Missing a trick in geothermal exploration

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Expansion of geothermal energy use across the globe is restricted by out-of-date prejudices. It is time for geothermal exploration to be extended to a broader range of environments and rejuvenated with the latest insights from relevant geoscience disciplines.

Pressure is growing to accelerate uptake of renewable energy resources worldwide. Geothermal energy could provide an important alternative to fossil fuels. Volcanically active regions, such as Iceland and New Zealand, have a successful and well-established infrastructure to harvest this resource. However, current conceptual models for geothermal exploration are largely based on the tectonic settings typical of those countries, which are located along unusually active plate tectonic boundaries. Attempts to apply these models to different environments and geological settings, such as in east Africa where the continent is starting to break apart, have, unsurprisingly, generated confusing and ambiguous results.

However, we should not dismiss potentially valuable geothermal resources in east Africa simply because they do not comply with conditions found in other environments. Rather, geothermal exploration in incipient continental rifts, as well as in a range of other tectonic settings, should be rejuvenated. The benefits for developing African nations could be vast.

Figure 1 | A fossilized clay horizon exposed on Gran Canaria, the Canary Islands. Clay layers form due to pervasive alteration of volcanic rocks by percolating hydrothermal fluids. Evidence for an actively forming, extensive clay horizon is a prerequisite for exploration strategies based on traditional models of geothermal resources[6,7]. However, the composition of rocks in places such as the Canary Islands and the western branch of the East African Rift Valley are not conducive to the formation of extensive clay horizons. Thus, such regions, which otherwise exhibit signs of vigorous geothermal activity, are often prematurely dismissed as further exploration sites for this important renewable energy source.

Advantages of geothermal energy

Geothermal resources stand out among the different types of renewable resources because they offer energy that is constant, supplied by magma or the decay of radioactive elements within the Earth, and available on demand. In contrast, the most rapidly growing renewables, wind and solar, are weather dependent. As such, wind and solar energy cannot be depended on for constant output or to meet fluctuating demands[1]. In addition, wind produces just electricity; it can only produce heat indirectly, typically using heaters that are expensive to run. Although solar energy can produce both electricity and heat, solar outputs in winter are simply insufficient to run central heating systems[2]. Biomass fuels also provide both heat and power[3], but are subject to severe feedstock limitations. These limitations do not apply to geothermal energy, and as the low-carbon imperative becomes ever more pressing[4], the case for geothermal energy ought to be unassailable.

In 2006 an imminent step change in geothermal energy exploitation was predicted[5] that extended far beyond the traditional volcanic regions such as Iceland and New Zealand. Additional settings where geothermal energy exploration could be viable include moderately volcanically active regions that are remote from plate boundaries, or where tectonic plates break up and crustal extension is still incipient, as well as regions of granitic rocks that expel heat through radioactive decay and hot sedimentary aquifers. Although uptake of geothermal energy has grown in the intervening years, it has not followed the predicted exponential trajectory. The lack of expansion of geothermal energy generation is due largely to the substantial cost required to drill into reservoirs of hot fluids. However, before drilling can begin, the location of the hot fluid reservoirs must first be predicted using conceptual models, and these models simply do not exist for a broad range of tectonic settings.

Traditional model shortcomings

Geothermal exploration has a long record of success in active volcanic regions such as Italy and New Zealand — where one tectonic plate subducts beneath another, generating volcanism at the surface — and Iceland, athwart the Mid-Atlantic Ridge, where the tectonic plates are spreading apart and generating abundant magmatic activity. The approach to exploration in these locations has been so successful that an orthodox 'formula' for exploration has emerged. Specifically, for a region to be considered suitable, it is currently required to show evidence for a heat source, such as a magma body, a fracture network in the rocks through which magmas and fluids can percolate, and deep hydrothermal circulation beneath a lens of clay minerals[6]. The concept behind this formula is that the hot fluids circulating within the hydrothermal systems significantly alter the lava flows and pyroclastic sediments that typically dominate the surrounding strata, creating extensive layers of specific types of clay minerals[7] (Fig. 1). Such layers are easily detected using geophysical methods, most notably the magnetotelluric technique[6], providing a useful indicator of a potentially viable geothermal resource. This is all very well where active volcanoes are underlain by thick sequences of lavas and pyroclastic rocks that are prone to be altered to such clay minerals. In such cases, the identification of hydrothermal alteration zones can be regarded as a sufficient condition for the presence of a promising geothermal resource. However, it is a mistake to regard it as an infallibly necessary condition.

As geothermal exploration spreads to countries with more diverse geology, blind adherence to this model runs the risk of dismissing viable geothermal targets simply because the tell-tale clay cap is not detected. For example, many of the rocks underlying present-day volcanoes in the Mediterranean[8], Tenerife[9] and much of the Indonesian volcanic arc[10] are carbonate-rich, sedimentary rocks that are not prone to forming clay minerals when bathed in hydrothermal fluids. Yet incorporation of water and carbon dioxide from these sedimentary rocks into rising magmas tends to increase the explosivity of eruptions in those regions[10], which can be confidently expected to give rise to zones of high fracture permeability that are well suited to host active hydrothermal convection systems. It should not matter to the geothermal explorer whether deep hydrothermal convection is occurring in volcanic, sedimentary or metamorphic rocks: the important factors of high temperature and elevated permeability can be present in any kind of rock.

As geothermal exploration moves into non-volcanic terrains[5], the need for fresh geoscientific thinking becomes even more pressing. For example, more moderate geothermal heat sources — those in the temperature range 80–150 °C and known as mid-enthalpy systems — associated with highly permeable faults in buried granitic rocks and overlying sedimentary rocks in northern England have recently been identified[11]. Yet, these non-volcanic reservoirs defy analysis according to the traditional approach.

Broadening geothermal horizons

The development of Africa is a global humanitarian priority. If such development can avoid many of the mistakes that have left the countries of the Global North locked into the use of fossil fuels, so much the better. Many countries in the continent have young volcanic systems, but geothermal exploration has only progressed in Kenya and Ethiopia. These countries are located in the main East African Rift System, where the continent is slowly breaking apart. Here, thick successions of volcanic rocks underlie recently active volcanic craters and the traditional exploration model can be expected to yield useful results. However, as the rift system is traced southwards from Kenya, it splits into two branches. The western branch, running through Uganda, Rwanda and neighbouring countries, is relatively young, and active volcanoes rest on ancient metamorphic basement rocks rather than thick volcanic successions. Geothermal prospects in these countries have been largely dismissed by international consultants, simply on the basis that the extensive clay layers predicted by traditional models for geothermal exploration could not be detected there. Yet coarse-grained, quartz-rich metamorphic rocks are not conducive to clay formation. The presence of active volcanoes and hot springs should take precedence over geophysical detection of clay lenses in such settings.

There is no region on the planet that could benefit more from rapid and widespread development of geothermal energy than East Africa. Ten countries straddle the East African Rift System, and between them they have a population approaching 300 million. As yet, only around 15% of this population is connected to the electricity grid, and average per capita energy consumption is only 10% of the average for sub-Saharan Africa as a whole[12]. Economic activity has been steadily growing in East Africa despite the global slump of the past six years, and demand for energy is growing even more rapidly than gross domestic product[13]. Every additional geothermal borehole offers the capacity to connect tens of thousands of people to the grid for the first time. Condensate from geothermal boreholes could even provide much-needed potable water in rural areas. Elsewhere in Africa, mid-enthalpy resources remain totally unexplored. Yet with modern technology these systems offer not only power, but also heat that can be used to assist agriculture, by drying crops and operating thermally powered refrigerators.

As the rising demand for low-carbon energy sources inspires geothermal exploration in less-familiar environments[5], within and far beyond volcanic regions, there is a need to re-evaluate our exploration paradigms from first principles. More than twenty years have elapsed since the last thorough synthesis was made of state-of-the-art volcanology and geothermal exploration principles[7]. Much has changed in that time, both in our understanding of volcanic systems and in the types of terrains now being considered for geothermal exploration. The time is ripe to refresh our approach to geothermal exploration by calling on the latest insights from interdisciplinary geoscience. ❐

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