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Geologic remote sensing for geothermal exploration: A review

Freek van der Meer[a,*], Christoph Hecker[a], Frank van Ruitenbeek[a], Harald van der Werff[a], Charlotte de Wijkerslooth[b], Carolina Wechsler[b]

[a] *University of Twente, Faculty of Geo-information Science and Earth Observation (ITC), Hengelosestraat 99, 7514 AE Enschede, The Netherlands*
[b] *Transmark Renewables, Herengracht 386, 1016 CJ Amsterdam, The Netherlands*

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ABSTRACT

This paper is a comprehensive review of the potential for remote sensing in exploring for geothermal resources. Temperature gradients in the earth crust are typically 25–30 °C per kilometer depth, however in active volcanic areas situated in subduction or rift zones gradients of up to 150 °C per kilometer depth can be reached. In such volcanic areas, meteoric water in permeable and porous rocks is heated and hot water is trapped to form a geothermal reservoir. At the Earth's surface hot springs and fumaroles are evidence of hot geothermal water. In low enthalpy systems the heat can be used for heating/cooling and drying while in high enthalpy systems energy is generated using hot water or steam. In this paper we review the potential of remote sensing in the exploration for geothermal resources. We embark from the traditional suite of geophysical and geochemical prospecting techniques to arrive at parameters at the Earth surface that can be measured by earth observing satellites. Next, we summarize direct and indirect detection of geothermal potential using alteration mineralogy, temperature anomalies and heat fluxes, geobotanical anomalies and Earth surface deformation. A section of this paper is dedicated to published remote sensing studies illustrating the principles of mapping: surface deformation, gaseous emissions, mineral mapping, heat flux measurements, temperature mapping and geobotany. In a case study from the La Pacana caldera (Chili) geothermal field we illustrate the cross cutting relationships between various surface manifestations of geothermal reservoirs and how remotely sensed indicators can contribute to exploration. We conclude that although remote sensing of geothermal systems has not reached full maturity, there is great potential for integrating these surface measurements in a exploration framework. A number of recommendations for future research result from our analysis of geothermal systems and the present contributions of remote sensing to studying these systems. These are grouped along a number of question lines: 'how reproducible are remote sensing products', 'can long term monitoring of geothermal systems be achieved' and 'do surface manifestations link to subsurface features'?

Introduction

Radioactively generated heat in the core of the Earth is the driver of the Earth's internal heat engine. Heat moves to the surface through conductive and convective processes. In addition, the top layer of the Earth surface is heated by solar radiation. Typical temperature gradients in the Earth crust are in the order of 25–30 °C per kilometer depth (equivalent to a conductive heat flux of 0.1 MW/km^2). However near tectonic plate boundaries specifically near diverging plate boundaries (like in active rift systems such as the mid-Atlantic rift and the East African rift), converging plate boundaries (subduction zones; Indonesia, Philippines, Chili), and along recent volcanic in intraplate settings (Hawaii, Yellowstone/US) volcanic activity results in gradients as high as 150 °C per kilometer depth. These high gradients through magma conduits trigger fluid circulation from fresh water from precipitation, ground water, lake water intrusion (meteoric water) which results in hot springs, steam vents. The amount of heat flow (heat flowing by conduction through a unit area in mW/m^2) is dependent on the temperature gradient and the thermal conductivity (in W/m °C) of the medium (rock, water).

In terms of geologic setting, geothermal systems can be classified in volcanic systems and in sedimentary systems (occurring in sedimentary basins) while another classification is in hydrothermal (water or vapor/steam dominated), hot dry rock (HDR), geopressured and magmatic (Barbier, 2002). Geopressurized reservoirs are deep (4–5 km) reservoirs in sedimentary basins that contain hot water under pressure, magmatic refers to energy stored in magma

* Corresponding author. Tel.: +31 534874353.
E-mail address: f.d.vandermeer@utwente.nl (F. van der Meer).

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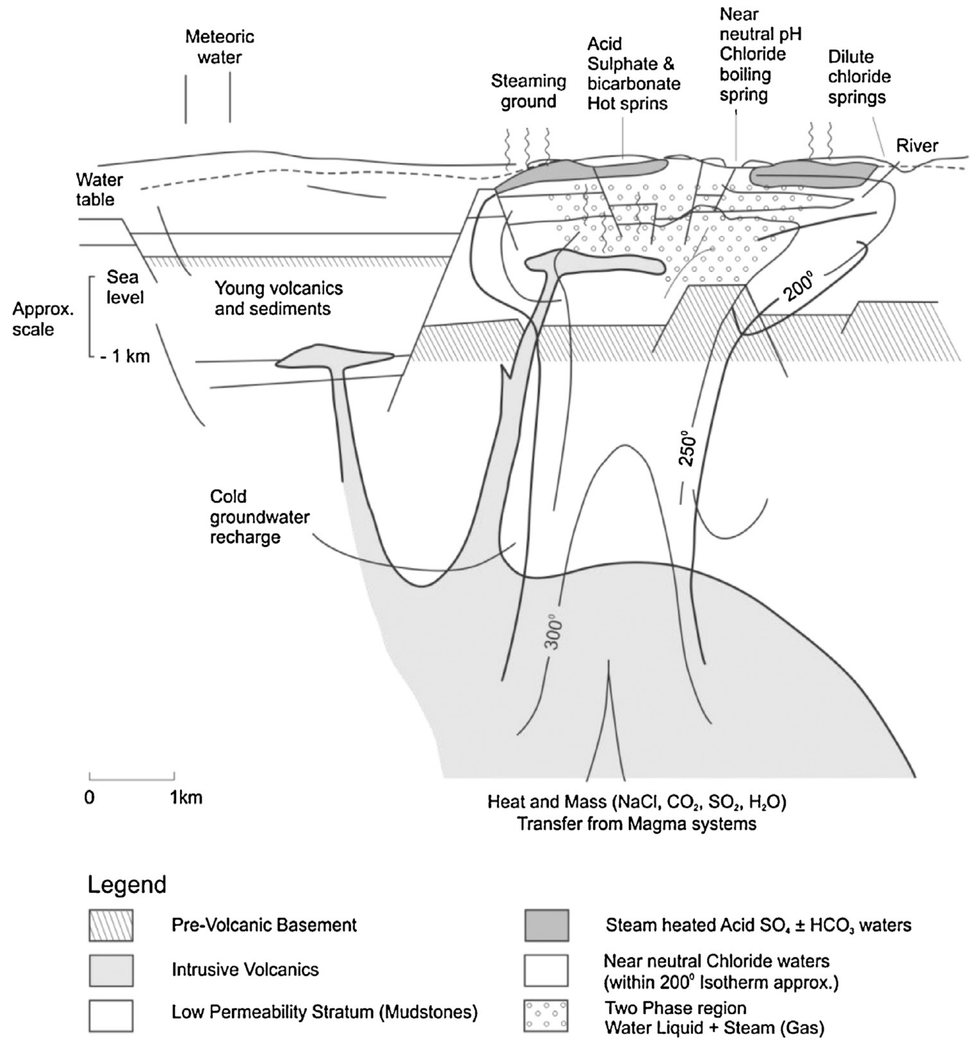

Fig. 1. Conceptual geologic model of a volcanic geothermal system where recharge results from meteoric groundwater driven by heat from supplied from a buried magmatic system leading to a convective column. Steam separation results in fumaroles and steam adsorption by groundwater while hot springs occur associated with the formation of silica.

Modified after Henley and Ellis (1983).

bodies, hot dry rock (HDR) are dry and impermeable hot rocks where by means of hydraulic fracturing ('fracking') a man-made reservoir is created.

Fig. 1 shows a conceptual model of a volcanic geothermal system. Water recharge results from meteoric groundwater infiltrating into the system driven by heat supply from a deep source of buried magmatic bodies. The magmatic body is the heat source leading to convection. Steam separation results in fumaroles and steam adsorption by groundwater which at the surface results in hot springs, steaming ground associated with the formation of silica and various alteration mineral assemblages. Gases venting from fumaroles are primarily water vapor and carbon dioxide, however also sulfurous gases are emitted.

Heat from geothermal reservoirs can be used to generate energy (electrical power) by using the steam to drive turbines in case of high temperature (>200 °C) reservoirs. Sometimes water is injected into the geothermal system to enhance the process. In case of normal geothermal gradients (30 °C/km) and low (<150 °C) temperature reservoirs, heat can be used for direct use (Lund et al., 2005) involving heating of buildings, drying of agricultural products etc. Geothermal generated energy has a number of benefits: it is renewable, it provides a stable base-load power for several decades and it is environmentally friendly with low carbon dioxide emissions compared to alternatives like fossil fuels (Mock et al., 1997). The downside maybe the emission of volcanic gases notably SO_2, CO_2 and H_2S which may be enhanced due to geothermal exploration and which are associated with respiratory mortality (Hansell and Oppenheimer, 2004). In low enthalpy systems there is the competition between aquifers used for shallow geothermal energy and for the production of drinking water. Geothermal activity gives rise to temperature variations beyond natural conditions which adversely affects groundwater quality (Bonte et al., 2013). Groundwater potentially can be polluted from reservoir fluids but also corrosion in the pipeline system used for exploration can adversely affect groundwater quality. Lastly, geothermal energy production can result in surface deformation. Lastly, geothermal energy production can result in surface deformation (Carnec and Fabriol, 1999).

Geothermal energy provides approximately 0.4% of the world global power generation with a growth rate of 5%. A good review of energy from geothermal resources is found in (Fridleifsson, 2001). At present the largest providers are in USA, Philippines, Indonesia, Mexico and Italy. To put this in perspective, solar energy plays a very limited role in global power generation (<0.2%), but it has a very high growth rate of 25–30%, especially in USA, Spain, China, Australia and India.