PROCEEDINGS, Thirty-Third Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 28-30, 2008
SGP-TR-185

IDENTIFYING FRACTURES USING FLUID INCLUSION STRATIGRAPHY: INSIGHTS FROM FLUID INCLUSION THERMOMETRY

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ABSTRACT

Identification of open, permeable fractures in geothermal wells for fluid extraction and possible stimulation (EGS) is attempted using fluid inclusion stratigraphy (FIS) techniques. FIS analyzes fluid inclusion gaseous species in well cuttings to characterize fluid types at depth. We further investigate the application of this technique to locating open fractures by correlating unique fluid inclusion gas signatures to thermometric data of major fracture swarms.

Multiple fracture systems from three cored wells were sampled for calcite and quartz mineralization in addition to transparent mineral phases from the adjacent host formation. Their fluid inclusion trapping temperatures and salinities were analyzed using a Linkam PR600 thermometric stage. In each well, production zones identified by temperature and geophysical logs have a fracture density of >5 fractures/10m with apertures >20mm each. Production fracture fluid inclusion populations exhibit uniform salinities and trapping temperatures for both vein and wallrock minerals that correlate well with production fluids. FIS data, sampled at 5-10m intervals over production zones, typically exhibit anomalously high intensities, or peaks, for most gaseous inorganic species; N_2, Ar, CO_2 and He are commonly associated with large-aperture (>50mm) fractures and fracture swarms. Non-producing zones have similar fracture densities as productive fractures systems, but differ by having multiple fluid inclusion populations typically recording trapping temperatures 20-50°C above current temperature profiles, and smaller FIS gas peaks. In the case of Steamboat 87-29, closed fractures FIS analyses indicate lower H_2O and CO_2 signatures offset from peaks represented by other inorganic gases. At present we are confident that FIS cuttings analysis at 10m sampling interval can locate fractures zones best suited for production and EGS stimulation with much improved identification of older, yet still producing fractures, at tighter intervals (<5m).

INTRODUCTION

Fluid Inclusion Stratigraphy (FIS) is a method being developed for the geothermal industry (Hall, 2002) which applies the mass quantification of fluid inclusion gas data from drill cuttings and applying known gas ratios and compositions to determine depth profiles of fluid barriers in a modern geothermal system (Norman, 2005). Identifying key gas signatures associated with fractures for isolating geothermal fluid production is the latest advancement in the application of FIS to geothermal systems (Dilley, 2005; Dilley, 2007). Locating fractures and accurately determining their relative “age” or degree of contribution to the current geothermal system is especially applicable to potential enhanced geothermal resources primed for artificial fracturing. Open and producing fractures and those only recently closed by mineralization are likely better candidates for localized EGS enhancement. Differentiating these fractures from those zones of paleomineralization associated with an extinct geothermal event using FIS gas signatures is critical for such an application (Dilley, 2007). This paper is a corollary study to help identify the limitations and verify the application of this technique using fluid inclusion thermometry to characterize fluid types associated with major fracture zones.

Modern zones of production are often defined by open, large-aperture fracturing and/or fracture swarms. In each case, cogenetic vein mineralization from these fractures may be the best tool for examining trapped production fluids, however isolating solely this vein material from exploration drill cuttings is not practical. One issue of concern associated with FIS, in attempt to maintain the benefits of low cost and fast turn-over rates, is determining the minimum sample spacing required to accurately locate and characterize a significant fracture zone. In addition, we hope to verify the assumption that fluids trapped within matrix-dominated well cuttings are representative of those both currently permeating the substrata and thus hosted within vein mineralization associated with major fractures. Fluids trapped within microfractures of primary matrix mineral phases and secondary replacement mineralization, namely within crystalline-hosted geothermal systems, suggest extensive overprinting by hydrothermal fluids (Moore, 1987). Using fluid inclusion thermometry on several geothermal wells, we attempt to map the distribution of various fluid populations surrounding major fracture systems to determine the distal extent to which vein-hosted production fluids may be identified by FIS gas signatures.

This project is funded by the Department of Energy, Enhanced Geothermal Systems Technology Development program. The DOE award number is DE-FG36-06GO16057.

METHODS

Cored samples from three crystalline hostrock geothermal wells were selected for analysis of fracture-hosted fluids: Steamboat 87-29, Glass Mt. 88-28, and Karaha T2. Vein and vug material and surrounding host rock associated with major fracture swarms for each well were sampled from various intervals and their fracture aperture measured. Thermometric analysis of secondary quartz and calcite-hosted fluid inclusions were compared with transparent mineral phases from the adjacent wallrock (≤2cm away) using a Linkam PR600 thermometric stage (Fig 1). Multiple T_m (ice, eutectic) and T_h values were used to determine fluid populations for each fracture system.

Core from Steamboat 87-29 was selected to characterize the distance and pervasiveness over which fracture-generated fluids effect hostrock fluid inclusions. Two major fracture intervals were isolated for study: 818' (which we will refer to as Region 1) representing a zone of major production characterized by broad, FIS fracture signatures of high CO_2, H_2O, N_2, and Ar and total gas; and 1112' (Region 2) representing a significant, yet cooler zone of production corresponding with a more narrow, apical FIS signature (Dilley, 2007). In addition to the central vein mineralization, surrounding matrix material was sampled at increasing spatial intervals from both central fractures: *approximately* 1, 10, 50cm, 1, 5, 10, 20, 25, 30m; where available, core intervals containing fracture swarms were selected to analyze fluid inclusion homogeneity among dendritic extensions of the main fracture. Fracture frequency, aperture, and degree of mineralization were measured and noted in detail for both systems.

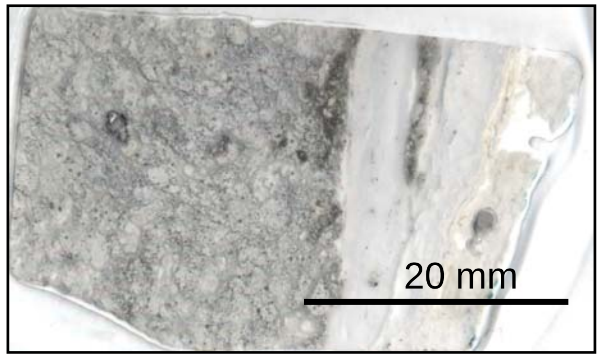

Figure. 1. Example of thick section of vein and hostrock: sampled from 226' in Steamboat 87-29 exhibiting grey quartz and milky white quartz in vein fracture, propyliticalteration, and strong siliceous alteration of matrix.

FLUID INCLUSION THERMOMETRY

Vein and Matrix Continuity

Salinity and temperatures of homogenization analyzed at various depths for our three wells (Fig 2) indicate that fluids from both veins and wall rock represent overlapping fluid populations. The broad salinities and trapping temperatures encountered, however, imply either heterogeneous trapping from mixed fluids, boiling or a long and varied hydrothermal history exhibiting fluid signatures from current as well as past fluids. Overprinting by current production fluids, however, would likely be highlighted in FIS gas profiles negating this possible confusion.

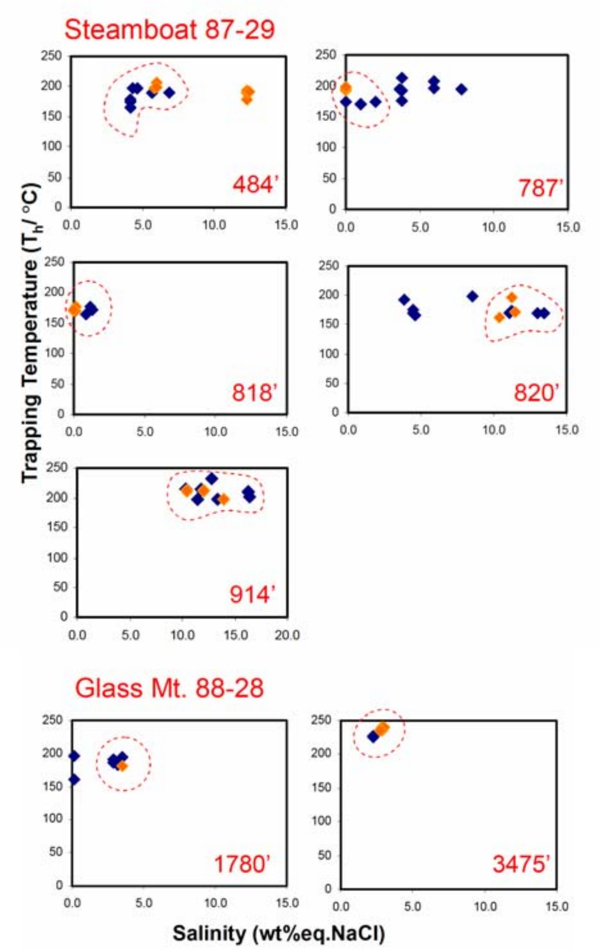

Figure. 2. Salinities (as a function of Tm(ice)) plotted against trapping temperature (as a function of Th) indicating populations of entrapped production fluids. Orange (vein) samples and blue (matrix) samples are represented in each population.

Some zones of hydrothermal mineralization do not comply well with matrix fluid entrapment (Fig 3). In the case of deeper, non-productive zones (Karaha 4344 and Steamboat 87-29) we observe distinctive populations recorded separately by both matrix and vein material. However, the scope of FI thermometry in this investigation is limited. The standard deviation observed within some alteration zones with solely matrix-trapped fluids (Figure 4) indicate the same degree of deviation observed between vein and matrix inclusion as exemplified by Steamboat 87-29:1130' (Fig 3). In addition, leaking of fluids within friable vein mineralization is overwhelmingly encountered during the heating and freezing analyses of Glass Mt and Karaha samples, drastically limiting the number and size of inclusions which may be measured as well as the population count on those veins representing a higher homogenization temperature (T_h>200ºC).

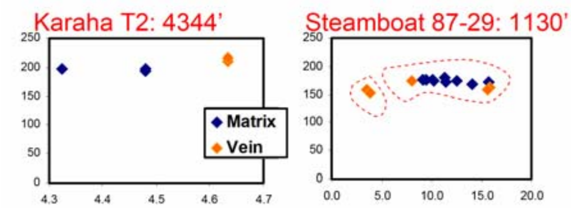

Figure. 3. Vein (orange) and matrix (blue) inclusions representing separate fluid populations.

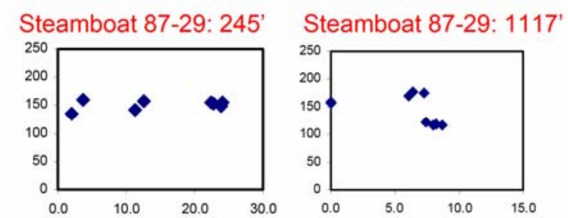

Figure. 4. Spectrum of fluid compositions observed within single matrix phenocrysts, representing potential range of fluids trapped within host rock and standard deviation for fluid inclusion thermometric measurements. Trapping temperature (C) is represent on the x-axis, weight percent equivalents NaCl represented on the y-axis.

Over a broad range of analyses, matrix or wall rock mineralization behaves similarly to vein material along fractures in its ability to trap production fluids for analysis by FIS. Friability and limited volume of vein material inhibit its usefulness as a major source of trapped fluids. This analysis confirms that the microfracturing of wall rock and the occurrence of microveining immediately adjacent to mineralized fracture zones (≤2cm) is extensive thus expanding our ability to directly sample evidence of production fluids along fracture zones.

Permeation of Fracture Hosted Fluids

Two producing fracture systems at Steamboat Springs, NV (cored well: 87-29) were identified for study by 'positive' FIS gas signatures (Dilley 2007) in agreement with temperature and drilling logs. All core materials and well log data were obtained from EGI at the University of Utah.

Region 1 (Steamboat 87-29: 818')

A major zone centered at 818' contains a central fracture, measuring over 7cm in aperture and hosting a white calcite vein on one side (~1.5cm) and grey quartz on the other side (~0.8cm). Chlorite and sericitic alteration are observed in a broad, 75cm-wide areole surrounding the central vein, accompanied by an apparent swarm of large (>5mm wide) and open fractures extending from 785' to 825'. Extensive chlorite alteration of the host-rock associated with swarms of thin (<3mm wide) clay-filled fractures and dense configurations of microfractures (≤1mm; often 2-3 per foot of core) may be observed at the more distal extensions of this zone from 755' to 860'. FIS logs characterize this zone as containing broad peaks in CO_2, Ar, H_2O and Total-Gas spanning from 750'-925' with the strongest signal occurring at ~820' (Fig 5). This zone also represents the hottest region of production in the well according to temperature logs, peaking at 162°C (Fig 6).

Thermometric measurements of quartz and calcite vein mineralization and transparent (mostly quartz) matrix-hosted inclusions throughout this region indicate multiple populations of fluid-rich phases exhibiting widely variable salinities (wt% NaCl) and temperatures of homogenization (T_h). Vein-hosted fluid inclusions at 818' best resemble actual well-temperature values; however, surrounding matrix and vein inclusions contain Th values upwards of 200°C (Fig 6). Th (vein) and Th (matrix) overlap consistently at 787', 818', 820', and 914', suggesting that productions fluids have sufficiently permeated the host formation. Samples from 755', 787', 780'and 829' contain fluid inclusion populations resembling the lower salinity and minimal Th values observed at 818' surrounding the central fracture (Fig 7). In particular, sampled fracture-fill quartz veining at 755' represents fluid inclusions of similar compositions implying a genetic relationship of these minor fractures to the central fracture.

The broad distribution of signature fluid compositions with depth through both dendric fractures and wallrock alteration observed within this zone of study comply well with the broad nature of the FIS fracture signatures. The occurrence of multiple fluid populations at various depths of study is likely evidence of overprinting from earlier stages of the Steamboat geothermal system or heterogeneous distribution of production fluids through fracture units of opposing stress and origin. In either case, locating fluids associated with this main-production fracture based on agreement with overlapping fluid populations may be accomplished with FIS sampling as coarse as 30ft (~10m) intervals, likely due to the dense configuration and open apertures of the surrounding fracture swarm.

Region 2 (Steamboat 87-29: 1112')

A second major production zone centered at 1112' also contains a singular major fracture, measuring approximately 6cm in diameter and partially filled with quartz. The hostrock in this zone exhibits pervasive chlorite alteration throughout, however the extent of modern secondary fracture permeability appears limited. Fractures in this zone occur with less frequency (<1 fractures per foot) and are on average thinner (<2mm) and closed due to clay fill. This region also lies within the designated production zone though exhibits a slightly lower temperature and is positioned at the top of a steep decline in thermal gradient (Fig 6). FIS logs identify at least 2 major fracture swarms occurring at approximately 1010' and 1112' marked by consecutive apical peaks in all inorganic gaseous species, particularly CO_2, N_2 and total gas (Fig 8). One series of closed fractures at ~1035' indicate a slight negative signal in H_2O and CO_2, possibly representing a sink for mobile, gaseous species (Dilley, 2007).

Thermometric measurements of this region indicate little communication between open, producing fractures and surrounding swarms of veins and microfractures. Minor overlap in fluid populations is observed between open fracture swarms observed at 1004' and 1112' (Fig 9). Fluids measured at 1117' strongly correlate with the salinity and Th compositions of producing fluids (812') in Region 1 above in addition to best matching the well log temperature (~158°C), though their FIS signature is indistinguishable from that observed at 1112' (Fig 8). In addition, matrix (Th) and adjacent vein (Th) fluid inclusions from the same depth interval represent little overlap. The ubiquitous matrix alteration in this region signifies extensive regional hydrothermal influence, unlike the more localized, fracture-directed permeability observed above. A reduction in primary porosity due to matrix alteration is congruent with a reduction in microfracture and matrix permeability. Multiple geothermal stages and an evolved history of geothermal fluids may be responsible for the scattered distribution of fluid compositions not associated with presumed, open fractures. Overprinting by current production fluids, as demonstrated in this region, are clearly highlighted in FIS profiles.

SUMMARY AND CONCLUSIONS

Certain fluid inclusion gas signatures have been associated with known open, producing fracture zones for wells Steamboat 87-29, Glass Mt 88-28, and Karaha T2 (Dilley, 2007). According to fluid inclusion thermometry, fluids trapped in matrix mineralization along secondary microfractures agree reasonably well with fluids observed within adjacent (< 2-3cm) secondary mineralization of large-aperture vein material. This expands the minimum sampling interval of wallrock cuttings which may help identify producing fracture in FIS analysis by also exhibiting signature gas ratios. Microfractures, particularly those observed within primary quartz; thin, dendritic fracture swarms; and pervasive replacement mineralization of wallrock is thought to aid in the distribution of production fluids beyond the arterial fractures of a geothermal system. Where secondary permeability is dominant and fractures are abundant and open, as observed near 818' depth of Steamboat 87-29, current production fluids infiltrate fluid inclusions upwards of ~25m (75 ft) from the apparent source. Here, FIS signatures thought to be associated with fractures are expansive and dictated by the occurrence of open, prolific secondary permeability. In contrast, a lack of both primary porosity and open fracture swarming due to extensive hydrothermal alteration may limit the pervasiveness of production gas signatures into new fluid inclusions; hence FIS fracture signatures appear narrow and apical, as observed near 1112' of the same well. Production is measurable at both 818' and 1112' depth in this well and FIS signatures are detectable regardless of their shape and extent, largely aided by tight sample spacing near known fractures (1m). From this, we conclude that:

(1) Sampling intervals of 1-5meters (3-15ft) from well cuttings is sufficient to accurately observe fracture signatures where fracture swarms are rehealed, sparse (<2x2mm/ft) and alteration mineralization limits both primary and secondary permeability – as in the case of Region 2 surrounding 1112' in Steamboat 87-29. These fractures have experienced multiple hydrothermal events, are likely older and less desirable for EGS stimulation.

(2) Greater sampling intervals of 5-10meters (15-30ft) are sufficiently frequent to detect major producing fracture zones using FIS where the crystalline host rock is largely unaltered and permeability is dominated by microfractures and fracture swarms. These fracture zones prove to be larger, less mineralized and best suited for EGS stimulation.

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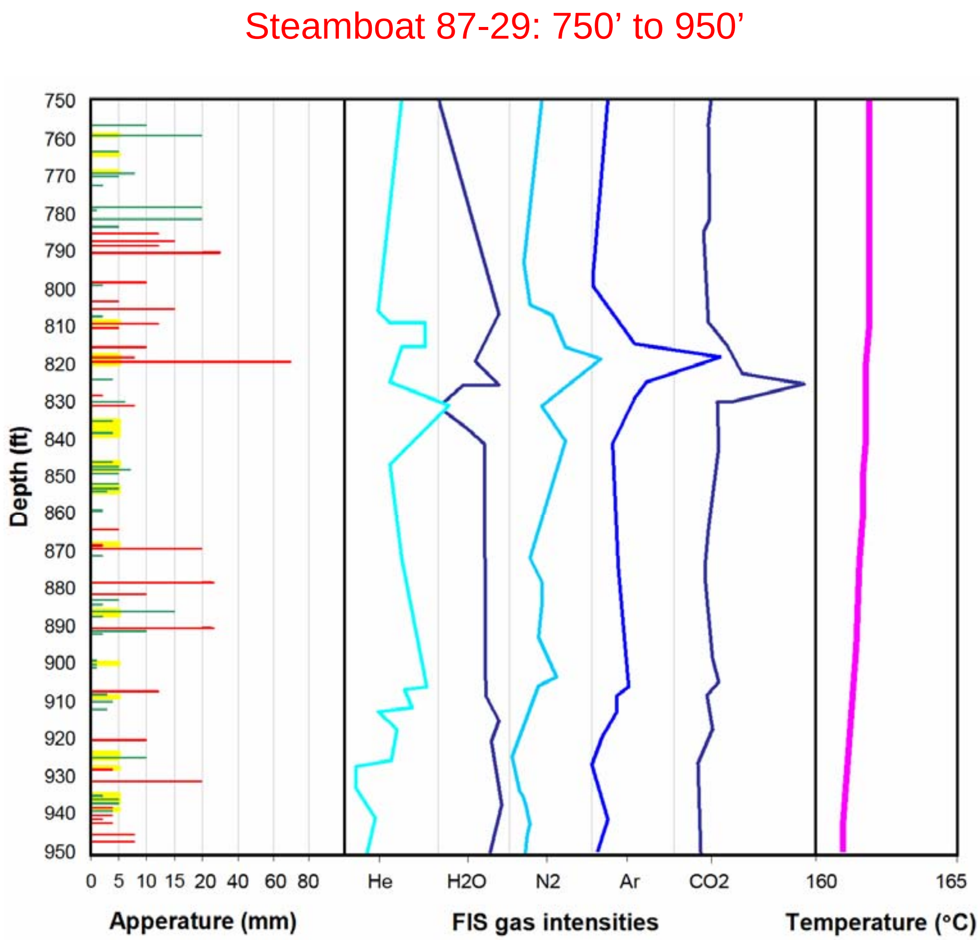

Figure 5. Logs of fracture occurrence;, Fluid Inclusion Stratigraphy (FIS) gas values; and temperature log as a function of depth for Region 1 of Steamboat 87:29 surrounding main fracture at 818'. Log of observed fractures in core plotted for frequency, aperture (mm) and degree of vein fill; open fractures (red), closed fractures (green) and extensive replacement mineralization of matrix (yellow). All core and temperature log data provided by EGI, University of Utah. FIS data presented in entirety in Dilley, 2007.

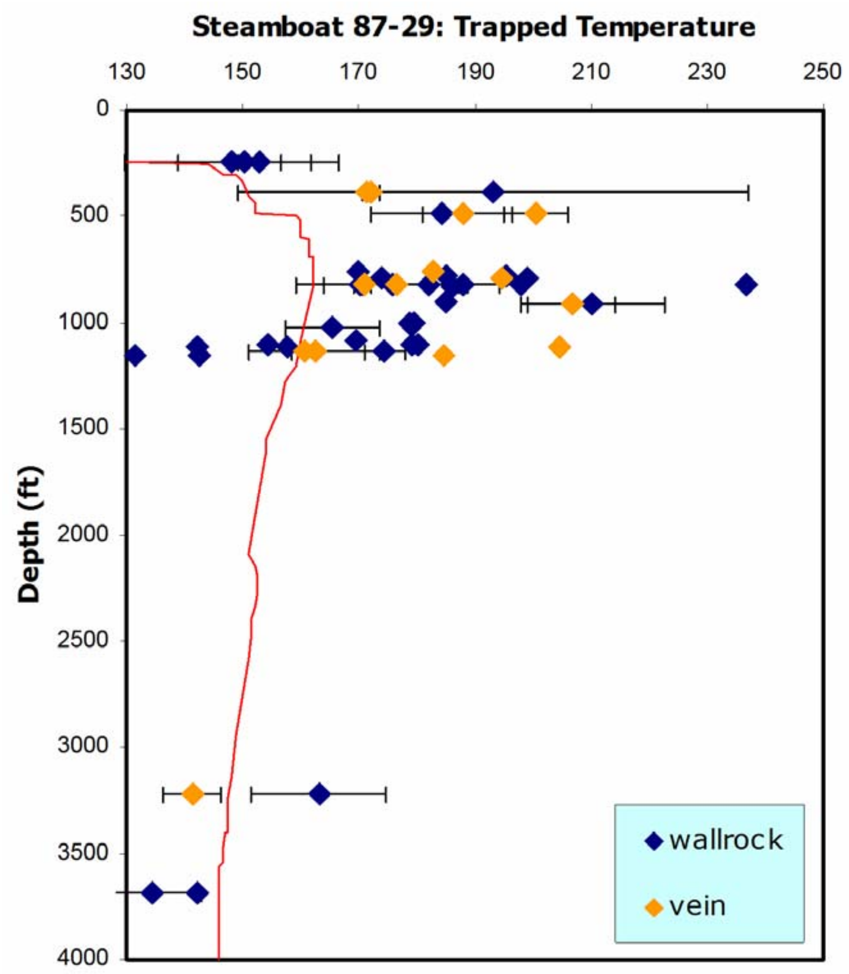

Figure 6. Mean fluid inclusion trapping temperatures (Th) measured from transparent mineral phases at various depths of Steamboat 87-29 plotted against actual temperature log (red line). X-error bars represent 1-sigma standard deviation of all measured values (≥ 12 total) at that depth.

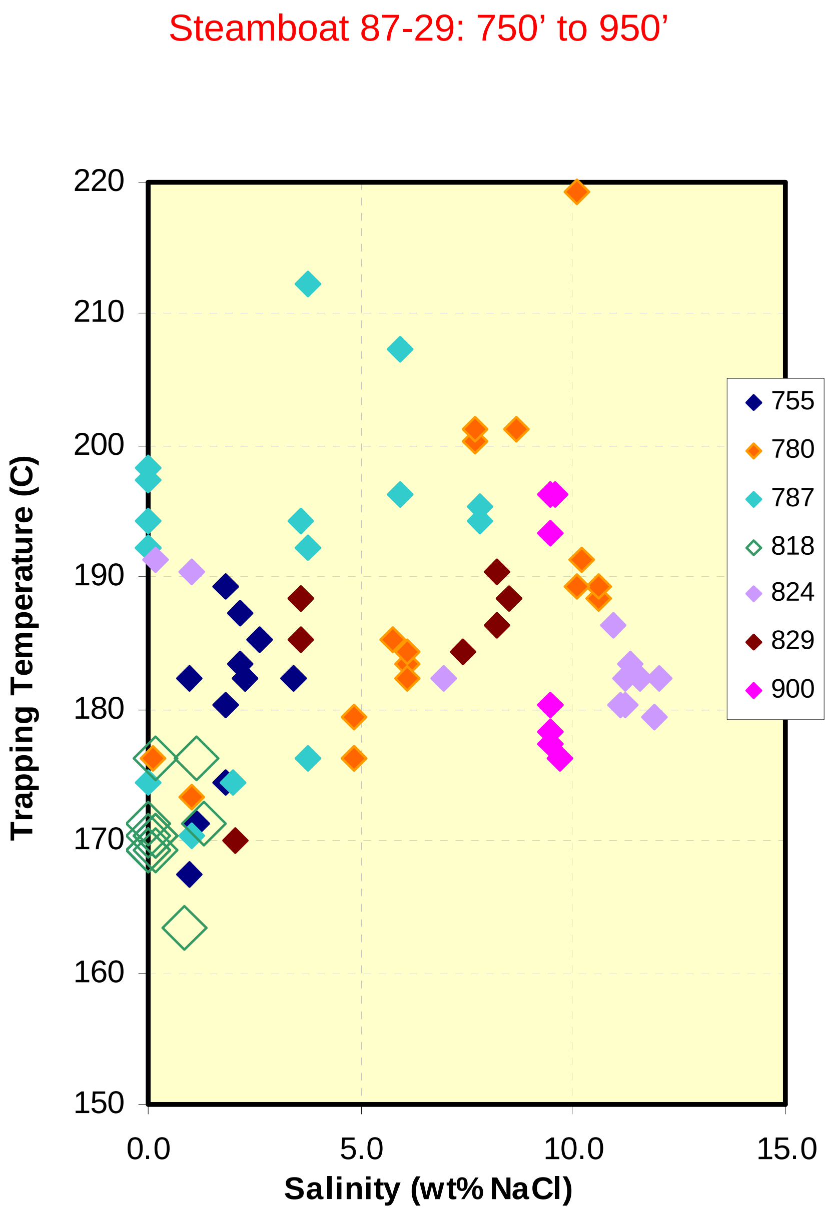

Figure 7. Distribution of fluid populations determined by congruent Th and Tm (ice) values for Region 1 of study at Steamboat 87:29 surrounding main production fracture at 818'.

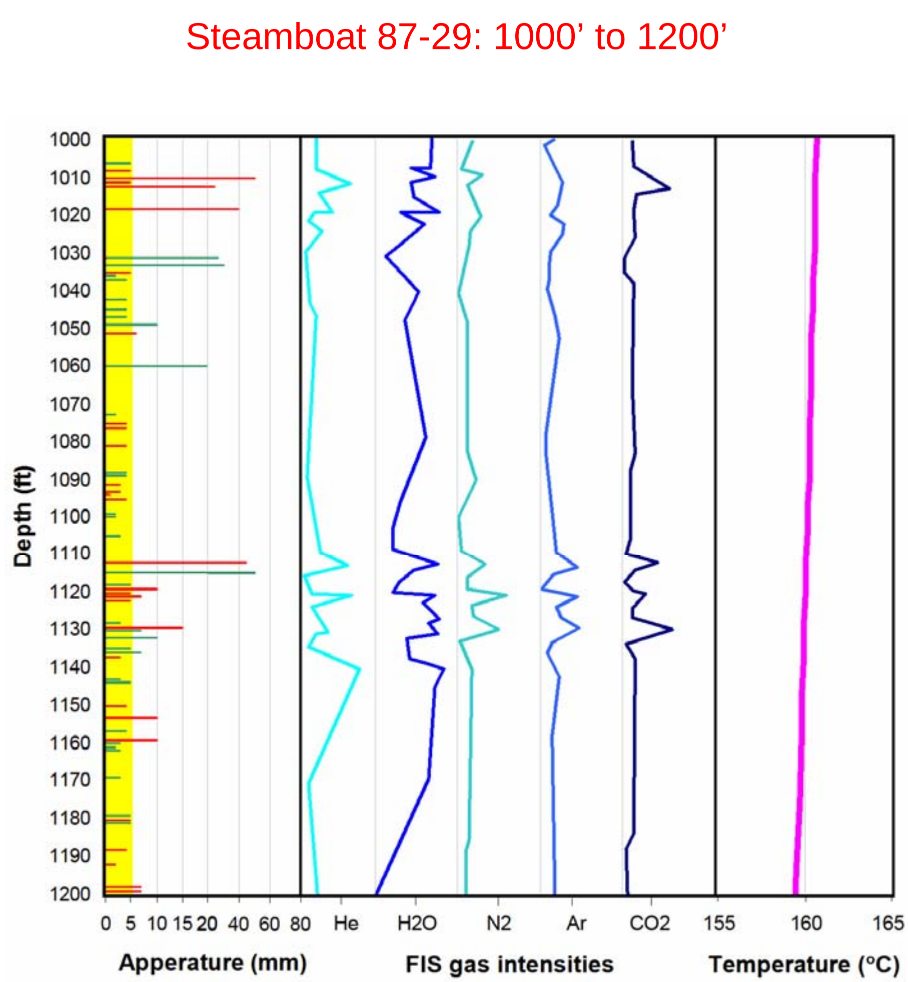

Figure 8. Logs of fracture occurrence, Fluid Inclusion Stratigraphy (FIS) gas values and temperature log as a function of depth for Region 2 of Steamboat 87:29 surrounding main fracture at 1112'. Log of observed fractures in core plotted for frequency, aperture (mm) and degree of vein fill; open fractures (red), closed fractures (green) and extensive replacement mineralization of matrix (yellow). All core and temperature log data provided by EGI, University of Utah. FIS data presented in entirety in Dilley, 2006.

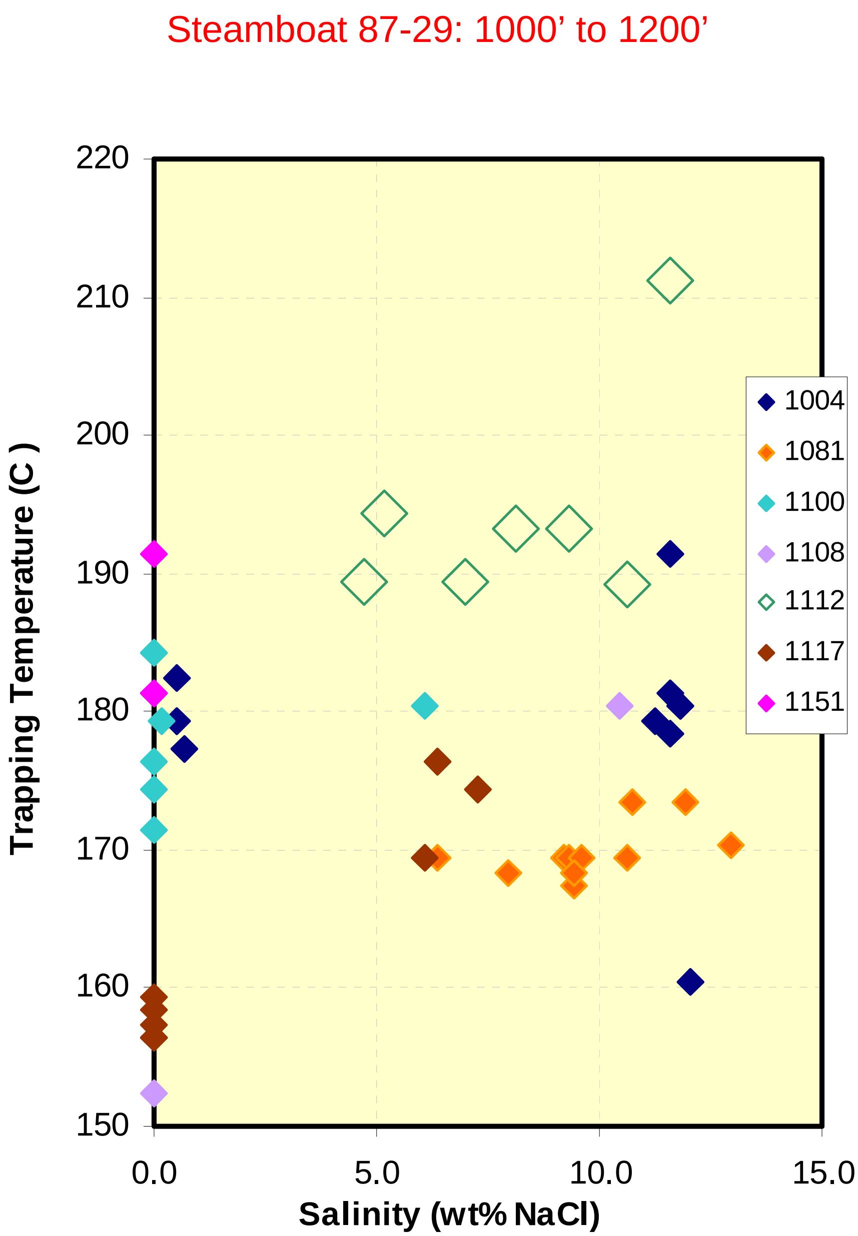

Figure 9. Distribution of fluid populations determined by congruent Th and Tm (ice) values for Region 2 of study at Steamboat 87:29 surrounding main production fracture at 1112'.