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A simple geochemical prospecting method for geothermal resources in flat areas

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ABSTRACT

In this paper a relatively inexpensive and efficient strategy for geothermal exploration by using geochemical prospecting tools to determine the placement of initial exploratory well(s) is proposed.

The method involves categorizing the hierarchy of thermal manifestations from which the presence of a buried thermal anomaly can be identified in a given geothermal area, and then locating the centre of the thermal anomaly. This is done by using simple, easy to obtain data on the depth, temperature, and some common chemical parameters determined in wells of the shallow unconfined aquifer, from which thermal gradients can be calculated if the temperature of the local rainfall is known.

The proposed strategy was applied by the author in Yemen; on a national scale in 2001–2006 (Minissale et al., 2007), and a local scale in 2007–2010 in the Dhamar region (Minissale et al., 2013). In the paper about the Dhamar area, briefly summarized here, how the placement of its first exploratory well was determined is described.

The methodology proposed is particularly effective and convenient in developing countries, such as those located along the African Rift, e.g. Zambia and Malawi, where geothermal exploration is still in its infancy, and where waiting for expensive geophysical investigations might postpone the development of geothermal resources for decades.

1. Introduction

Like solar and wind energy, geothermal energy is renewable. Its transport to the surface from the interior of the Earth is a steady stable process. In spite of its ideal characteristic as a green energy source for the future, and although its utilization for power generation is more than a century old, geothermal energy is still quite underdeveloped in many countries.

There is a number of reasons why geothermal energy has not expanded more rapidly, even in countries that have a high geothermal potential as evidenced by volcanoes and hot springs. These reasons include:

1) difficulty in deciding, on a national scale, the best area(s) in which to explore to a great depth;
2) difficulty in deciding which prospecting methodology should be applied to better define the underground temperature profiles (generally geophysical methods) and the reservoir characteristics;
3) difficulty in evaluating the relative importance of different geological, geophysical, and geochemical data sets with respect to identifying viable geothermal prospects;
4) awareness that unsuccessful exploratory drilling could block future activities in a potential area for many years;
5) risk aversion by decision makers;
6) opposition of residents because of potential pollution caused by geothermal power plants;
7) insufficient regulatory basis governing the geothermal power industry in countries where there is not a consolidated geothermal tradition, either during the exploration or the development phases;
8) time and effort required to perform comprehensive geothermal exploration, especially in remote areas;
9) difficulty in obtaining financial support, national or international, if the strategy of the development and implementation of geothermal projects are not well prepared and presented; and last, but not least,
10) the involvement of poorly trained and unqualified experts in geothermal exploration and development.

For countries where the first phase(s) of surface exploration have not yet been completed, or have not even begun (*e.g.* many countries

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along the African rift), a simple methodology is proposed here that should simultaneously reduce the cost of the exploration phase and speed up the positioning and drilling of the first exploratory wells. The most cost-effective design of the first exploratory wells is also considered.

2. Rationale

The heat flux from the Earth's interior is relatively high where the mantle is at shallow depth, and the mantle is shallower: *i)* along the mid-ocean ridges, *ii)* where it is uplifted at plate boundaries (*e.g.* the Pacific ring of fire), *iii)* where it is uplifted in continental rifting areas (*e.g.* the African Rift Valley) or *iv)* where mantle plumes have intruded the continental lithosphere (e.g. at Yellowstone). As a consequence, all existing producing geothermal systems are located in such areas of high heat flow, along with volcanoes, earthquakes, and strong hydrothermal CO_2 emissions, as first reported and mapped on a global scale by Barnes et al. (1978).

The "*juvenile*" heat from the Earth's interior is transferred outward through rock conduction, mantle convection and fluid advection, including: ascending magmas, magmatic gases, hydrothermal/metamorphic gases, and geothermal/hydrothermal waters.

In contrast to the outward transfer of heat, there is a downward transfer of cold rain and snow from the atmosphere, and cool surface water is gravitationally forced to descend underground (if not drained by rivers directly to the oceans), with a capacity for maintaining relatively low temperatures in shallow aquifers. This is particularly evident in stable, flat cratonic areas, where the thermal gradient is quite steady in all continents, commonly in the range 30–35 °C/km, corresponding to an apparent heat flux of 50–60 mW/km^2. Thermal emissions are rare in continental interiors and focused only along major regional faults (e.g. Minissale et al., 2000). Indeed, deep hot fluids can ascend through shallow cool aquifers occasionally by upward convection through fault systems, but are generally highly diluted and cooled by the shallow aquifer water.

At convergent margins the two opposite convective motions (crustal: warming and atmospheric: cooling) are sometimes juxtaposed in a narrow area because of the presence of a mountainous topography (e.g. Oliver, 1986). Therefore, at plate boundaries, the persistence of high advective heat flow at shallow depth is a complex dynamic balance between the contrasting fluid motions described. The escape of hot fluid to the surface is favoured by active tectonics and physical-chemical processes, such as boiling and vapour transport.

In general, the persistence of a high advective heat flow at shallow depth in hydrothermal systems around volcanic/magmatic systems is made possible by hydrothermal *self-sealing* processes, that alter (argillification) the cooled edges of hydrothermal systems, and/or precipitate silica and other secondary minerals, in veins, faults and fractures at the top and sides of convecting hydrothermal systems (Facca and Tonani, 1967). The persistence of heat underground is facilitated if there is a primary permeability contrast in lithology between the reservoir rock hosting the hydrothermal fluids and the overlying formations, for example the impermeable clay-rich flysch cap-rock present at Larderello (Italy) above a limestone reservoir (Cataldi et al., 1963). Nevertheless, as suggested by Facca and Tonani (1967) for the Geysers geothermal system in California, this lithological contrast at the top of the reservoir is not strictly necessary, because there the reservoir and cap-rock are both in the *Franciscan formation* (McNitt, 1961).

From a surface perspective, Craig (1963) showed that, although having a deep magmatic heat source, all the geothermal systems known at that time are supplied by local meteoric water mainly. A contribution of magmatic water is nonetheless present as a minor fraction in all volcanic/hydrothermal systems (Giggenbach, 1992). Therefore, we have an intrinsic paradox in geothermal systems: they are prevalently recharged by local cold meteoric waters, that eventually may completely obscure the presence of a geothermal system from the surface because of self-sealing on top of the geothermal reservoir. This is the ultimate reason why detection of geothermal systems at depth may be difficult from surface measurements, even in some active volcanic areas.

In general, the presence of surface thermal features such as steaming ground and steam condensates, boiling waters/mud pools, mud pots, or gas vents indicates that the local geothermal gradient is high. But such features may be rare, even around volcanoes that have erupted in historical time, because of self-sealing processes. Volcanoes that are considered quiescent for lack of hydrothermal surface emissions can erupt violently after only a short period of seismic precursory activity. This occurred in 1980 at Mount St. Helens (Washington State, USA), where fumarolic activity and even thermal springs were completely absent around the volcano prior to the eruption (Korosec et al., 1981).

Because volcanoes are generally high in elevation, and recharge of cold meteoric precipitation is more abundant near their summits than at their bases, active geothermal systems are often located beside volcanoes and may be partly recharged through the volcanic ducts (Calamai et al., 1970). As a consequence, thermal springs are often laterally displaced with respect to hydrothermal systems, in low topographic areas, sometimes quite far from the central craters (e.g.: Ingebritsen et al., 2006). In regions where several active volcanoes (i.e. a volcanic district) are close, and/or nested, and old calderas possibly hosting crater lakes overlap younger volcanoes or younger calderas, this simple scheme, that is viable for isolated volcanoes (e.g. Mt. Amiata volcano in Tuscany Italy; Minissale et al., 1997a), may not be valid. Moreover, faults and fractures, and contrasting permeability, play a relevant role to modify fluid motions, especially at their intersections (e.g.: Craw, 2000) in channelling deep hot fluids to the surface. Therefore, an active volcanic/geothermal region may have no thermal features at the surface or, in contrast, more than 20,000 thermal features like the biggest volcanic/geothermal region in the world in the Yellowstone National Park, with about 65 km^2 mapped as thermal ground (Lowenstern et al., 2015 and references therein).

3. Hierarchy of thermal emissions

It is beyond the scope of this manuscript to go into detail on how thermal features are distributed in high-temperature geothermal areas like the Yellowstone Park or the Taupo volcanic zone in New Zealand, or geothermal-rich countries like Indonesia or The Philippines, where there are hundreds of active volcanoes and thousands of thermal manifestations and many geothermal power plants in operation. The intention here is to focus on countries in which there are scattered active or quiescent volcanic areas, such as most countries along the Tethys suture (e.g.: Greece, Turkey, Iran) or along the African Rift Valley (e.g.: Eritrea, Congo, Malawi, etc.), or even erratic alkaline volcanoes in cratons, such as the Mt Ararat in Turkey, whose last eruption took place in 1840. The first step in geothermal prospecting in such regions is to make an inventory of thermal fluid emissions on the surface and to assess their potential significance in terms of subsurface temperatures. According to the experience of the author (Minissale, 2002a, 2002b, 2004, 2014), this is the proposed list starting from the most promising:

1) Supercritical (low-pressure) fumaroles: $T > 371$ °C (theoretically) up to 1000/1200 °C.
2) Superheated fumaroles (generally low pressure): $160° < T < 371$ °C.
3) Steam-saturated fumaroles of the "*solfatara*" type: often around 160 °C.
4) Steam-saturated fumaroles $100° < T < 160$ °C.
5) Boiling fumaroles at atmospheric pressure: $85° < T < 99$ °C, according to elevation.
6) Boiling water/mud pool, mud pot, sometimes very acid: $85° < T < 99$ °C.