THERMAL METAMORPHISM

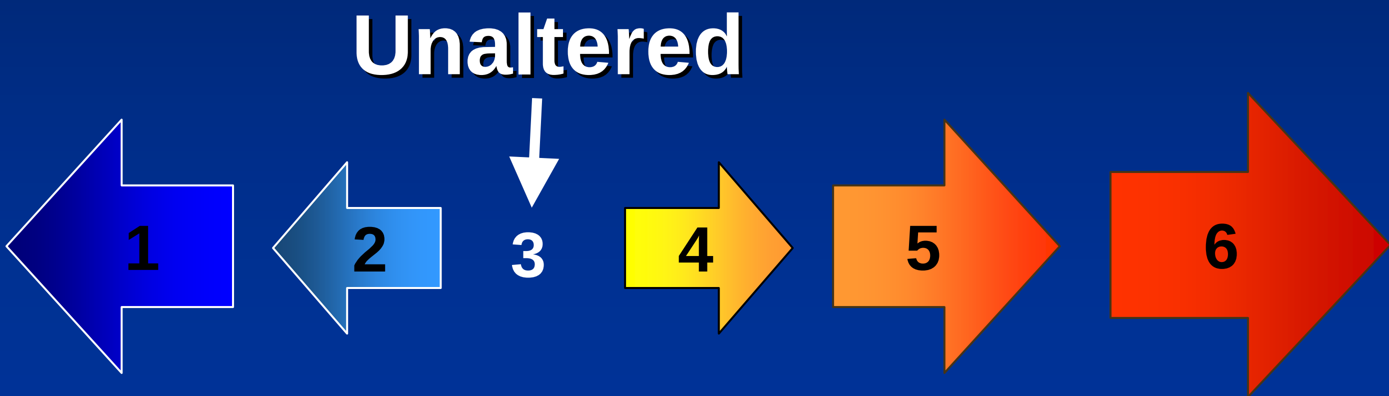
- Textural and chemical equilibration of unequilibrated chondrites.
- Produced by heating within asteroidal parent bodies.
- Heat source?
  - ^{26}Al heating or possibly other short-lived radionuclices.
  - Gravitational heating
  - Electron magnetic induction
- Occurred for quite extended period time after accretion of asteroidal parent bodies.
- Typified by petrologic types 3-6 ordinary chondrites (E, C, R, unique chondrites).

OVERVIEW

- Concept of petrologic type
- Effects of thermal metamorphism
  - Textural in type 3-6 ordinary chondrites
  - Compositional changes
- Assessing metamorphic temperatures (types 4-6 OCs)
- Metamorphism of type 3 chondrites (UOC, CO)
- Onset of thermal metamorphism in chondrites
- Thermal histories of chondrite parent bodies

THERMAL METAMORPHISM

PETROLOGIC SEQUENCE
(Van Schmus and Wood, 1967)



Aqueous Alteration

Fluids

Thermal Metamorphism

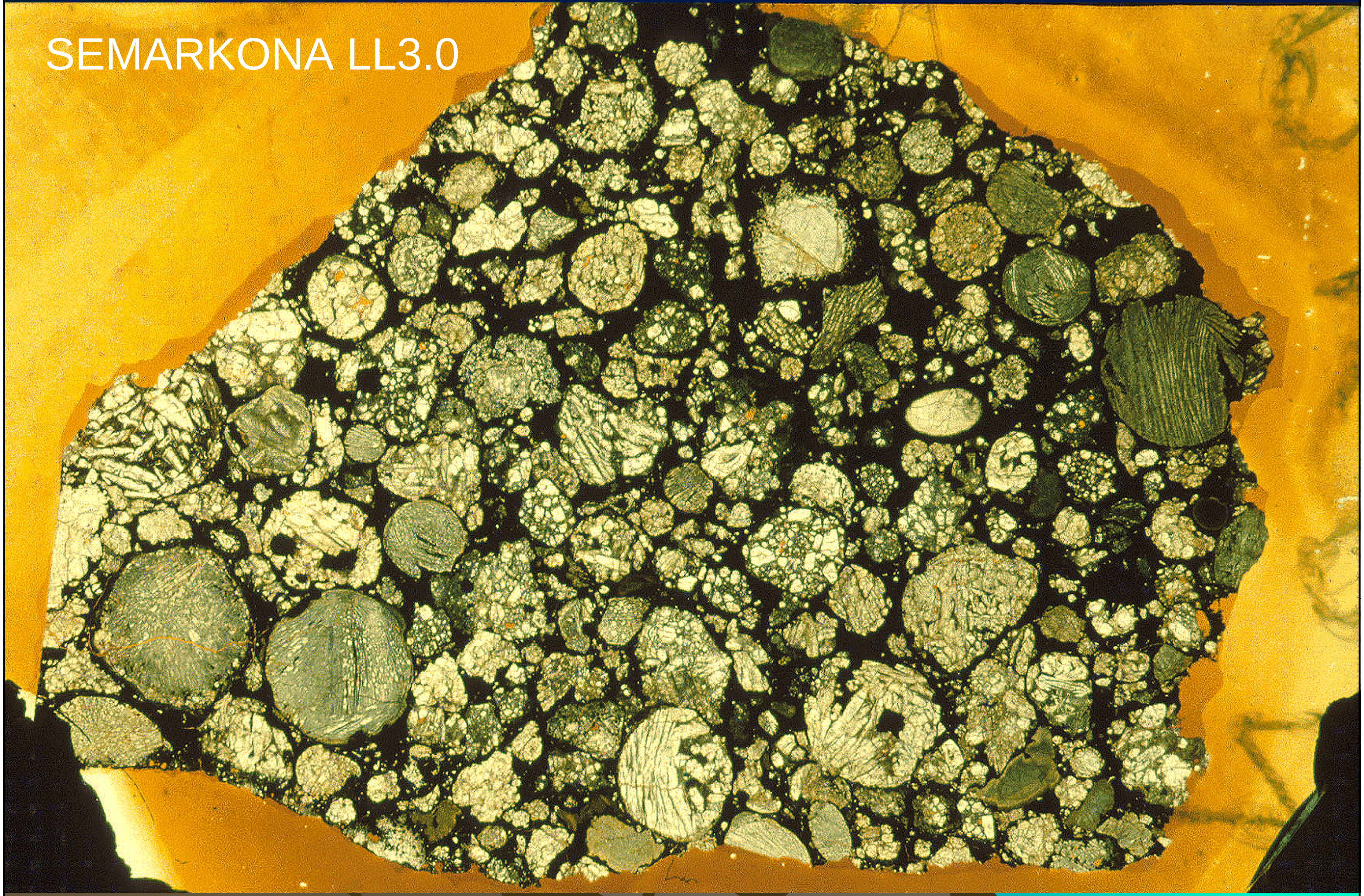
Heat ±Fluids

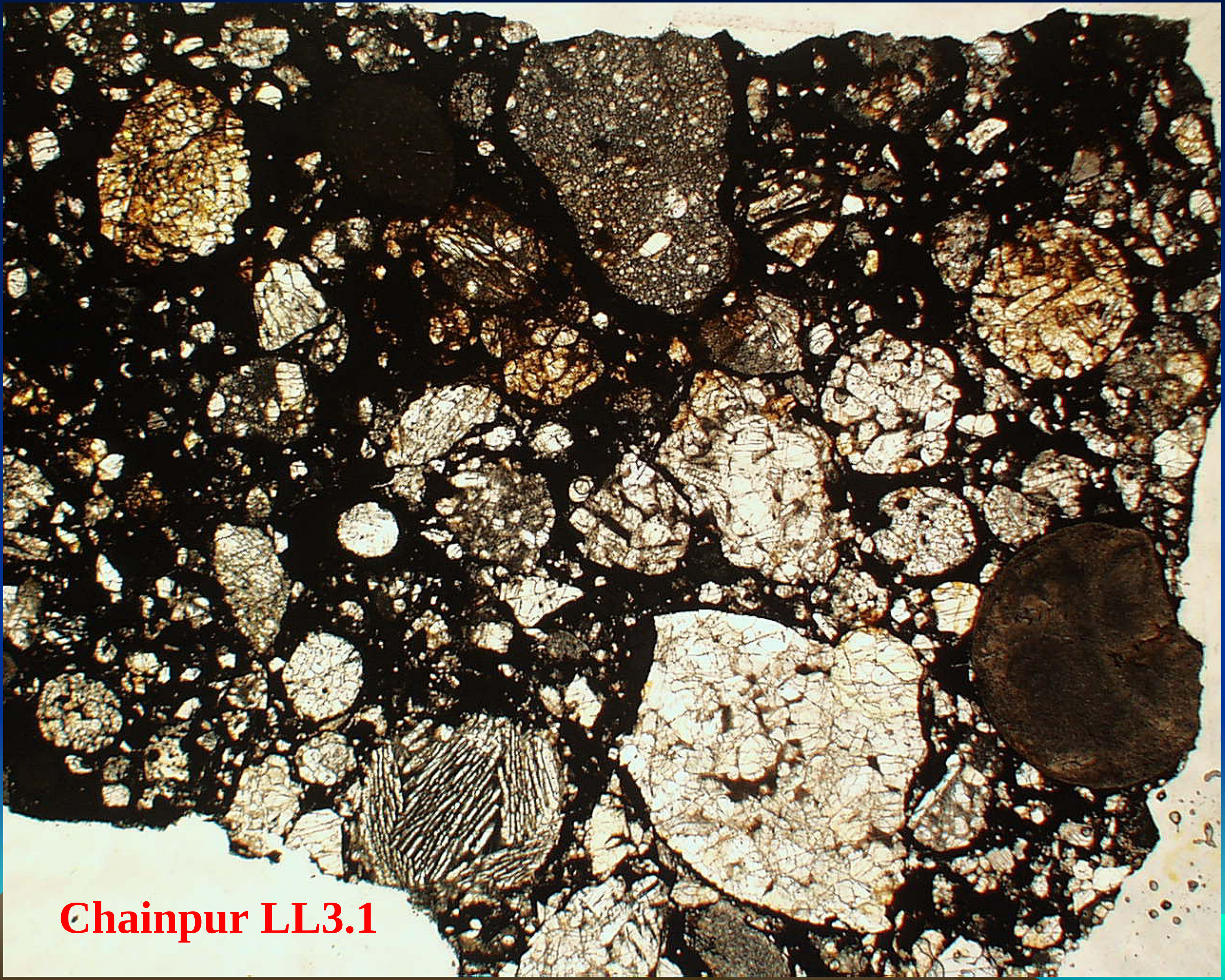
TEXTURAL CHANGES

- Exemplified by ordinary chondrites
- With increasing degrees of thermal metamorphism:
  - Outlines of chondrules become less well-defined.
  - Chondrule glass recrystallizes (feldspar)
  - Opaque fine-grained matrix recrystallizes
  - Progressive recrystallization of chondrules and matrix

Major textural changes

Petrologic Type	3	4	5	6
Matrix	fine-grained opaque in low type 3s	transparent, recrystallized coarsening from 4 to 6		
Chondrule-matrix Integration	chondrules very sharply defined	chondrules well defined	chondrules readily delineated	chondrules poorly defined
Chondrule glass	clear, isotropic	devitrified, absent		

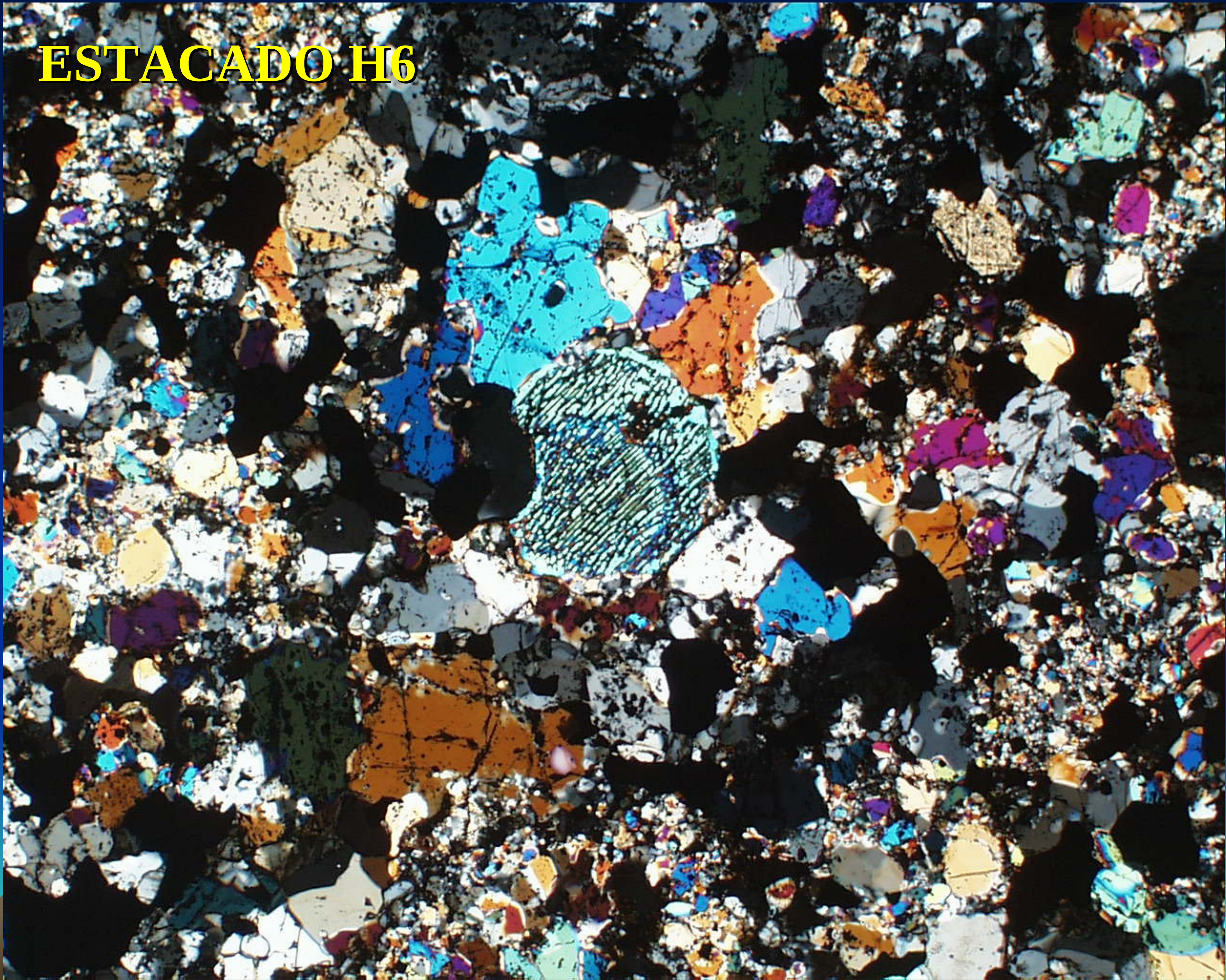

SEMARKONA LL3.0


Chainpur LL3.1


AVANHANDAVA H4


AVANHANDAVA H4

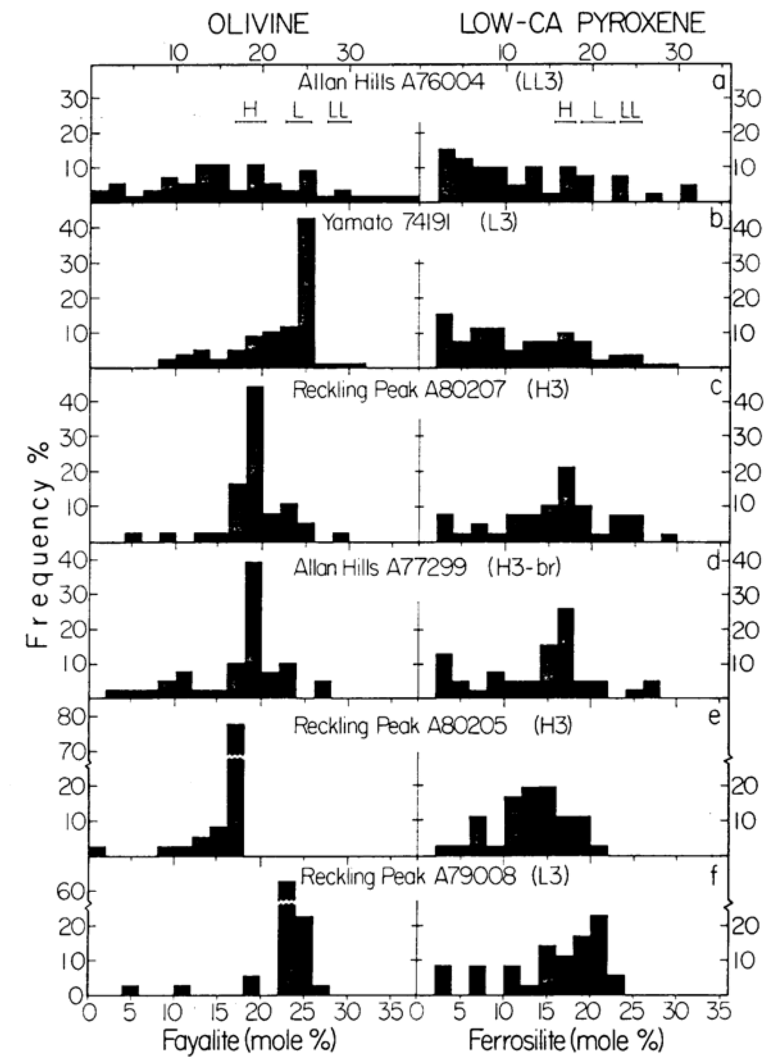

ESTACADO H6

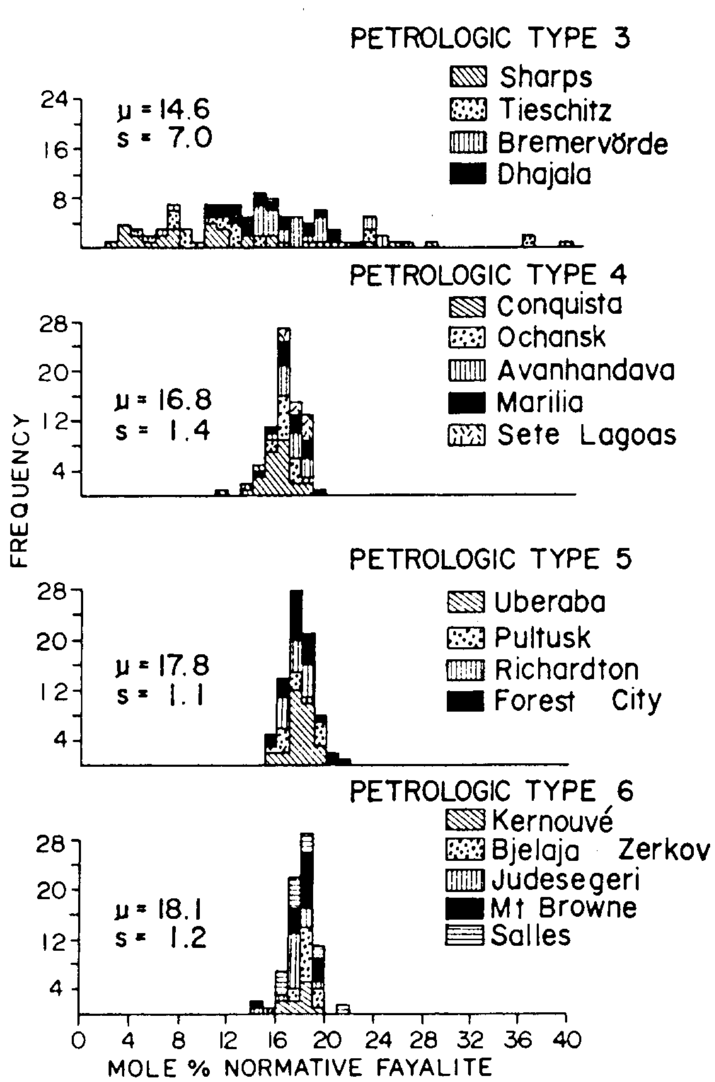

ESTACADO H6

Mineralogic/Chemical Changes

Petrologic Type	3	4	5	6
Olivine/pyx compositional heterogeneity	$\geq$5%	$\leq$5%	homogeneous	
Low-Ca pyx structure	mostly monoclinic	<20%	>20%	orthorhombic
Feldspar	minor primary	secondary <2 µm grains	secondary 2-50 µm grain	secondary >50µm grains

OLIVINE AND PYROXENE

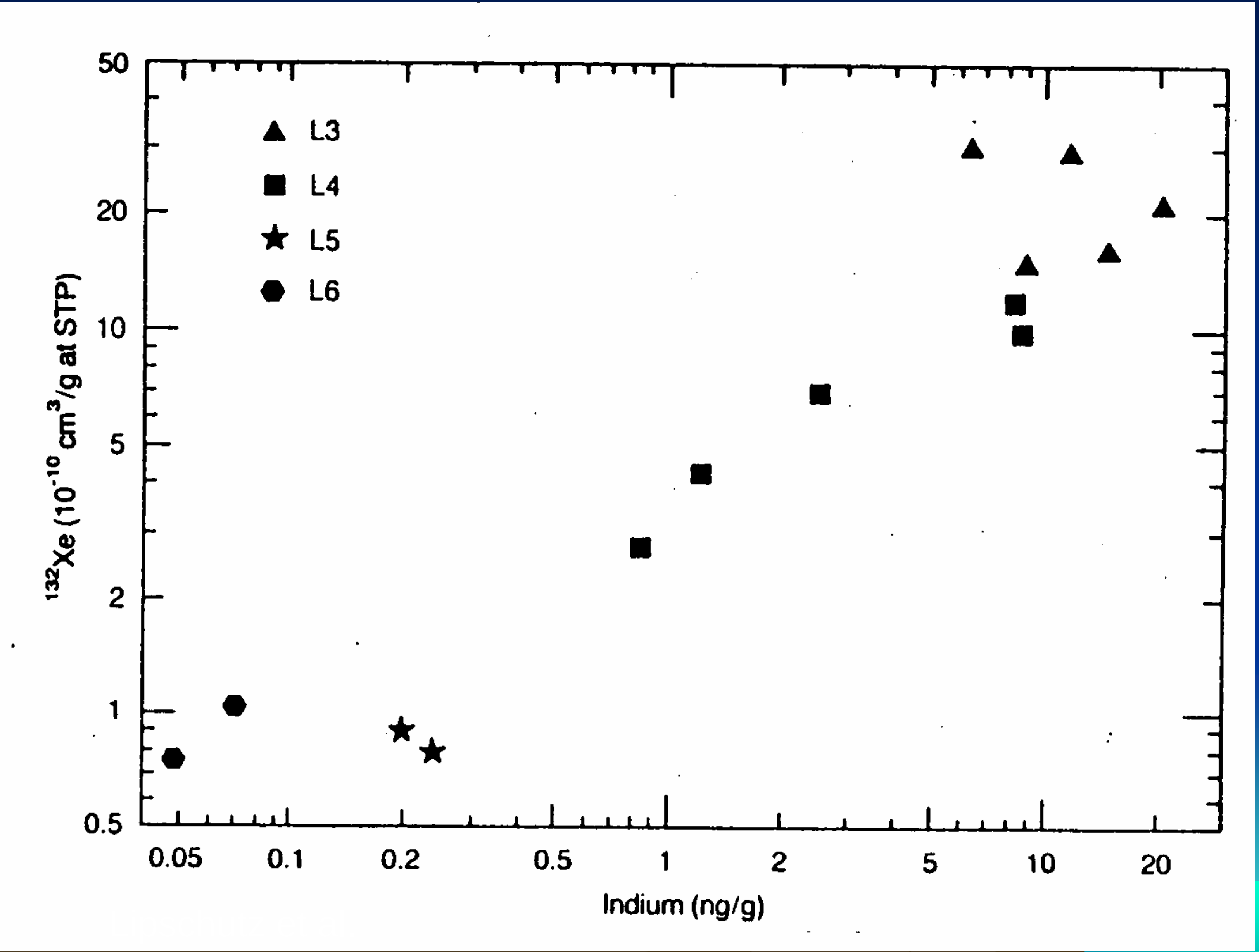




CLINOENSTATITE⇒ORTHOENSTATITE

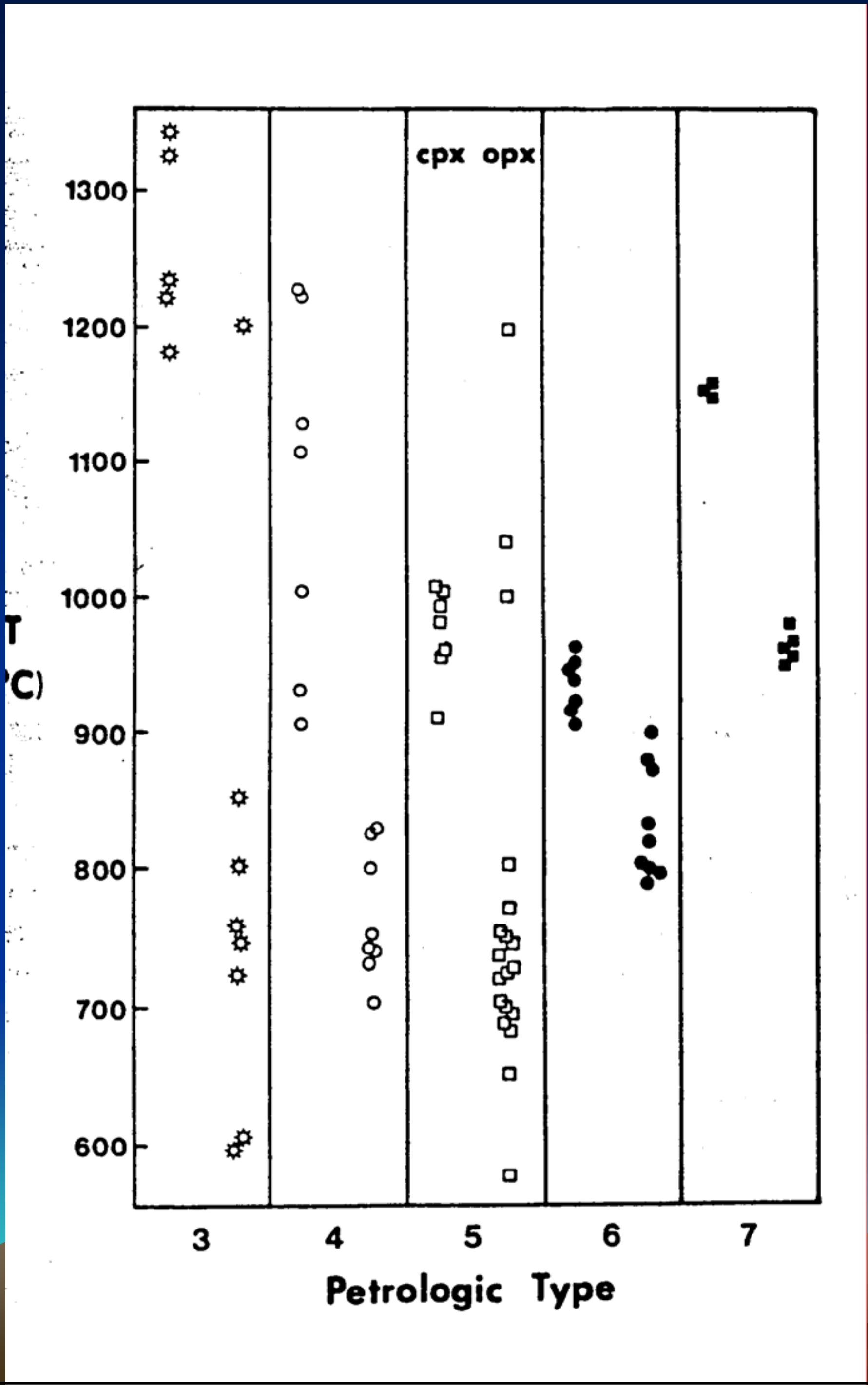
- Striated low Ca-pyroxene in type 3 chondrites
  - Quenching protopyroxene forms intergrowth of monoclinic and orthorhombic polymorphs
  - Polysynthetic twinning
- Thermal metamorphism inverts metastable monoclinic polymorph to orthopyroxene.
- Striated appearance disappears through metamorphic sequence.
- In type 6s, opx is present

LOSS OF HIGHLY VOLATILE ELEMENTS



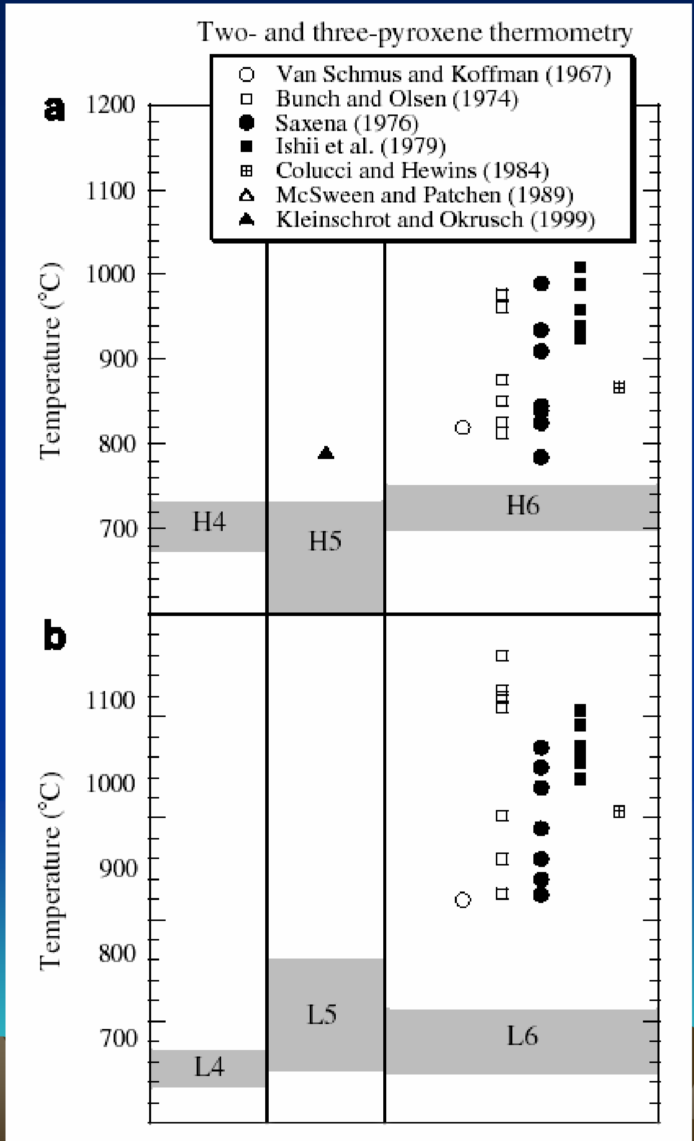
DETERMINATION OF METAMORPHIC TEMPERATURES

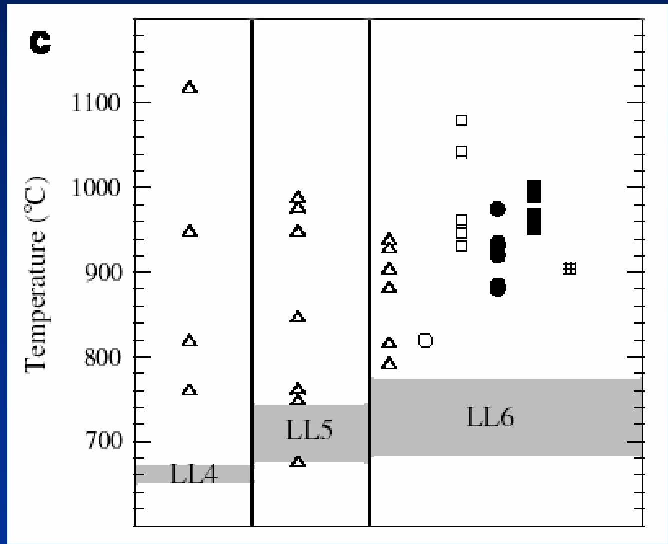
- Very challenging even for ordinary chondrites.
- Limited mineral geothermometers are applicable to chondritic assemblages.
- Main thermometers:
  - Two and three pyroxene geothermometry
  - Oxygen isotope thermometry
  - Olivine-spinel geothermometry
  - Ordering of feldspars



- Two pyroxene (Mg-Fe) geothermometry.
- Augite (cpx) and low-Ca pyx are present in chondrules in primitive chondrites
- Not equilibrated in type 4-5 chondrites
- May not even be equilibrated in type 6 chondrites.

METAMORPHIC EQUILIBRATION TEMPERATURES



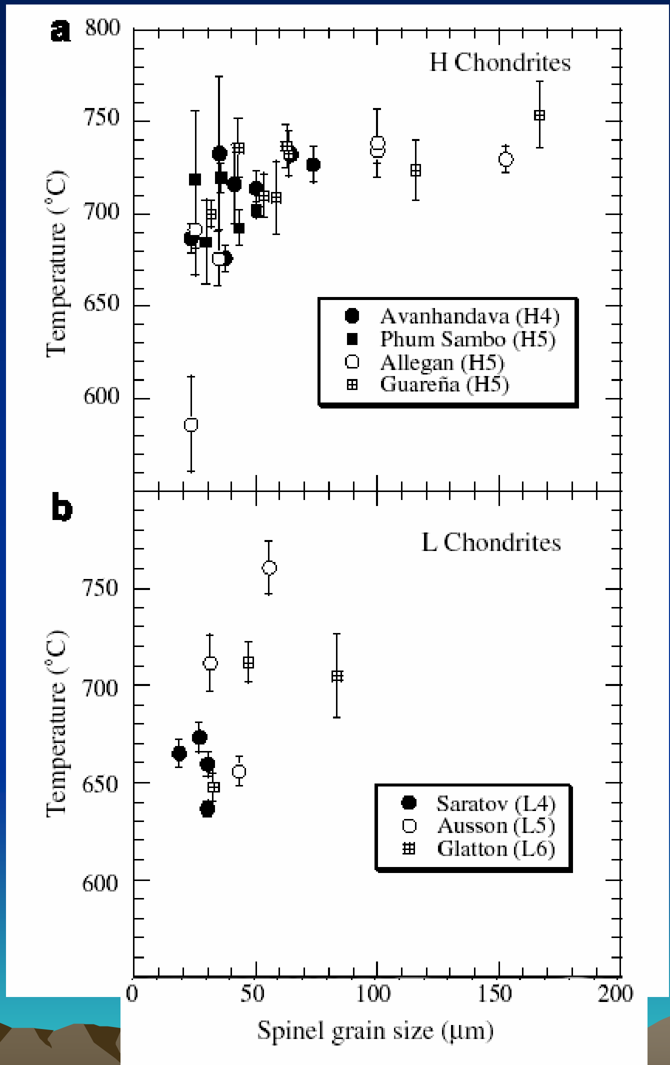


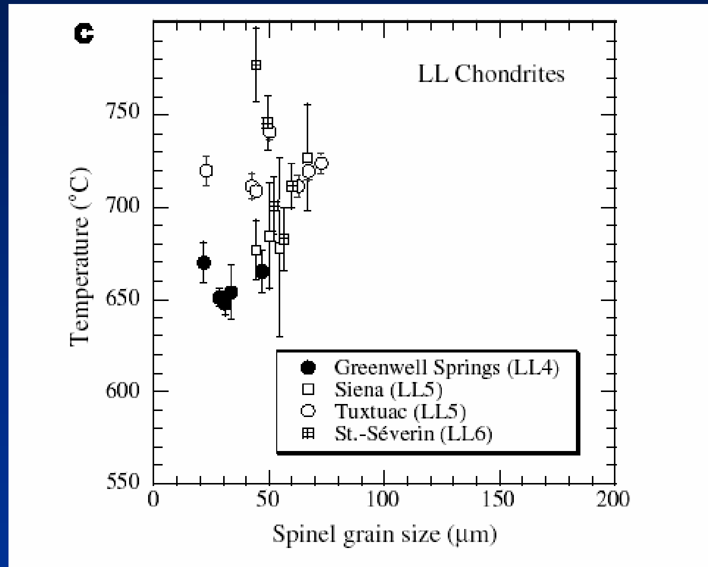
TYPE 4-6 ORDINARY CHONDRITES

Shaded regions – olivine-spinel data

Kessel et al. (2007) GCA

OLIVINE-SPINEL THERMOMETRY





TYPE 4-6 ORDINARY CHONDRITES

Shaded regions – olivine-spinel data

Kessel et al. (2007) GCA

TEMPERATURE ESTIMATES FOR H chondrites

	Two and three pyx	Ol-sp (Mg-Fe)
LL4	760-1120ºC	650-670ººC
LL5	680-1000ºC	680-740ºC
LL6	790-1090ºC	690-790ºC
L4		640-675ºC
L5		650-710ºC
L6	860-1140ºC	660-720ºC
H4		680-725ºC
H5		600-725ºC
H6	790-1000ºC	700-740ºC

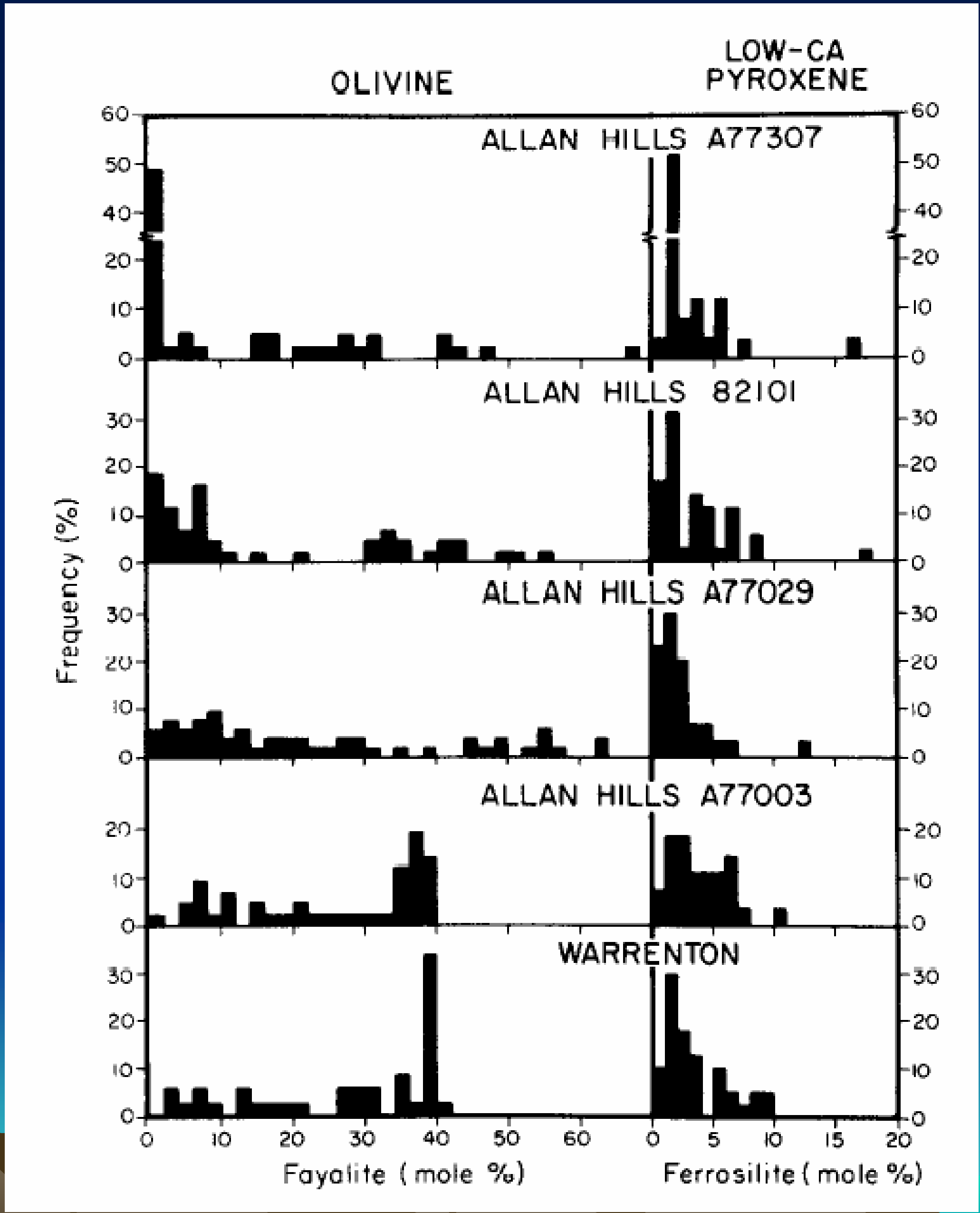
Metamorphism in Type 3 chondrites

- Significant metamorphic effects occur between petrologic type 3 and 4 chondrites.
- Compositional zoning develops in olivine
- Matrix recrystallizes
- Mesostasis recrystallizes
- Organic material undergoes graphitization

TRACING METAMORPHISM IN TYPE 3 CHONDRITES

- Divided into subdivisions – 3.0, 3.1….3.9
- Thermoluminescence (TL) (Sears et al.)
  - TL sensitivity related to recrystallization of chondrule mesostasis
  - Changes in TL may be related to ordering in feldspar
- Graphitization of organic material (Brearley, 1990; Bonal et al. 2005)
  - Electron diffraction
  - Raman spectroscopy
- Traces progressive graphitization of organic material.

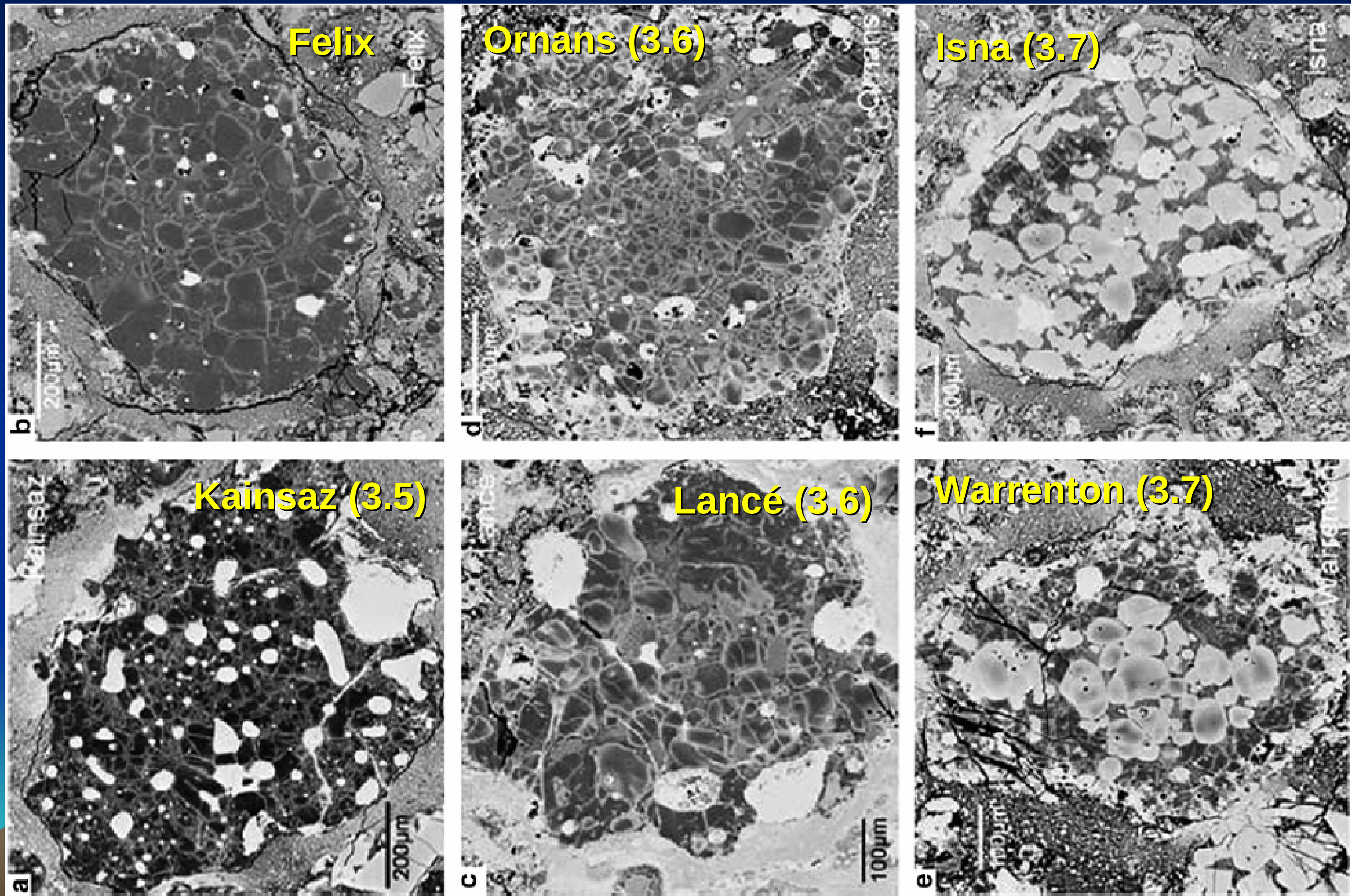
CO3



Chondrule olivines and pyroxenes

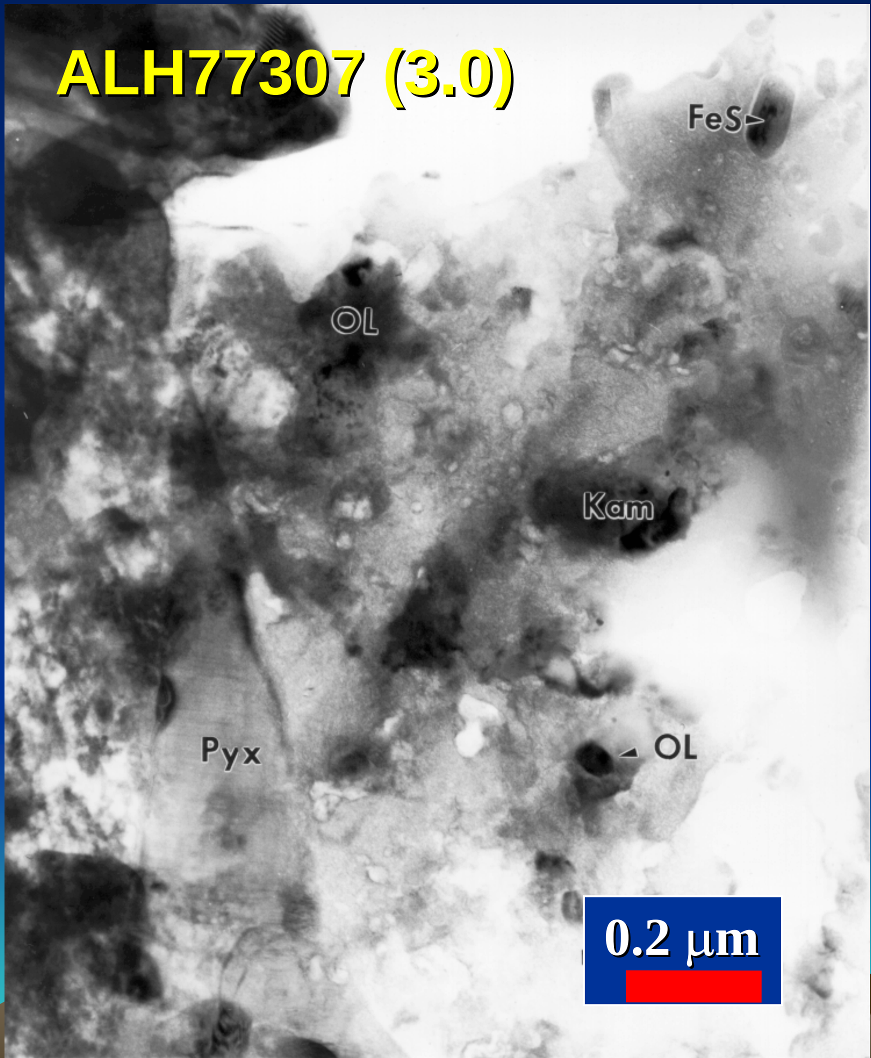
Scott and Jones (1990) GCA

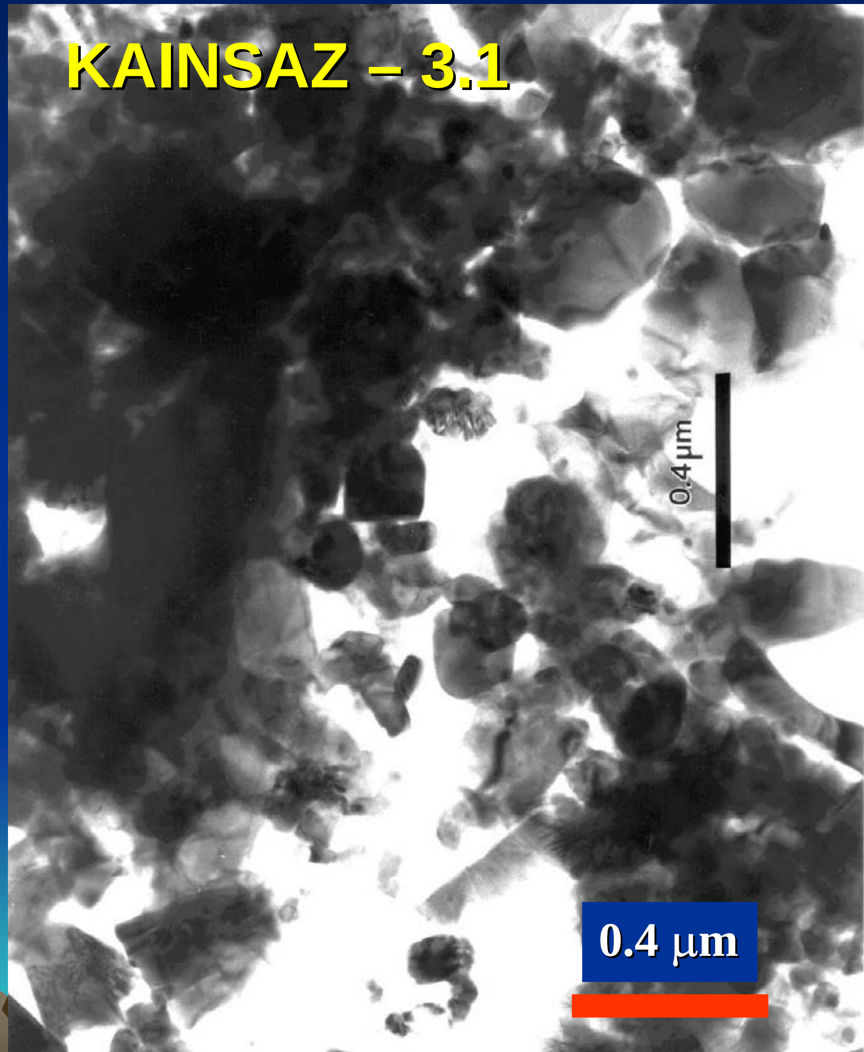
COMPOSITIONAL EQUILIBRATION IN CO CHONDRITES



Bonal et al. (2007) GCA

RECRYSTALLIZATION OF MATRIX





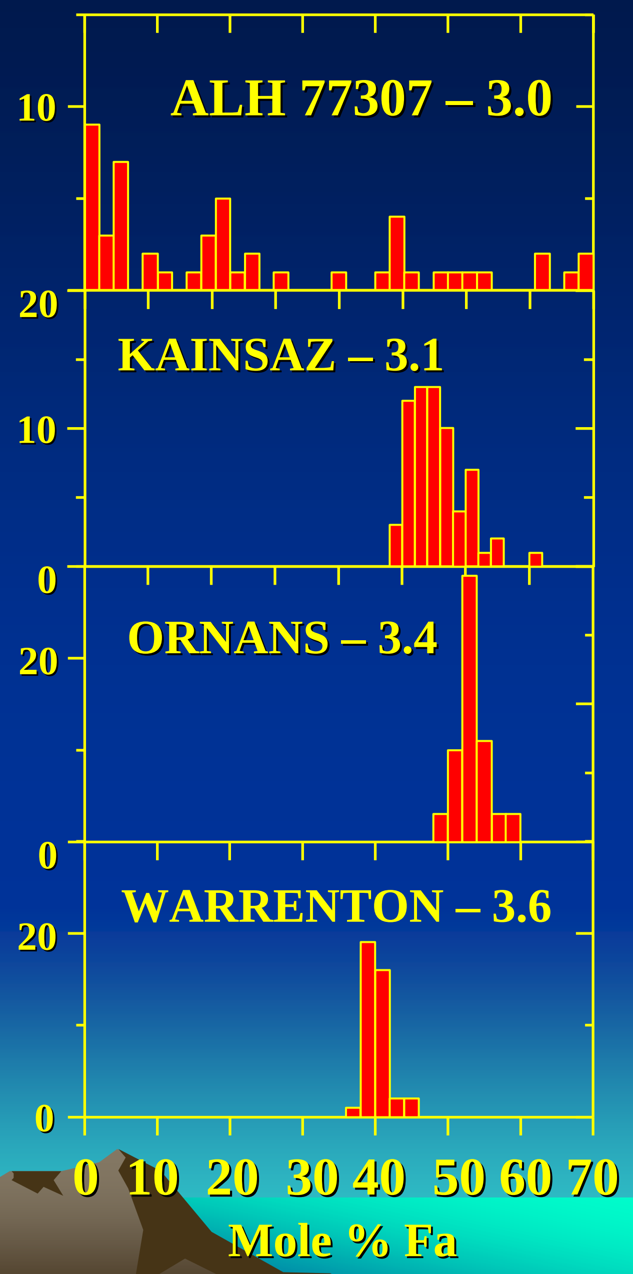
Significant amorphous material

FeO-rich olivine

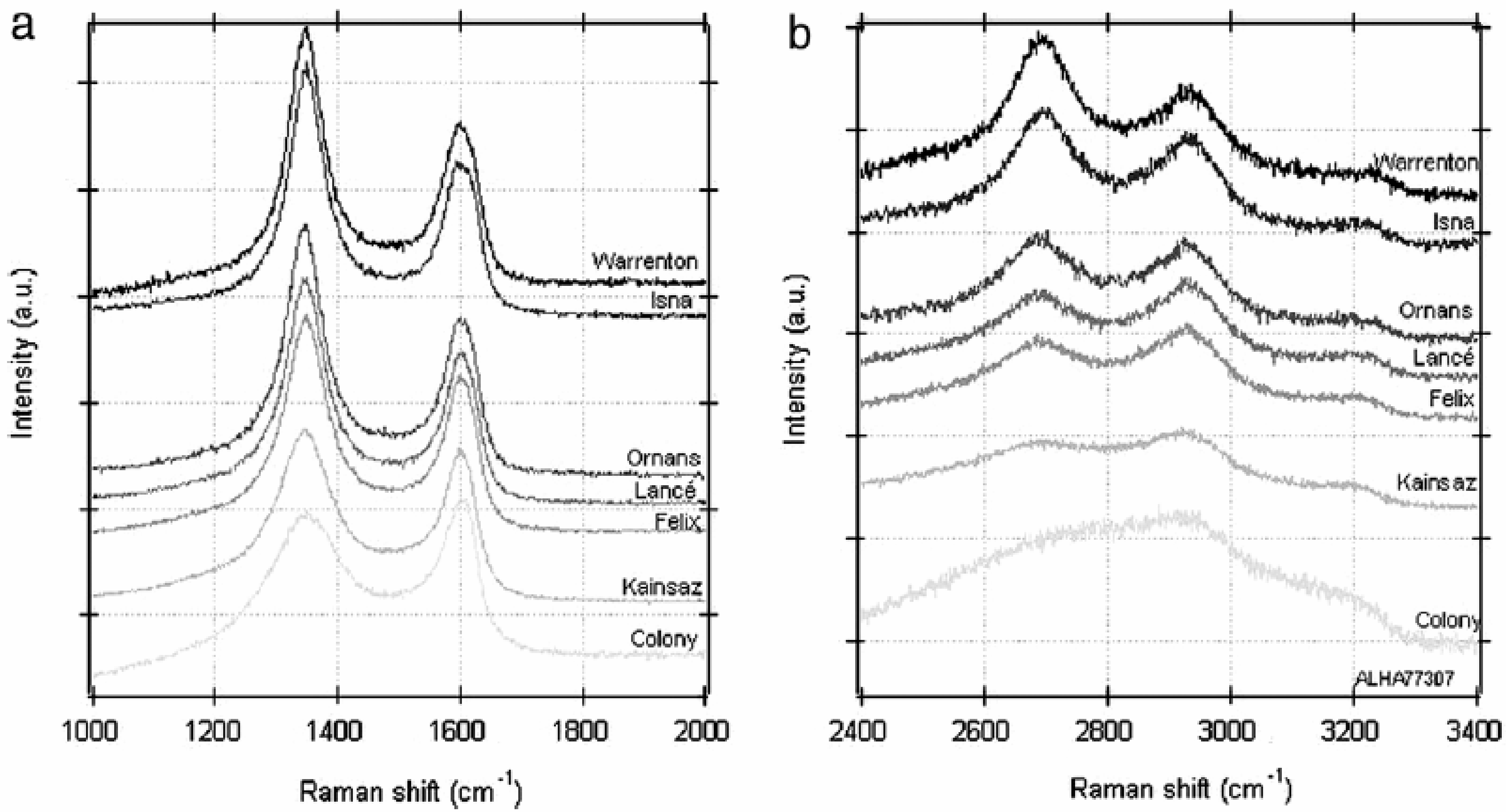
Effects of Metamorphism on matrices (CO3s)

- Amorphous matrix in type 3.0 chondrites forms FeO-rich olivine.
- Matrix olivines highly unequilibrated in type 3.0 chondrites.
- Equilibrate early in petrologic sequence.

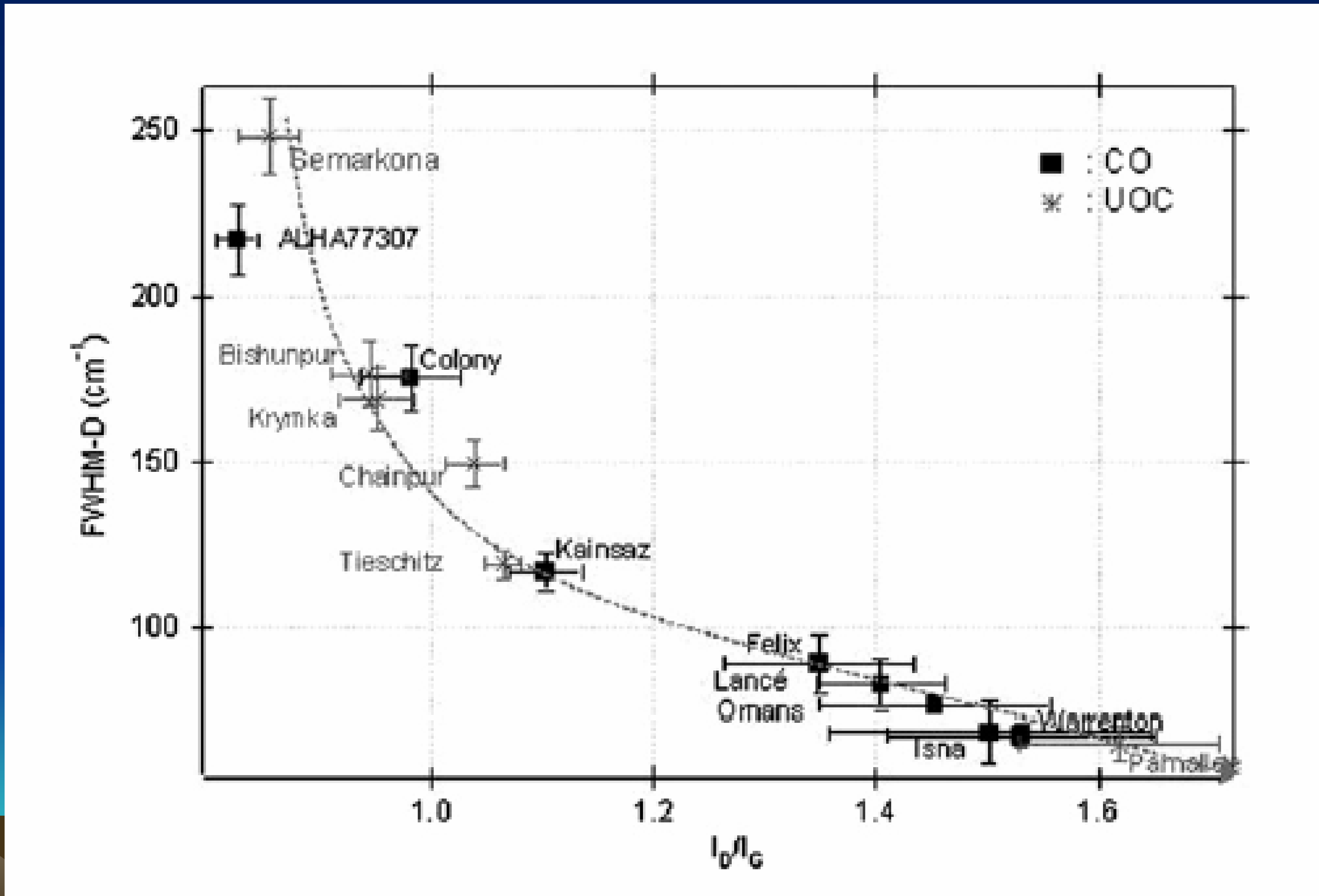
CO3 chondrites



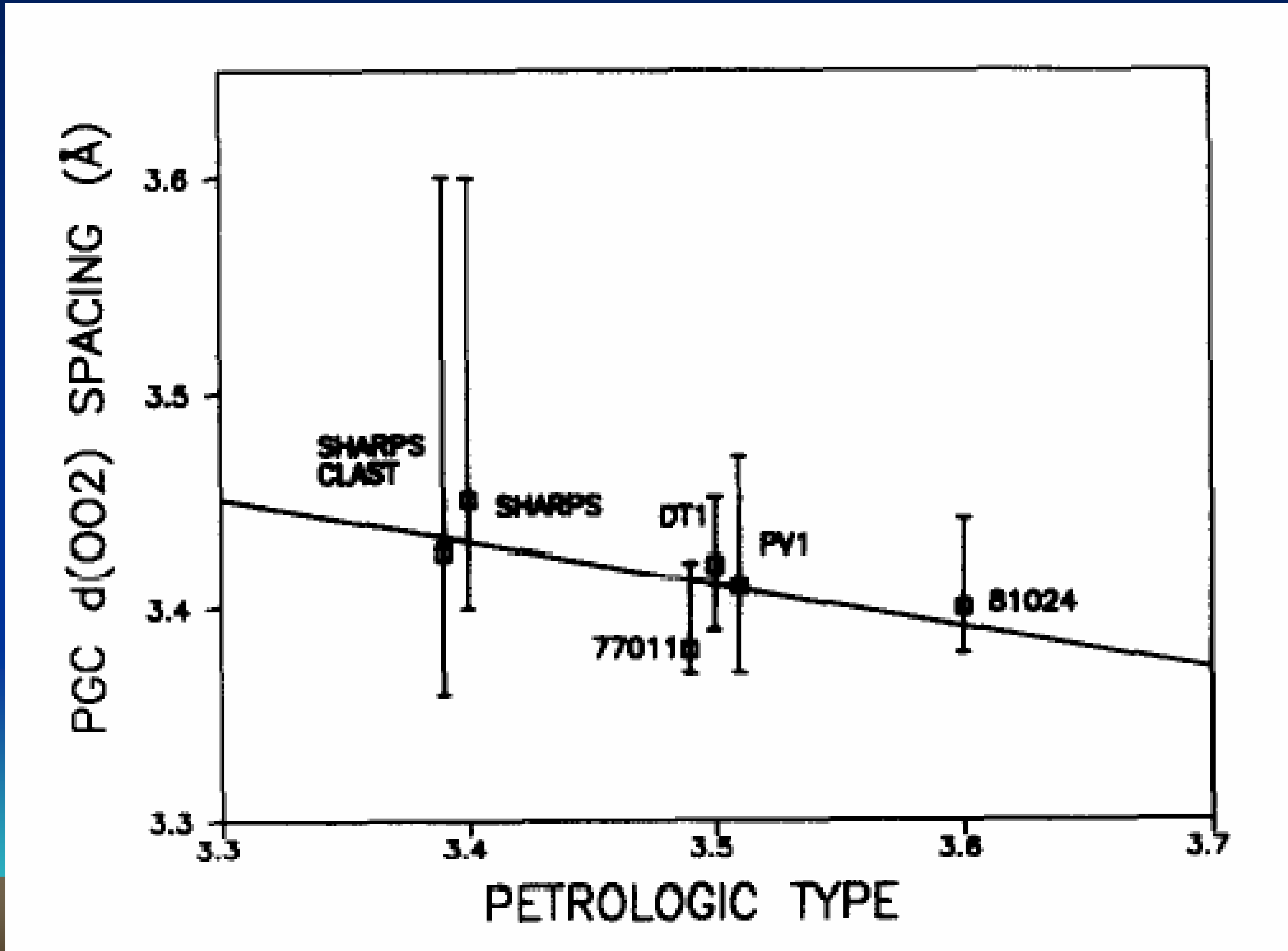
Variation in Raman spectra (CO3s)



Raman maturity tracers



Variation in d(002) graphite

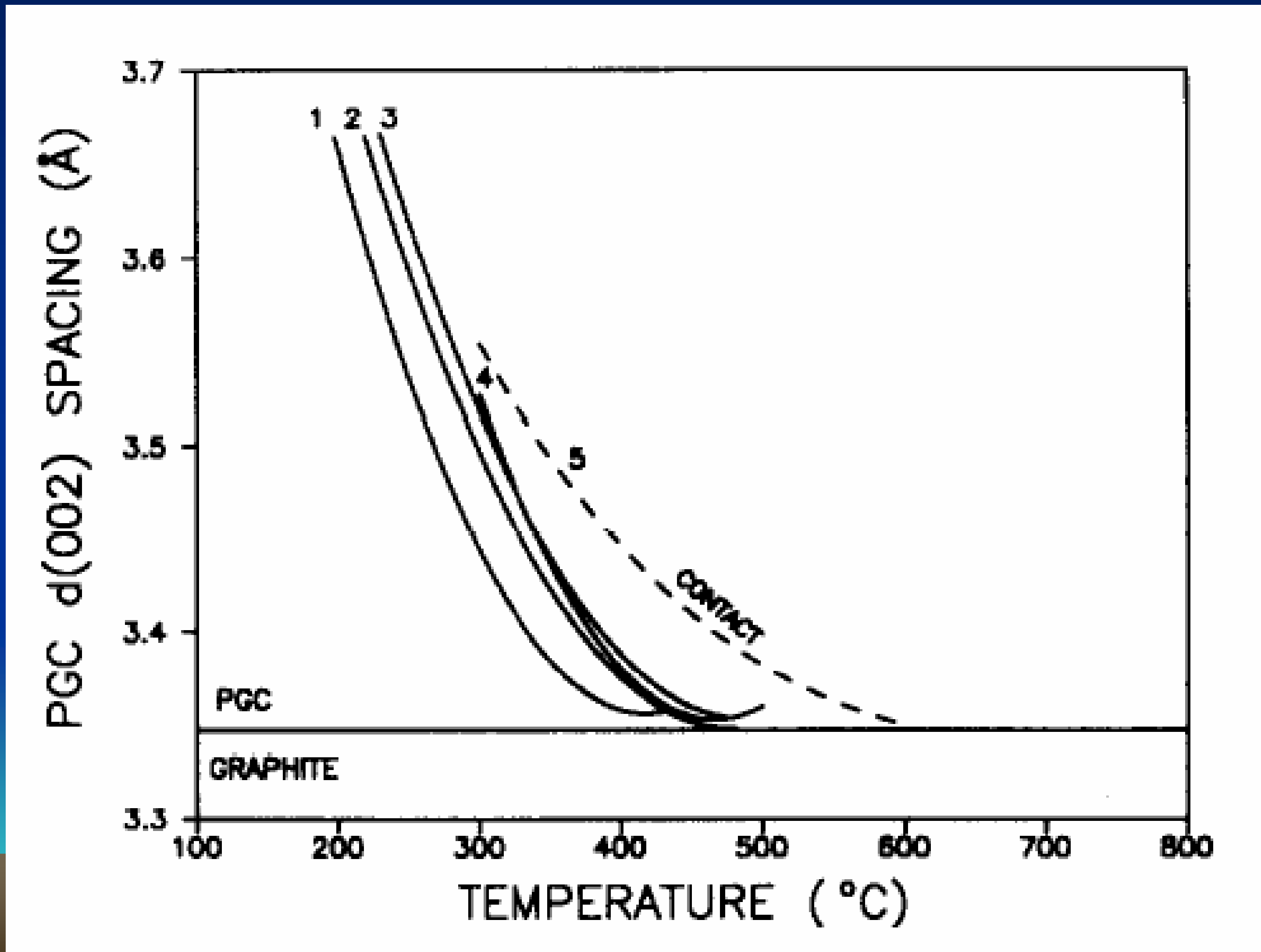


TYPE 3 CHONDRITES (UOCs)

TEMPERATURES OF METAMORPHISM

- Difficult to determine.
  - Constraints are limited.
  - More investigation is necessary
- TL sensitivity (Sears and Hasan, 1980).
  - 500-600ºC for type 3 chondrites.
  - Based on low to high albite transition
- Poorly graphitized carbon thermometer (Rietmeijer and MacKinnon, 1985).
  - Type 3.4-3.5 chondrites (300-450ºC) (Brearley, 1990)
- Graphitic carbon (Raman)
  - Tieschitz (3.6) – >350ºC – PGC – Christophe Michel-Levy and Lautie (1981).
- Equilibration of matrix olivines (Brearley et al. 1989)
  - >400ºC.
- Best current estimate - >250ºC for type 3.0, ~350ºC for type 3.5

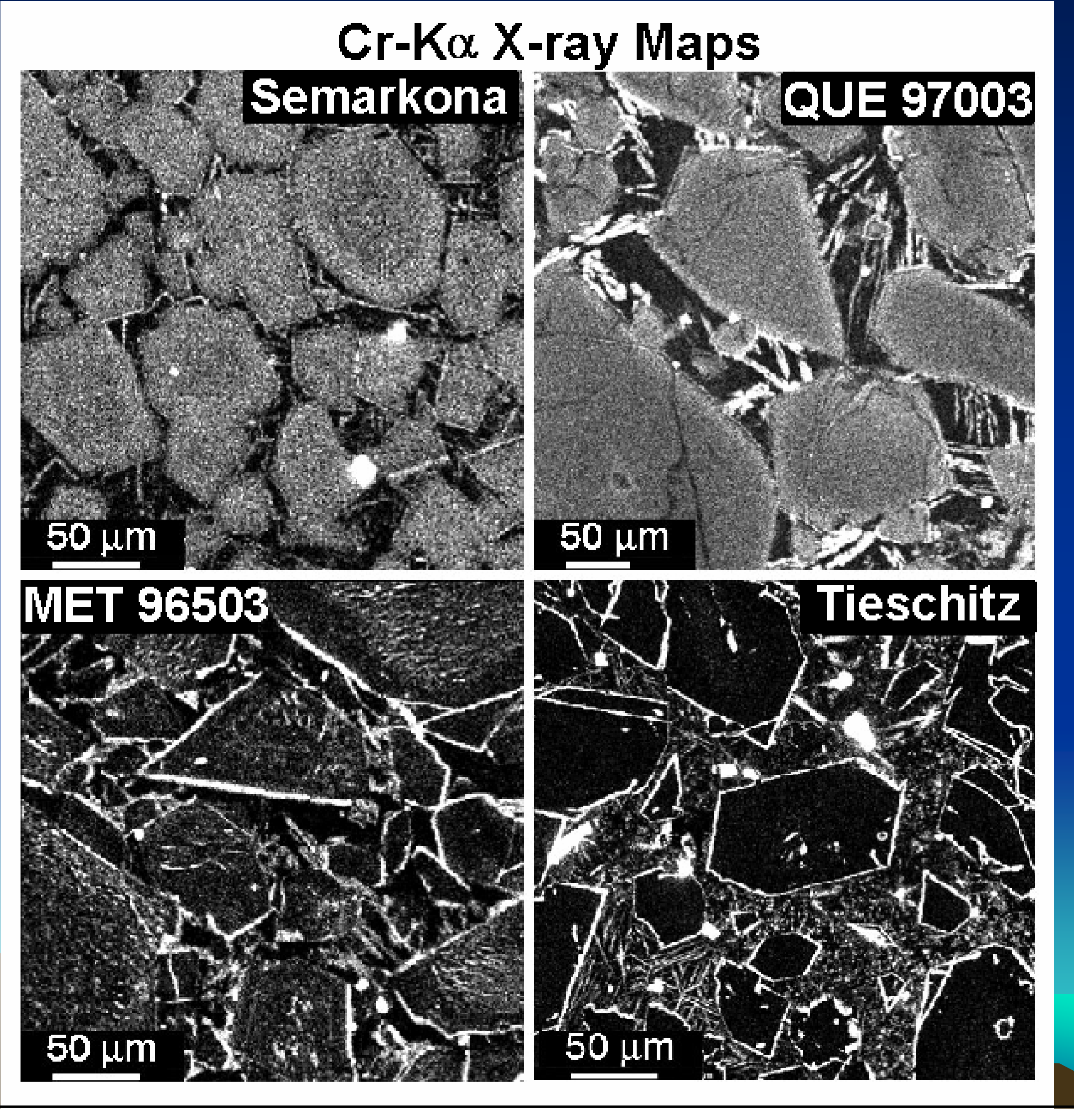
Poorly graphitized carbon thermometer (d002)



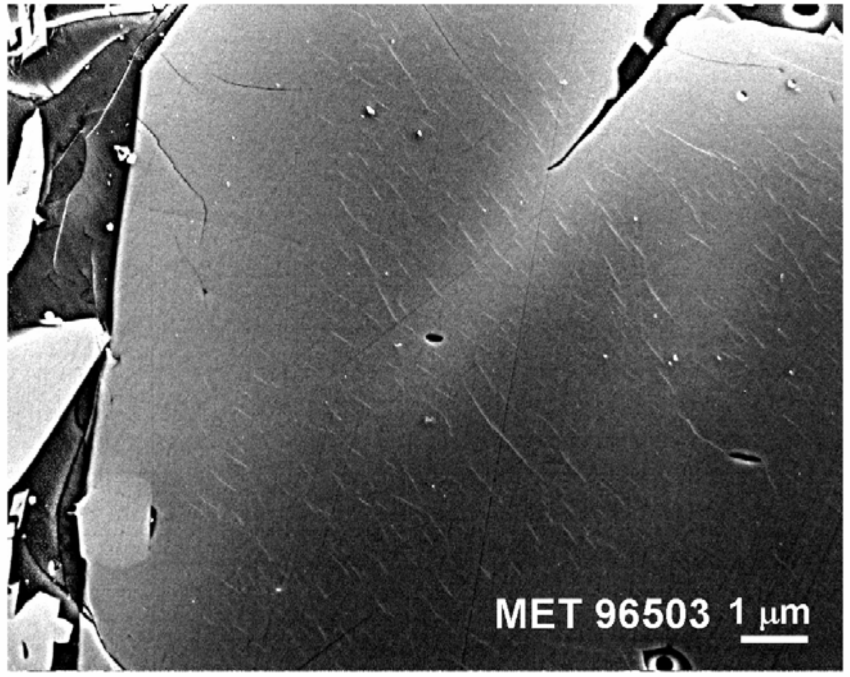
ONSET OF THERMAL METAMORPHISM

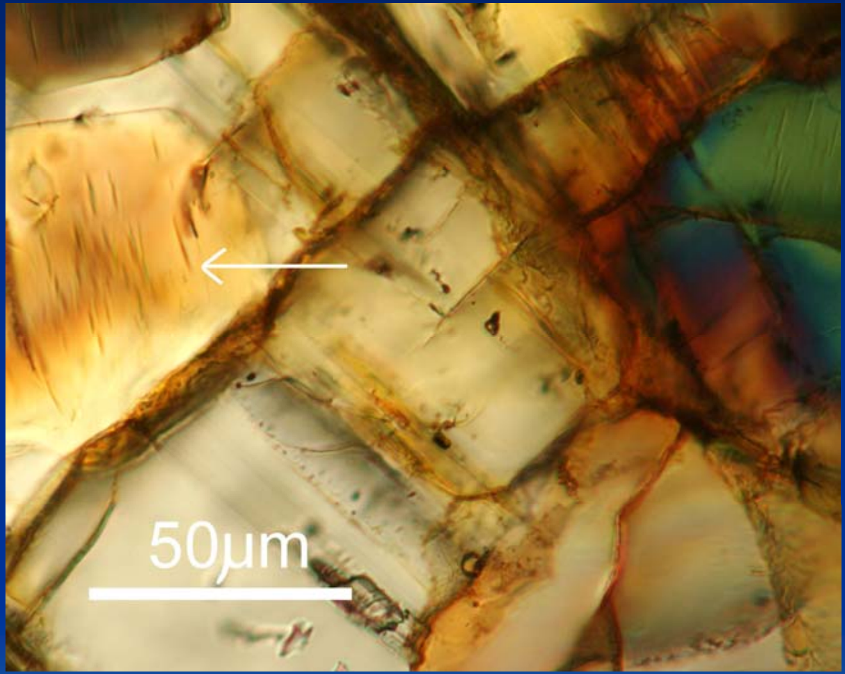
- Even type 3.0 chondrites show evidence of metamorphism.
- Subtle changes are apparent that merit subdivision of type 3.0s (Grossman and Brearley, 2005).
- Cr-content of olivines in chondrules
- Sulfur distribution in matrices
- Changes in chondrule mesostasis compositions.

Cr distribution in UOC chondrules



Cr exsolution in olivine

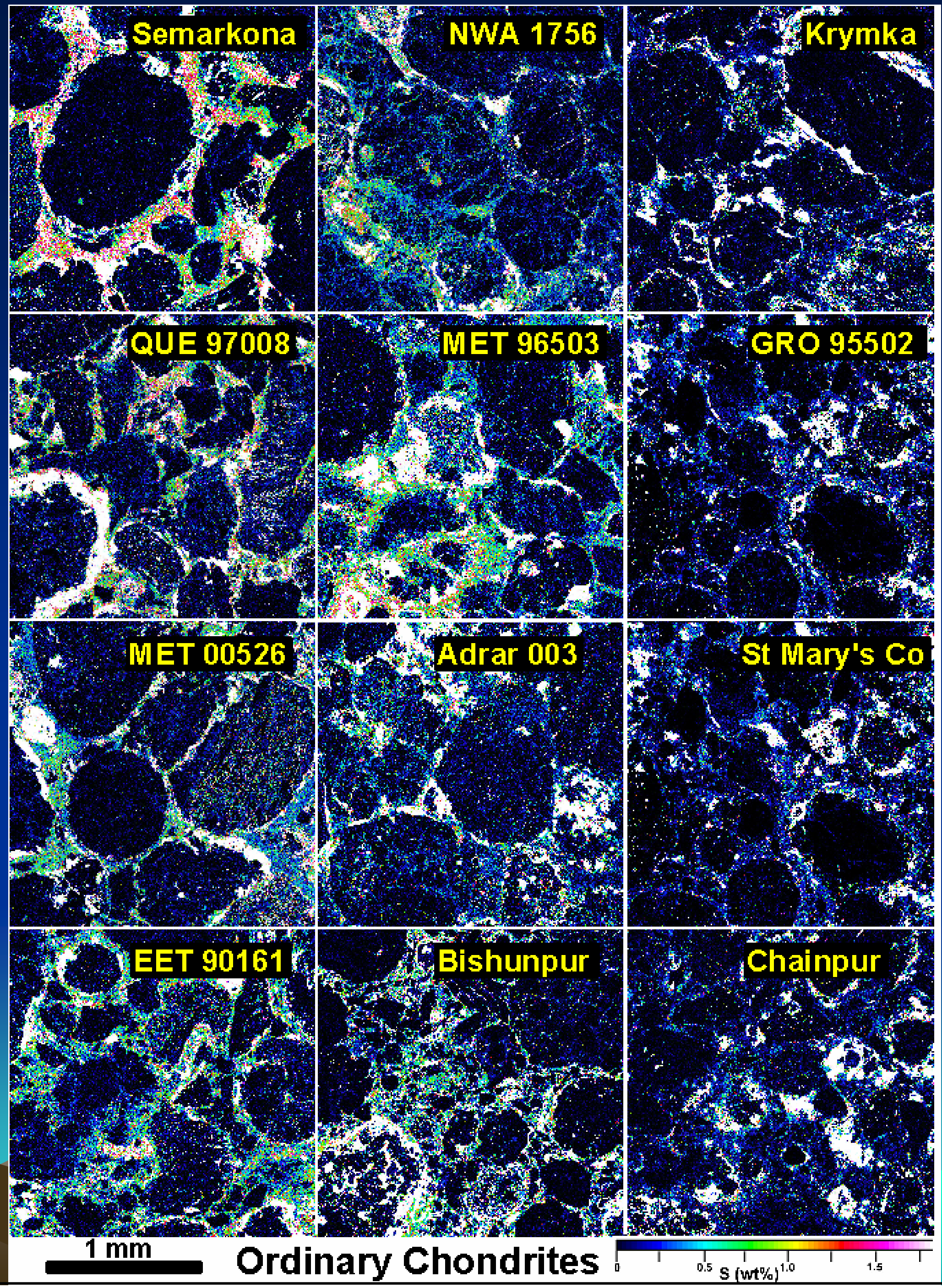




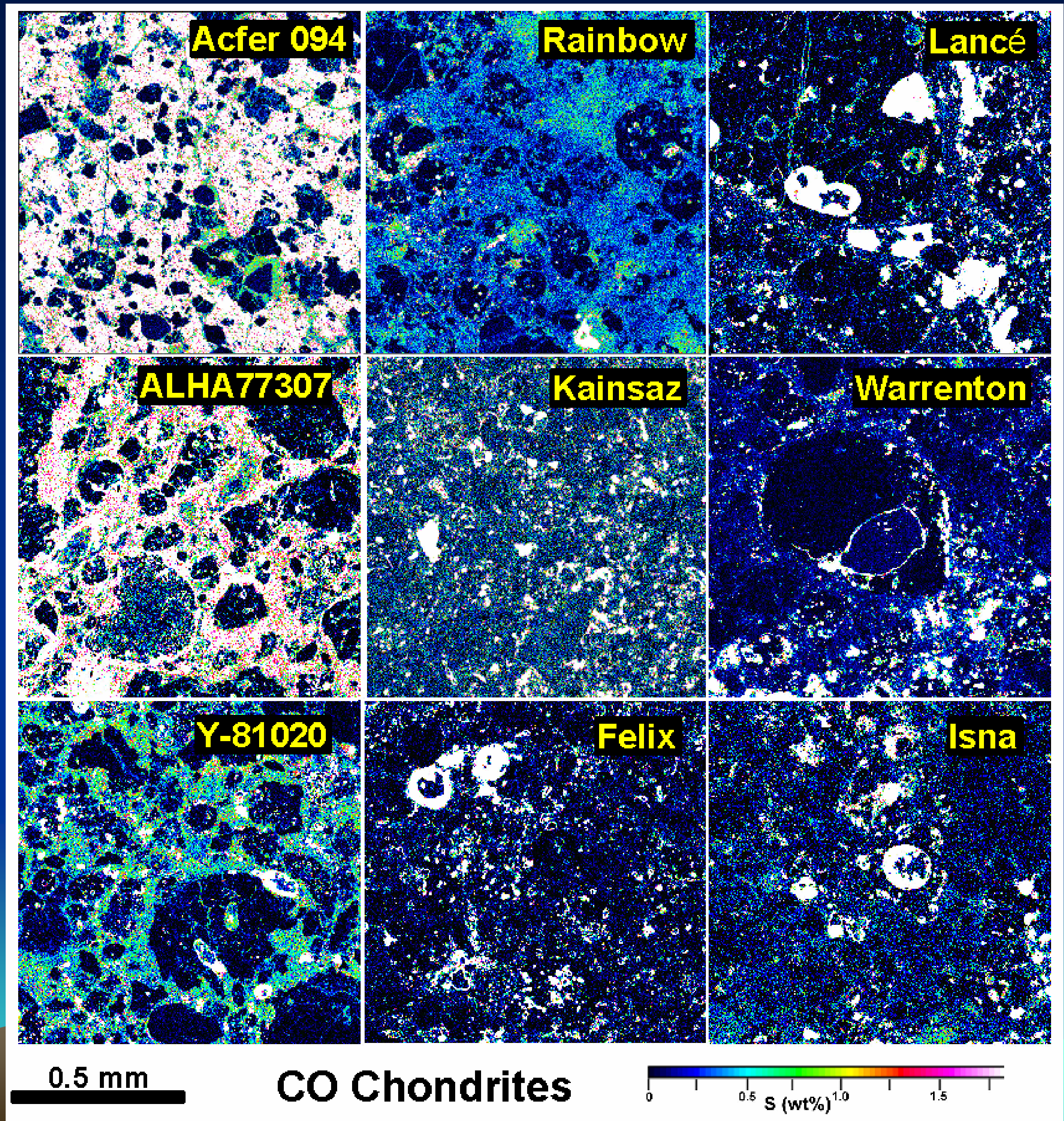
Lamellae of Cr-rich phase – probably chromite based on TEM

Grossman and Brearley (2005)

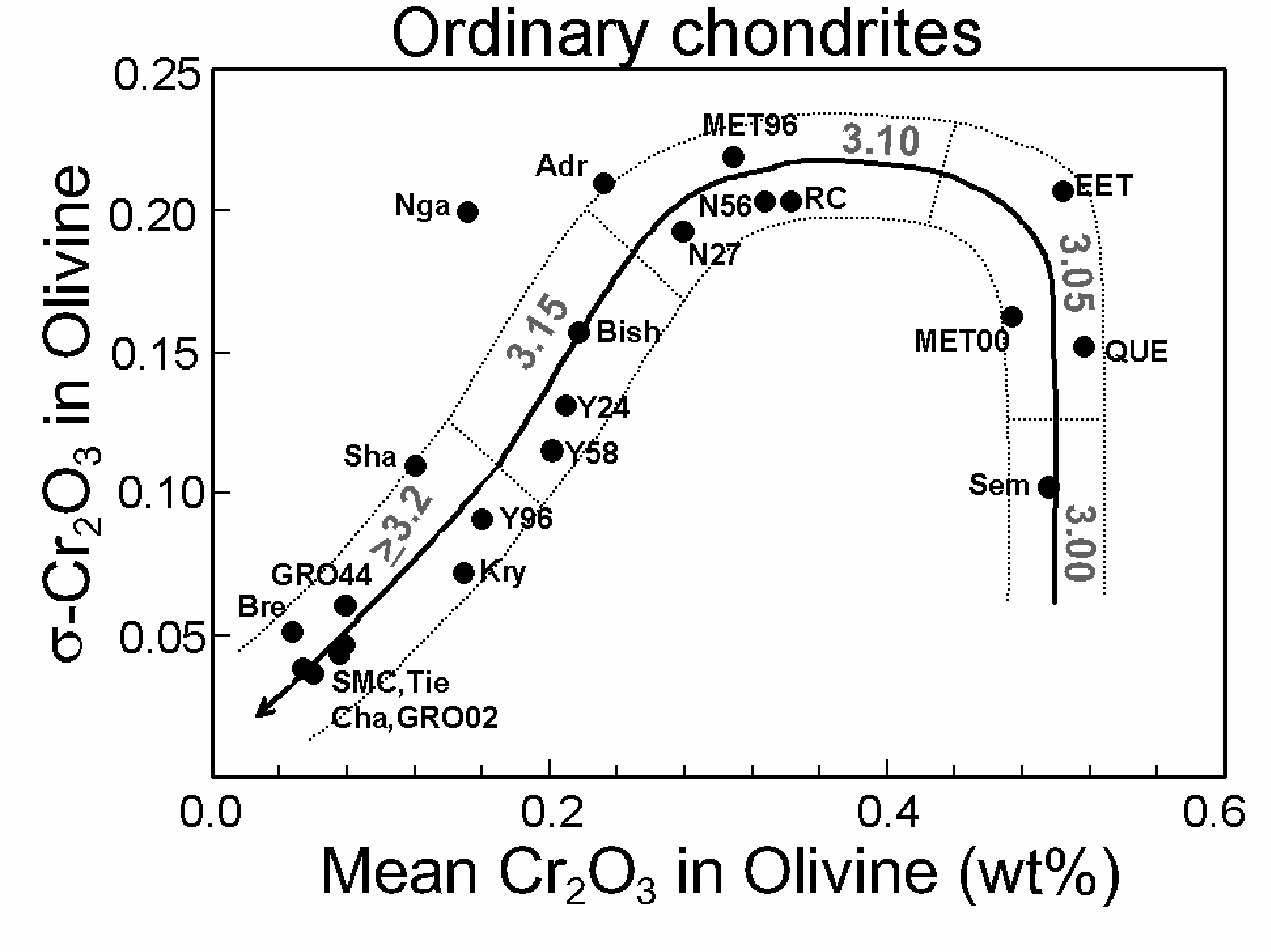
SULFUR IN UOC MATRICES



CO3 MATRICES

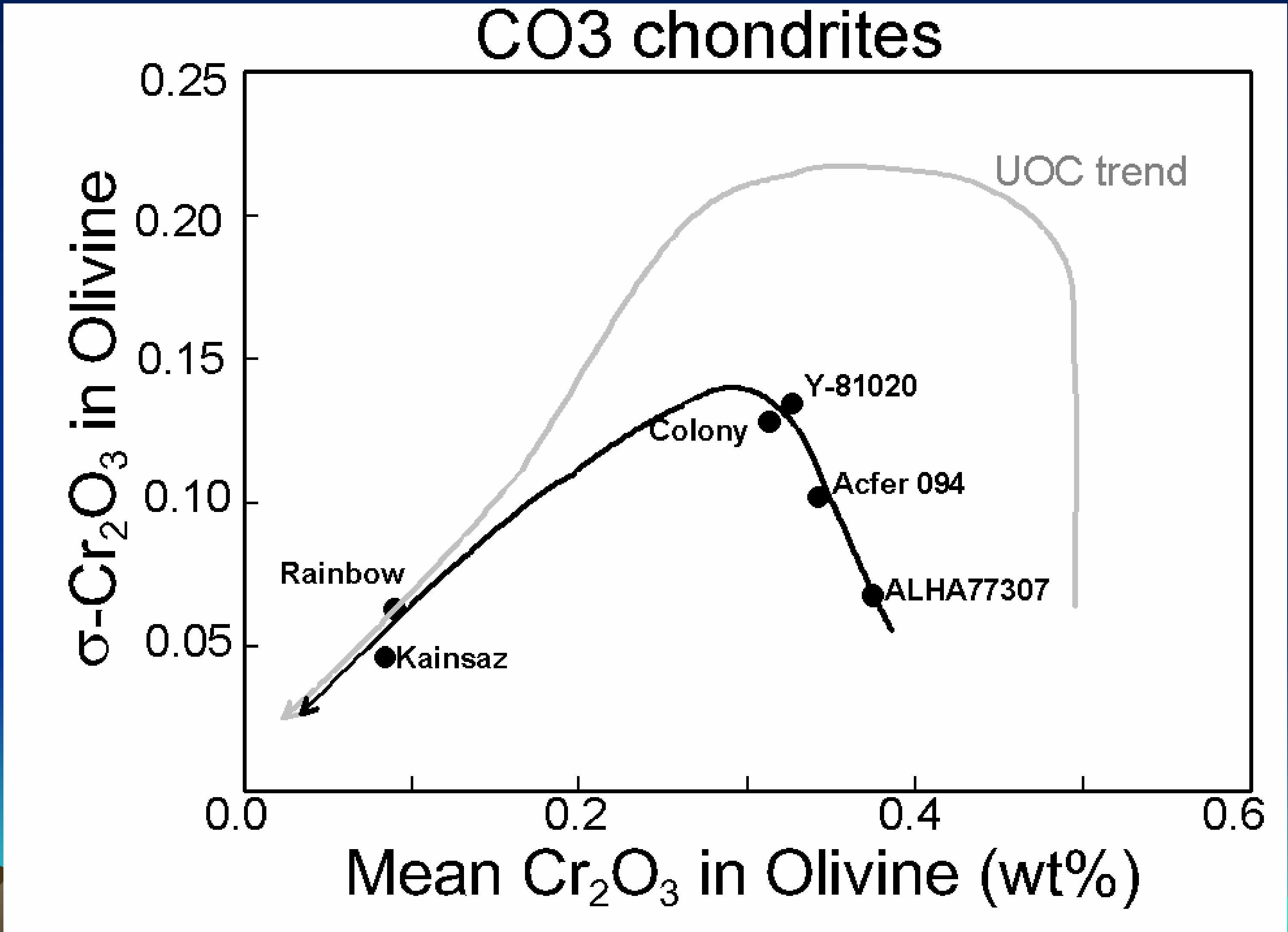


Cr variation in very primitive UOCs



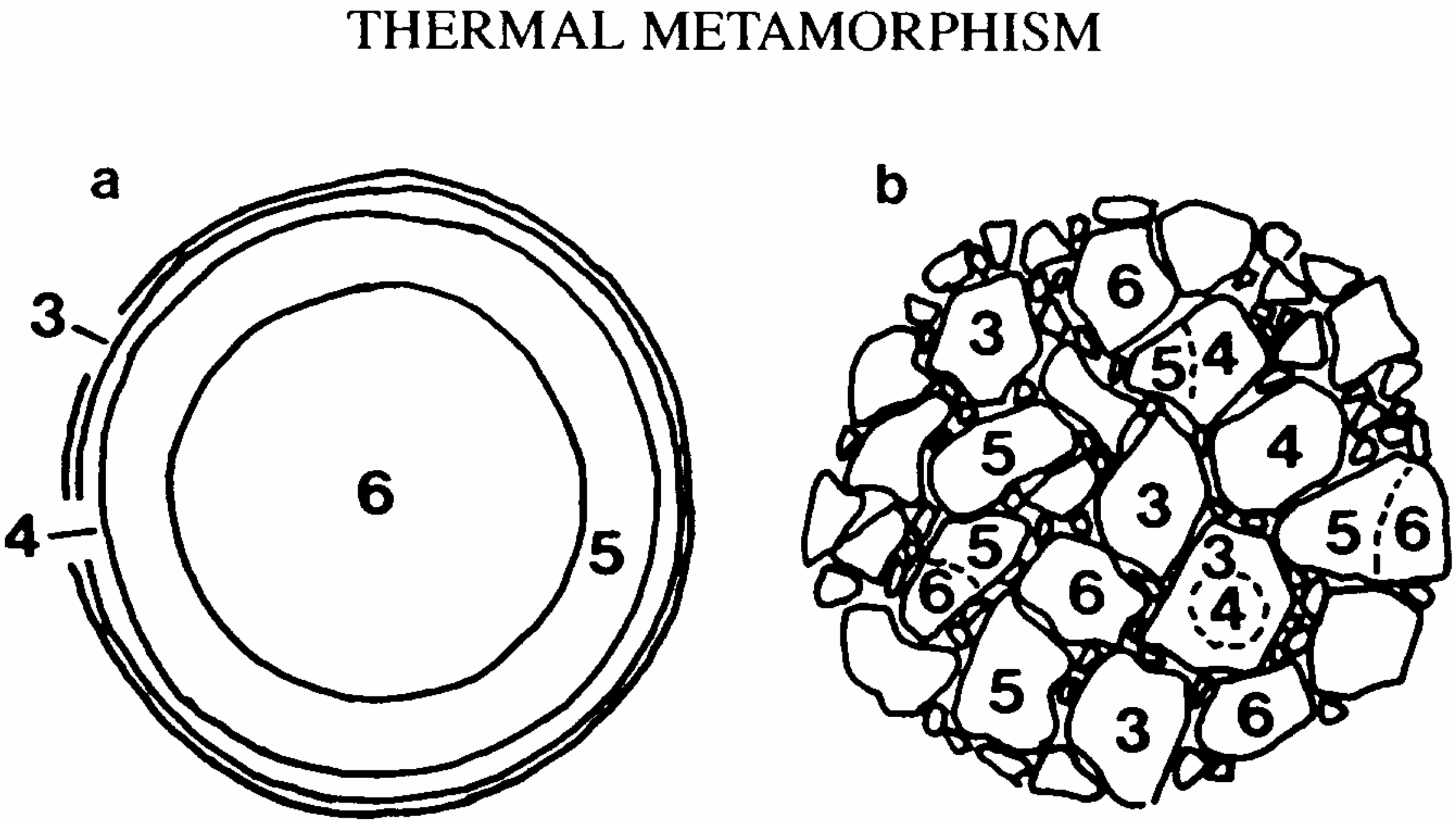
Grossman and Brearley (2005) GCA

Cr variation in very primitive CO3s



Grossman and Brearley (2005) GCA

STRUCTURE OF OC PARENT BODIES



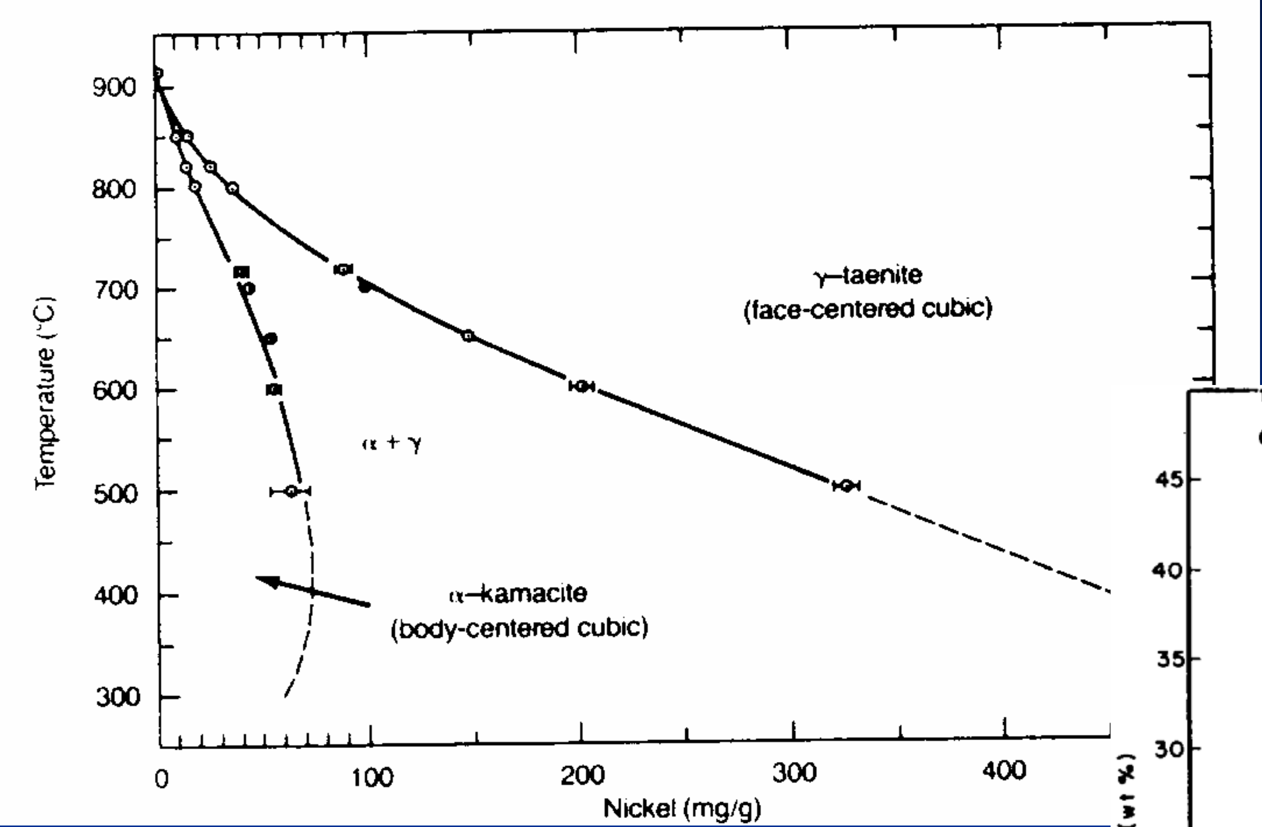
ONION SHELL

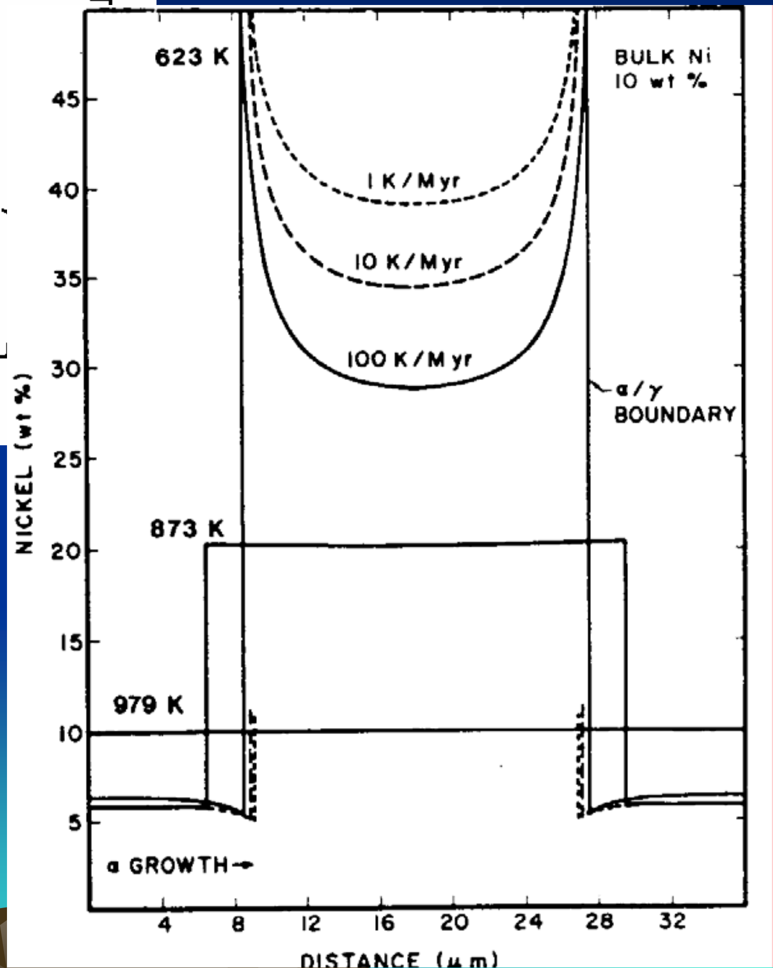
RUBBLE PILE

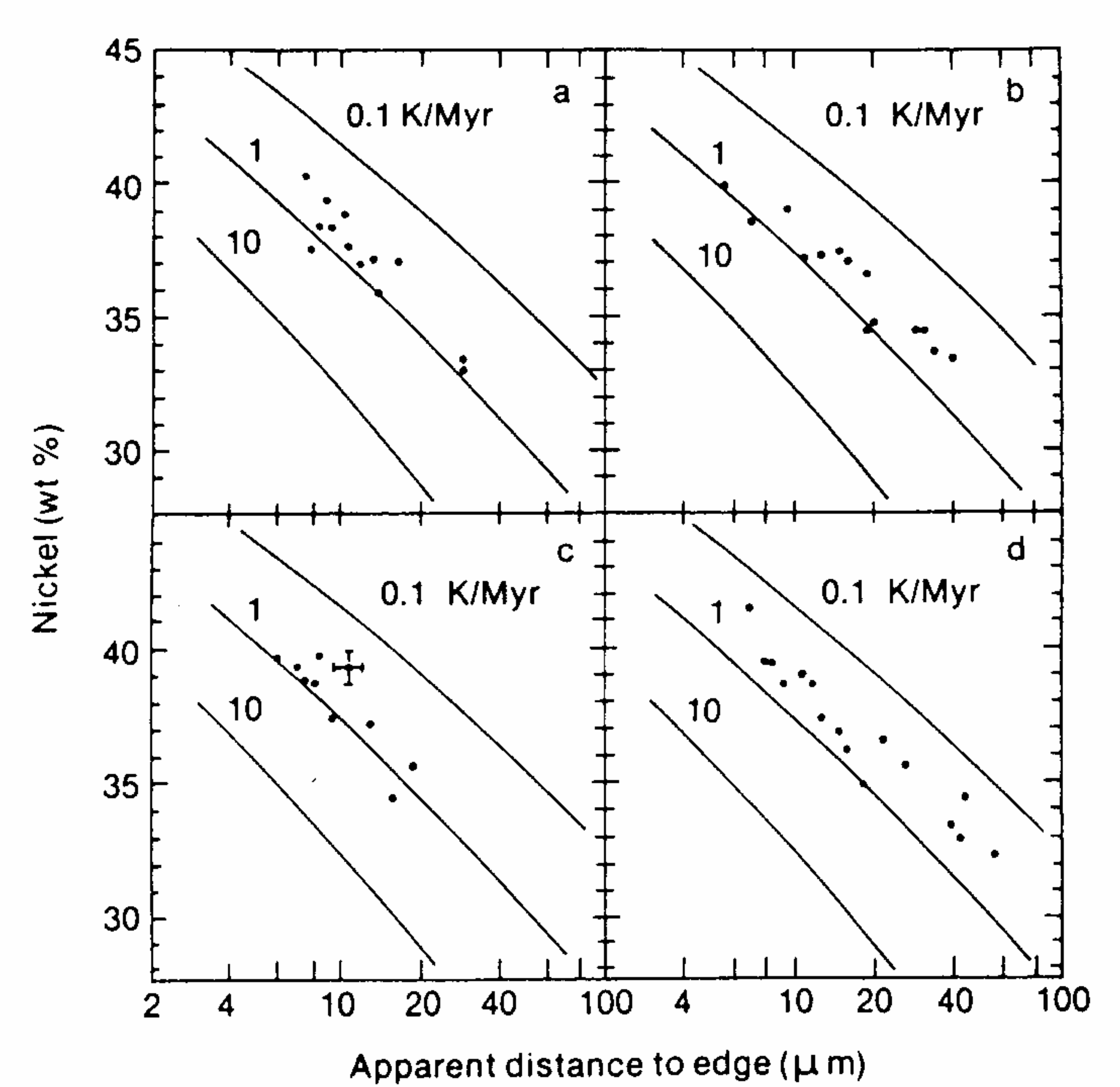
CONSTRAINTS ON THERMAL STRUCTURE OF ASTEROIDS

- Metallographic cooling rates
- Fission track cooling rates
- Geochronology (U-Th dating)
- Equilibration temperatures of types 4-6 chondrites
- Estimates of sizes of parent bodies of ordinary chondrites

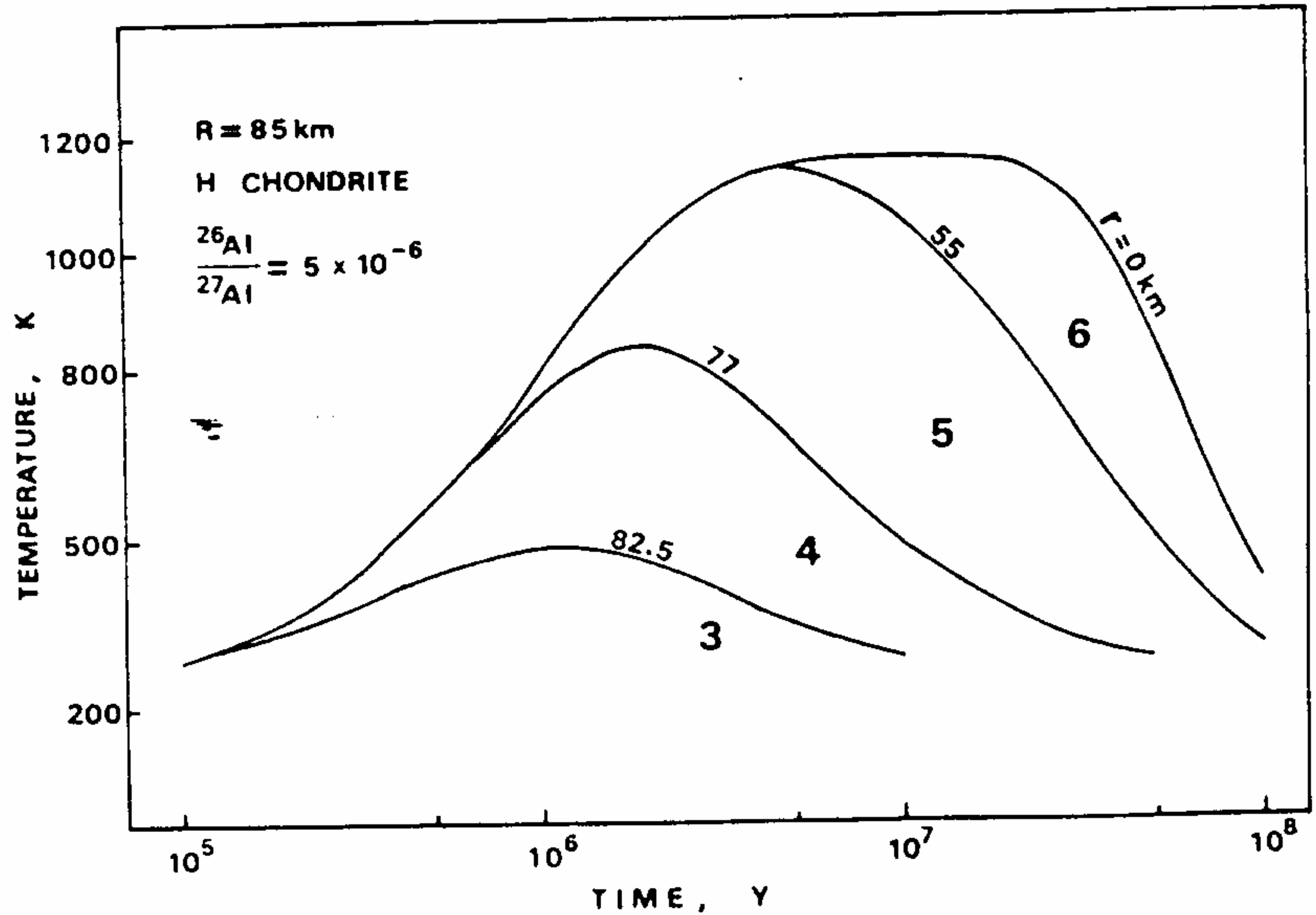
Metallographic cooling rates



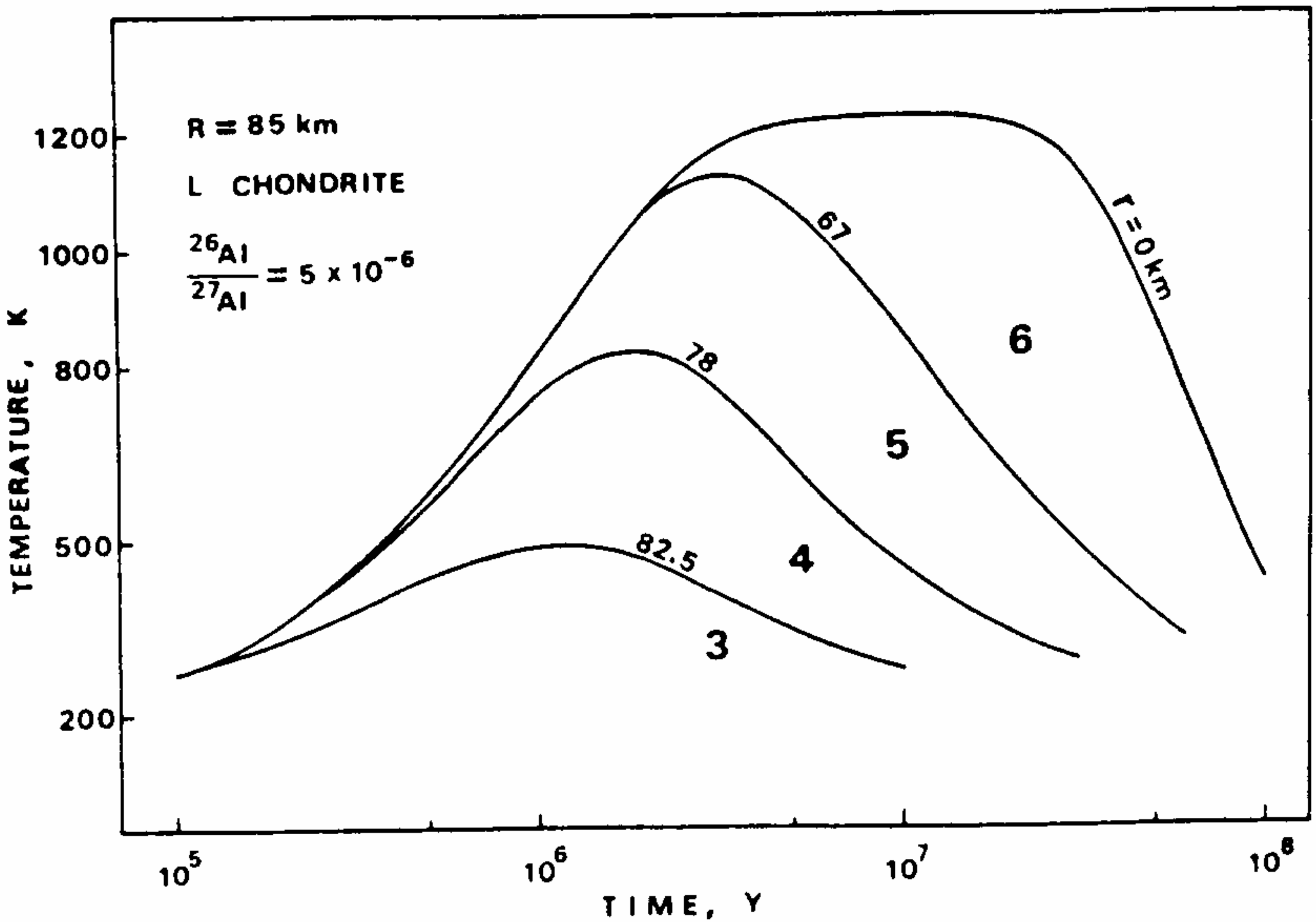


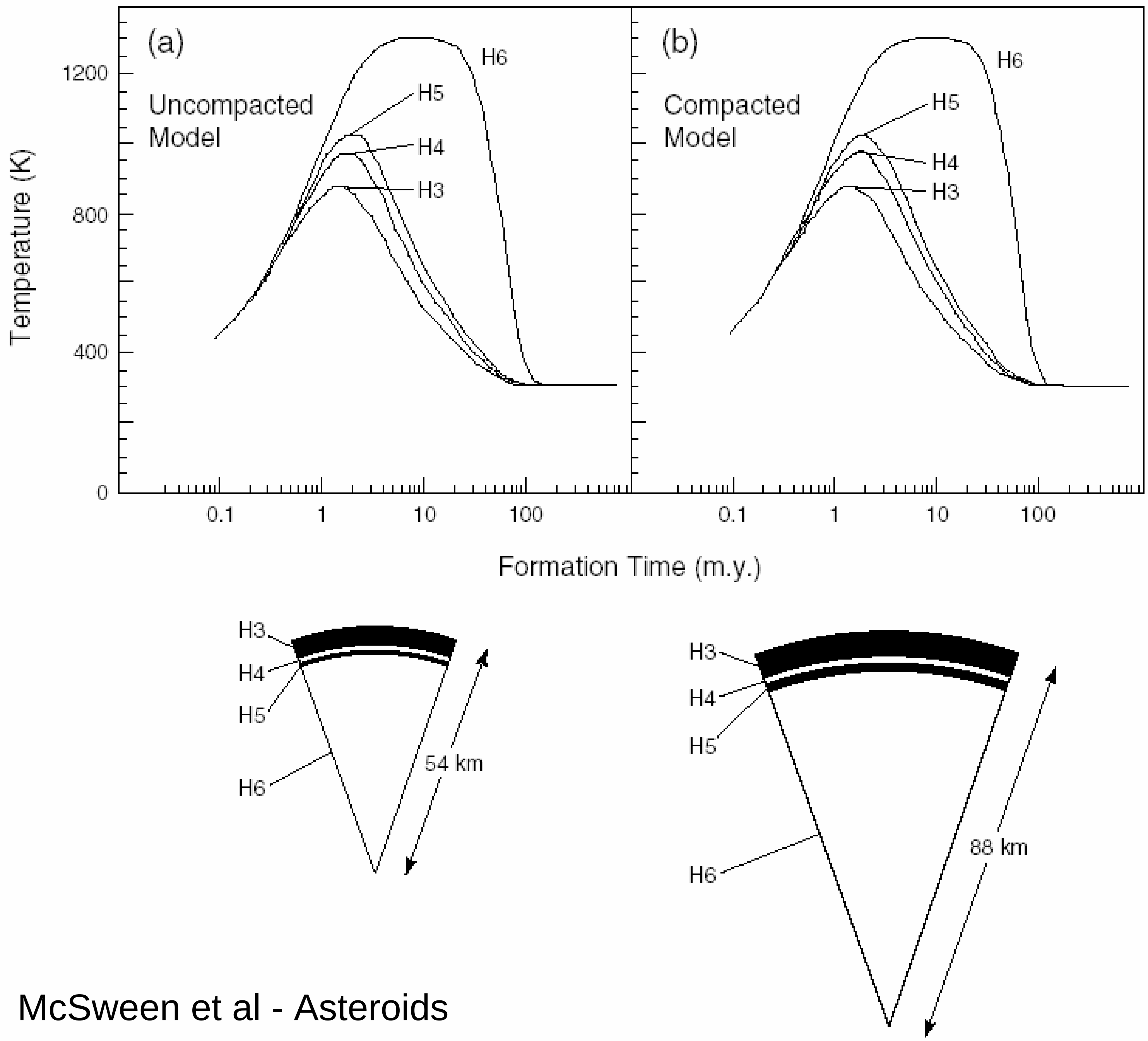


Mezo-Madaras L3



Miyamoto et al. (1981) PLPSC


R = 85 km
L CHONDRITE
$\frac{^{26}Al}{^{27}Al} = 5 \times 10^{-6}$
1200
1000
800
500
200
TEMPERATURE, K
10^5
10^6
10^7
10^8
TIME, Y
r = 0 km
67
78
82.5
3
4
5
6
(b)



McSween et al - Asteroids

SOME OUTSTANDING ISSUES

- Metallographic, fission track and geochronology all measure cooling rates >550ºC (1-100ºC/Ma).
- Cooling rates through 750ºC may be higher (100-300ºC - ol-sp Mg-Fe exchange) – incompatible with current thermal models (Kessel et al., 2007).
- Metamorphic temperatures are somewhat uncertain
  - Inferred high temperatures may be relicts retained from chondrule formation that have not fully equilibrated.
- Correlation of metamorphic temperatures with petrologic type is typically assumed but may not be justified.

OLIVINE-SPINEL THERMOMETRY