OBSERVING DYNAMIC PERMEABILITY IN THE HEYUAN GEOTHERMAL FAULT FROM MICROSTRUCTURAL ANALYSIS

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ABSTRACT

Microstructural textures can provide insights into how the permeability of a fault zone evolves on both long and short timescales. A fault can act either as a permeable pathway (conduit) or an impermeable seal (barrier) evolving over time. A seismic event temporarily increases permeability by fracturing; subsequent fluid flow and oversaturation can then precipitate and seal the fractures again. Thus, the fault zone can become less permeable over time (and therefore less favourable for geothermal fluid flow). Here we investigate in particular the seismic-interseismic relationship between fluid flow and quartz precipitation, which can occur in multiple cyclical and/or episodic stages, as shown by detailed microstructural analysis on the Heyuan geothermal fault zone in South China.

The Heyuan geothermal fault zone provides a unique study area in which to investigate this phenomenon. It features a giant quartz reef, formed through continued precipitation of different minerals from hydrothermal fluid flow. The geothermal fluid flow continues to the present to feed hot springs. Our working hypothesis is that the exposed quartz reef can be used as a chemical and structural proxy into fluid circulation patterns at deep sections of the active fault, since exhumation exposed the formerly deeply situated structures. Detailed microstructural analysis of this unit and the fault zone facies unearths a complex history of multiple brittle-ductile deformation cycles, and recystallisation. These processes operate over vastly different timescales. Initial findings validate the relationship between seismic-interseismic periods. Over long-timescales gradual precipitation during inactivity will decrease permeability, whereas seismic cycles can lead to short-timescale increases in permeability in the fault zone, and subsequent fluid flow. Coupled with macro-scale analysis, this information can be used to identify the upflow "sweet spots" and may be utilized for targeting key zones which are most sensitive to these permeability increases, such as presently still acting for the active hot springs along the Heyuan fault.

1. INTRODUCTION

The basis of this study has been centered upon a long-lived, currently active, geothermal fault zone in the province of Guangdong, South China. The Heyuan Fault provides a unique study site due to the vast outcrops of quartz reef along the fault line, which we propose to represent a snapshot time-series of the deep fluid circulation pattern.

This gives us the opportunity to investigate the problem which is of particular interest to geothermal studies: whether a fault behaves as a seal or a conduit, or both. In this case, we look to show that over long timescales the permeability of the fault zone will be gradually reduced due to increasing precipitation from the hydrothermal fluids; while on short timescale we postulate that there are repeated cycles of fracturing which lead to episodic increases in permeability.

The relationship between fluid flow and seismic-interseismic cycles along fault lines is not well documented in geothermal settings. However, it is commonly observed that the permeability of a fault is cyclical and may increase during periods of activity and decrease, due to secondary mineralisation and resulting clogging, during inactivity (Bruhn *et al.* 1994). Additionally, works by Sibson (1990, 1992) propose that fluids can be released along previously impermeable faults immediately following an increase in shear stress, decrease in normal stress or increase in fluid pressure, when these faults are favourably orientated for reactivation.

Therefore, the purpose of this study is to work towards bridging the gap between previous studies, which have investigated these phenomena (seismic-interseismic relationship with fluid flow and precipitation) and understand how they apply to a large-scale geothermal setting. Furthermore, by using microstructural techniques as a novel method in geothermal investigations, we can provide a new insight to unravel these complexities in a 'bottom-up' approach.

2. GEOLOGICAL SETTING

The Heyuan Fault was formed, along with a series of NNE and NEE trending faults in the South China block, as a result of the late Mesozoic extensional regime (Ruoxin, Liu, Guanghong, Xie, Xinhua, Zhou, Wenji, Chen, Qicheng 1995). This period was accompanied with significant granitic intrusion (Wang et al. 2014) into the Caledonian folded Proterozoic-Silurian basement. One of these large granitic batholiths, termed the Fogang Batholith, is subsurface to the west of the fault, with the Heyuan main fault cross-cutting the Xinfengjiang pluton extension in the east (Chen & Talwani 1998; Qiu & Fenton 2015). North-west trending strike-slip faults, cross cut the Heyuan fault and indicate the change in the stress field from the extensional regime which formed the Heyuan fault (Figure 1).

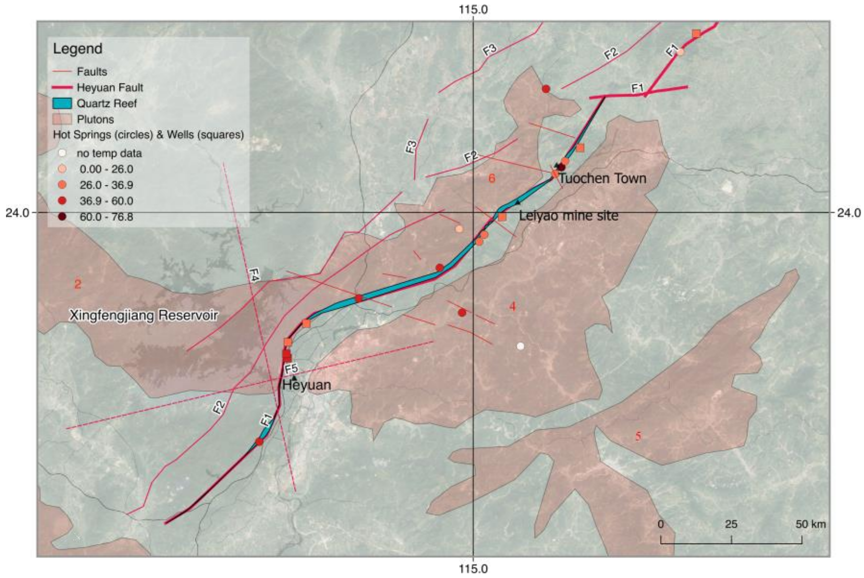

Figure 1: Overview map of the Heyuan fault zone. The Heyuan and related faults are shown along with the major granitic plutons, hot springs and sample locations. The estimated outcrop area of the quartz reef is highlighted in blue, based on field observations and satellite imagery. F1-Heyuan Fault; F2-Renzishi Fault; F3-Daping-Yanqian Fault; F4-Shijiao-Xingang-Baitian fault; F5-Nanshan-Aotou Fault. Major plutons include: 2-Fogang, 4-Baishigang, 5-Longwo, 6-Xingfengjiang. Hot spring temperatures are shown in °C.

Along the length of the Heyuan Fault, large exposures of quartz reef (up to tens of meters thick) outcrop locally and can be seen clearly in satellite imagery. The quartz reef is composed of an apparent solid fault core, which transitions into the surrounding fault zone facies, and granitic host rock, by decreasing quartz vein structure presence (Figure 2). This massive quartz structure has been emplaced through precipitation of hydrothermal fluids, likely from deep within the crust, which has since been uplifted.

Abundant hot springs manifest along the length of the Heyuan Fault, with temperatures ranging from 24°C-76°C. Sampled springs investigated during the field campaign in this study measured 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.

3. METHODOLOGY

3.1. 'Bottom-up' Microstructural to Macro-scale analysis

In order to determine and differentiate between the generations of fractures and veins on the microscale, the following factors were used:

- Mineralogical composition
- Mode of fracture (e.g. mode I, mode II-III shear)
- Frequency/spacing, abundance
- Orientation (low angle/concordant, high angle/discordant) – relates to faulting/stress regime.

Once the generations were differentiated, they could then be related to the meso-scale fractures and veining seen during field surveying at the outcrop scale, and then to the macro-scale counterparts (the Heyuan main fault, and the related cross-cutting faults) which we can relate to the paleo, neotectonic and current stress regimes.

4. RESULTS

4.1. Overview of the fault zone facies

In order to provide context for the micro-scale observations, a brief overview of the fault zone facies, and their macroscopic transitions as found through the field study is described below.

At the main study site (just south of Leiyao mine site, figure 1), the fault zone width is around 600 m. From the footwall moving southeast, the host granite transitions over several mylonitized zones, ranging in thickness between several centimetres to tens of centimetres. Trending towards the centre of the fault zone the frequency and thickness of quartz veins in the granite and mylonite increase. There is a gradual transition into a ~75 m wide cataclastic zone, which is composed primarily of quartz and minor adularia, before an unseen contact into the quartz reef. At this section of the Heyuan fault, the quartz reef has an outcrop with of over 200 m. On top of the quartz reef a small section of hanging wall is preserved which shows the presence of a second cataclasite facies, before transitioning into the host granite.

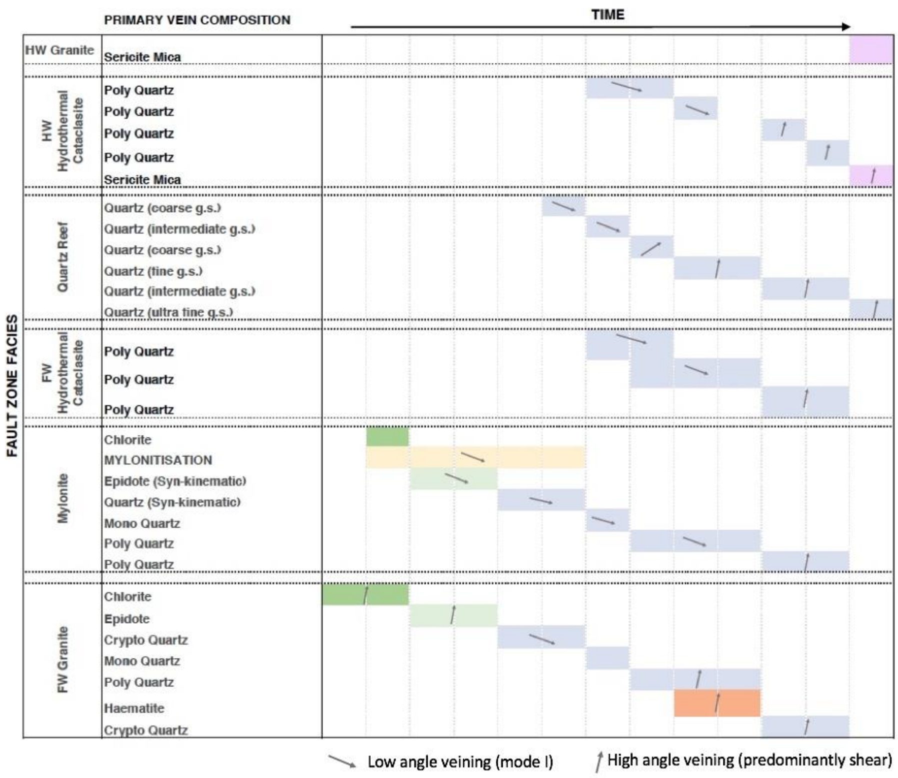

Figure 2: Vein Generations across the Heyuan Fault Zone. Multiple generations of veining have been identified on the micro-scale, within each of the fault zone facies. These generations can be correlated in time and character across the facies, to be identified as veining 'events'. Arrows signify approximate angle of veining i.e. high angle (generally oblique to foliation) or low angle (and concordant with any foliation present). No arrow infers that the vein angle was not obvious e.g. highly deformed.

4.2. Microstructural analysis: Vein generations

On the microscale, the fracturing and veining that occurs within the different fault zone facies are evidently formed under different conditions. Conventional brittle fracturing and veining is widespread throughout each of the fault zone facies, as expected above the brittle-ductile transition. However, in the mylonite where ductile deformation predominates by way of viscous granular flow, multiple brittle veining episodes have been preserved (Figure 3). These brittle cycles can only be as a result from a sudden increase in strain rate, as would occur during a seismic event. The veining generations differentiated within the fault zone facies on the micro-scale are shown in figure 2.

- Each vein generation can be identified within each of the fault zone facies by its set of characteristics (composition, grain size, abundance, orientation, fracture mode).
- There is a progression in vein composition over time: with chlorite transitioning to epidote, and subsequent evolution towards pure quartz.
- There is a change in fracture/vein orientation from low angle (concordant with mylonite foliation), to a short period of moderately inclined, to high angle sub-vertical veining.
- Change from mainly mode I (pull-apart) style fracturing to shear fracturing, which generally accompanies the later stage change to high angle fracturing.
- Each generation of veining has a unique set of characteristics that can be tied to a corresponding event in the adjacent fault zone facies.
- The changes in composition, fracture orientation and mode all appear relatively concurrently across the fault zone facies (as would be expected), thought it should not be assumed, as there may be a lag effect, or chemical interaction occurring within these zones that would have had a noticeable effect on vein signature.

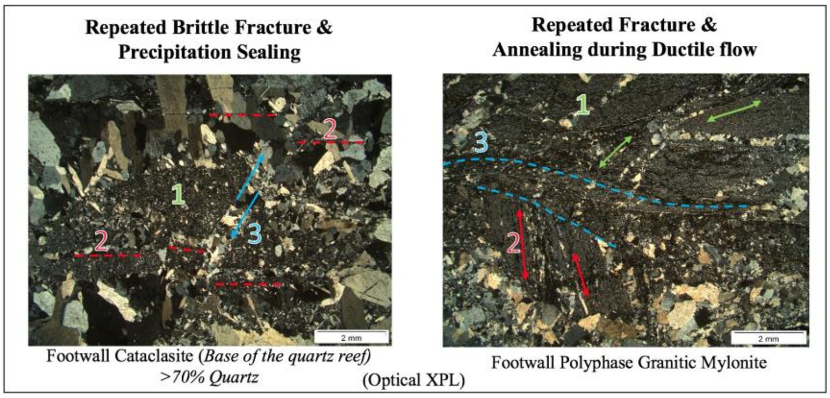

Figure 3: Contrasting styles of fracturing and veining across the fault zone, as shown under crossed polarised light microscopic images. On the left, a hydrothermal "cataclasite" shows repeated stages of brittle fracturing, cataclasis and sealing by precipitation (order of events are highlighted in the image). The right image shows a mylonite from the beneath the hydrothermal cataclasite in the footwall, which displays brittle-ductile behaviour through repeated fracturing and annealing of quartz veins. The multiple brittle veining episodes occurred during and subsequent to numerous ductile mylonitisation events.

- The mylonitic zone displays repeated phases of ductile creep, interspersed with multiple embrittlement events (Figure 3.).

4.3. Microstructural Analysis of the Quartz Reef

The primary question first asked when beginning the micro structural analysis of the quartz reef, was to establish how it was composed: as a solid homogeneous body, a series of quartz veins, or recrystallized precursors? The following observations have helped to answer this question: The quartz reef, while broadly composed of a series of veining episodes has a highly complex internal structure, and is composed of multiple fracturing, cataclastic and recrystallisation events. The complex fabric which composes the quartz reef can be broadly sub-divided into individual, reoccurring features (Figure 4). Each of these features has a unique set of characteristics and can be grouped by its grain size control mechanism. The most recent event, which generated finely abraded material by shear fracturing, has shown no quartz precipitation, in contrast to previous fracture events.

This repetitive occurrence of the veins and their overprinting relationships indicate (i) brittle fracturing inducing a temporary permeability increase and (ii) precipitation of vein fillings resulting in a decreasing permeability and eventual clogging of the system.

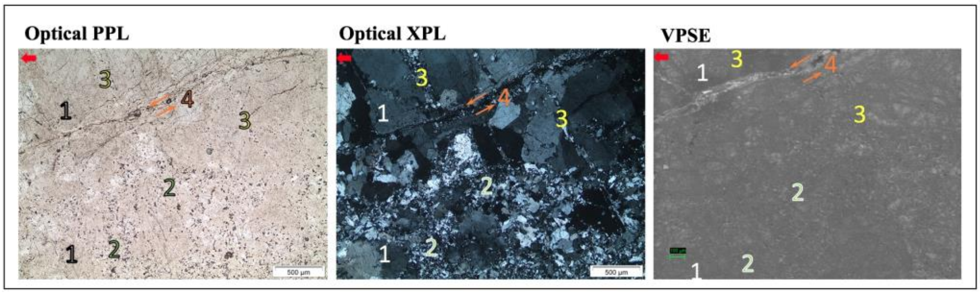

Figure 4: Micrograph images of the quartz reef, displaying multiple grainsize dependent features which have occurred at incremental stages, due to varying formation mechanisms. All three images show the same view, under different conditions: left and centre using an optical light microscope with plane light (PPL) and cross polars (XPL), and on the right using variable pressure scanning electron microscopy (VPSE). Red arrows indicate 'way up'. Stage 1: large idiomorphic quartz grains form due to type void opening from initial vein building of the quartz reef; Stage 2: Recrystallisation occurs on cataclasized fragments, generating fine to intermediate grain sizes (lower half of the images); Stage 3: Incremental fracture opening precipitates fine crystal growth (best viewed in optical XPL image); Stage 4: Shear fracturing cross cuts all other features and abrasions on fracture walls generates ultra-fine grain size quartz material, with no recrystallisation or precipitation (highlighted in the optical XPL image by the orange arrows, denoting the direction of shear offset). A clear distinction can be seen in the VPSE in the latest stage fracturing due the lack of recrystallisation. In contrast, there is a much subtler differentiation between the large stage 1 quartz and the fine-intermediate grained cataclastic material which has been recrystalised; this is due to the abundant fine fracturing which overprints the entire material.

4.4. Linking Micro-scale to Macro-scale

As aforementioned, the scope of this project is to look to unravelling the various generations of fracturing and fluid flow in the geothermal fault zone, and subsequently link it from the micro-scale veining episodes up to the macro-scale fault zones. From initial observations and analysis linking these scales, we can see that there are several factors influencing the permeability across the fault zone:

- The change in stress regime: as shown by the micro-scale veining orientations and fracture mode, which links to the changes in faulting regime of the Heyuan normal fault to a compressional regime and associated cross-cutting strike-slip faults. Thus, the shear stress on the existing faults and the creating of new faults/fracture networks.

- The dynamic fluid flow on short and long timescales, due to the seismic-interseismic relationship between fluid flow and quartz precipitation. The permeability of a fault is dependent on the point in time and the timescale in question.

- Specific fault zone facies can become more (or less) susceptible to chemical and/or mechanical alteration and related permeability in zones which cross the brittle-ductile transition.

5. SYNTHESIS & HYPOTHESIS

Multiple generations of veining have occurred throughout the fault zone, with an evolution in composition, orientation and fracture mode, as a result of a change in the fluid source, flux and stress regime. Each veining generation represents an episode of (i) coseismic fracturing, followed by subsequent episodes of (ii) fluid flow and (iii) mineral precipitation and clogging. Multiple stages of ductile creep and embrittlement have been identified, indicating a potential seismic-interseismic relationship with fluid flow (Bruhn *et al.* 1994).

A change from mainly mode I (pull-apart) style fracturing to shear fracturing, which generally accompanies the later stage change to high angle fracturing is seen on both the micro-scale and the meso-macro scale fracturing, which correlates with a change in the stress regime from extensional to compressional and the creation of strike-slip faults which cross-cut the Heyuan fault.

The quartz reef has been continually building up over time, though repeated fracturing and precipitation of the hydrothermal fluids suppling the hot springs, associated with the extension of the Heyuan fault. Original veins are repeatedly cataclasized though seismic events, increasing the permeability of the quartz reef locally, before recrystallisation occurs. Later shear fracturing related to a change the stress regime to compressional has shown an increase in the permeability with only minor precipitation or recrystallisation in these fractures locally.

In order to evaluate the dynamic permeability of the Heyuan fault we can categorise these findings into two groups: those which occur on the long timescale and contribute to a permeability reduction, and those which occur on a short timescale and contribute to increases in permeability. For the former, we have the gradual formation of the quartz reef over time from precipitation of hydrothermal fluids through a series of veining generations, which effectively seals the fault and reduces the permeability. On the short timescale, pulses of permeability are shown to have occurred through multiple cycles of embrittlement between ductile creep interseismic phases, which suggests a sudden increase in strain rate related to seismic even and subsequent fluid release.

6. SUMMARY

The Heyuan geothermal fault zone comprises a giant quartz reef, built up since the Mesozoic, due to hydrothermal fluid flow precipitating from multiple generations of veining and cycles of embrittlement. The near-continuous long time-scale precipitation of quartz reduces the permeability of the Heyuan fault zone and effectively acts a seal or barrier to fluid flow. However, repeated cycles of embrittlement are widespread throughout the fault zone with highly cataclasized facies and intense micro-fracturing in the quartz reef, providing short time-scale permeability increases. A change in the orientation, mode of fracturing, and lack of re-sealing and precipitation in the youngest fracture generation, is evident across the micro to macro scales; this coincides with a change in the stress regime, creating new cross-cutting faults and fracture networks which increase the permeability, aiding the current fluid flow supplying the present-day hot springs.

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