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Diffuse surface emanations as indicator of structural permeability in fault-controlled geothermal systems

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ABSTRACT

Diffuse degassing processes provide valuable information on geothermal reservoir characteristics not only in the context of monitoring, but also for exploration purposes. Areas with increased gas emissions can be indicative of major upflow zones from the reservoir through deep-reaching, permeable fault zones. These fault zones may act as preferential target areas for geothermal production drillings. In this study it is successfully demonstrated that diffuse degassing measurements can be used for the detection and characterization of permeable structural elements. The combination of following techniques has been applied at the Brady's geothermal system in the Basin-and-Range Province (Nevada, USA): accumulation chamber method for carbon dioxide and hydrogen sulfide measurements, alpha-spectroscopic measurements of radon and thoron activity concentrations, and gamma-spectroscopic measurements of selected nuclides.

1. Introduction

Many of the medium- to high-enthalpy geothermal systems emit large volumes of various gases to the atmosphere (e.g., carbon dioxide, hydrogen sulfide and others), some of which are due to subsurface degassing processes of volatiles from magma (Giggenbach, 1996). In addition, naturally-occurring gaseous radioactive decay products find their way from deep reservoir rocks to the surface. Variations of electromagnetic gamma radiation within geosystems are ubiquitous and depend primarily on the radioelement content of the subsurface (Galbraith and Saunders, 1983). Gas emissions are commonly concentrated along deep-reaching fault zones, which act like release valves and connect geothermal reservoirs with the surface. However, only a few faults from complex fault systems enable geothermal fluid flow (Faulds et al., 2004, 2006).

Herein, the focus is on extensional fault-controlled geothermal systems. In contrast to volcanic systems, where exploration aims to detect the heat source and the associated hydrothermal convection system; exploration of fault-controlled geothermal systems requires the detection of permeable faults where active flow of geothermal fluids dominates the placement of reservoirs and geothermal surface manifestations. In volcanic systems geothermal fluids often migrate to the surface and form abundant hot springs with characteristic geochemical signatures (Giggenbach, 1991). *Blind* or *hidden* systems, commonly occurring in the Basin-and-Range Province, often lack geothermal surface manifestations, such as fumaroles and in particular hot springs, and must be inferred from other surface and subsurface data without clear indications of prospective sites. The three geothermal systems at the Hot Springs Mountains in the Basin-and-Range Province (Brady's, Desert Peak, Desert Queen) are not yet fully understood in terms of dimension and recharge mechanisms (Fig. 1; Faulds et al., 2004, 2006). With the presented approach of a multi-parameter diffuse degassing analysis at the Brady's geothermal system, faults shall be detected that channel geothermal fluids.

Apart from geothermal activity due to active extension (extensional/amagmatic geothermal systems), some geothermal systems in the Basin-and-Range Province also originate from magmatic intrusions and volcanism (magmatic geothermal systems), in particular at or near its western and eastern boundaries (McNitt, 1995; Wisian et al., 1999; Coolbaugh et al., 2002).

1.1. The Brady's geothermal system in the Basin-and-Range Province

About 59 medium- to high-enthalpy hydrothermal systems and 101 low-enthalpy to warm hydrothermal systems have been identified in the Basin-and-Range Province (Coolbaugh et al., 2002). According to the classification of geothermal systems after Hochstein (1988) and Bendritter and Cormy (1990), the Brady's geothermal field is defined as a medium-enthalpy geothermal system with maximum measured

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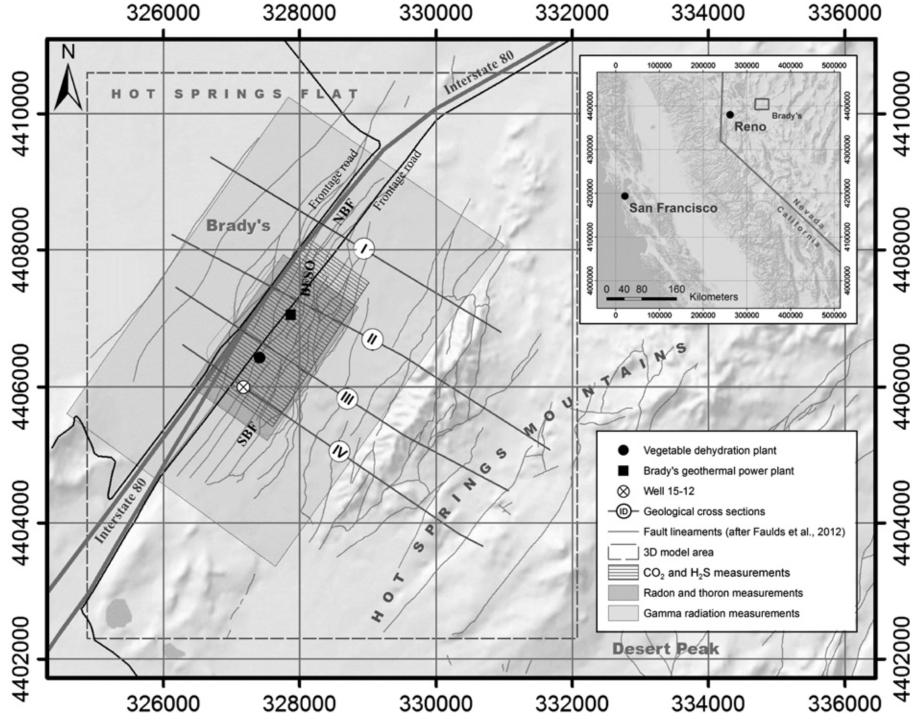

Fig. 1. Local sketch map of the Brady's geothermal system illustrating the schematic boundaries of the surveyed area for the applied methods. The Brady's geothermal system belongs to the Hot Springs Mountains, an area with three independent thermal plumes (Brady's, Desert Peak, Desert Queen) (Benoit et al., 1982; Faulds et al., 2010a). Details on the geological cross sections I-IV and the 3D model can be found in Jolie et al. (2014). SBF: Southern Brady's fault; NBF: Northern Brady's fault; BFSO: Brady's fault step over; Coordinate System: NAD 1983 UTM Zone 11 N.

reservoir temperatures of 212 °C (Benoit et al., 1982; Welch and Preissler, 1986). It is located in the western part of the Basin-and-Range Province within the NE-trending Humboldt structural zone, east of the Walker Lane dextral fault system (Faulds et al., 2005) and is characterized as an extensional amagmatic geothermal system with active faulting. The basement is composed of Mesozoic metamorphic and plutonic rocks, which are covered by Cenozoic volcanic and sedimentary sequences. The structural–geological framework is described in detail in Jolie et al. (2015). The structural key element of the geothermal system is the Brady's fault — a ~10 km long, NNE-oriented fault zone dipping 60°–80° to the NW (Figs. 1 and 2; Rudisill, 1978).

The Brady's geothermal reservoir is utilized by a vegetable dehydration plant and a geothermal power plant (Lund, 1994; Nevada Division of Minerals, 2012). Before exploitation of the Brady's geothermal system was started manifold geothermal surface activity in the form of hot springs and spouting geysers was reported (Russell, 1885; Yager, 1971). Fumarolic activity became much more widespread after geothermal production began, whereas hot springs became extinct. This development results from a lowered water table in the geothermal system caused by exploitation, which reduces reservoir pressure and increases subsurface boiling. Active geothermal surface manifestations along the step over region of the Brady's fault zone, such as fumaroles, mud pools, warm and steaming grounds, hydrothermal alteration zones, indicate structural permeability dominated by dilational fault zones (Fig. 2A–F; Faulds et al., 2006, 2010a; Jolie et al., 2015). Today, active geothermal manifestations occur in particular along the Brady's fault, while outside this major fault zone is no surficial evidence of an active geothermal system. Yet, it is hypothesized that gases with a geothermal origin also ascend to the surface in zones far from active geothermal surface manifestations. In this context the exploration approach was planned over a large area covering also areas without any obvious geothermal surface manifestations (Fig. 1). Along the central part of the Brady's fault step over and the Brady's main fault silicified sand, calcareous sinter deposits and mud deposits evidence former, but not necessarily present-day geothermal fluid flow. Abundant near-surface cavities along the Brady's fault step over (Fig. 2G) are actively forming today as a result of dissolution of rocks by acidic condensed steam. Estimates of their dimensions, abundance and coverage are difficult. Some of the cavities are accessible from the surface, others are filled up with boulders. The cavities are aligned along fault traces, thus presumably fault-controlled (fault traces mapped by Faulds and Garside, 2003; Faulds et al., 2012).

1.2. Diffuse degassing processes

Large amounts of different natural gases are emitted to the atmosphere by diffuse degassing processes in both volcanic and non-volcanic environments contributing to global degassing that was often underestimated (Moerner and Etiope, 2002). The process of gas migration described herein as diffuse degassing is a combination of diffusion and advection (López et al., 2004). Most common volcanic gases are H_2O, CO_2 and SO_2, in smaller amounts H_2S, HCl, H_2, N_2, CO, CH_4 and others, and noble gases like helium or radon (Giggenbach, 1996). Diffuse degassing measurements have already been applied for various purposes worldwide, such as volcanic hazard analysis, volcano monitoring, environmental monitoring (e.g., landfills), mineral exploration and others (Barretto, 1981; Hernández et al., 2001; Cardellini et al., 2003; IAEA, 2003; Pérez et al., 2004; Fridriksson et al., 2006; Chiodini et al., 2010). Besides these well-established applications, gas measurements hold the potential to provide a successful detection tool for the identification of permeable zones in fracture-controlled geothermal reservoirs even in areas without eminent geothermal surface manifestations (Giammanco et al., 1998; Padrón et al., 2003).

The aim of this study is to show that extensional tectonics in the Basin-and-Range Province facilitates gas migration from deep sources to the surface due to abundant deep-reaching fault systems. Gas emissions can be determined by different geochemical exploration methods. Standard sampling techniques already exist for visible gas emanations in hot springs, fumaroles, solfatara and mud pools. There are also useful exploration techniques for measurements of invisible diffuse degassing