On the Geothermal Potential of the Heyuan Fault, South China

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SUMMARY

Geothermal energy potential in China is high, and although they currently lead the way in direct heat production, geothermal power generation is still low. Hot spring analysis and surface heat flux data indicate significant potential resources for the major industrial province of Guangdong, South China. This pilot study investigates the Heyuan Fault, Guangdong, as a potential site for a geothermal power plant. Here we line out (i) preferred locations of possible hot spots on fault intersections, (ii) the possible sources of the heat anomalies, (iii) potential pathways for hot fluid circulation in the upper crust, (iv) available hot spring data and (v) the future work plan to investigate the geothermal hot spots.

We find that hot springs occur along the NE trending Heyuan Fault, clustering where NNW striking faults crosscut the Heyuan. The increased heat flow can be explained partly by radioactive decay of a large granite pluton beneath the fault, however, additional heat sources may need to be considered to explain the heat flow maxima of above 85 mWm^{-2}. We postulate that advective (topographically driven) and convective (deep fluids ponding at the brittle-ductile transition) processes may be operating to generate these heat anomalies.

Expansive quartz reef systems exposed on the Heyuan Fault, are proposed here, to represent uplifted sections of these deep fluid circulation patterns. 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.

Key words: Heyuan fault, geothermal resources, hot springs, structural controls, quartz reef **.**

INTRODUCTION

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 Heyuan fault provides a unique setting to investigate the mechanics of fault intersections and fluid flow due to the expansive uplifted giant quartz reefs which represent the paleohydrothermal flow within the fault.

While the primary investigation is to understand the geothermal potential of the Heyuan fault, several paradoxes exist within this unique fault system, which will be investigated along the course of this study; i) How can an abundance of hot springs manifest along a fault line which is in compression? ii) Where do the massive quantities of silica originate to generate such a giant quartz reef? And iii) are there additional heat mechanisms contributing to the elevated surface heat flux?

Currently it is accepted that the heat source for these hot springs is the radioactive decay of a large granite pluton intruded in the Mesozoic (Sun et al. 2015; Zhang et al. 2015). In the province of Guangdong, there are more than 320 hot springs, seven of which are above 90 ºC (Xi et al. 2015) and a clear trend can be seen along the Heyuan fault and cross-cutting fault intersections. The distribution of hot springs and approximate temperatures are shown in Figure 1. Though the surface heat flow is elevated across much of South China and ranges from an average of more than 72 mW/m2, to more than 90 mW/m2 (Hu et al. 2000; Wang et al. 2012), other mechanisms of additional heat contribution should also be considered.

The Heyuan fault itself is known to be aseismic with 'localised barrier' style permeability (Qiu & Fenton 2015), meaning it is characterised by a well-developed core and poorly developed damage zone (Caine et al. 1996) – in other words, it should not be an ideal candidate for channelling fluid. So why do these hot springs manifest all along the fault line? The giant quartz reef is what comprises this well-developed fault core, seemingly acting as a seal. Current literature also does not well understand the formation mechanisms for these giant quartz reefs, particularly in settings such as these, in the absence of mafic bodies, where mass balance problems arise and the sheer volume of silica cannot be reconciled. Active strike-slip faults cross-cut the Heyuan fault (Qiu & Fenton 2015) which may provide fluid channels at these intersections, as described in other studies where fault intersections act as conduits for fluid flow (Chadwick & Leonard 1979; Curewitz & Karson 1997). Lastly, and of key importance, is the understanding of the deformation and precipitation micro-structures. Classically in geohydrothermal studies these features are not documented due to the precedence of a mineral and ore focus. However, understanding these features will shed new light on how the permeability of the fault system evolves dynamically in cycles over time, as well as across the fault zone.

This research used a combination of macro-scale investigation: structural field analysis, GIS, modelling (which is the focus of this paper) and micro-scale analysis of samples collected across the fault zone: micro-structural analysis, geochemistry, fluid inclusions studies, to try and answered these questions on the fracturing, permeability and fluid flow evolution of the fault; which hopes to also provide a unique contribution to aiding geothermal energy engineering research.

GEOLOGICAL SETTING

Located in the Guangdong province of South China, 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 (Lee, C. F., Ye, Hong., Zhou 1997). The basement underlying Guangdong is of Proterozoic to Silurian age which was folded and metamorphosed during the Caledonian Orogeny and subsequently, following sedimentation, further folded and uplifted during the Indosian and Yanshannian Orogeny; with the latter episode coinciding with significant granitic magmatism in the Mesozoic (Wan 2012). Various basins in the area created during the Mesozoic to Cenozoic, as well as scarps and thermal springs, are present as a result of this fault zone (Wang et al. 2014).

The fault zone cuts through a large body of Mesozoic granitic intrusions (termed the Fogang Batholith, Baishigang and Xinfenggjiang plutons) and overlying insulating sediments. The 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. 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. In these areas, the quartz reef comprises the fault core; which transitions into the country rock by decreasing quartz vein structure presence.

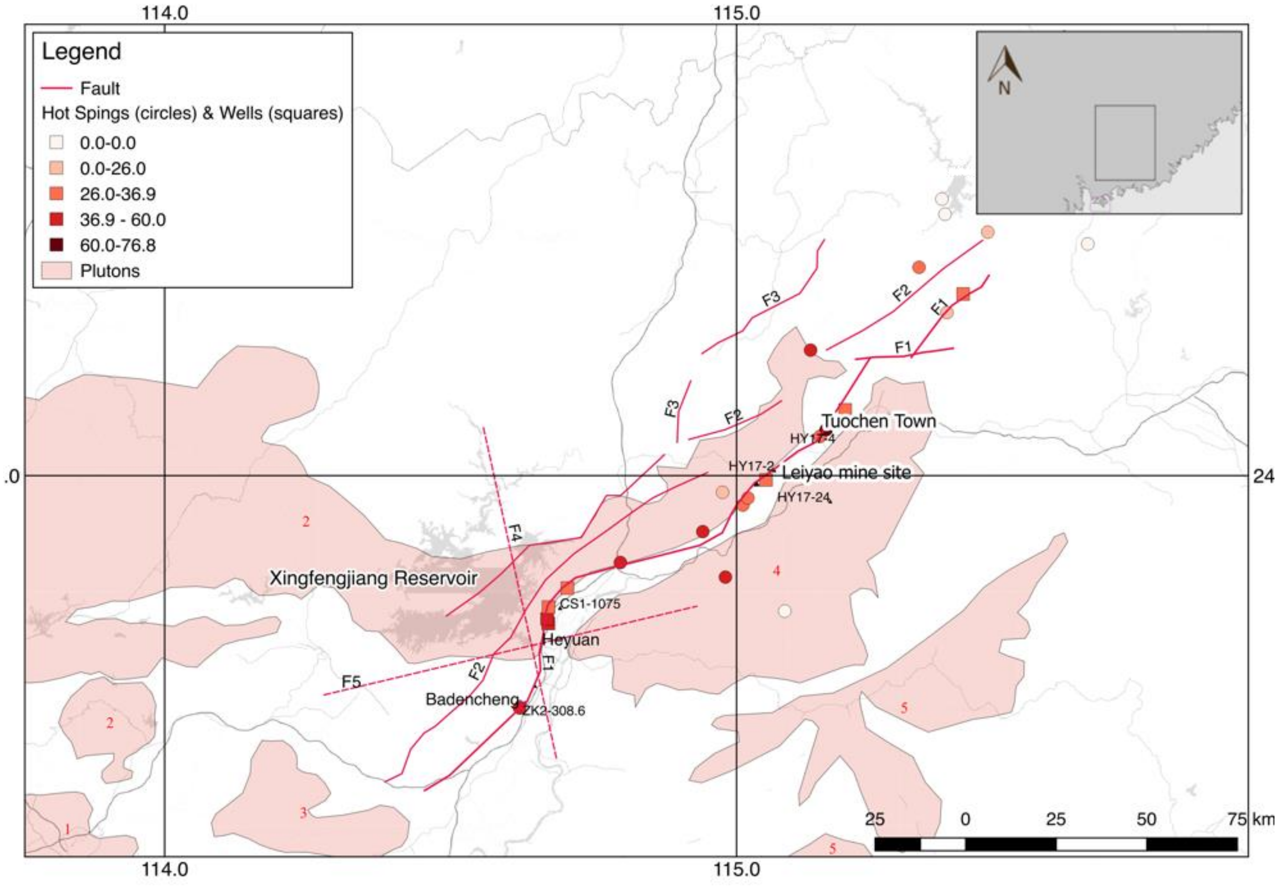

Figure 1. Overview map of the Heyuan fault zone. The Heyuan and related faults are shown along with the major granitic plutons, hot springs and sample locations. How springs (circles) and hot water wells (squares) are shown by temperature (°C). Clusters of highest temperature springs and wells occur at the fault intersections (F1, F4 & F5); at Tuochen town and midway along the Heyuan Fault (F1). F1-Heyuan Fault; F2-Renzishi Fault; F3-Daping-Yanqian Fault; F4-Shijiao-Xingang-Baitian fault; F5-Nanshan-Aotou Fault.

METHOD AND RESULTS

The analysis for this study is broken down into the macro-scale and micro-scale components, which will then ultimately be brought together, along with input from contemporary studies on the geophysical and hydrological fields, to produce a multiscale geothermal model. This paper focuses on the macro-scale results obtained to date, while the micro-scale analyses are currently underway.

MACRO-SCALE

Macro-scale evaluation is used to create the framework of the study. This will ascertain the fault geometry, current, neotectonic and paleostress regime, and provide a cross-sectional overview of the fault zone. Data is obtained through geological fieldwork: structural measurements and sample collection across the fault zone, with subsequent bulk geochemistry of these samples to be undertaken.

Field work

Geological field work was undertaken across two separate trips to the Heyuan Fault; a reconnaissance in June 2016, and more detailed structural, neotectonic and sampling campaign in February 2017. A key site of focus was on a road transect aside state route 205 near Liucheng Town whereby a cross-section through the fault could be seen from the granite country rock in the footwall, moving up into the lower mylonite and subsequent cataclastic zone, with increasing frequency of quartz veining. The accumulation of quartz veins eventually building into the quartz reef, which was observed above this location at the Leiyao quarry, one of several sites in the area where the quartz is mined. Near the top of the quartz quarry a small ultracataclastite zone was identified, which marked the transition to the hanging wall. Moving to the south-east across the river, we were able to observe, measure the fracture geometry and sample the hanging wall granite for direct comparison to the footwall granite. Hot springs along the fault were sampled (geochemistry to be analysed in a contemporary study) and surface temperatures obtained at each locality.

We collected over 50 samples across the fault zone, including from core samples drilled into the quartz reef at the quarry site down to depth over 60 m. These have been made into thin sections, with offcuts for various geochemical analysis and micro-CT scanning.

Paleo-Neotectonic structural evolution

Lineament Analysis

Using the ASTER Global DEM V2 from the 'Global Data Explorer' NASA EarthData (http://gdex.cr.usgs.gov/gdex/) and over laying MERIS Near IR Surface Reflectance swaths from the ESA CCI Land Cover Project (http://maps.elie.ucl.ac.be/CCI/viewer/index.php) lineament analysis was performed to identify linear features (or 'mega-lineaments') visible on a scale greater than 1:750,00 m. These lineaments were checked against the Multispectral Landsat Layer and "World Imagery" layer (SPOT 5 image resolution of 2.5m and Digital Globe .05-0.5 m resolution) for secondary verification. This data is currently still being processed, however it is noted that in addition to the vast array of lineament concordant with known faults in the area, at least three mega-lineaments (which are not recognised on published maps) cross-cut the Heyuan fault (Figure 3).

Fracture classification

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 2).

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	
3	NW	Sub-vertical	Unfilled	Thrust re-activated

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

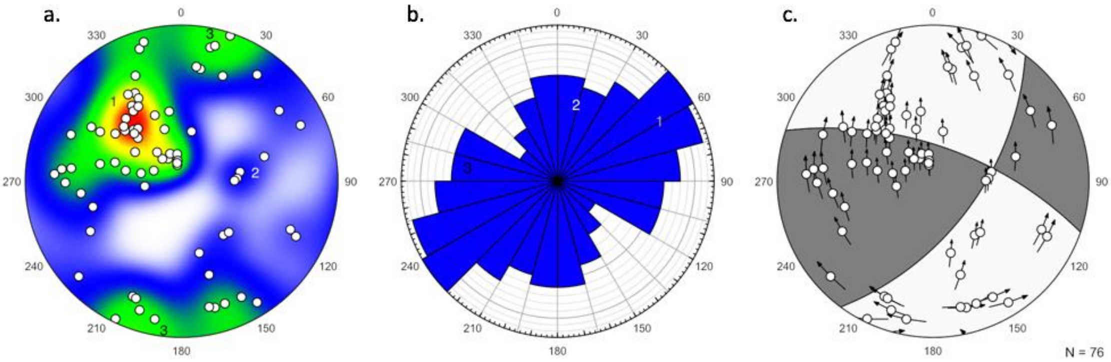

Figure 2. Spherical projection and orientation of fracture planes within the quartz reef and wider fault zone. a.) Stereonet showing poles to fracture planes, with modified Kamb contouring at multiples of uniform density, highlighting point clusters (Vollmer 1995). b.) Circular histogram of the fracture 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.

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 developed through the influence of the cross-cutting strike-slip faulting which formed during thrust re-activation of the Heyuan fault. These sub-vertical fractures would provide the upper level pathways for the current hydrothermal fluid circulation.

Further analysis showed that these fracture orientations could be further sub-divided into at least four groups, with frequent occurrences of conjugate sets in both low angle (attributed to the normal faulting regime) and high angle (attributed to towards a change to compression). The most recent, sub-vertical fractures appear to be generated as an effect of the cross-cutting strike-slip fault movement.

The Hot springs

Hot spring sampling

The temperatures of three hot springs situated on the Heyuan fault were measured in the field 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 thermal springs in the area with similar results, as shown in **Error! Reference source not found.**.

No.	Data Source	Latitude	Longitude	Description	Temperature (°C)
L1	Field collected	23° 51' 09N	114° 47' 31"E	Artesian (abandoned building of resort)	55.7
L2	Field collected	23° 51' 07N	114° 47' 25"E	Pumped for local village	57.9
L3	Field collected	24° 04'32"N	115° 08' 57"E	Pool	62.5
M4	Mao et al. (2015)	24°04′29″N	115°08′59″E	spring	63.2
M5	Mao et al. (2015)	23°51′11″N	114°47′29″E	spring	56.7
M6	Mao et al. (2015)	23°26′49″N	115°06′26″E	spring	78.6
M7	Mao et al. (2015)	23°12′10″N	114°21′31″E	spring	59.8

Table 2. Temperatures measured at hot springs along the Heyuan Fault zone (data obtained from this study and from Mao et al., 2015).

Synthesis of the Heat Flow Data and Hot Spring Activity

A study by Sun et al. (2015) showed that radiogenic heat produced from five sampled granite bodies across Guangdong province ranged from 5.28-7.11μW/m^3, which would provide a significant crustal heat contribution. While additional insulation of the granite body is provided by a covering of Palaeozoic and Mesozoic sediments locally. 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. However, the following considerations need to be taken into account to assess the role of radiogenic heat as the main heat source for the geothermal anomaly. Classical geothermal crustal models (Lachenbruch & Sass 1977) use a model for geothermal heat production with a 10 km thick radiogenic granite on the top of the crust.

As radiogenic elements are incompatible and tend to remain segregated in the melt phase, the upper zones of the granite body will commonly be enriched in the radiogenic heat sources. Therefore, measurements targeting the heat producing elements will likely be biased towards these upper zone as deeper wells into the granites are seldom available. The values are therefore upper bounds of the heat production and in the classical 1-D geothermal models the heat production is normally assumed to exponentially decay with depth (Vigneresse & Cuney 1991). Based on the uranium, thorium and potassium isotopic concentrations measured in the Fogang granite, Sun et al. (2015) calculated the heat production rate of 6.77 μW/m^3. This value is higher than the average world value of 2.55μW/m^3.

First described by Birch et al (1968), a linear relationship exists between heat flow (q_0) and surface heat production (A_0), as shown below, where D represents the depth of the zone affected by the radiogenic heat from the granite, while q* is the heat flow from beneath the granite (Webb et al. 1987) i.e. from the mantle.

$$q_o = q^* + DA_o$$

Below we postulate an average depth of the pluton to be 10km, as is commonly assumed, to calculate the upper bound of radiogenic heat production. Using an average mantle heat flow of 25 mW/m^2 for q* and 6.77μW/m^3 heat production. The calculated heat flow (q_o) is 92.7 mW/m^2, which is the upper bound contributed by granite. Given this is an upper bounding limit, based on a potentially enriched radiogenic phase at the top of the granite, we may also need to consider an additional heat source mechanism, such as: 1) higher mantle heat flow, 2) advection of hot fluids from adjacent areas, 3) shear heating, or 4) magmatic intrusions. To verify these possibilities, it requires sufficient geophysical investigations and analyses, which are beyond the scope of this study.

MICRO-SCALE ANALYSES

The current flow regime, fluid and permeability evolution (as well as the formation of the giant quartz reef) requires the above macro-scale analysis, combined with detailed micro-scale analysis. This includes investigation in to the microstructures, precipitation and deformation mechanisms. This research is currently being undertaken via light microscopy, SEM and BDSE. Various geochemical investigations in to paleohydrothermal conditions (mylonite and cataclasite matrix & vein fluid evolution) which gives temporal and spatial evolution of fluids is also underway with results to be published in follow up. Geochemical analysis is currently being performed on the present day hot spring fluids in a contemporary study, which will be used to compare against the geochemical results obtained from the veins across the fault zone. Preliminary microstructural results show a complex history of repeated fracturing and healing, while element mapping of the fault zone facies surrounding the quartz reef shows no depletion of SiO_2.

MODELLING

GeoModeller software by Intrepid Geophysics (http://www.geomodeller.com) was used to build a preliminary structural model from a combination of field measurements in conjunction with published fault orientation data (i.e. Cheng et al. (2012)). GeoModeller will then be used for combining all micro to macro-scale elements (with the inclusion of additional analyses performed by 3rd party studies: hydrological, geophysical etc.) and incorporating thermal conductivity and heat production-rate data to produce the geothermal model.

Preliminary Structural Model Results

Preliminary modelling has been undertaken to build the structural framework of the Heyuan fault, related faults, and cross-cutting faults using a combination of field data, geological maps and published literature, e.g. Cheng *et al.* (2012). In the MERIS Near IR Surface Reflectance overlay shown, we can see at least two linear features trending NNE, which also appear to disrupt some of the ENE trending fault lines (Figure 3). Geological maps of the area do not show any bedrock terminations or bedding features that would account for this. NW orientated features also appear to cross-cut the Heyuan Fault, as shown by lineament analysis. Geological maps indicate slips along partial segments of some of these hypothesised planes, along with an aligned outcrop of quartz reef. We therefore postulate that these linear features are potential additional fault lines.

Note that fault intersections of known faults, as well as hypothesised faults (corresponding the surface manifestations in lineament analysis) coincide with clustering of hot spring activity and elevated temperatures of hot springs (as shown in Figure 1), therefore supporting the proposed intersection relationship of two tectonic faults leading to geothermal manifestations.

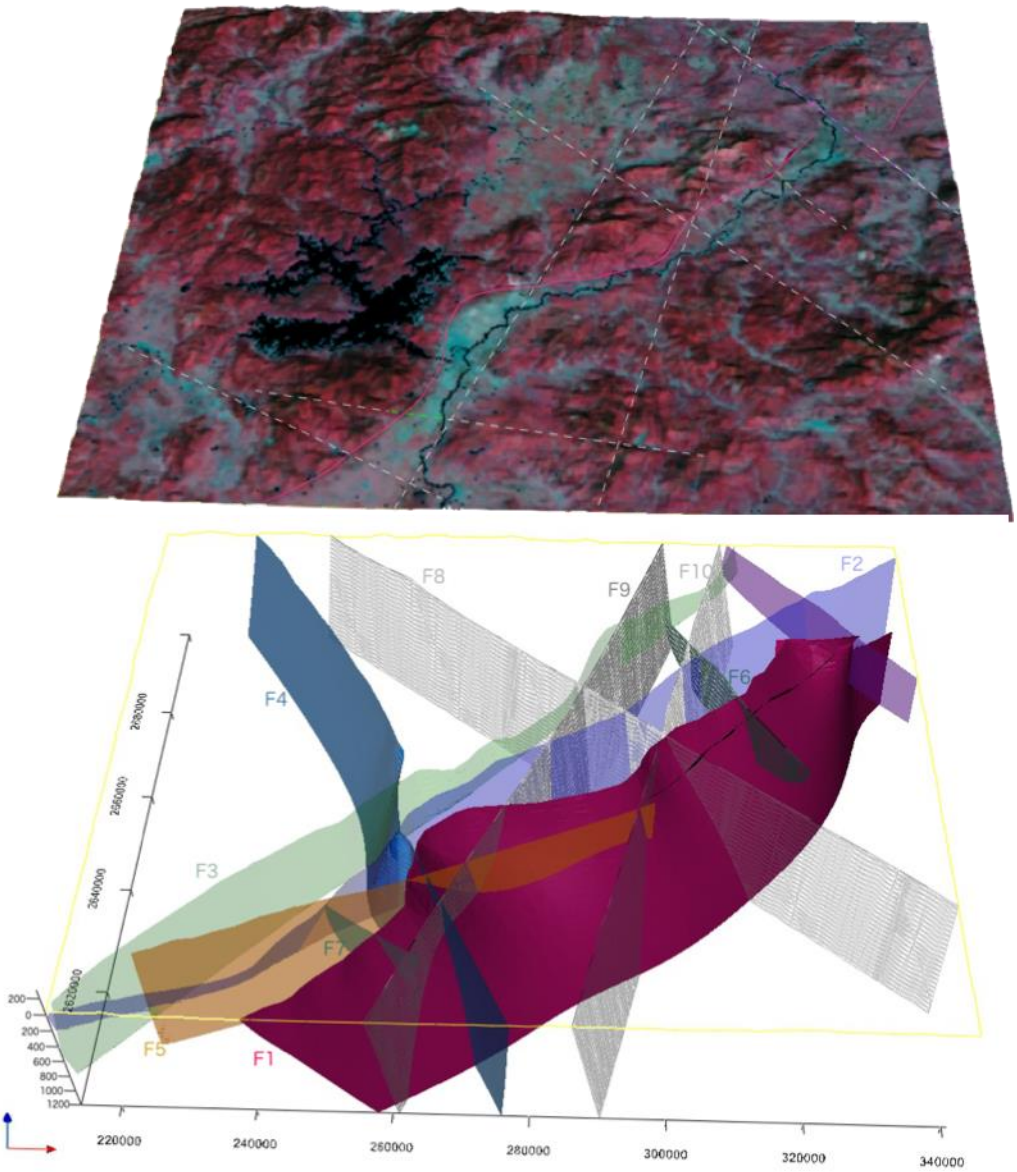

Figure 3. Structural model of the Heyuan and known related faults (solid colour) and hypothesized cross-cutting faults (grey wireframe). Modelled using GeoModeller from Intrepid Geophysics (http://www.geomodeller.com. Vertical exaggeration x2. MERIS Near IR Surface reflectance imagery highlights alignments and lineations developed in the ground surface which may indicate subsurface structures. F1-Heyuan Fault; F2-Renzishi Fault; F3-Daping-Yanqian Fault; F4-Shijiao-Xingang-Baitian fault; F5-Nanshan-Aotou Fault.

HYPOTHESES

In a thrust fault, the compressional regime, coupled with the seismic inactivity results in a low permeability structure to the Heyuan Fault. Regardless of the provenance of the fluids supplying the hot springs, the transport from the source must be reconciled.

Additional Faults

At least two additional NW-striking faults are proposed here - not formerly recognised, cross-cutting the Heyuan Fault - due to GIS lineament observations, partial correlation with locally mapped faults, structural field measurements and alignment of mapped quartz reef manifestations. There is also indication of two possible additional faults cross-cutting the Heyuan Fault, from a strong NNE alignment, which needs further investigation.

Fluid 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.

This massive quartz structure has been emplaced through precipitation of hydrothermal fluids. As there appears to be no depletion of SiO_2 in the fault zone facies surrounding the quartz reef, this indicates that the silica has come from a source outside of the fault system, 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.

We hypothesise that NW-aligned faults cross-cutting the Heyuan fault, provide the intersections which act as conduits to channel these fluids upwards (e.g. Chadwick & Leonard 1979; Curewitz & Karson 1997). These fluids may have accumulated and ponded at the brittle-ductile transition due to the decrease in pressure at the point, thus enabling the deep fluid circulation pattern. The formation of the giant quartz reef and change in stress regime will have changed the permeability style from that of a conduit (in a normal faulting regime) to that of a barrier (in compression) with the fluids migrating up from the fault intersections being trapped beneath the quartz reef seal. Sub-vertical fracture systems attributed to these cross-cutting faults then provide the upper level channels through the quartz reef, which feed the present day hot springs.

CONCLUSIONS

Preliminary work for the assessment of the Heyuan Fault, South China as a potential geothermal target revealed: preferred sites of geothermal activity along faults cross-cutting the Heyuan Fault in a NNE to NW direction; high levels of background heat production by radioactive decay of the granitic basement; a complex pattern of heat focussing through deep fluid pathways feeding into the shallow hot spring systems.

The giant quartz reef of the Heyuan fault precipitated via an accumulation of quartz veins over time during normal faulting in the Mesozoic. Initial investigations into the geochemical source of the silica to provide the reef have so far shown no depletion in the surrounding country rock, mylonite or cataclastic zones. An absence of any known mafic bodies in the vicinity points to a deeper source.

An abundance of hot springs present today, with the Heyuan in a compressive state, indicate a change in fluid flow regime. The surface manifestation of the hot springs coincides with fault intersections along with elevated temperatures, providing evidence of the upward fluid flow pathway. Fractures analysed throughout the fault zone are consistent with a change in stress regime from normal faulting to a thrust regime. A sub-vertical fracture system overprinting previous orientations represents the influence of the cross-cutting strike-slip faults which developed during this change in regime, and facilitates the upper fluid flow pathway for the present day hot springs.

In subsequent work these deep-heat feeder systems will be further analysed as potential geothermal targets. This will be done through investigating the massive quartz reefs as proxies of these deep fluid systems through microstructural analyses and fluid inclusion studies. Ultimately this information, along with contemporary studies being performed on the hydrogeology, geophysics and geochemistry, will form a complete multi-disciplinary model to assess the geothermal potential, and identify target areas for the determination of the cost-benefit analysis of a geothermal power plant.

ACKNOWLEDGMENTS

We would like to acknowledge Jie Liu and Kerry Zhang of Sun Yat-sen University in Guangdong for facilitating the fieldwork and help with this research. Also to Marco Herwegh & Alfons Berger at the University of Bern, not only for providing the facilities for the micro-scale analysis component, but also for their insight, support. This work forms part of the research being supported by the Australian Government Research Training Program Scholarship.

REFERENCES

Caine, J.S., Evans, J.P. & Forster, C.B., 1996. Fault zone architechture and permeability structure. *Geology*, 24(11), pp.1025–1028.

Chadwick, R.A. & Leonard, R.B., 1979. *Structural controls of hot-spring systems in southwestern Montana*, Helena, Montana.

Cheng, H.H. et al., 2012. Finite element investigation of the poroelastic effect on the Xinfengjiang Reservoir-triggered earthquake. *Science China Earth Sciences*, 55(12), pp.1942–1952.

Curewitz, D. & Karson, J.A., 1997. Structural settings of hydrothermal outflow: Fracture permeability maintained by fault propagation and interaction. *Journal of Volcanology and Geothermal Research*, 79(3–4), pp.149–168.

Hu, S., He, L. & Wang, J., 2000. Heat flow in the continental area of China: A new data set. *Earth and Planetary Science Letters*, 179(2), pp.407–419.

Lachenbruch, A.H. & Sass, J.H., 1977. Heat flow in the United States and the thermal regime of the crust. In J. G. Heacock, ed. *The Earth' Crust: Its Nature and Physical Propeties*. Washington D.C.: American Geophysical Union, pp. 626–675.

Lee, C. F., Ye, Hong., Zhou, Q., 1997. On the potential seismic hazard in Hong Kong. *Episodes*, 20(2), pp.89–94.

Mao, X. et al., 2015. Geochemical and isotopic characteristics of geothermal springs hosted by deep-seated faults in Dongguan Basin, Southern China. *Journal of Geochemical Exploration*, 158, pp.112–121.

Qiu, X. & Fenton, C., 2015. Factors Controlling the Occurrence of Reservoir-Induced Seismicity. *Engineering Geology for Society and Territory - Volume 6*, (June), pp.567–570.

Regenauer-lieb, K. et al., 2015. Stimulating Granites : From Synchrotron Microtomography to Enhancing Reservoirs. , (April), pp.1–6.

Sun, Z. et al., 2015. Radiogenic Heat Production of Granites and Potential for Hot Dry Rock Geothermal Resource in Guangdong Province , Southern China. *World Geothermal Congress 2015*, (April), pp.2–6.

Vigneresse, J.L. & Cuney, M.B.T.-T. heat flow and the lithosphere structure, 1991. Are granites representative of heat flow provinces. In *Terrestrial heat flow and the lithosphere structure*. pp. 86–110.

Vollmer, F.W., 1995. C program for automatic contouring of spherical orientation data using a modified Kamb method. *Computers & Geosciences*, 21, pp.31–49.

Vollmer, F.W., 2015. Orient 3: a new integrated software program for orientation data analysis, kinematic analysis, spherical projections, and Schmidt plots. *Geological Society of America Abstracts with Programs*, 47(7), p.49.

Wan, T., 2012. *the Tectonics of China: Data, Maps and Evolution*, Springer Berlin Heidelberg.

Wang, A.D. et al., 2014. Guangdong, a Potential Province for Developing Hot Dry Rock Geothermal Resource. *Applied Mechanics and Materials*, 492, pp.583–585.

Wang, J. et al., 2012. Estimate of Geothermal Resources Potential for Hot Dry Rock in the Continental Area of China Estimate of Geothermal Resources Potential for Hot Dry Rock in the Continental Area of China. *专题论文 (Special Issues)*.

Webb, P.C., Lee, M.K. & Brown, G.C., 1987. Heat Flow - Heat Production Relationships in the U.K. and the Vertical Distribution of Heat Production in Granite Batholiths. , 14(3), pp.279–282.

Xi, Y. et al., 2015. Geothermal structure revealed by Curie isotherm surface in Guangdong province. *International Workshop and Gravity, Electrical & Magnetic Methods and their Applications, Chenghu, China, 19-22 April 2015*, (April 2015), pp.189–192.

Zhang, Y. et al., 2015. Petrogenesis of Jurassic fractionated I-type granites in Southeast China: Constraints from whole-rock geochemical and zircon U-Pb and Hf-O isotopes. *Journal of Asian Earth Sciences*, 111, pp.268–283.