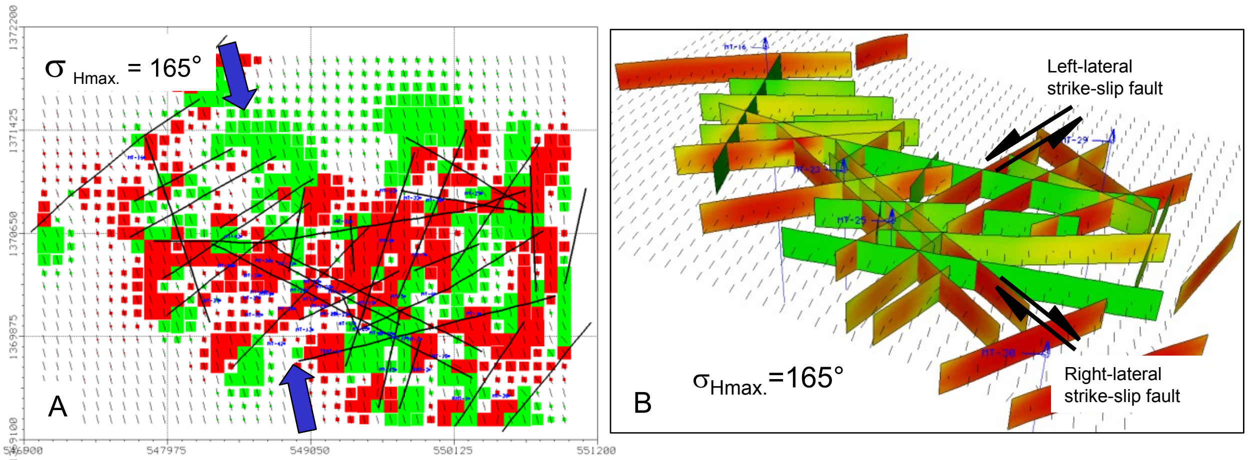

Figure 3: A) Map of stress perturbations calculated around the surface faults using *Poly3D* and a maximum horizontal stress of 165°. Green = effective extension; red = effective compression; short black lines = calculated local orientation of $\sigma_{H.max}$. B) Calculated slip (shear stress : normal stress) along fault surfaces with the same remote stress orientation. The hotter the colour, the greater the tendency to slip.

Conclusions

Integration of the temperature logs, state of stress, structure and fault permeability anisotropy in the field aids an understanding of the heat flow distribution through time. Prospective hot areas can be delineated and new sub-vertical wells can optimally target heat anomalies with deviation azimuths to the SSW to maximize the chance of fracture and fault intersection. Furthermore, if the HFR concept were to be applied at the edge of the Momotombo field, hydraulic fractures would propagate parallel to the maximum horizontal stress (NNW-SSE) and would be sub-vertical. With this geometry a hydraulic fracture may intersect one of the 2 main fault trends (and their associated fractures), which would be beneficial for creating a heat exchanger with good connectivity, but would carry the risk that a conductive fault may short-cut the injector-producer doublet.

Acknowledgements

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