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GEOTHERMAL WELL TARGET APPROACHES
IN THE EXPLORATION STAGE

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ABSTRACT

Identifying target for geothermal wells is the most difficult and risky task in an exploration stage of a geothermal project. Similar methodologies and criteria for well sitting often yield different results in different geothermal fields. There is no simple formula or procedure that provides where to drill the first well; each project must be based on site specific conditions. This paper shows the main approaches applied by the experts in difficult task of defining target for geothermal wells.

1. INTRODUCTION

The construction of an accurate conceptual model is of extreme importance to estimate: the depth/size of the resource, the heat source location and upflow and outflow zone, the capacity, the recharge and discharge zones, and the possible permeable targets for exploration drilling. This model is elaborated based on the information derived from surface exploration.

The surface exploration methods vary depending on the different stages of the geothermal project, which are:

- Reconnaissance (regional survey);
- Pre-feasibility;
- Feasibility;
- Project Design;
- Construction;
- Production.

The main exploration activities are achieved during the reconnaissance and pre feasibility stages.

The reconnaissance or regional survey serves to delineate the main geothermal areas, and assign priorities for further exploration. The study area is usually greater than 500 km^2. The pre-feasibility study is used to confirm the existence of the geothermal reservoir and characterize it, estimate the geothermal potential of the system, and identify promising targets for the exploration wells. Usually, the cost in this study is higher than the reconnaissance stage. The covered area is around 100 km^2.

The most common methods used in these stages are shown in Table 1. The costs and the probability of the success increase with each exploration stage (Figures 1 and 2), due the increment of field measurements density and the use of more specialized techniques, which allow the improvement of

the resolution and penetration capacity at depth.

TABLE 1: Main surveys carried out in the reconnaissance and pre-feasibility exploration stage

| Regular surveys in Reconnaissance stage	Regular surveys in Pre feasibility stage

1. Remote Sensing
2. Regional Structural and Geologic Analysis
3. Aerial Geophysical Surveys
   Aeromagnetic
4. Ground Geophysical Surveys
   Gravity
   Resistivity DC
5. Regional Geochemical Surveys
   Sampling springs and water wells
   Hydrothermal Alteration
   Geochemistry
6. Regional Heat
	1. Specific Aerial Photography
	2. Detailed Structural Mapping
	3. Ground Geophysical Surveys
	   Gravity
	   Magnetotellurics (TDEM/MT)
	   Magnetic
	   Passive seismic
	4. Geochemical Surveys
	   Sampling all surface Fluids
	   Hydrothermal Alteration Geochemistry
	   Isotope Analysis and Geothermometry
	   Diffuses gases survey
	5. Supplemental Heat Flow- if required
	6. Consideration of different Drilling Approaches
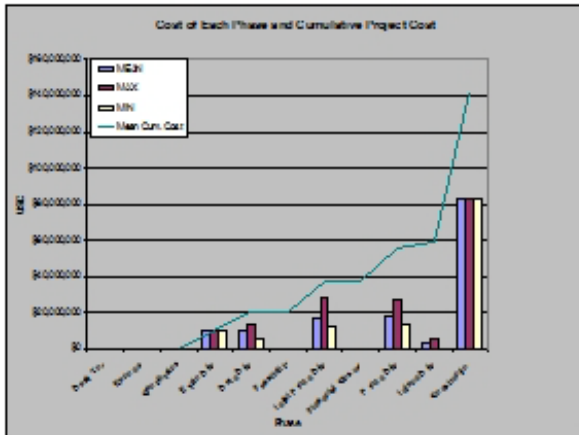
FIGURE 1: Cost of geothermal project phases (Brophy, 2008)
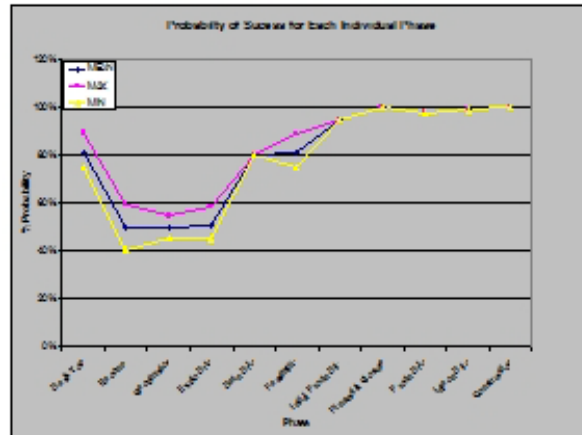

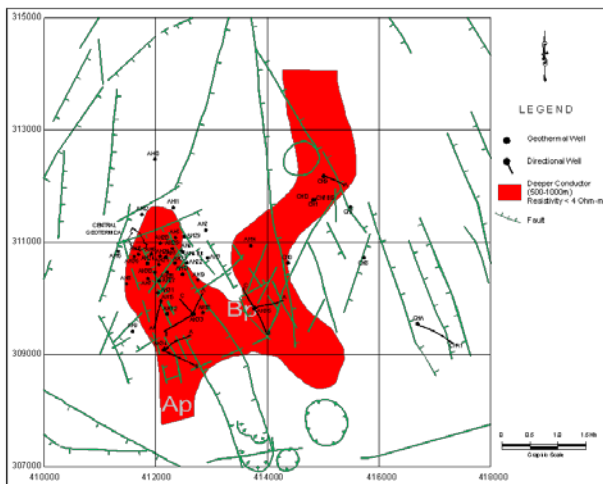FIGURE 2: Probability of success of geothermal project phases (Brophy, 2008)

FIGURE 3: MT low resistivity anomaly of Ahuachapán geothermal field in the early stage of exploration

This paper briefly outlines the main approaches commonly used to target wells and assess resource capacity in conventional permeable geothermal high temperatures reservoirs (from 200 to 350°C) at the exploration stage of a prospect.

2. EXPLORATION APPROACHES

The different approaches used to target wells discussed in this paper are: Anomaly Hunting, Geological Model Approach, Anomaly Stacking (overlapping areas with anomalies) and Conceptual Model Targeting. (Cumming, W, 2009).

2.1 Anomaly hunting

The Anomaly Hunting is usually based on either an analogy or an assumed correlation. An example is the Ahuachapan geothermal field, where, in the early stage, the MT low resistivity distribution layer, shown in Figure 3, was used as a guide in locating geothermal wells. Most of the wells located in Chipilapa area (eastern part of anomaly in red) had no characteristics of being production wells.

Another example of Anomaly Hunting would include targeting a well to intercept the high resistivity core, delineated by the magnetotelluric survey (MT), and associated with the propylitic reservoir, as shown in Figure 4.

Unfortunately there is no guarantee of finding high temperature reservoir due to the possibility that the system can be experiencing a cooling process and the resistivity trace may still remain.

A good example of this case is the San Vicente geothermal field, where the deep resistivity core associated with the propylitic reservoir was intercepted by the exploratory well SV-2 at the depth range predicted by the conceptual model. However, a temperature inversion at the bottom of the well was encountered (Figure 5).
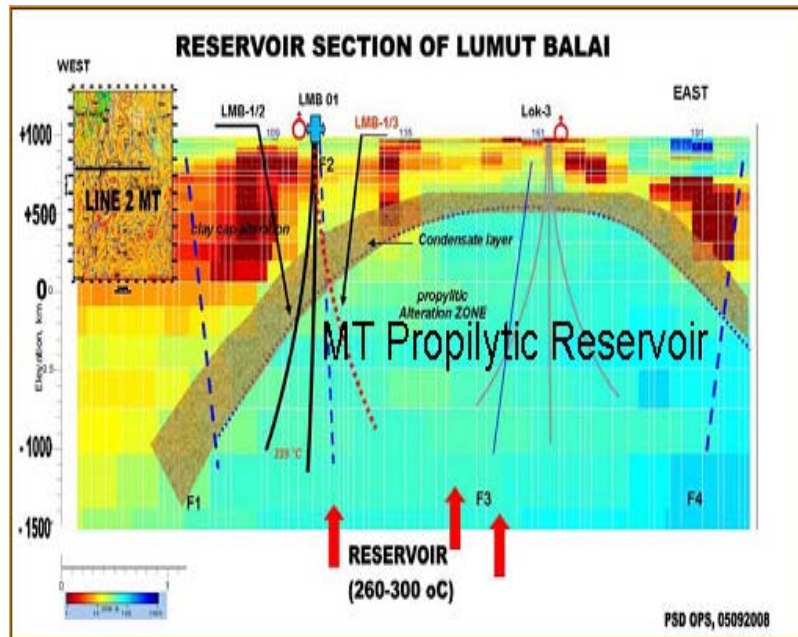

FIGURE 4: MT resistivity core associated with the production reservoir (Kamah et al., 2010)
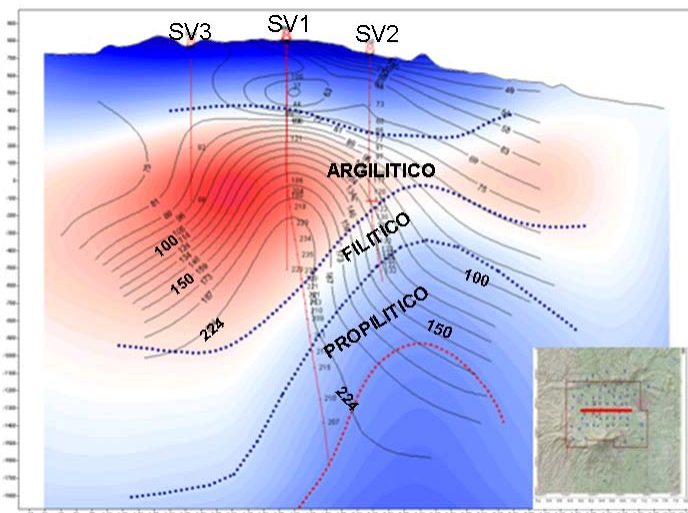

FIGURE 5: MT profile (blue and red background)), temperature (contours) and mineralogical facies intercepted by the geothermal wells in San Vicente geothermal field, El Salvador

In the propylitic zone, where chlorite and epidote were found, it was expected to have temperatures higher than 230 °C (epidote formation temperature), but the measured reservoir temperature was only 132°C. The same thermal disequilibrium is shown by the results of the fluid inclusion analysis (Figure 6). This evidence suggests that a cooling process had been experimented inside the geothermal reservoir of San Vicente field or that the system is partially fossilized.

The reason for any mismatch must be reviewed and applied for the next well to be drilled.

2.2 Geological model approach

The Geological Model Approach Target requires detailed structural mapping, starting from aerial photo and satellite image analysis, and followed by field work.
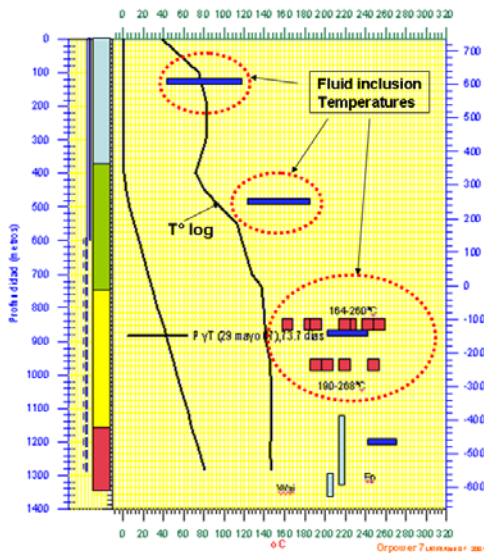

Figure 6: Fluid inclusion and Log temperature comparison of the SV-2 geothermal well (Torio-Henríquez, 2009)

From detailed structural analysis, well is sited towards a fault or intersection of faults as shown in Figure 7. The productive part of a geothermal field may lie within a fault zone, with permeability at intermediate depths of about 500 to 1500 m, commonly occurring where faults intersect weak formations.

For a single fault, the damage zone is at a scale of metres or tens of metres requiring wells to be oriented correctly to maximise the number and quality of intersections between them.

Andesite is the most common lithology in which permeable zones develop in volcanic geothermal systems.

The good result obtained by SKM in San Jacinto Tizate, in Nicaragua, identified the target well based on the local system of faults and found good permeability, as shown in Figures 7.
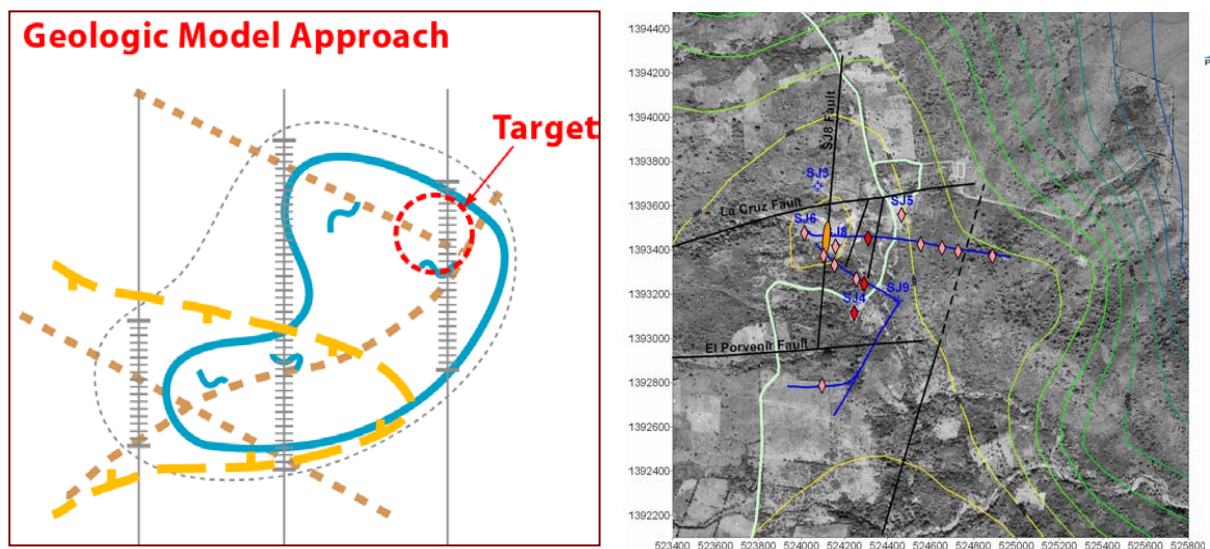

FIGURE 7: Geological approaches including the fracture zone, and well tracks, permeability, and fault in San Jacinto Tizate, Nicaragua. (Brophy, 2008; P. White, SKM)

2.3 Anomaly stacking

In the Anomaly Stacking Approach, the target of the geothermal well is based on an overlapping anomaly zone, where a number of roughly coincident anomalies are considered together, as shown in Figure 8.

However, Anomaly Stacking requires more care because coincident patterns often have a disproportionate effect on perceptions of uncertainty. For example, low resistivity and low magnetic intensity are commonly found over geothermal fields. The coincidence of a magnetic low with a resistivity low has sometimes greatly increased well targeting confidence. However, magnetic laws may also be characteristics of inter-volcanic valleys (Cumming, W, 2009).

Moreover, there are many more valleys than geothermal fields. If coincident features are interpreted in the context of the physical properties of a conceptual model consistent with all the available information, misinterpretations attributable to coincidence are less likely to occur.

One case where this approach was not good enough to obtain success was the case of the reinjection well TR-10A at the Berlin geothermal field. The well was aimed to intercept the permeability associated with "La Planta" fault, located in a very active seismic zone, inside a very well-defined MT anomaly, and overlapped by a high anomaly of radon and thorium concentration suggesting good permeability (Figure 9).
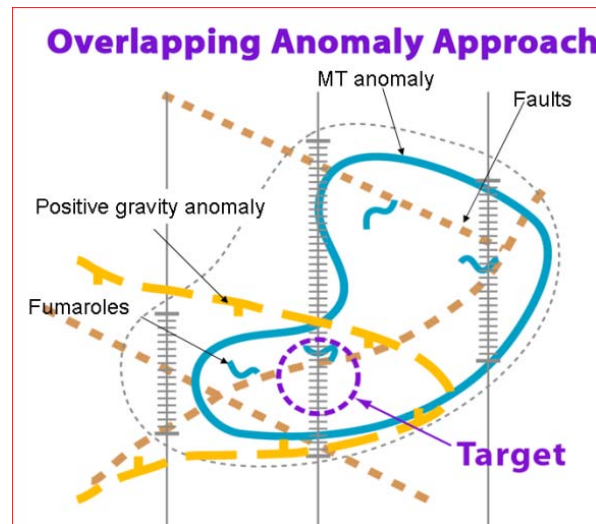

FIGURE 8: Overlapping anomaly approach (Mod. from Brophy, 2008)

Despite of the overlapping and interesting anomalies, no permeability was intercepted by the well. One of the reasons was that the fractures were already sealed by secondary minerals.

In Krafla, Iceland, good results were obtained targeting an overlapping anomaly area, similar to the TR10A, where the majority of the local earthquakes were located on the boundary between low and high resistivity anomalies, and defined fracture orientations as shown in the Figure 9.

2.4 Conceptual model approach

A Conceptual Model Approach for a geothermal resource assessment is done by integrating data sets of all geoscientific discipline to construct a physical model. It avoids the artificial perception of reliability, characteristics of Anomaly Stacking by explicitly illustrating how data sets constrain geothermal target parameters (Cumming, W, 2009).

The main components in a conceptual model are: heat source, production reservoir, sealing cap layer, upflow and outflow zones, and the recharge and discharge zones.

The passive seismic monitoring distribution at depth, the geo-volcanology and in some cases magnetotelluric (MT) survey can provide information about the location of the heat source.

The reservoir is constrained by MT resistivity core, a positive gravity anomaly and a low magnetic anomaly. The temperature is estimated from the geothermometry and the host rock type defined by the geology.

The recharge and discharge areas of the geothermal system are determined by the isotopes analysis.

The upflow zone is the reservoir zone in which flow is predominantly vertical and temperature generally increases with depth. In the outflow zone, flow is predominantly horizontal and temperature declines with depth below the main outflow zone, as seen on the right side of the upflow in Figure 12.
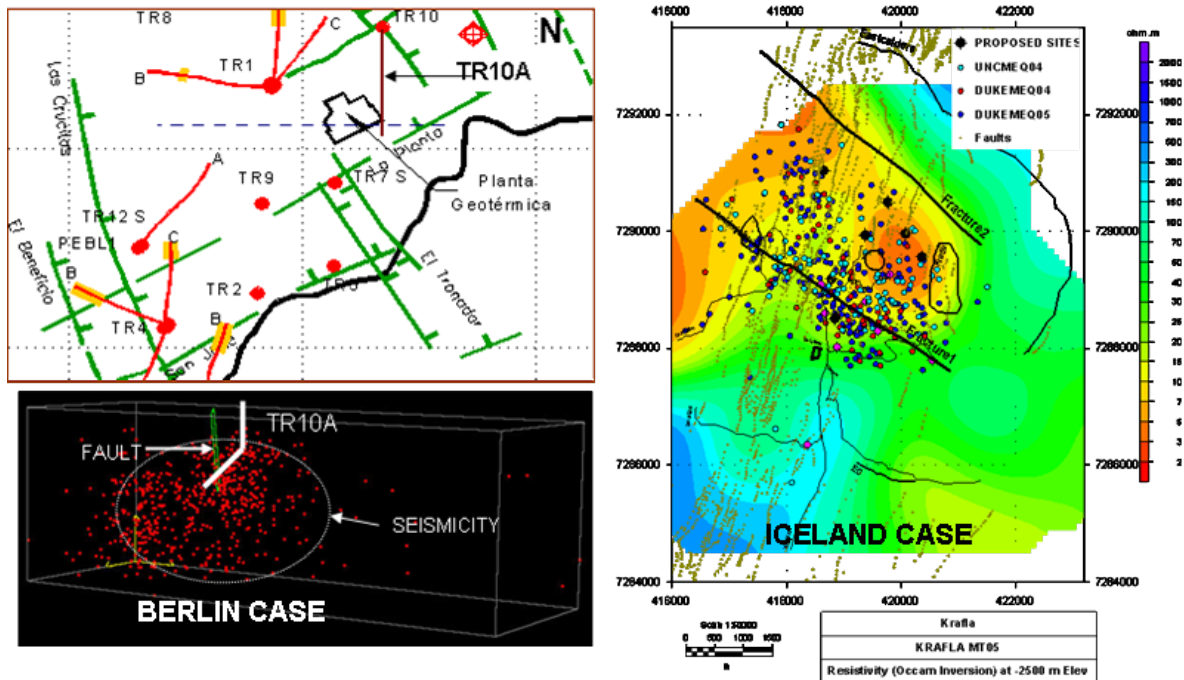
FIGURE 9: Examples of overlapping anomalies target in Berlin geothermal field, El Salvador and Krafla geothermal field, Iceland (Gautason et al., 2009)
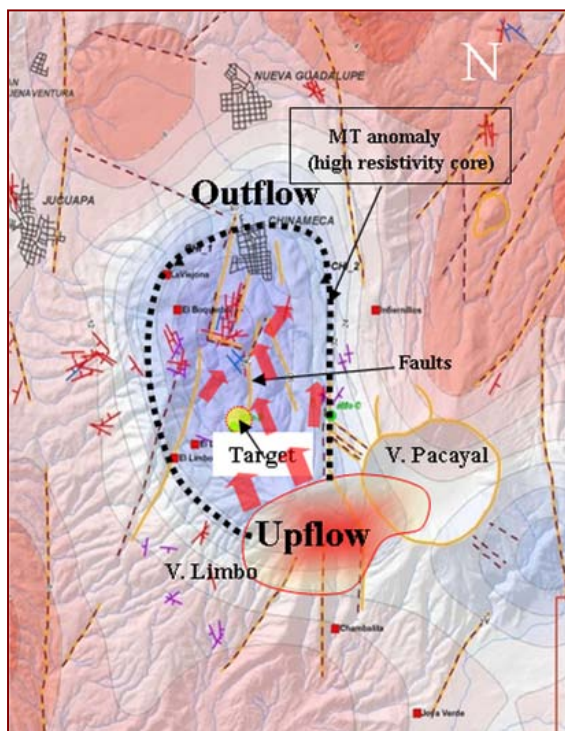

FIGURE 10: Successful target well, based on Conceptual Model Approach in Chinameca geothermal field. El Salvador

The Chinameca geothermal field in El Salvador is a good example of a successful target well location by using the Conceptual Model Approach, combined with geologic, structural and hydrogeologic models. The target was located close to the upflow zone, inside the MT anomaly and intersecting a local system fault where the geothermal fluids flow (Figure 12).

One advantage of using a conceptual model approach in well targeting is that the well will directly test the physic-chemical properties of the model, especially temperature, and any necessary revision based on the well results can be directly included in the resource assessment or follow-up targeting.

The Conceptual Model Approach also provides a basis for an effective basis of knowledge as wells are drilled and resource assessments are proven.

There is no simple formula or procedure that provides where to drill the first well; each project must be based on site specific conditions.

More prudent explorers target wells based on a combined geologic, structural and hydrogeologic models rather than on surface anomalies. Priority targets are generally the upflow zones, often occurring at fault intersections.

3. CONCLUSIONS

There is no simple formula or procedure that indicates where to drill the first well; each project must be based on site specific conditions.

From the different approaches presented in this paper, the conceptual model approach in well targeting is that the well will directly test the physic-chemical properties of the model, especially temperature, and any necessary revision based on the well results can be directly included in the resource assessment or follow-up targeting.

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