Geothermics xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Geothermics

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

Evolution of hot fluids in the Chingshui geothermal field inferred from crystal morphology and geochemical vein data

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ARTICLE INFO

Keywords:
Chingshui geothermal field
Clumped isotopes
Fluid inclusions
Calcite
Formation scaling

ABSTRACT

The Chingshui geothermal field once hosted the first geothermal power plant in Taiwan from 1981 to 1993. After a long period of inactivity, this field is attracting renewed interest to meet the need for clean energy. A 213-m length of cores (IC-21) with continuous recovery, the longest in the Chingshui geothermal field, was recovered from 600 m to 813 m below the surface in 2010. Three types of calcite crystal morphologies have been identified in the veins of the cores of well IC-21: bladed, rhombic and massive crystals. Bladed calcites are generated via degassing under boiling conditions with a precipitation temperature of ~165 °C and calculated $\delta^{18}O$ value of −6.8‰ to −10.2‰ VSMOW for the thermal water. Rhombic calcites grow in low concentration Ca^{2+} and $CO_3{}^{2-}$ meteoric fluids and precipitate at approximately ~180 °C. Finally, massive calcites are characterized by co-precipitation with quartz in the mixing zone between meteoric water and magmatic or metamorphic fluids with calculated $\delta^{18}O$ value of up to 1.5 ± 0.7‰ VSMOW. Furthermore, the scaling and hot fluids at a nearby pilot geothermal power plant confirm a meteoric origin. Based on these observations, we propose that the current orientations of the main conduits for geothermal fluids are oriented at N10°E with a dip of 70°E. This result provides the basic information needed for deploying production and injection wells in future developments of the geothermal power plant in this region.

1. Introduction

Minerals deposited in veins provide important records for studying the evolution of hot fluids in geothermal systems. Isotopic data from fracture-filled carbonate minerals are particularly useful to constrain the geochemical characteristics of fluid reservoirs and possible post-depositional and syntectonic fluid processes (Iwatsuki et al., 2002; Li et al., 2013; Luetkemeyer et al., 2016; Wallin and Peterman, 1999; Wang et al., 2010). Additionally, the crystal morphology, which results from the interaction of crystal surfaces and fluids during crystal growth, indicates not only their chemical composition but also the physical parameters relevant to crystallization including temperature, supersaturation, pressure, fluid dynamics and impurities in parent phases (Aquilano et al., 2016). Degassing during boiling is one of the most important factors controlling crystal morphologies in geothermal fields and ore deposits. Many studies have been published that discuss the relationships between different types of crystal morphologies in non-boiling and boiling conditions (Bodnar et al., 1985; Canet et al., 2011; Griffiths et al., 2016; Harvey and Browne, 1992; Keith and Muffler, 1978; Moncada et al., 2012; Pei et al., 2017; Simmons and Christenson, 1994; Tulloch, 1982).

The Chingshui geothermal field in northeastern Taiwan (Fig. 1) is an excellent case study for combining both crystal morphology and geochemical data to construct a hydrological model and to estimate fluid evolution in a geothermal system. There are many published geochemical and isotopic data from the hot fluids collected at the pilot geothermal production wells in the field (Chiang et al., 1984; Lin, 2000; Liu et al., 1990, 1982; Yui et al., 1993). The calculated $\delta^{18}O$ values of hot fluids, based on calcite veins from outcrops and cores, were significantly different from those of discharged water from the wells suggesting different sources for the parent fluids of the calcite veins and current geothermal fluids (Lu et al., 2017). It is therefore important to

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https://doi.org/10.1016/j.geothermics.2017.11.016
Received 30 June 2017; Received in revised form 20 October 2017; Accepted 29 November 2017

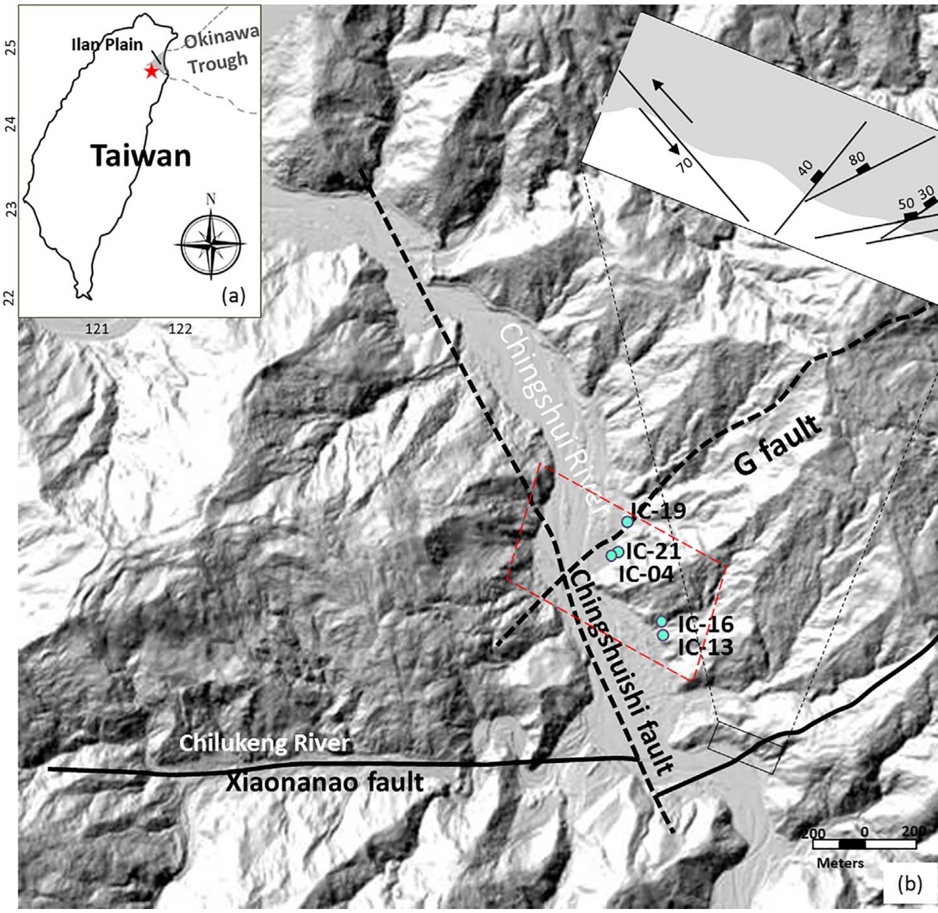

Fig. 1. (a) The Chingshui geothermal field (red star) is located in the southwest of Ilan Plain, an area formed during back arc extension of the Okinawa Trough. (b) The red dashed box is the main hot water upwelling zone in the Chingshui area. Three major faults, the Xiaonanao, the Chingshuishi, and the G faults, and several subsidiary normal faults with strike-slip components (black box) have been found in this area. The drilled wells, such as IC-04, −09, −13, −16, −19, and −21 are predominantly distributed in a 1.3 km^2 by the Chingshui River. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

assess conduit orientations and to construct a hydrological model to design the production and injection wells for the future development of geothermal power plants in the Chingshui geothermal field.

There was 213 m (depth 600–813 m) of continuous core recovered from borehole IC-21, which is the longest core in the Chingshui geothermal field. Abundant calcite veins with different orientations and crystal morphologies were identified and collected for geochemical analyses. In this paper, we use crystal morphologies, isotopic compositions ($\delta^{18}O$ and $\delta^{13}C$ values), and temperatures from fluid inclusions and clumped isotopes of calcites to understand the calcite precipitation conditions in the wells and outcrops, and to evaluate the parent sources and orientations of fluid conduits in the Chingshui geothermal field. The aim of this study is to construct a hydrological model to design the production and injection wells for the future development of geothermal power plants.

2. Background

2.1. Geological setting

The Chingshui geothermal field is located in the Valley of Chingshui River, approximately 13 km southwest of the Ilan Plain, northeast Taiwan (Fig. 1). The geothermal field is hosted in argillite/slate of the > 3,000 m-thick Miocene Lushan Formation (Hsiao and Chiang, 1979; Liu et al., 1986; Tseng, 1978). The Lushan Formation is a fracture-controlled geothermal reservoir. Meteoric water seeps down through fractures to depth where it is heated to over 200 °C, and finally it flows back to the surface through the fault-controlled conduits (Chen, 1982). Although some researchers have advocated this model (Liu et al., 1990, 1982; Yui et al., 1993), the regional geological structures were mainly inferred from geophysical data due to poor outcrops, and they remain unclear and controversial (Chang et al., 2014; Lin and Lin, 1995; Lu et al., 2017; Tseng, 1978; Ho et al., 2014; Hsiao and Chiang, 1979; Su, 1978; Tong et al., 2008; Wu and Chang, 1976).

Two major regional faults, the Xiaonanao and Chingshuishi faults, and a few small unnamed faults cut through rock bodies in this area. The Xiaonanao fault has wide fractured zones and is rich in quartz veins with euhedral crystals along the Chilukeng River, while the Chingshuishi fault was only deduced from geophysical data. Several researchers correlated the fractured zones in the Chilukeng River with the gouges at the Hanshi River and viewed the Xiaonanao fault as a south-dipping thrust associated with the Plio-Pleistocene Orogeny (Hsiao and Chiang, 1979; Tseng, 1978). In addition, other researchers suggested that there was a third fault cutting through the Chingshui geothermal field, the ‘G fault’, based on fracture distributions from drilling and geophysical data (Huang and Chuang, 1986) (Fig. 1). Lu et al. (2017) reported a series of north-dipping small normal faults with strike-slips parallel to the Xiaonanao fault, which are associated with abundant calcite veins (square in Fig. 1). These observations imply that the normal faults might be associated with the latest phase of the Okinawa Trough opening (Kimura, 1985).

Thermal structure and hydrological circulation of the Chingshui field remain controversial. Lee et al. (2016) proposed cold water recharge from higher altitude anticlinal fractures to the south, which was heated by the high geothermal gradient and finally upwelled along the Chingshuishi and G faults. However, Chang et al. (2014) reported that the Chingshuishi fault and the smaller south-dipping faults parallel to the Xiaonanao fault that are hypothesized to act as water infiltrating fractures are in fact an upwelling permeable zone as demonstrated by magnetotelluric surveys (MT).