Geothermics 57 (2015) 84–94

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics

Seismic velocity structure of a fossilized Icelandic geothermal system: A combined laboratory and field study

Melchior Grab*, Benjamin Zürcher, Hansruedi Maurer, Stewart Greenhalgh

ETH Zürich, Institute of Geophysics, Sonneggstrasse 5, 8092 Zurich, Switzerland

A R T I C L E I N F O

Article history:
Received 27 February 2015
Accepted 4 June 2015
Available online 26 June 2015

Keywords:
Geothermal
Elastic rock properties
Host rock heterogeneity
Scale dependence
Seismic tomography

A B S T R A C T

Magmatic geothermal systems, as they exist in Iceland, are complex geological structures. Key features, such as hydrothermal upwelling zones and intrusive heat sources, are embedded in a highly heterogeneous host rock. The latter comprise quasi-horizontally layered basaltic lava flows of variable texture and morphology, repeatedly intruded by magma chambers and numerous intersecting sub-vertical dykes and sub-horizontal sheets. In order to estimate whether seismic techniques can detect the important geothermal features, this study examined the seismic velocity structure of the fossil geothermal system of Geitafell in southeast Iceland.

We combined seismic tomography field experiments with ultrasonic measurements in the laboratory to obtain a comprehensive picture of the velocity systematics and to investigate the scale-dependence of experimental velocity determination. We recorded six shallow seismic profiles over outcrops of different parts of the exposed magmatic system and we investigated 10 specimens of basalt, dolerite, and gabbro in the laboratory. Our results demonstrate that in the fossilized geothermal system of Geitafell, seismic velocities can vary over a wide range of around 1500 m/s. Considering this large spread of wavespeeds, velocity anomalies caused by geothermal activity are likely to be masked by the heterogeneity of the host rock. This places stringent demands on acquiring high quality data and an optimal survey design for successful seismic exploration. Moreover, we discovered that ultrasonic velocities measured in the laboratory under comparable pressure (depth) conditions are up to 15% higher than seismic velocities inverted from the field data. This is of great importance and must be taken into account when interpreting exploration-scale field tomograms with the help of laboratory test data.

1. Introduction

In Iceland, geothermal heat has traditionally served as an important energy source. To improve the efficiency of electric power production, there have recently been increased efforts to exploit super-heated fluids from greater depths, which are more energetic than the hot fluids used previously for electricity production (Elders and Fridleifsson, 2010). Geothermal fields suitable for this purpose include Reykjanes and Krafla, both of which are located within the Icelandic neo-volcanic zone comprised of postglacial lavas (Fig. 1). Reykjanes is located in southwest Iceland near the coast and is characterized at the surface by volcanic fissure swarms believed to be fed from deep magma reservoirs at the base of the crust. Krafla, in contrast, lies at the north central part of Iceland and has in addition to the fissure swarms a central volcano and caldera structure, due to the presence of an intra-crustal magma chamber (Thordarson and Hoskuldsson, 2002). The fluids in the case of Reykjanes are saline whereas those at Krafla are not.

To elucidate the structure of magmatic geothermal reservoirs and to detect hydrothermal activity at depths up to several kilometers, active and passive seismic methods are among the most commonly used geophysical techniques. Tomographic images of compressional (V_P) and shear (V_S) wave velocities have been used to map geological structures such as the geometry of the caldera (Tryggvason et al., 2002; Vanorio et al., 2005; Alfaro et al., 2007) or the presence of active and distinct central volcanoes (Brandsdóttir et al., 1997; Menke et al., 1998). Moreover, the state of the pore fluid within the geothermal reservoir can be inferred, for instance from the V_P/V_S ratio (Tryggvason et al., 2002; Geoffroy and Dorbath, 2008; Adelinet et al., 2011a,b; Jousset et al., 2011).

Although such seismic methods have been used for many decades in geothermal exploration worldwide, it is still very challenging to obtain explicit and definitive evidence for the presence

* Corresponding author at: Sonneggstrasse 5, NO H35, CH-8092 Zurich, Switzerland. Tel.: +41 44 633 7282; mobile: +41 78 602 5316.
E-mail address: melchior.grab@erdw.ethz.ch (M. Grab).

http://dx.doi.org/10.1016/j.geothermics.2015.06.004
0375-6505/

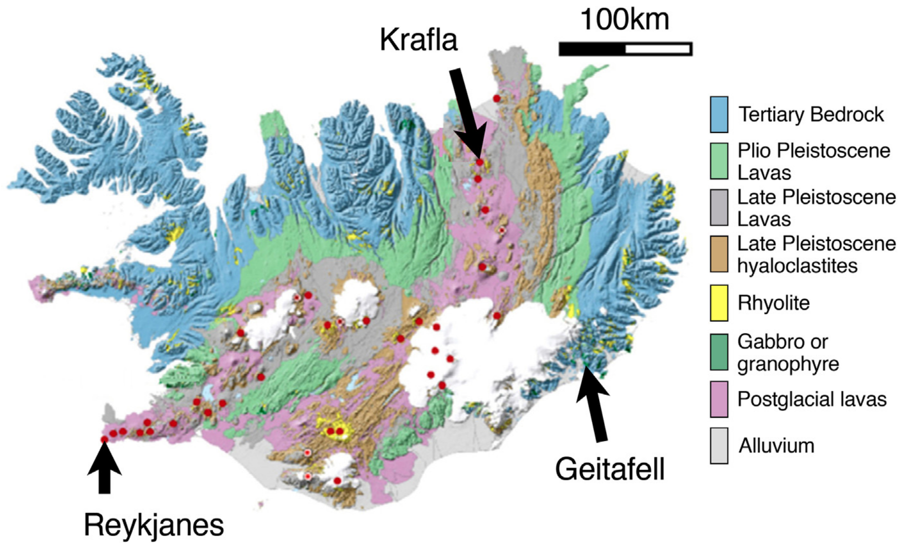

Fig. 1. Geological map of Iceland, modified after Franzson et al. (2011). The active systems Reykjanes and Krafla are located on the mid-Atlantic spreading ridge. Toward the west and east, older units outcrop and eroded systems can be observed such as at Geitafell.

of economically profitable energy resources in the deep subsurface. The difficulty arises from the fact that typical features of present day geothermal activity, such as hydrothermal upwelling zones and deep intrusive heat sources, are embedded in a highly heterogeneous host medium, created over its eventful history. Layered lava flows of variable texture and structure, old intrusive bodies such as dykes and sills, and zones of rock alteration due to former geothermal activity, tend to overprint the signatures of today's geothermal activity. Consequently, geophysical exploration techniques yield information on the entire integrated effects and not just the anomalous hot fluids. It is the objective of this work to characterize the seismic velocity structure of typical Icelandic geothermal systems in order to estimate to what extent subsurface geothermal activity can be detected and delineated by seismic imaging techniques.

In the past, several laboratory studies have been carried out to determine the ultrasonic velocities of the Icelandic rocks. For example, Jaya et al. (2010) investigated a basalt from Krafla and a hyaloclastite from Hengill, Adelinet et al. (2010) made sound speed measurements for a basalt from the Reykjanes peninsula, and Vinciguerra et al. (2006) examined basalts from Seljadur. But given the high diversity of rock types and rock conditions present in a geothermal system, it is clear that laboratory experiments only provide a limited number of point sample measurements, and do not deliver a holistic image of the highly heterogeneous seismic velocity structure of Icelandic systems. Furthermore, laboratory measurements are usually performed on samples in the several centimeters size range and at ultrasonic frequencies. Such measurements are not directly representative of seismic velocities observed in situ at seismic frequencies (below 100 Hz) and at the spatial scale of tens of meters to several kilometers. This scale-difference can lead to discrepancies and uncertainties as highlighted by Zamora et al. (1994), Vinciguerra et al. (2006), and Tiwary et al. (2009). It is therefore useful to verify the upscaling, for example by low frequency laboratory experiments using strain gauges (e.g. Adelinet et al. (2010, 2011a,b) and Adam and Otheim, 2013), or by field seismic tomography experiments (e.g. Vinciguerra et al., 2006).

For these reasons, our approach in the present study was to combine laboratory measurements on rock samples with in situ seismic surveying. As an analog to today's active systems, we selected the Geitafell fossilized geothermal system in southeast Iceland (Fig. 1), the geology of which has been extensively studied in the past (e.g. Fridleifsson, 1983; Burchardt et al., 2011). Due to the effects of rifting and subsequent erosion, the once deeply buried igneous formations are now exposed at the surface, enabling the collection of rock samples for laboratory velocity determinations and the conduct of shallow seismic tomography experiments. This makes it possible to compare the ultrasonic wavespeeds of the different rock types, which are from well defined parts of the ancient geothermal system but limited in number, with seismic velocities from the field tomograms, which are limited in their ability to resolve single rock units, but in return can cover a wide range of different alteration zones within the geothermal system.

The structure of the paper is as follows. We first provide a brief overview of the Geitafell geothermal system and describe the sites where the field tomograms were recorded and the rock samples were collected. In addition, we briefly cover the methods employed in the field- and laboratory experiments and show examples of the recorded data. Next we present the resulting V_P field tomograms at 6 sites distributed over the Geitafell system, and the results of laboratory V_P and V_S measurements on 10 rock samples, including basalts, dolerites, and one gabbro. We then compare the field velocities from the tomograms at depths below weathering with laboratory velocities at confining pressures corresponding to similar depths. This permits an evaluation of to what extent in situ velocities can be explained and interpreted with the help of laboratory wavespeed determinations. Finally, we seek to quantify the extent of background velocity heterogeneity of Icelandic geothermal systems and answer the question of whether it is possible to recognize the likely signature of hydrothermal upwelling zones and magmatic intrusions in the presence of such background velocity variability.

2. Field experiment locations, geological setting and rock samples

2.1. Field sites

For the in situ seismic experiments, two sites were selected which are shown in Fig. 2. One is at Geitafell (from which the fossil geothermal system derived its name) and the other is at Hoffell, a small settlement located approximately 5 km to the southeast of Geitafell. From outcrop observations, it was possible to define three main lithological units which dominate the fossil geothermal