Application of Fluid Inclusion Studies
to
Oil and Gas Exploration

Martin Feely,
Earth and Ocean Sciences,
National University of Ireland, Galway.

The Application of Fluid Inclusion Studies to Oil & Gas Exploration.

Overview of Fluid Inclusion Studies and Applications

Sampling, Sample Preparation, Fluid Inclusion Petrography

Analytical Methods

Microthermometry, Geothermobarometry

Review of Case Histories from the OIL & Gas Exploration Sector

Parson's Pond project—Dr James Conliffe, GSNL

Tour of Facilities, MAF-IIC Laboratories, Memorial University.

What are Fluid Inclusions?

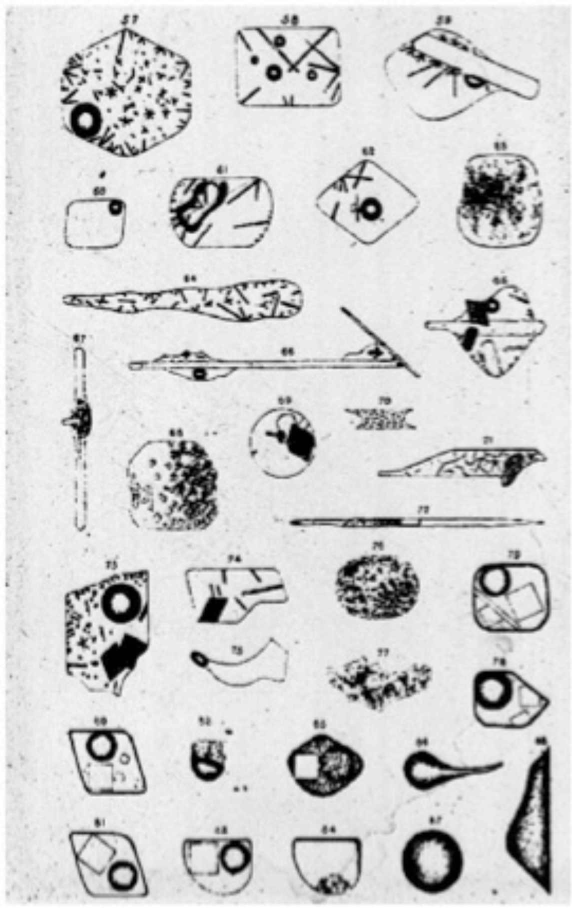
FLUID INCLUSIONS ARE TINY BUBBLE- LIKE INCLUSIONS IN CRYSTALS. THEY ARE COMPOSED OF LIQUID ±SOLID ± GAS PHASES IN VARYING PROPORTIONS.
THEY REPRESENT FLUID TRAPPED DURING OR AFTER CRYSTAL GROWTH.

THEY HAVE THE POTENTIAL TO ELUCIDATE THE PTVX PROPERTIES OF FLUIDS DURING MANY GEOLOGICAL PROCESSES e.g. MINERALISATION, PETROLEUM MIGRATION, MAGMATIC AND METAMORPHIC PROCESSES.

And now the Biosphere and Martian exploration!

Fluid Inclusions

- Early work by H.C. Sorby (1858)



FLUID INCLUSION STUDY METHODS.

PETROGRAPHY

MICROTHERMOMETRY

LASER RAMAN

UV MICROSCOPY

FLUORESCENCE LIFETIME MICROSCOPY

ELECTRON MICROSCOPY.

What Are Fluid Inclusions ?

Microscopic volumes of fluid (liquid ±gas±solid) trapped during and/or after mineral growth in a rock.

Where Are They Found ?

Most geological settings. Includes Sedimentary Basins such as in Rockall & Porcupine Regions.

Why Study Fluid Inclusions ?

1. **Timing of fluid movements**

2. **Recording fluid movement events.**

3. **Chemistry of fluids.**

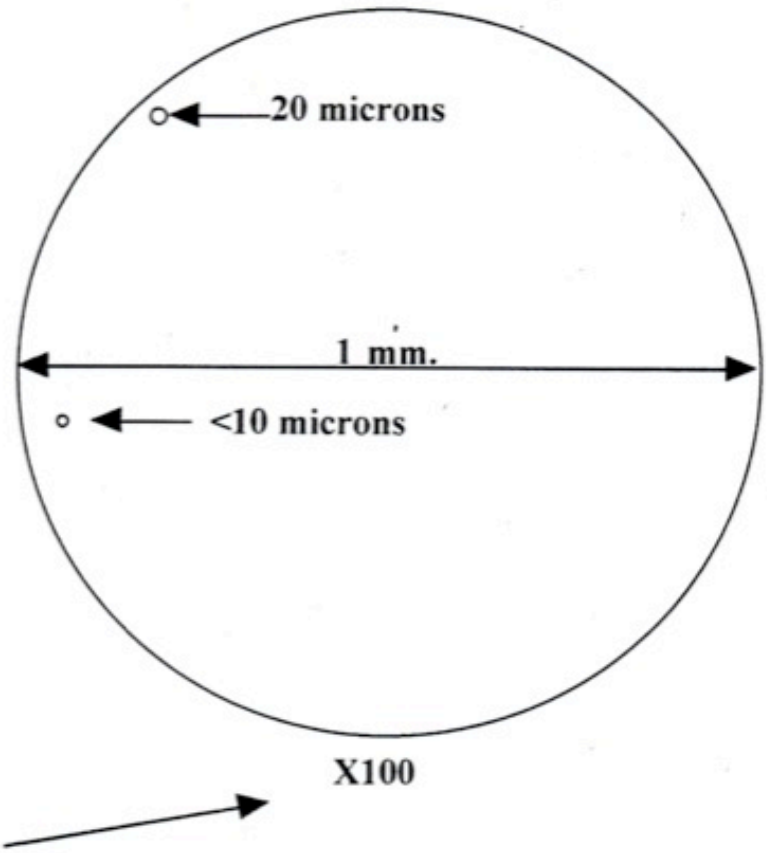
4. **Temperature of fluid entrapment.**

5. **Pressure of fluid entrapment.**

6. **Exploration for Oil & Gas and Mineral Deposits.**

1 micron (μm) = 0.001mm

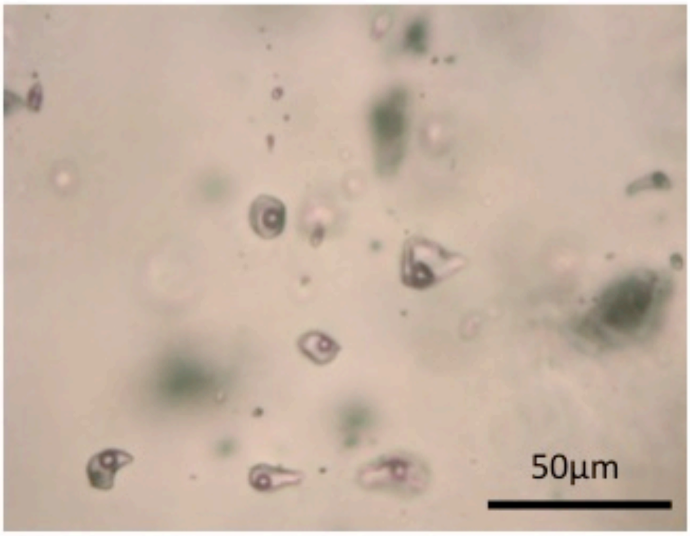
20 microns = 0.02mm

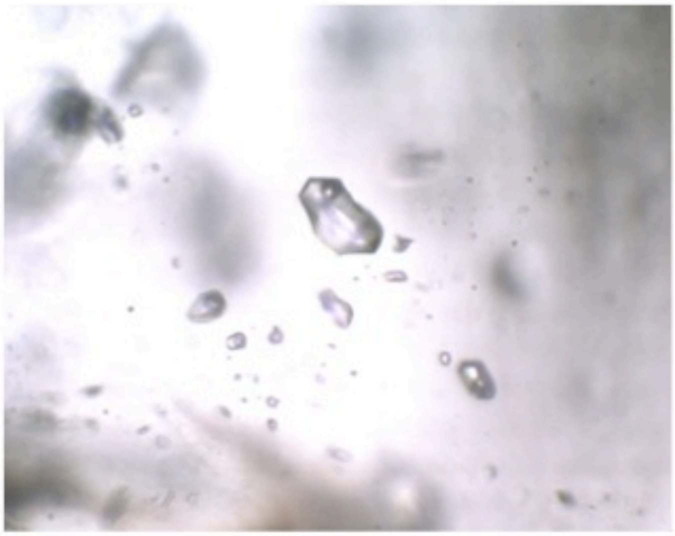


∘ Ballpoint of biro.

What are Fluid Inclusions

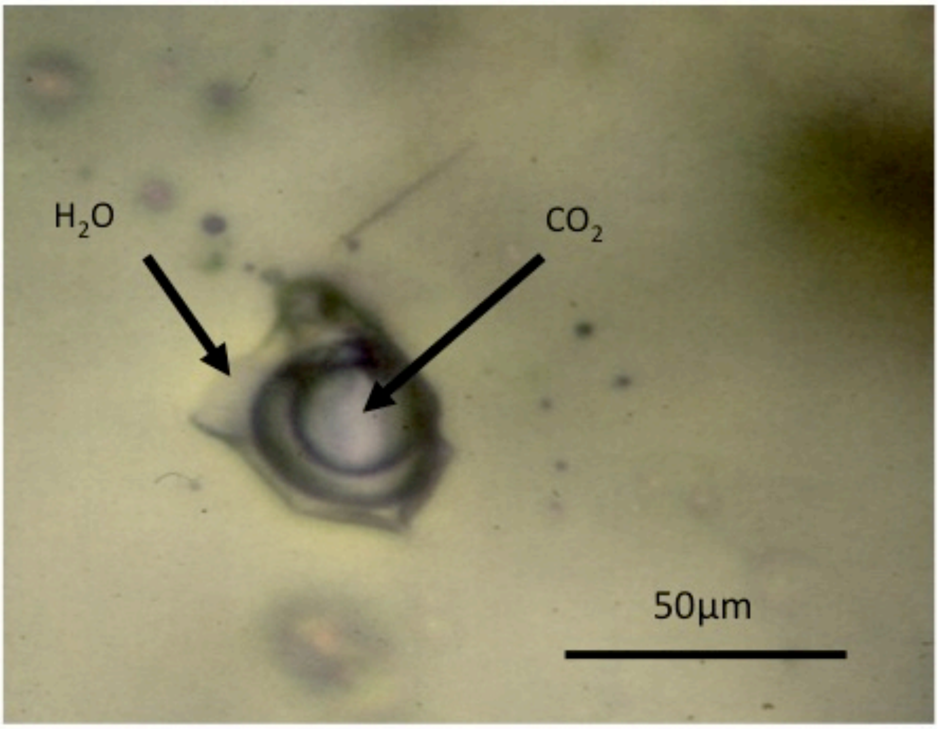
Aqueous Fluid Inclusions





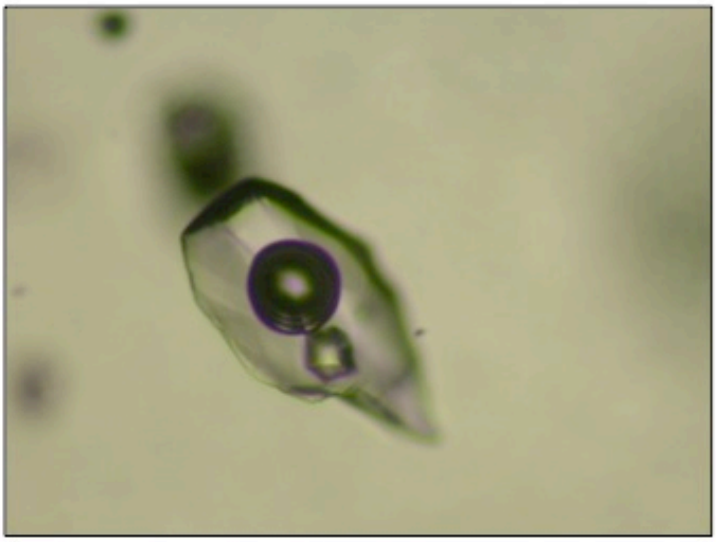
What are Fluid Inclusions

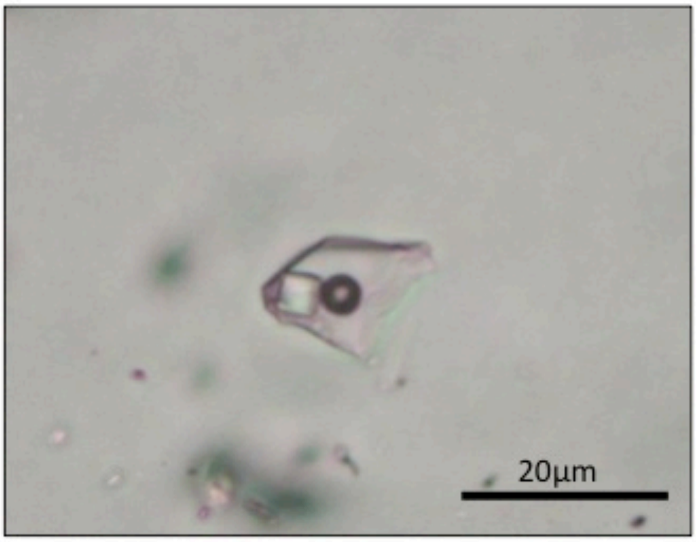
$H_2O + CO_2$
Fluid
Inclusions



What are Fluid Inclusions

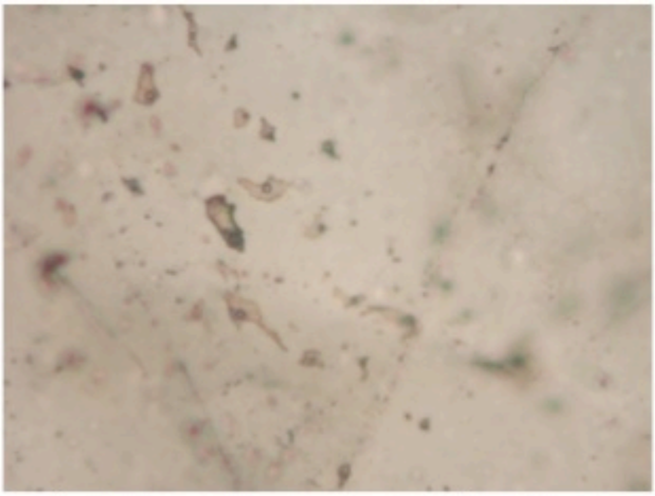
Daughter and/or captive minerals



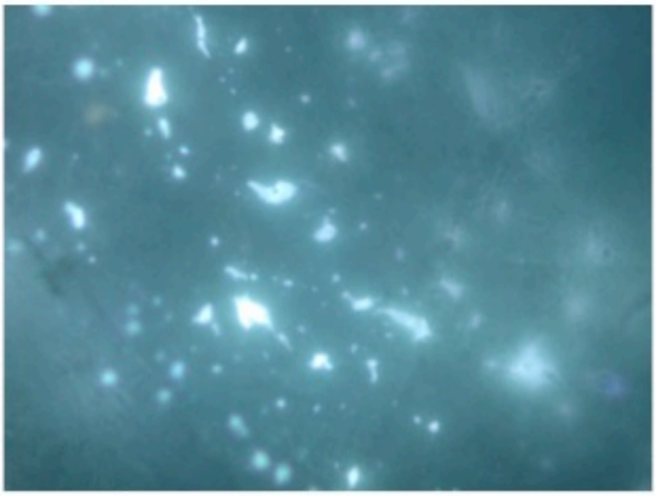


What are Fluid Inclusions

Hydrocarbon Bearing Fluid Inclusions



Transmitted Light Only



UV Light

Occurrence and distribution

MOST INCLUSIONS < 100 MICRONS AND COMMONLY RANGE BETWEEN 2 and 20 MICRONS.

THE TOP TEN*:

*RATINGS ARE BASED ON ROBUSTNESS, TRANSLUCENCY AND OCCURRENCE

1-Quartz

2-Fluorite

3-Halite

4-Calcite

5-Apatite

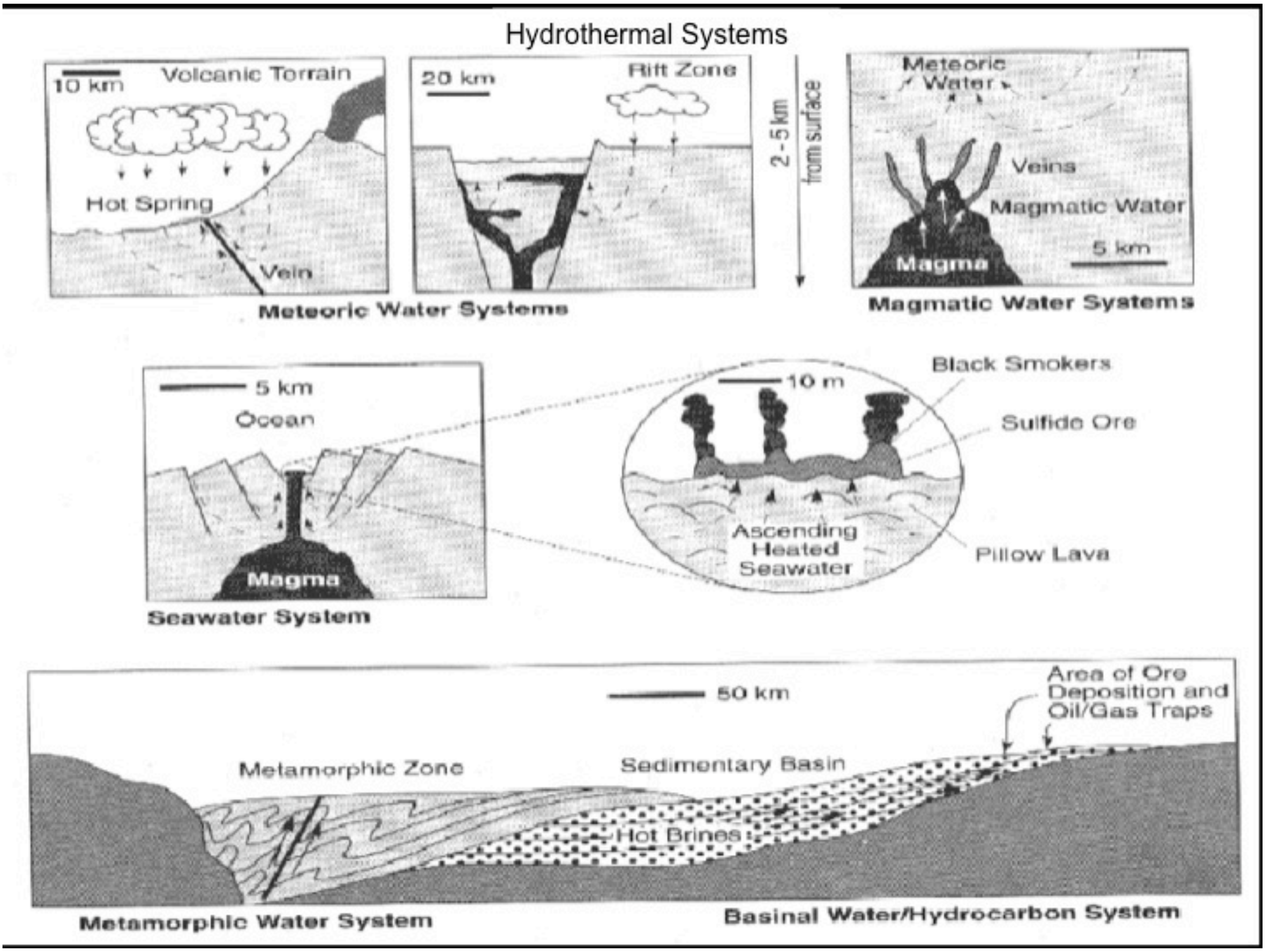
6-Dolomite

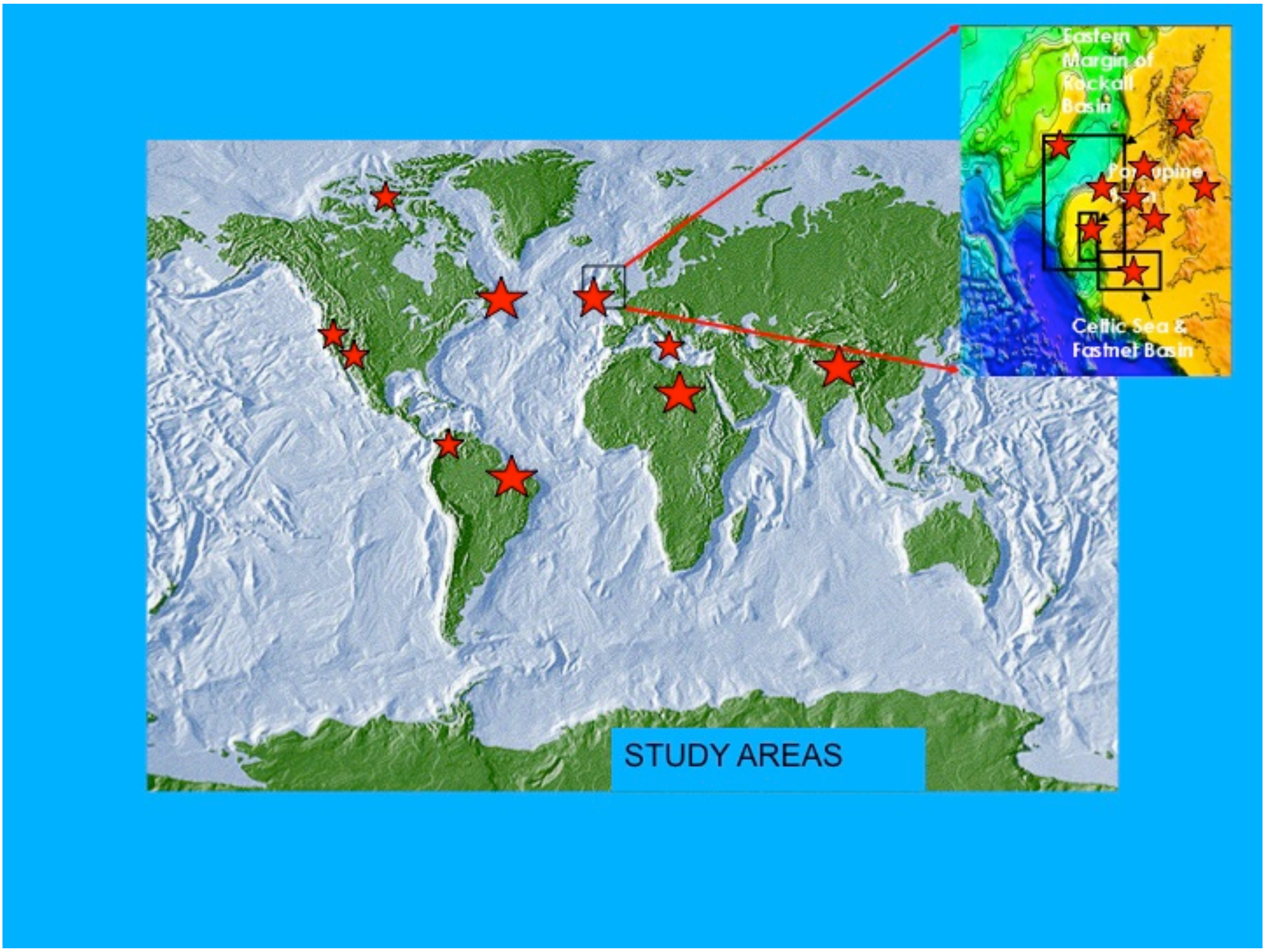
7-Sphalerite

8-Barite

9-Topaz

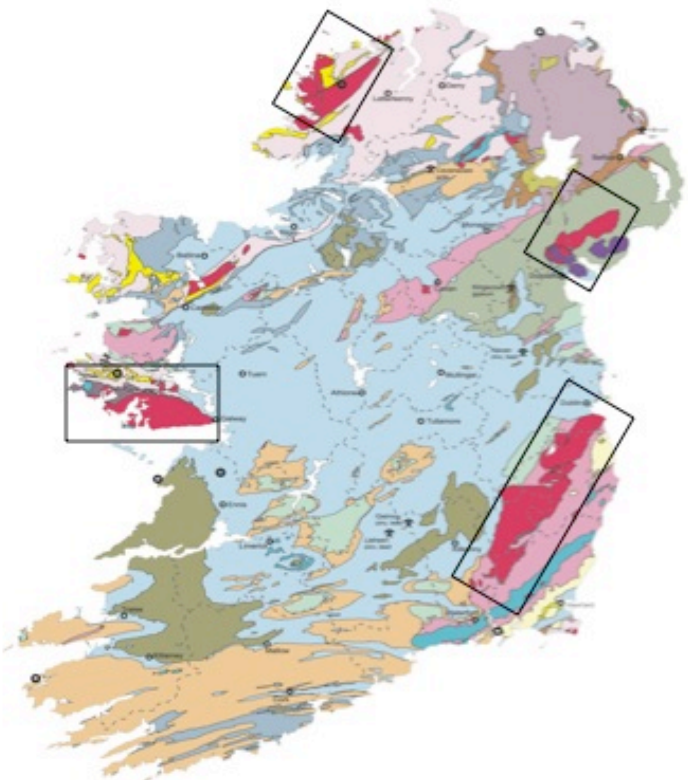
10-Cassiterite

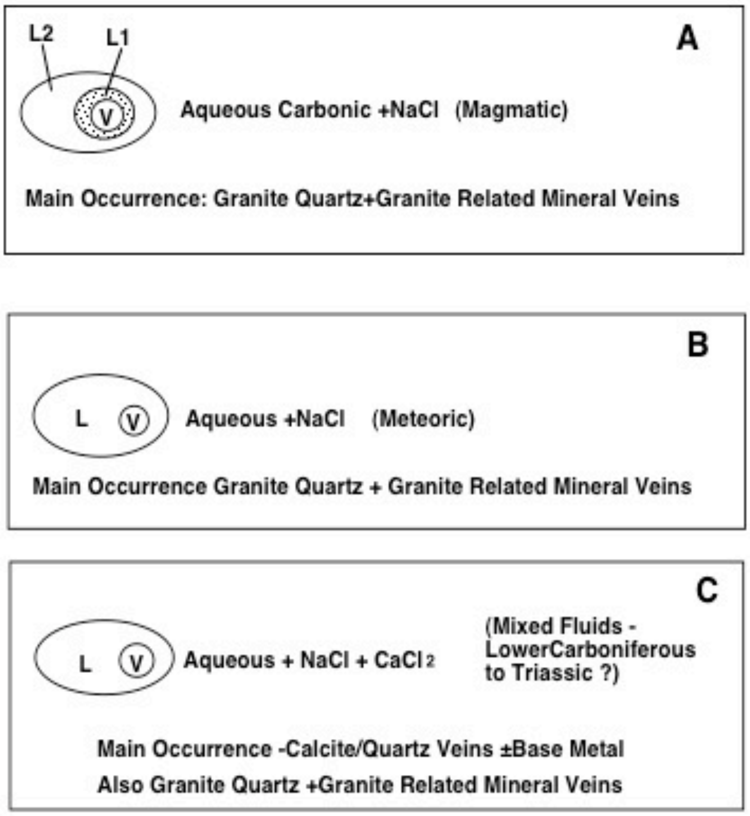

Hydrothermal Systems
10 km
Volcanic Torrain
Hot Spring
Vein
20 km
Rift Zone
Meteoric Water Systems
2 - 5 km from surface
Meteoric Water
Veins
Magmatic Water
5 km
Magma
Magmatic Water Systems
5 km
Ocean
Magma
Seawater System
10 m
Black Smokers
Sulfide Ore
Ascending Heated Seawater
Pillow Lava
50 km
Area of Ore Deposition and Oil/Gas Traps
Metamorphic Zone
Sedimentary Basin
Hot Brines
Metamorphic Water System
Basinal Water/Hydrocarbon System



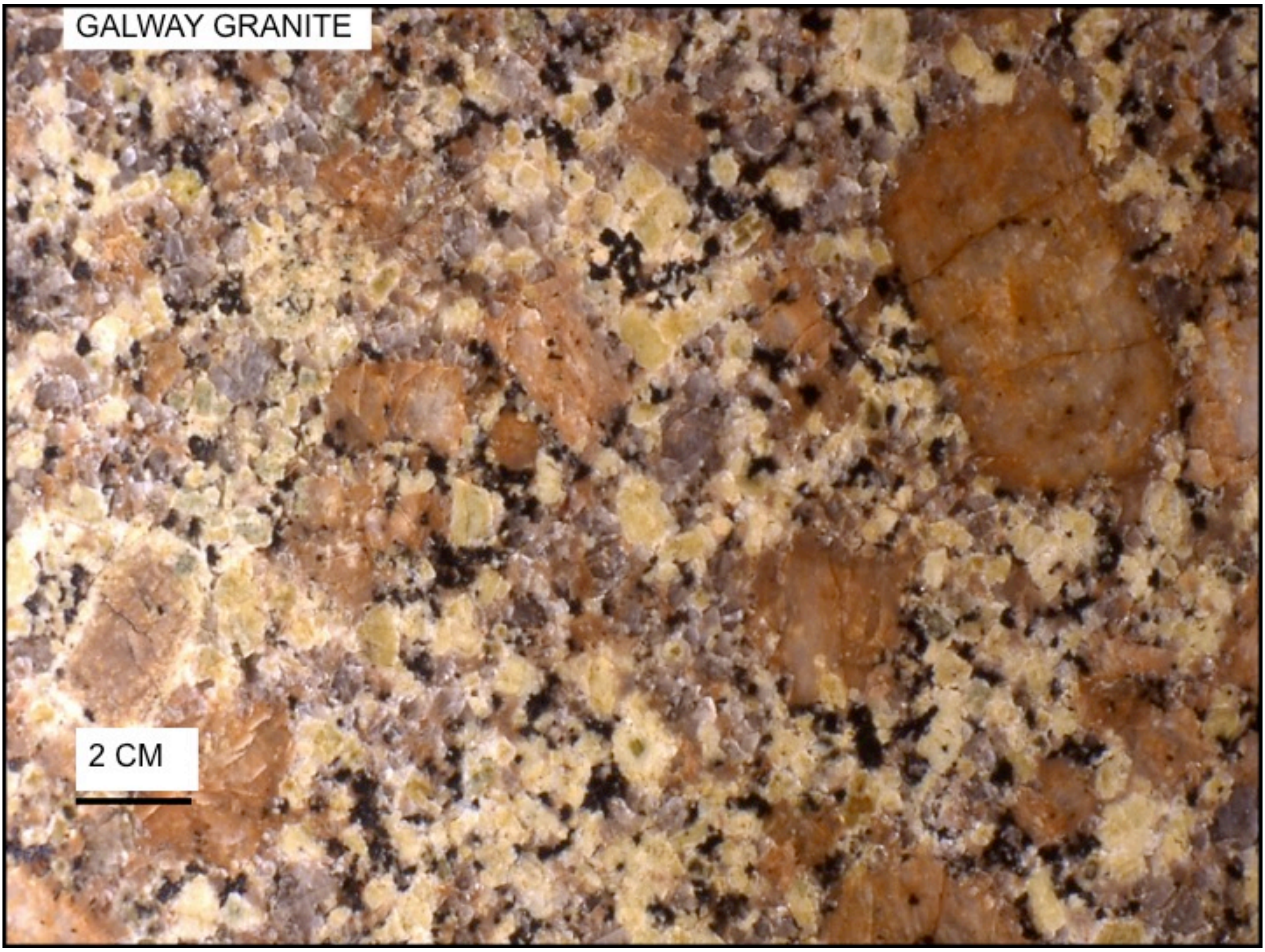
Eastern
Margin of
Basin
Celtic Sea &
Fastnet Basin
STUDY AREAS

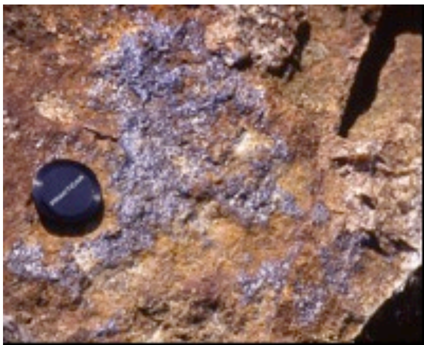
FLUIDS IN IRISH GRANITES



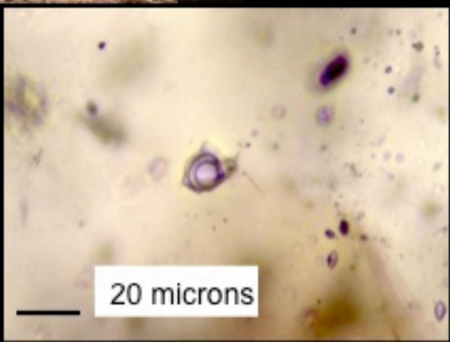


Main Fluid Inclusion Types In Granites & Veins


GALWAY GRANITE
2 CM

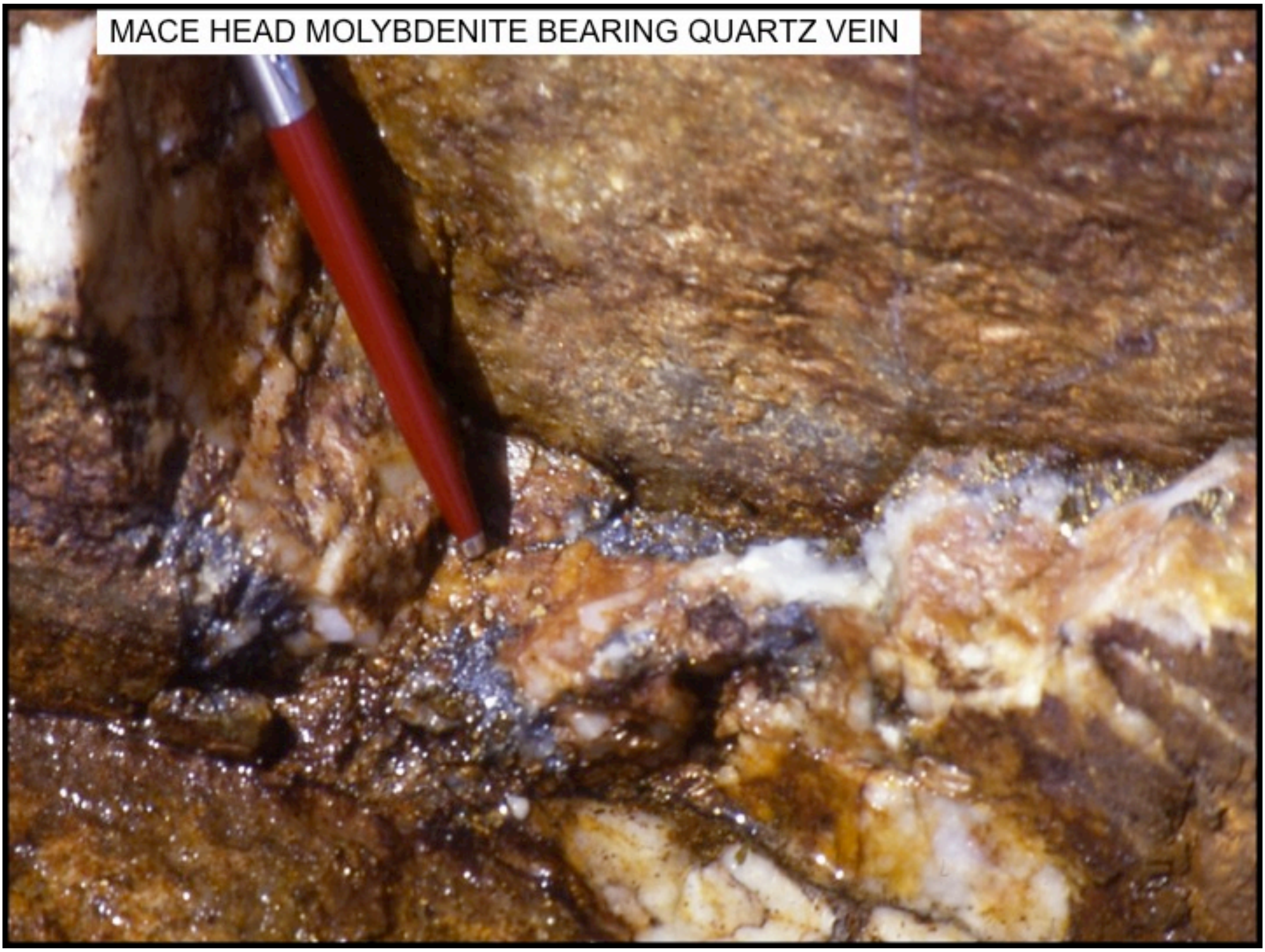


Molybdenite Re-Os age determinations

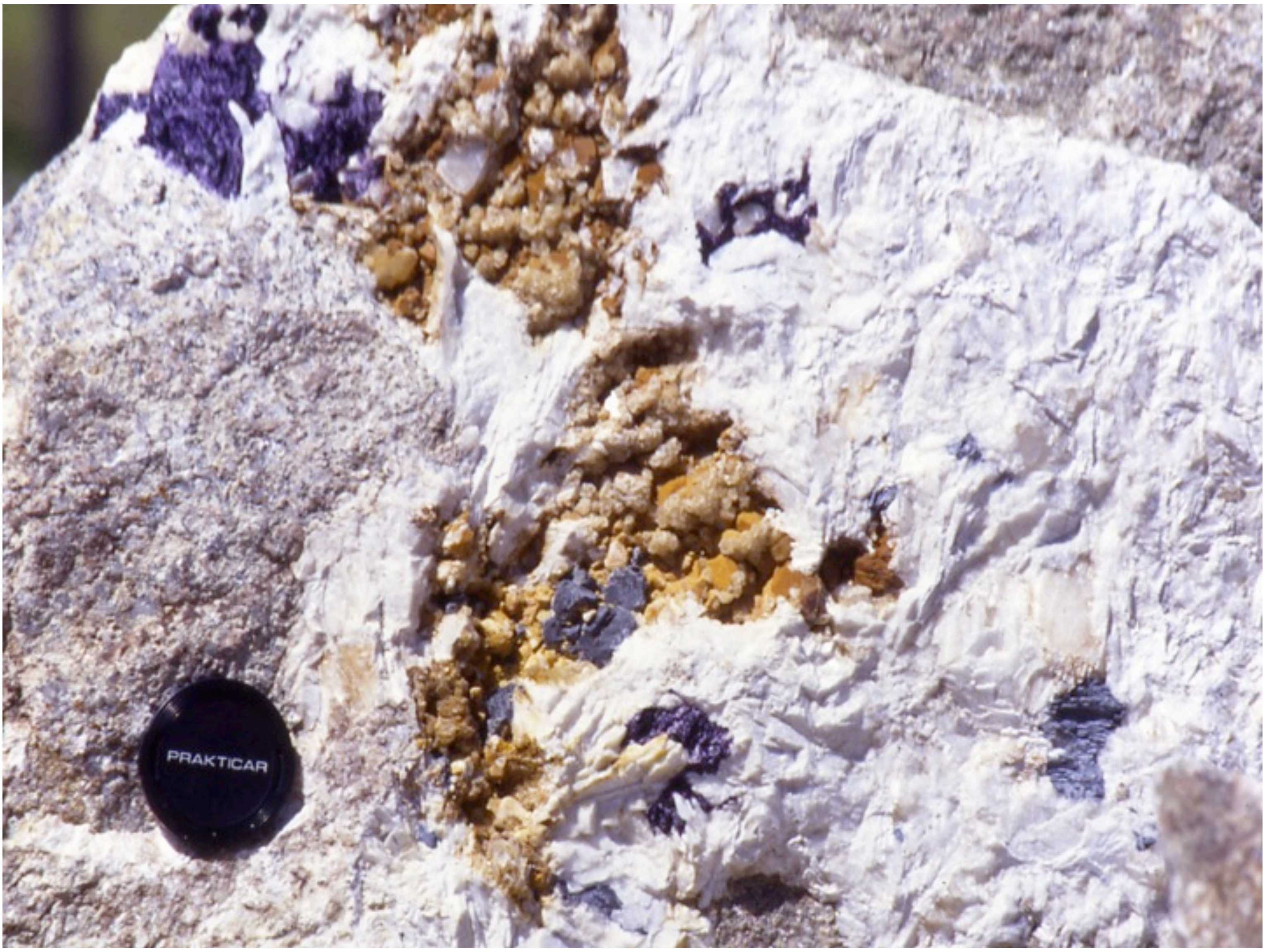


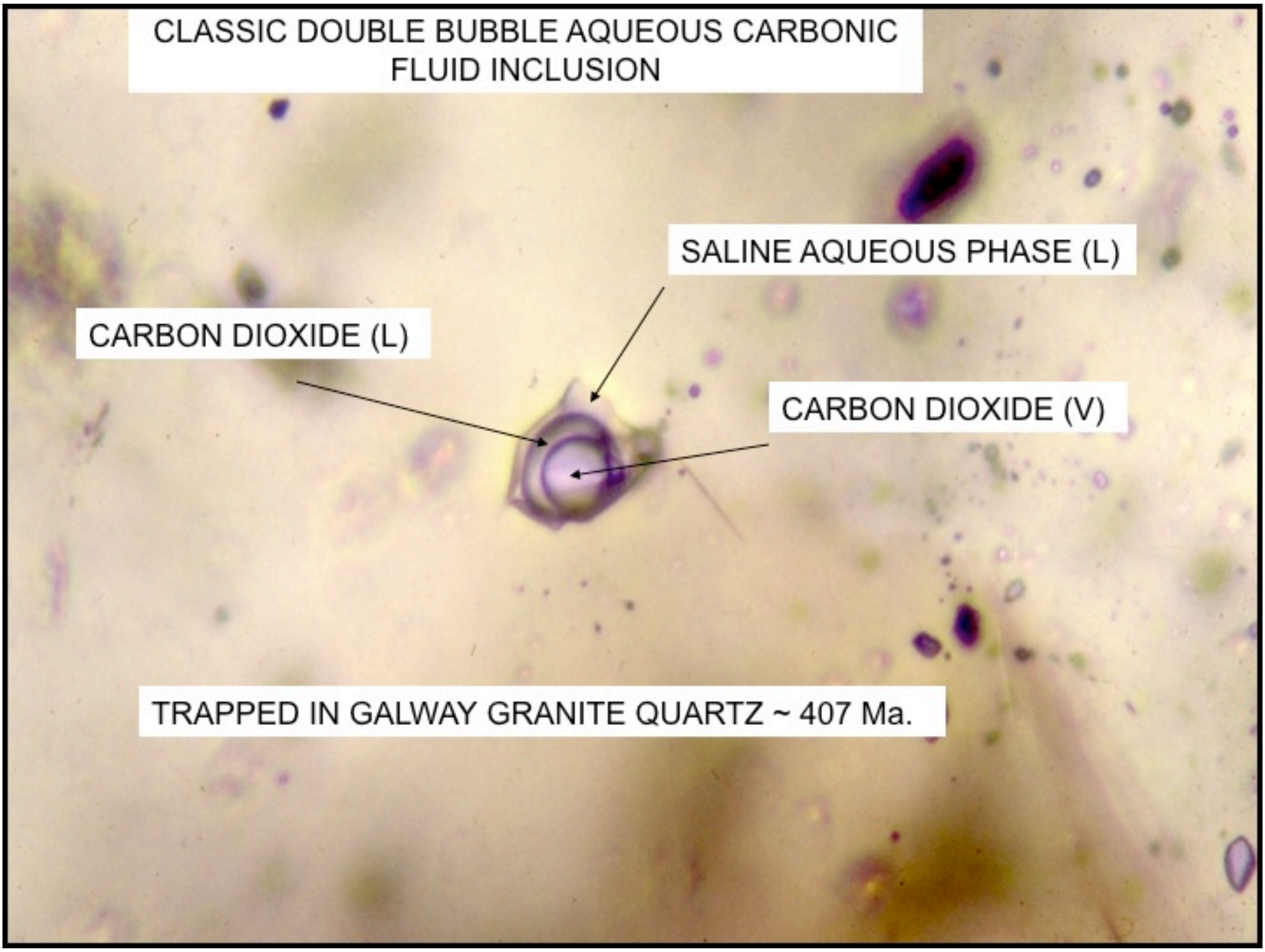
Aqueous-carbonic fluids trapped in Mo-Cu quartz veins

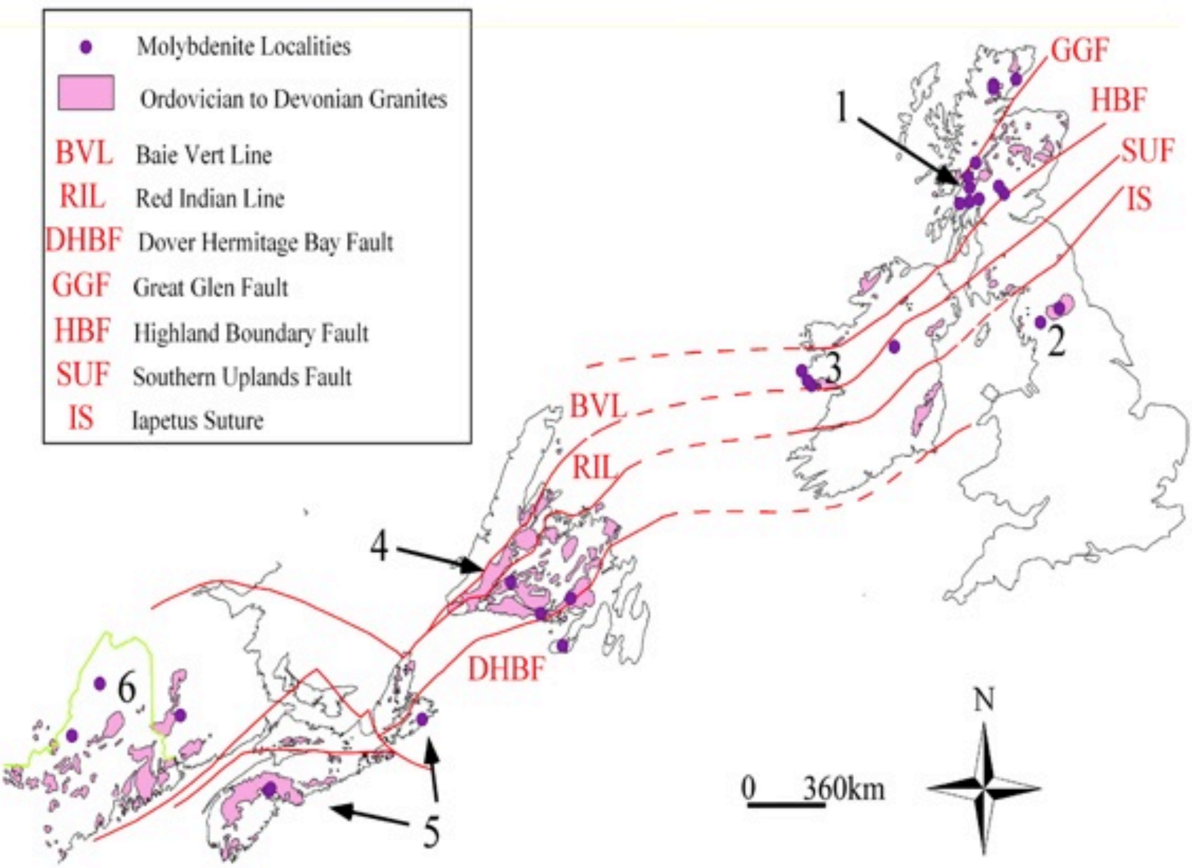
Zircon U-Pb age determinations



MACE HEAD MOLYBDENITE BEARING QUARTZ VEIN


PRAKTICAR


CLASSIC DOUBLE BUBBLE AQUEOUS CARBONIC FLUID INCLUSION
SALINE AQUEOUS PHASE (L)
CARBON DIOXIDE (L)
CARBON DIOXIDE (V)
TRAPPED IN GALWAY GRANITE QUARTZ ~ 407 Ma.



1. Scottish Granite Mo-system.

2. Lake District Granite Mo-system.

3. Connemara Granite Mo-system.

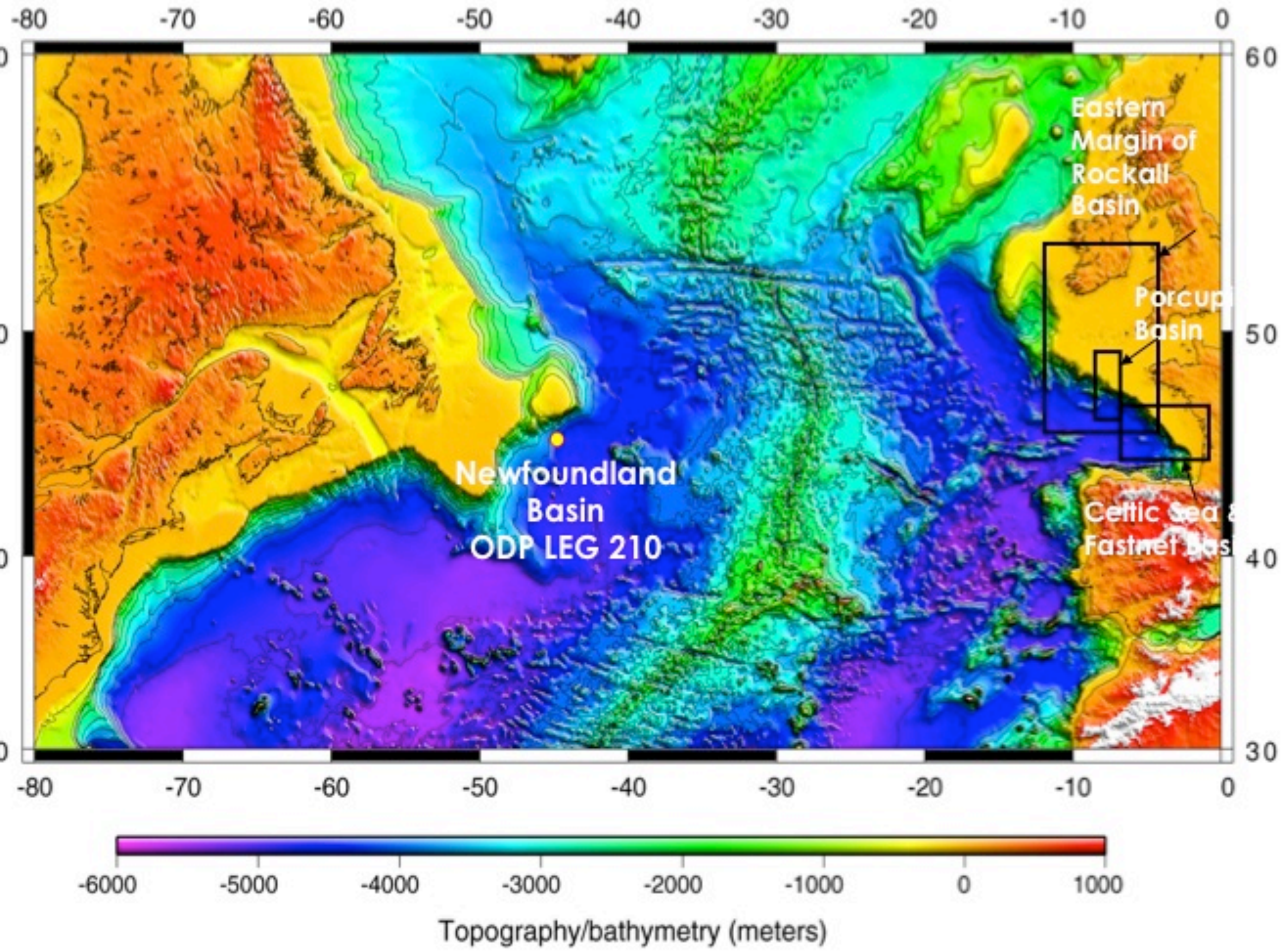
4. Newfoundland Granite Mo-system.

5. Nova Scotia Granite Mo-system.

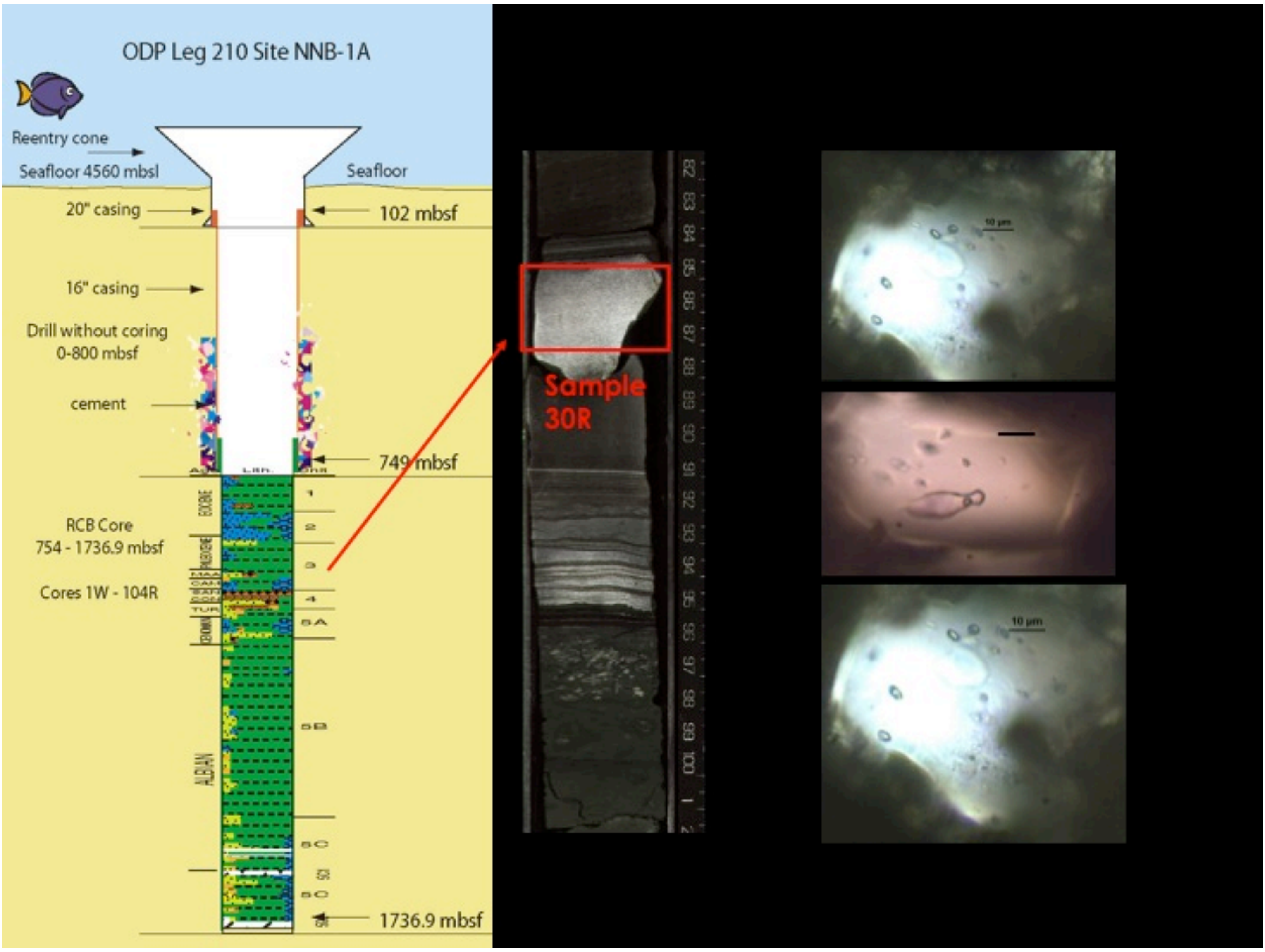
6. New England/New Brunswick Granite Mo-system

Francois Granite, south coast, Newfoundland. Wall is ~ 300m high.

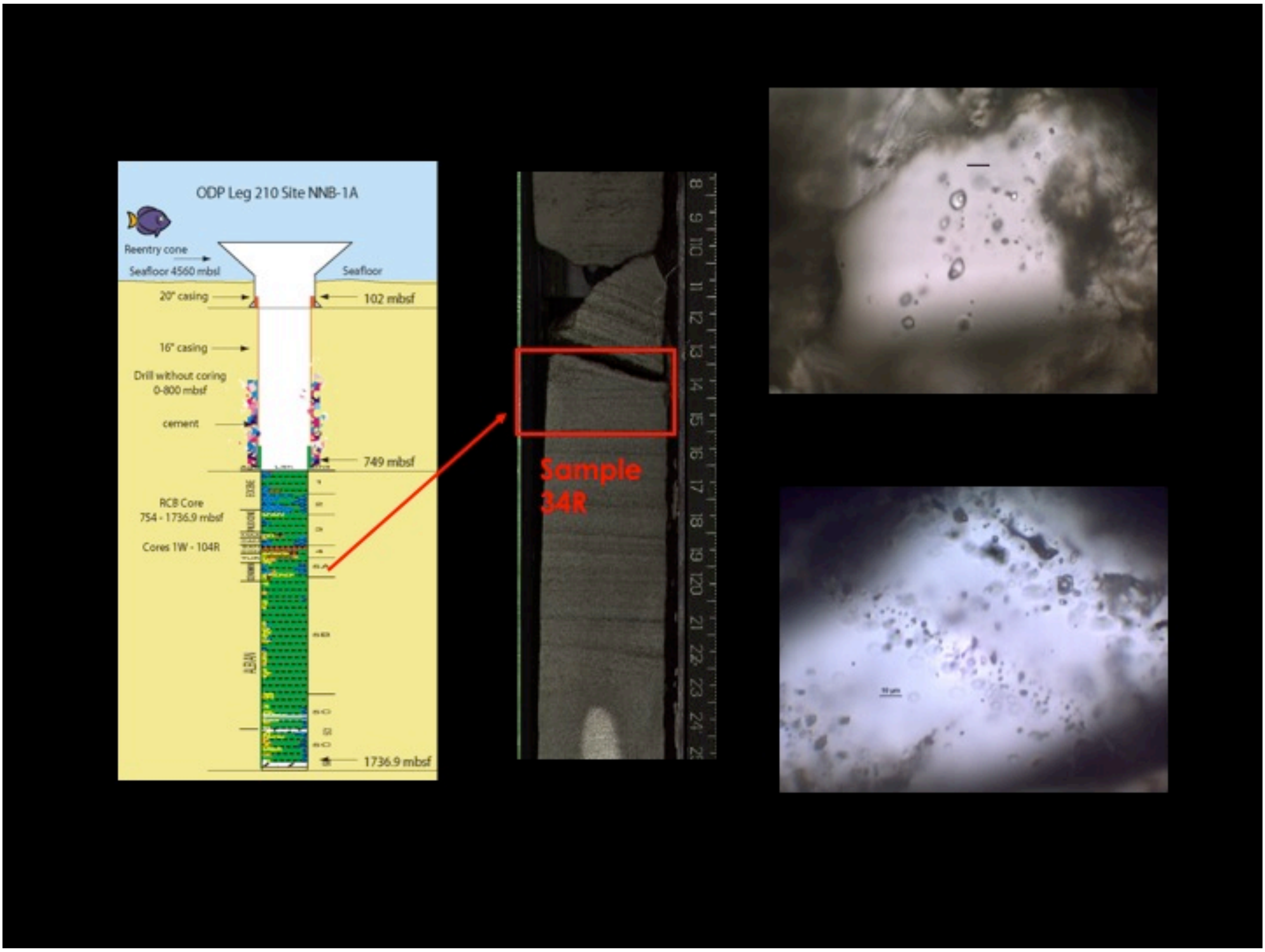
Euhedral molybdenite crystal in Ackley City Granite, Newfoundland. Pen length = 14 cm



-80 -70 -60 -50 -40 -30 -20 -10 0
60 50 40 30
Eastern
Margin of
Rockall
Basin
Basin
Newfoundland
Basin
ODP LEG 210
-6000 -5000 -4000 -3000 -2000 -1000 0 1000
Topography/bathymetry (meters)



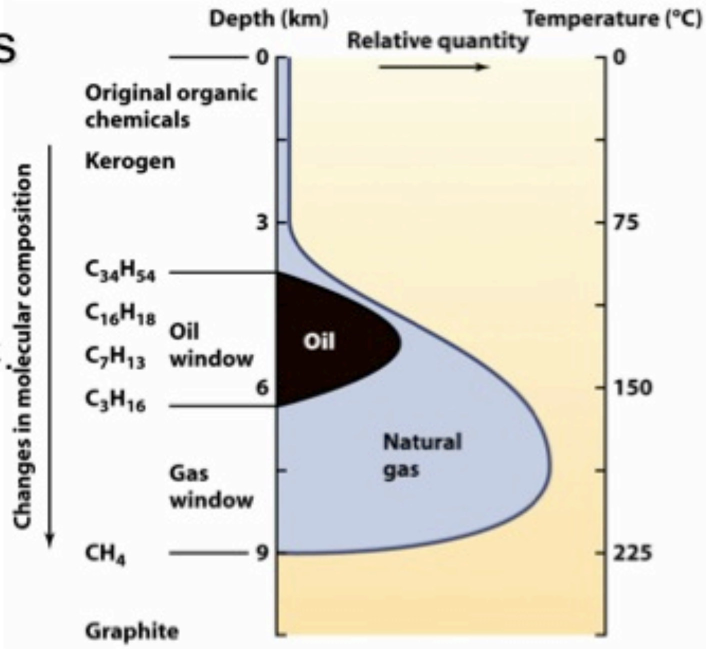
ODP Leg 210 Site NNB-1A
Reentry cone
Seafloor 4560 mbsl
Seafloor
20" casing
102 mbsf
16" casing
Drill without coring
0-800 mbsf
cement
749 mbsf
RCB Core
754 - 1736.9 mbsf
Cores 1W - 104R
ALBIAN
1736.9 mbsf
Sample
30R
10 µm
10 µm

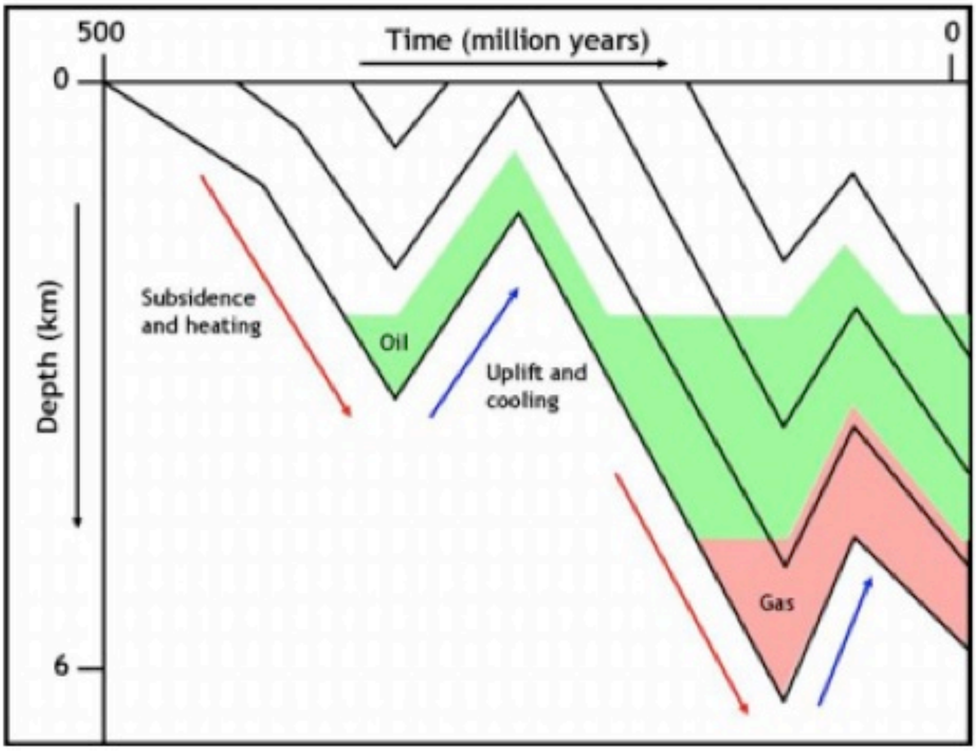


ODP Leg 210 Site NNB-1A
Reentry cone
Seafloor 4560 mbsl
Seafloor
20" casing
102 mbsf
16" casing
Drill without coring
0-800 mbsf
cement
749 mbsf
RCB Core
754 - 1736.9 mbsf
Cores 1W - 104R
1736.9 mbsf
Sample
34R

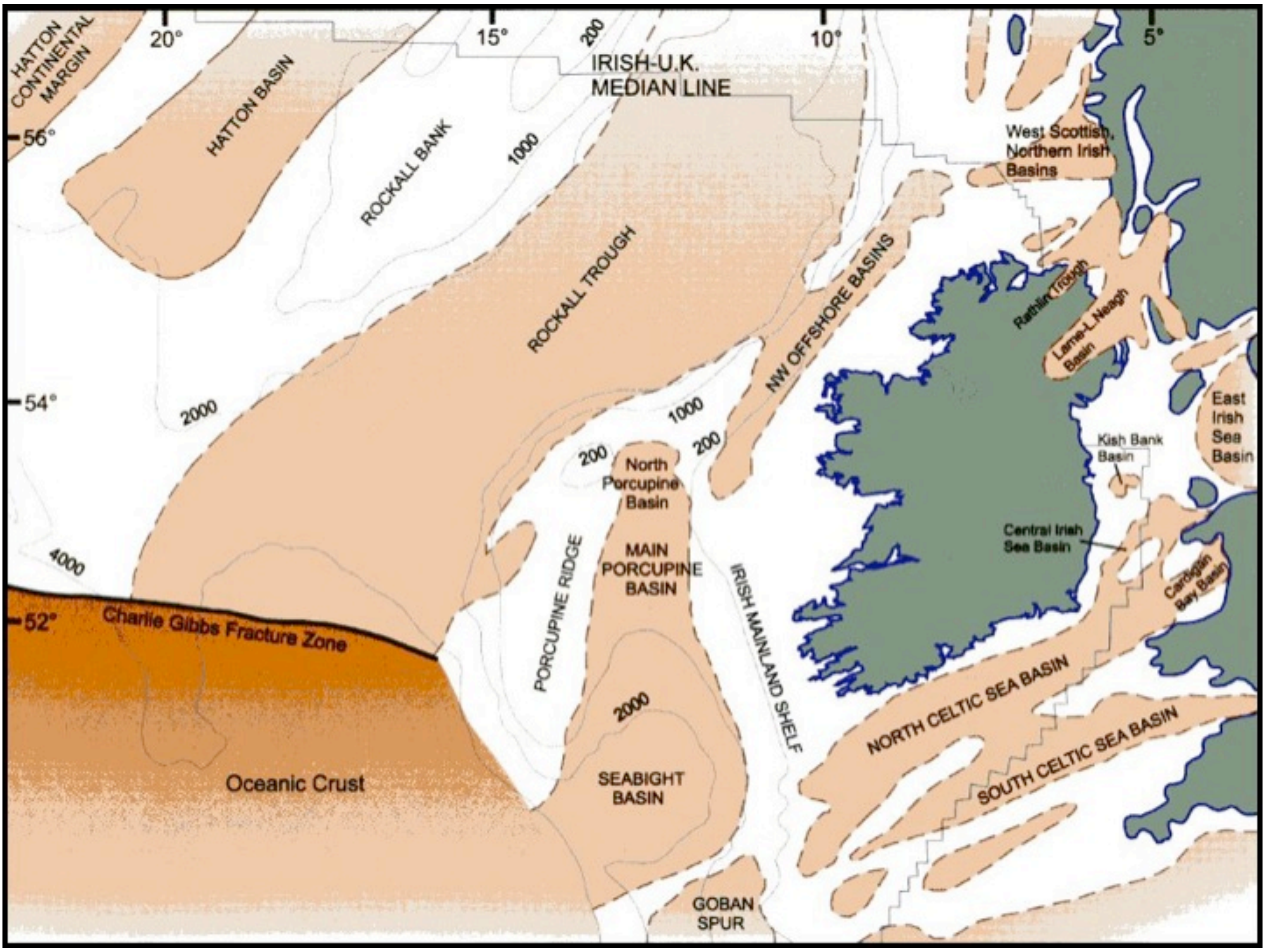
Oil and Gas Genesis

- Burial to depths of 2 to 4 km heats the black shale.
  - Heating breaks the organics down into waxy kerogen.
  - Kerogen-rich source rocks are called oil shales.
- Continued heating breaks down kerogen.
- Oil and gas form in specific T ranges.
  - Oil and gas – 90° to 160°C.
  - Gas only – 160° to 250°C.
  - Graphite – >250°C.

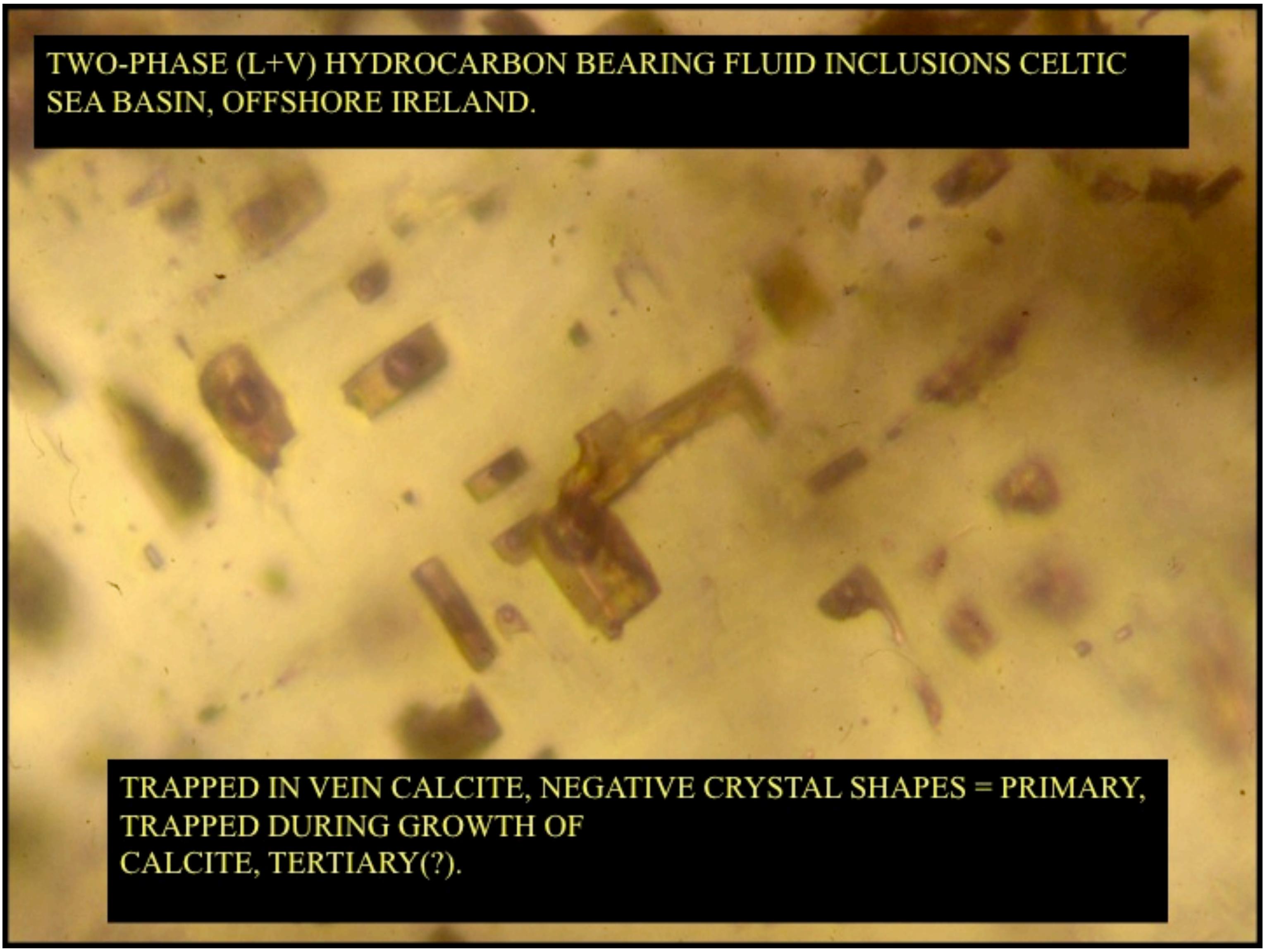




Example of cross-plot used for describing the burial of sediments through time. The subsidence curves describe the burial history of the sediments. The figure indicates when they are within the oil/gas window. If organic rich sediments are uplifted, they also cool, and stop generating hydrocarbons until the are reburied.

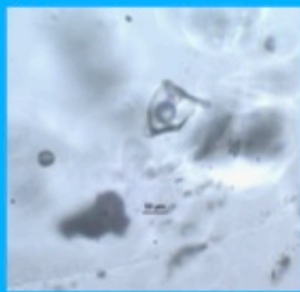


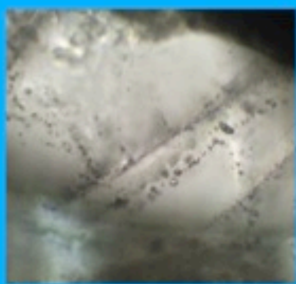
HATTON CONTINENTAL MARGIN
20°
15°
200
10°
5°
IRISH-U.K. MEDIAN LINE
56°
HATTON BASIN
ROCKALL BANK
1000
West Scottish, Northern Irish Basins
ROCKALL TROUGH
NW OFFSHORE BASINS
Rathlin Trough
Larne-L.Neagh Basin
54°
2000
1000
200
200
East Irish Sea Basin
Kish Bank Basin
North Porcupine Basin
MAIN PORCUPINE BASIN
PORCUPINE RIDGE
IRISH MAINLAND SHELF
Central Irish Sea Basin
Cardigan Bay Basin
4000
52°
Charlie Gibbs Fracture Zone
NORTH CELTIC SEA BASIN
SOUTH CELTIC SEA BASIN
2000
Oceanic Crust
SEABIGHT BASIN
GOBAN SPUR

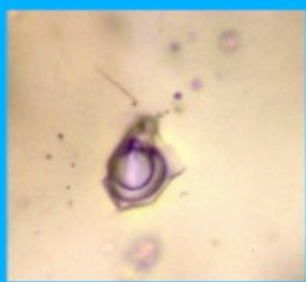

TWO-PHASE (L+V) HYDROCARBON BEARING FLUID INCLUSIONS CELTIC SEA BASIN, OFFSHORE IRELAND.
TRAPPED IN VEIN CALCITE, NEGATIVE CRYSTAL SHAPES = PRIMARY, TRAPPED DURING GROWTH OF CALCITE, TERTIARY(?).

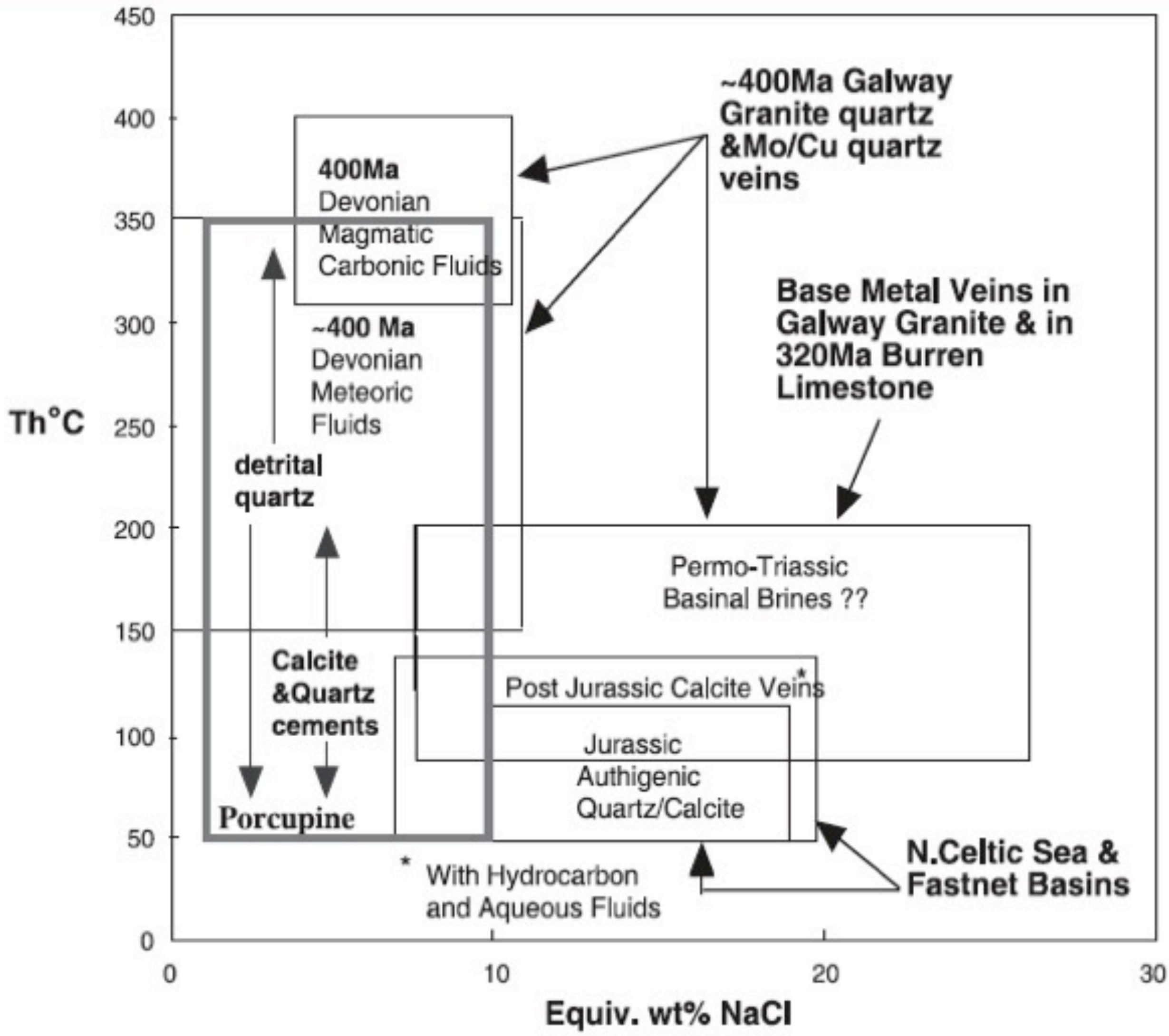
Geofluid Research Group

Fluid Inclusion microthermometry







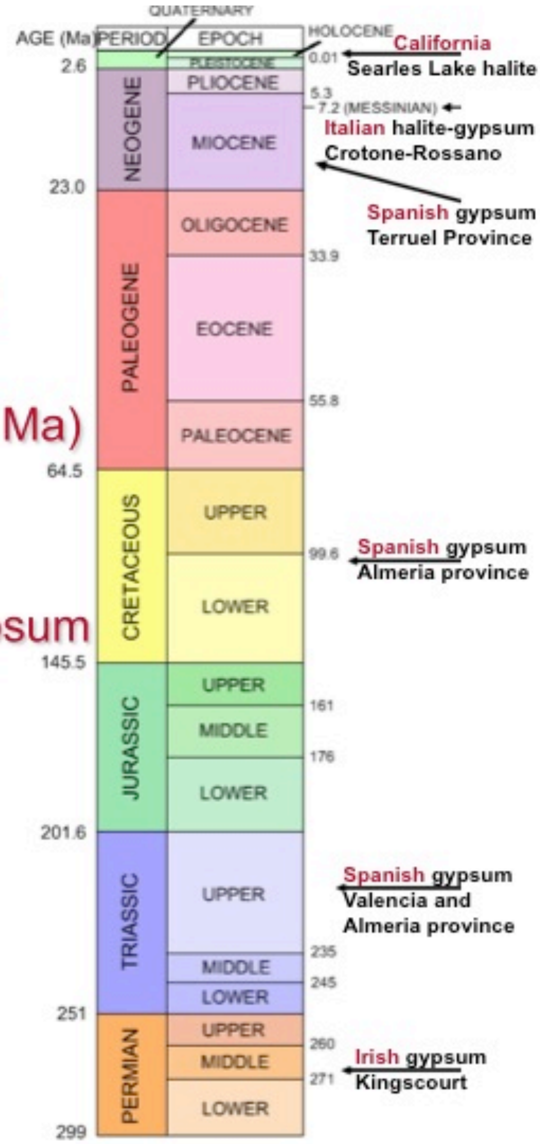


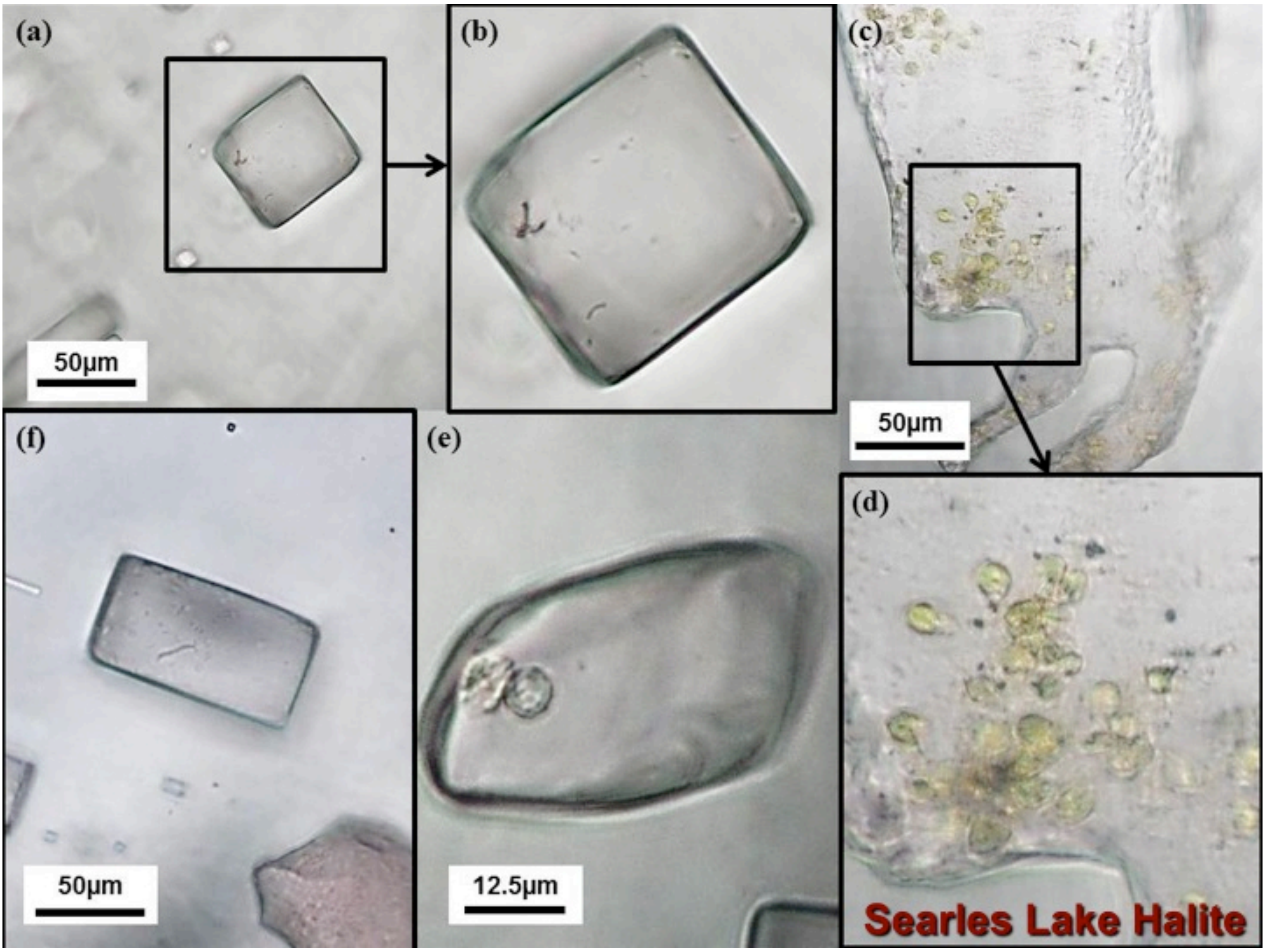
~400Ma Galway Granite quartz &Mo/Cu quartz veins
400Ma Devonian Magmatic Carbonic Fluids
~400 Ma Devonian Meteoric Fluids
Base Metal Veins in Galway Granite & in 320Ma Burren Limestone
detrital quartz
Permo-Triassic Basinal Brines ??
Calcite &Quartz cements
Post Jurassic Calcite Veins*
Jurassic Authigenic Quartz/Calcite
Porcupine
N.Celtic Sea & Fastnet Basins
* With Hydrocarbon and Aqueous Fluids
Th°C
Equiv. wt% NaCl


0.5 cm
100 µm
50 µm
Searles Lake
Halite
Samples

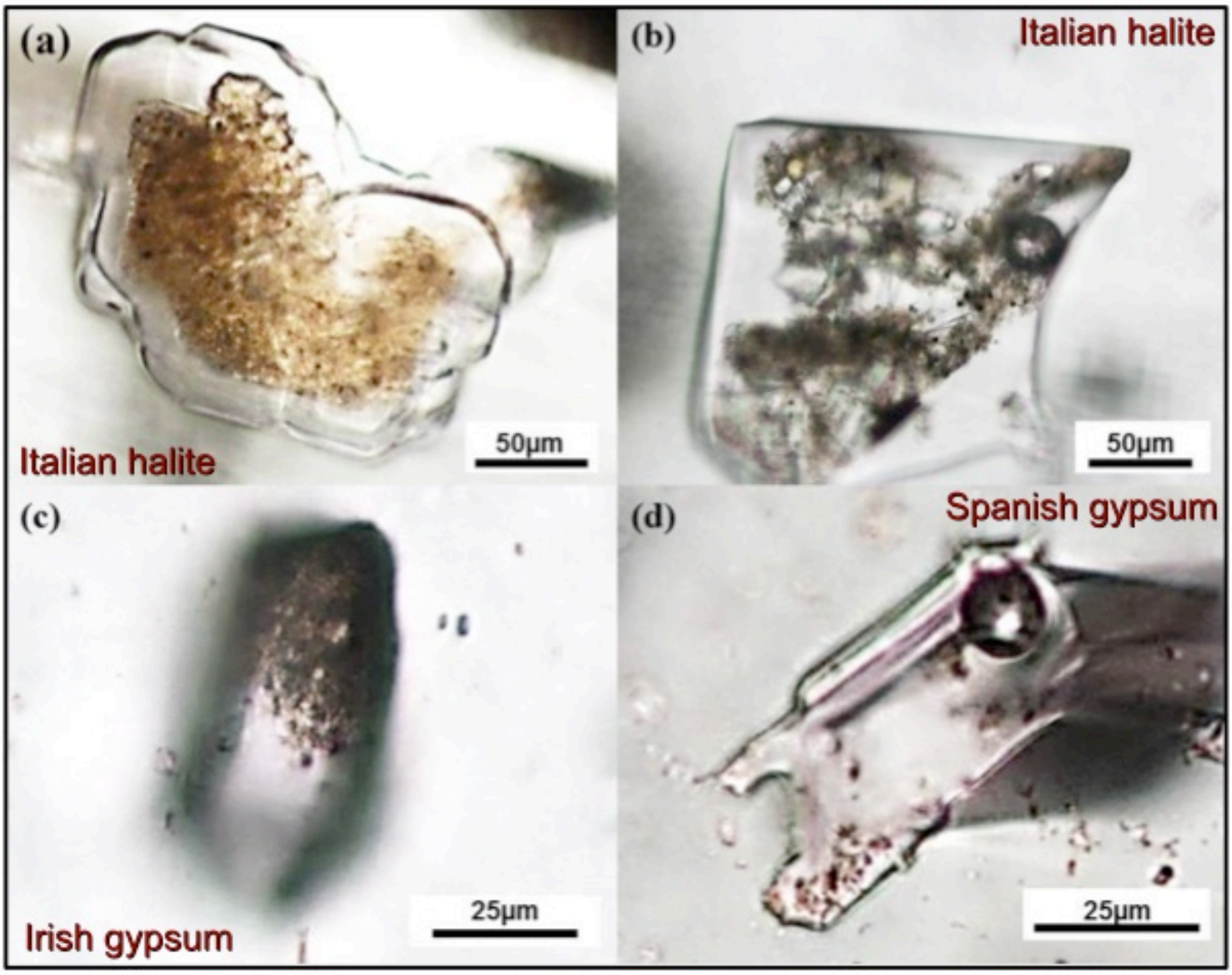
Sample Collection

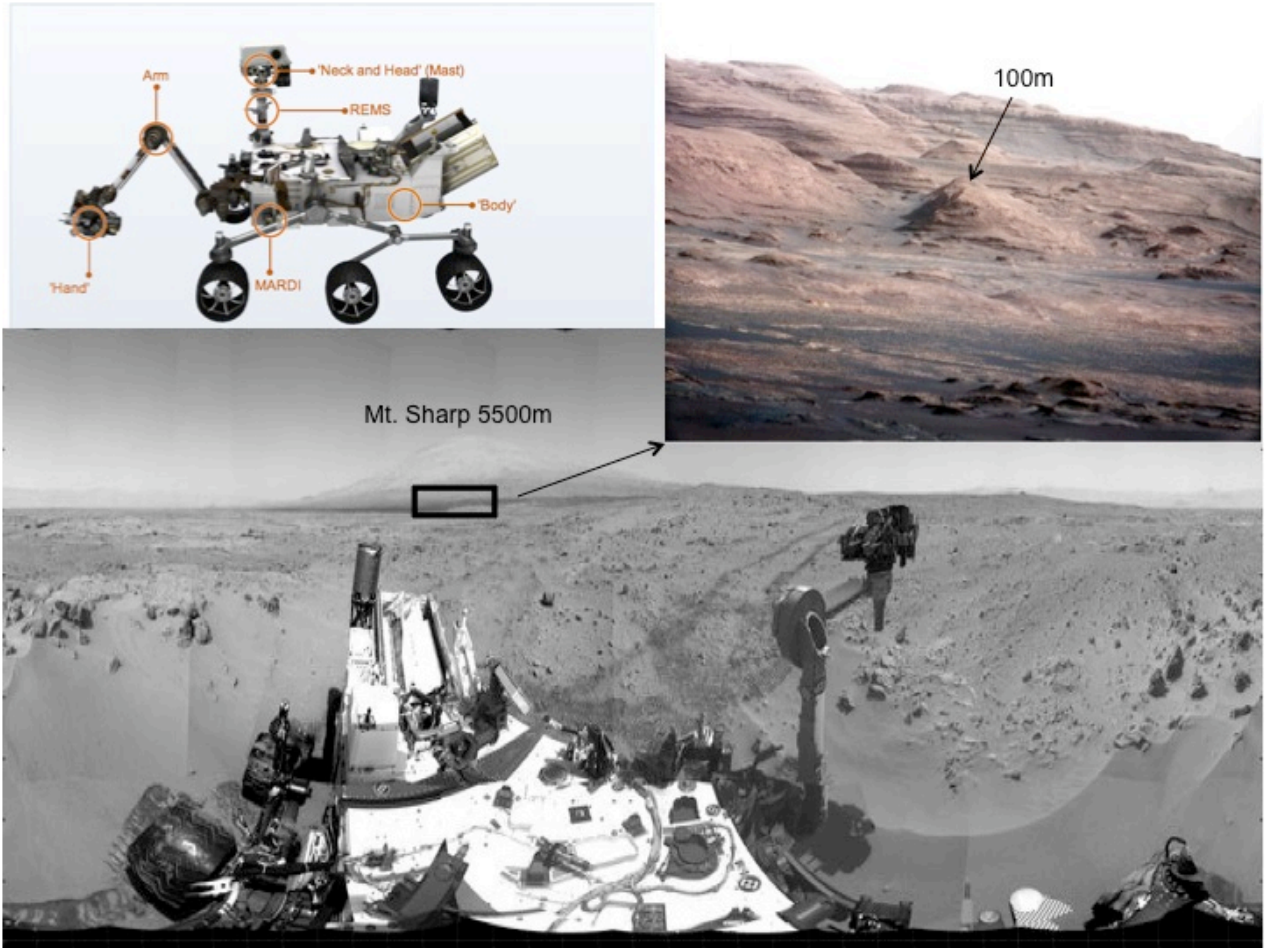
➤ <u>Recent USA halite samples (up to 150ka)</u>
  – Searles Lake, Death Valley, California
- Messinian Italian halite and gypsum (~5-7 Ma)
  – Halite from the Crotone basin
  – Gypsum from the Rossano basin
- Miocene-Cretaceous-Triassic Spanish gypsum
  – Valencia province
  – Terruel province
  – Almeria province
- Permian Irish gypsum
  – Kingscourt Co.Cavan




(a)
50μm
(b)
(c)
50μm
(d)
Searles Lake Halite
(f)
50μm
(e)
12.5μm

Fluid Inclusion Petrography




Arm
'Neck and Head' (Mast)
REMS
'Body'
'Hand'
MARDI
100m
Mt. Sharp 5500m

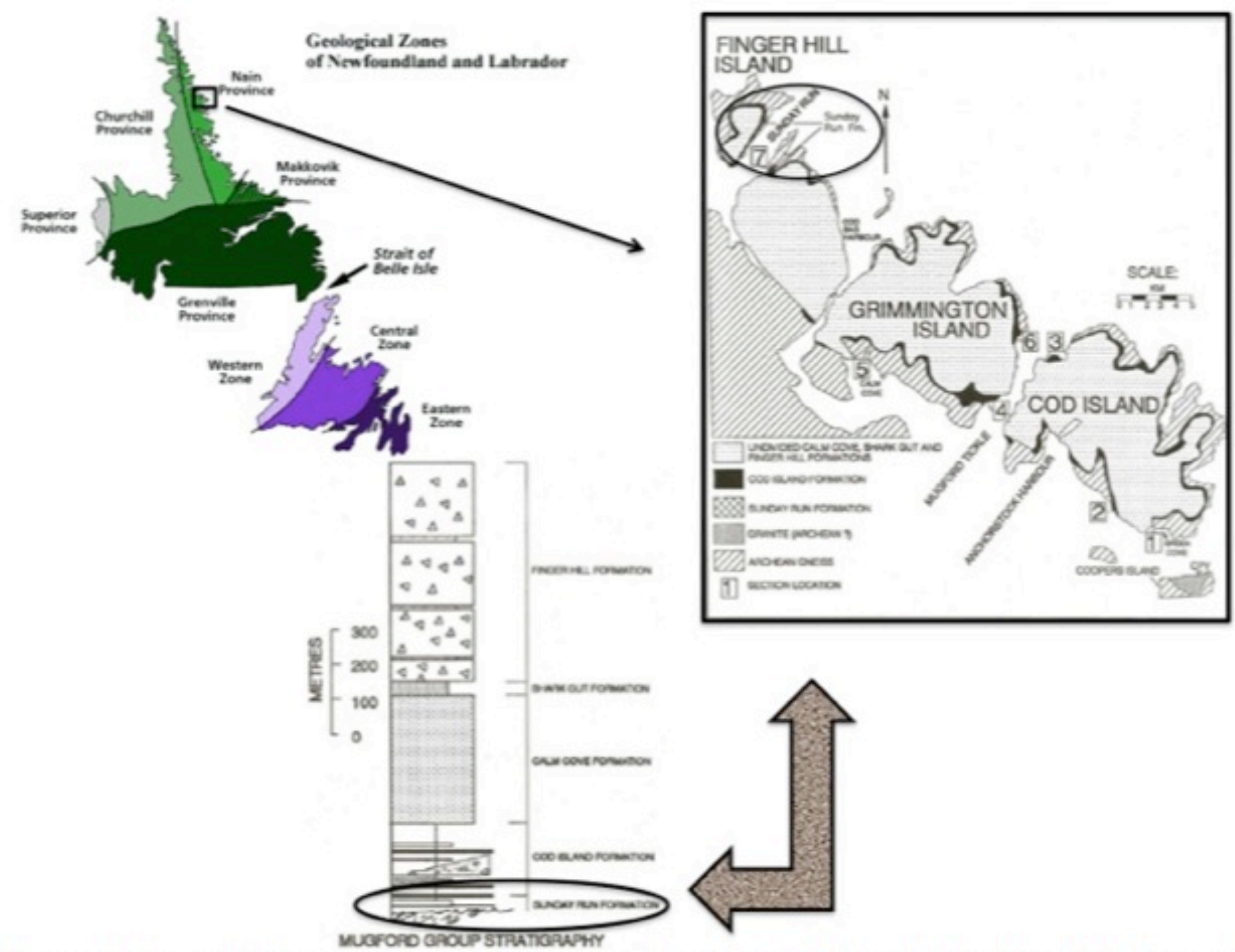


Figure 1. Composite diagram showing the location of the Mugford Group in Northern Labrador and the stratigraphic setting of the Sunday Run Formation.

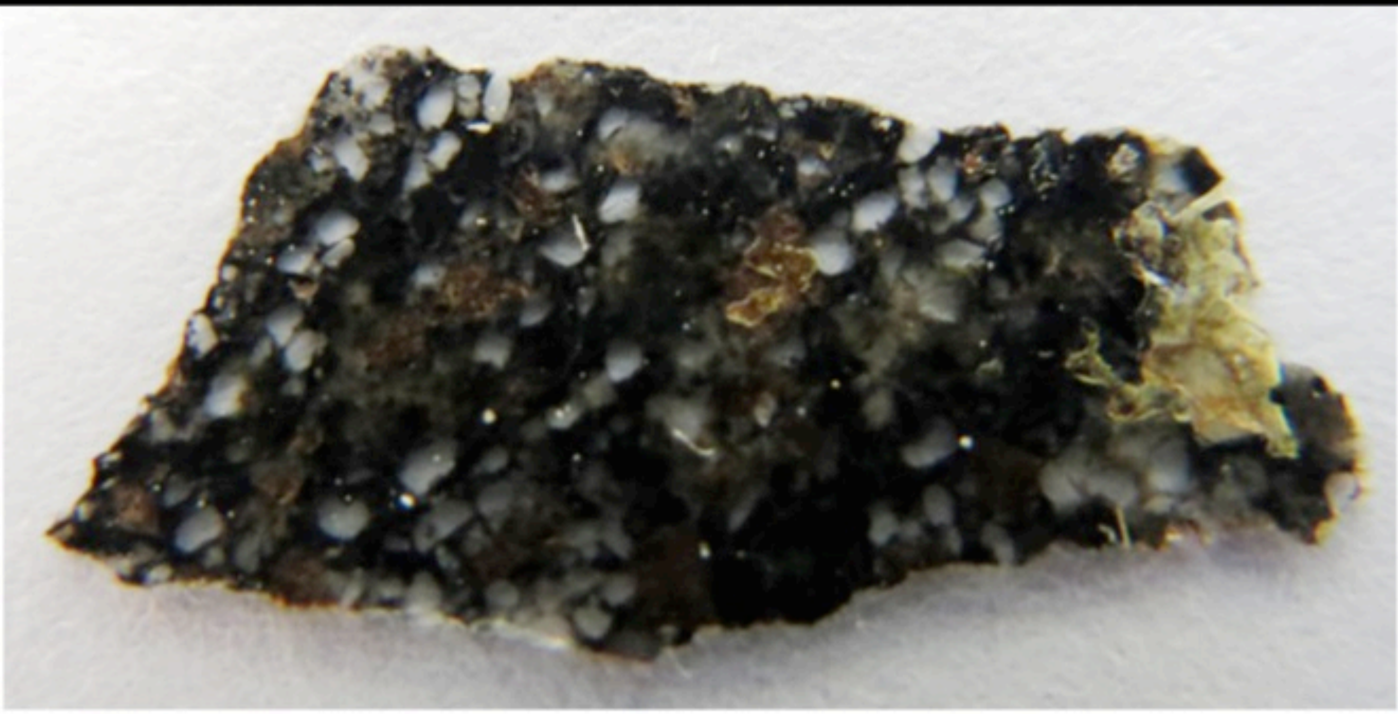
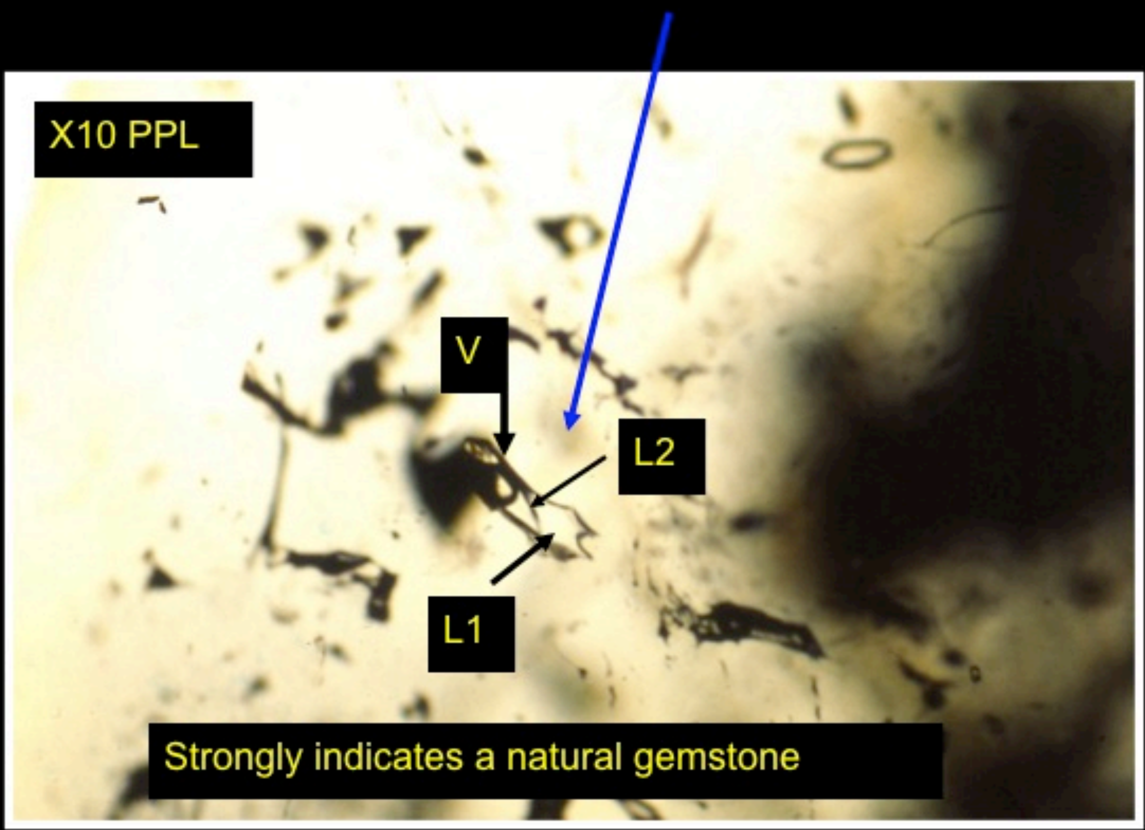


Figure 1. Sunday Run Formation sample showing quartz pebbles. This is a specially prepared fluid inclusion wafer. Pebbles are <5mm across and contain an abundance of fluid inclusions (FI) containing fluids that are at least 2 billion years old. These FI are the focus of this study.

Three-phase inclusions in Tourmaline-(Trichites)

Two liquids and a gas phase occupy the cavity

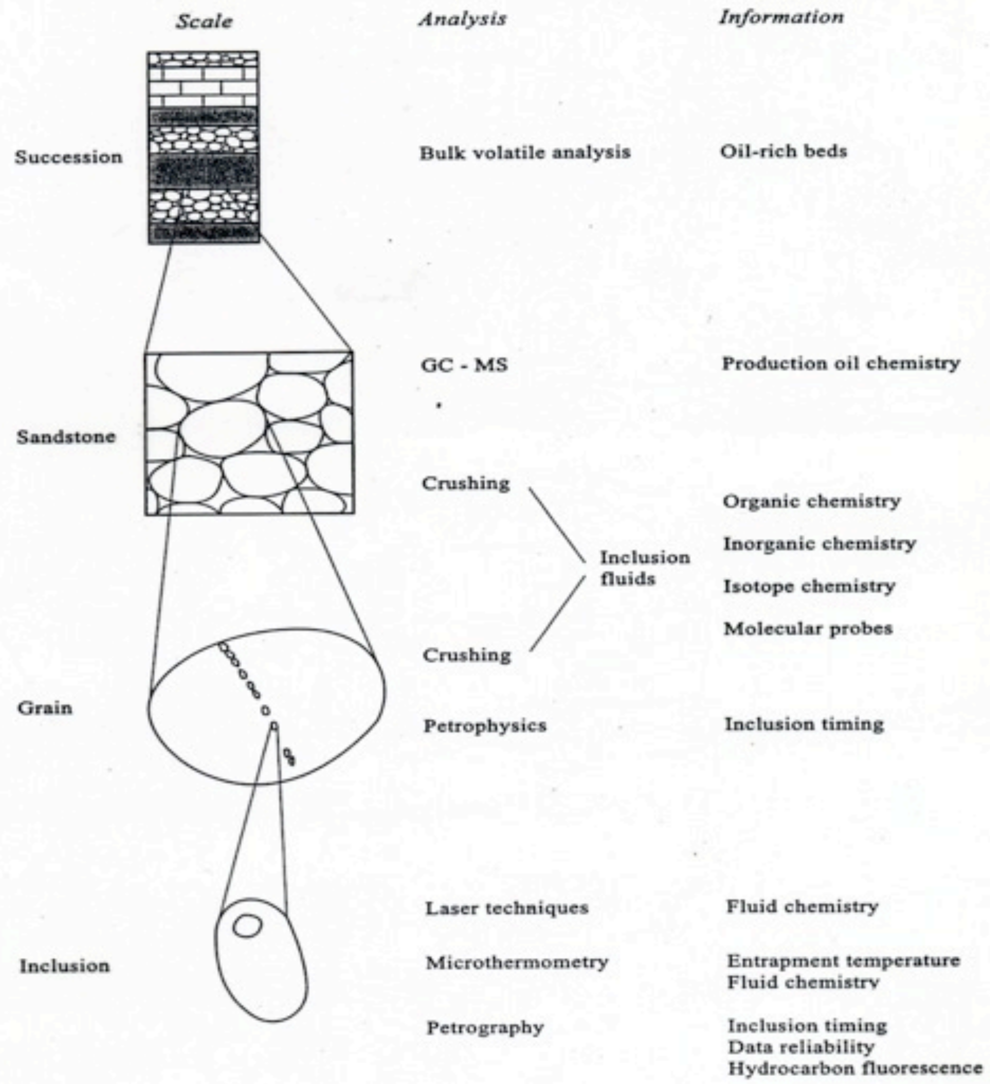


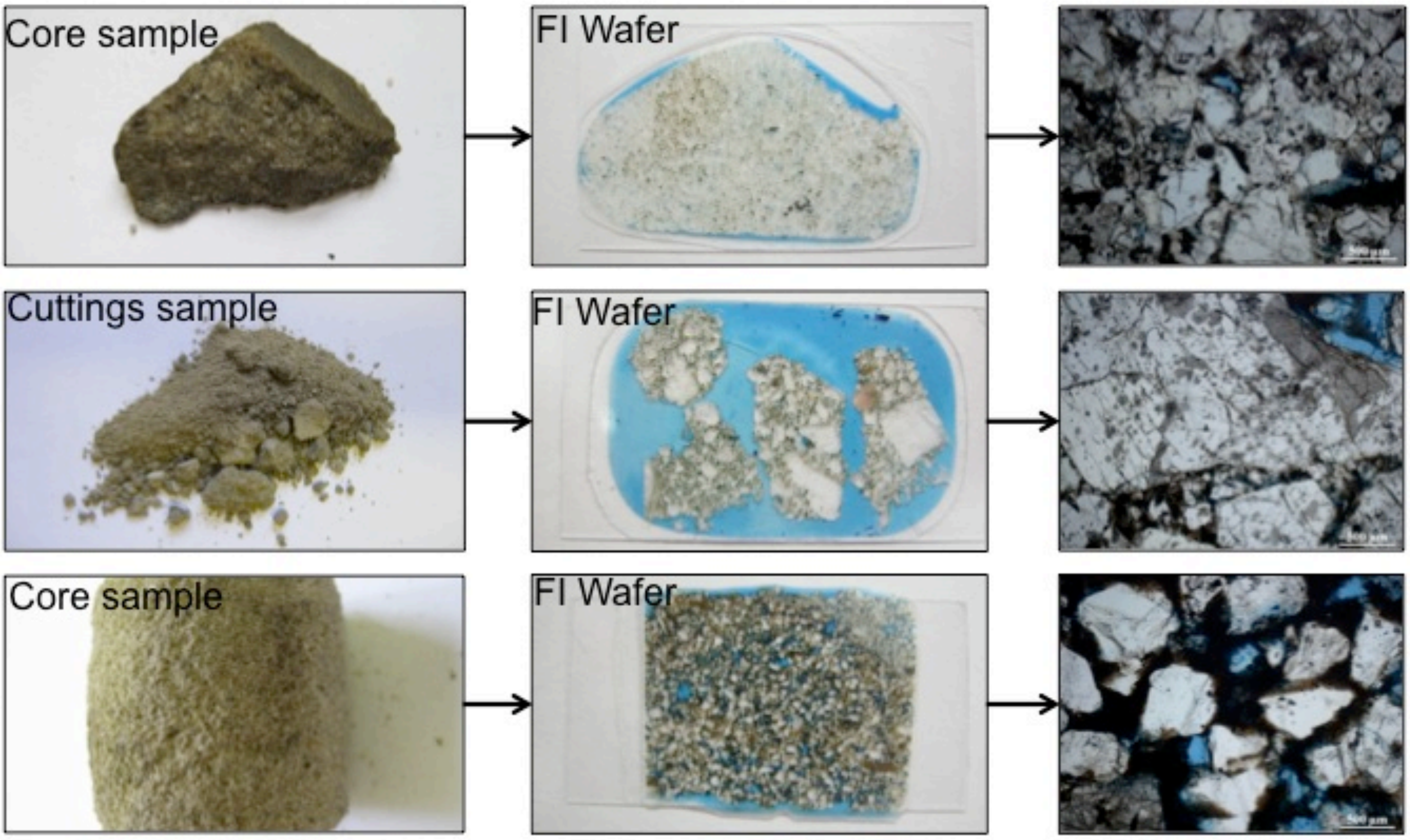
Application of Fluid Inclusion Studies to Oil and Gas Exploration

LECTURE 2:

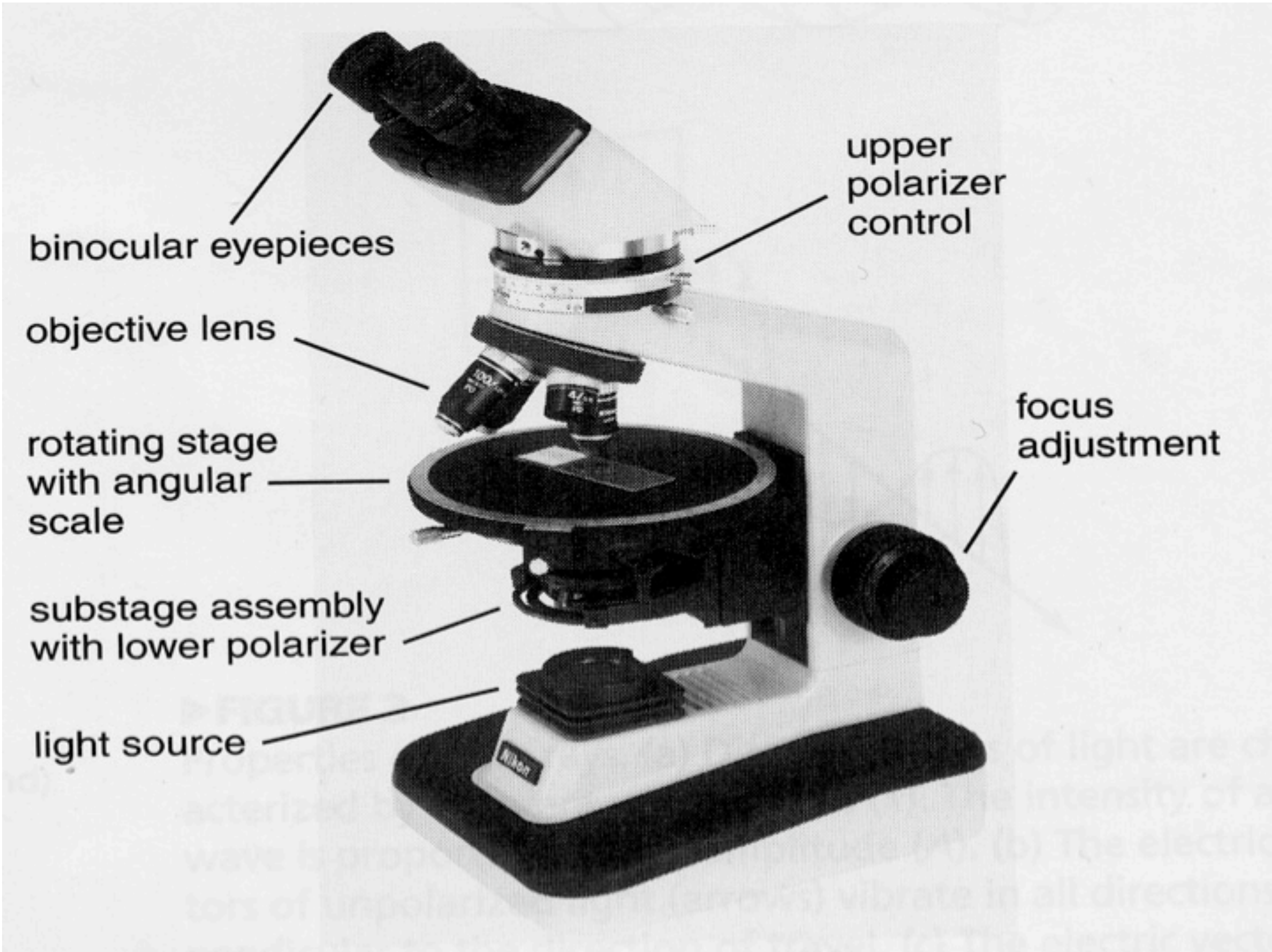
SAMPLING AND PETROGRAPHY

FLUID INCLUSIONS – OFFSHORE ANGOLA, PRE-SALT



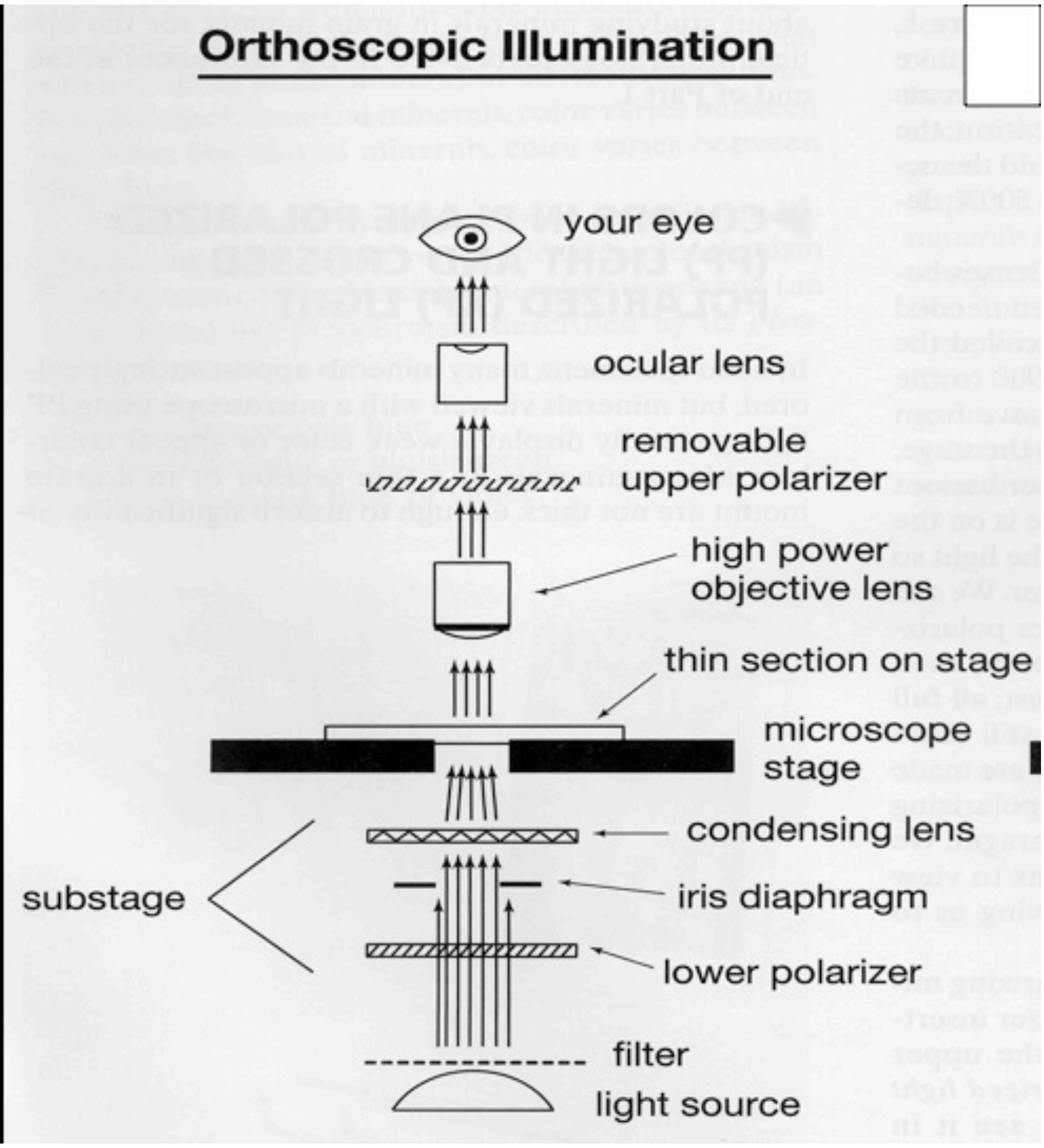


1st column ~5 cm in longest dimension, 2nd column the fluid inclusion wafers are 4 x 2.2 cm and 3rd column photomicrographs taken under x40 magnification.


binocular eyepieces
upper
polarizer
control
objective lens
focus
adjustment
rotating stage
with angular
scale
substage assembly
with lower polarizer
light source
Nikon

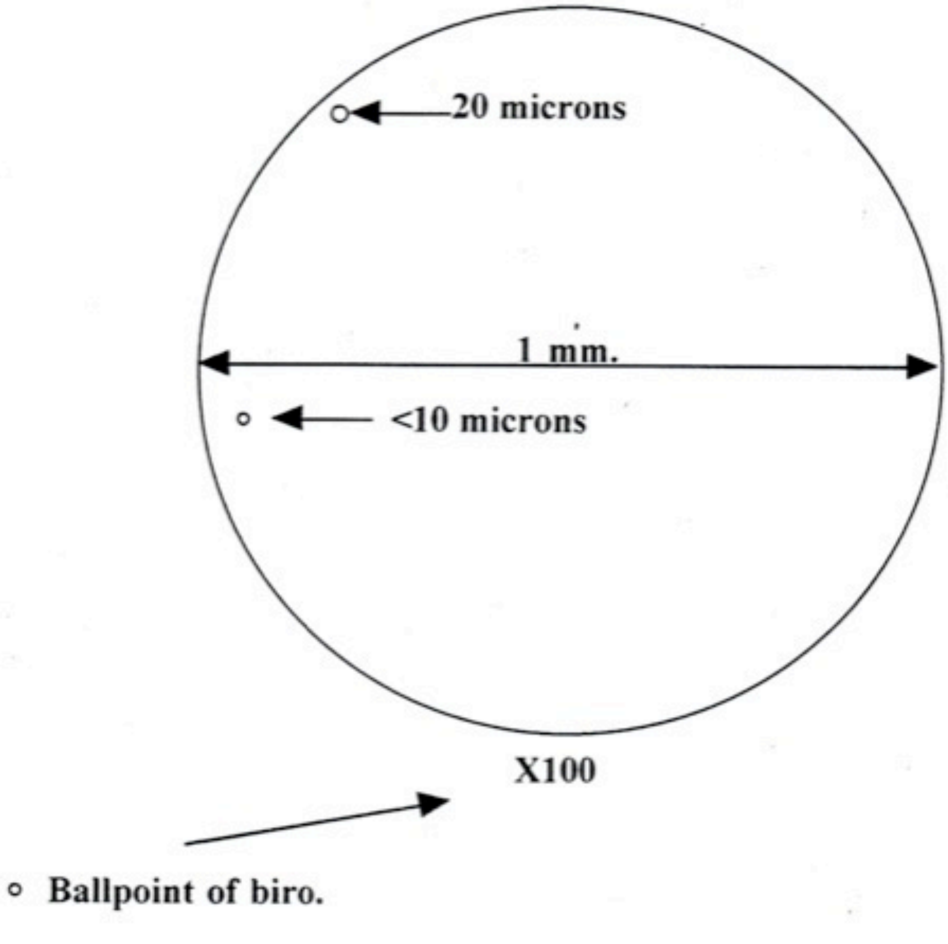
LIGHT PATH
THROUGH
THE MICROSCOPE

FOR FLUID INCLUSION
PETROGRAPHY
SUBSTAGE
CONDENSING LENS
MUST BE IN PLACE
JUST BELOW THE THIN
SECTION/WAFER

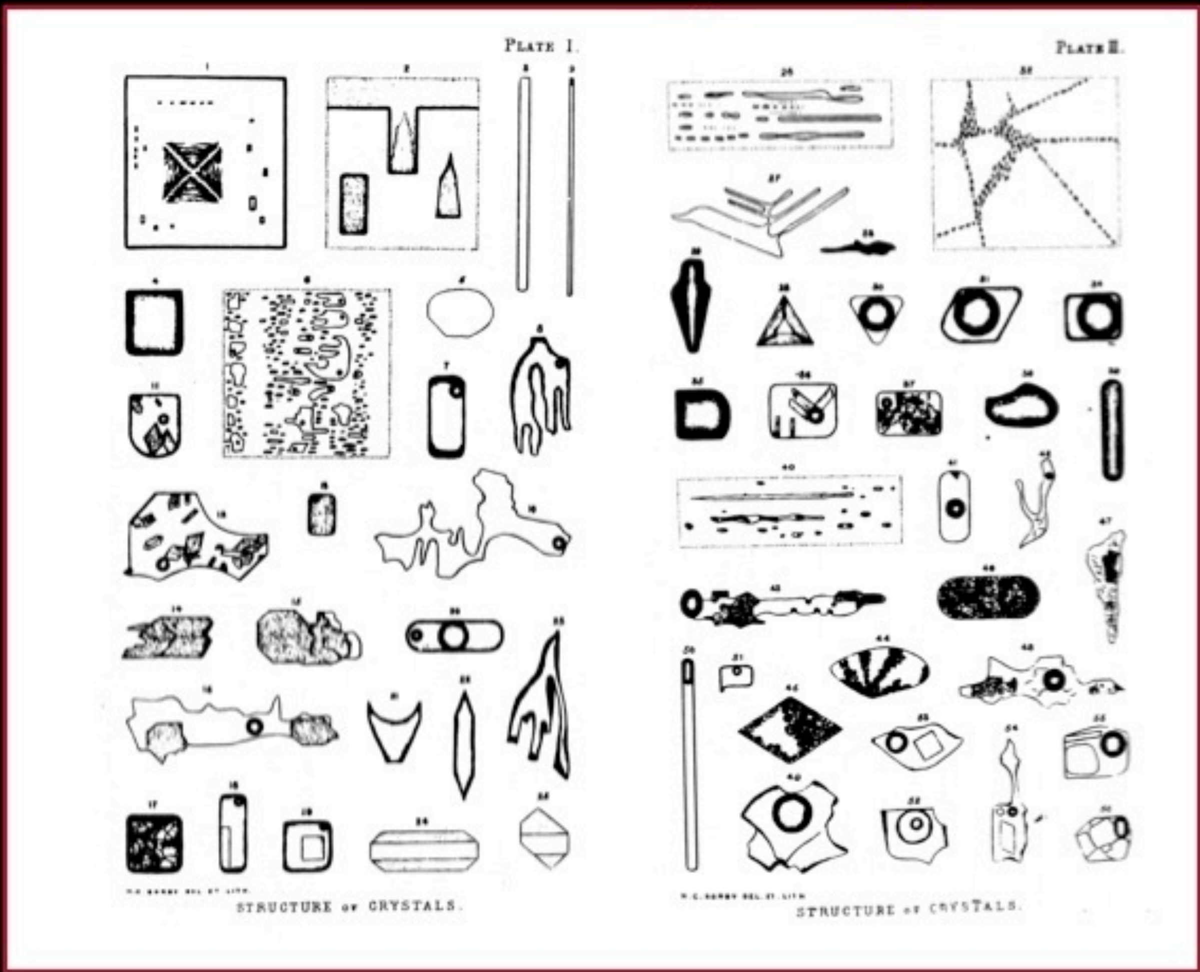


1 micron (μm) = 0.001mm

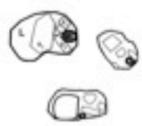
20 microns = 0.02mm

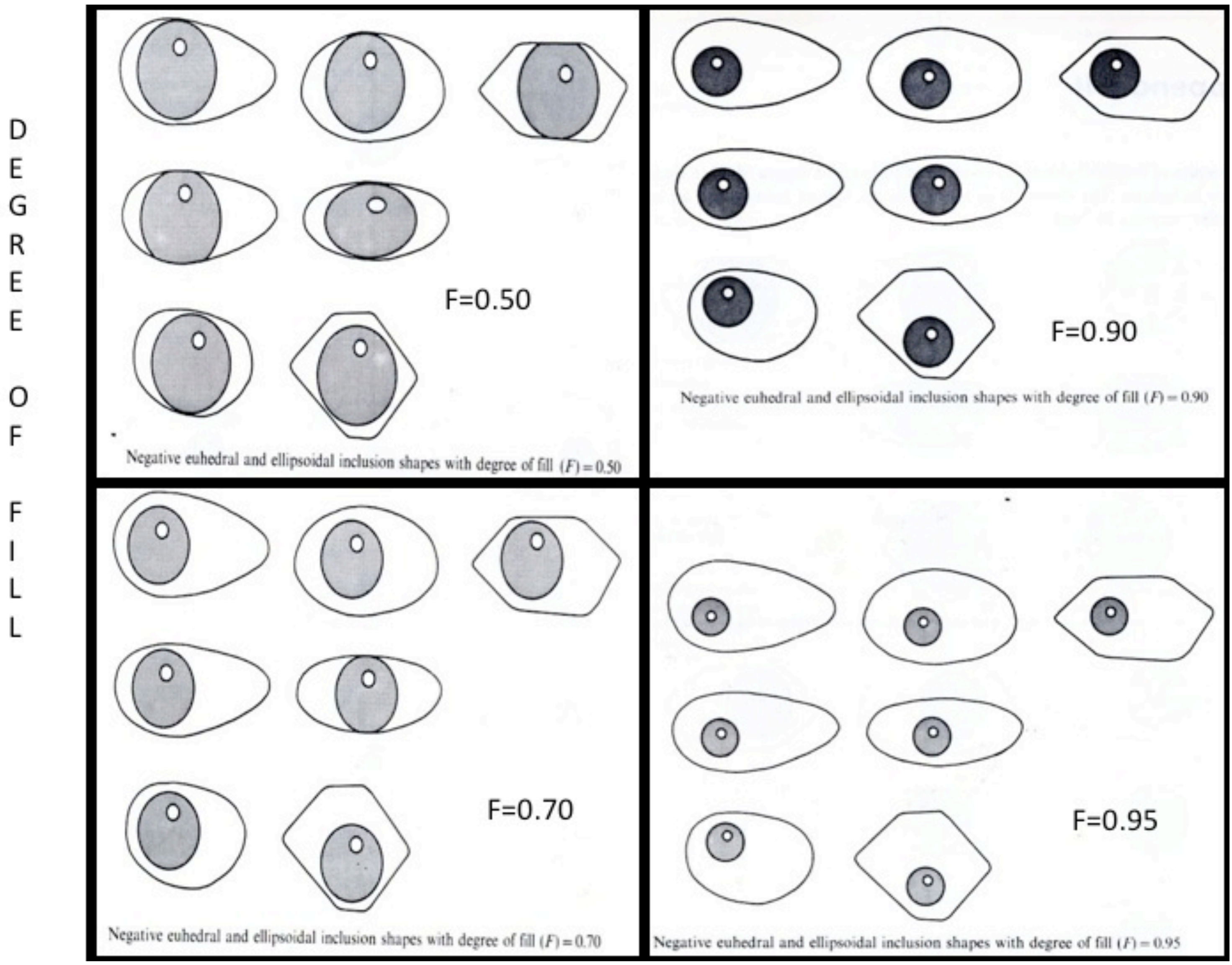


Inclusion morphologies



Compositional Classification

INCLUSION TYPE	ESSENTIAL PHASES	TYPICAL EXAMPLES	INCLUSION TYPE	ESSENTIAL PHASES	TYPICAL EXAMPLES
Monophase liquid	L = 100%		Multiphase solid	S < 50%	
Liquid-rich two-phase	L > 50%		Multisolid	S > 50%	
Vapour-rich two-phase	V = 50 to 80%		Immiscibile liquid	L_1, L_2	
Monophase vapour	V ≅ 100%		Glass	GL > 50%	not shown



DEGREE OF FILL
F=0.50
Negative euhedral and ellipsoidal inclusion shapes with degree of fill (F) = 0.50
F=0.90
Negative euhedral and ellipsoidal inclusion shapes with degree of fill (F) = 0.90
F=0.70
Negative euhedral and ellipsoidal inclusion shapes with degree of fill (F) = 0.70
F=0.95
Negative euhedral and ellipsoidal inclusion shapes with degree of fill (F) = 0.95

Genetic Classification

Primary origin

1. Inclusions are parallel to growth zones or crystal faces.
2. Inclusions occur in a three-dimensional random distribution.
3. Inclusions are isolated, occurring at distances > 5 x inclusion diameter away from adjacent inclusions.
4. Large size relative to host crystal.

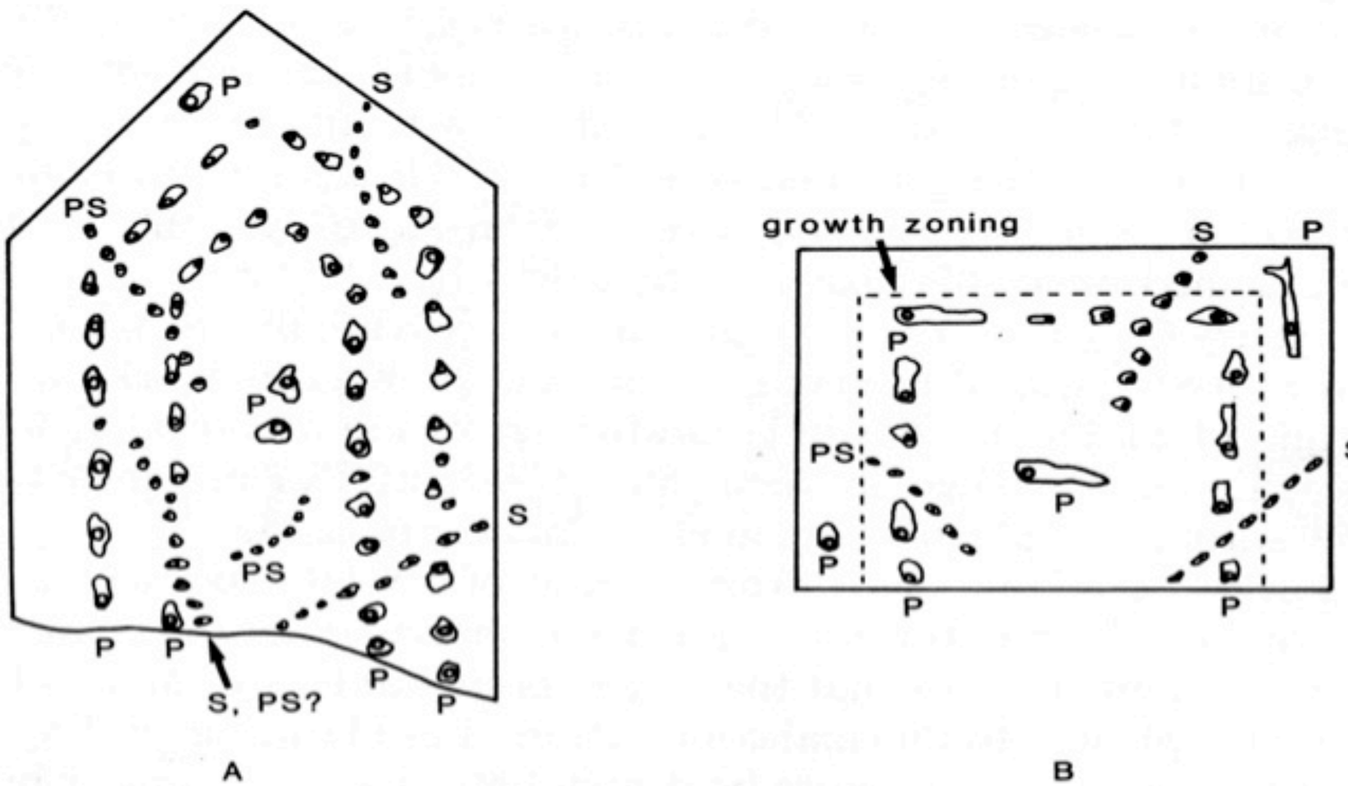
Criteria for Secondary origin

1. Occurrence as planar groups, outlining healed fractures.
2. Thin, flat, or irregular shape.

Criteria for Pseudosecondary origin

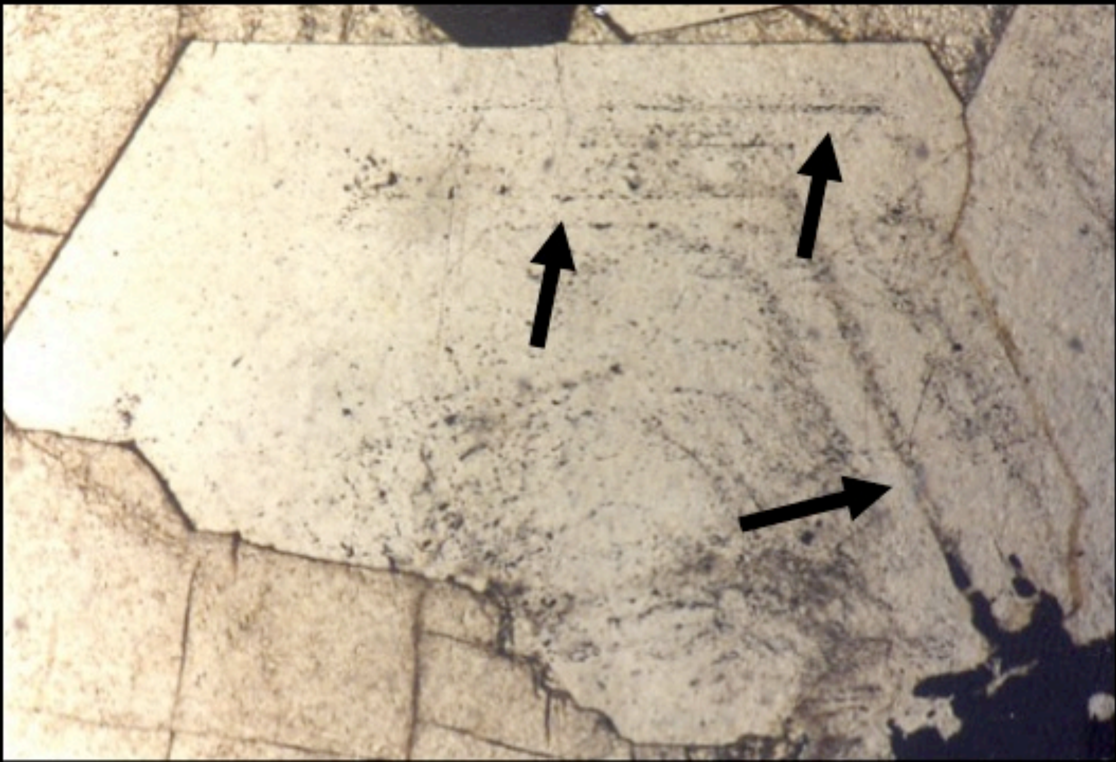
Occurrence as for secondary inclusions, but with the fracture terminating inside the body of the crystal.

Genetic Classification

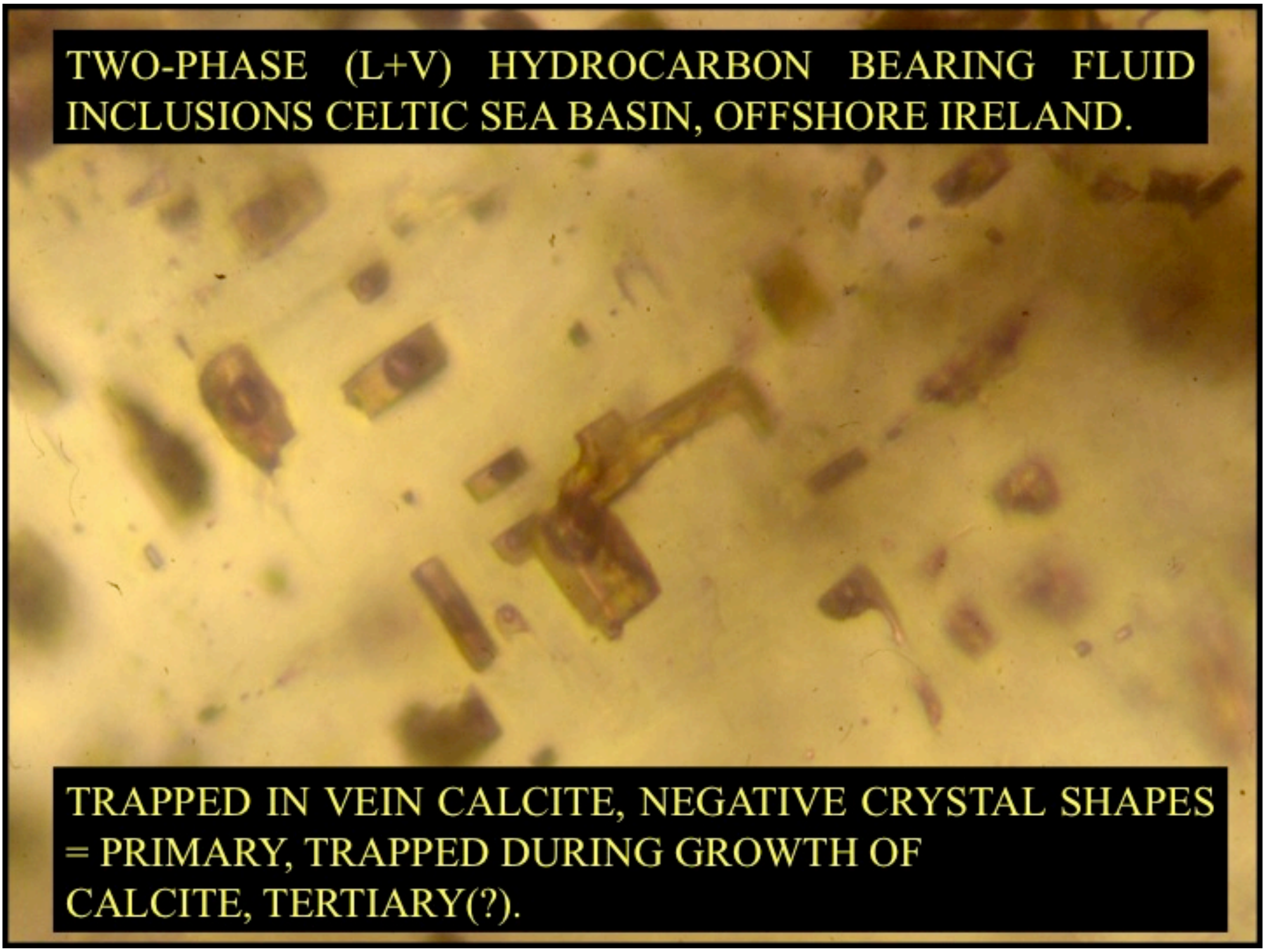


Idealized distribution of P, S and PS fluid inclusions in quartz (A) and fluorite (B). (from Shepherd et al., 1985)

PRIMARY FLUID INCLUSIONS IN VEIN QUARTZ.




0.5 cm
100 µm
50 µm
Searles Lake
Halite
Samples


TWO-PHASE (L+V) HYDROCARBON BEARING FLUID INCLUSIONS CELTIC SEA BASIN, OFFSHORE IRELAND.
TRAPPED IN VEIN CALCITE, NEGATIVE CRYSTAL SHAPES = PRIMARY, TRAPPED DURING GROWTH OF CALCITE, TERTIARY(?).

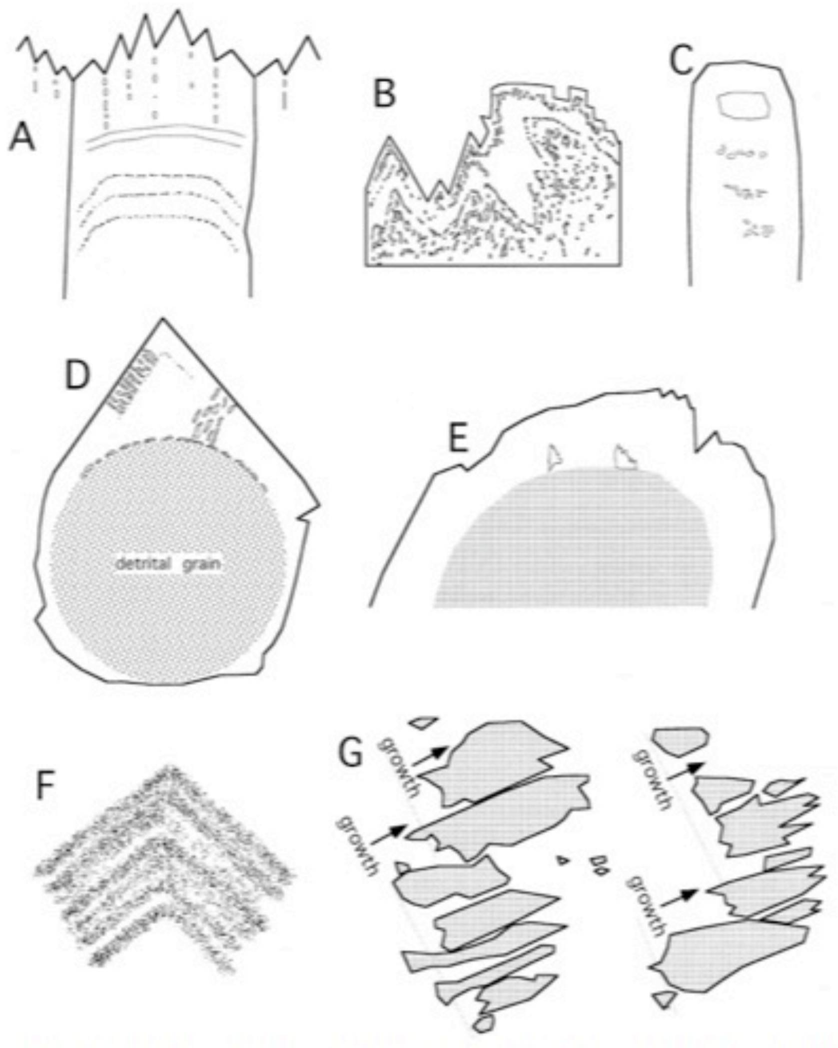
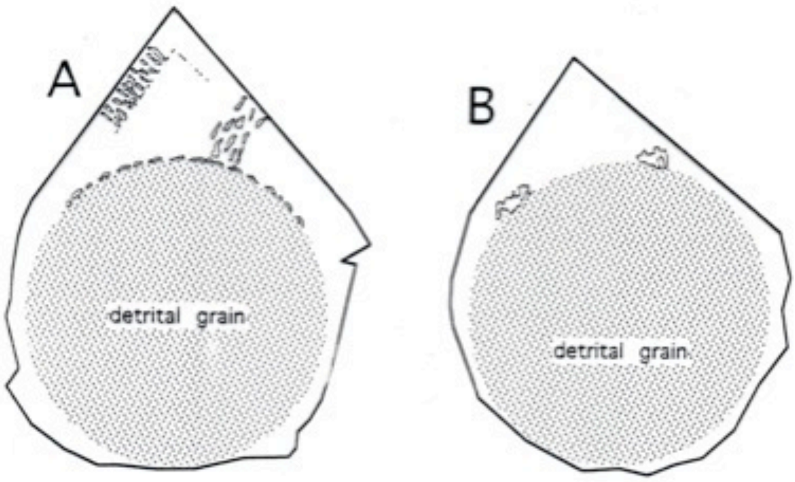
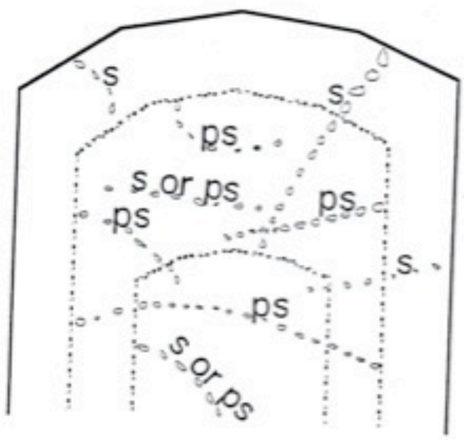


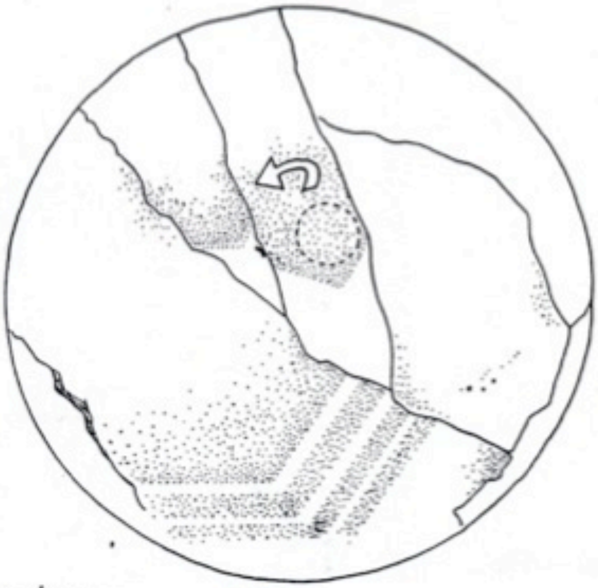
Fig. 8. Sketches of distribution of primary fluid inclusions in various minerals of the sedimentary realm (modified from Goldstein and Reynolds, 1994). (A) Calcite; (B) Dolomite; (C) Anhydrite; (D) Quartz overgrowth; (E) Feldspar overgrowth; (F) Chevron halite; (G) Gypsum (modified from Lowenstein, written communication).


A
B
detrital grain
detrital grain


s
s
ps
s or ps
ps
ps
s
ps
s or ps

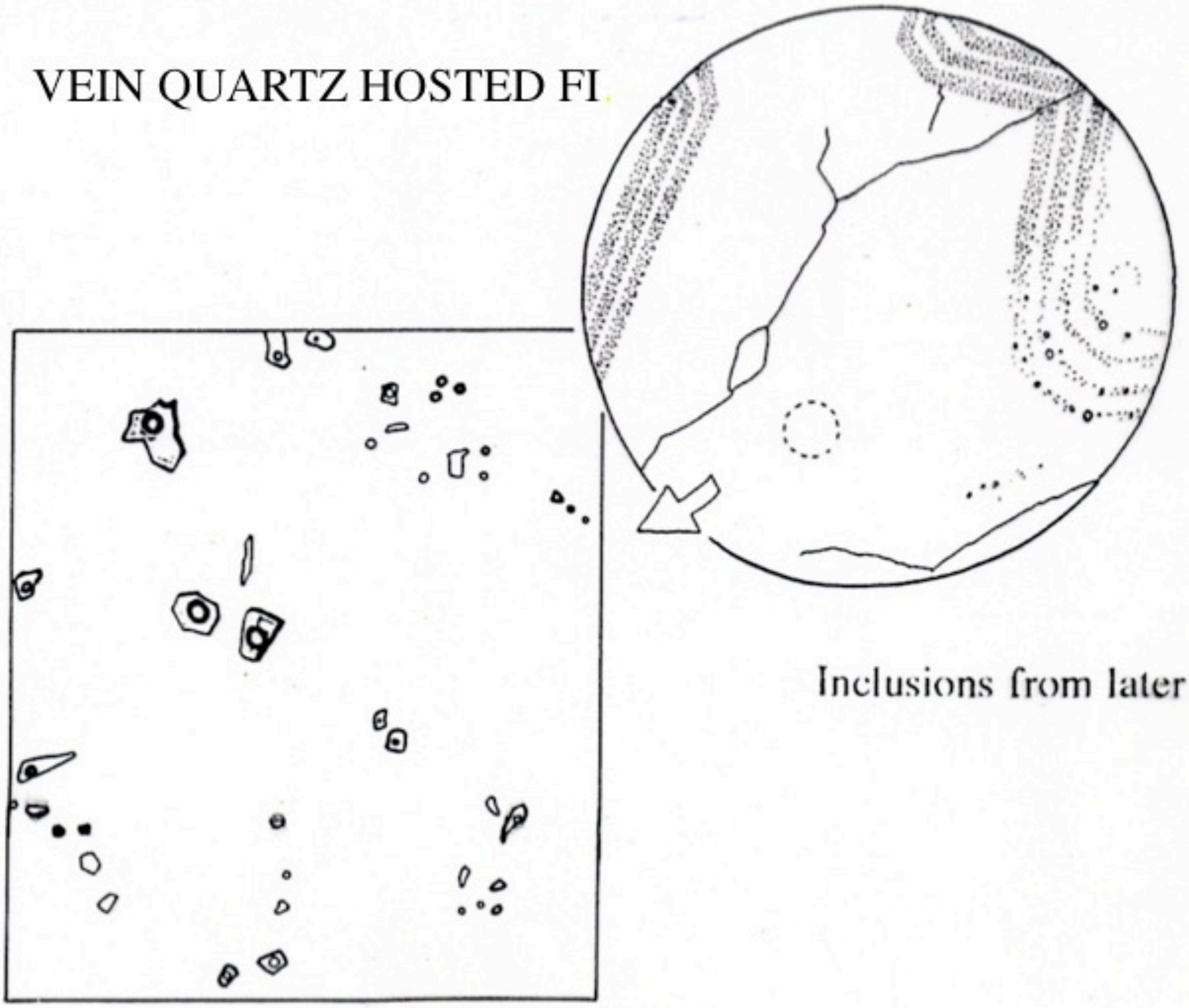
VEIN QUARTZ HOSTED FLUID INCLUSIONS

Thin-section of vein quartz from Glenmalure

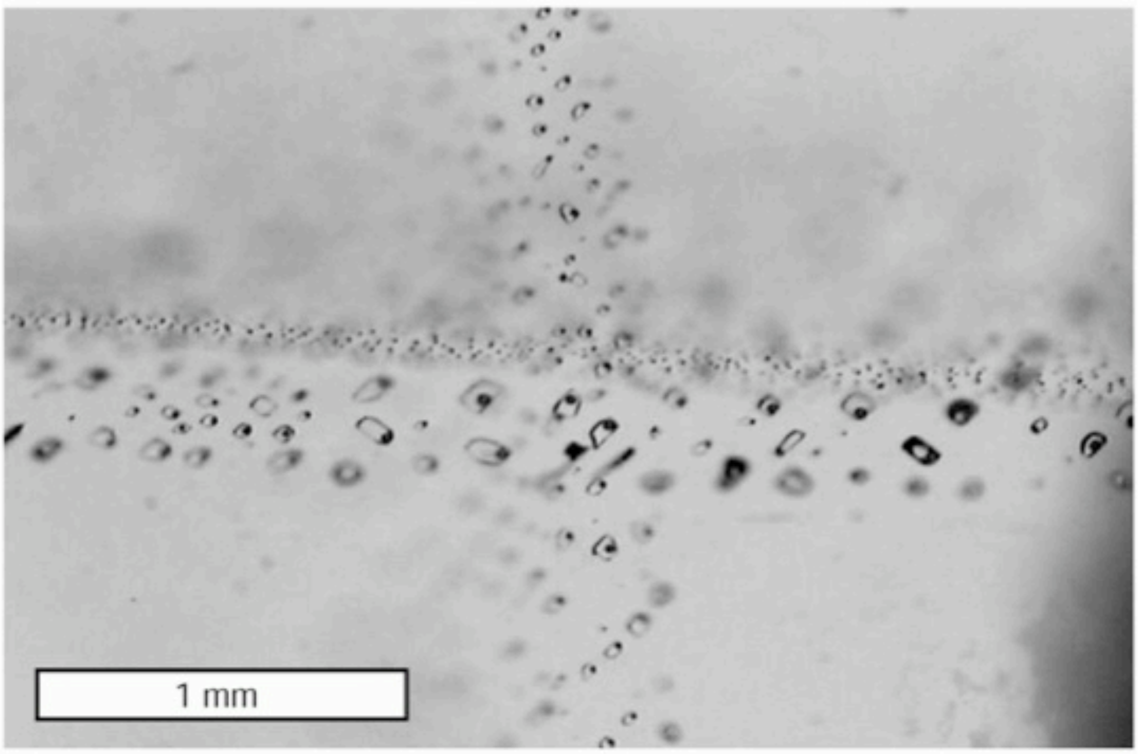


Inclusions from earlier generation

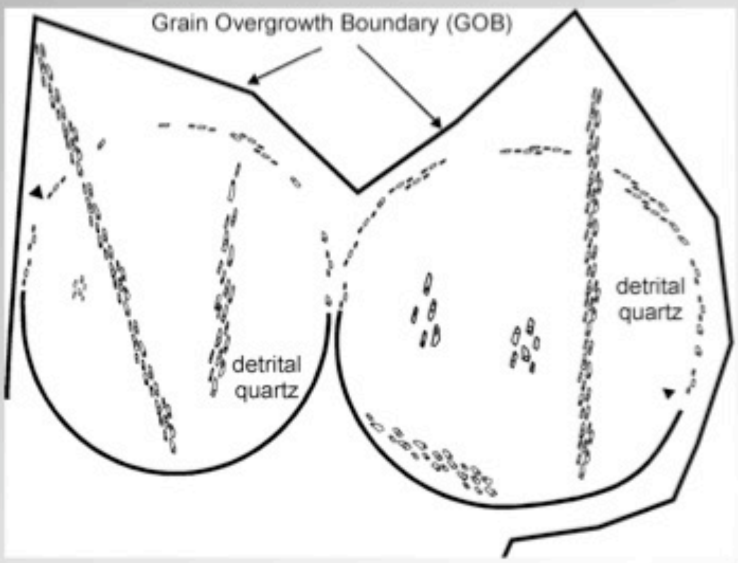
VEIN QUARTZ HOSTED FI



Inclusions from later generation



Several planar arrays of secondary fluid inclusions that formed in healed fractures. Cave-in -rock Fluorite, Illinois.

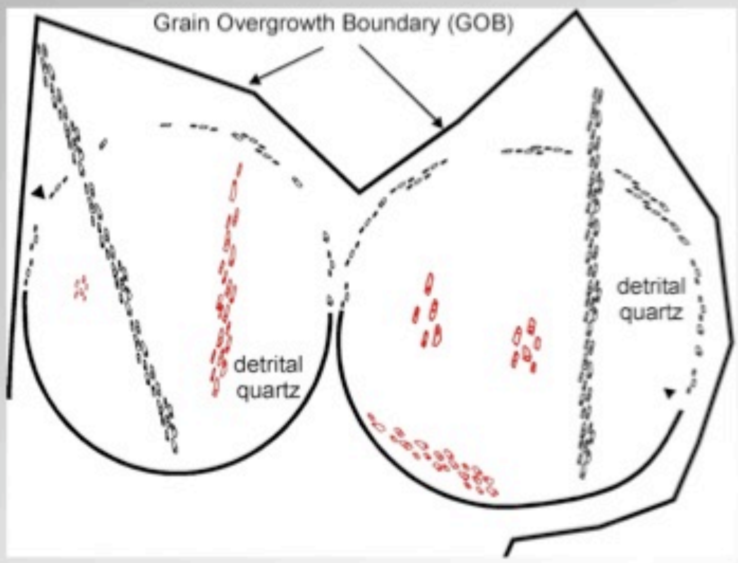


Fluid Inclusion Petrography

Schematic representation of fluid inclusions in a sandstone

- 3 generations of fluid represented

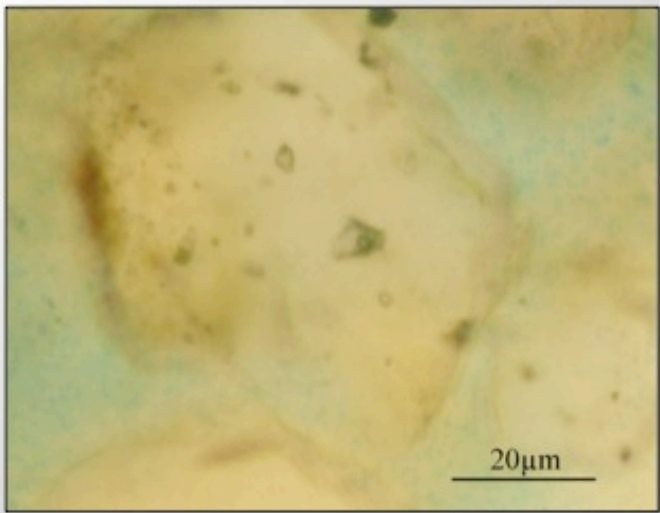
Fluid Inclusion Petrography



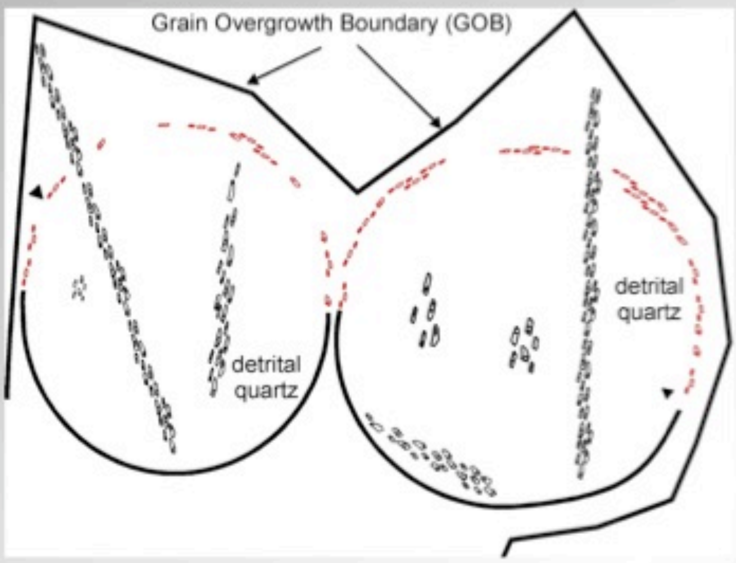
Schematic representation of fluid inclusions in a sandstone

Inclusions hosted in trails or clusters within detrital quartz grains

- Represent fluids activity prior to cementation



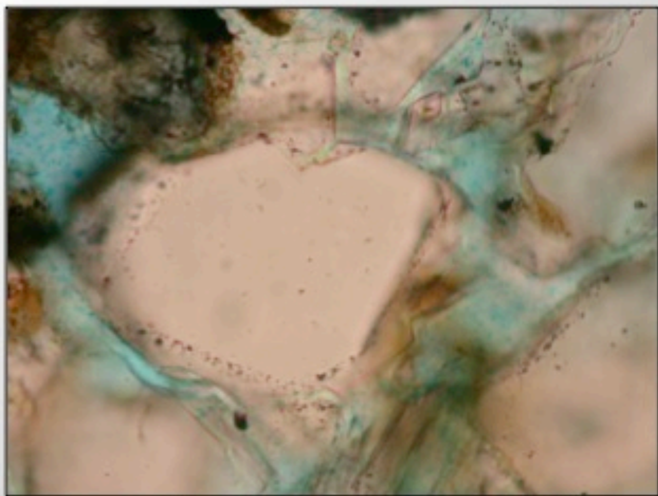
Fluid Inclusion Petrography



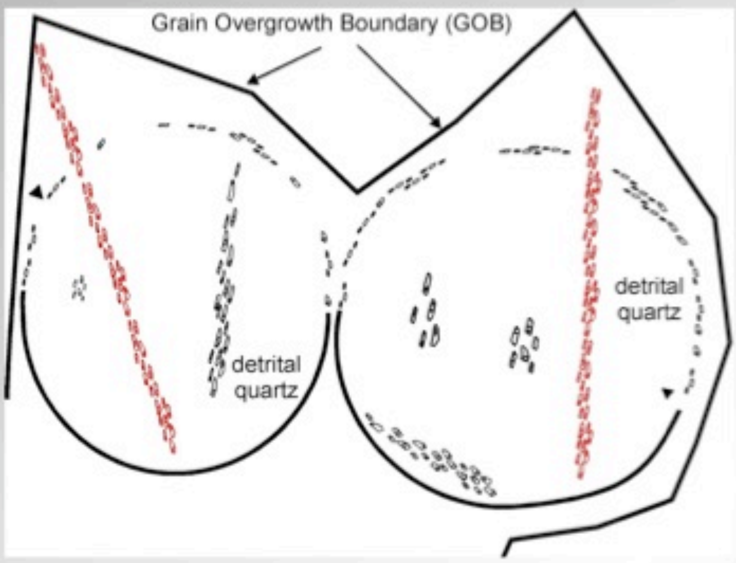
Schematic representation of fluid inclusions in a sandstone

Inclusions hosted within cements at grain overgrowth boundaries

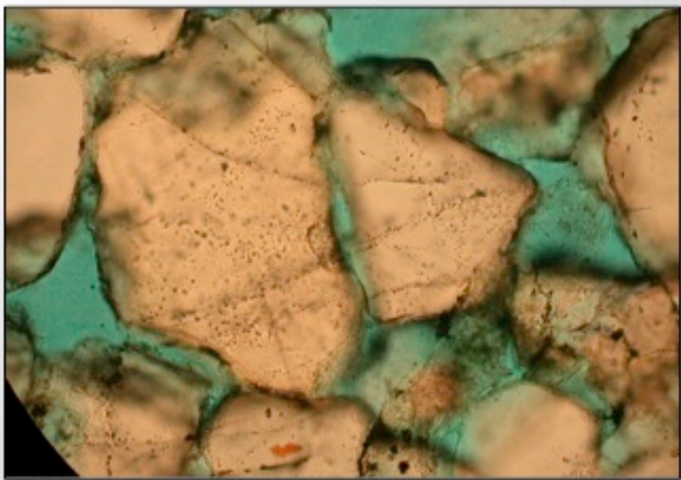
- Represent fluids present during cementation



Fluid Inclusion Petrography



Schematic representation of fluid inclusions in a sandstone

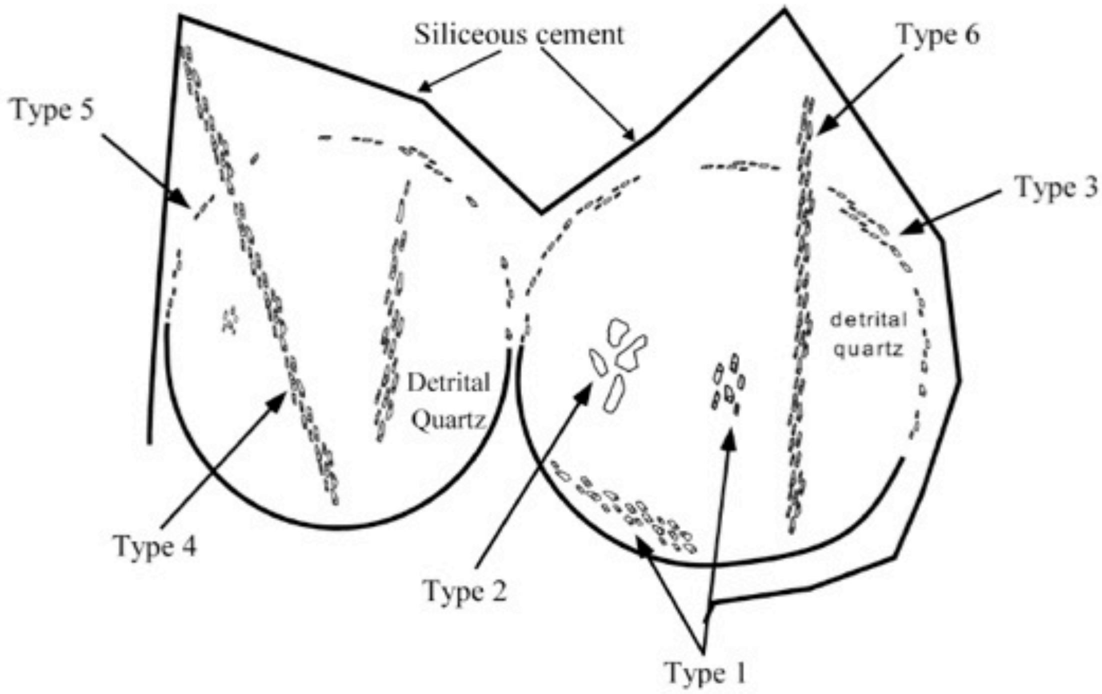


Inclusions hosted in trails that crosscut grain boundaries

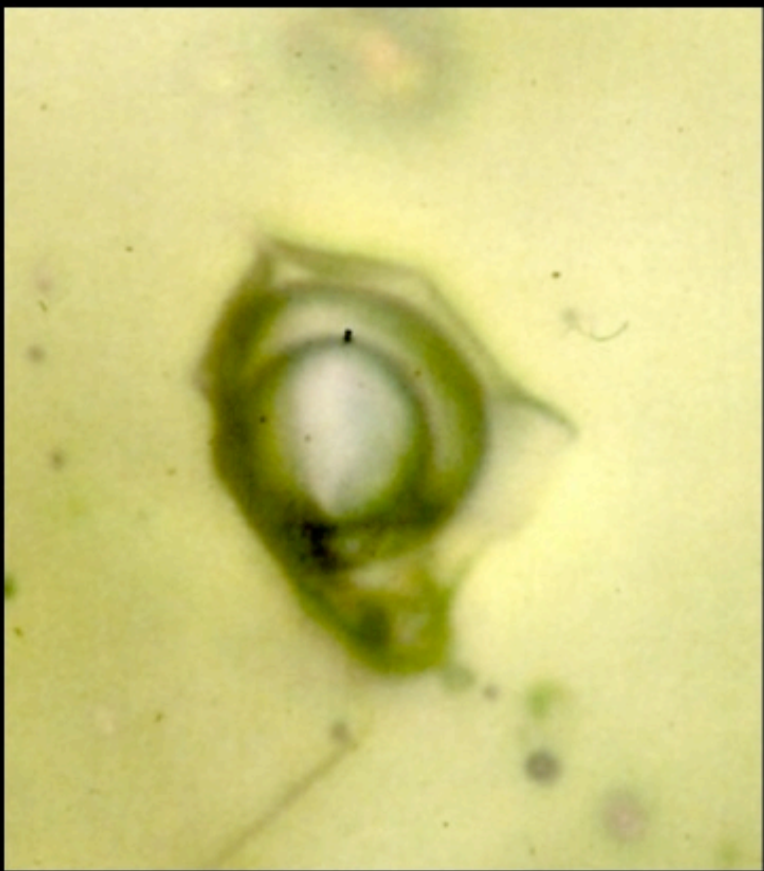
- Represent fluids present after cementation

5. Fluid Inclusion Petrography

Six main fluid inclusion types (Type 1, Type 2, Type 3, Type 4, Type 5 and Type 6) were recorded during the study. This fluid inclusion classification is based upon: (a) their phase relations (presence at room temperature of liquid + vapour phases or, liquid phase only) and (b) the textural relationship between inclusions and their host mineral and /or cement (Table 2). Fluid inclusions in all samples possess a range of morphologies: from ellipsoidal to irregular shapes, and rare negative crystal shapes.



~400 Ma aqueous carbonic fluid inclusion from the Galway Batholith



DOUBLE BUBBLE AQUEOUS-CARBONIC FLUID INCLUSION

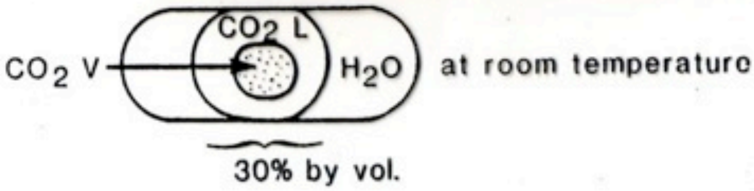


Figure 6.38 Worked example to calculate the bulk density and wt% CO_2 content of an H_2O–CO_2 inclusion.

A. $T_H CO_2$ ($L + V \rightarrow L$) $= 26°C = 0.7 g\ cm^{-3}$ (from Figure 6.17)

B. CO_2 phase occupies 30% by volume (visual estimate)
H_2O phase occupies 70% by volume (visual estimate)

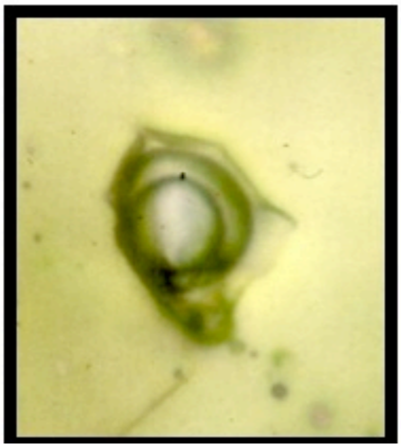
C. Assume (i) salt content of H_2O phase is low or negligible and therefore density can be taken as $1.0 g\ cm^{-3}$ at room temperature
(ii) solubility of CO_2 in H_2O phase and H_2O in CO_2 phase are negligible at room temperature.

D. Thus bulk density of $H_2O - CO_2$ inclusion is given by

$$\underset{(\text{vol} \times \rho)}{(0.3 \times 0.7)} + \underset{(\text{vol} \times \rho)}{(0.7 \times 1.0)} = 0.91 g\ cm^{-3}$$

Wt% CO_2 is given by

$$\frac{0.21}{0.91} = 23.1 \text{ wt\% } CO_2$$



Application of Fluid Inclusion Studies to Oil and Gas Exploration

LECTURE 3

FLUID INCLUSION ANALYTICAL METHODS

FLUID INCLUSION ANALYTICAL METHODS

POLARISED LIGHT MICROSCOPY

MICROTHERMOMETRY

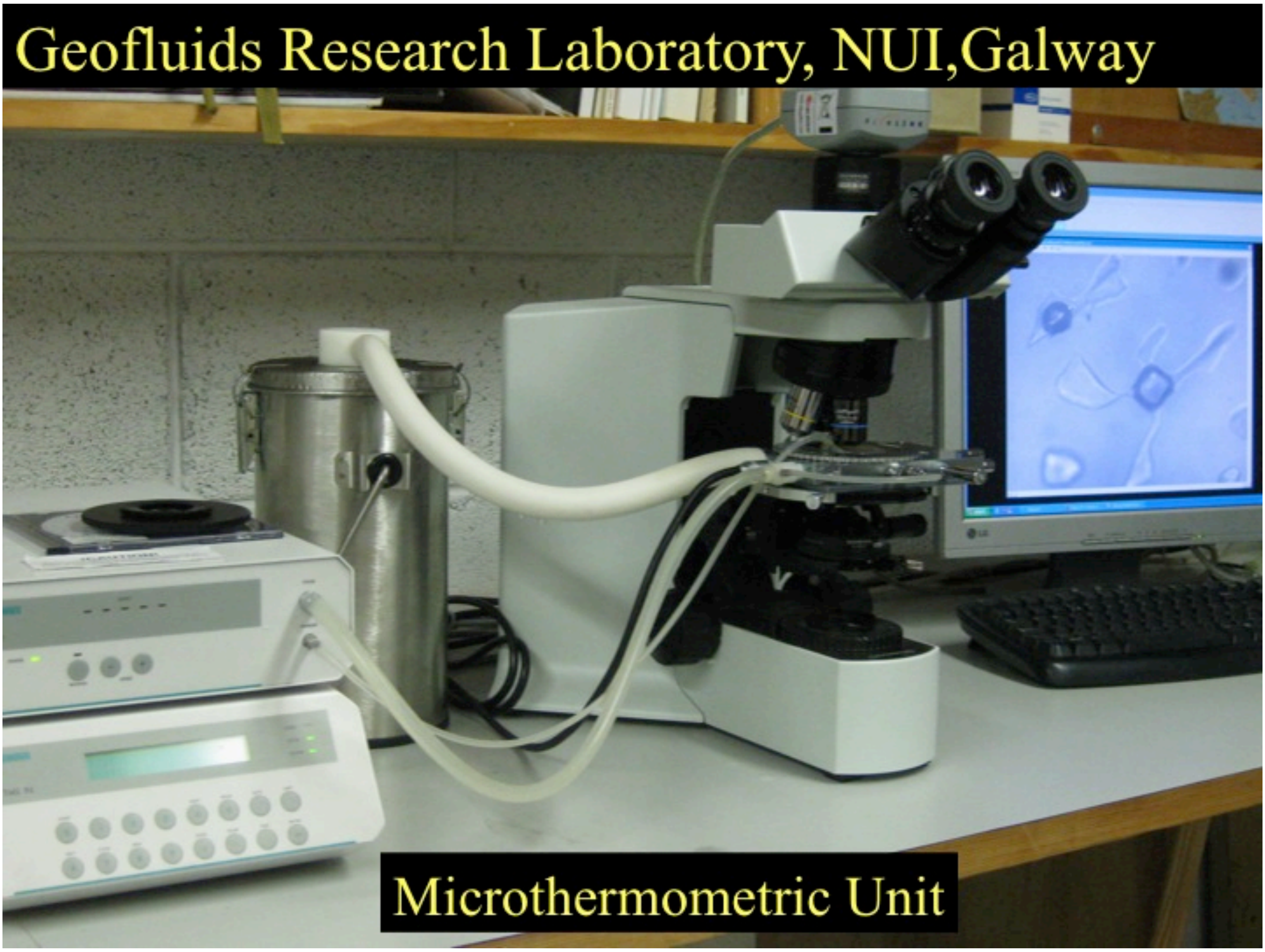
UV-MICROSCOPY

CATHODOLUMINESCENSE

FLUORESCENCE LIFETIME MICROSCOPY

LASER RAMAN MICROSCOPY

SCANNING ELECTRON MICROSCOPY


Geofluids Research Laboratory, NUI,Galway
Microthermometric Unit

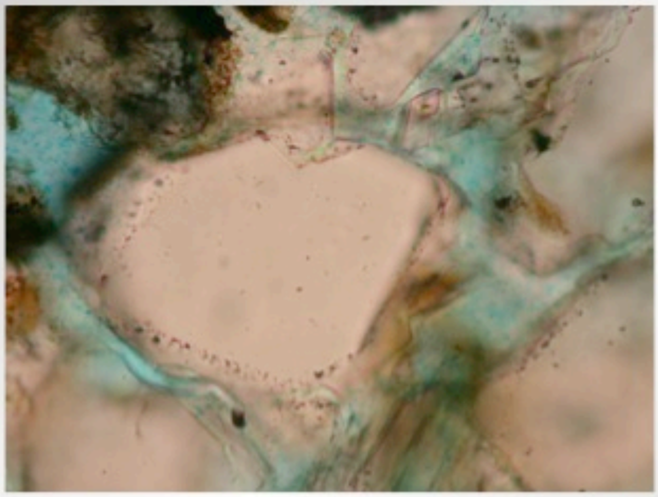
Fluid Inclusion Microthermometry

- Microthermometry is carried out using a Linkam THMSG 600 heating freezing stage
- Specific phase changes within an inclusion are measured
- Behaviour upon heating and freezing of inclusions is indicative of fluid composition and minimum trapping temperatures

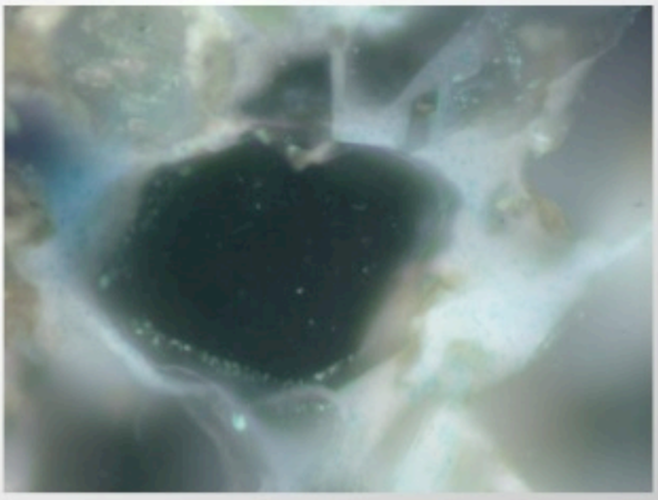
UV Fluorescence

- Samples examined under ultra-violet (UV) light using a Nikon Diaphot microscope with an epifluorescence attachment
- Used to distinguish between HCFI and aqueous inclusions

UV Fluorescence



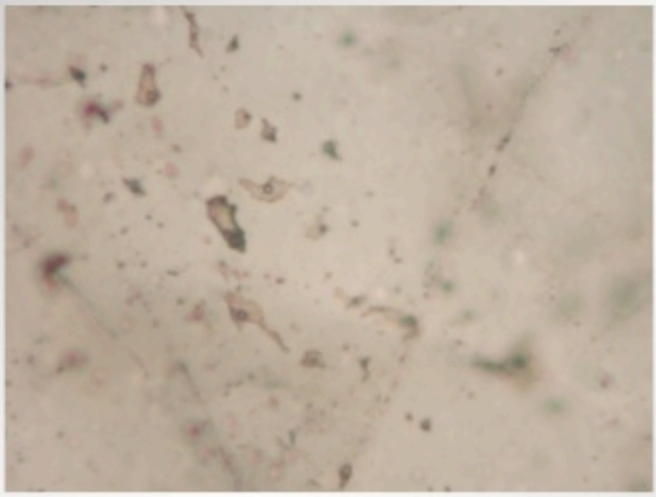
Transmitted Light Only



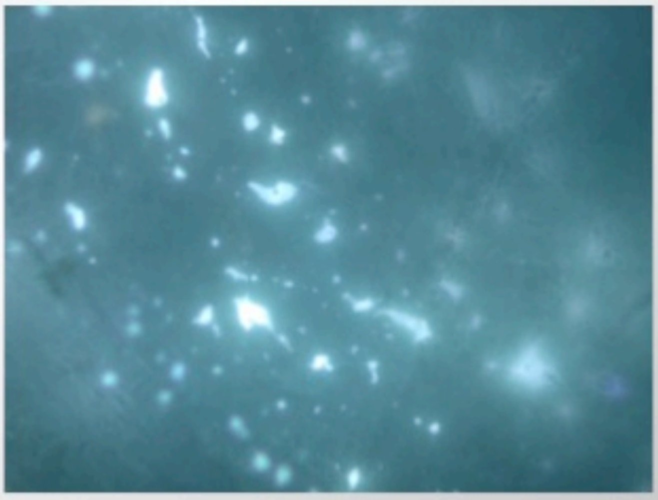
UV Light (365 nm)

Magnification x50

UV Fluorescence

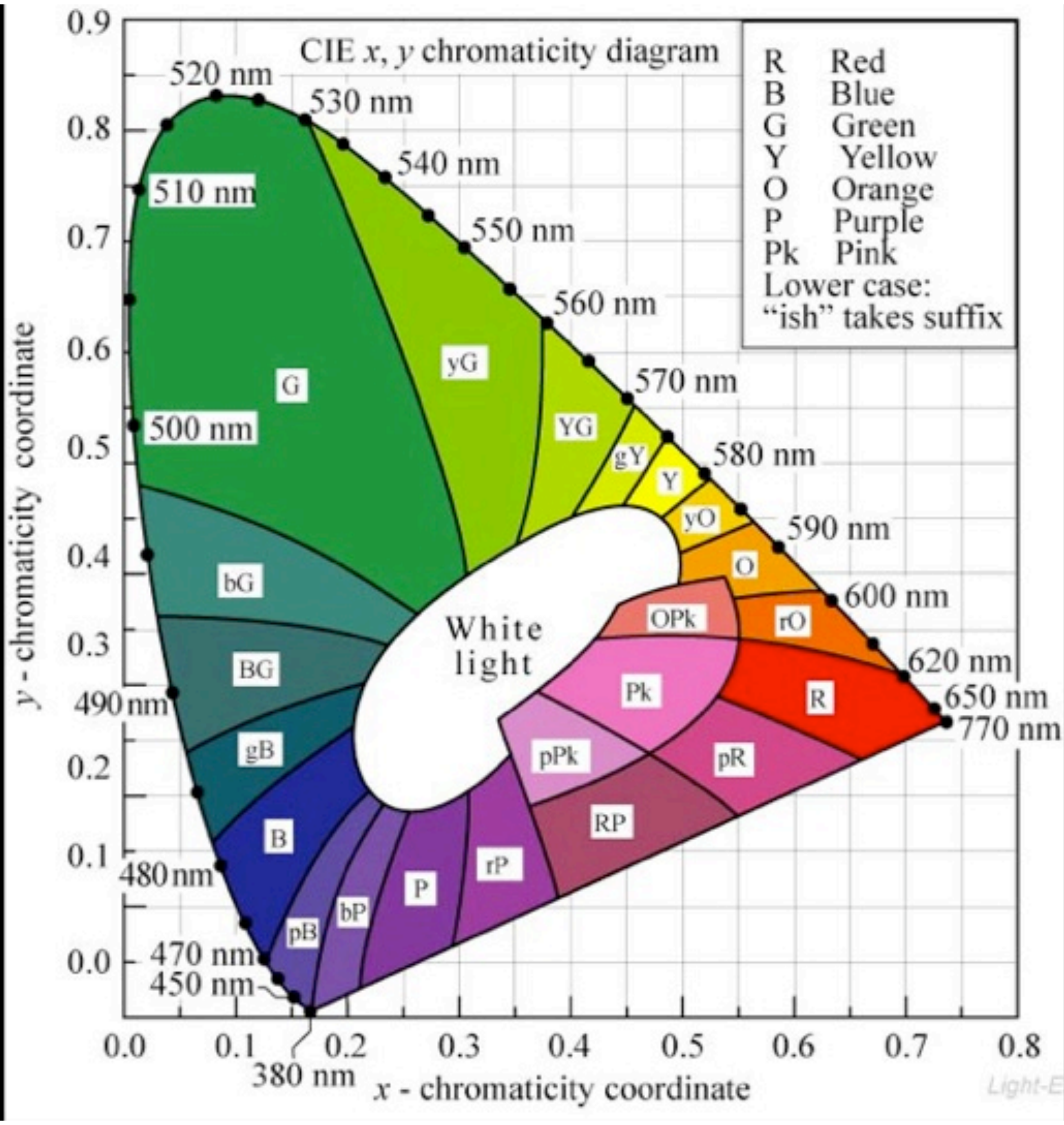


Transmitted Light Only



UV Light (365 nm)

Magnification x100



CIE x, y chromaticity diagram
R Red
B Blue
G Green
Y Yellow
O Orange
P Purple
Pk Pink
Lower case:
"ish" takes suffix
520 nm
530 nm
540 nm
510 nm
550 nm
560 nm
570 nm
500 nm
580 nm
590 nm
600 nm
620 nm
650 nm
770 nm
490 nm
480 nm
470 nm
450 nm
380 nm
G
yG
YG
gY
Y
yO
O
OPk
rO
R
White light
Pk
pPk
pR
RP
bG
BG
gB
B
pB
bP
P
rP
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
y - chromaticity coordinate
x - chromaticity coordinate

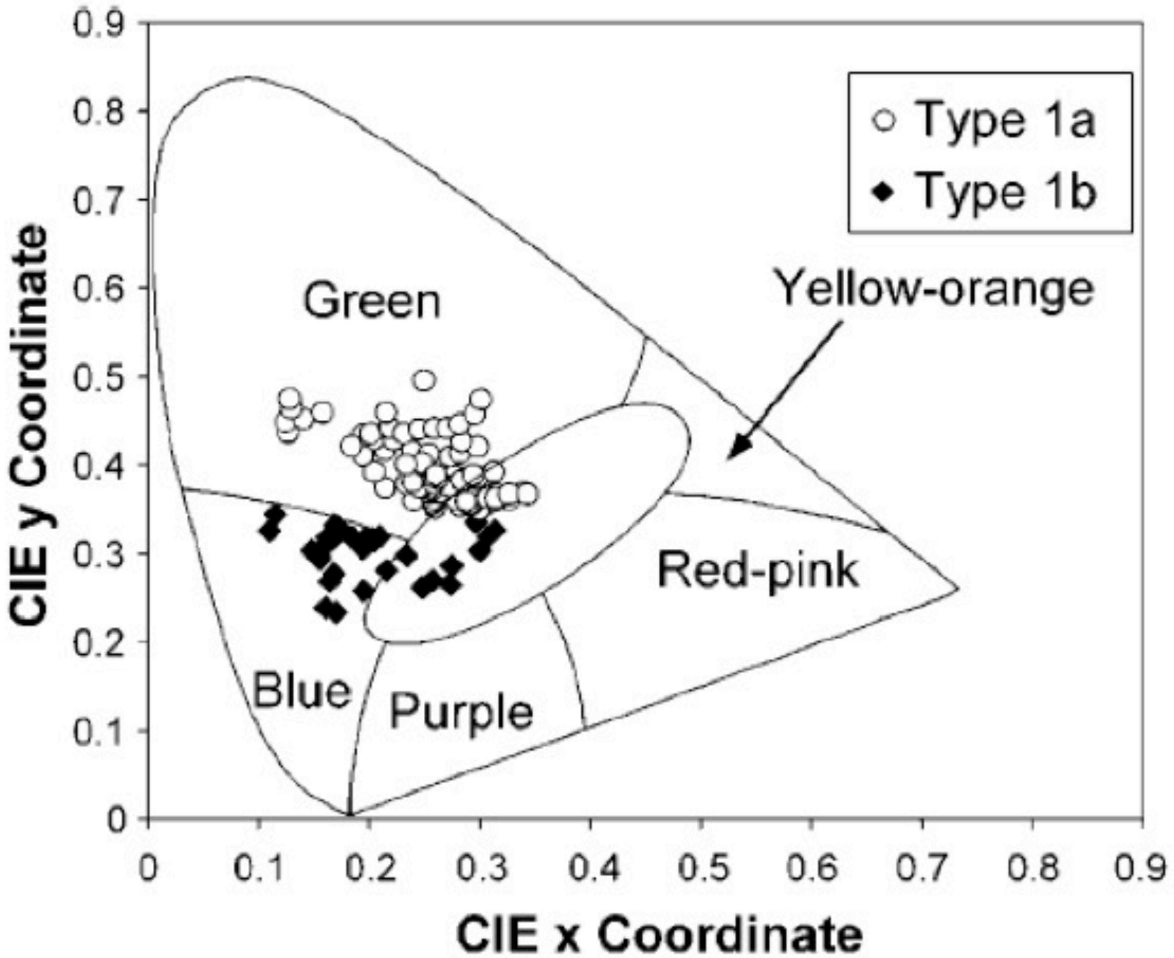
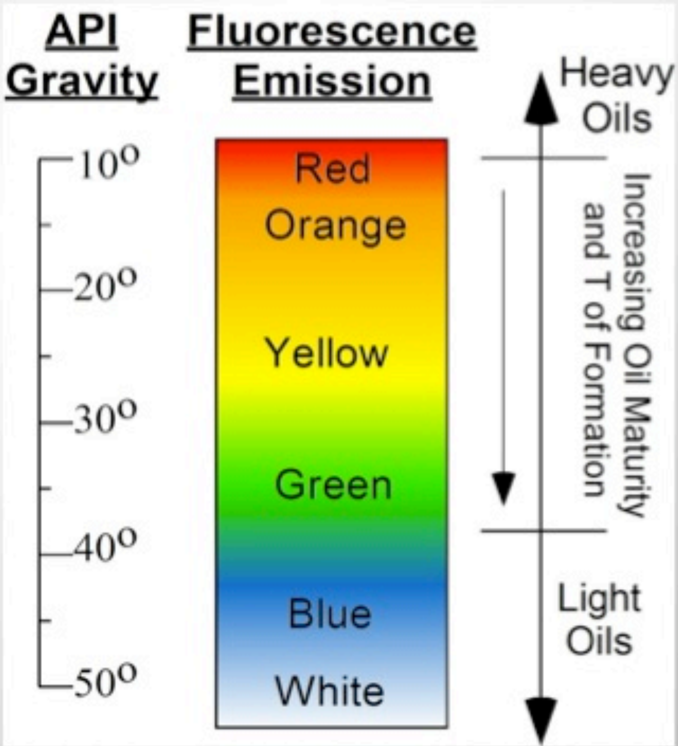


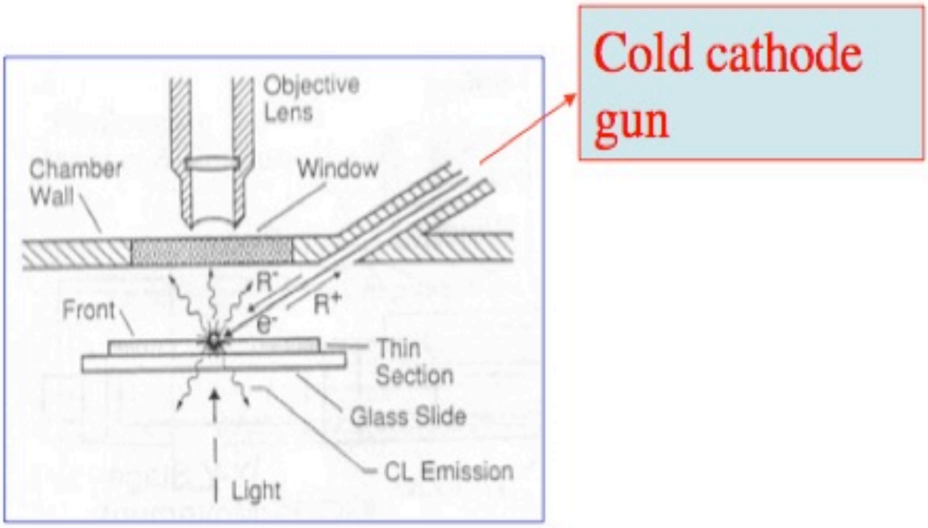
Fig. 5. Fluorescence colours of HCFI from the Porcupine Basin, plotted on CIE-1931 diagram.

UV Fluorescence

- When exposed to UV light hydrocarbons emit light in the visible spectrum
- The relationship between fluorescence colour of HCFI and chemical composition of oils is highly complex but can give a first approximation of the composition of the hydrocarbon.



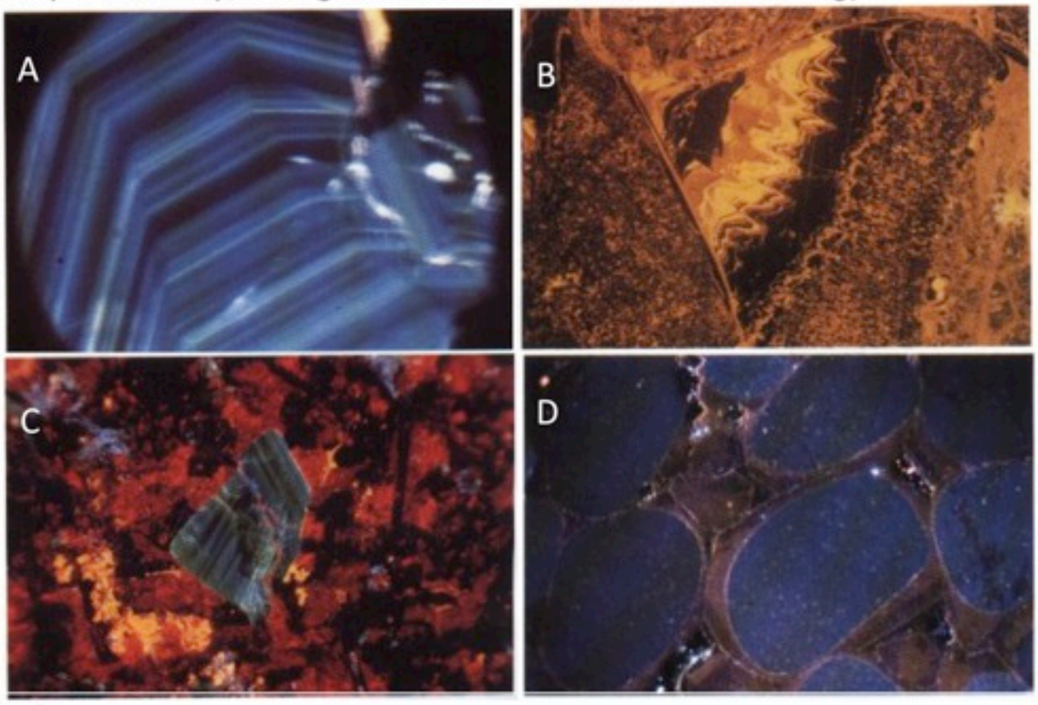
(Cold) CL Microscope Attachments



CMAs are relatively inexpensive attachments to microscopes. A high voltage (10-30 keV) cold cathode gun discharges electrons in a low vacuum chamber (rough pump only). A plasma results that provides charge neutralization (no carbon coating necessary). A camera (film or digital) and/or monochrometer are attached to acquire images and/or wavelength scans of the light.

Cathodoluminescence

Evaluating minerals for heterogeneous growth
(complex history, overgrowths, dissolution, crack infilling)



A: Casserite, SnO_2

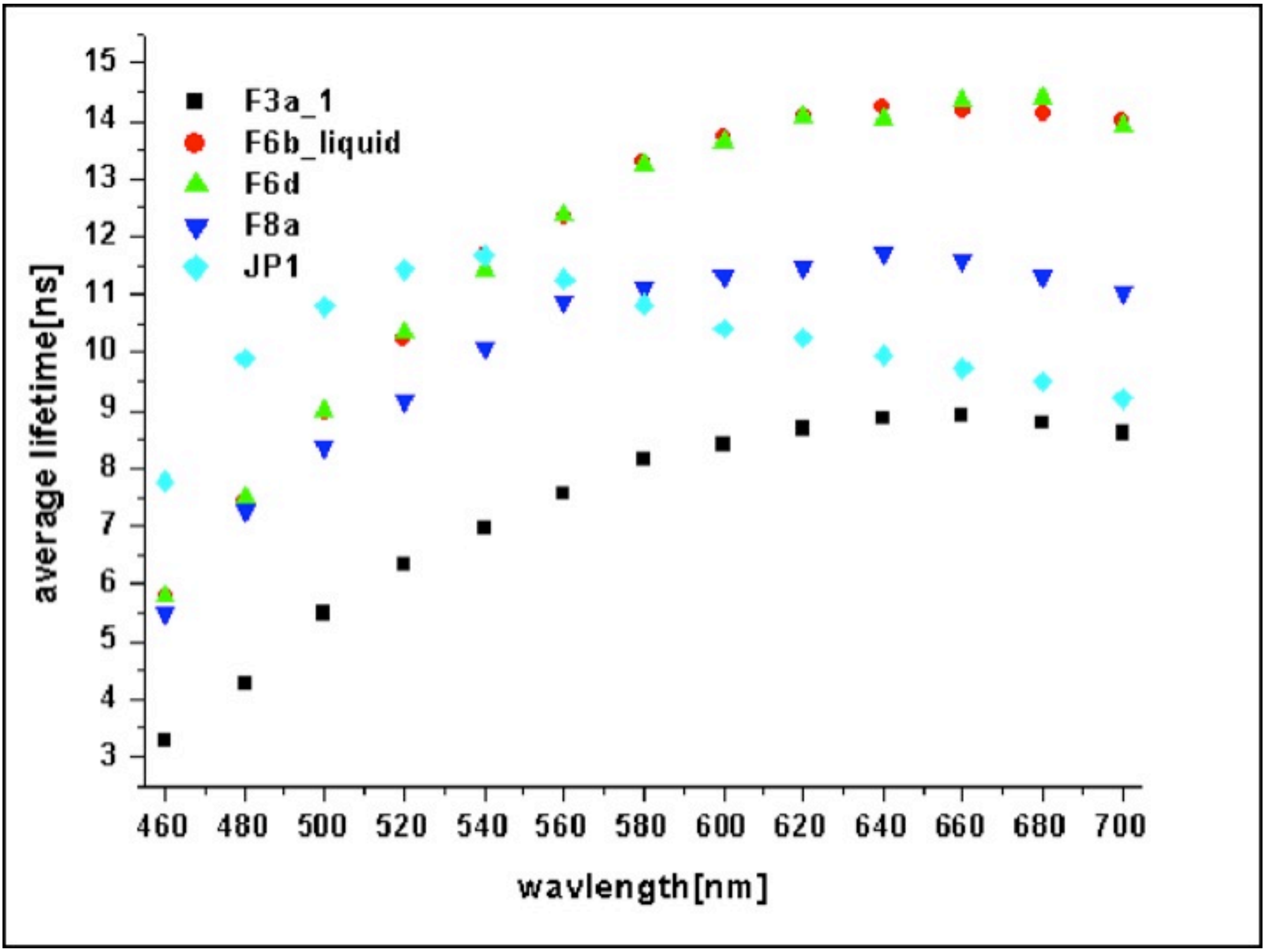
B: Crinoidal limestone

C: Red = dolomite, orange = calcite; dark grey = baddeleyite (ZrO_2)

D: St Peter Sandstone; mature quartz with zoned authigenic quartz overgrowths

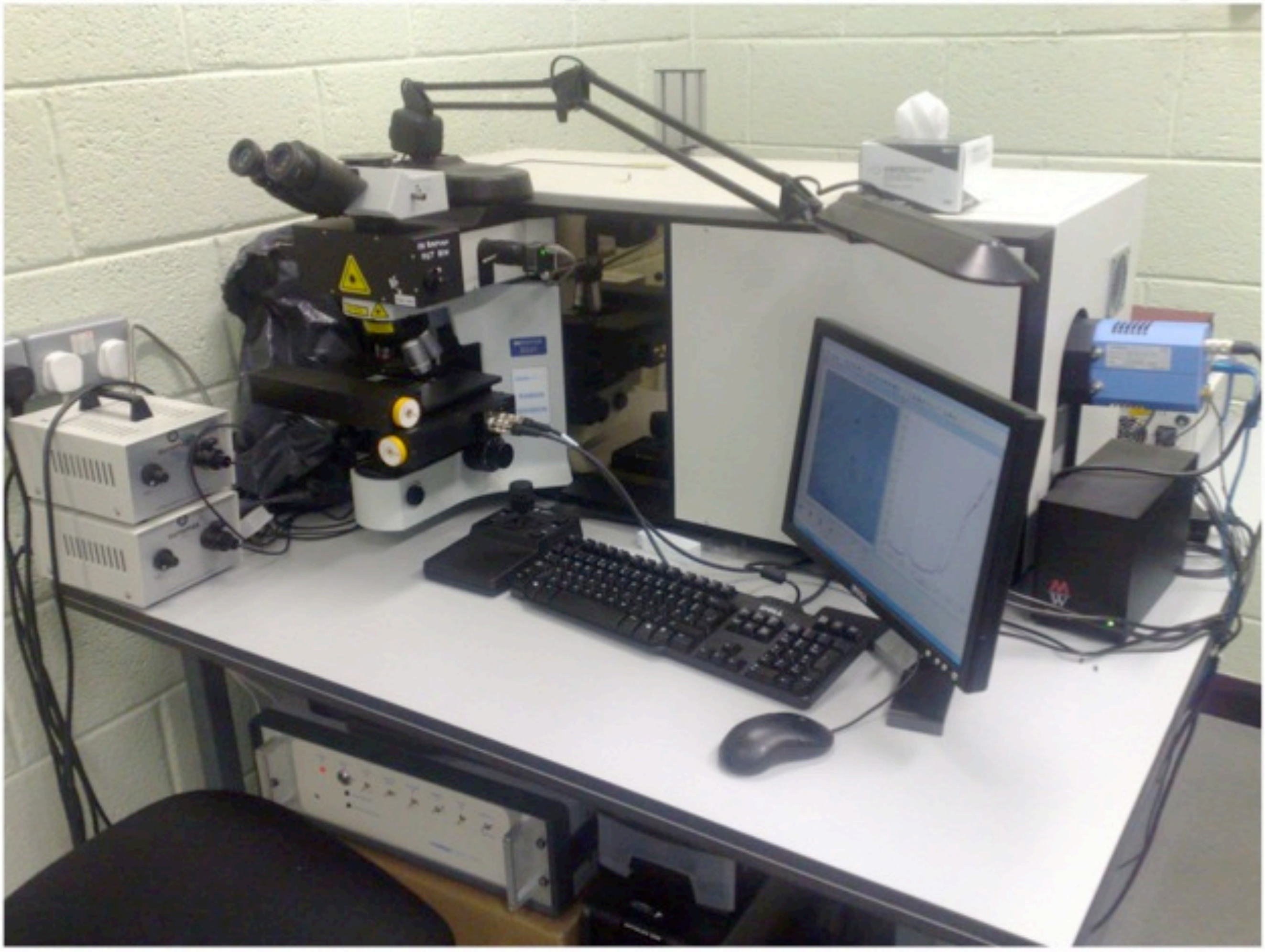
(from Marshall,1988, CL of Geological Materials)

Figure 5: Upright ISS Alba system for Fluorescence Lifetime Imaging Microscopy.

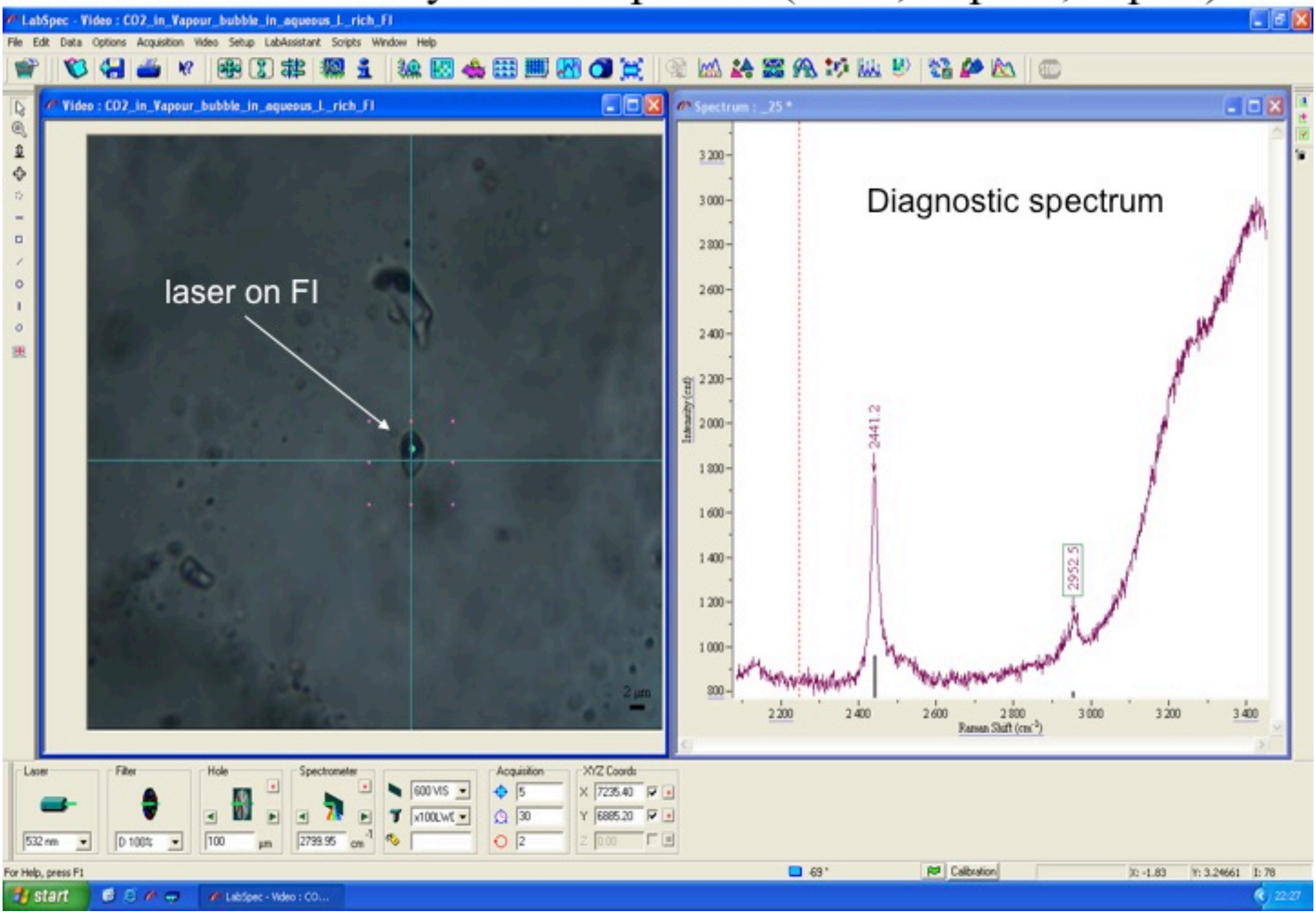


F3a_1
F6b_liquid
F6d
F8a
JP1
average lifetime[ns]
wavlength[nm]

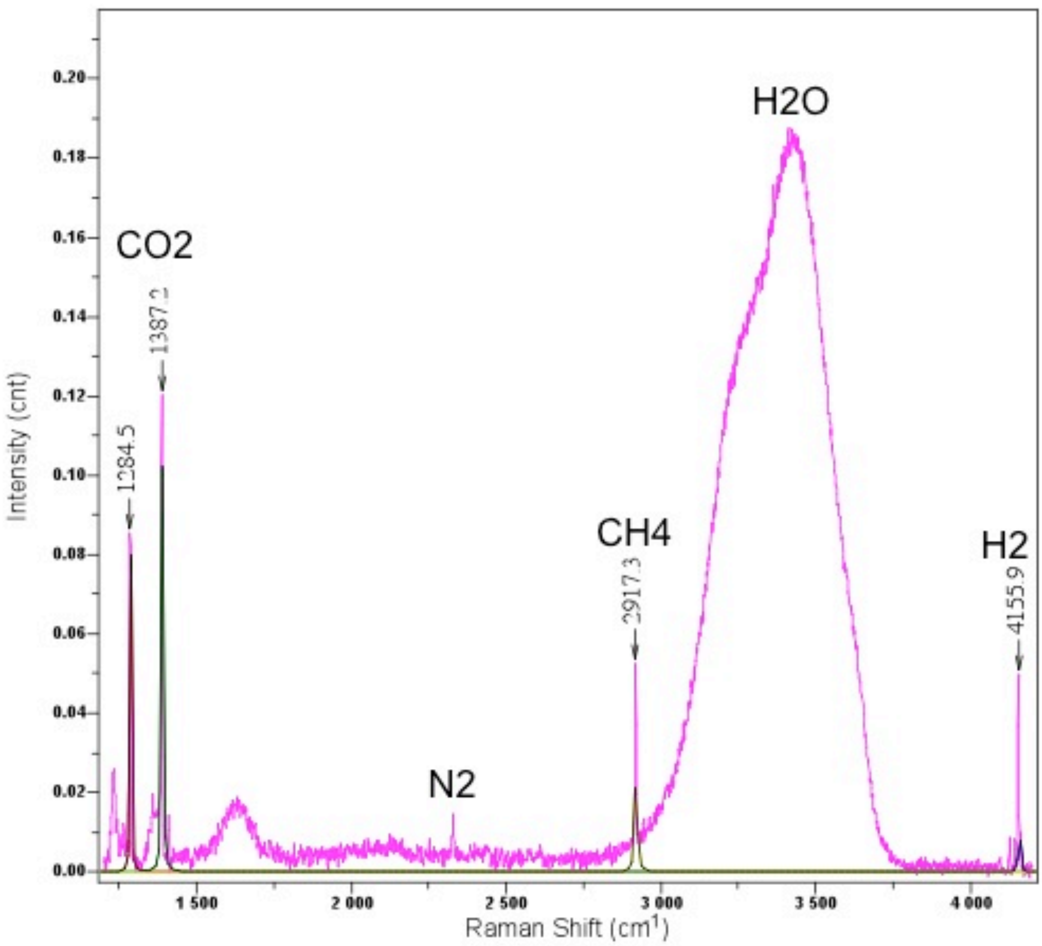
Raman spectroscopy of FIs at NUI Galway



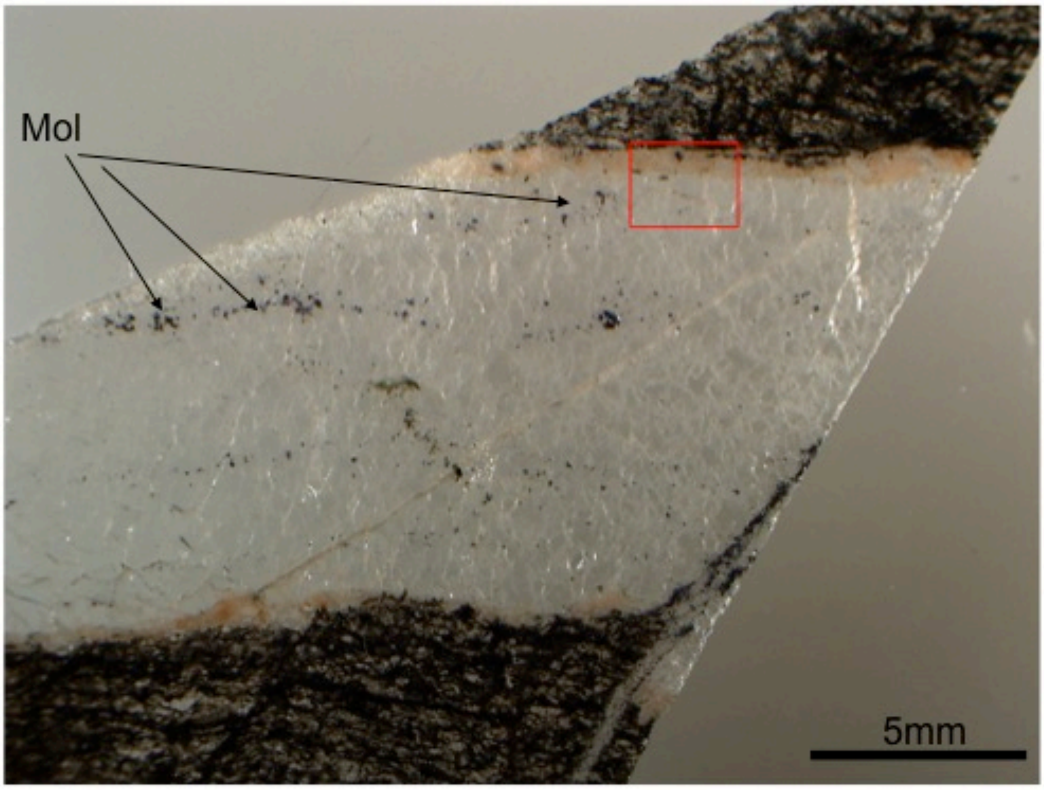
In situ microanalysis of FI phases (solid, vapour, liquid)

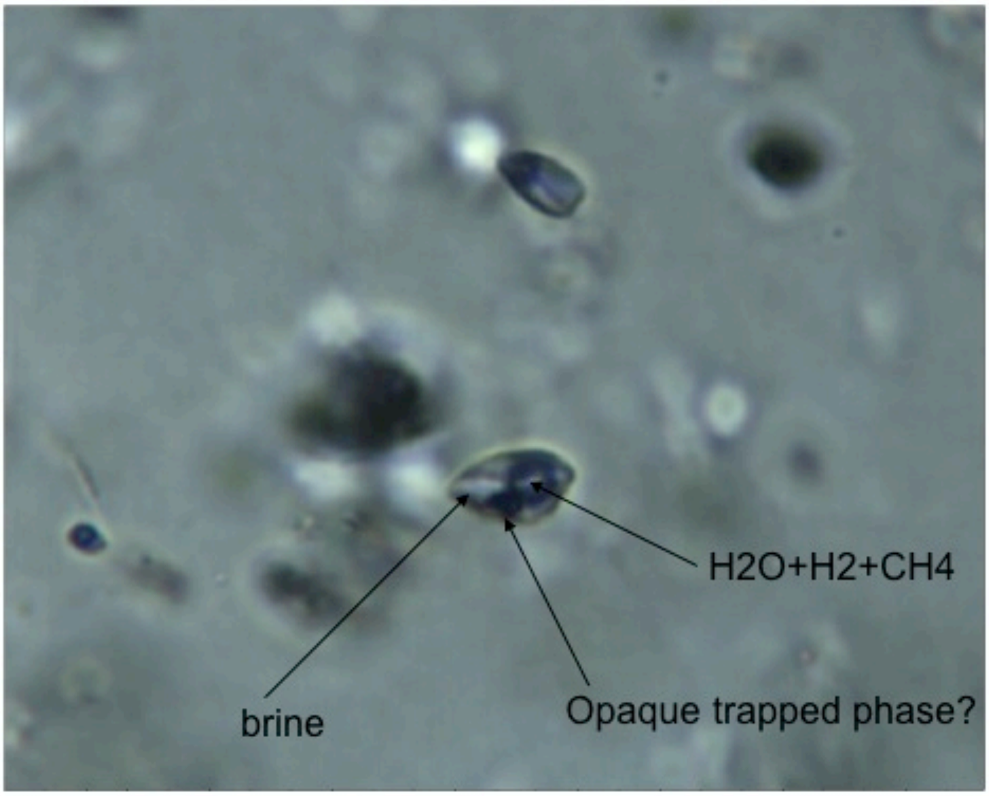


Raman peaks of gases trapped in FIs

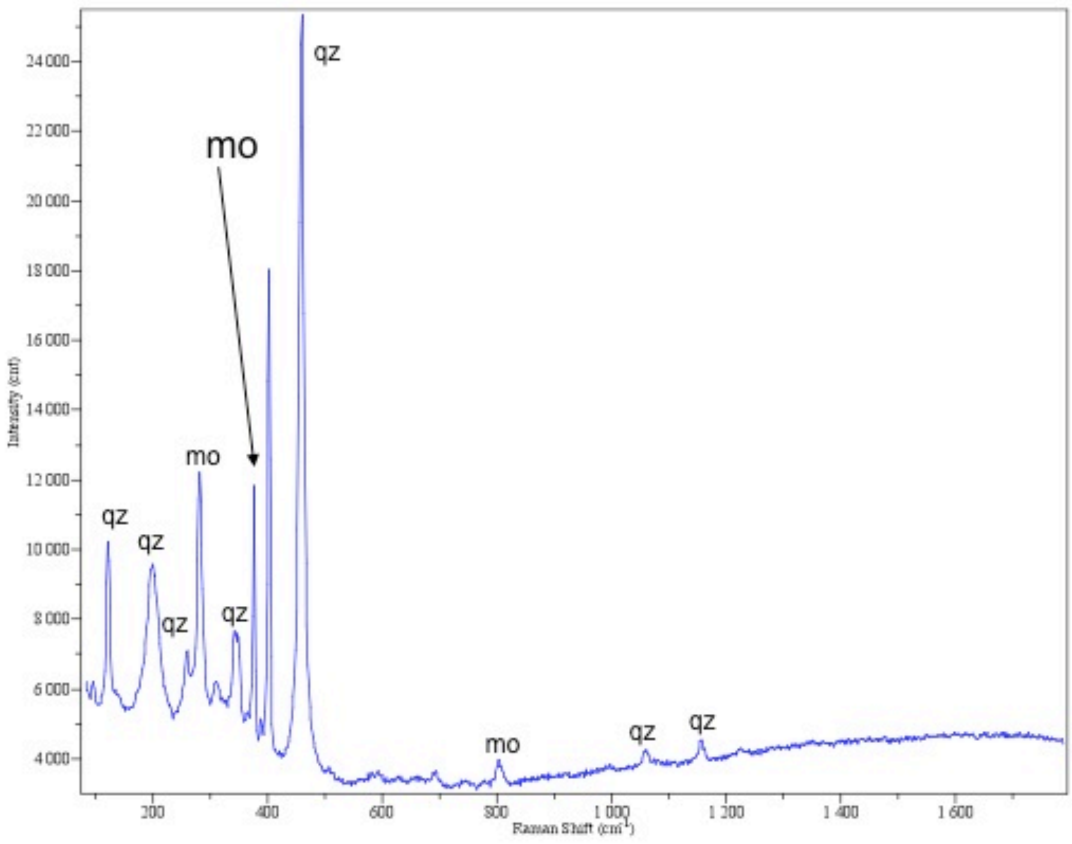


Hydrothermal vein from a Mo-Cu deposit, Newfoundland

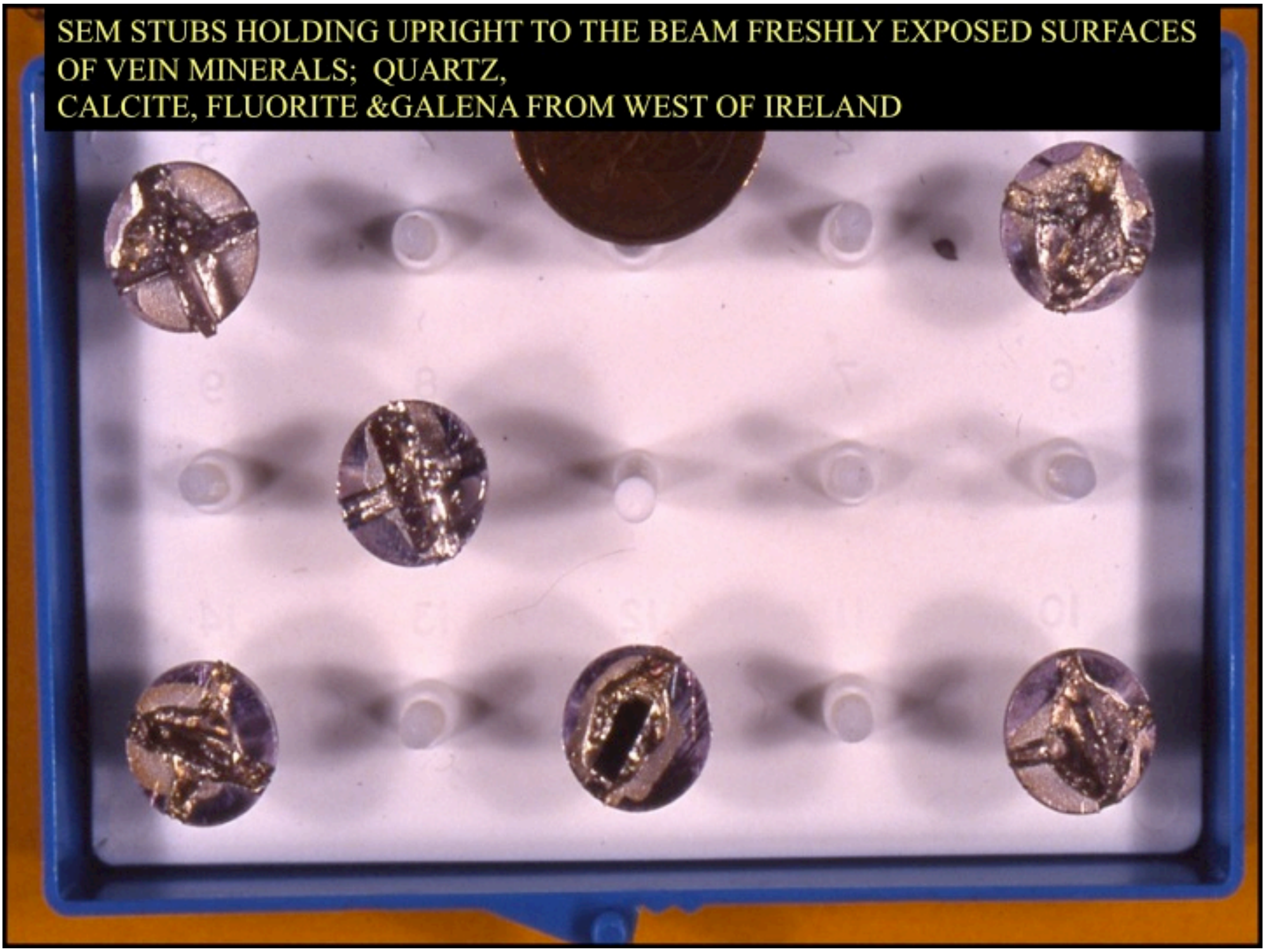



H2O+H2+CH4
brine
Opaque trapped phase?

Mixed Raman spectrum: quartz + opaque phase in FI




SU-70

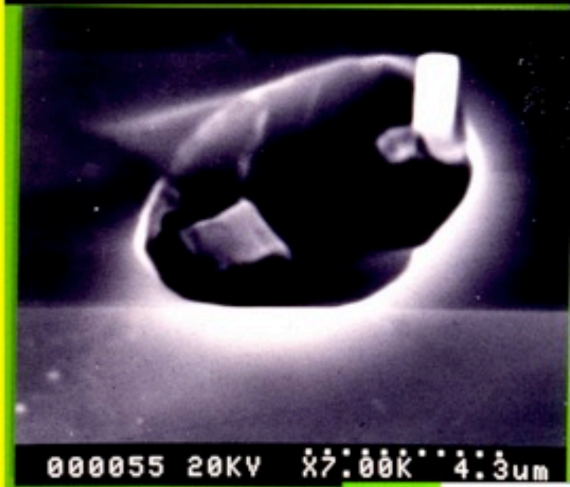


SEM STUBS HOLDING UPRIGHT TO THE BEAM FRESHLY EXPOSED SURFACES OF VEIN MINERALS; QUARTZ,
CALCITE, FLUORITE &GALENA FROM WEST OF IRELAND

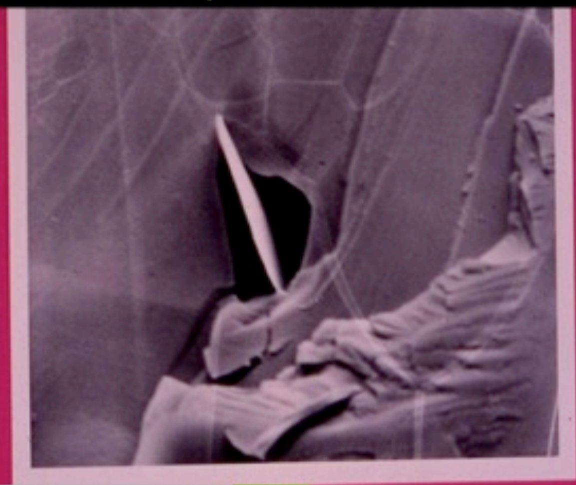
OCTAHEDRON OF FLUORITE; FLUORITE HOSTED INCLUSION, CLARE, IRELAND.

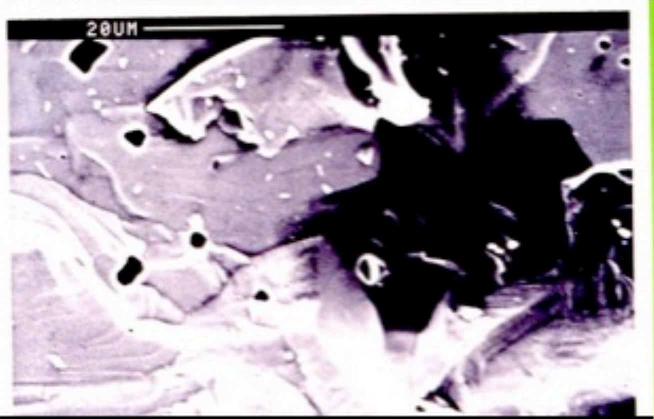
SPATIAL DENDRITES OF HALITE; FORMED ON SURFACE OF QUARTZ FROM FRESHLY OPENED HIGHLY SALINE INCLUSIONS, CONNEMARA

PYRITE CUBE IN OPENED INCLUSION IN QUARTZ FROMMACE HEAD, IRELAND



MICA IN GRANITE QUARTZ, MACE HEAD,IRELAND





SEVERAL EMPTY INCLUSIONS IN QUARTZ MACE HEAD, IRELAND.

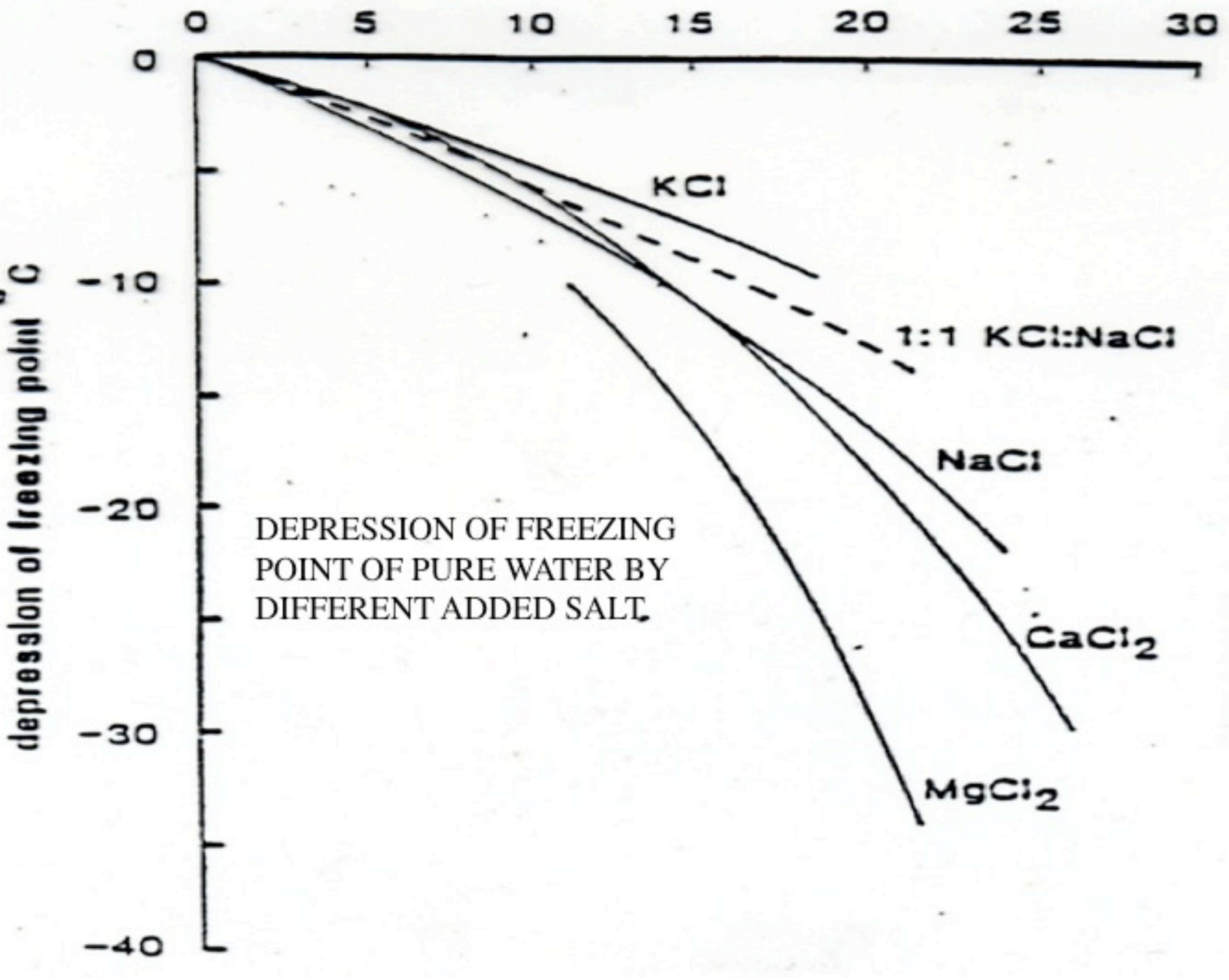
Application of Fluid Inclusion Studies
to
Oil and Gas Exploration

LECTURE 4

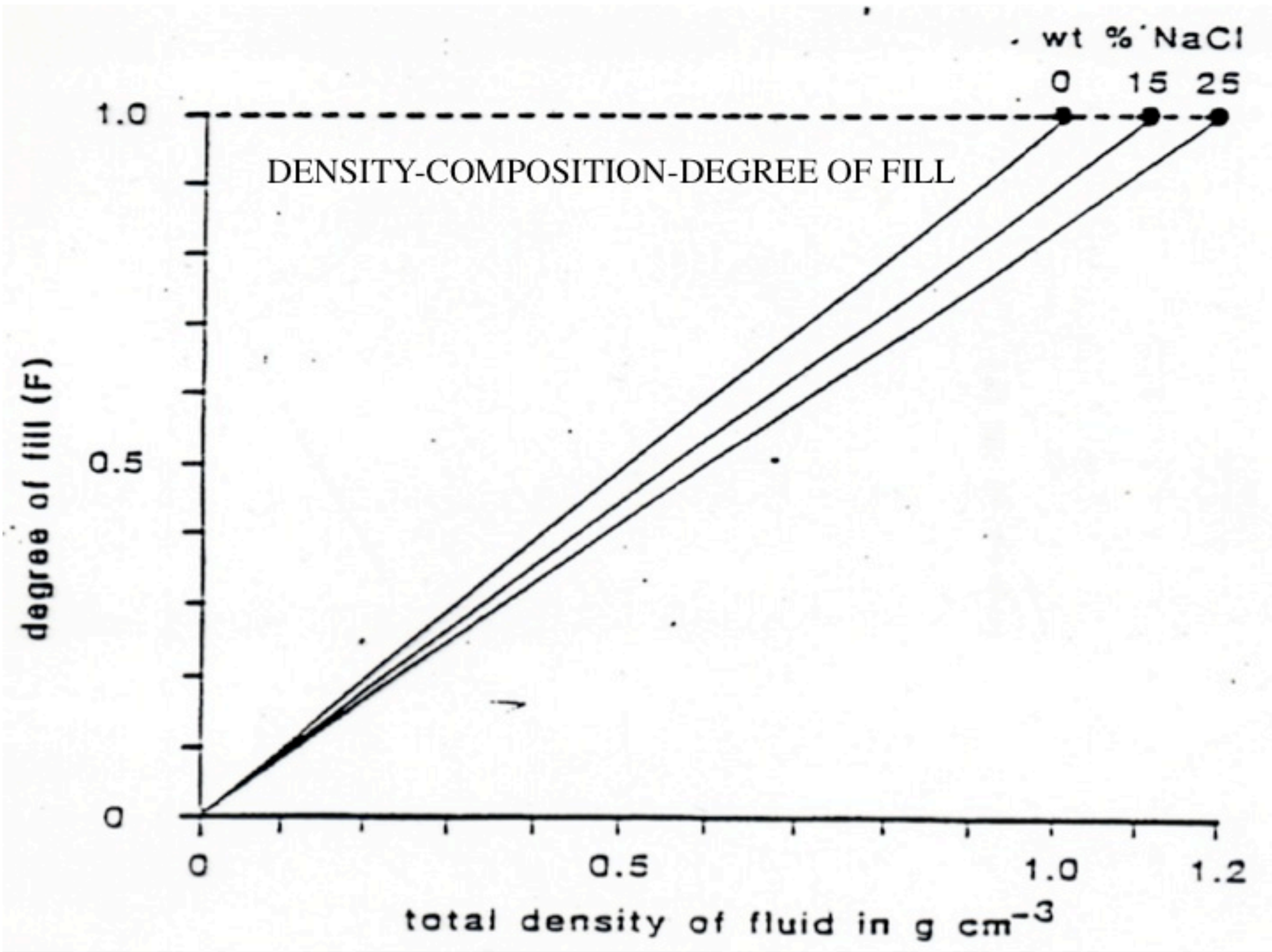
FLUID INCLUSION MICROTHERMOMETRY
AND
FLUID P–T-X MODELLING

Fluid Inclusion Microthermometry

- Microthermometry is carried out using a Linkam THMSG 600 heating freezing stage
- Specific phase changes within an inclusion are measured
- Behaviour upon heating and freezing of inclusions is indicative of fluid composition and minimum trapping temperatures



DEPRESSION OF FREEZING POINT OF PURE WATER BY DIFFERENT ADDED SALT.



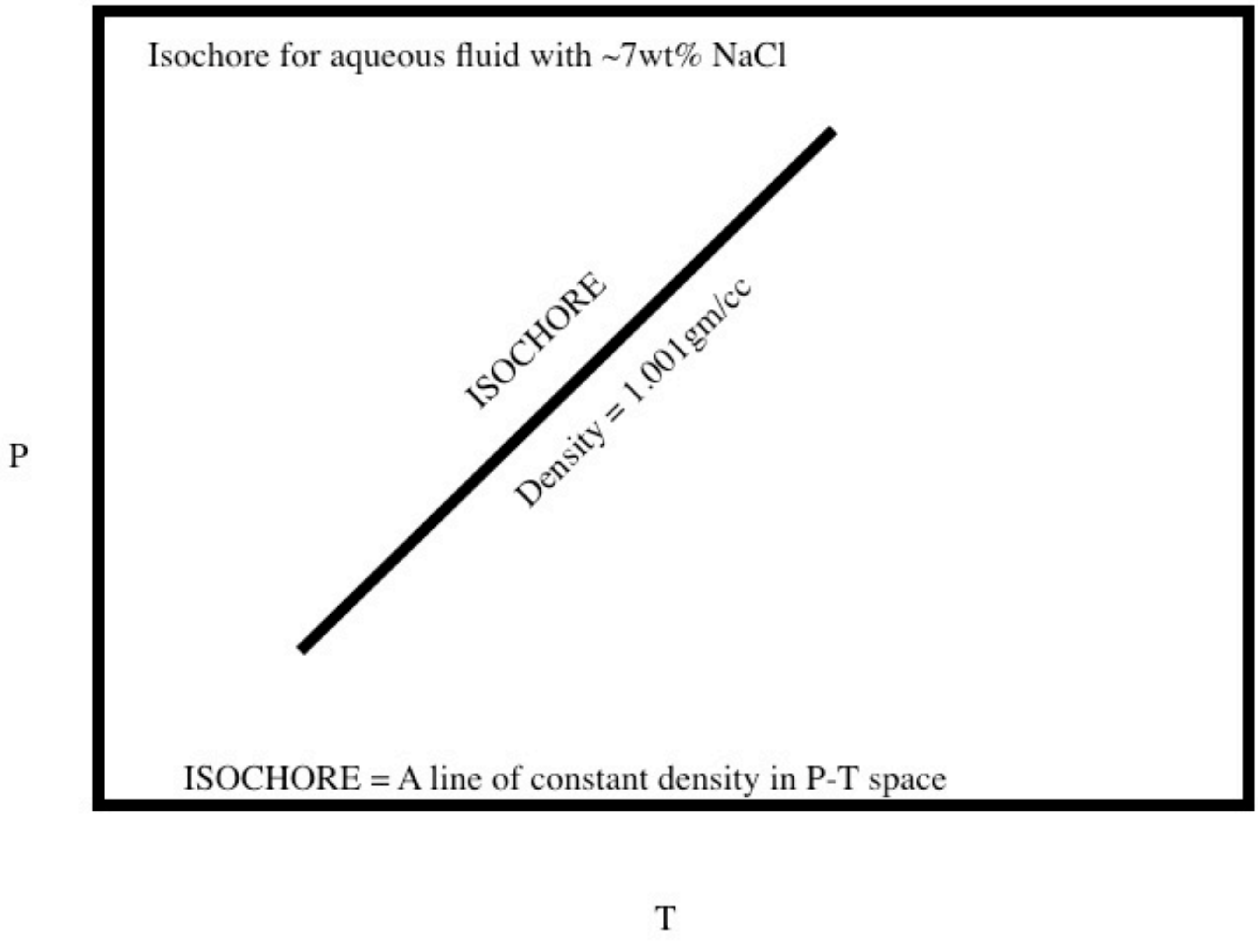
wt % NaCl
0
15
25
1.0
DENSITY-COMPOSITION-DEGREE OF FILL
0.5
0
degree of fill (F)
0
0.5
1.0
1.2
total density of fluid in g cm⁻³

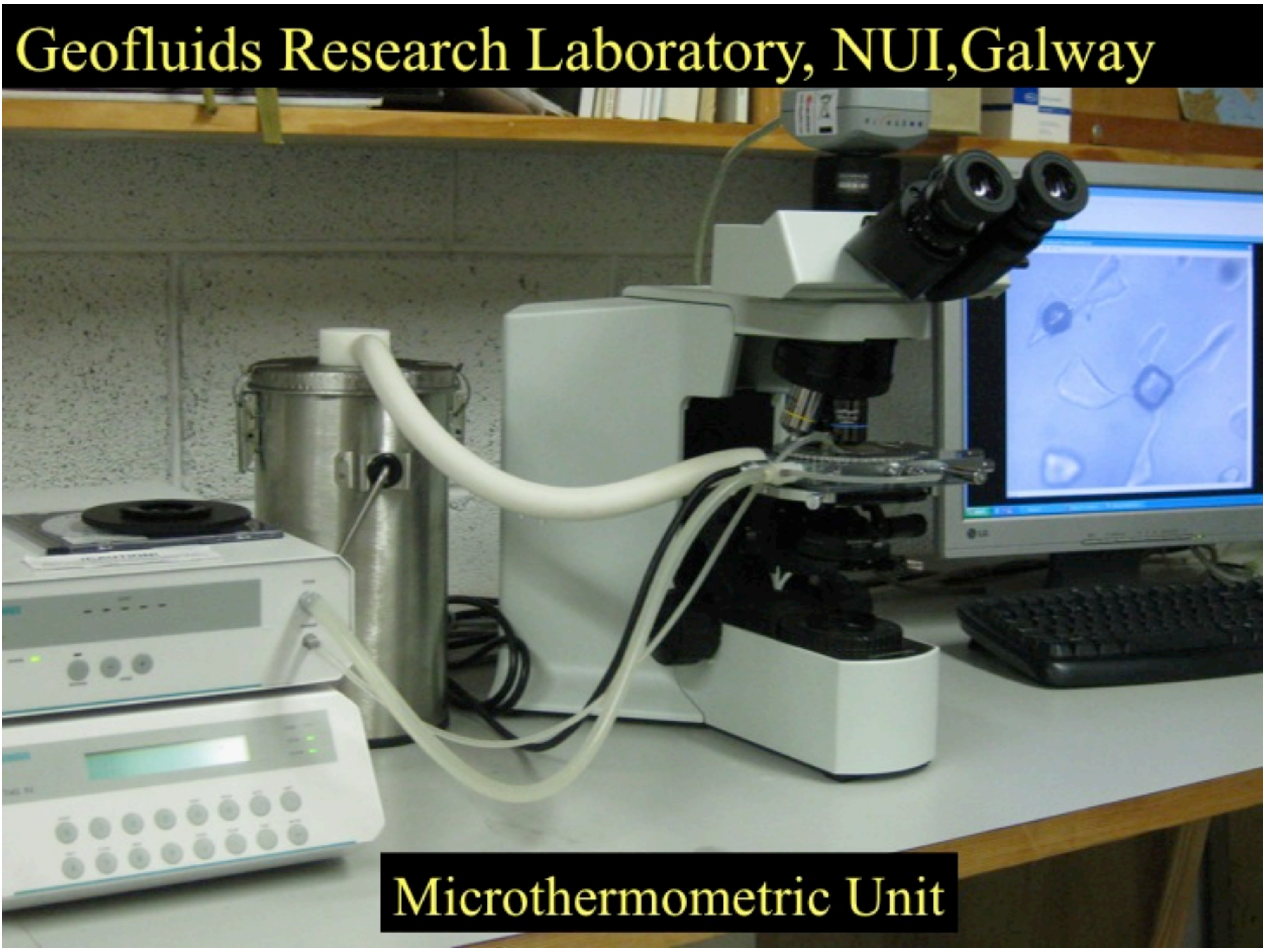
TABLE 17.—*Densities of 5 weight percent NaCl solutions, g/cm³*

[The uncertainties in the densities are: 3-place figures ±0.005 and ±0.05 for 2-place figures.]

Temp °C	Pressure (bars) 100	200	300	400	500	600	700	800	900	1000	1250	1500	1750	2000
25	1.033	1.038	1.042	1.046	1.051	1.055	1.059	1.063	1.067	1.070	1.079	1.087	1.095	1.103
50	1.027	1.031	1.034	1.041	1.046	1.049	1.054	1.057	1.061	1.064	1.073	1.081	1.089	1.097
75	1.016	1.020	1.023	1.032	1.037	1.042	1.047	1.050	1.053	1.057	1.065	1.073	1.083	1.091
100	1.003	1.006	1.010	1.020	1.026	1.031	1.036	1.040	1.044	1.047	1.055	1.064	1.074	1.082
125	0.985	0.989	0.995	1.005	1.012	1.017	1.024	1.028	1.031	1.035	1.043	1.053	1.064	1.073
150	0.964	0.970	0.975	0.986	0.994	1.000	1.008	1.012	1.017	1.021	1.030	1.041	1.052	1.062
175	0.940	0.946	0.953	0.966	0.974	0.980	0.988	0.994	0.999	1.004	1.014	1.026	1.038	1.049
200	0.913	0.920	0.929	0.941	0.952	0.958	0.967	0.973	0.978	0.985	0.996	1.010	1.023	1.035
225	0.882	0.890	0.901	0.914	0.926	0.933	0.942	0.951	0.957	0.963	0.977	0.991	1.007	1.019
250	0.848	0.857	0.871	0.885	0.894	0.905	0.915	0.924	0.932	0.939	0.955	0.971	0.987	1.002
275	0.809	0.821	0.838	0.851	0.864	0.875	0.884	0.896	0.905	0.913	0.932	0.950	0.967	0.983
300	0.765	0.783	0.802	0.815	0.828	0.841	0.852	0.865	0.876	0.885	0.906	0.926	0.946	0.963
325	--	0.741	0.764	0.776	0.790	0.804	0.816	0.831	0.843	0.854	0.879	0.902	0.922	0.941
350	--	0.70*	0.72*	0.734	0.749	0.765	0.777	0.794	0.808	0.821	0.849	0.875	0.897	0.918
375	--	0.66*	0.68*	0.69*	0.700	0.709	0.725	0.755	0.770	0.786	0.819	0.846	0.871	0.893
400	--	--	--	--	0.678	0.694	0.709	0.720	0.731	0.748	0.785	0.815	0.842	0.867
425	--	--	--	--	0.64*	0.65*	0.666	0.676	0.687	0.716	0.747	0.783	0.812	0.839
450	--	--	--	--	--	--	0.625	0.635	0.645	0.681	0.711	0.750	0.781	0.810
475	--	--	--	--	--	--	--	--	--	0.64*	0.676	0.714	0.747	0.779
500	--	--	--	--	--	--	--	--	--	--	0.63*	0.677	0.718	0.748

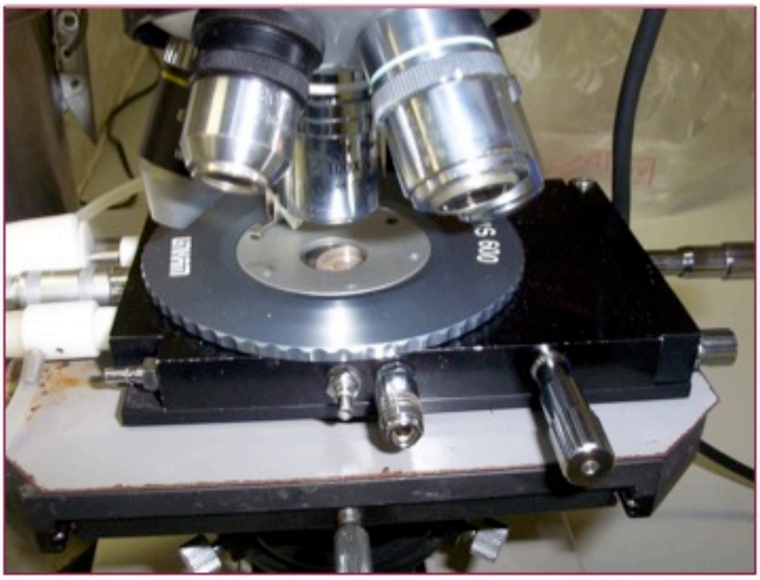
*Extrapolated values


Isochore for aqueous fluid with ~7wt% NaCl
ISOCHORE
Density = 1.001gm/cc
ISOCHORE = A line of constant density in P-T space
P
T


Geofluids Research Laboratory, NUI,Galway
Microthermometric Unit

Linkam THMS 600

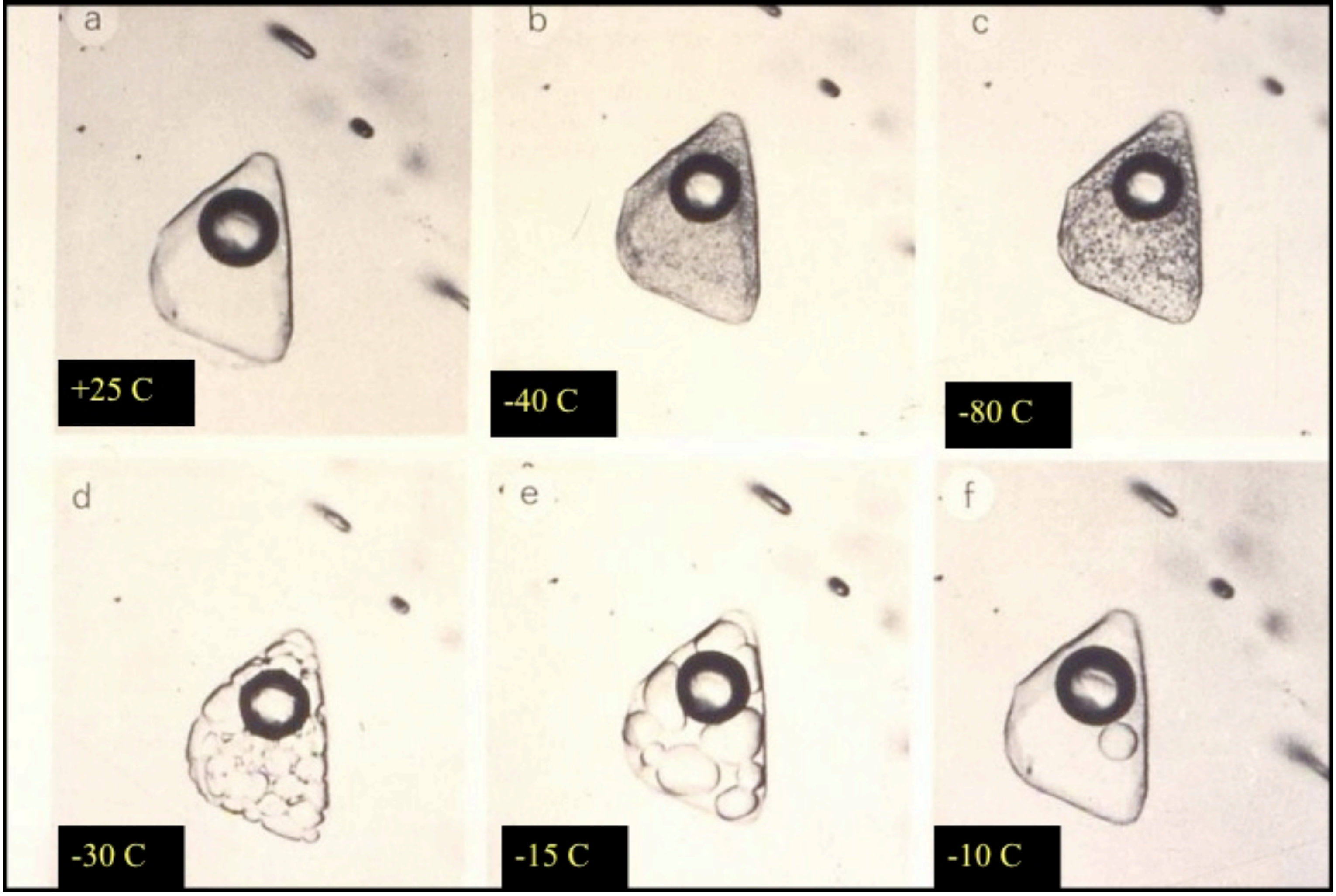
Fluid inclusions are observed using high power objectives (×40, ×60 or ×100).



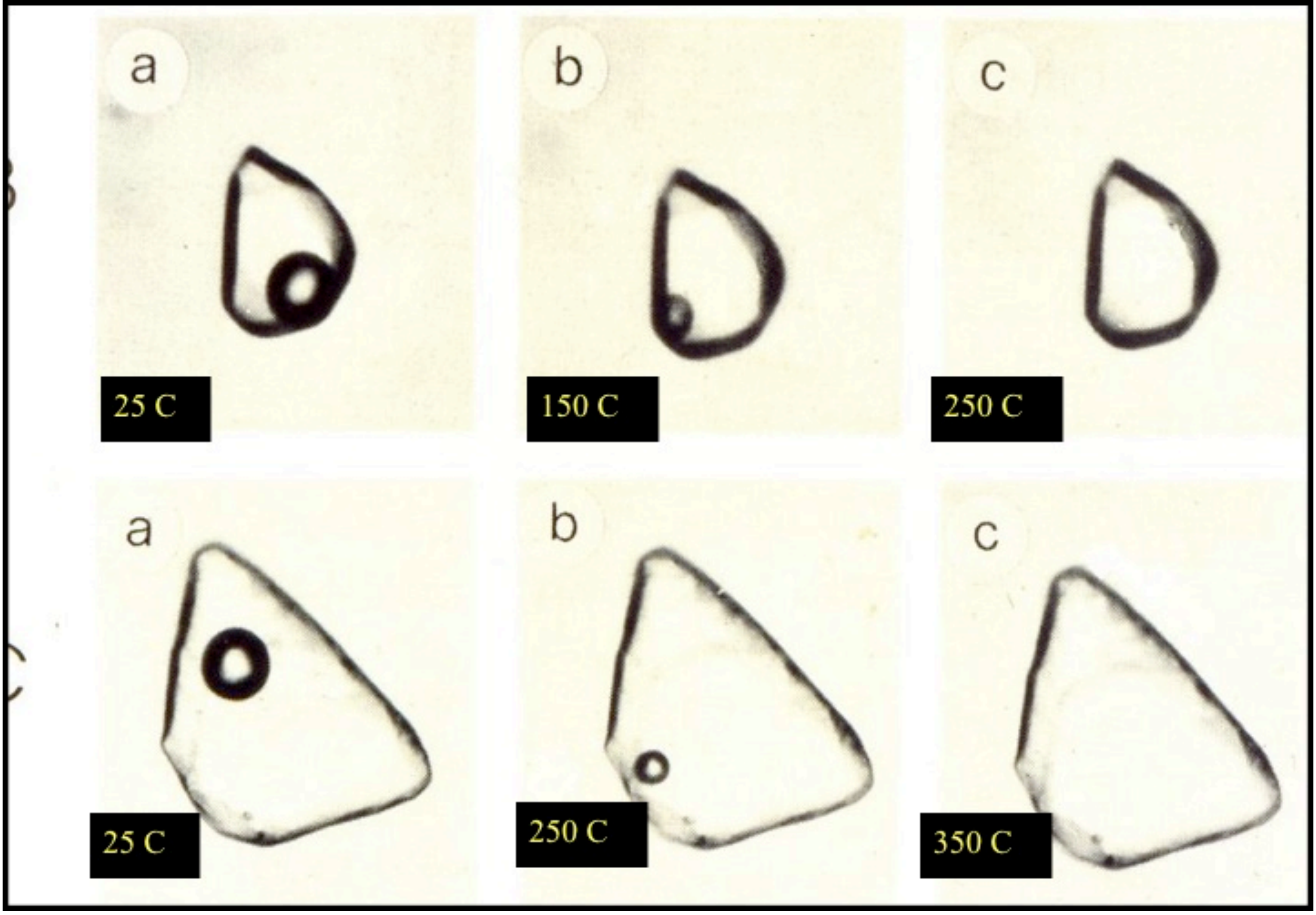
Technical Specifications

Temperature range: -180°C to +600°C
Temperature resolution:0.1C(-180 to+200°C)
1°C (+200 to +600°C)
Temperature control: fully automatic
and programmable
Max sample size: 20 mm diameter;
1.5 mm thickness
Viewing area: 2.2 mm diameter

TWO-PHASE AQUEOUS INCLUSION FREEZING RUN



TWO-PHASE AQUEOUS INCLUSION ON A HEATING RUN



An animated introduction to fluid inclusions

by

A H Rankin
School of Earth Sciences and Geography
Kingston University, Surrey KT1 2EE

http://www.kingston.ac.uk/esg/

KINGSTON UNIVERSITY

The following slides illustrate how primary (P) and secondary (S) inclusions develop during crystal growth and healing of secondary fractures

Some animation has been added

To see changes hit return

Aqueous solution

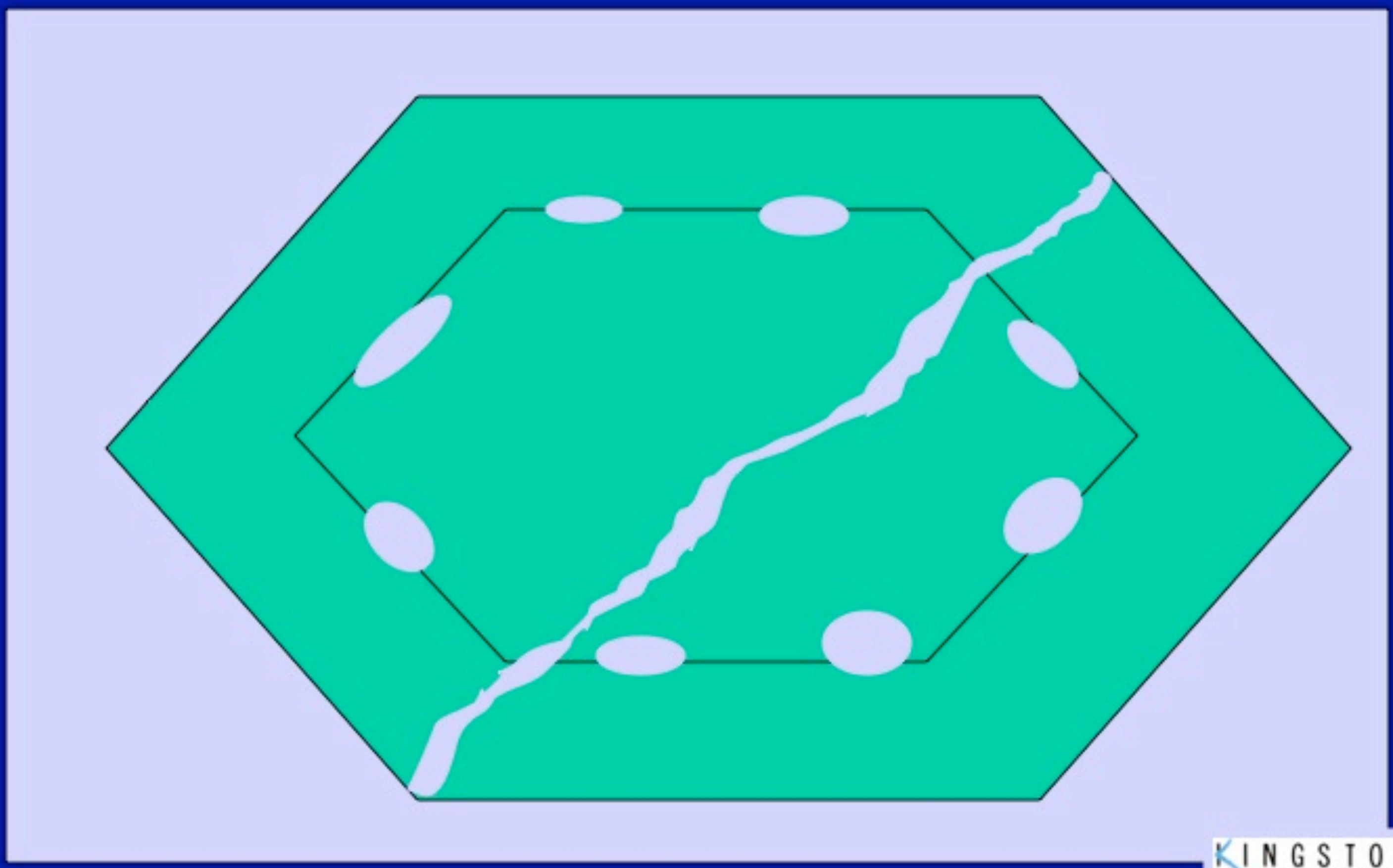
Crystal

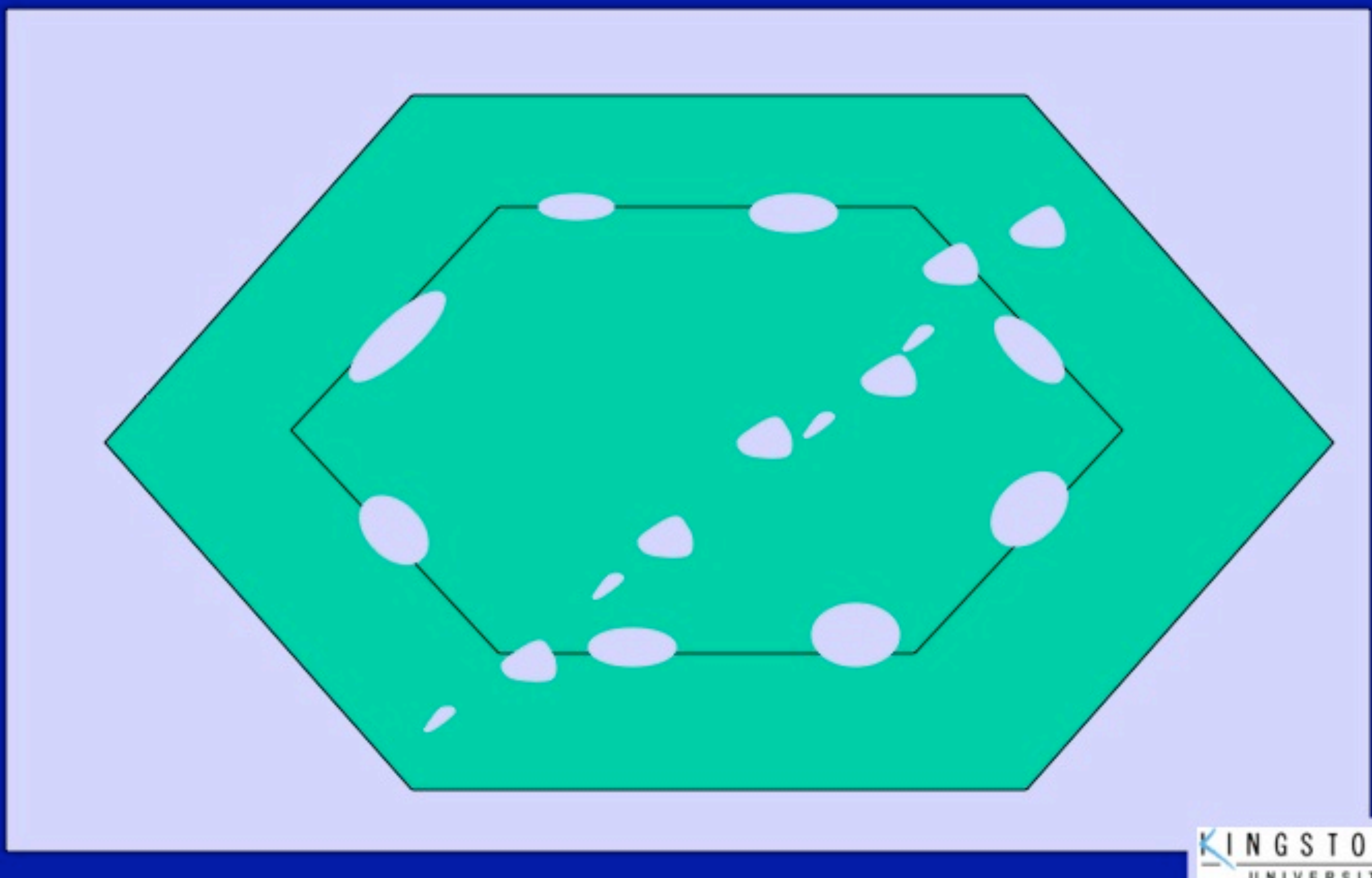
KINGSTON UNIVERSITY

Formation of Primary and Secondary inclusions

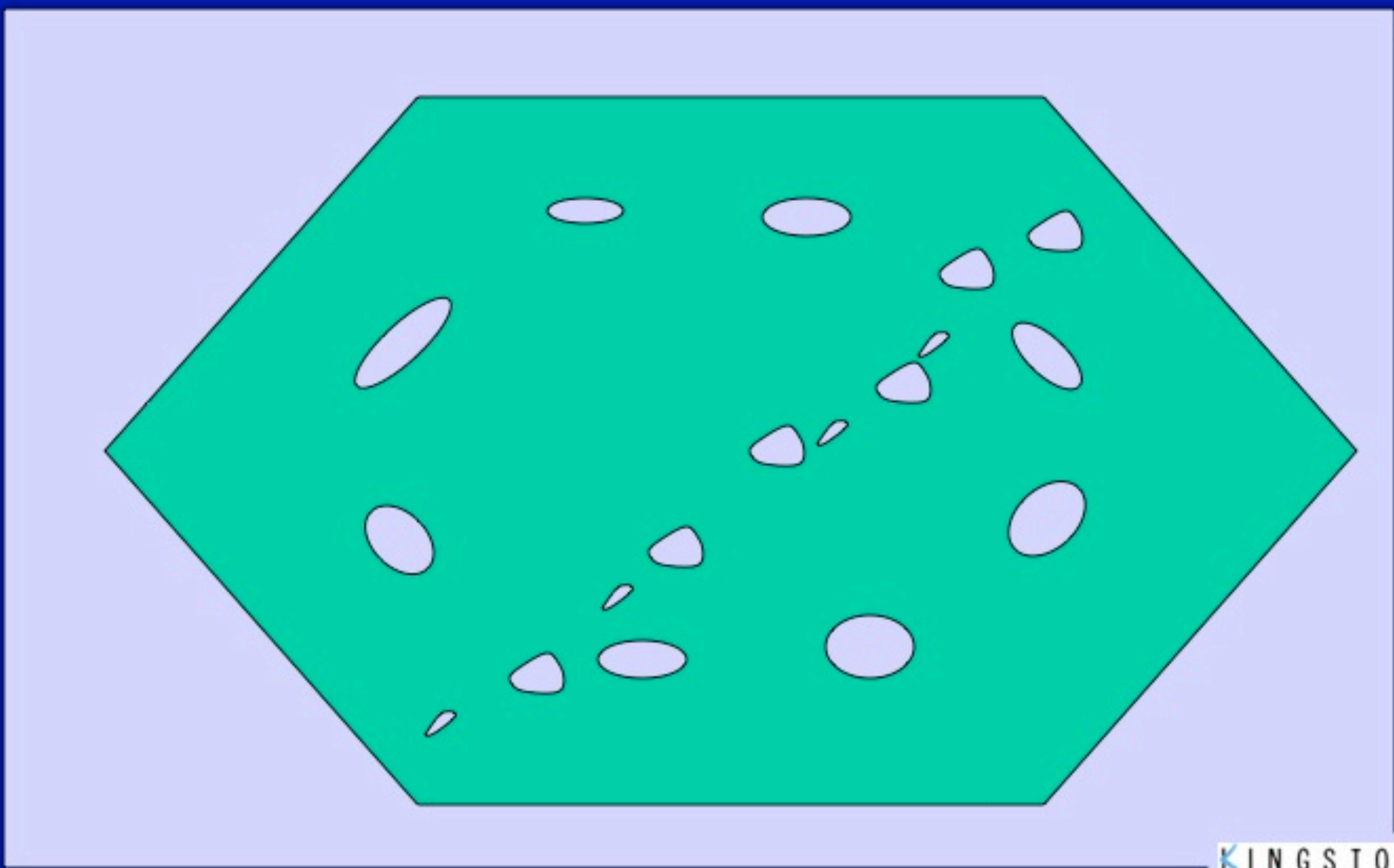
primary inclusions form during primary crystal growth often along growth zones

secondary inclusions form after primary growth, usually along healed micro-fractures

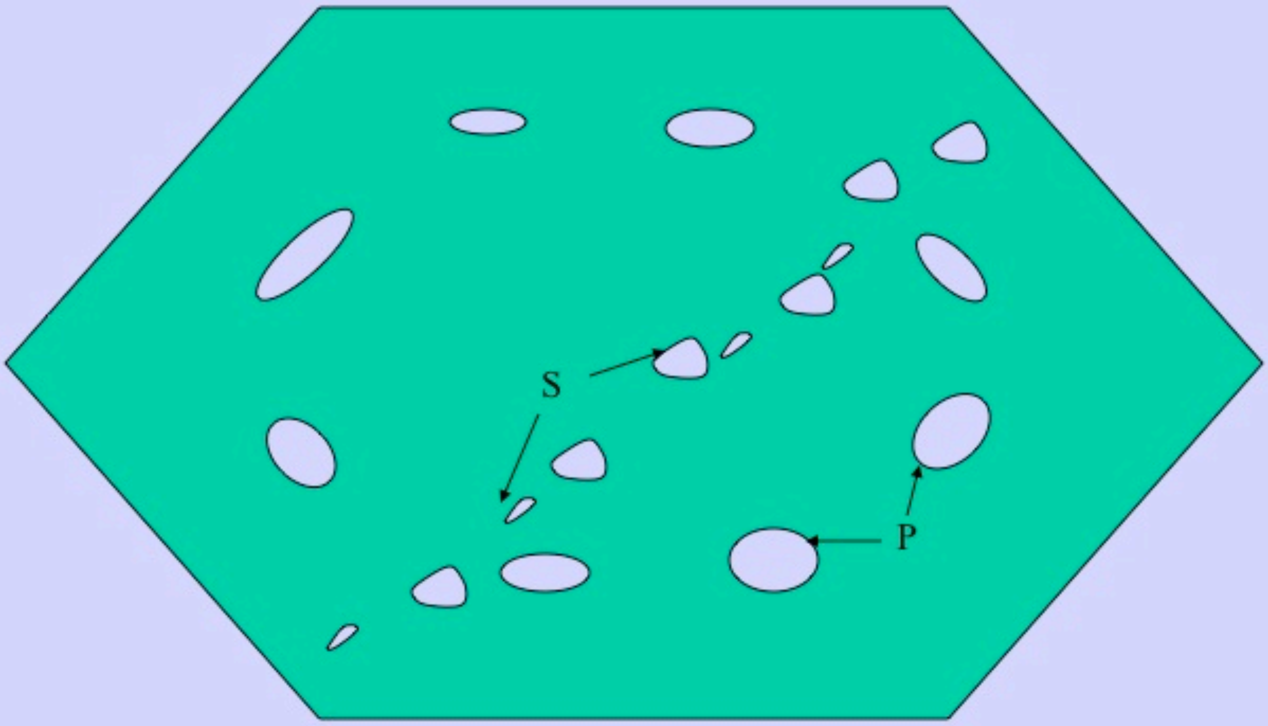




KINGSTON UNIVERSITY

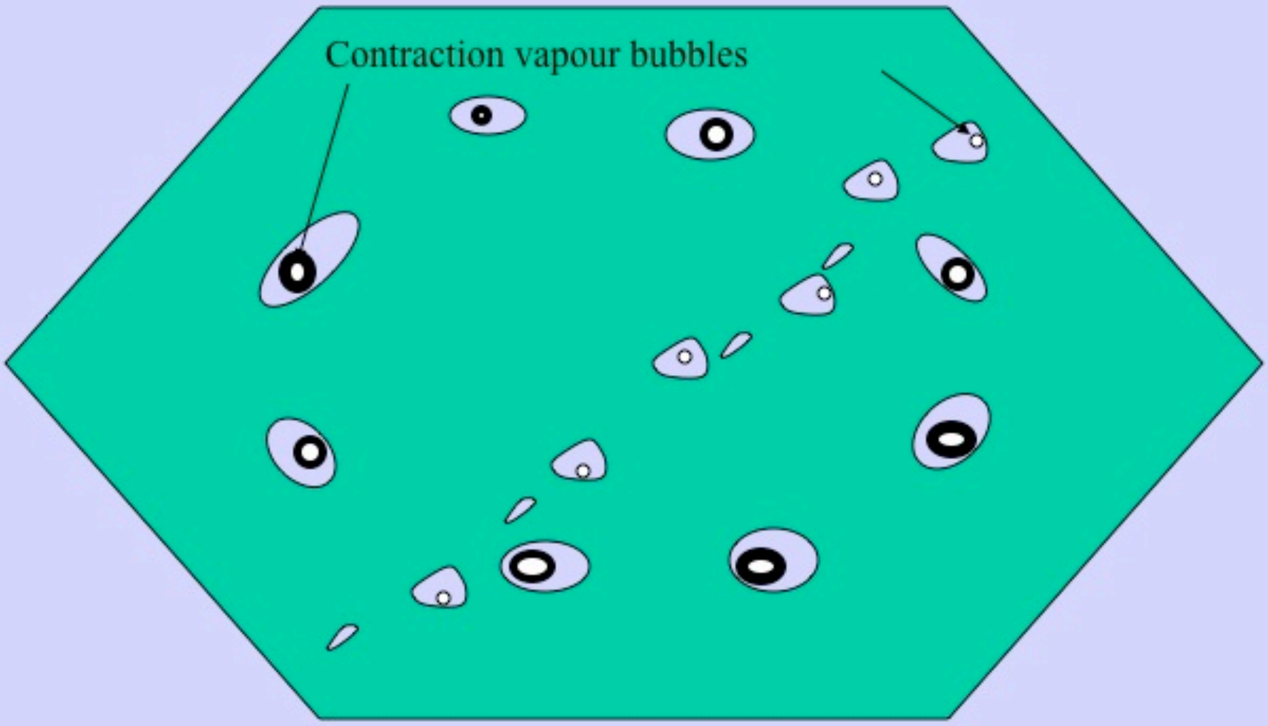


KINGSTON UNIVERSITY


S
P

Inclusions formed from trapping of homogeneous aqueous fluid will develop vapour bubbles on cooling due to differential thermal contraction of fluid and host mineral.

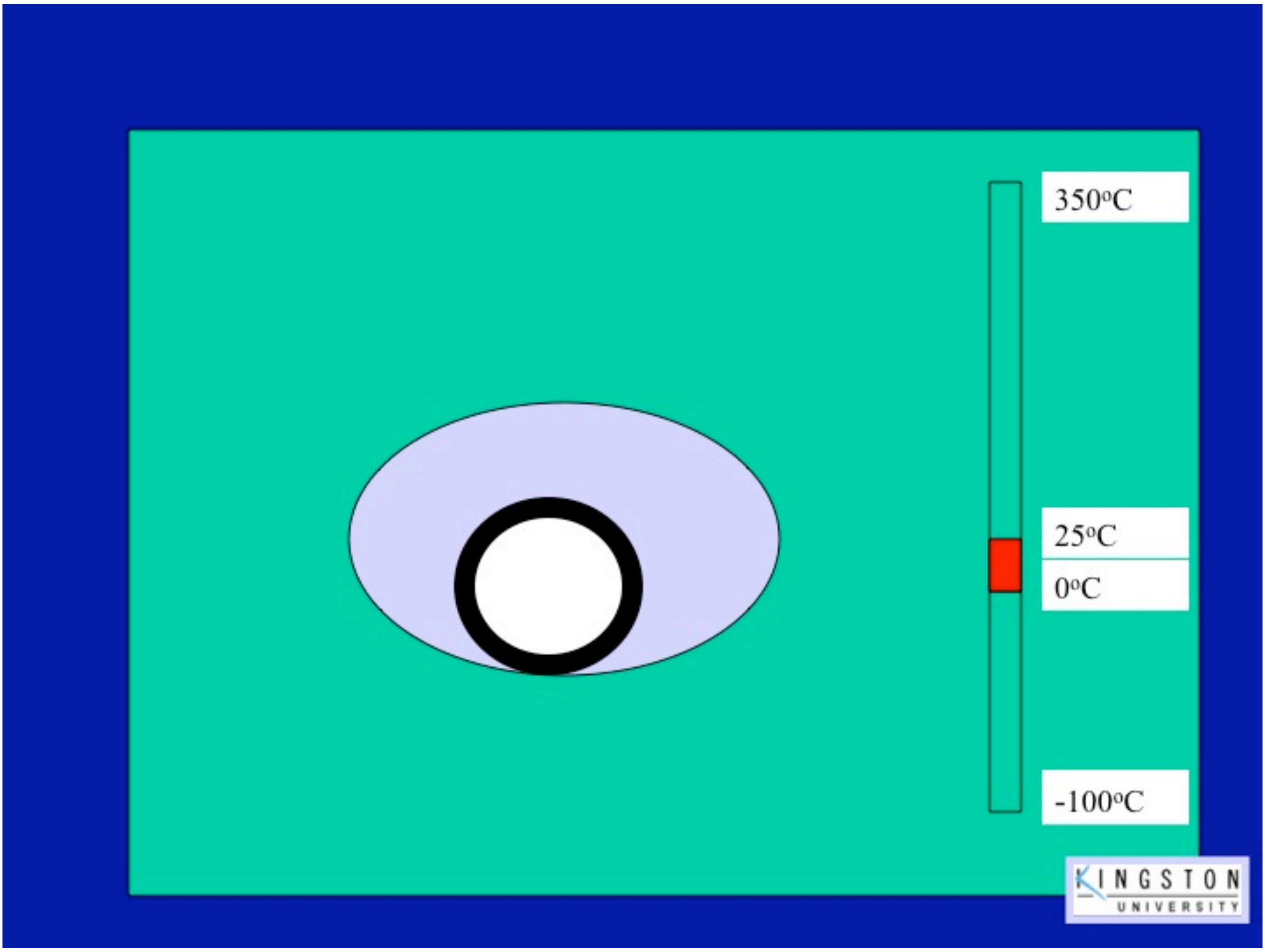
The next slide shows groups of two phase (vapour- liquid) primary and secondary inclusions with distinctly different vapour-liquid ratios, indicative of different PT trapping conditions

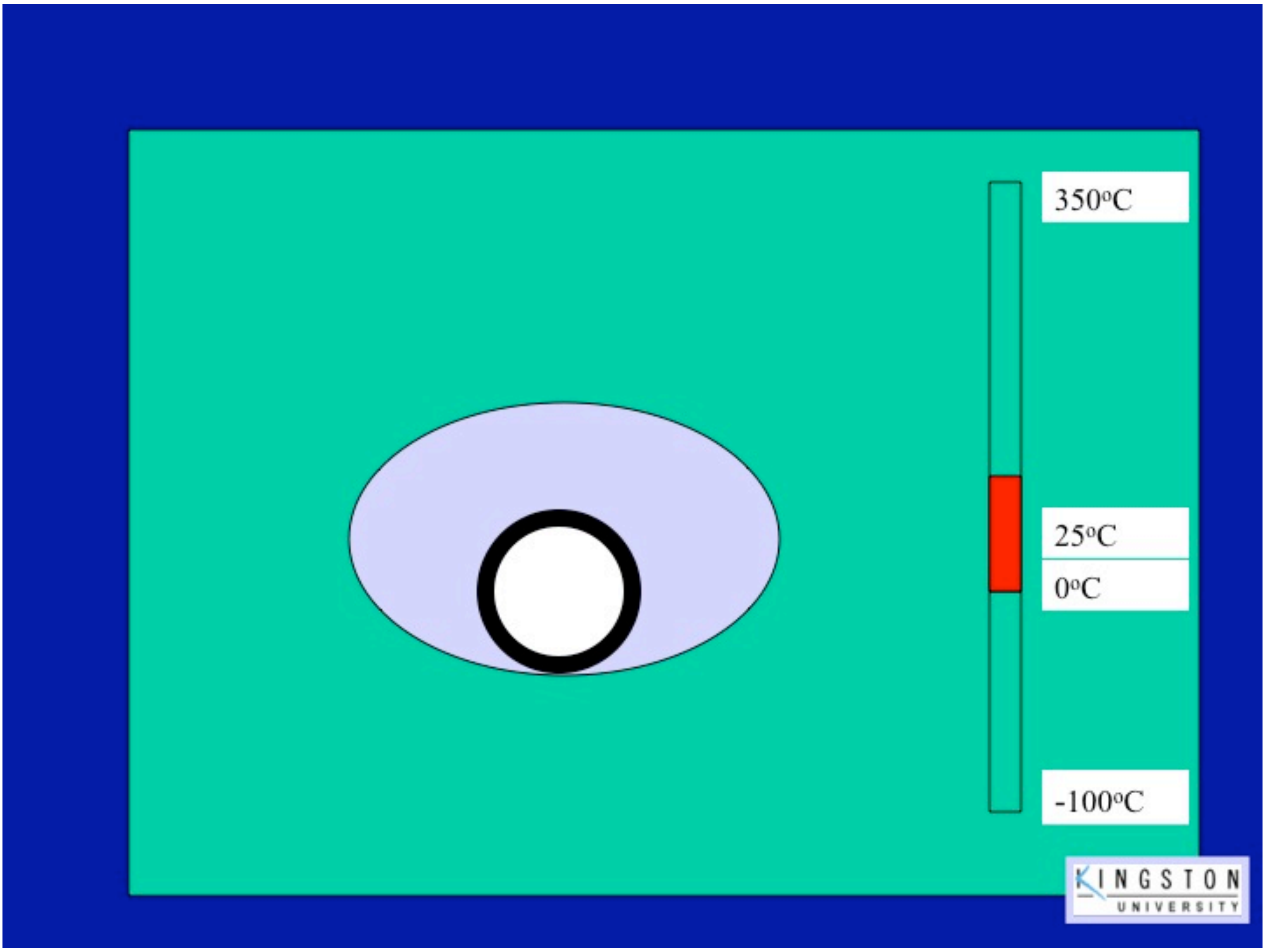

Contraction vapour bubbles

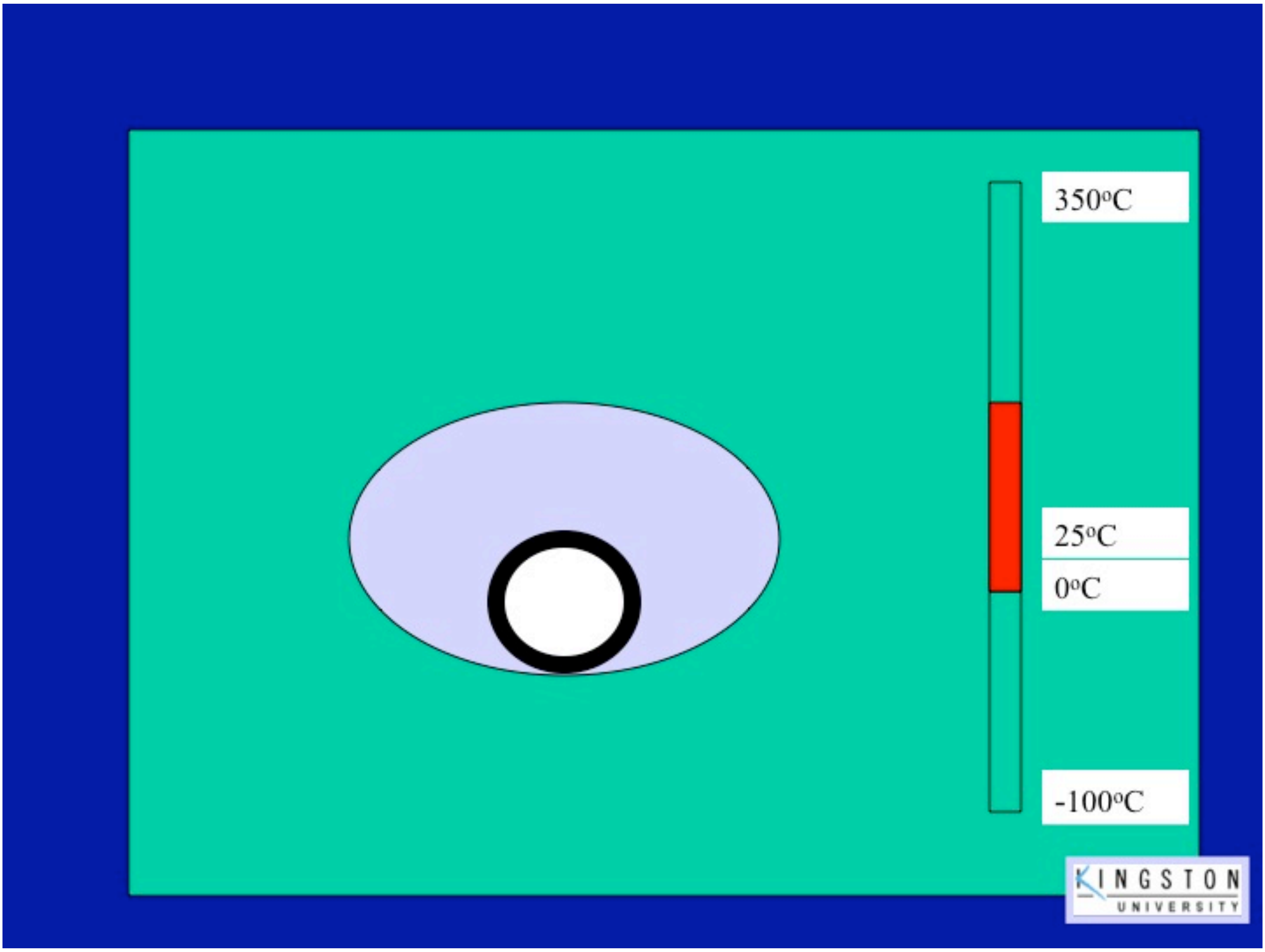
The following slides show the homogenisation of liquid and vapour in a two phase aqueous inclusion during laboratory heating. The temperature at which this occurs is the *Homogenisation temperature* (Th) The bubble returns on cooling.

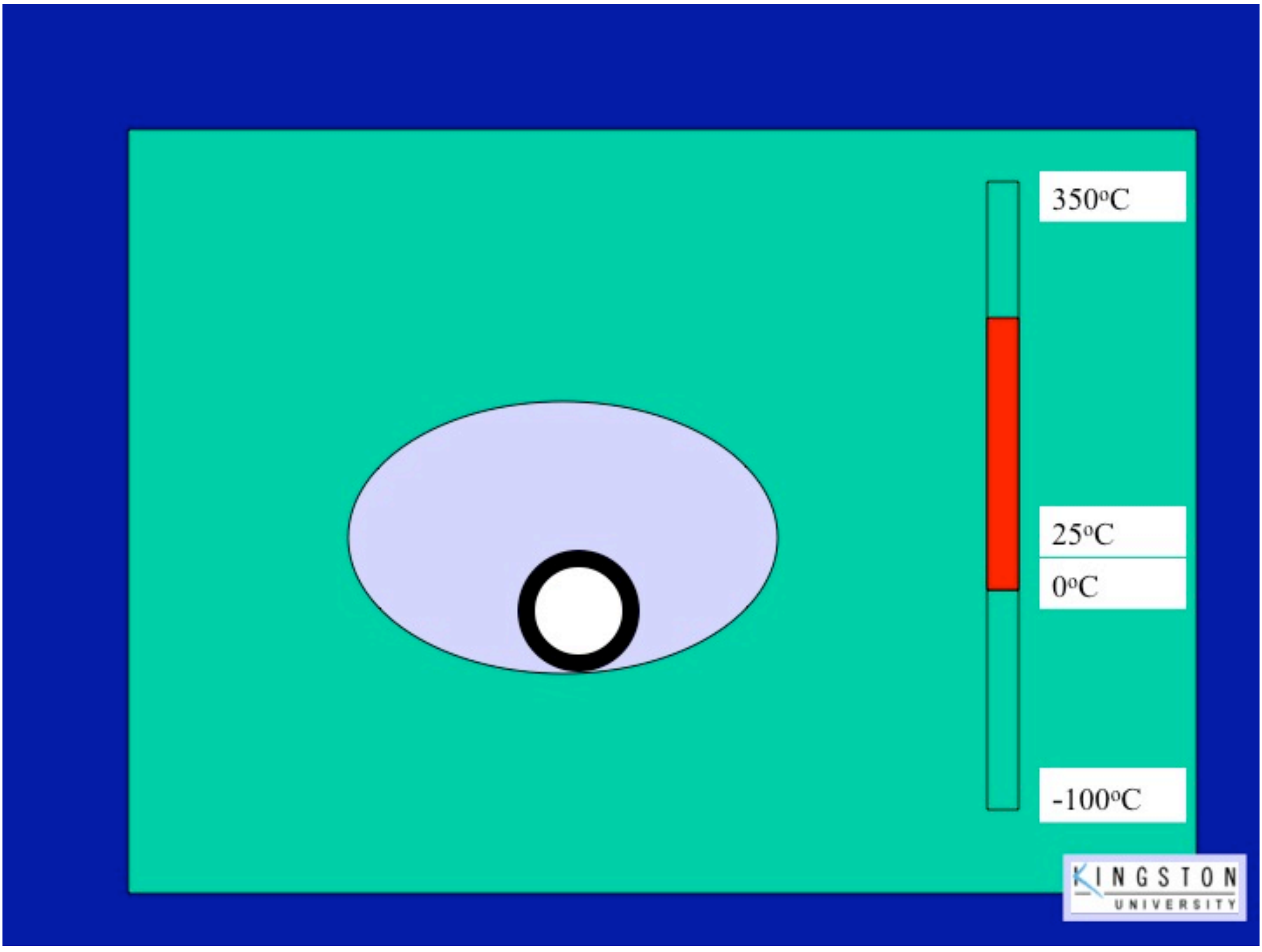
Heating

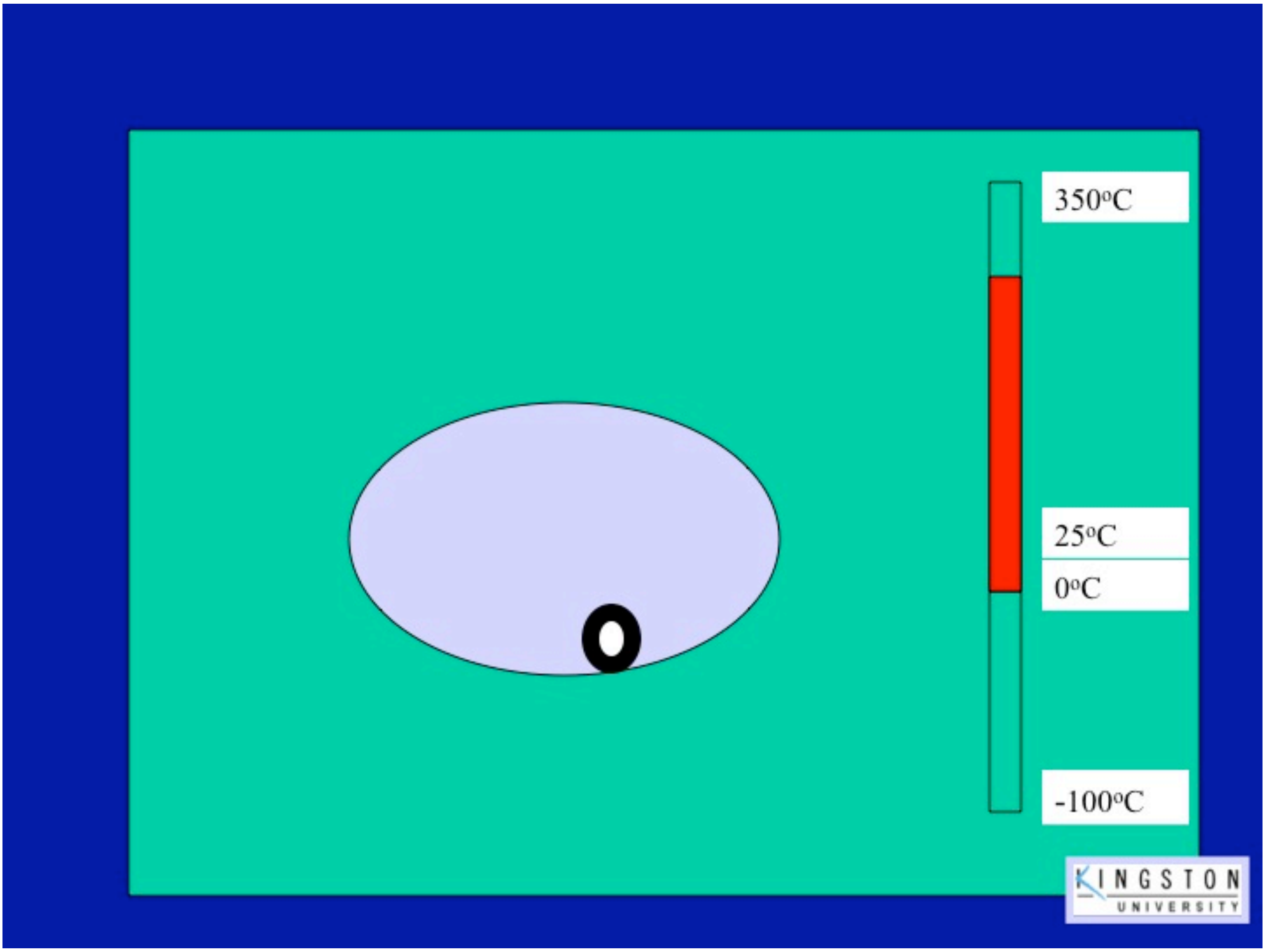
Cooling

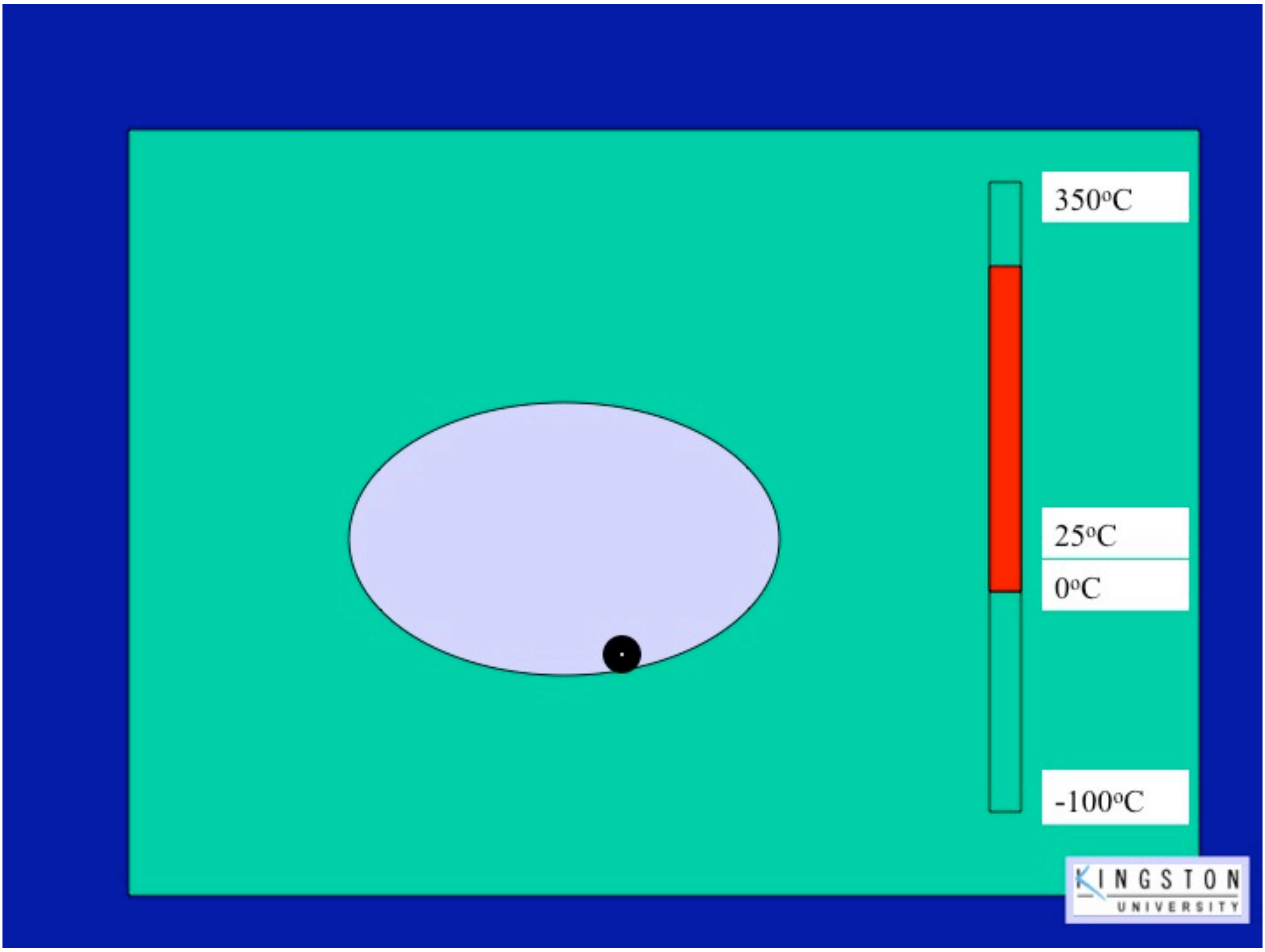

350°C
25°C
0°C
-100°C

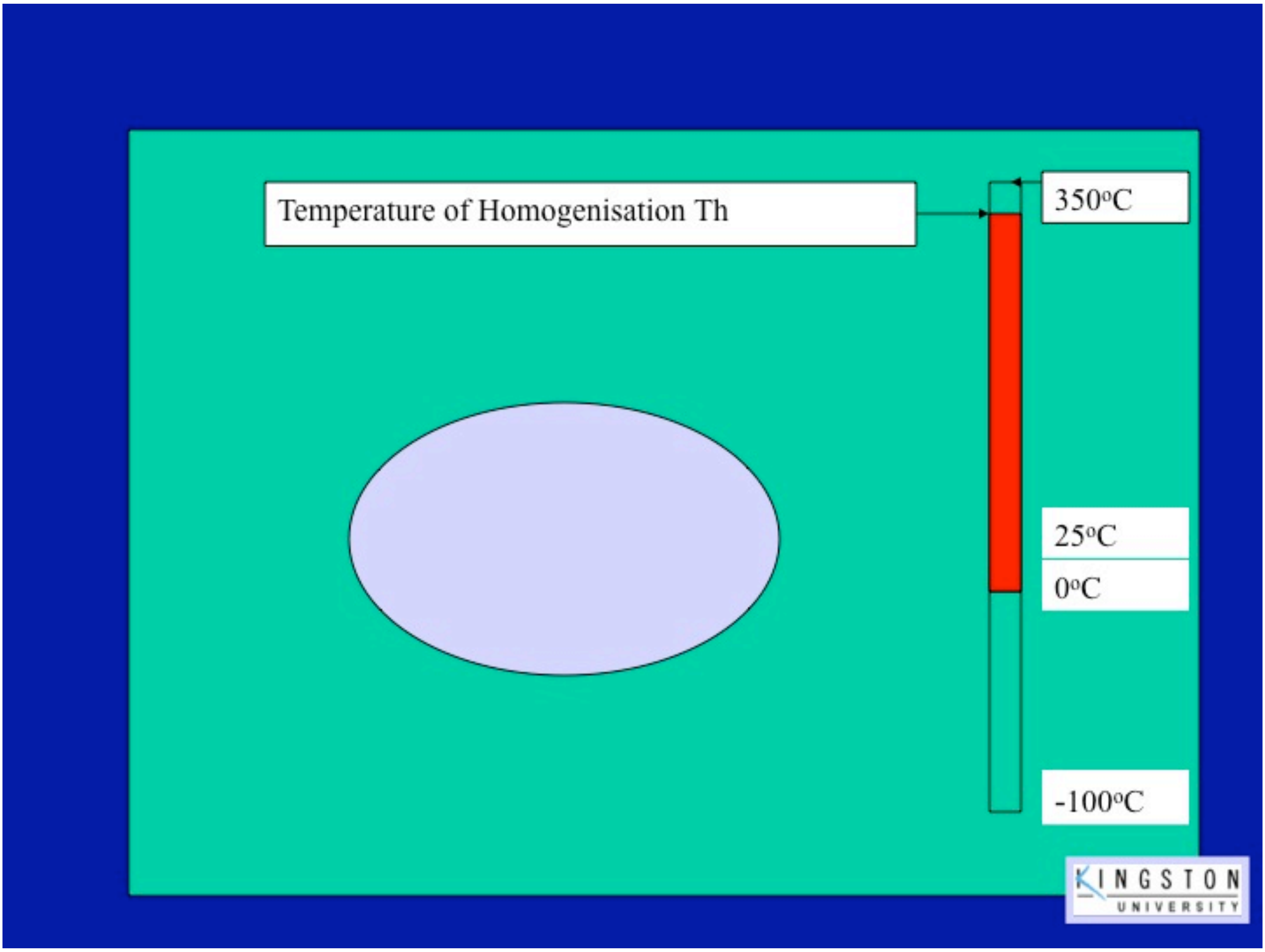

350°C
25°C
0°C
-100°C

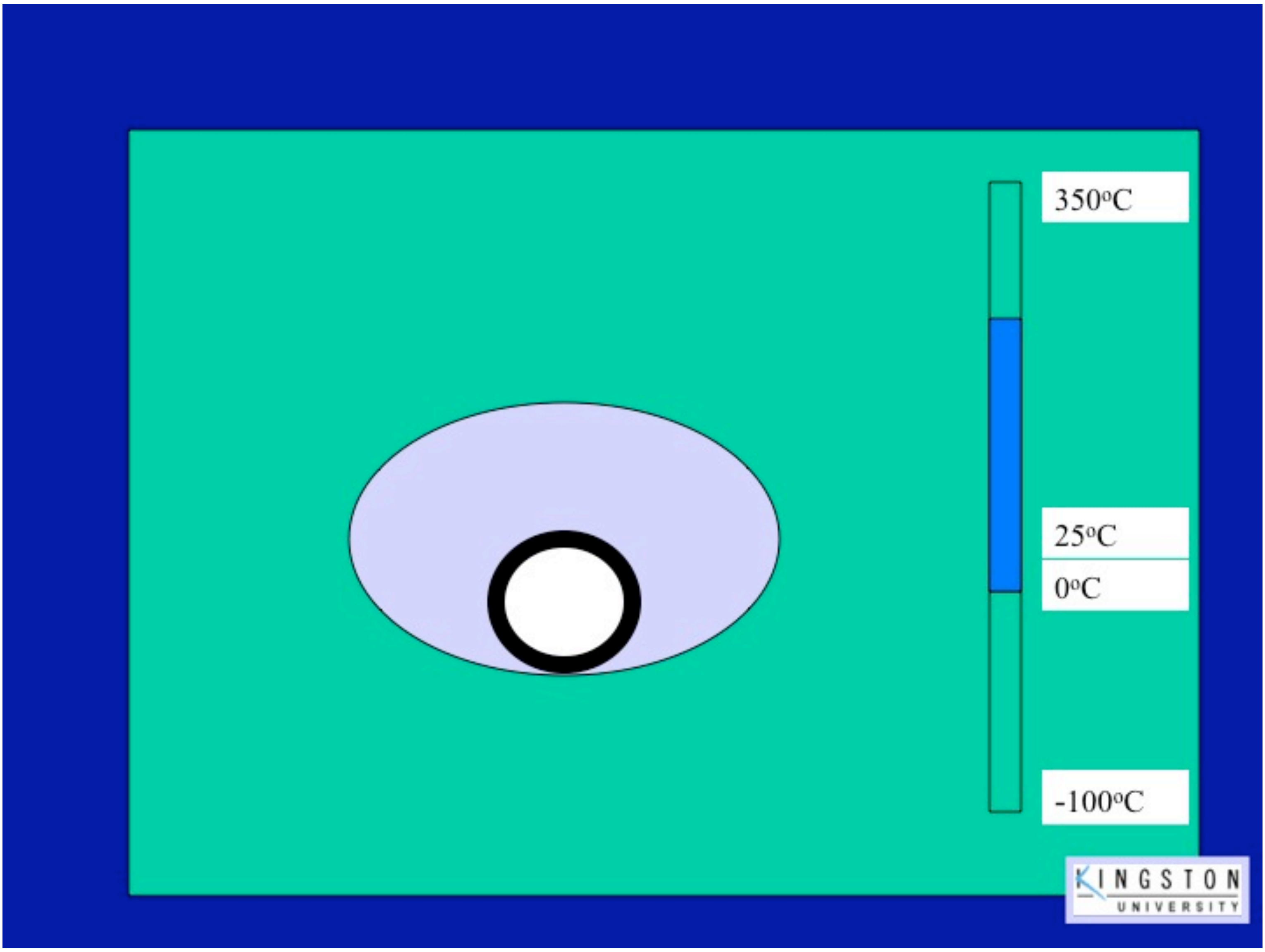

350°C
25°C
0°C
-100°C
KINGSTON UNIVERSITY


350°C
25°C
0°C
-100°C
KINGSTON
UNIVERSITY

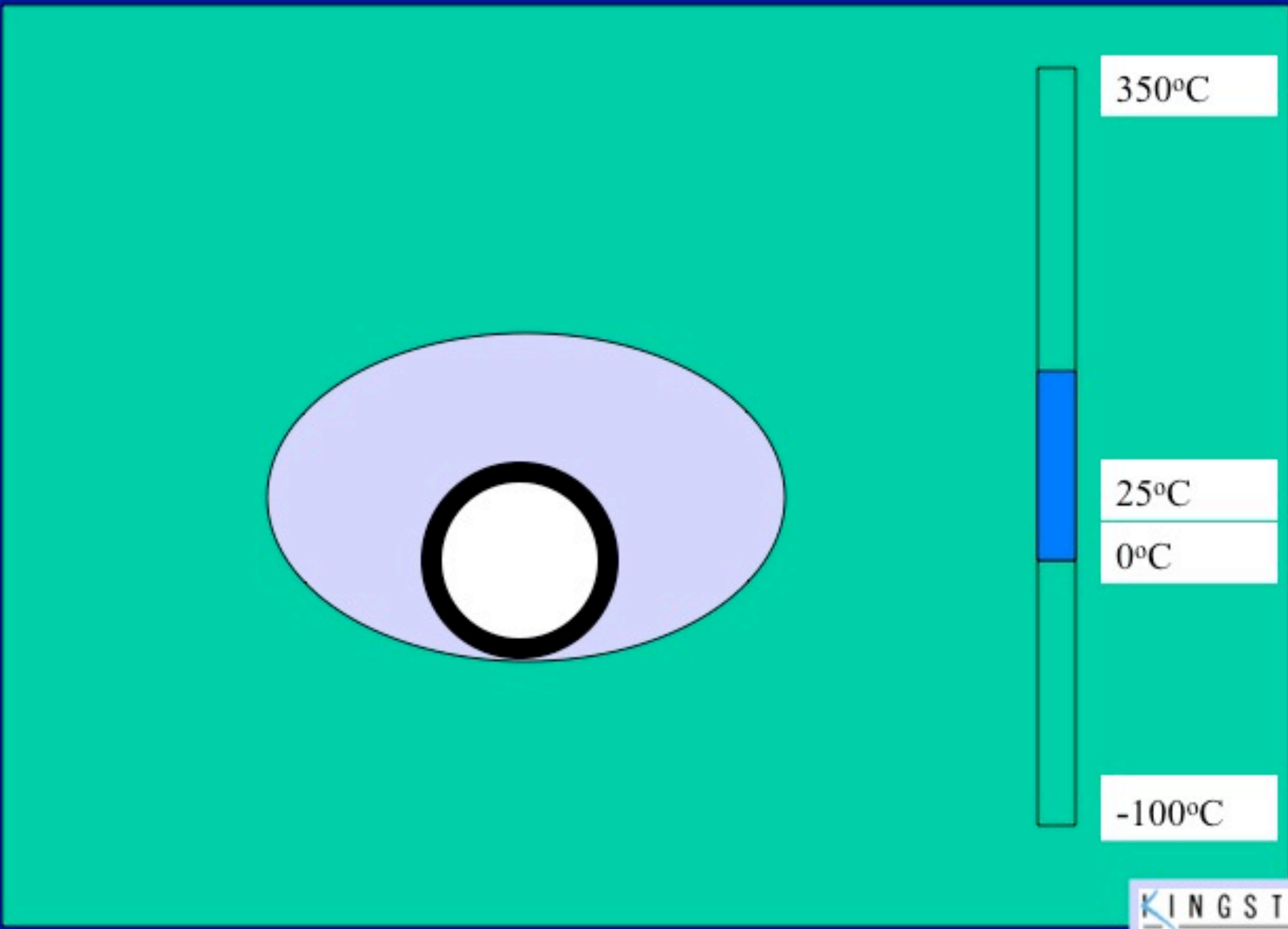

350°C
25°C
0°C
-100°C


350oC
25oC
0oC
-100oC
KINGSTON UNIVERSITY

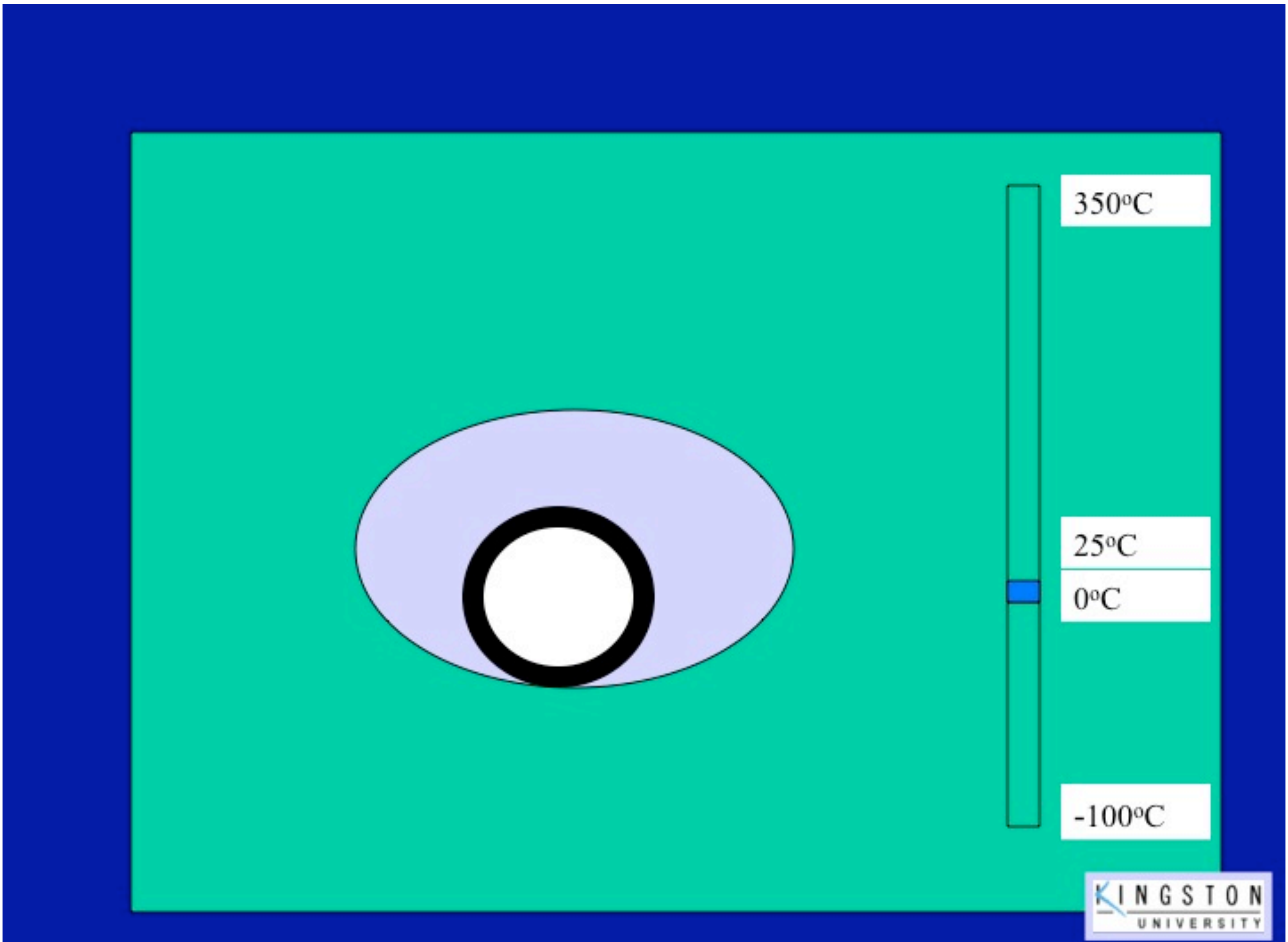

Temperature of Homogenisation Th
350°C
25°C
0°C
-100°C
KINGSTON UNIVERSITY

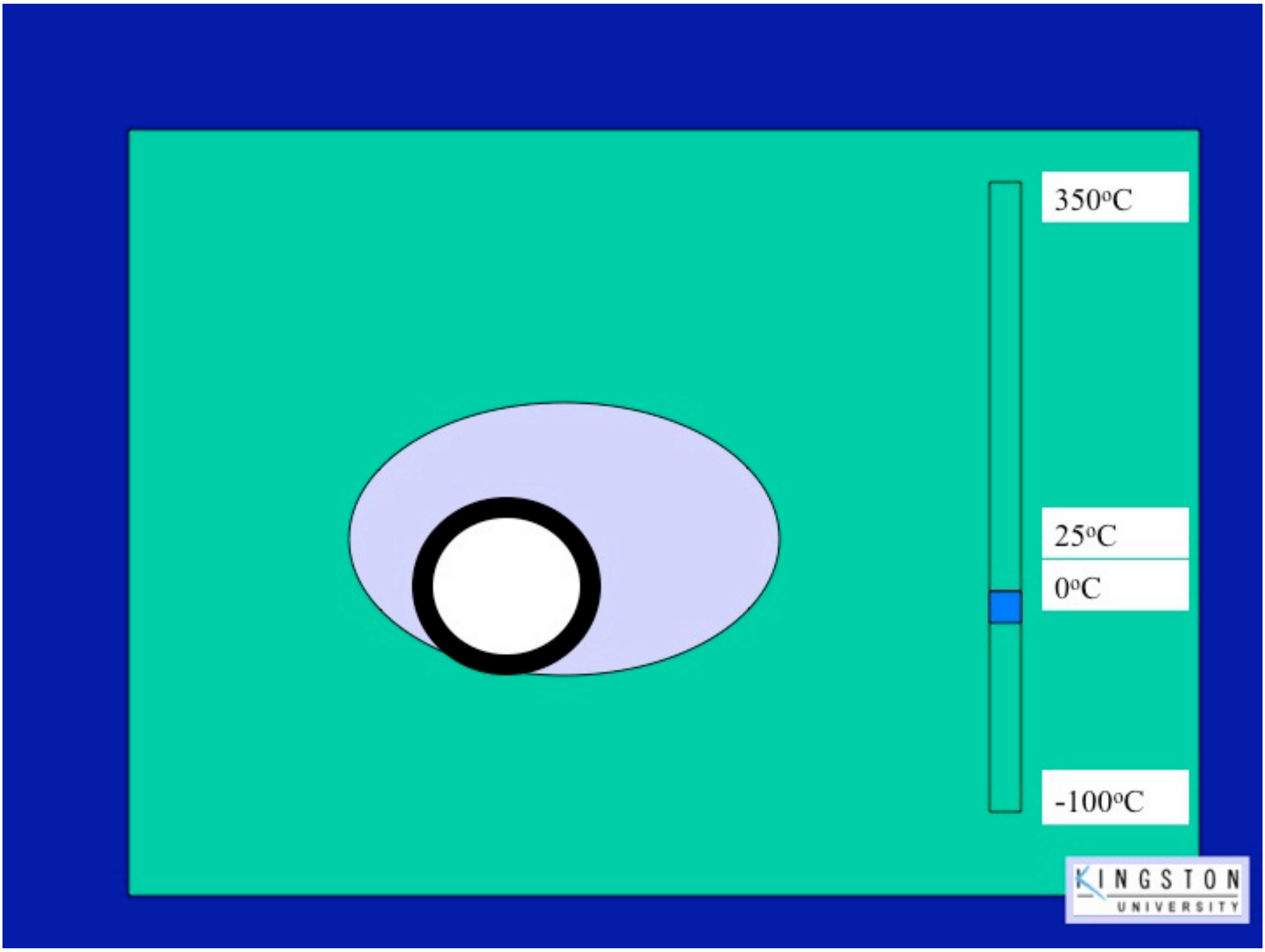


350°C
25°C
0°C
-100°C
KINGSTON
UNIVERSITY



350°C
25°C
0°C
-100°C


350°C
25°C
0°C
-100°C
KINGSTON UNIVERSITY

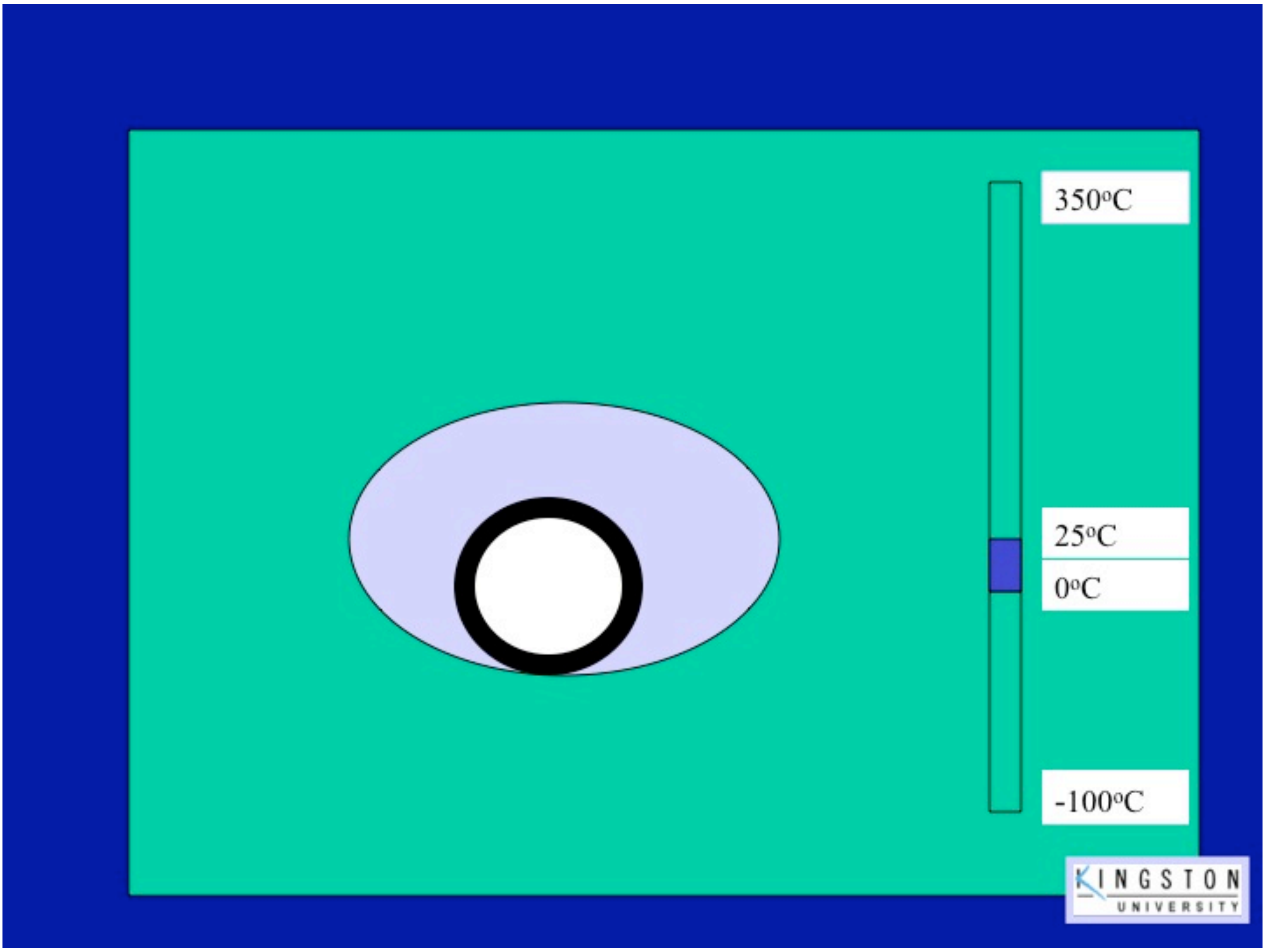

350°C
25°C
0°C
-100°C
KINGSTON UNIVERSITY

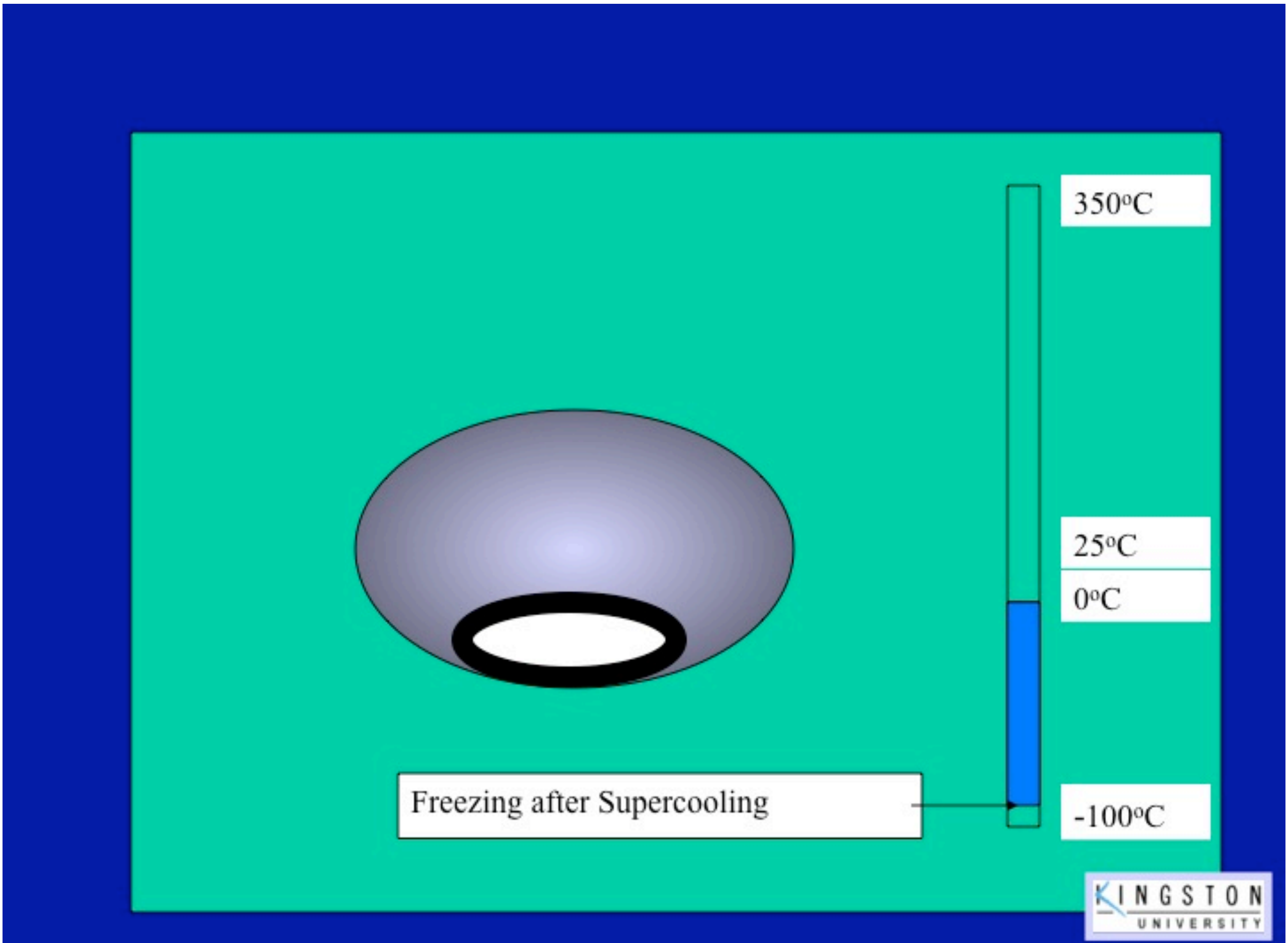
The next slides show the freezing and subsequent melting of a two phase aqueous inclusion. Note the first and last melting temperatures which tell us about composition

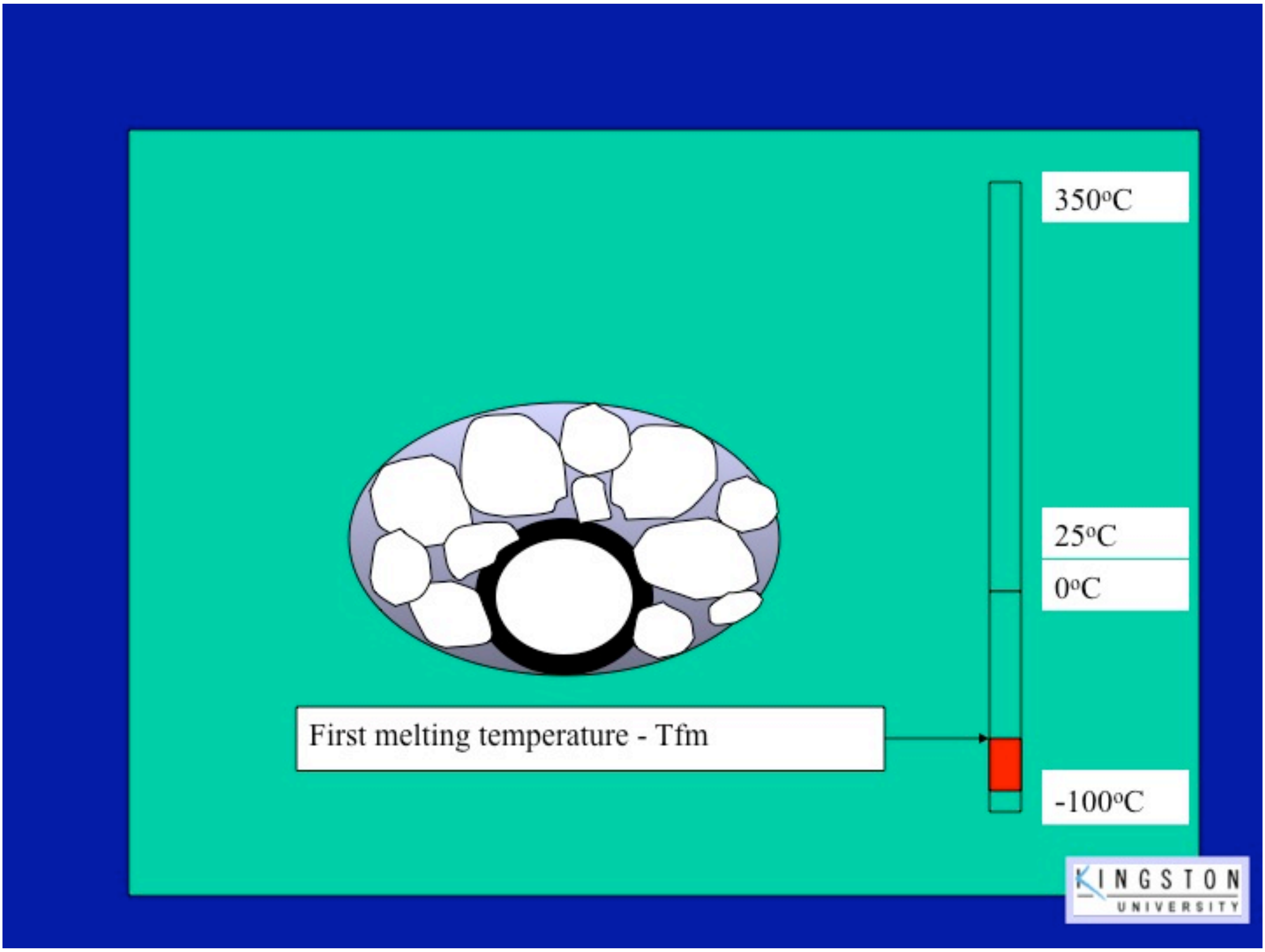
Heating

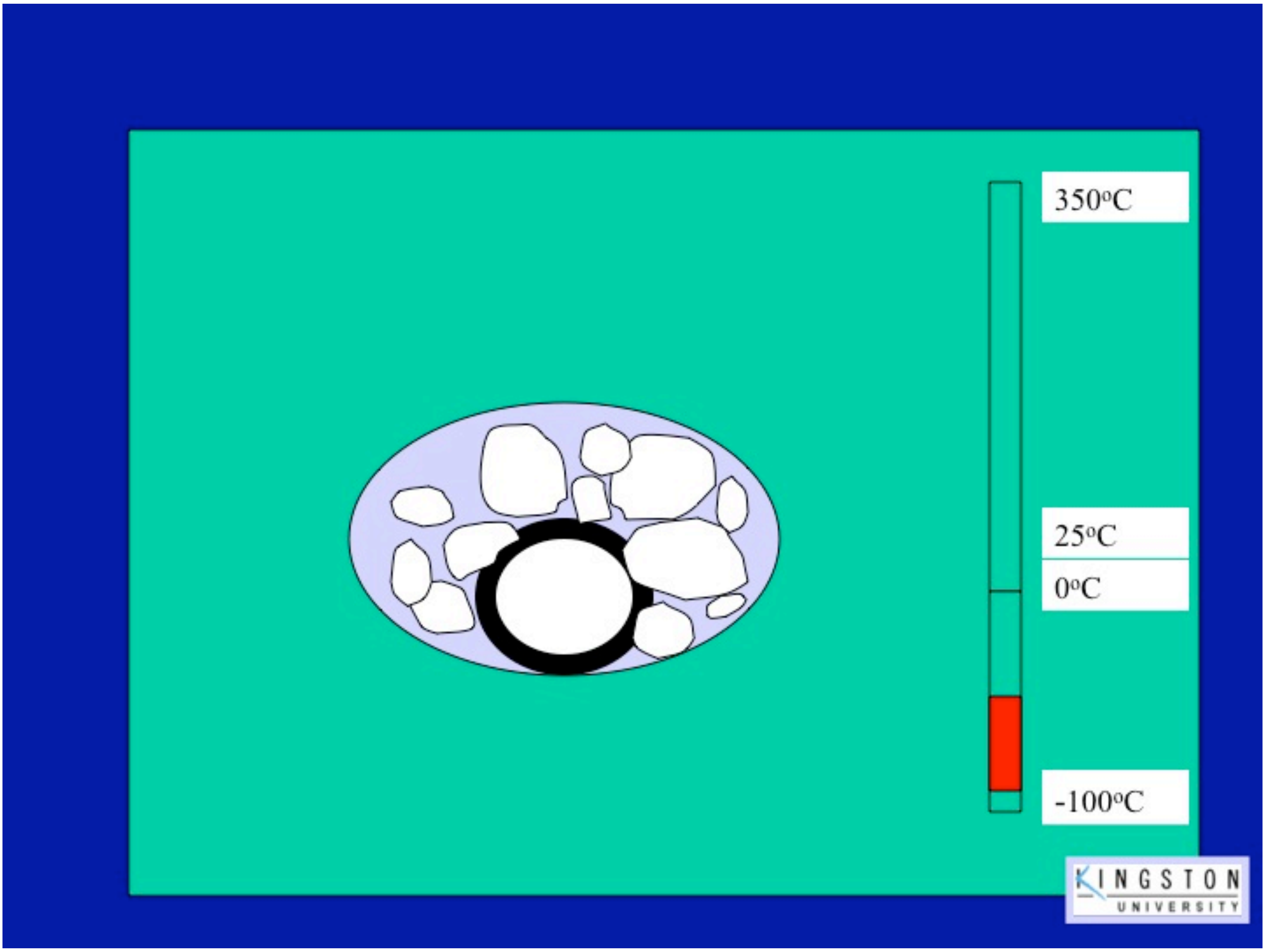
Cooling

KINGSTON UNIVERSITY

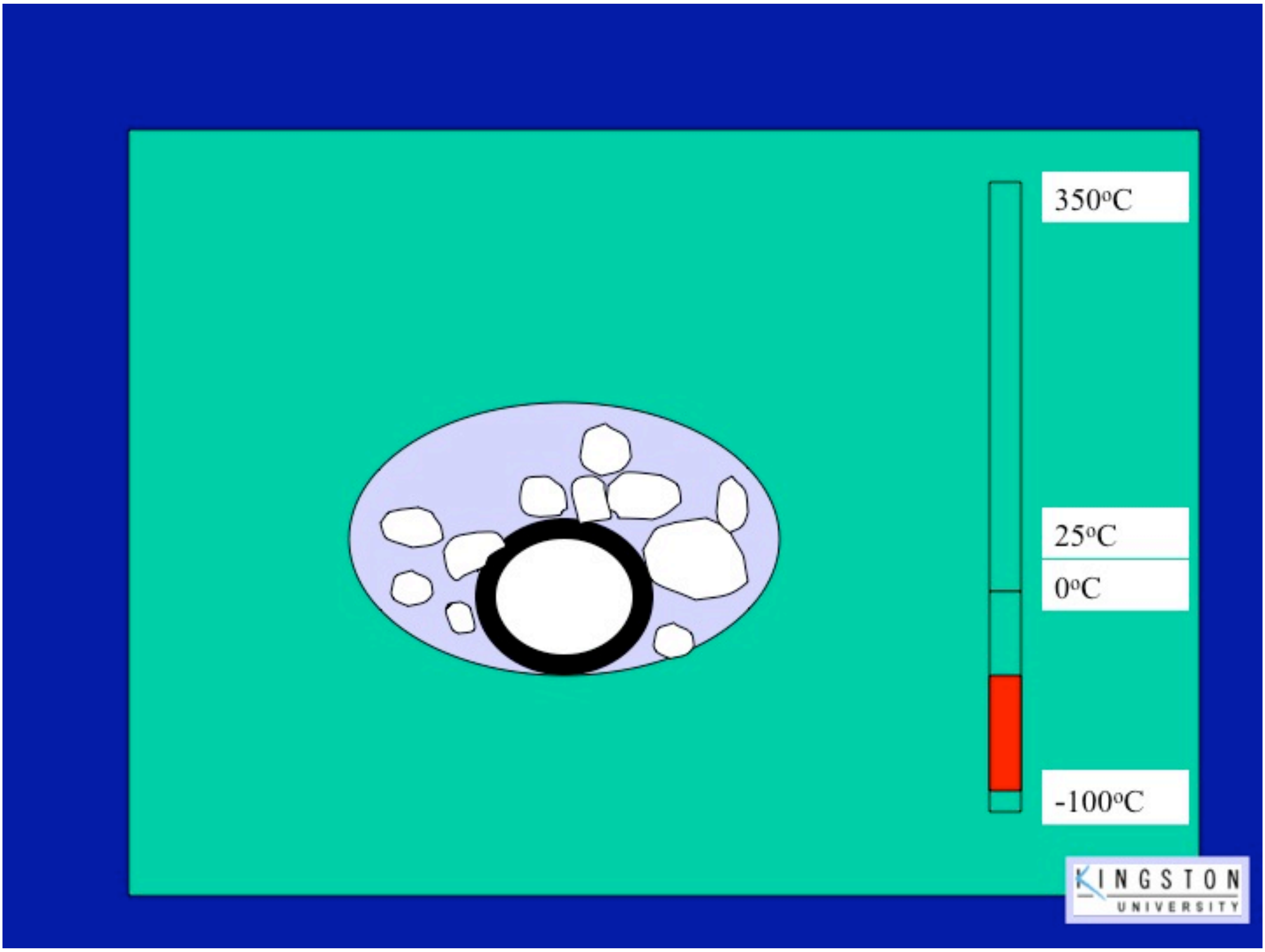

350°C
25°C
0°C
-100°C
KINGSTON
UNIVERSITY


350°C
25°C
0°C
-100°C
Freezing after Supercooling
KINGSTON UNIVERSITY

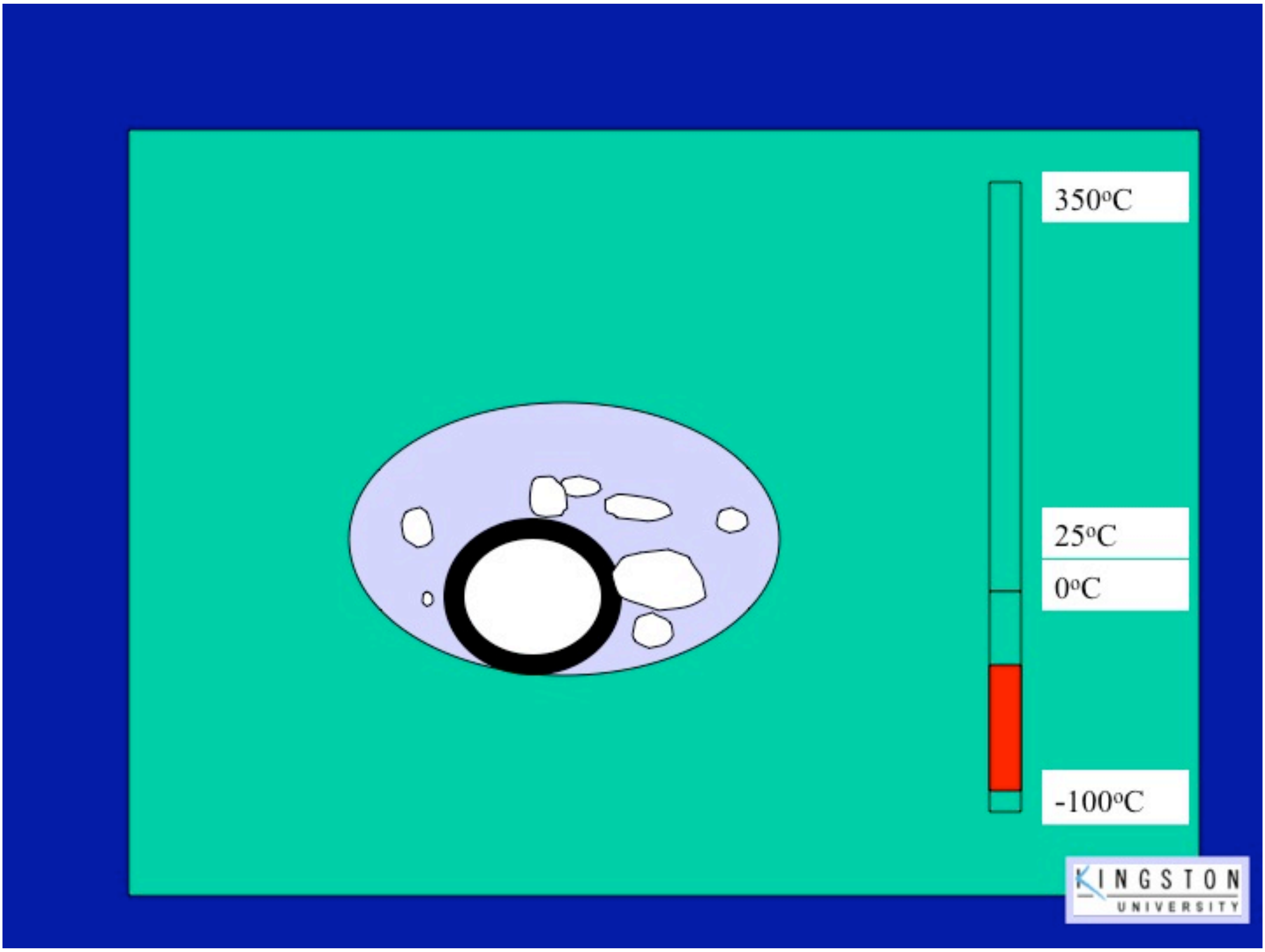

350°C
25°C
0°C
First melting temperature - Tfm
-100°C
KINGSTON UNIVERSITY



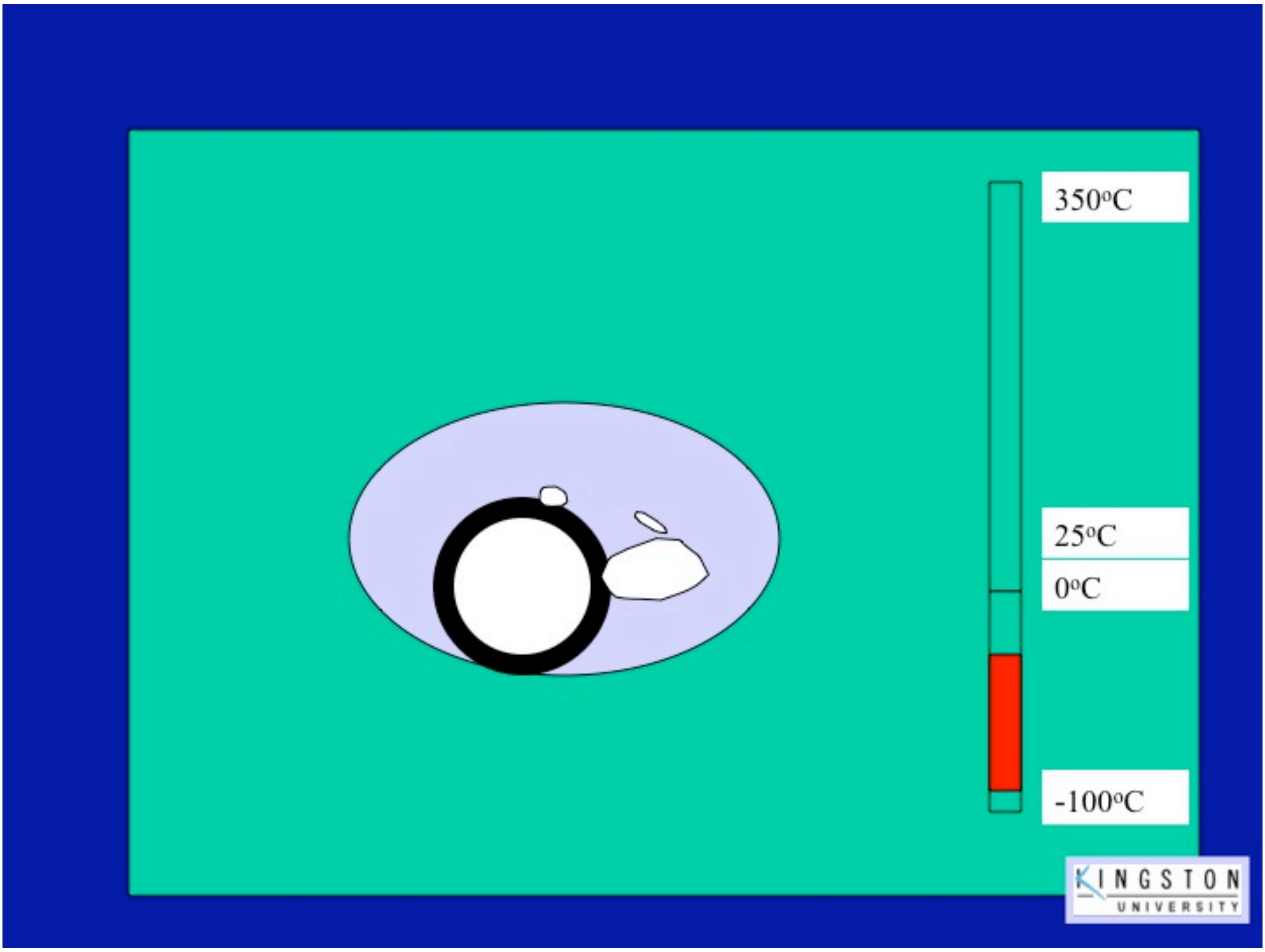
350°C
25°C
0°C
-100°C
KINGSTON UNIVERSITY

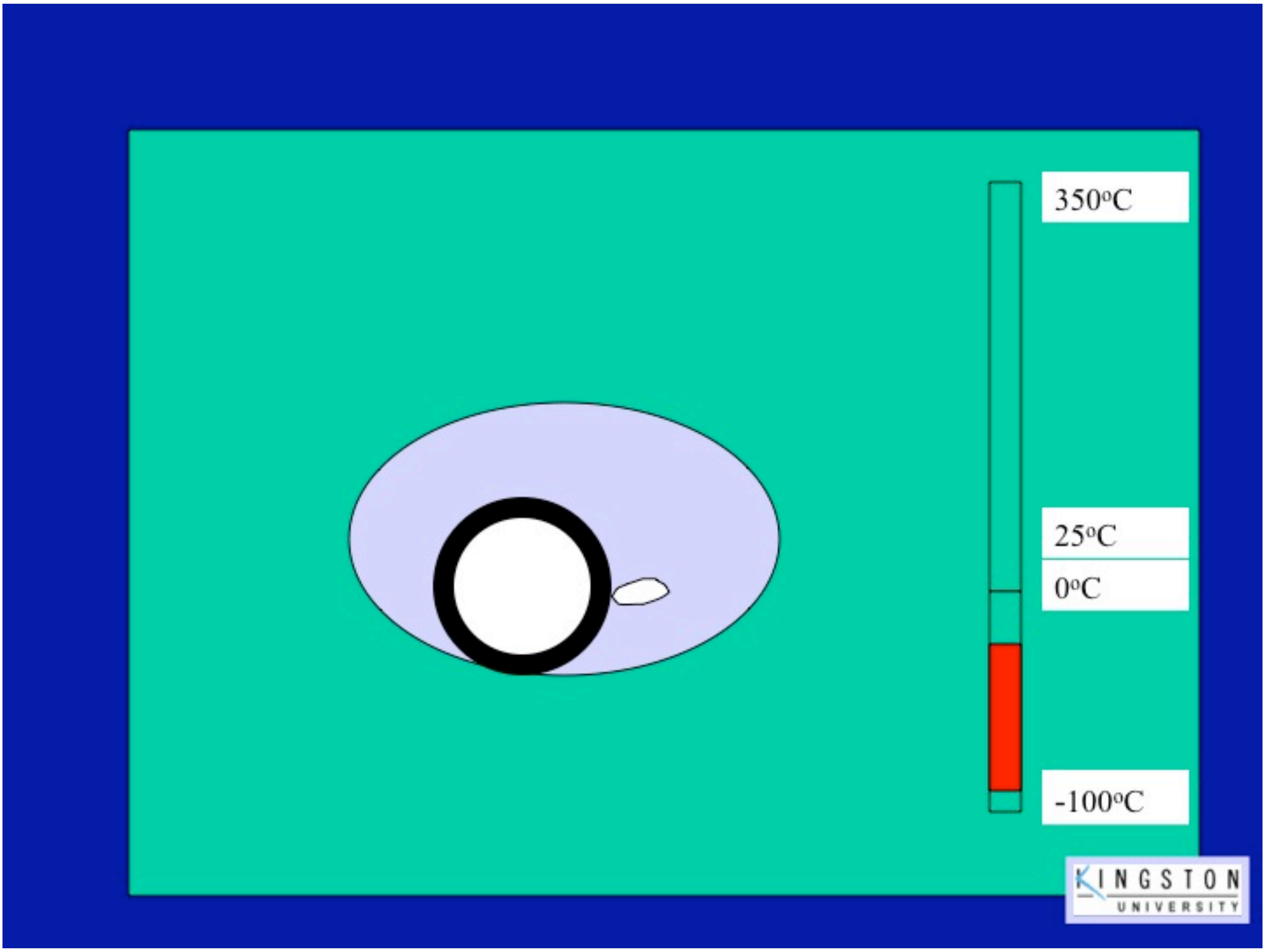


350°C
25°C
0°C
-100°C
KINGSTON UNIVERSITY

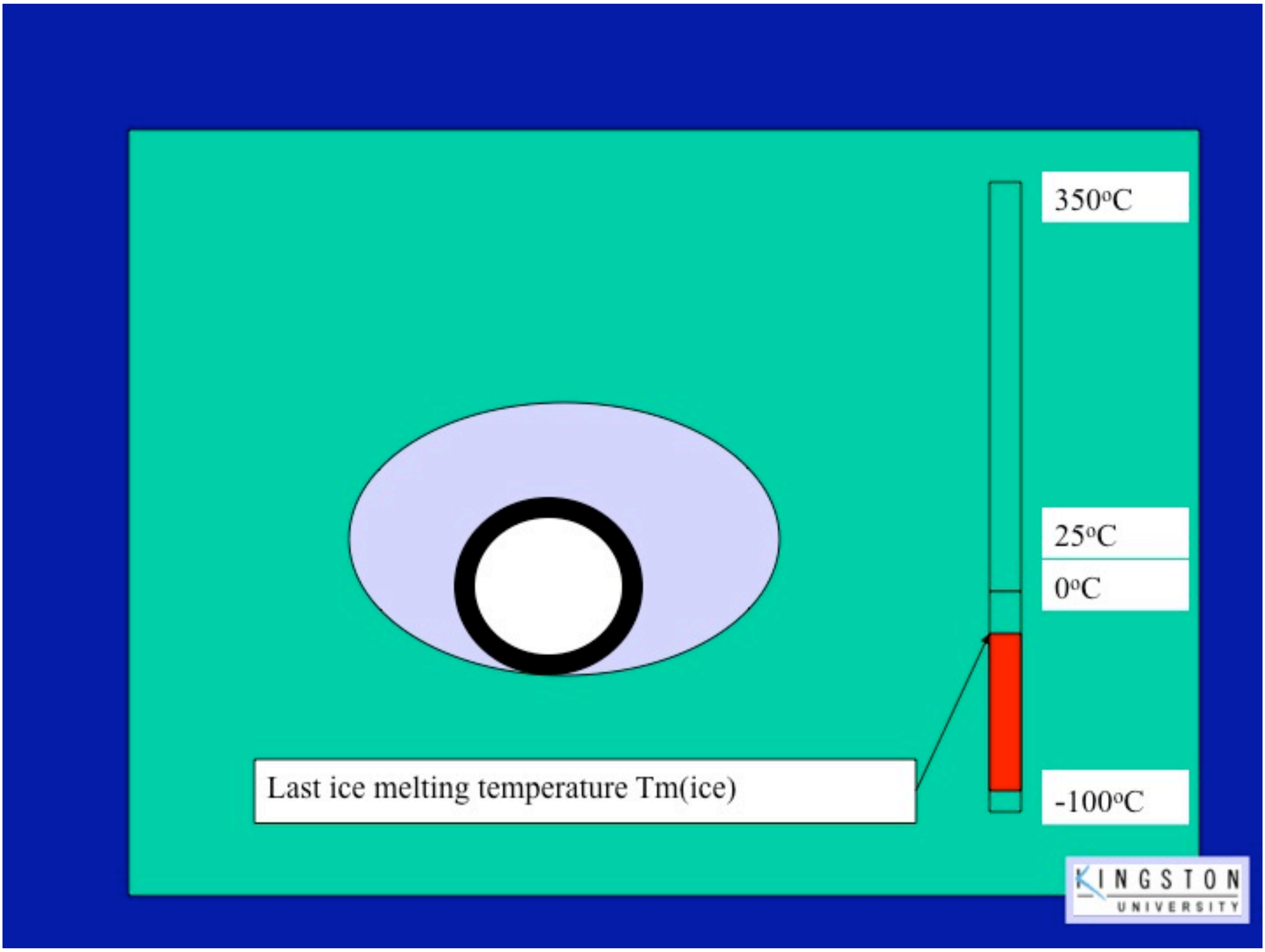


350°C
25°C
0°C
-100°C
KINGSTON UNIVERSITY


350°C
25°C
0°C
-100°C



350°C
25°C
0°C
-100°C
KINGSTON UNIVERSITY


350°C
25°C
0°C
-100°C
Last ice melting temperature Tm(ice)
KINGSTON UNIVERSITY

The next slides show more complex aqueous inclusions with daughter minerals, liquid carbon dioxide and liquid hydrocarbons (oil)

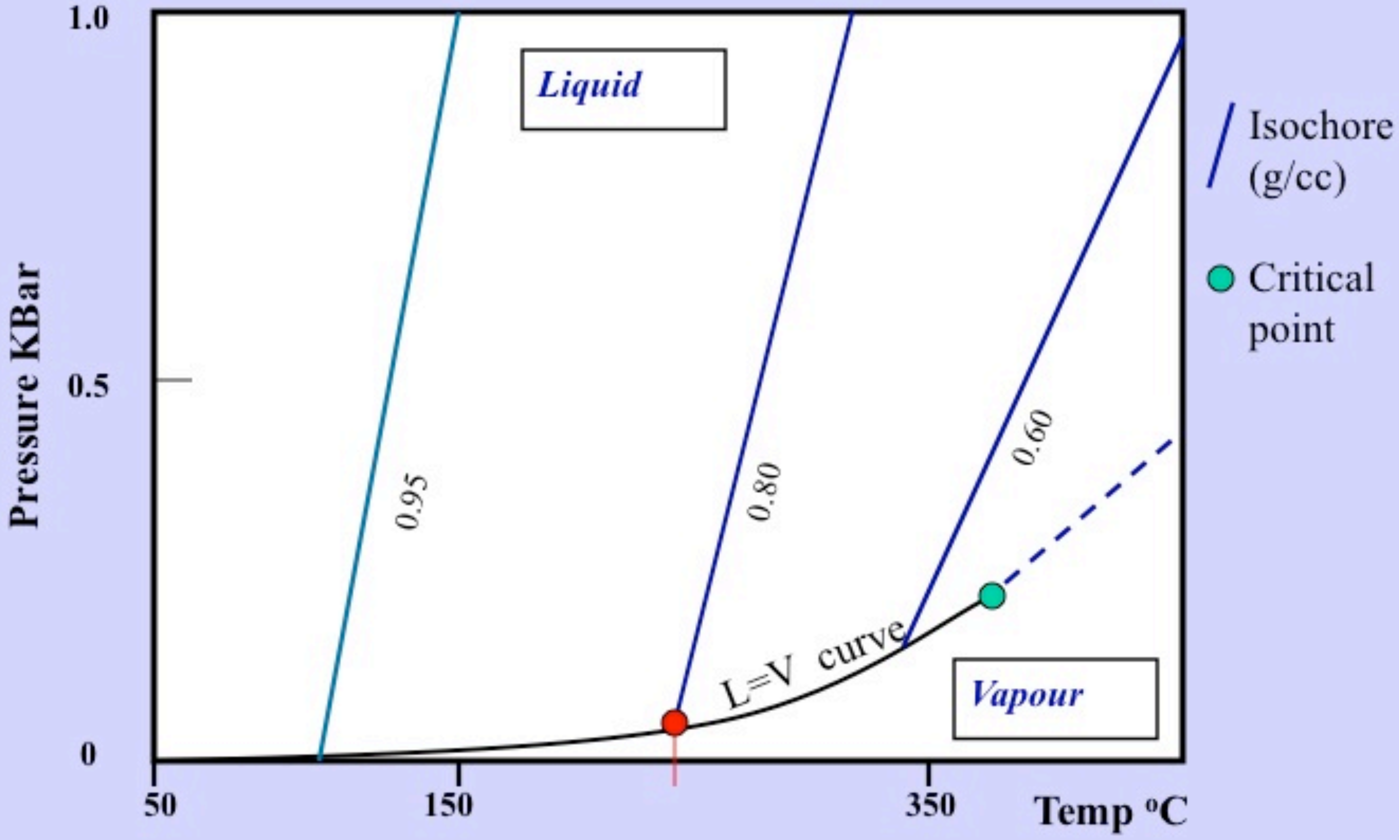
KINGSTON UNIVERSITY

The next slides illustrate the use of heating and freezing data for simple two phase aqueous inclusions.

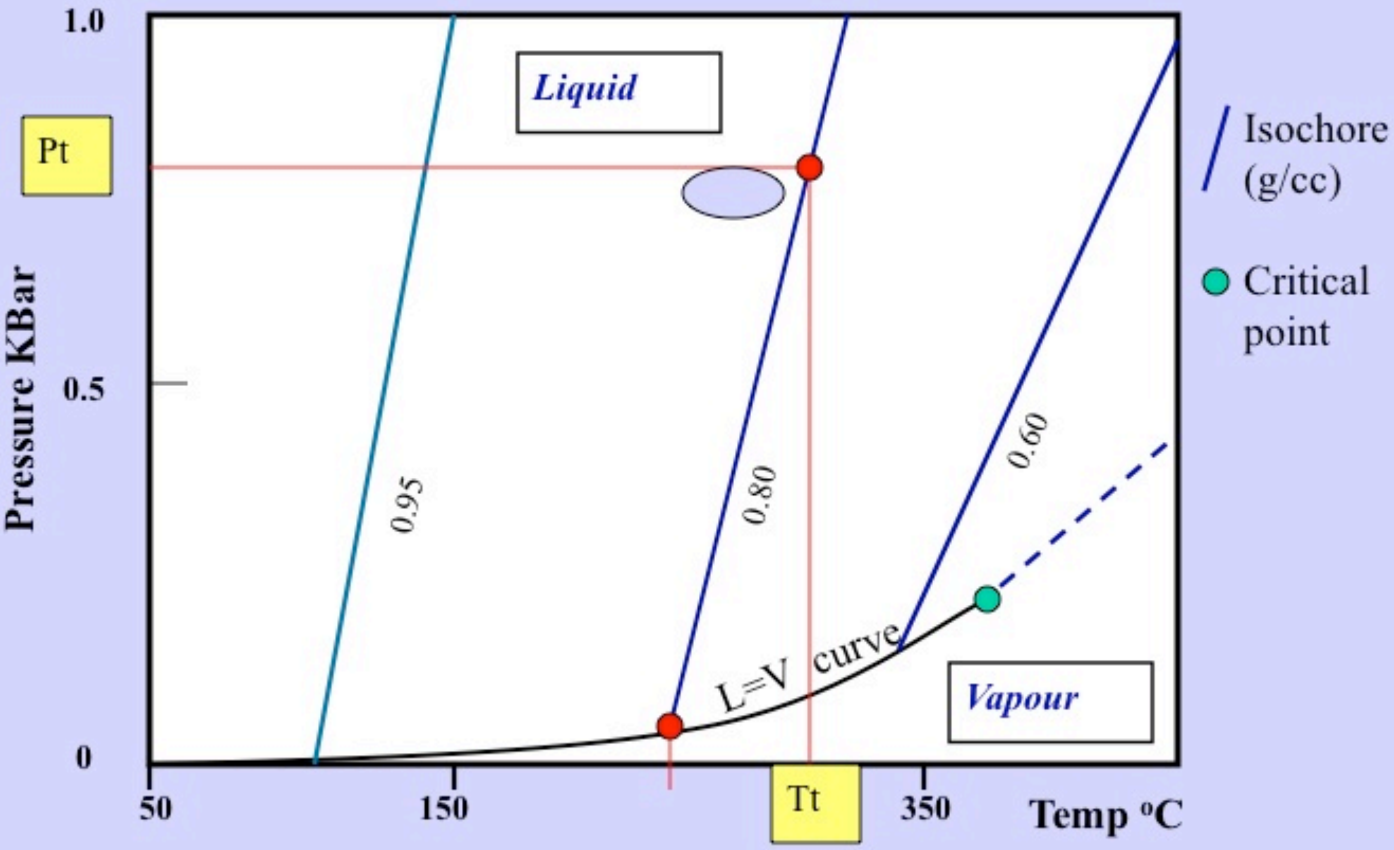
Heating and freezing data (Th, Tfm, Tmice) are interpreted in terms of the simple H_2O and NaCl-H_2O systems

Principle of fluid inclusion geothermometry

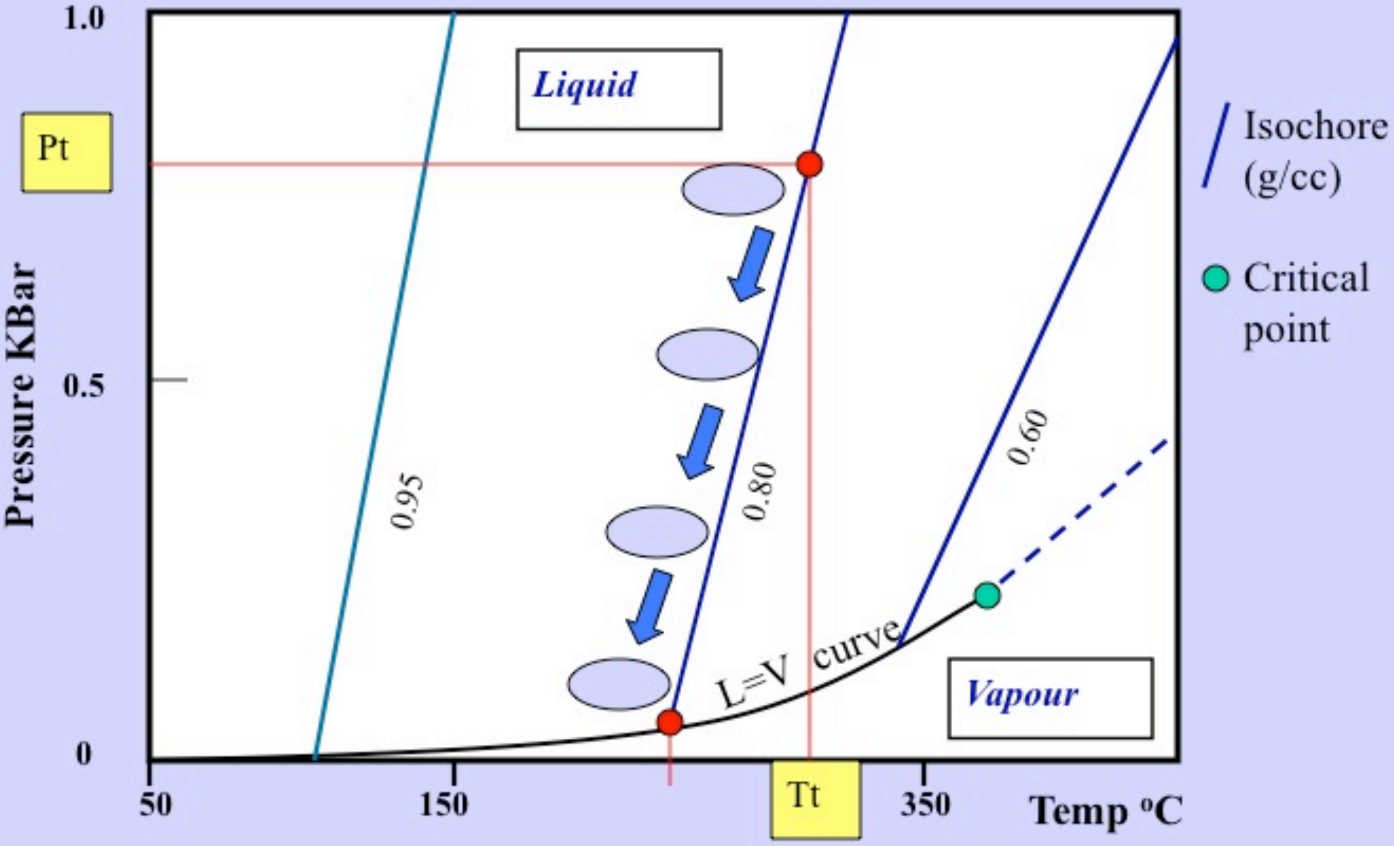
PVT diagram for pure water



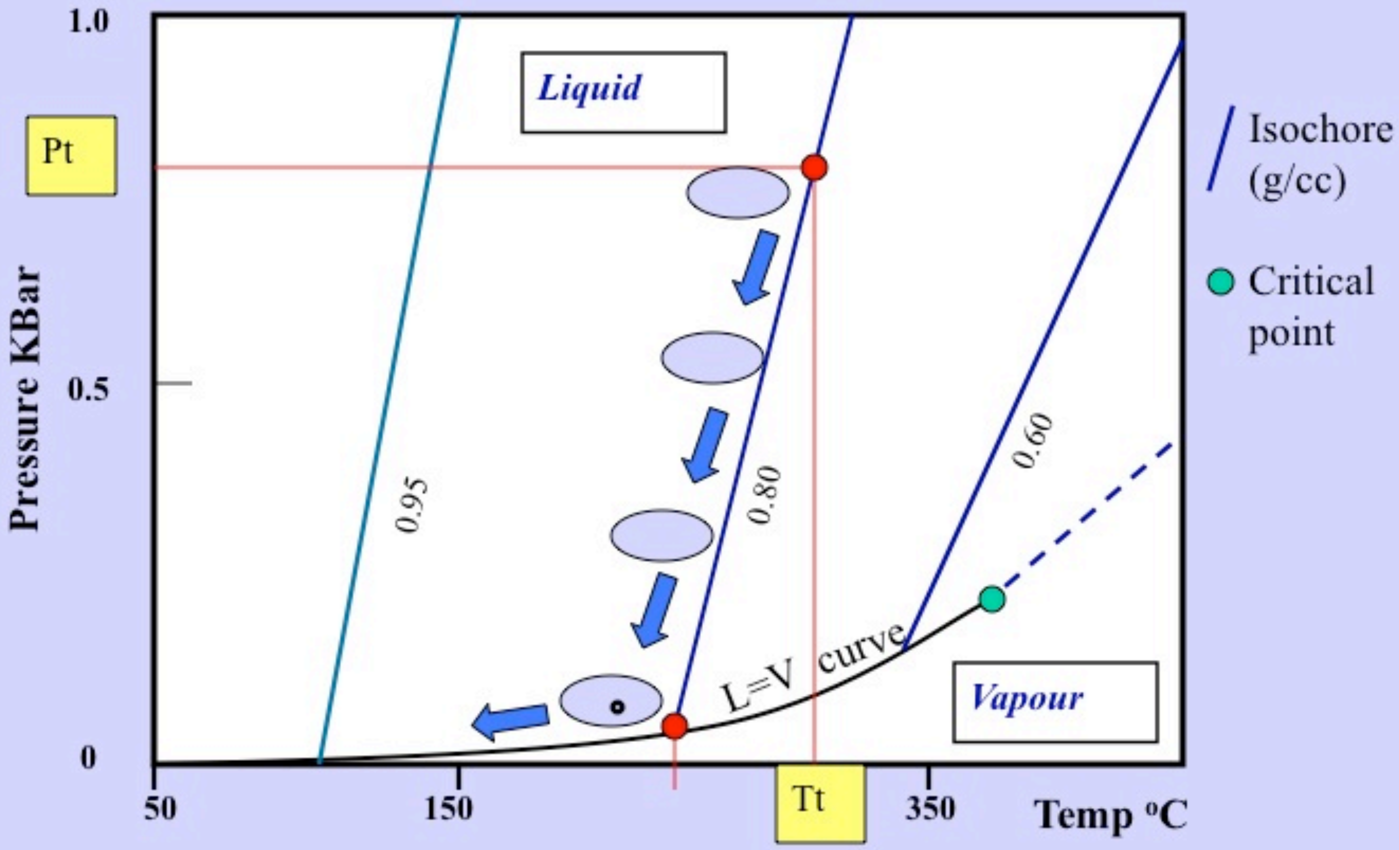
Consider an inclusion trapped at a given temperature and pressure (Tt, Pt)



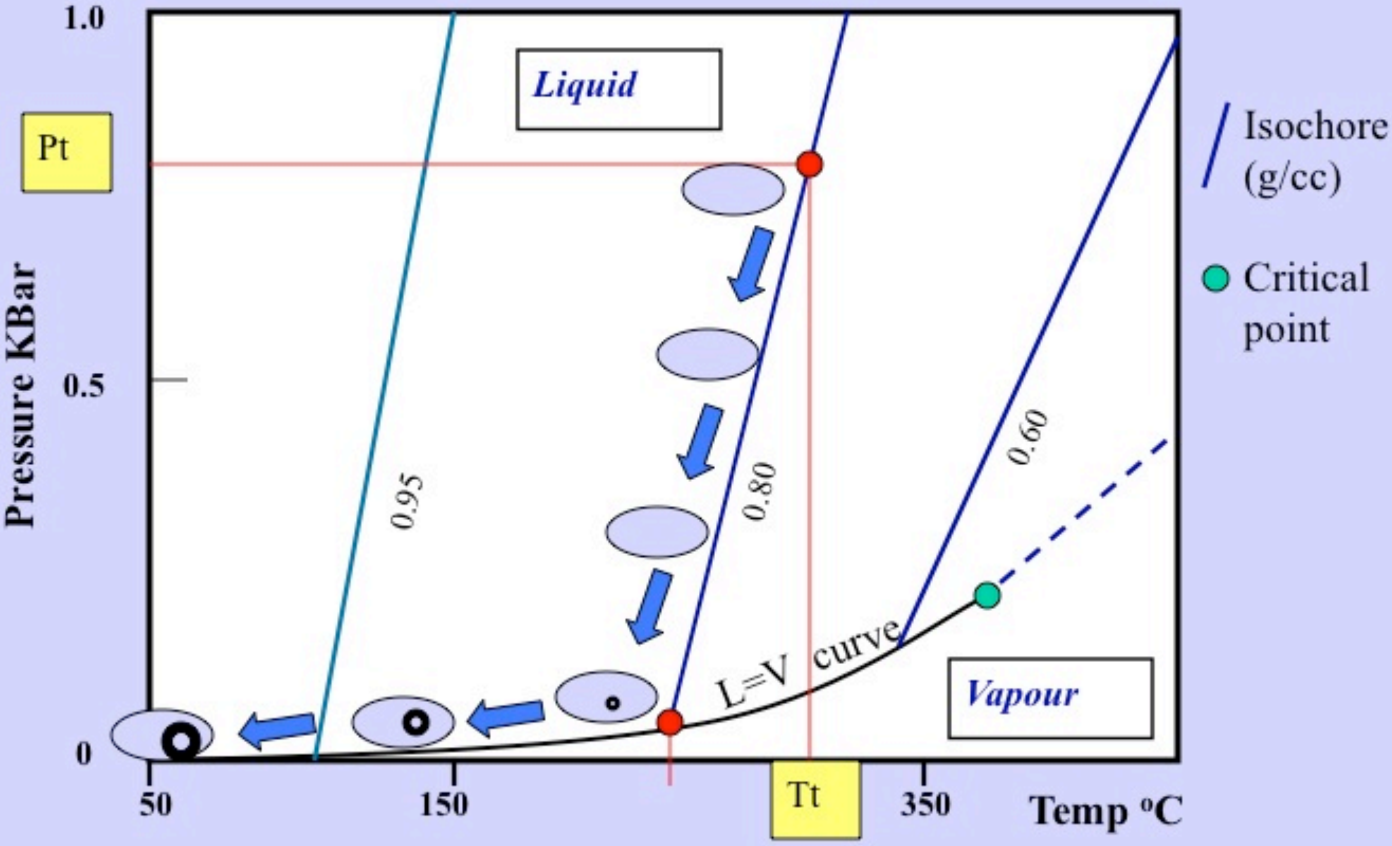
On cooling, the inclusion follows an isochoric PT path until it meets the L=V curve



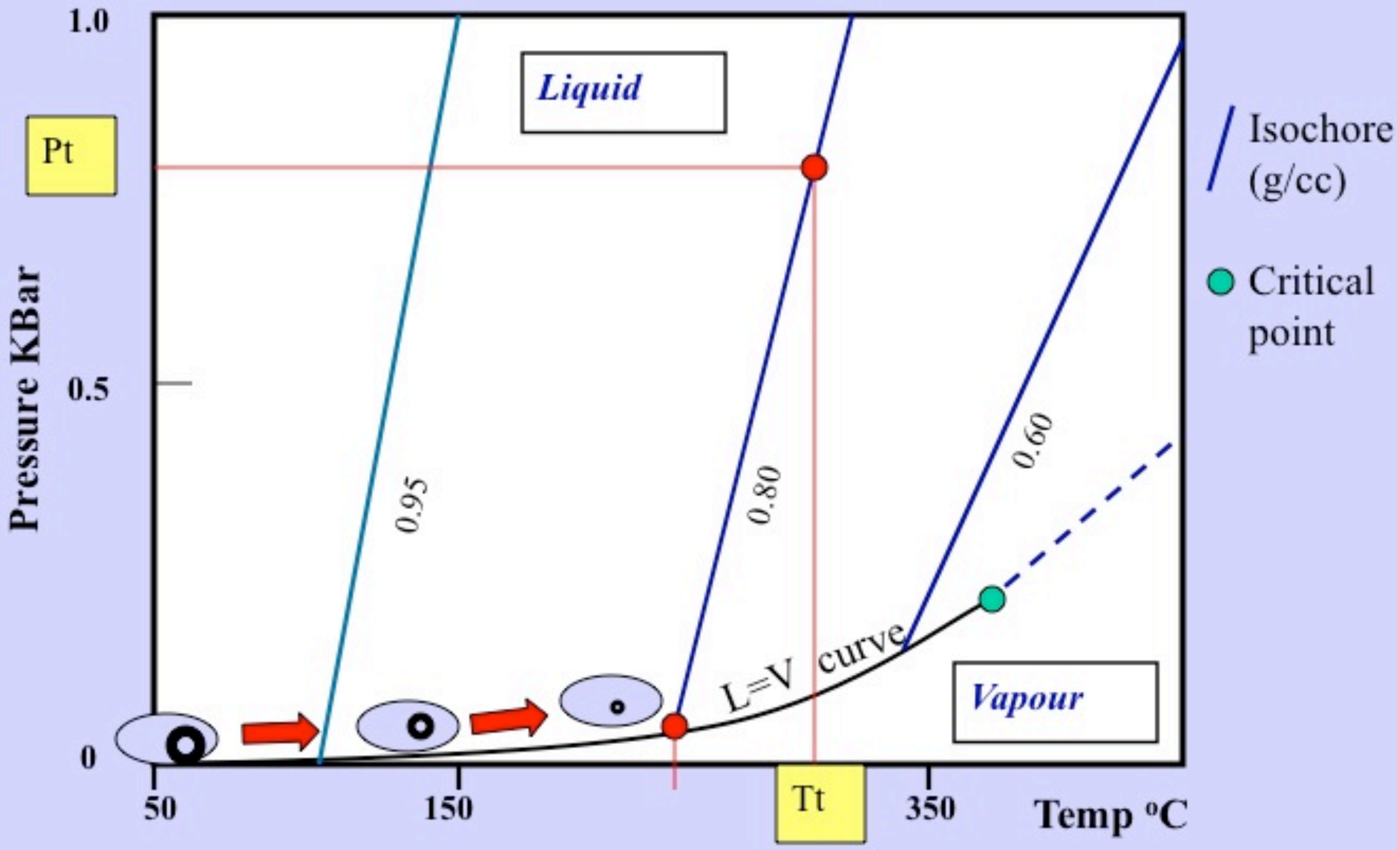
Beyond this point the inclusion cools along the L=V curve and a vapour bubble nucleates



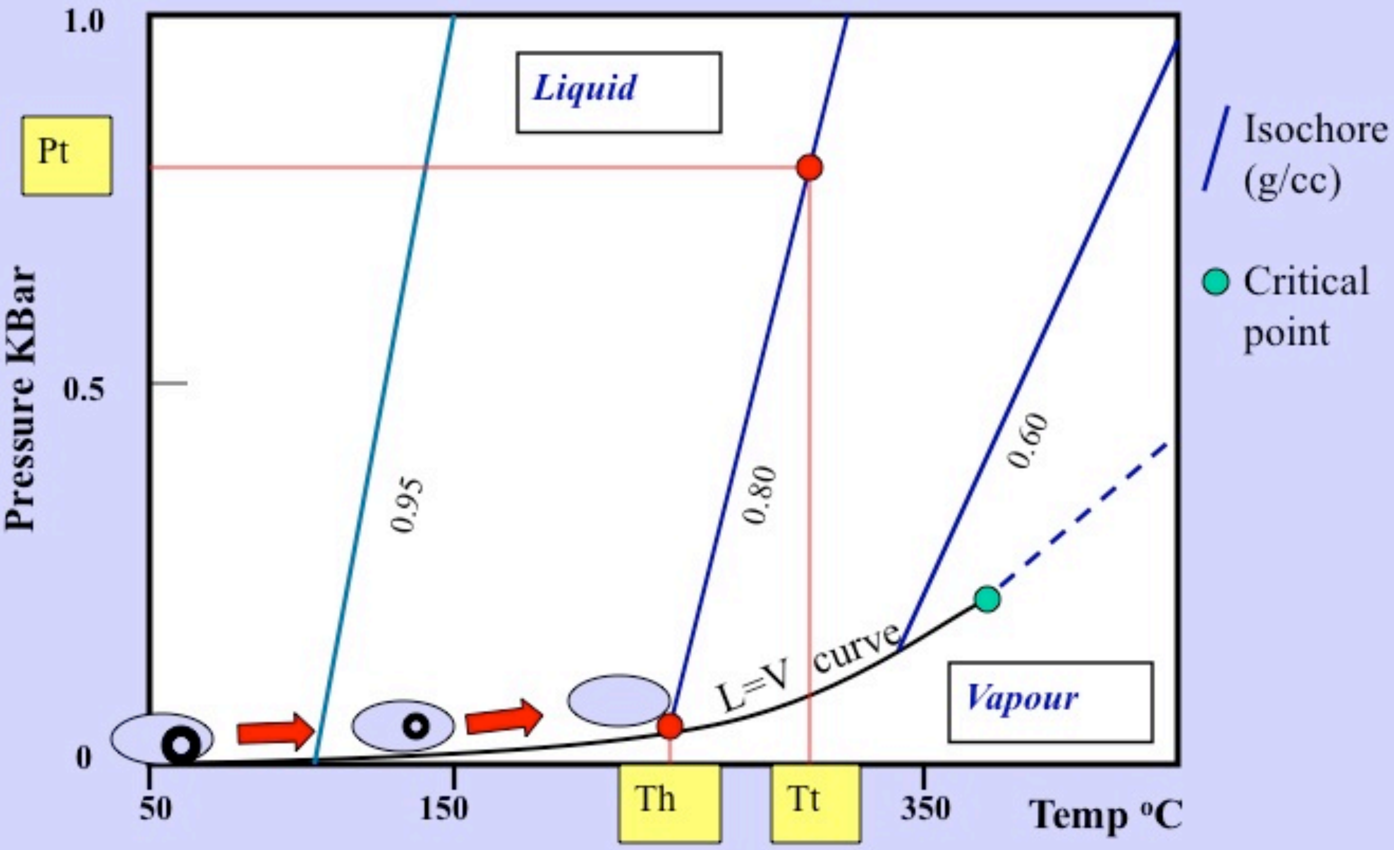
Continued cooling results in further shrinkage of liquid and growth of the vapour bubble



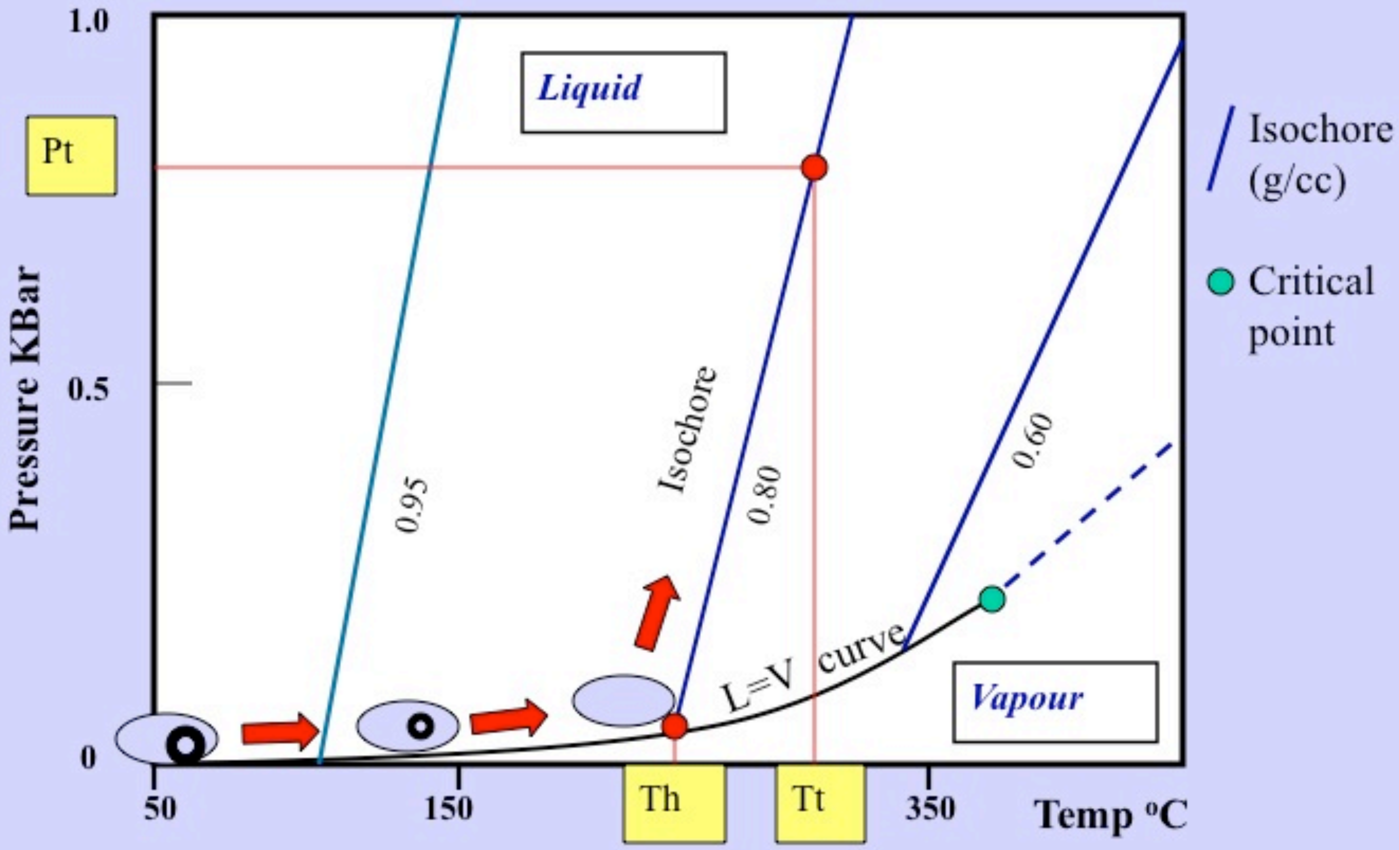
On heating along the V/L curve, the liquid expands and the bubble shrinks

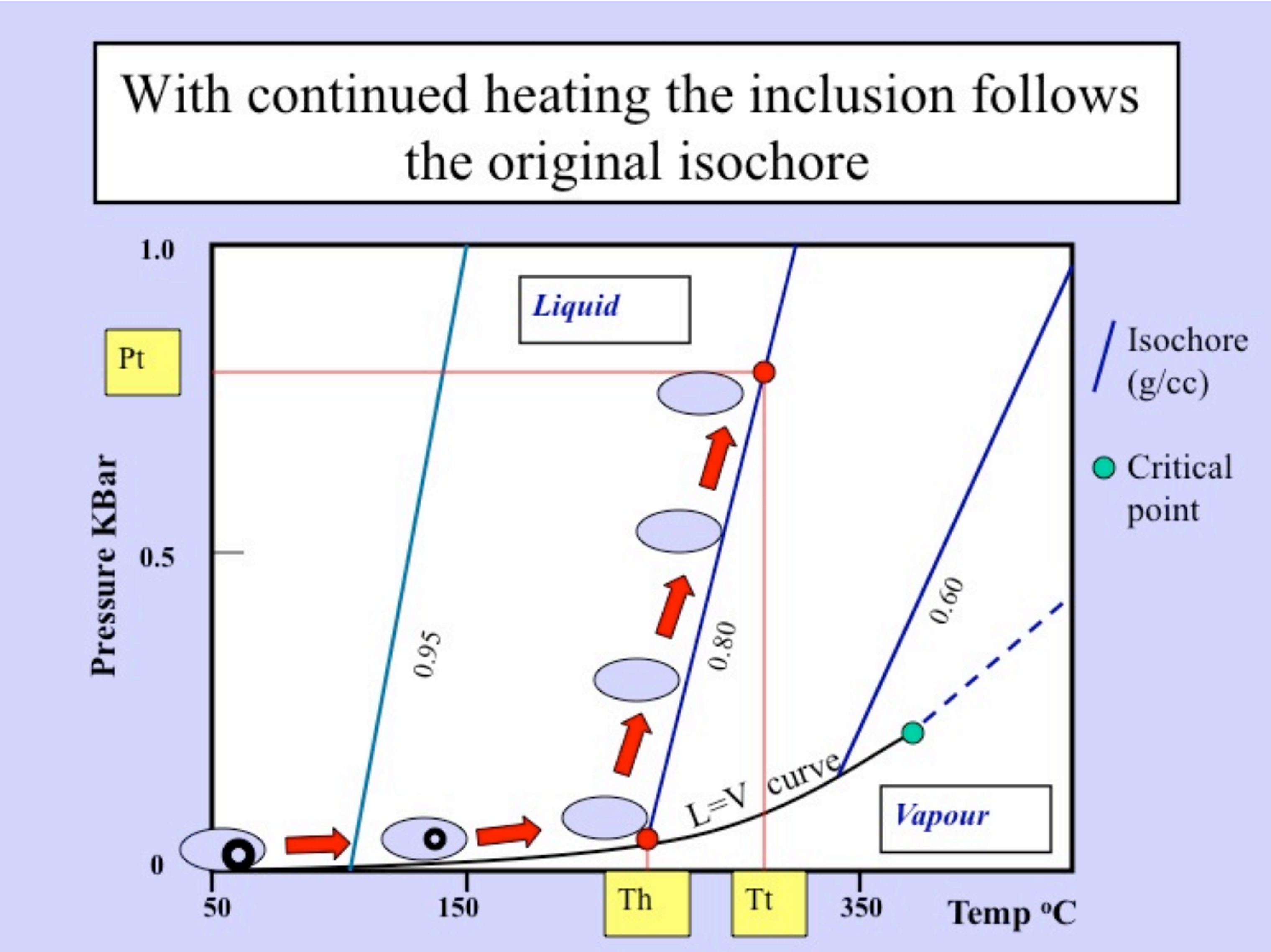


Until the bubble disappears at the homogenisation temperature (Th)



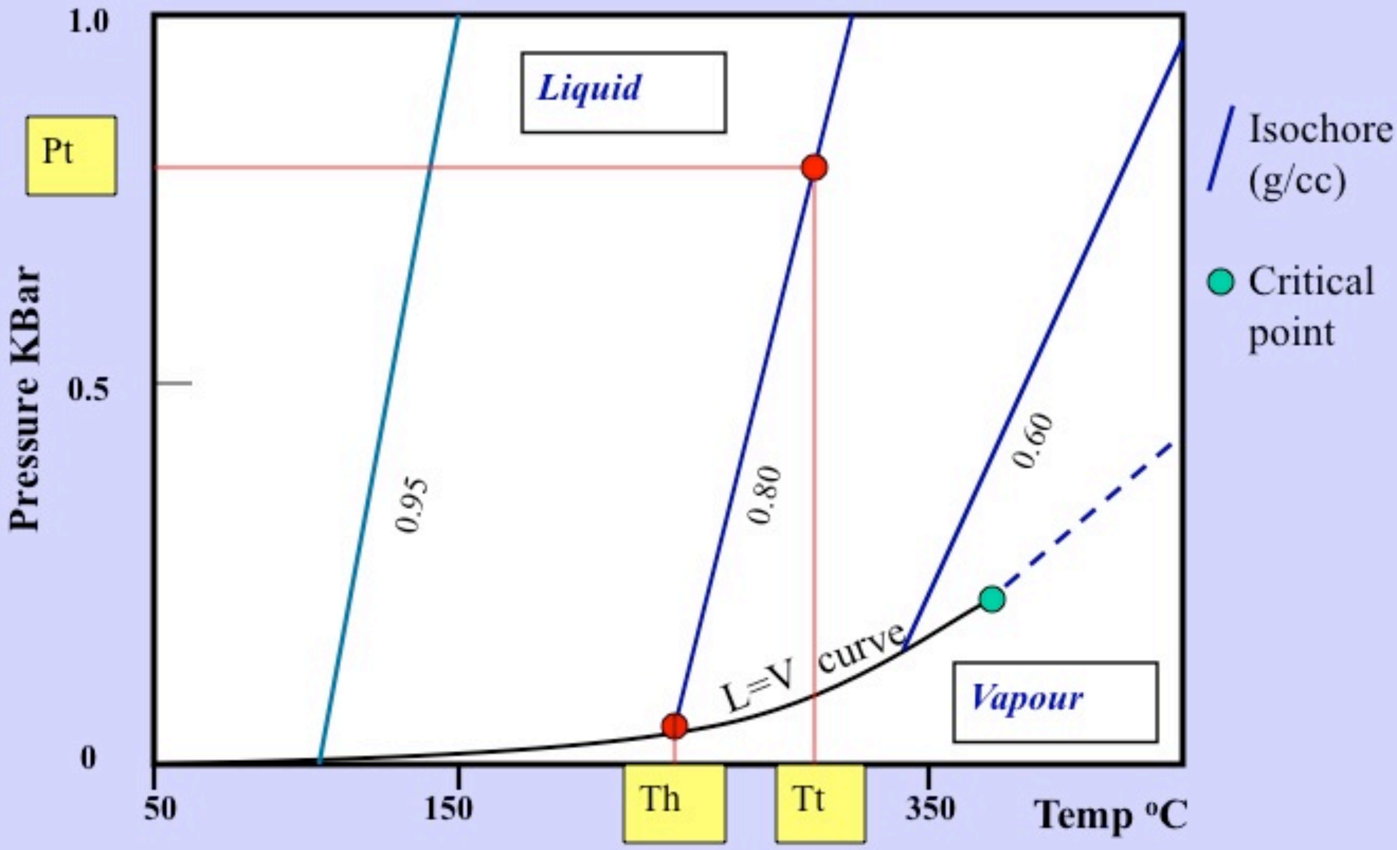
The point Th uniquely defines the isochore along which the inclusions originally cooled



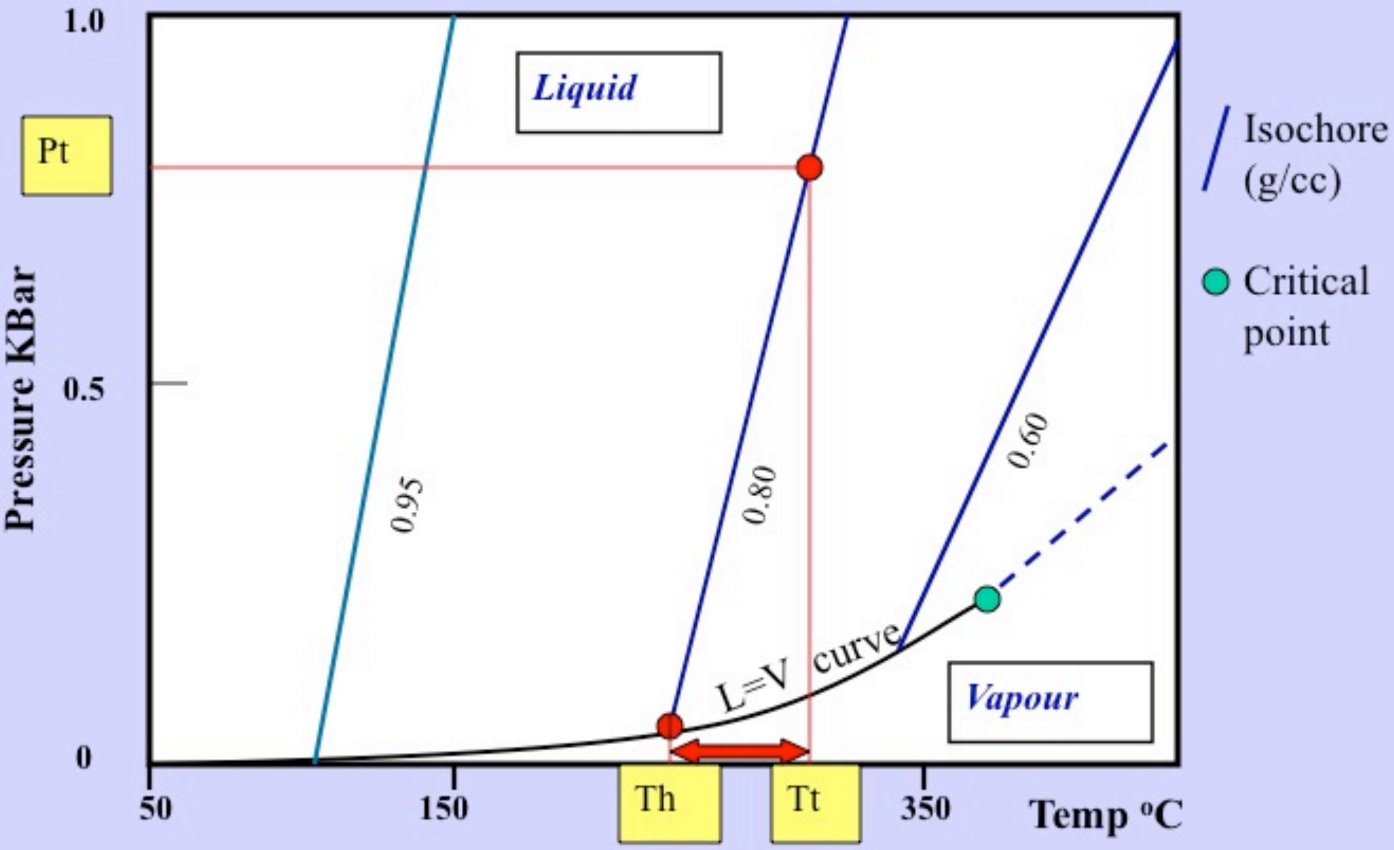


With continued heating the inclusion follows the original isochore
1.0
0.5
0
Pressure KBar
Pt
Liquid
Vapour
0.95
0.80
0.60
L=V curve
50
150
Th
Tt
350
Temp ºC
Isochore (g/cc)
Critical point

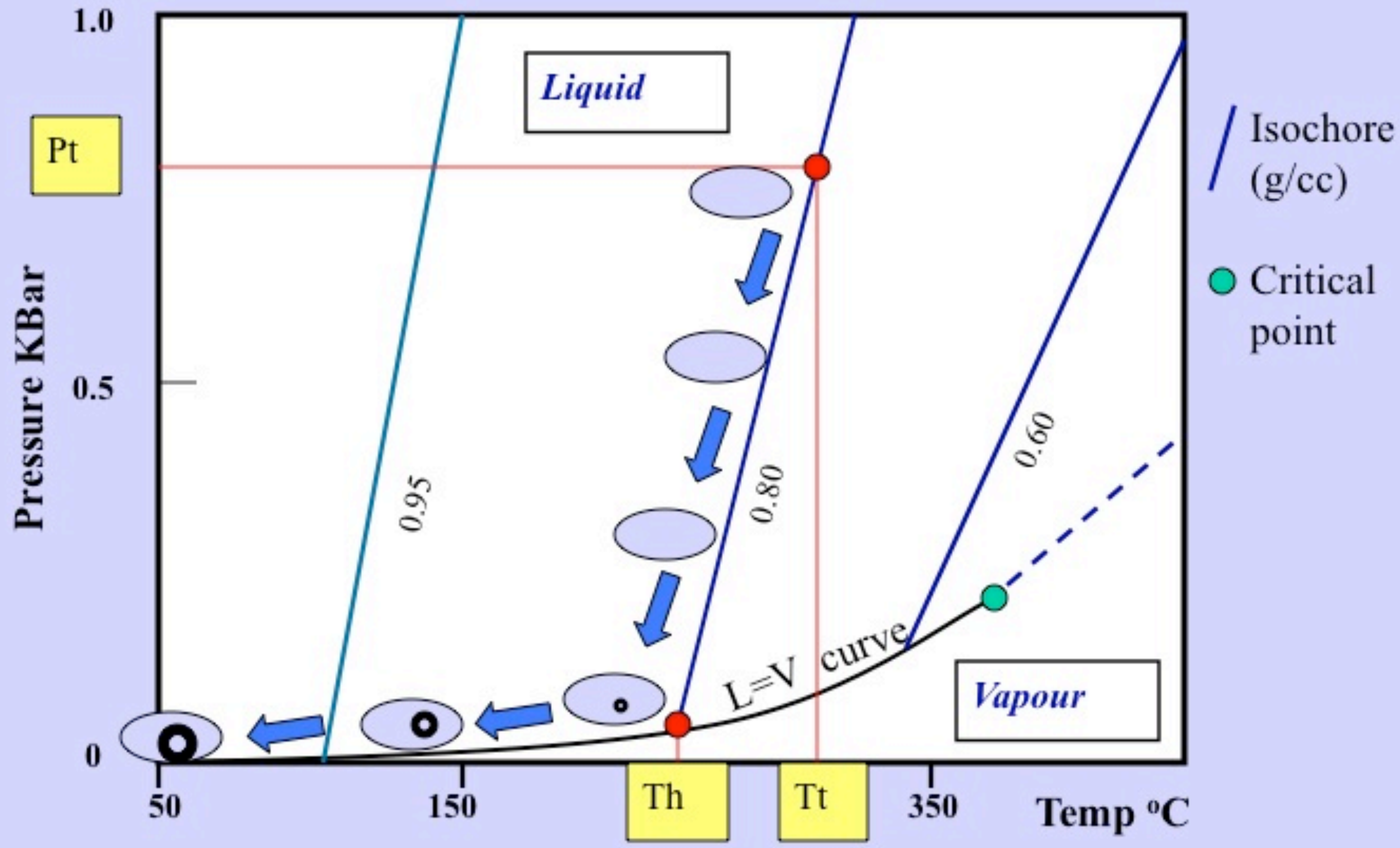
If Pt is known, or estimated, the trapping temperature (Tt) can be determined

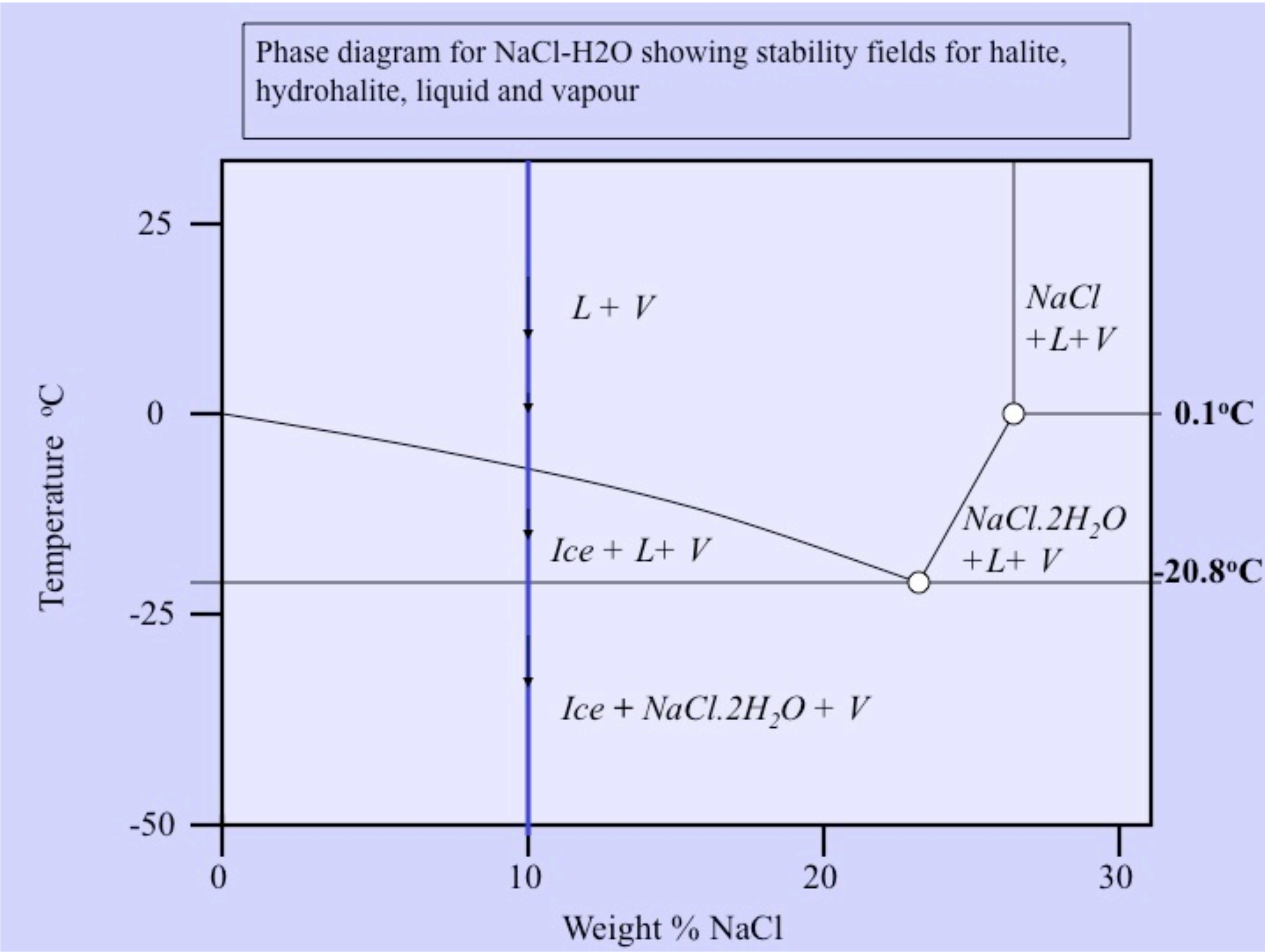


The difference between Th and Tt is known as the *Pressure Correction*

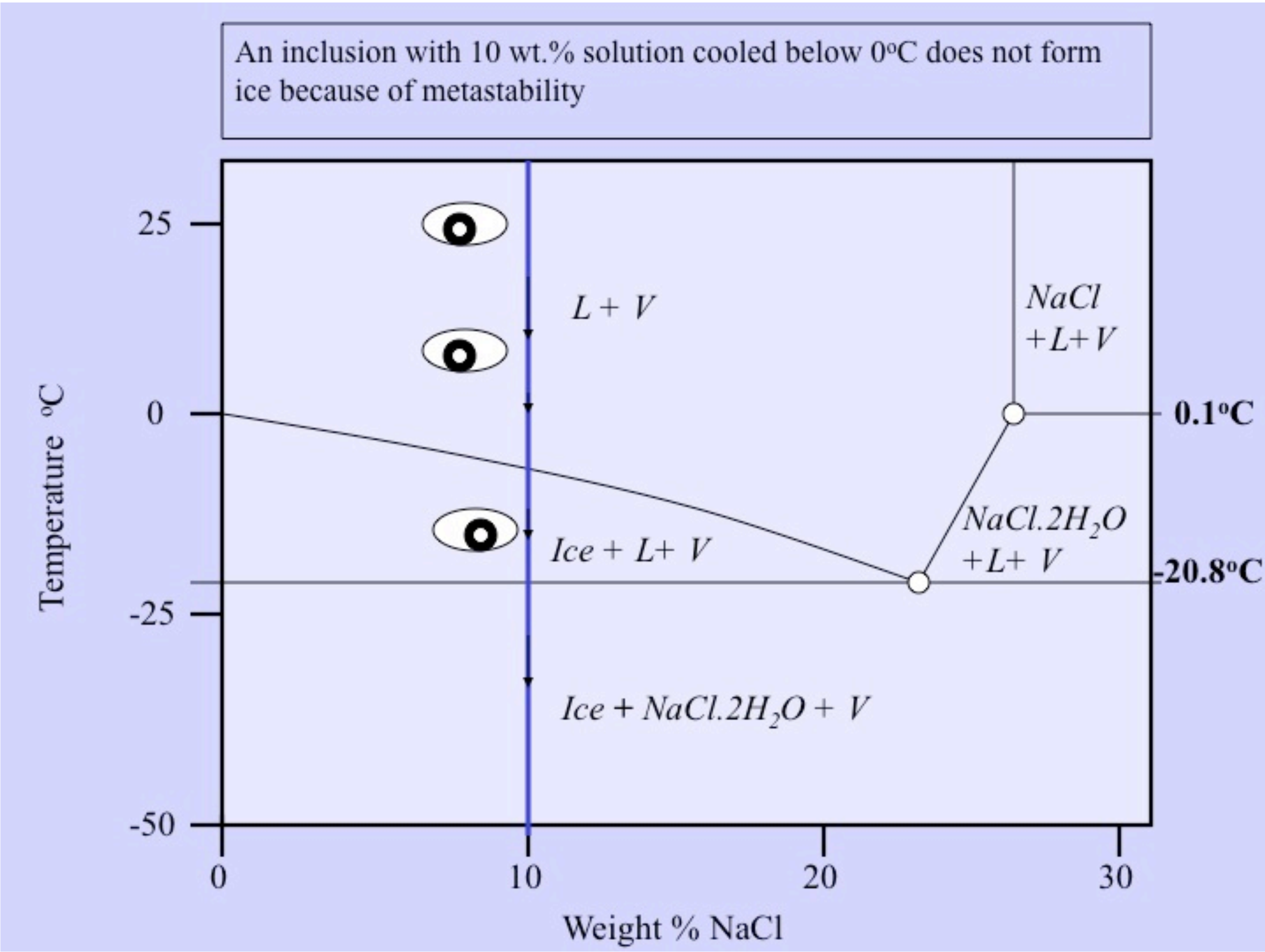


The bubble reappears on cooling and Th can be re-determined

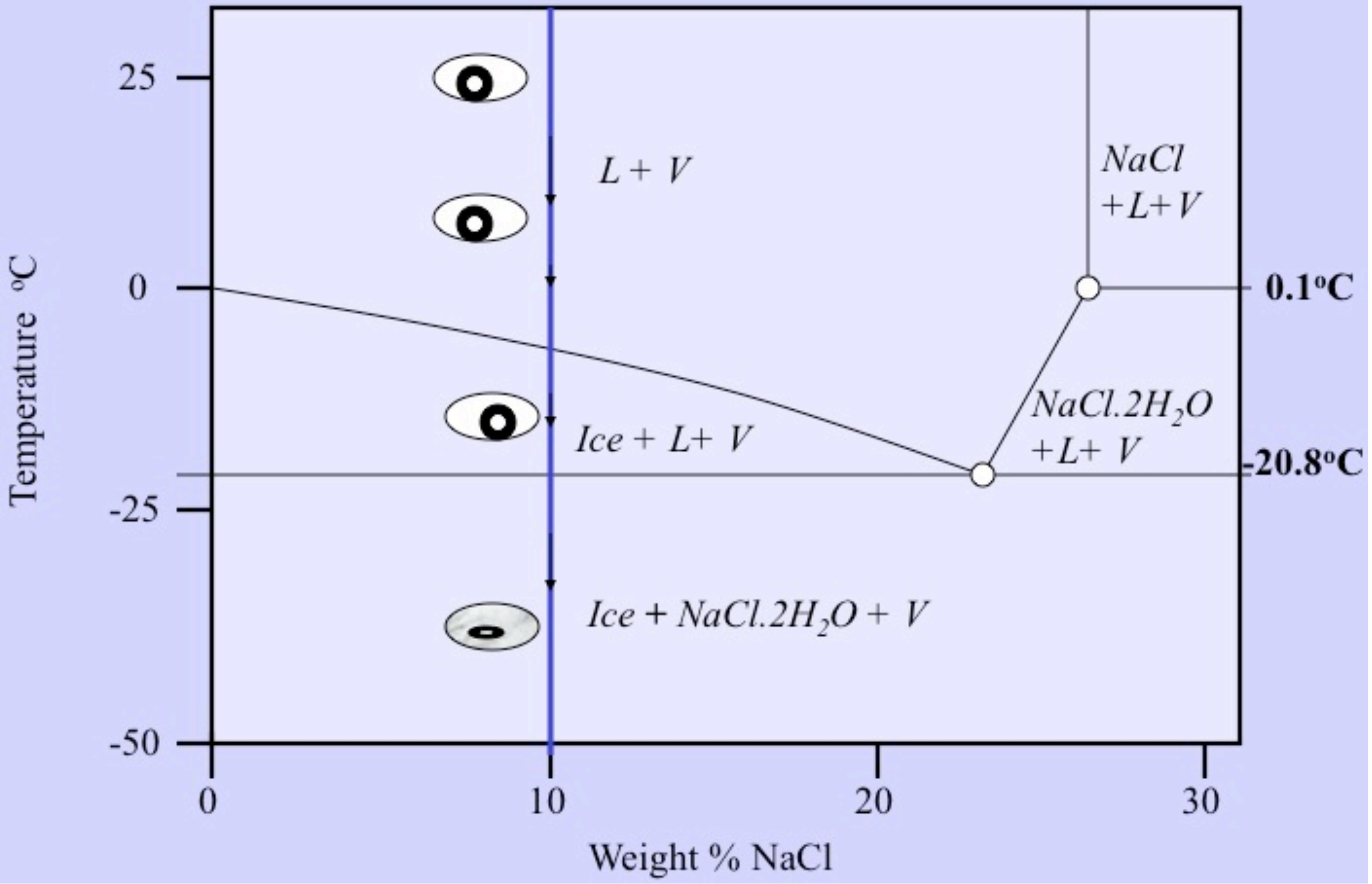


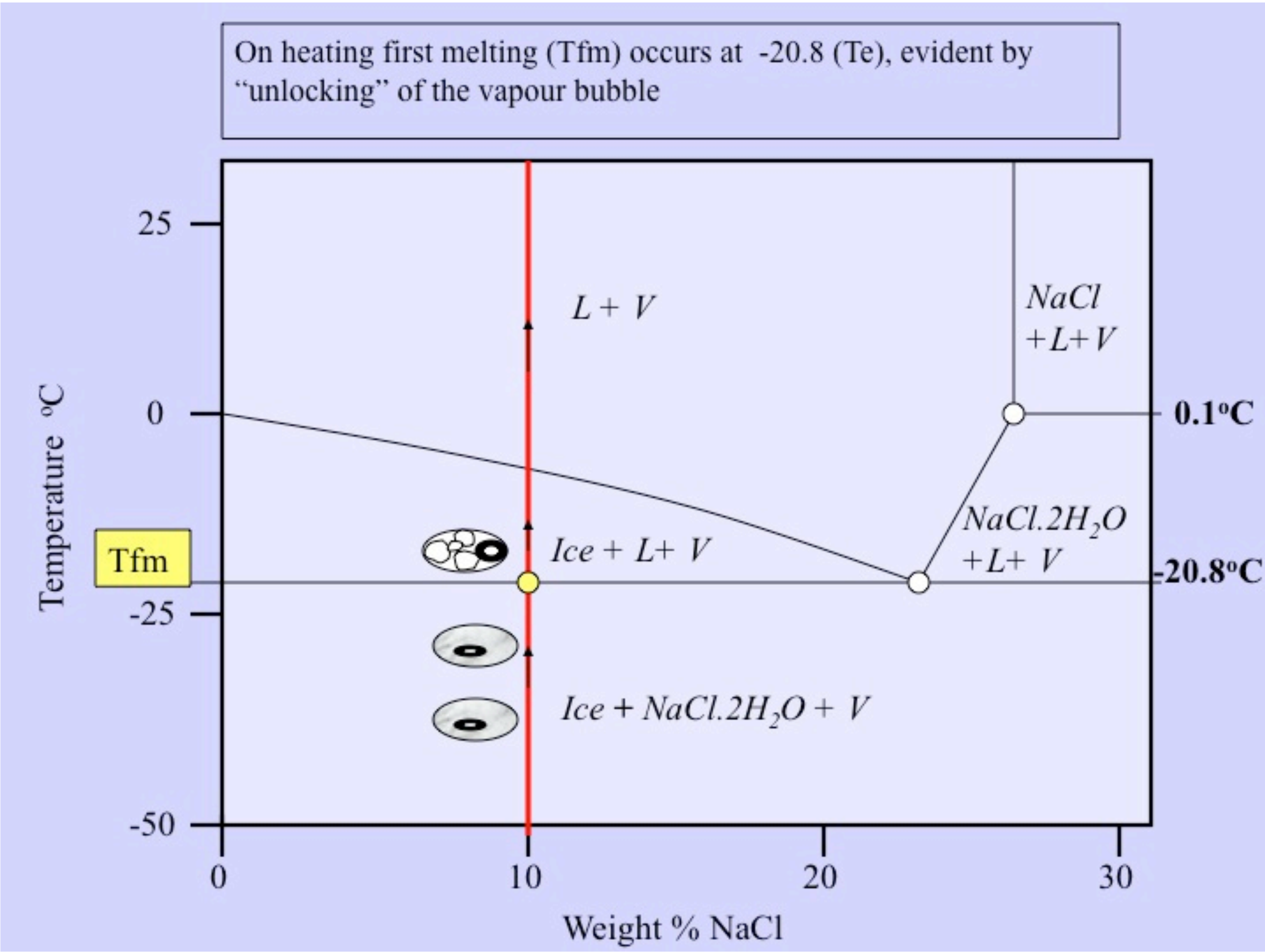


Phase diagram for NaCl-H2O showing stability fields for halite, hydrohalite, liquid and vapour
25
0
-25
-50
Temperature °C
L + V
NaCl
+L+ V
0.1°C
NaCl.2H2O
+L+ V
Ice + L+ V
-20.8°C
Ice + NaCl.2H2O + V
0
10
20
30
Weight % NaCl

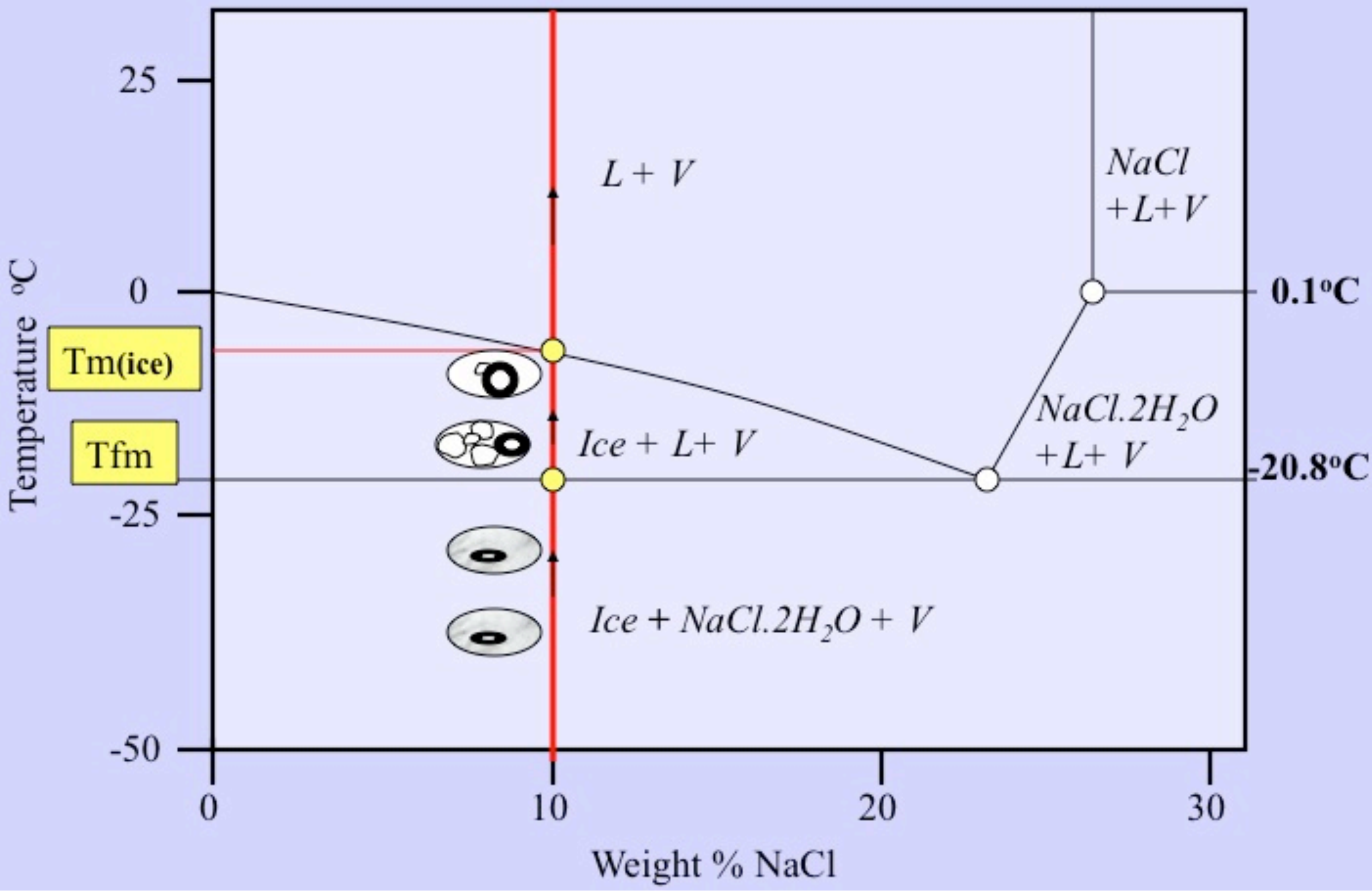

An inclusion with 10 wt.% solution cooled below 0°C does not form ice because of metastability
25
0
-25
-50
Temperature °C
0
10
20
30
Weight % NaCl
L + V
NaCl
+L+ V
0.1°C
NaCl.2H2O
+L+ V
Ice + L+ V
-20.8°C
Ice + NaCl.2H2O + V

Rapid cooling below the eutectic temperature (Te) is usually needed before the inclusion freezes

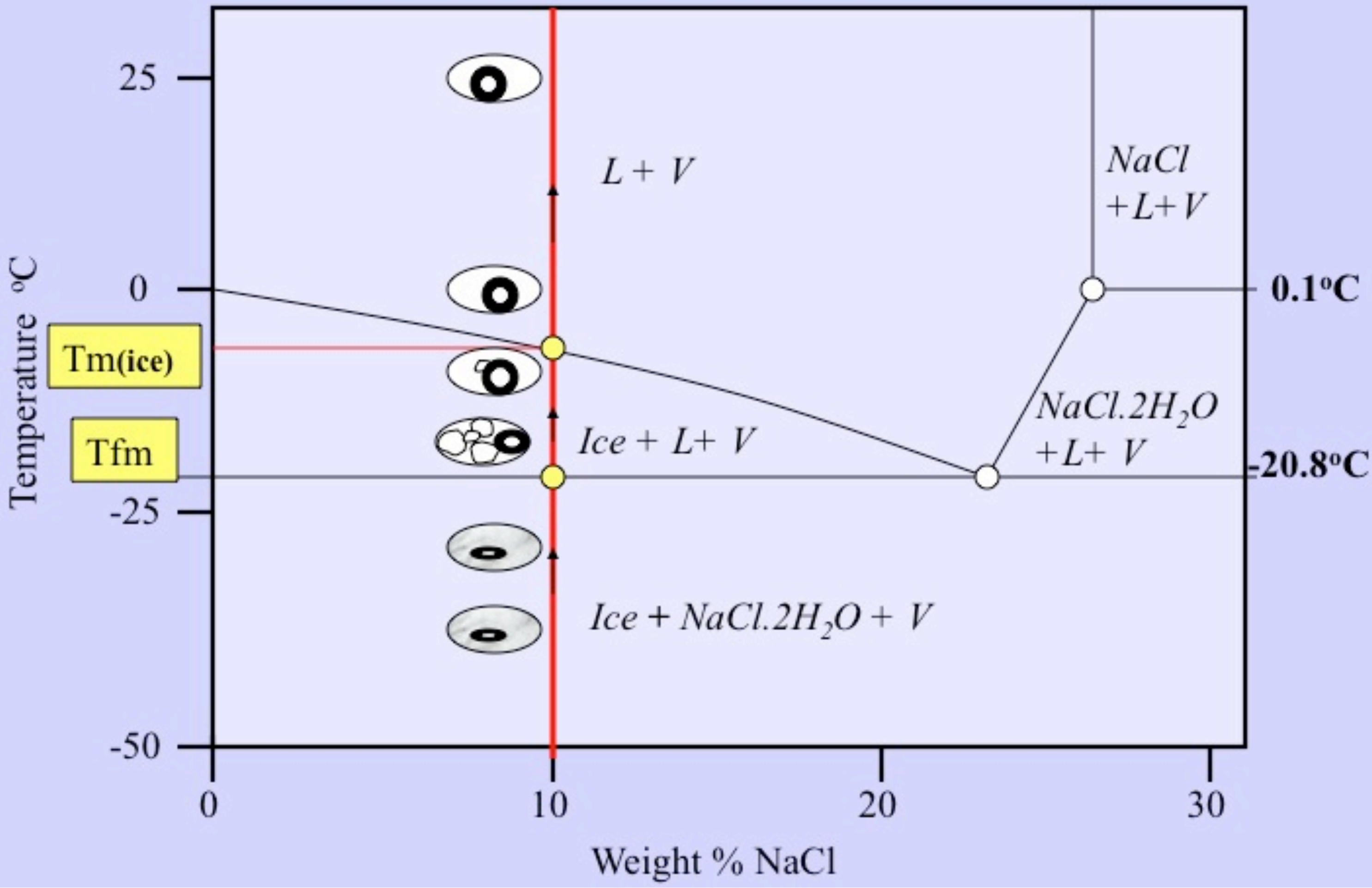



On heating first melting (Tfm) occurs at -20.8 (Te), evident by "unlocking" of the vapour bubble
Temperature °C
25
0
-25
-50
Tfm
L + V
Ice + L+ V
Ice + NaCl.2H2O + V
NaCl
+L+ V
NaCl.2H2O
+L+ V
0.1°C
-20.8°C
0
10
20
30
Weight % NaCl

Continued heating results in the melting of the last ice crystal (Tm_ice) at -6°C



Continued heating results in the melting of the last ice crystal (Tm_ice) at -6°C



Sedimentary/
Diagenetic Environments

Range of Fluid Trapping Scenarios:

Fluid Inclusion Mineral Hosts
Fluid Salinities and Temperatures

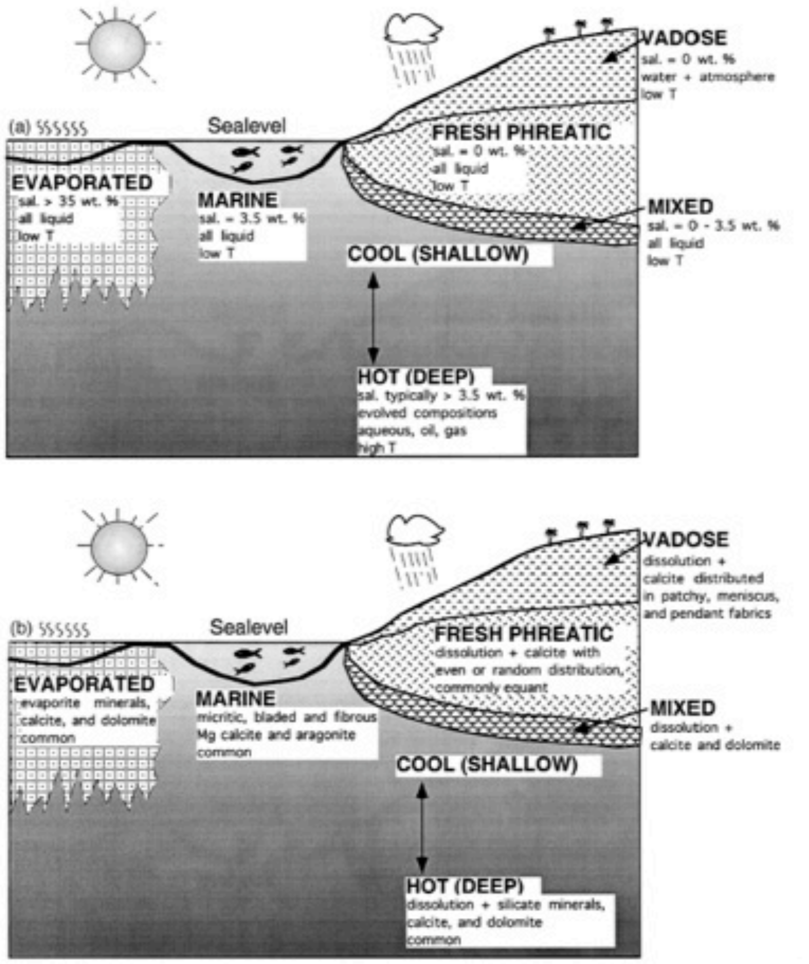


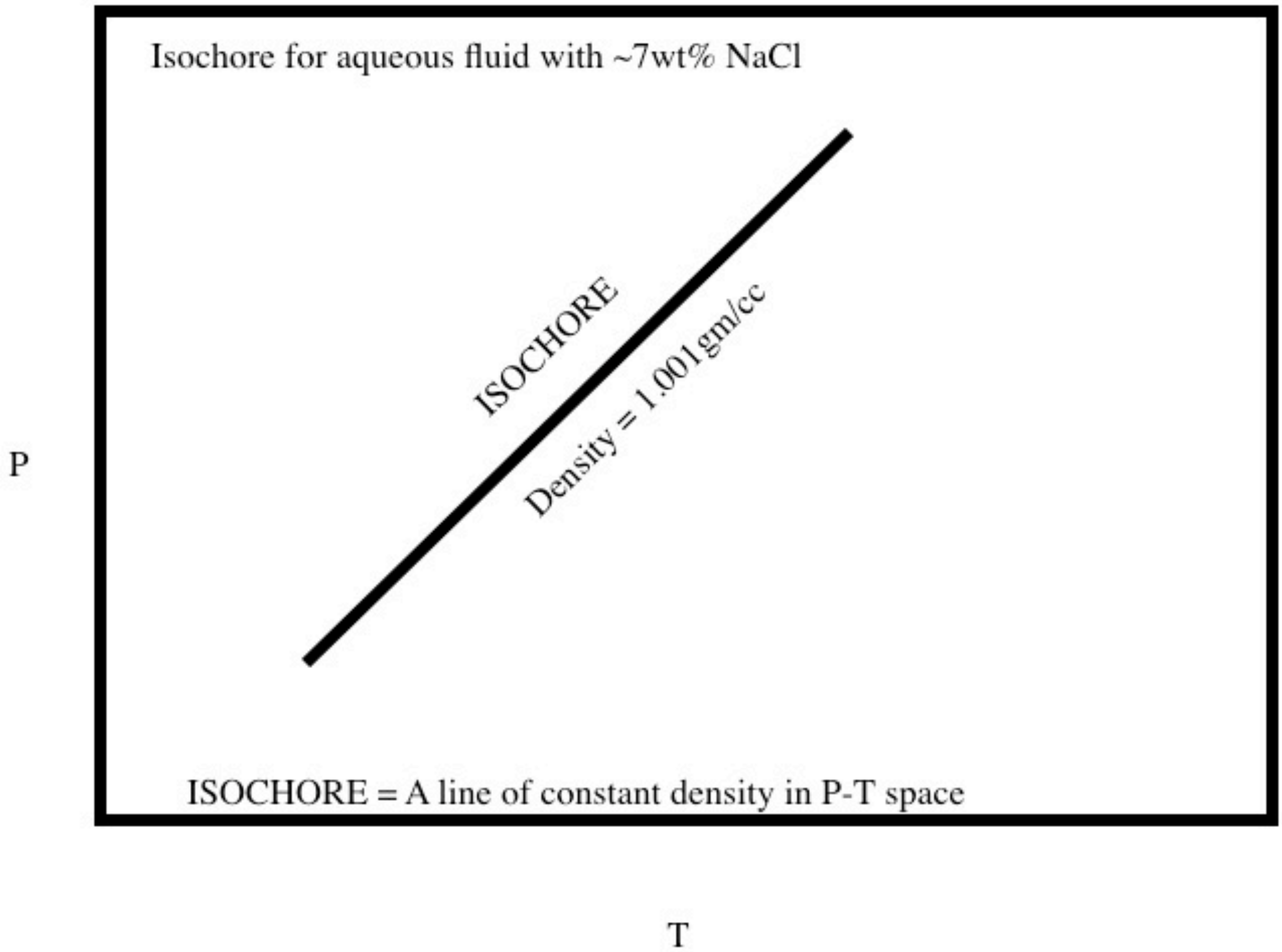
Fig. 1. Schematic representation of environments in sedimentary systems with characteristics of fluids applicable to fluid inclusion work (a) and diagenetic processes important for each environment (b).

Geothermal gradient	20-50°/ km burial
Hydrostatic gradient	100bars/km burial
Lithostatic gradient	226bars/km burial

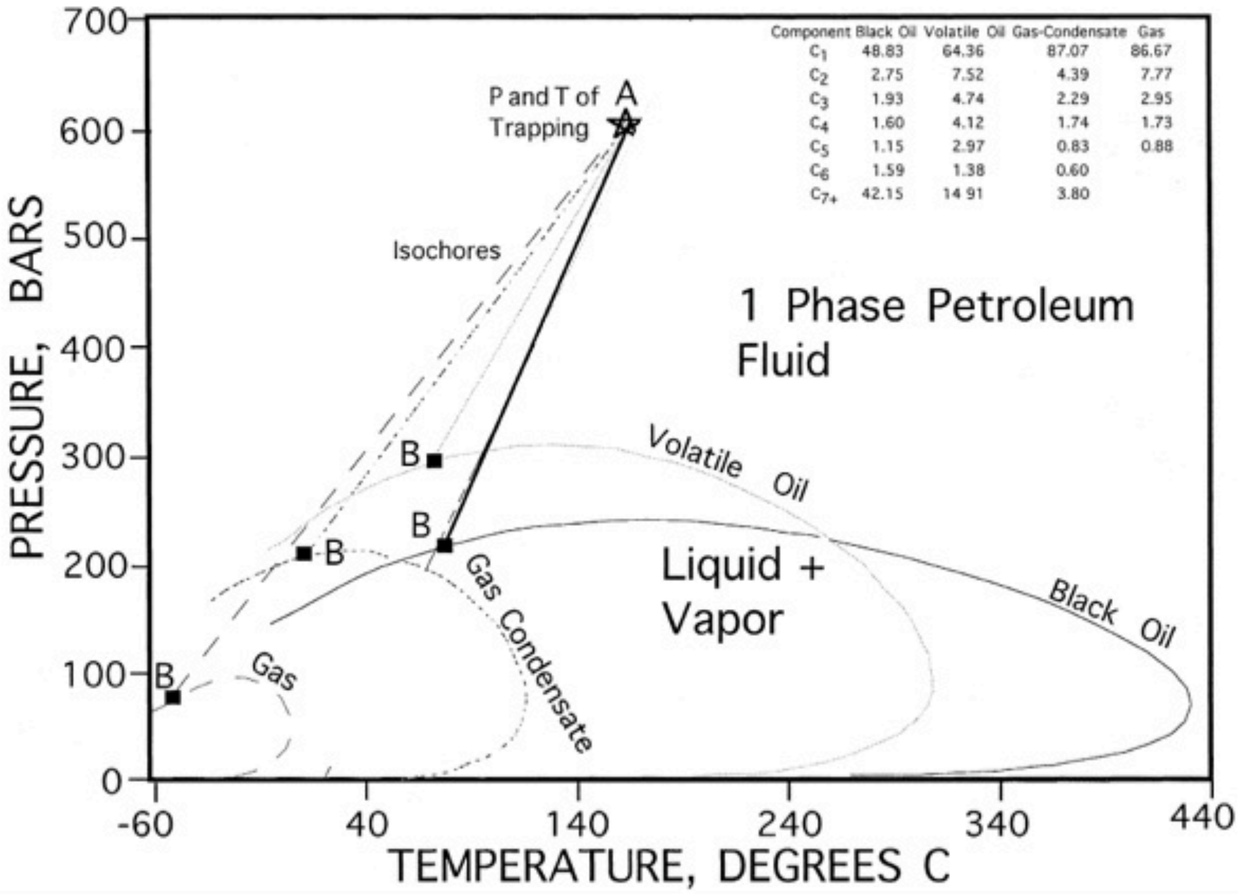
Table 1. Commonly encountered conditions in diagenesis

Dissolved Species	Eutectic temperature	Eutectic Composition
NaCl	-20.8	23.3% NaCl
KCl	-10.6	19.7% KCl
$CaCl_2$	-49.8	30.2% $CaCl_2$
$MgCl_2$	-33.6	21.0% $MgCl_2$
NaCl-KCl	-22.9	20.1% NaCl, 5.81% KCl
NaCl-$CaCl_2$	-52.0	1.8% NaCl, 5.81% $CaCl_2$
NaCl-$MgCl_2$	-35	1.56% NaCl, 22.74% $MgCl_2$

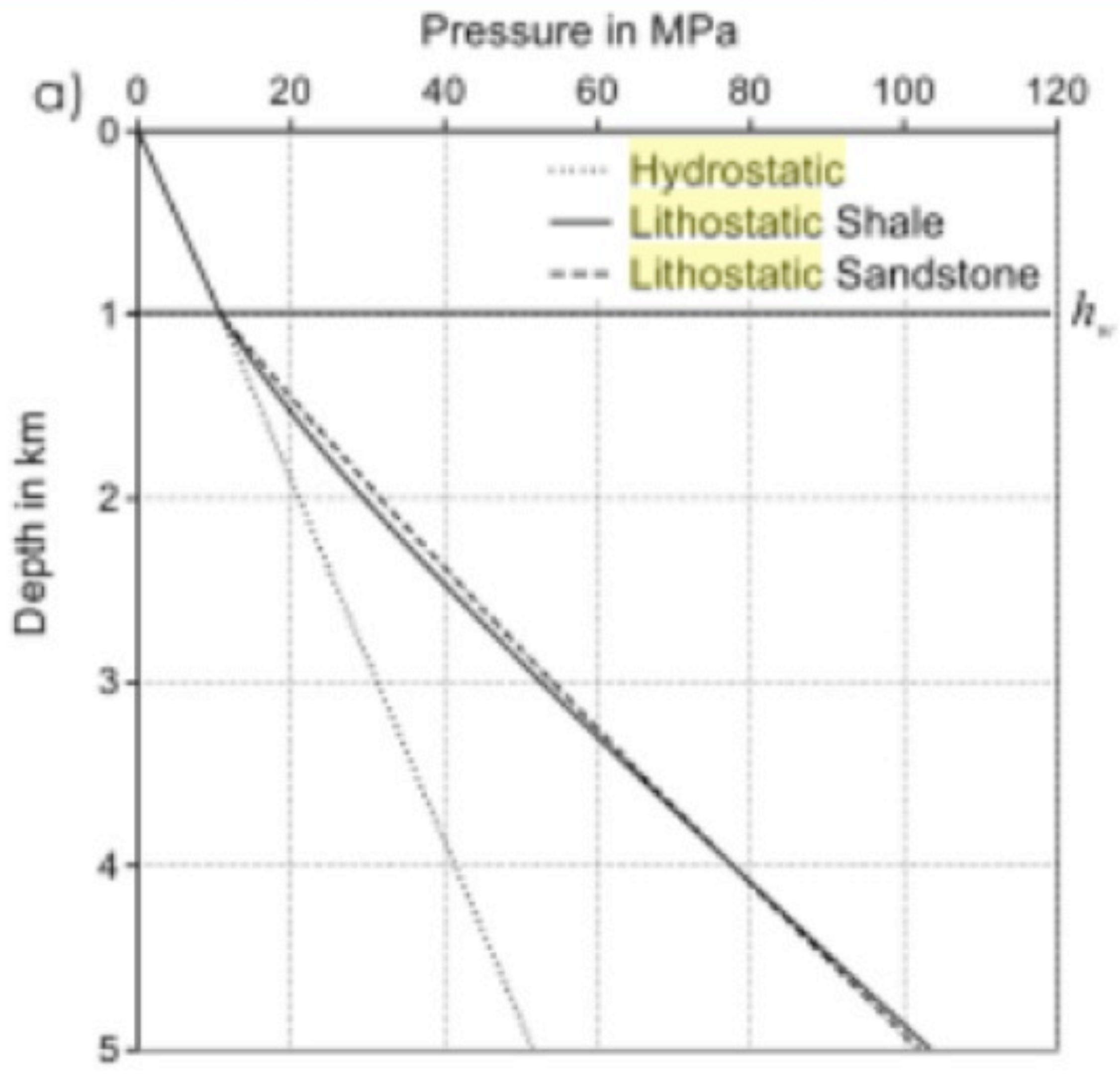
Table 5. Characteristic eutectic points for salts in inclusions


Isochore for aqueous fluid with ~7wt% NaCl
ISOCHORE
Density = 1.001gm/cc
ISOCHORE = A line of constant density in P-T space
P
T

Phase envelopes for a series of generic oil compositions



Component	Black Oil	Volatile Oil	Gas-Condensate	Gas
C_1	48.83	64.36	87.07	86.67
C_2	2.75	7.52	4.39	7.77
C_3	1.93	4.74	2.29	2.95
C_4	1.60	4.12	1.74	1.73
C_5	1.15	2.97	0.83	0.88
C_6	1.59	1.38	0.60	
C_{7+}	42.15	14 91	3.80	



Pressure in MPa
a)
0
20
40
60
80
100
120
0
1
2
3
4
5
Depth in km
Hydrostatic
Lithostatic Shale
Lithostatic Sandstone
h_w