# Fluid Inclusions: The Basics



## Fluid Inclusions: The Basics

When a mineral forms in the presence of a fluid phase, some of the fluid may be trapped as defects in the growing crystal to produce fluid inclusions. Fluid inclusions are also produced when mineral precipitation occurs in the process of healing fractures in existing minerals.

The fluid phase may be liquid or vapor, and may include aqueous solutions, volatiles such as  $CO_2$ ,  $CH_4$ ,  $N_2$ , etc., liquid hydrocarbons, or silicate, carbonate or sulfide melts.

When observed at ambient conditions in the laboratory, most fluid inclusions contain more than one phase.



# Fluid Inclusions: The Basics

- How do we classify fluid inclusions?
- How do we select which FI to study?
- Why do we do microthermometry, and what information is provided from microthermometric analysis of FI?



# **Classification of Fluid Inclusions**

Traditionally, fluid inclusions have been classified based on (1) room temperature phase properties and (2) when the FI were trapped relative to mineral growth or some other process.

Room temperature phase relations provide information on the compositions of the inclusions and constrain the types of analyses that might be used to study the inclusions and the order in which various analyses might be conducted. RT phase relations also constrain the region of PT space in which the FI could have been trapped.

Temporal classification constrains the timing of inclusion trapping within the overall paragenetic sequence.



#### **Trapping or Formation Conditions**



### Fluid Inclusion Terminology Trapping or Formation Conditions

Temperature

It is important to recognize that it isn't the PT trapping conditions of the fluid inclusions that we want to know. Rather, we want to know the PT conditions associated with some geologic process, such as the conditions of Cu mineralization in an ore deposit. The FI can help us to determine those conditions IF we can show that the FI are temporally, spatially and genetically related to Cu mineralization.

 $T_{f}$ 



<sup>D</sup>ressure

 $P_{f}$ 

#### **Homogenization Temperature**



#### **Homogenization Temperature**



#### **Homogenization Temperature**

LP.

Temperature

Except in the special case in which the fluid inclusion is trapped on the liquidvapor coexistence curve (i.e., a "boiling" fluid), the homogenization temperature of a fluid inclusion only represents a minimum temperature of formation and serves to identify the isochore (line of constant density) along which the FI was trapped (or later reequilibrated).

Vapor





Pressure

<u>Isochore</u> (= line of constant density or volume)



Temperature



<u>Isochore</u> (= line of constant density or volume)



**Temperature** 



#### **Pressure Correction:**



#### **Pressure Correction:**



**Temperature** 



#### **Pressure Correction:**

**Combining microthermometric** data (Th) to obtain the PT 1.0 coordinates of the isochore corresponding to the FI Th 0.B and composition, and phase Pressure GPa equilibrium data relevant to Calcite + Quartz the mineral system containing 0.6 the FI, a unique trapping Pressure temperature and pressure for the FI may be determined. Wollastonite lce 0.2Γ.P. Vapo 600 800 1000 400 Temperature "C Fluids Research Laboratory Temperature BUBBLES 'Я'

### Fluid Inclusion Terminology Eutectic or First-Melting Temperature





#### Final (Ice)-Melting Temperature



Salinity usually expressed in terms of an NaCl-equivalent salinity, unless there is other information to suggest a different fluid system. What information or observation might suggest that a different fluid system should be used to interpret the FPD?



#### **Daughter Mineral**



For halite-bearing inclusions the salinity is determined from the temperature of dissolution of the halite, and the known solubility of NaCl as a function of T.



Single Phase

- Two-Phase (liquid + vapor) Liquid-rich Vapor-rich
- Halite-bearing
- CO<sub>2</sub>-bearing
- Multi-phase
- Petroleum





-90°C

#### Single Phase

- Two-Phase (liquid + vapor) Liquid-rich Vapor-rich
- Halite-bearing
- CO<sub>2</sub>-bearing
- Multi-phase
- Petroleum



Can we say anything about the composition of this FI based on this behavior?



#### Single Phase

Two-Phase (liquid + vapor) Liquid-rich Vapor-rich

#### Halite-bearing

CO<sub>2</sub>-bearing

Multi-phase

Petroleum

What do we mean when we say an inclusion is "liquid rich"?





Single Phase

Two-Phase (liquid + vapor) Liquid-rich Vapor-rich

Multi-phase

Petroleum



**Single Phase** 

Two-Phase (liquid + vapor) Liquid-rich Vapor-rich

Halite-bearing

CO<sub>2</sub>-bearing

Multi-phase

Petroleum



#### **Room Temperature**



Single Phase

Two-Phase (liquid + vapor) Liquid-rich Vapor-rich

Halite-bearing

CO<sub>2</sub>-bearing

Multi-phase

Petroleum





Liquid-rich and vapor-rich fluid inclusions should NOT be defined based on the relative proportions of liquid and vapor in the FI at room temperature. Rather, the distinction should be based on the mode of homogenization because FI that contain >50 volume % vapor at room temperature do not always homogenize to the vapor phase. For example, a pure  $H_2O$  FI that contains 50-69 vol % vapor at room T, and would be referred to as "vapor rich" based on the phase proportions, would homogenize to the liquid phase. The relationship between vol% vapor at room T and mode of homogenization varies with salinity.



#### **Single Phase**

- Two-Phase (liquid + vapor) Liquid-rich Vapor-rich
- Halite-bearing
- CO<sub>2</sub>-bearing
- Multi-phase
- Petroleum





BUBBLES 'S

#### Single Phase

- Two-Phase (liquid + vapor) Liquid-rich Vapor-rich
- Halite-bearing



### CO<sub>2</sub>-bearing Multi-phase

Petroleum

If an  $H_2O-CO_2$  FI contains three fluid phases at room temperature, the outer phase wetting the mineral walls will always be the  $H_2O$ -rich liquid, the innermost phase will always be the  $CO_2$  vapor, and the intermediate phase will always be  $CO_2$ liquid.

#### **Single Phase**

- Two-Phase (liquid + vapor) Liquid-rich Vapor-rich
- Halite-bearing
- CO<sub>2</sub>-bearing
- Multi-phase
- Petroleum





**Single Phase** 

- Two-Phase (liquid + vapor) Liquid-rich Vapor-rich
- Halite-bearing
- CO<sub>2</sub>-bearing
- Multi-phase

Petroleum



Single Phase

- Two-Phase (liquid + vapor) Liquid-rich Vapor-rich
- Halite-bearing CO<sub>2</sub>-bearing Multi-phase

Petroleum

Multi-phase FI are generally described based on the number of phases, and the identity of those phases if known, i. e., a four phase FI containing liquid, vapor and halite and sylvite daughter minerals.





Single Phase

Two-Phase (liquid + vapor) Liquid-rich Vapor-rich

Halite-bearing

CO<sub>2</sub>-bearing Multi-phase

Petroleum

Can we determine which is halite and which is sylvite?





#### Single Phase

- Two-Phase (liquid + vapor) Liquid-rich Vapor-rich
- Halite-bearing
- CO<sub>2</sub>-bearing
- Multi-phase
- Petroleum





#### Single Phase

Two-Phase (liquid + vapor) Liquid-rich Vapor-rich

Halite-bearing

CO<sub>2</sub>-bearing

Multi-phase

Petroleum





#### Single Phase

Two-Phase (liquid + vapor) Liquid-rich Vapor-rich

Halite-bearing

CO<sub>2</sub>-bearing

Multi-phase

Petroleum





#### Single Phase

- Two-Phase (liquid + vapor) Liquid-rich Vapor-rich
- Halite-bearing
- CO<sub>2</sub>-bearing
- Multi-phase
- Petroleum





#### Single Phase

Two-Phase (liquid + vapor) Liquid-rich Vapor-rich Halite-bearing CO<sub>2</sub>-bearing Multi-phase





Petroleum



Historically, FI have been classified as primary, secondary & pseudosecondary, but this classification is less useful than other methods of describing temporal relationships of FI.



Primary FI are inclusions that trap fluid present at the active growth surface of the host mineral. The best evidence of primary origin is when FI decorate a growth zone in a crystal.

# Primary



Examples of primary inclusions trapped along growth zones.











# Secondary



![](_page_37_Picture_7.jpeg)

![](_page_37_Picture_8.jpeg)

Fluids Research Laboratory

#### Secondary inclusions trapped along healed fractures.

![](_page_38_Figure_1.jpeg)

Pseudosecondary (Goldstein, 2003)

Pseudo-secondary inclusions trapped along healed fractures that terminate at internal growth zones in the crystal.

![](_page_38_Picture_4.jpeg)

While the traditional terms used to describe the temporal classification of fluid inclusions are primary, secondary, and pseudo-secondary, it is often not possible to determine with certainty which category best describes the inclusions being studied. Many (if not most) researchers report that they identified primary FI following the criteria of Roedder (1984). Yet, when one examines photographs of the FI in published papers, the FI are clearly not primary. *Most FI in most samples are best classified as being of indeterminate origin.* 

![](_page_39_Picture_1.jpeg)

While the traditional terms used to describe the temporal classification of FI are primary, secondary, and pseudo-secondary, it is often not possible to determine with certainty which category best describes the inclusions being studied. Many (if not most) researchers report that they identified primary FI following the criteria of Roedder (1984). When one examines photographs of the FI in published papers, the FI are clearly not primary. *Most FI in most samples are best classified as being of indeterminate origin.* 

![](_page_40_Figure_1.jpeg)

While it can be useful to determine the temporal classification of FI being studied, it is more important to be able to place the FI into a relative chronology and to relate specific FI to the question or problem being studied.

![](_page_40_Picture_3.jpeg)

After the fluid inclusions associated with the process being examined have been identified, the next step is to determine if the microthermometric data obtained from those FI faithfully record and preserve the original PT trapping conditions. The first step in this process is to identify Fluid Inclusion Assemblages.

A Fluid Inclusion Assemblage (FIA) represents a group of fluid inclusions that were all trapped at the same time.

![](_page_41_Picture_2.jpeg)

After the fluid inclusions associated with the process being examined have been identified, the next step is to determine if the microthermometric data obtained from those FI faithfully record and preserve the original PT trapping conditions. The first step in this process is to identify Fluid Inclusion Assemblages.

A Fluid Inclusion Assemblage (FIA) represents a group of fluid inclusions that were all trapped at the same time. A Fluid Inclusion Assemblage (FIA) represents a group of fluid inclusions that were all trapped at the same time.

![](_page_42_Picture_2.jpeg)

Many students (and some more experienced inclusionists!) confuse the terms "Fluid Inclusion Assemblage" and "Fluid Inclusion Type"

Fluid Inclusion Assemblage (FIA): a group of petrographicallyassociated fluid inclusions, i.e., a group of FI that were all trapped at the same time [Touret; Diamond; Goldstein & Reynolds].

*Fluid Inclusion Type*: describes the phases and their relative proportions in the FI at room temperature, such as liquid-rich inclusion, vapor-rich inclusion, halite-bearing inclusion, etc.

### Fluid Inclusion Assemblage ≠ Fluid Inclusion Type

![](_page_43_Picture_4.jpeg)

After the fluid inclusions associated with the process being examined have been identified, the next step is to determine if the microthermometric data obtained from those FI faithfully record and preserve the original PT trapping conditions. The first step in this process is to identify Fluid Inclusion Assemblages.

![](_page_44_Figure_1.jpeg)

Fluid inclusion assemblages are identified using petrography, and ONLY petrography. Microthermometry is NOT included in the definition of an FIA.

Which of the 6 different FIAs should we collect data from?

![](_page_44_Picture_4.jpeg)

### FIAs are identified based on petrography!

![](_page_45_Picture_1.jpeg)

System Administrator Sep 3, 2022 at 8:44:30 AM 88:66:5a:34:95:28

### **Characteristics of FIAs**

• A single thin section may contain many 10s to 1000s of FIAs (but only one or a few different fluid inclusion types).

![](_page_46_Figure_2.jpeg)

### **Characteristics of FIAs**

- Often, the majority (>90%) of the FI in a thin section cannot be assigned to an FIA.
- The "size" of an individual FIA is usually such that it is completely contained within a single microscope field of view (or 2-3 x the FOV diameter) when examined at low to moderate magnification (5x to 20x objective).

![](_page_47_Figure_3.jpeg)

![](_page_47_Picture_4.jpeg)

![](_page_48_Picture_0.jpeg)

Even if we can't determine the temporal classification of FI in an individual vein, if the sample contains multiple veins (or other features that can be placed into a paragenetic sequence) we can sometimes determine the relative ages of types of FI in the sample.

![](_page_49_Picture_0.jpeg)

Richardson & Pinckney (1984) conducted a detailed fluid inclusion study of the Cave in Rock fluorspar deposits. Fluorite shows distinct color banding that can be used to correlate zones within deposits and between nearby deposits.

![](_page_50_Figure_1.jpeg)

![](_page_50_Figure_2.jpeg)

From Richardson & Pinckney, 1984

![](_page_50_Picture_4.jpeg)

Photograph provided by A. Fall; sample provided by Paul Spry from collection of C. Richardson

![](_page_50_Picture_6.jpeg)

It is important to recognize that FI may not sample fluids representing the entire fluid history of the system being studied. If a suitable host mineral is not precipitating, or is dissolving, FI will not be trapped, and earlier-formed FI may be destroyed.

![](_page_51_Figure_1.jpeg)

After we have identified the FI (and FIAs) that are associated with the process we are studying, the next step is generally to conduct microthermometry.

Why do we conduct microthermometry? i.e., what information do we obtain from microthermometric analysis of FI?

### Measurements (data) versus Interpretation

What are some examples of things that we measure during microthermometry?

What are some examples of information we obtain from interpretation of things we measure during microthermometry?

![](_page_52_Picture_5.jpeg)

One of the main reasons that we conduct microthermometric studies is to determine if the FI that constitute an FIA have recorded and preserved information on the original trapping conditions, and to confirm three assumptions or criteria required for FI to provide valid info on the conditions of trapping, and these are referred to as *"Roedder's or Sorby's Rules"*.

- 1. The inclusion traps a single, homogeneous phase.
- 2. Nothing is added to, or removed from, the inclusion following trapping.
- 3. The inclusion volume remains constant following trapping, i.e., represents an isochoric system.

![](_page_53_Picture_4.jpeg)

### How do we test "Roedder's Rules"?

![](_page_54_Picture_1.jpeg)

Does this inclusion obey Roedder's Rules?

Cannot determine from a single inclusion

![](_page_54_Picture_4.jpeg)

### How do we test "Roedder's Rules"?

![](_page_55_Picture_1.jpeg)

Do the inclusions in this FIA obey Roedder's Rules?

Probably must confirm by microthermometry

![](_page_55_Picture_4.jpeg)

FI in FIAs are tested for adherence to "Roedder's Rules" based initially on room temperature petrography followed by microthermometry if all of the FI in the FIA appear to show similar RT phase behavior.

![](_page_56_Picture_1.jpeg)

![](_page_56_Picture_2.jpeg)

![](_page_56_Picture_3.jpeg)

FI in FIAs are tested for adherence to "Roedder's Rules" based initially on room temperature petrography followed by microthermometry if all of the FI in the FIA appear to show similar RT phase behavior.

![](_page_57_Figure_1.jpeg)

Fluids Research Laborator

Microthermometry indicates that some or all of the FI have reequilibrated - is this still an FIA?

Summary of the protocol to select and test if FI have sampled and preserved a record of the PTX trapping conditions.

- 1. Can you identify a Fluid Inclusion Assemblage?
- 2. Using petrography, do all the inclusions in the FIA "appear" to have the same number of phases and in the same proportions (or is there a bimodal distribution)?
- 3. Do all inclusions in the FIA show similar behavior during microthermometry?
- 4. If the answer to all questions above is "YES", the fluid inclusions probably obey Roedder's Rules. Trapping of multiple phases, leakage, and changes in inclusion volume after trapping all lead to variations in phase relations and/or microthermometric behavior.\*\*

Fluids Research Laboratory

\*\* Caution!

![](_page_58_Picture_6.jpeg)

Th and salinity data from fluid inclusions in zoned sphalerite from the Creede, CO, epithermal Ag-Zn-Pb mineralization (Roedder, 1974). [Average  $T_h = 240^{\circ}C$ 

The data shown in histogram form indicate that the crystal grew at 200-270°C from fluids with salinities of ~5-11 wt.% NaCl. However, these results tell us nothing about the temporal evolution of T and salinity during crystal growth.

![](_page_59_Figure_2.jpeg)

![](_page_59_Figure_3.jpeg)

![](_page_59_Figure_4.jpeg)

Because we are interested in the temporal evolution of temperature and salinity, we can label the relative ages of each growth zone (FIA) to show how fluid properties varied with time.

![](_page_60_Figure_1.jpeg)

![](_page_61_Figure_0.jpeg)

By plotting both salinity and temperature data for each individual FIA in the relative order in which the FIAs formed, much more information concerning the temporal variation in fluid properties during formation of the crystal are obtained. This information, in turn, can help to identify **PROCESSES** associated with crystal growth.

![](_page_61_Figure_2.jpeg)

Fluids Research Laboratory

![](_page_62_Picture_0.jpeg)

OK, so now that we know how to identify an FIA and to test if the FI have preserved a record of the original trapping PTX conditions, let's talk about how to collect and display FI data. To do this, let's go to the movies.

![](_page_62_Picture_2.jpeg)

In summary, after the FIA was identified using petrography and all of the FI in the FIA appeared to have the same phase proportions, the sample was heated at a rate of about 30°C/minute, starting from room temperature and stopping when all of the FI had homogenized at about 154°C. During heating, the entire field of FIs was monitored to determine if all of the FI in the FIA were behaving in a similar manner. Immediately after the FI had homogenized, the sample was cooled until all (or most) of the FI had re-nucleated a bubble – most had bubbles after cooling to ~145°C. At that point the sample was re-heated at a rate of 10°C/minute while monitoring a few (2-10) FI in the FIA, and the homogenization temperature of these FI was recorded. The FI being monitored (and presumably all of the other FI in this FIA) homogenized in the range 151.3°C to 153.6°C, and the temperature of this FIA would be reported as ~ 152±1°C.

The entire process, from the beginning of heating until the temperature of the FIA was determined, took approximately 6 minutes. Now, it is time to move on to the next FIA and repeat this process.\*\*

\*\* Note that another FIA in the same chip should not be heated if it had not been monitored during this initial heating experiment.

![](_page_63_Picture_3.jpeg)