# THE HEYUAN FAULT, SOUTH CHINA: A DEEP GEOTHERMAL PROSPECT – THE ROLE OF FAULT INTERSECTION RELATIONSHIPS AND FLUID FLOW

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## ABSTRACT

This pilot study investigates the Heyuan Fault, Guangdong, as a potential site for a geothermal power plant. The study focuses on two principal hypotheses: (i) that there are preferred locations of hot spots at fault intersections and (ii) that a combination of processes may be acting to contribute to the elevated surface heat flow.

Hot springs manifest at the surface along the Heyuan fault, concentrated in clusters occurring at intersections of cross-cutting faults. Chinese literature attributes the elevated heat flux to radioactive decay of a large granite pluton; however, additional heat sources may need to be considered to explain the heat flow maxima above 85 $mWm^{-2}$. We postulate that advective (topographically driven) and convective (tectonically-released deep fluids ponding at the brittle-ductile transition) processes may be operating to generate these heat anomalies.

We propose that expansive quartz reefs systems - exposed along the Heyuan fault – give evidence of these deep fluid circulation patterns that have since been uplifted. A detailed systematic analysis of reef structures will reveal (i) the fluid provenance, (ii) precipitation conditions and (iii) deformation mechanisms, which will ultimately help us understand how fault intersection relations control fluid flow; which is of key significance if it can be utilised for targeting geothermal energy.

## 1. INTRODUCTION

In 10 years' time, geothermal energy production looks set to proliferate in countries which have already demonstrated their capabilities through direct heat production, initiated power generation and/or made clear their political desire to develop clean energy in this field. One such country on the cusp of massive development in geothermal energy is China; already leading the way in direct heat production, with ambitious plans to increase geothermal power consumption over the next few years.

While their current geothermal energy production is relatively low (28 MWe) in comparison to other countries, e.g. USA (3.5 GWe), Indonesia (1.3 GWe), New Zealand (1 GWe) and Italy (0.9 GWe) (Bertani 2015), China have demonstrated their greener-energy intentions, and resources, by becoming one of the world leaders in direct heat production (18 GW thermal) closely followed by USA (17 GW thermal), Sweden (6 GW thermal), Turkey and Germany (each 3 GW thermal) (Lund and Boyd, 2015). Although geothermal electric power generation is in its infancy in China, they have ambitious plans to triple their geothermal power production in the next five years in a bid to reduce coal consumption and improve air quality (Chinadaily.com.cn, 2016).

This study focusses on a geothermal prospect situated in the province of Guangdong, China; a major industrial hub and the location of China's third largest city, Guangzhou (estimated 13 Million), neighbouring Shenzhen (10 Million) and with important links to the adjacent territory of Hong Kong (7.3 Million).

The Guangdong government and local drilling industry are supporting a multi-discipline reconnaissance study of the Heyuan Fault, with the aim of implementing a deep geothermal well to a depth of 3-4 km. The geothermal site of interest is located at the Heyuan fault – a creeping thrust fault, cross-cut by several more active faults. A unique feature which makes this site key for understanding fluid flow in these fault systems is the presence of large bodies of quartz reef deposited via hydrothermal precipitation associated with the fault, along with abundant hot springs along its length.

The initial work phase focuses on the meso-macro scale investigation, including field reconnaissance and geological and neotectonic investigation, which will be followed up by detailed microanalyses on samples of the quartz reef, including micro-structural evaluation and fluid inclusion studies. Results from these studies will be used to build a geological framework and, ultimately, a dynamic THMC model to assess how the fault intersection relations control fluid flow, which can then be used for targeting geothermal energy 'sweet spots'.

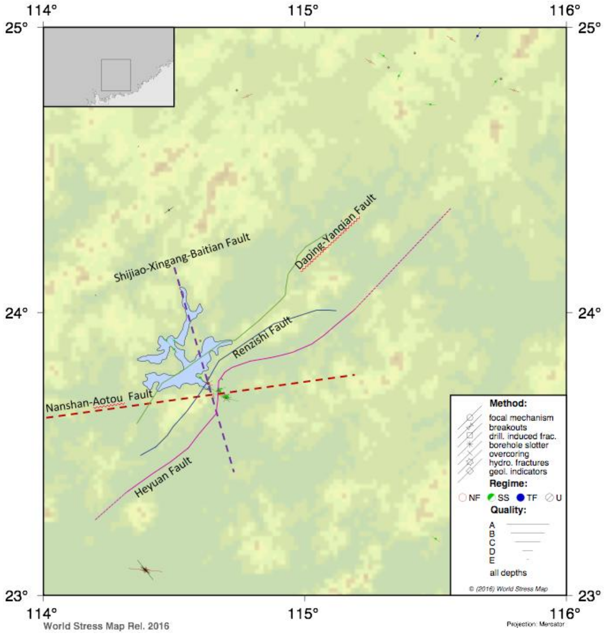


**Figure 1: Stress map of the study area encompassing the Heyuan fault and Xinfengjiang reservoir. Map prepared using CASMO (http://www.world-stress-map.org/casmo/) WorldStress Map Database Release 2016 (Heidbach et al. 2016) and adapted to show the position of the Heyuan and related faults.**

## 2. GEOLOGICAL SETTING

Situated within the Cathaysia block of South China, Guangdong is located over a Proterozoic to Silurian basement, folded during the Caledonian orogeny. Later, orogenic events in the Mesozoic (Indosinian and Yanshanian) increased deformation, with extensive magmatism accompanying each (Wang et al. 2014) and significant granitic intrusion occurring in the latter (Wan 2012). Towards the end of the Mesozoic, an extensional regime developed, which led to the creation of NNE and NEE trending fault zones and basins including the East China Sea Basin, the Heyuan Basin and several smaller basins throughout continental South China (Ruoxin, Liu., Guanghong, Xie., Xinhua, Zhou., Wenji, Chen., Qicheng 1995).

### 2.1 Faults

The Heyuan fault is situated within a series of adjoining and interacting faults that make up the ~700 kilometer NNE striking Shaowu-Heyuan Fault zone in South China (Lee, C. F., Ye, Hong., Zhou 1997). It extends from the NNE in the Fujian province to the SE through Jiangxi, with the main extent in Guangdong province.

The Shaowu-Heyuan Fault zone is also part of a larger interaction between three major fault zones, which trend NNE, NEE and NNW respectively. Along with the Heyuan fault, the Renzishi and Daping-Yanqian faults compose the NNE striking fault zone (Cheng et al. 2012). The Shijiao-Xingang-Baitian fault makes up the NNW zone and the Nanshan-Aotou fault the NEE zone. These NNW, NNE and NEE striking faults cut through a large E-W orientated Mesozoic granitic batholith (Chen & Talwani 1998; Qiu & Fenton 2015) (Figure 1).

Unique characteristics of the Heyuan Fault include (i) the marked change in strike trending from NNE to NEE and back to NNE, in contrast to the much more linear neighbouring faults, (ii) an abundance of hot springs sporadically along the length of the fault and (iii) most interestingly, large exposures of quartz reef (up to tens of meters thick) outcropping locally along the Heyuan Fault.

### 2.2 Hot springs

There are more than 320 hot springs in Guangdong province with temperatures above 30°C (Tian 2012 in Hui et al. 2015), with seven of these producing water at temperatures over 90°C (Xi *et al.*, 2015). The temperatures of three hot springs situated on the Heyuan fault were measured during this study to give readings between 55.7 to 62.5°C. These measurements are verified by analysis undertaken by Mao et al. (2015), who also sampled the thermals springs in the area with similar results.

Several shallow boreholes have been drilled by Industry within the Badengcheng area of the Heyuan fault, in the vicinity of the intersection of the NW-striking Shijiao-Xingang-Baitian Fault. The groundwater temperature profile is shown to vary, with surface temperatures recorded from the boreholes ranging from 27-64°C.

## 3. ACTIVE, NEO & PALEOTECTONICS

### 3.1 Current stress state

An overview of the current stress orientation across the Heyuan fault region has been obtained using the World Stress Map Project (Heidback et al., 2016), which denotes stress regimens from thrust faulting, strike-slip, normal faulting, a combination of these, or unknown. The data within the area of interest has been obtained primarily from focal mechanism solutions, with a small number from geological indicators and hydraulic fractures in the south-west of the region.

The map of the Heyuan fault area of interest shows predominantly strike-slip faulting with $S_{Hmax}$ aligned NW-SE; this stress field is compatible with observations of the Shijiao-Xingang-Baitian being an active strike-slip fault due to the oblique angle between $S_{HMax}$ and the fault line. Centred around the area of the intersection with the Heyuan fault, the stress indicators show both normal and thrust faulting; the latter aligned with the NW-SE principal stress direction of the strike-slip indicators, while the normal faulting appears oblique to this (trending either in E-W, N-S or NE-SW which is likely dependant on the fault strike and intersection angle) (Figure 1).

On a data quality ranking from A to E – with A being the highest quality and E denoting only the location without $S_{Hmax}$ orientation (Zoback 1991; Sperner 2003; and Heidback et al., 2010) – the data included for this area has been ranked as C, D and E. Further surveying and/or the use of additional techniques are therefore proposed for increased definition of the current stress pattern.

### 3.2 Fault stress (RIS studies):

Several authors have studied the stresses on the Heyuan and related faults in the area of the Xinfengjiang reservoir, due to increased seismicity following the construction of the Xinfengjiang Dam in 1962. (Ding 1989) has reported the maximum principal stress around the Xinfengjiang reservoir to be N73°W, with minimum principal stress N17°E. From this, Cheng *et al.*, (2012) calculated the Coulomb failure stress changes for the principal faults bounding the Xinfengjiang reservoir area, using a finite element method, yielding a stress drop ranging from of -3.5 to 2.7 kPa for the Heyuan Fault, prior to the main $M_s$ 6.1 earthquake which occurred in 1962.

Analysis by Wei et al. (1992) found five different focal mechanism solutions from 83 seismic events between 1983-1987 in the Xinfengjiang area, and ultimately concluded that the stress field was in N-S compression. Although the Heyuan fault is still referred to as a being a ‘normal fault’ geologically-speaking, due to the morphology of the hanging and footwall, it is now in a compressive state.

### 3.3 Geomorphology

The Heyuan fault shows apparent deformation, in comparison to the related faults which are much more linear and less distorted at the surface, that appears to be attributed to the stress of the cross-cutting faults. A marked change is seen in strike from NNE trending to NEE where it is cross-cut by the Shijiao-Xingang-Baitian fault, for example. The displacement on the Heyuan appears to be attributed to the left lateral movement on these more active NW trending strike-slip faults. This confirms that there has been a change in the stress regime or direction of the principal stress.

### 3.3.2 Field analysis

Leading out from the fault core into the granite hanging and footwall, there is evidence of multiple fracturing and fluid flow events. This can be seen by cross-cutting relations, overprinting features and deformation structures (Figure 2).

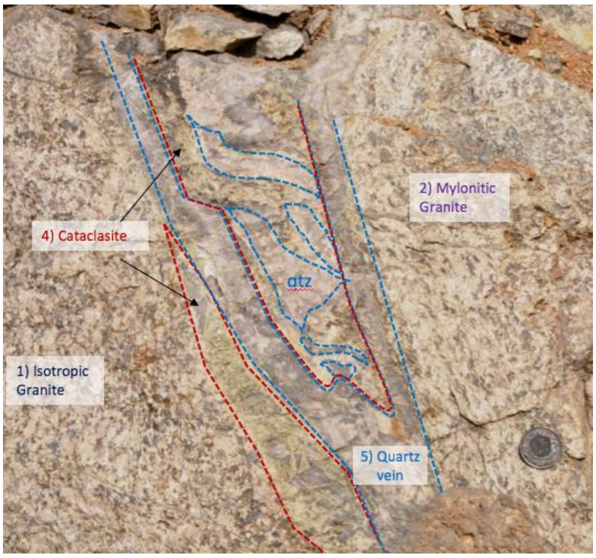


**Figure 2. Multiple reactivation fracturing and fluid flow events shown in the footwall of the Heyuan fault. In order of apparent formation; 1) isotropic granite, 2) mylonitic granite, 3) brittle fracturing and quartz precipitation (quartz shown in fragments contained within the cataclasite), 4) cataclasite formation and epodotisation, 5) fracturing and quartz vein precipitation (probably occurring in several events).**

**Field investigations found that fractures within the quartz reef from the core of the fault, outwards into the damage zone of the country rock, grouped into three distinct trends: 1) striking north-east and dipping to the south-east from gently to more steeply 2) north-east striking, with moderate dip to the north-west and 3) sub-vertical, unfilled fractures which cross-cut the mylonite and all other fractures (**

Table 1 & **Figure 3**).

| Fracture Group | Strike | Dip | Quartz Cementation | Stress |
|---|---|---|---|---|
| 1 | NE | SE - dipping more gently to more steeply. | Filled | Normal |
| 2 | NE | NW - moderately to steeply dipping. | Filled | Activated by cross cutting strike-slip faults |
| 3 | NW | Sub-vertical | Unfilled | Thrust re-activated |

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| 3 | NW | Sub-vertical | Unfilled | Thrust re-activated |

**Table 1. Summary of the main groups of fracture trends occurring in the study area, in order of occurrence.**

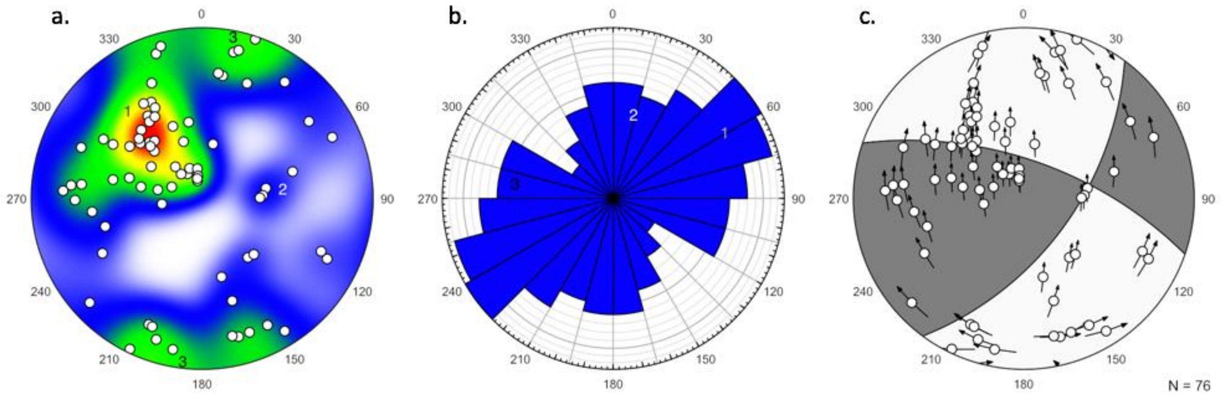


**Figure 3. Spherical projection and orientation of fracture planes within the quartz reef and wider fault zone. a.) Stereonet showing poles to fracture planes, with modified Kamb contouring at multiples of uniform density, highlighting point clusters (Vollmer 1995). b.) Circular histogram of the fracture planes, and c.) Fracture kinematics displayed via focal mechanism and tangent lines denoting the hanging wall motion. Figures prepared using Orient software (Vollmer 2015). The fracture planes fall into three groups, shown here as 1) NE-strike with varying SE dip, 2) NE-strike with moderate NW dip, and 3) NW strike sub-vertical fractures; noted by relative age, from oldest to youngest.**

### 3.3.3 Interpretation of results

Group 1, north-east striking fractures are cross-cut by the other two sets of fracture orientations, and it can therefore be concluded they were formed first. There are at least 2-3 generations ranging from very gentle to more steeply dipping. The alignment with the Heyuan fault indicates fracture formation as a result of the same extensional stress regime which the fault was under in the Mesozoic. The mylonite is concordant with these fractures and appears to have been generated during the same stress regime.

The group 2, north-east striking fractures, dip to the opposite direction and cross-cut the group 1 fractures, providing evidence of a change in stress – most likely activated from the north-west, strike-slip faults which cross-cut the Heyuan fault.

The sub-vertical fractures are evidently the latest event, cross-cutting all other features, and not yet filled with precipitate. It is proposed that the near vertical fractures, formed through thrust re-activation, are the current hydrothermal fluid circulation pathways

## 4. QUARTZ REEF

This massive quartz structure has been emplaced through precipitation of hydrothermal fluids, likely from deep within the crust, which has since been uplifted. Deep fluid circulation would have likely resulted from the dissolution precipitation reaction from the underlying granite, whereby K-feldspar reacting with $H^+$ is dissolved into muscovite plus $K^+$ and hydrous silica (Regenauer-lieb et al. 2015) as expressed below.

$$3KAlSi_3O_8 + 2H^+ \rightleftharpoons KAl_3Si_3O_{10}(OH)_2 + 2K^2 + 6SiO_2(aq)$$

These silica-rich fluids can then migrate and precipitate at shallower depths to form the quartz reef. So abundant is the quartz formation in this area that it is mined at Leiyao quarry for fibreglass production.

Preliminarily analysis of the quartz reef, undertaken during this study, has so far revealed a complex history of multiple phases of deformation and fracture healing.

### 4.1 Field observations

Field surveying and sampling of the quartz reef was undertaken at several locations where it outcrops along the Heyuan Fault. In these areas, the quartz reef comprises the fault core; which transitions into the country rock by decreasing quartz vein structure presence.

### 4.1.1 Quartz vein structures

Prior to performing the advanced microanalysis and absolute geochronology techniques, we can deduce the relative timing of events from the associated mineralogy (which precipitate at differing P-T conditions); as well as by identifying and categorising the quartz veins from field observable features, which enable rules of cross-cutting relations to be used. ).

Additionally, the quartz veins can exhibit certain characteristics which enable classification of the stress regimes at time of formation (

**Table 2. Classification of quartz veins observed in the field study area**

| Age | Quartz Vein Type | Description | Stress |
|---|---|---|---|
| Oldest | Type I | Milky, with diffuse boundary (shows grain size reduction). | Unknown |
| | Type II | Contains fibrous growths filled vugs, and large idiomorphic crystals in fractures in the direction of dilation (no shear sense). | Pull-apart |
| | Type III | Shear fractures (with dilatancy) containing idiomorphic crystals (cross cuts type II). | Shear |
| Youngest | Type IV | Fine Chalcedony (or quartz) type, with clear, sharp edges. (relatively undeformed). | |

### 4.1.2 Associated hydrothermal alteration mineralogy

Fluid circulation in geothermal settings leads to the alteration of primary minerals to a more stable state. We can use these secondary hydrothermally altered minerals as markers of their formation conditions (Figure 4), which were altered as a result of a change in temperature, pressure, fluid composition, or combination thereof.

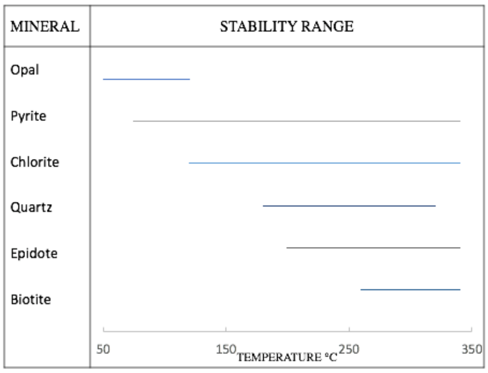


**Figure 4. Some of the common hydrothermal alteration minerals that are used at geothermometers (modified from Reyes, 1990).**

From field observations, a range of common hydrothermally altered minerals were present within the quartz reef and bordering vein structures. These included; biotite, chlorite, fluorite, epidote, chalcedony, quartz overgrowths and iron oxides, in order of apparent formation from oldest/deepest to youngest. Microanalyses will be performed on these samples for confirmation and further information.

***Hydrothermal mineral precipitates*** *(apparent relation to the main quartz reef mass – from oldest to youngest)*

1. Chlorite/Biotite
2. Epidote
3. Fluorite*
4. Chalcedony* - overprints the epidote, and chlorite, indicating later stage formation.
5. Quartz overgrowths* overgrowths over the chalcedony, indicating subsequent formation.
6. Dark Red Iron oxide (youngest) – likely infers contact with oxygenated groundwater, or meteoric source, rather than hypogene geothermal fluids (which would demonstrate redox) (Reyes 1990).

**mineral is stable over a wide range of temperatures. Therefore, cross-cutting relations are used to deduce relative timing of events.*

### 4.1.3 Interpretation

Multiple formations of vein structures were observed, which each show unique characteristics typical of differing stress fields, while the associated hydrothermal minerals highlight the wide-range of temperature conditions in which these quartz structures were precipitated. This shows that multiple fracturing and fluid flow events occured - over a prolonged period of time – as the stress state changed. We see a change from a tensional stress (e.g. during the extensional phase of the Heyuan fault), to that of a higher degree of shear, before veins are emplaced with little to no deformation – showing a relatively inactive period on the fault, much as it is today.

Further analysis and microstructural work is currently being undertaken, with exciting results emerging that will be published in follow-up.

## 5. GEOTHERMAL POTENTIAL

The Heyuan fault cuts through a large sub-surface granitic batholith, which was emplaced during the latter stages of the Mesozoic period (Chen & Talwani 1998; Qiu & Fenton 2015). The main granite body is termed the Fogang Batholith, with the Baishigang and Xinfenggjiang plutons forming extensions off towards the east and the Heyuan Fault cross cutting this extension.

The position of the batholith is also of importance, as coverings of Palaeozoic and Mesozoic sediments locally help to insulate granite body. A study by Sun et al. (2015) showed promising results of the radiogenic heat produced from five sampled granite bodies across Guangdong province which ranged from 5.28-7.11μW/m$^3$. Both A. D. Wang et al. (2014) and Sun et al. (2015) hypothesise that these granitic intrusions provide enough radiogenic heat to explain the hot spring activity at the Heyuan fault.

Published heat flow maps of the region (Hu et al. 2000; Wang et al. 2012) show surface heat flow in South China is elevated and ranges from an average of more than 72 mW/m$^2$, to more than 90 mW/m$^2$. While elevated radiogenic heat production reported by Sun et al. (2015) appears to confirm a significant crustal heat contribution through the granitic heat production, additional heat source contributions may need to be considered.

Sun *et al.* (2015) analysed 37 samples from the Fogang pluton and determined their density, as well as Th, U and K concentrations. The weighted mean Th, U, and $K_2O$ contents yielded values of 51ppm, 11ppm and 5.12% respectively, with a Th/U ratio of 4.96 and an average density of 2.57. From this, the heat production per unit volume is calculated as 6.77 $\mu W/m^3$, (significantly above the world average of 2.5 $\mu W/m^3$). An estimate of surface heat flow can be made using the heat production rate given by Sun *et al.* (2015).By adding an average mantle heat flow of 25 $mW/m^2$, and assuming a granite body thickness of 10 km (based on classic geothermal crustal models, i.e. (Lachenbruch & Sass 1977), the surface heat flux can reach over 80 $mW/m^2$.

While this may be sufficient to explain the thermal anomaly, additional heat source mechanisms should also be considered, including: i) higher mantle heat flow, ii) advection of hot fluids from adjacent areas, iii) shear heating (i.e. Sibson 1977) and iv) magmatic intrusions.

## 6. SYNTHESIS & HYPOTHESIS

### 6.1 Structural controls on fluid flow: Potential mechanisms for quartz reef formation.

While precipitation of the quartz reef was likely to have begun during the normal faulting of the Heyuan, the current stress regime (which has been discussed above as being compressive in nature with relative in-activity of the Heyuan fault itself) would not ordinarily allow for upward propagation of fluids along a fault plane to explain the hot springs along its length. Therefore we must consider additional mechanisms for fluid circulation pathways and upward migration for this to be reconciled.

Below, three fluid-release mechanisms which may explain the quartz reef formation and current hot spring manifestations are discussed. Future work will aim to critically evaluate these mechanisms in the context of the results generated from the various analyses performed.

#### 6.1.1 Fault Valve behavior – Sibson

Fault-valve behaviour has been proposed by Sibson (1990, 1992) to account for fluid release from impermeable faults immediately following an increase in shear stress, decrease in normal stress or increase in fluid pressure, which can occur in faults favourable to fault reactivation criteria. Sibson (1990) states optimal conditions for this fault-valve behaviour to be i) compression, ii) high fault angle, and iii) large volume of fluid stored in the overpressure zone.

Favourable conditions at the Heyuan fault which supports this model include:

- The change from extensional normal faulting to compressional regime
- Current thrust/reverse fault dip varies from ~32-62°, thereby providing the high-angle above 60° as stipulated in the model
- Quartz reef shows evidence of repeated fracturing (fault movement) and healing (hydrothermal cementation).
- Extensive quartz reef cementation provides confinement in the fault for potential suprahydrostatic gradient

Counter evidence of fault-valve behaviour at the Heyuan fault:

- Fluid discharge (I.e. from the hot springs) appears continuous in the observable period.
- Significant seismic activity in the recent period is attributed more to the strike-slip, cross-cutting faults than to the Heyuan, though this may be a sufficient trigger.

#### 6.1.2 Slow seismic movement

Periodically following stress accumulation, a ‘slow earthquake’ can occur over a period of weeks – increasing fault permeability and releasing fluid upwards - which allows new fluids below to be precipitated, re-sealing the fault. The periodicity is proportional to the permeability of the host rock, where lower permeability is said to result in a longer time between periods of activity  (and fluid release) (Poulet et al. 2014; Audet & Burgmann 2014), while the rate of fault re-sealing is also dependant on temperature.

However, given the huge permanent seismic monitoring array in place across the Xinfengjiang Reservoir area since the 1960s, it would seem unlikely that any slow seismic movement would have not been picked up, unless the data was not being filtered in a sufficiently low bandwidth to capture it.

#### 6.1.3 Fault-intersection conduits

The notion of enhanced permeability at fault intersections which allow for thermal fluids to be transmitted to the surface has been around for some time (Chadwick & Leonard 1979; Curewitz & Karson 1997). Further to this, analytical and numerical analysis has indicated that convection dominates along fault planes and preferential upwelling occurs at the fault intersections, providing sites of “enhanced dilation" (Person et al. 2012).

Further to this, we postulate that fluids ponding at the brittle-ductile transition (due to the decrease in pressure at that point), are channelled upwards where the NW-aligned faults are cross-cut by the Heyuan fault, thus enabling a deep fluid circulation pattern. Evidence of this is shown throughout the surface locations of the hot springs, which lie above the intersections of the cross-cutting high-angled faults across the more gently dipping Heyuan Fault.

### 6.2 Fluid source and circulation

The source of the fluids which supply the hot springs must come from either a meteoric or deep source, or combination of both.  A deep fluid provenance is a key indicator that the fault is very deep, even down as far as the mantle, and would be very beneficial for geothermal energy production.

In order for quartz reef formation to be precipitated, a deep fluid provenance is proposed to provide the hydrogen to facilitate the aforementioned reaction of the K-feldspar in the granite above 230ºC into muscovite, $2K^+$ + aqueous quartz.

Additionally, meteoric fluids could permeate down through the cross-cutting strike-slip faults which are more seismically active and therefore more permeable. These cross-cutting faults can act like ‘feeders’ to supply the deep regions of the Heyuan fault with fluids. Significant meteoric fluid mixing would dilute the deep fluid source signature.

## 7. SUMMARY

This initial investigation has focused on the meso-macro scale analysis of the fault intersection relations at the Heyuan fault, as a key component to fluid flow control and geothermal potential.

It is found that the stress regime at the NE-striking Heyuan fault has changed from that of extension which formed it in the Mesozoic, towards a thrust fault today, with NW-SE compression. NW-orientated strike-slip faults are more active in this regime and provide enhanced permeability at fault intersections, where they cross-cut the Heyuan fault.

Field evidence shows three main groups of fracture orientations are present in the quartz reef and fault damage zone; coupled with morphological changes in quartz vein structures, this indicates multiple fracturing and fluid flow events occurred, over a period of time, while changes in stress acted on the Heyuan fault. The change from purely extensional to shear is attributed here to left-lateral movement on the cross-cutting faults, which can also be seen on a macro-scale of the fault morphology in plain view where the Heyeuan fault appears distorted by the active Shijiao-Xingang-Baitian fault.

The NW-aligned, cross-cutting faults are of crucial importance to the geothermal potential of the Heyuan fault; they act as the fluid feeders from meteoric waters and, more importantly, enable the conduits for the upward migration of hydrothermal fluids (both deep and meteoric origin) due to the enhanced permeability created at fault intersections.

The elevated heat flux in the region correlates with published literature attributing a large granite batholith source. However, additional heat source contributions should be considered, such as shear heating along the fault plane, to explain the heat flow maxima upwards of 85 $mWm^{-2}$.

Follow-up work will focus on the micro-analyses of the quartz reef and adjacent fault zone samples, including microstructural analysis and fluid inclusion studies, which will provide deeper insight on the fluid provenance, precipitation conditions and deformation mechanisms.

## ACKNOWLEDGMETNS

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