Raman spectroscopy and high pressure minerals of meteorites

(Dr. Ivan BAZHAN)

RAMAN SPECTROSCOPY AND SPACE EXPLORATION

(Prof. Eiji Ohtani)

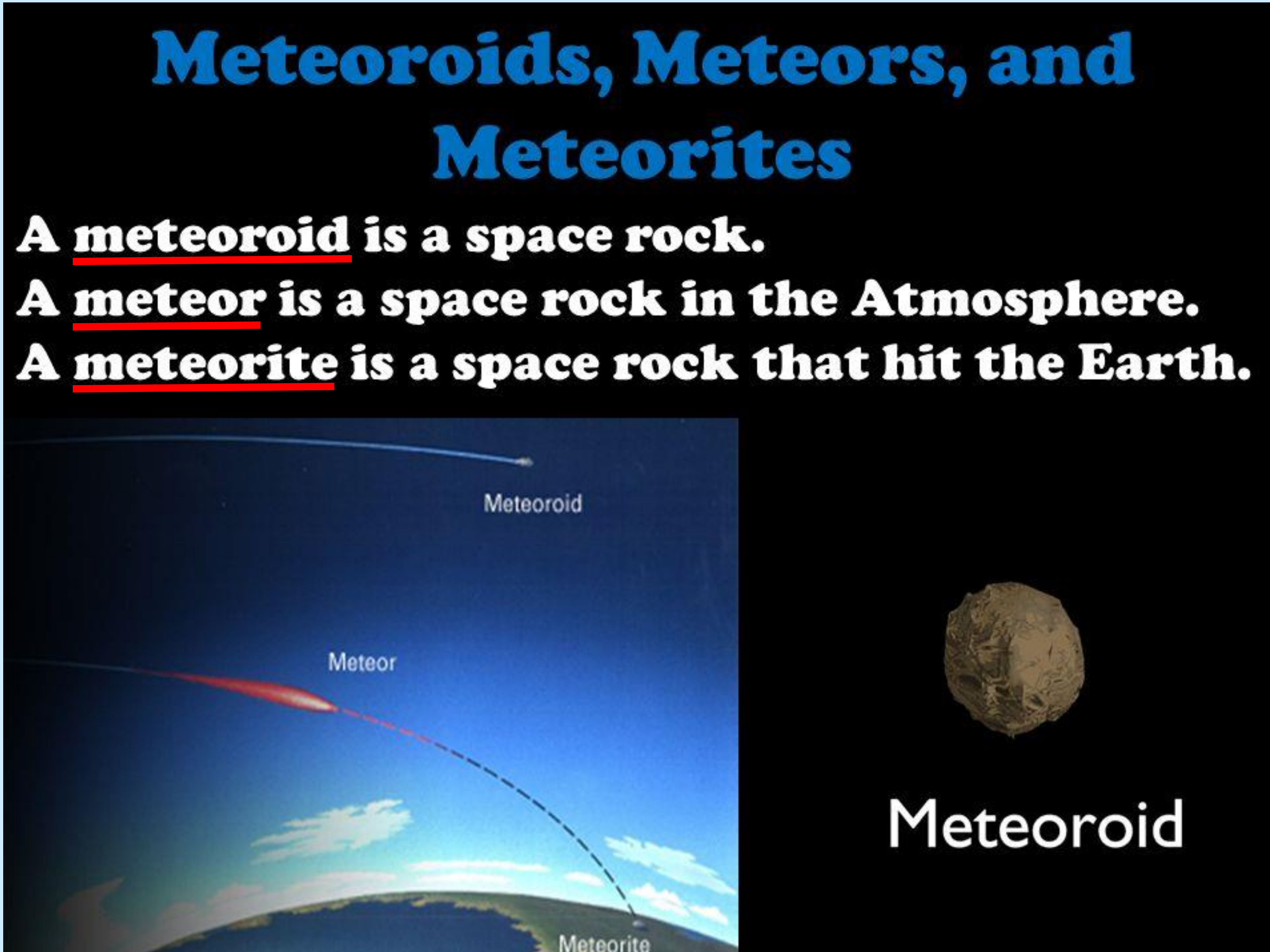
Raman spectroscopy between some key points of the meteorite investigations

(Dr. Ivan BAZHAN)

Content

1. What are meteorites?
2. Meteorite types
3. How meteorites were formed
4. Impact events
5. HP-minerals formation
6. Methods of investigations and Raman
7. Pressure-temperature estimation
8. Shock event time estimation
9. Parent body size estimation
10. *Thank you*

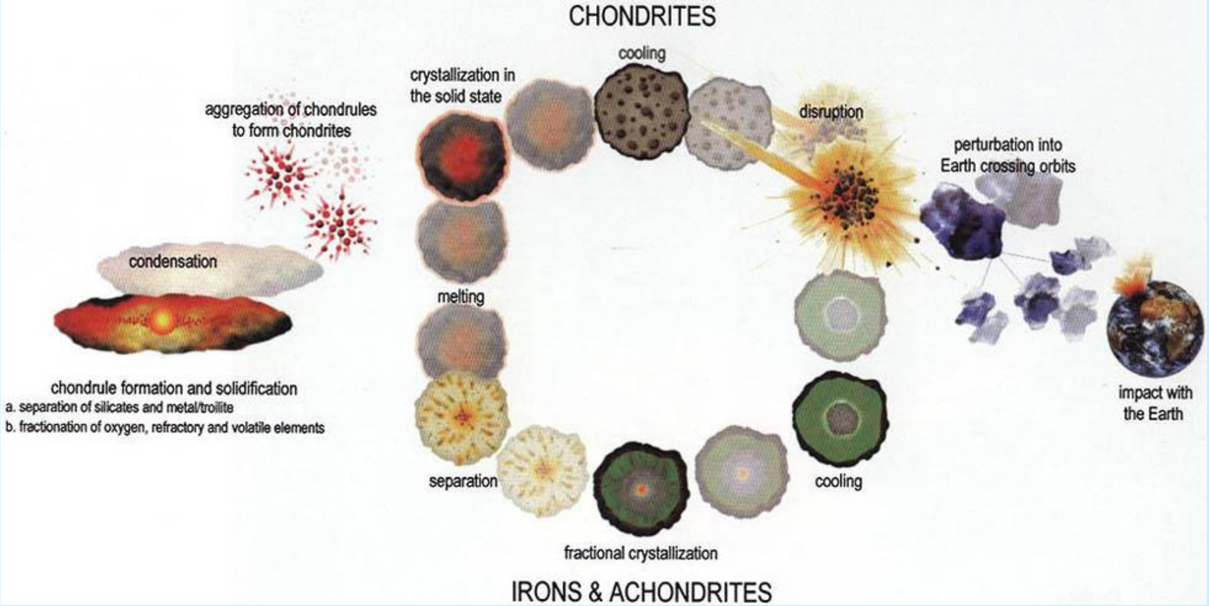
What are meteorites?



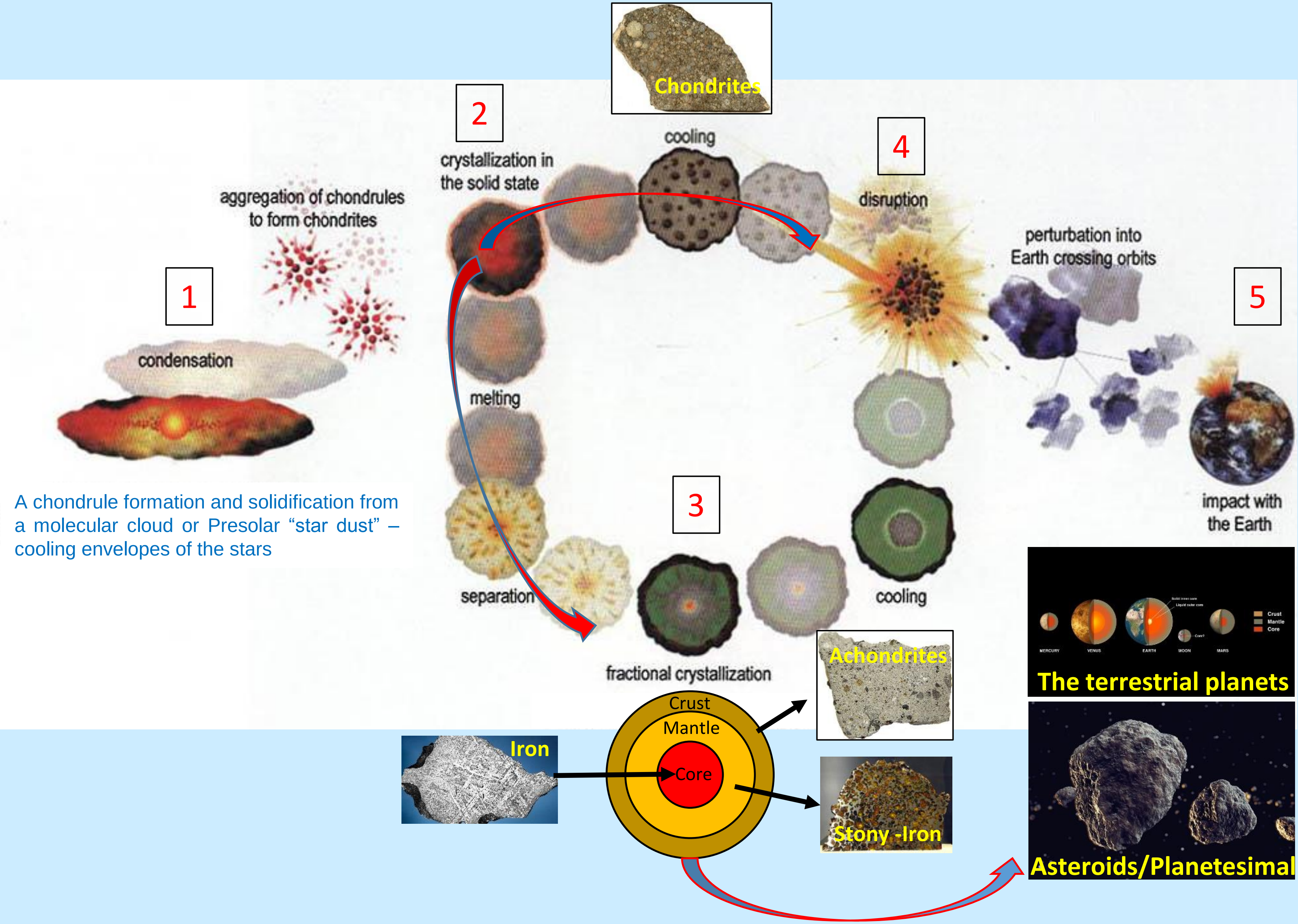
Meteorite types

Stony - Chondrites	Stony-Iron	Iron
		
Mainly Silicate and Oxide minerals + minor metal	Metal + Silicate minerals – 50% + 50%	Fe-Ni metal alloys – 100%

Stony - Achondrites



How meteorites were formed

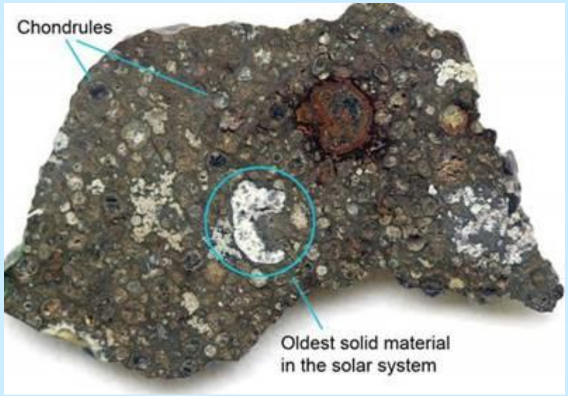


A chondrule formation and solidification from a molecular cloud or Presolar "star dust" – cooling envelopes of the stars

The key points of the meteorite investigations

1 Chronology Early Solar System Events

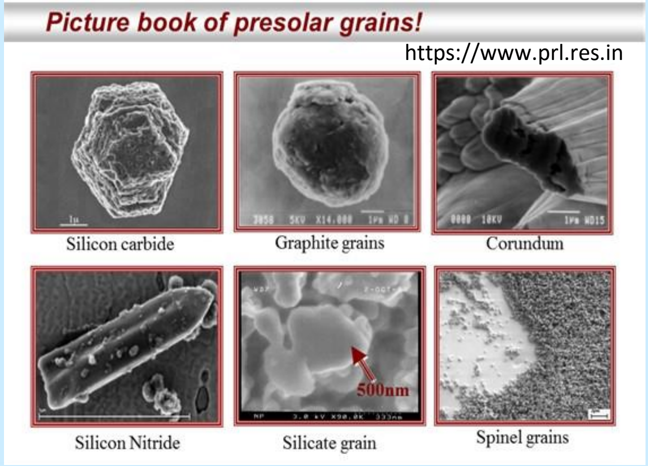
Chondrites contain **CAIs** *(Calcium- and aluminum-rich inclusions).*



Age (U/Pb) = 4.6 Billion years

2 Composition Early Solar System

Presolar grains and chondrules are the build units of Solar System.



Iron meteorites good estimate of the composition of the Earth's core and the cores of other planets.

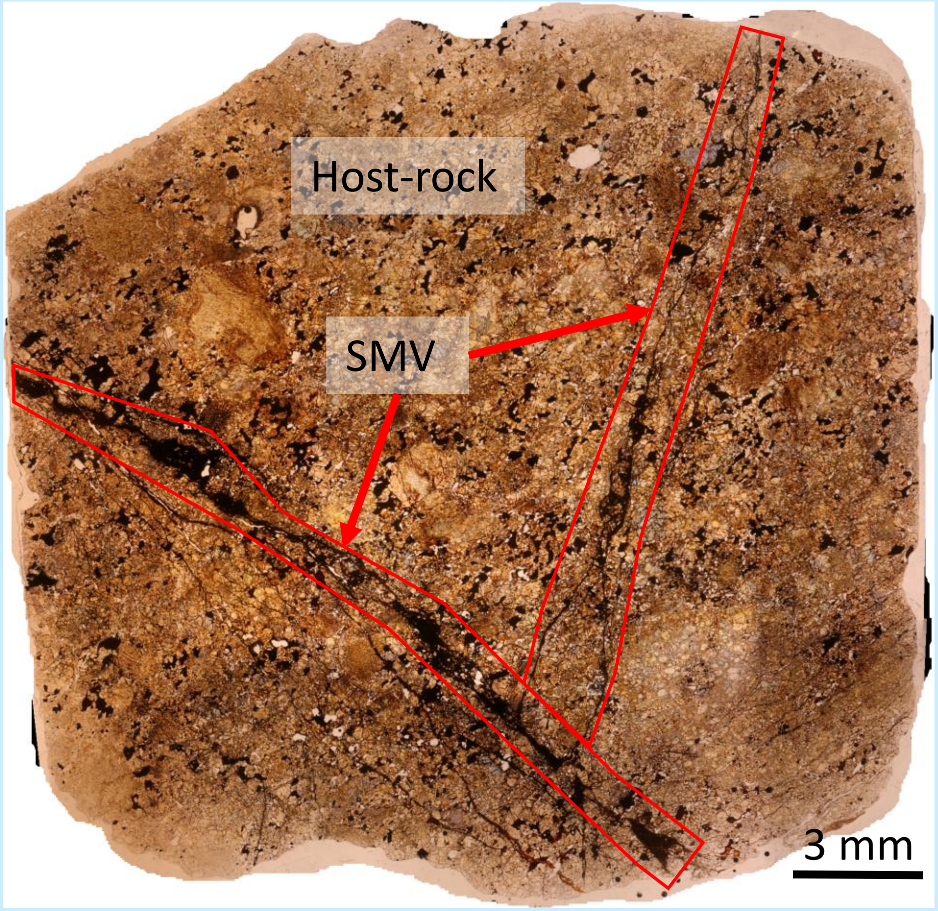
3 The impact mystery

Impact events

Impact events of the parent bodies

The shock event caused the melting of the host-rock forming the shock-melt veins (SMVs).
The SMVs are the result of a combination of two process: friction/shear heating and localized stress and temperature at the interfaces of mineral grains.

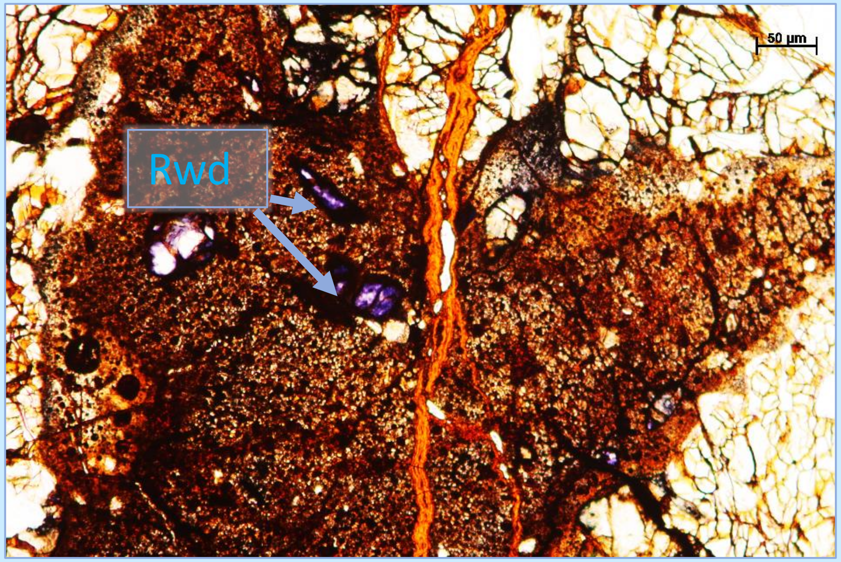
Chondrite L6 Dhofar 922



The host-rock with a black vein or shock-melt vein (SMV)

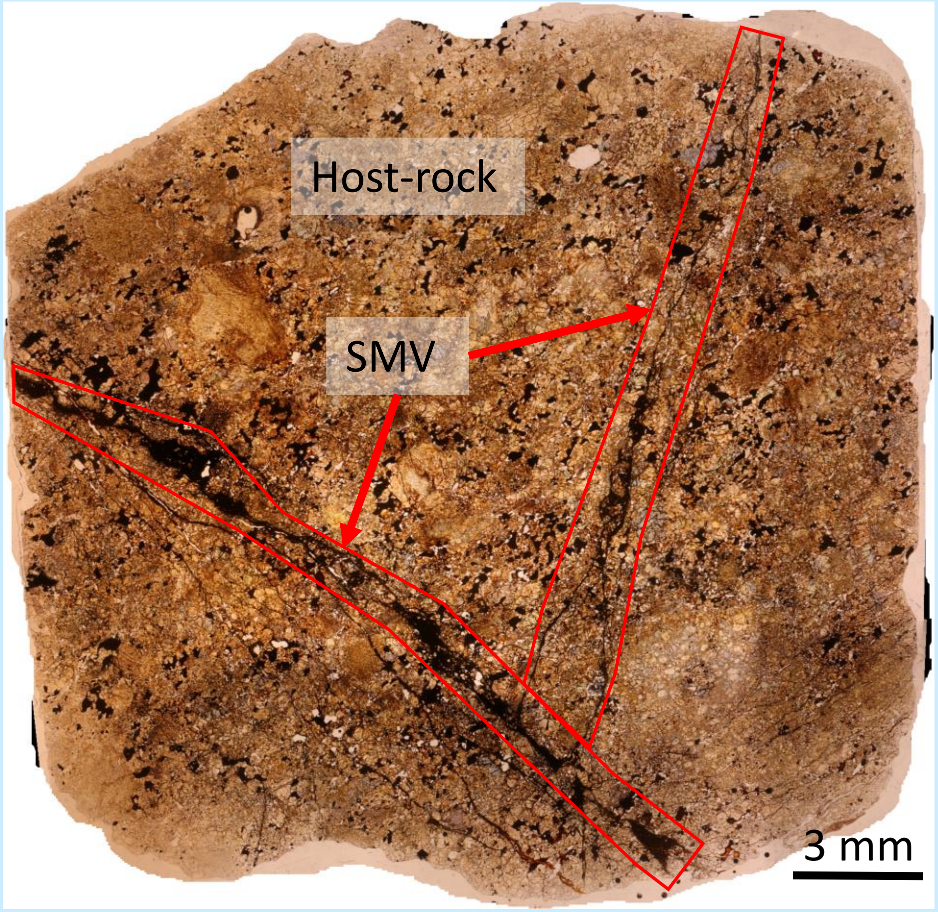
Impact events

During impact the main rock-forming minerals of the chondrites: **olivine, pyroxene, feldspar** transform to they high-pressure polymorphs .



Chondrite L6 Dhofar 922.
Rwd, ringwoodite

Chondrite L6 Dhofar 922



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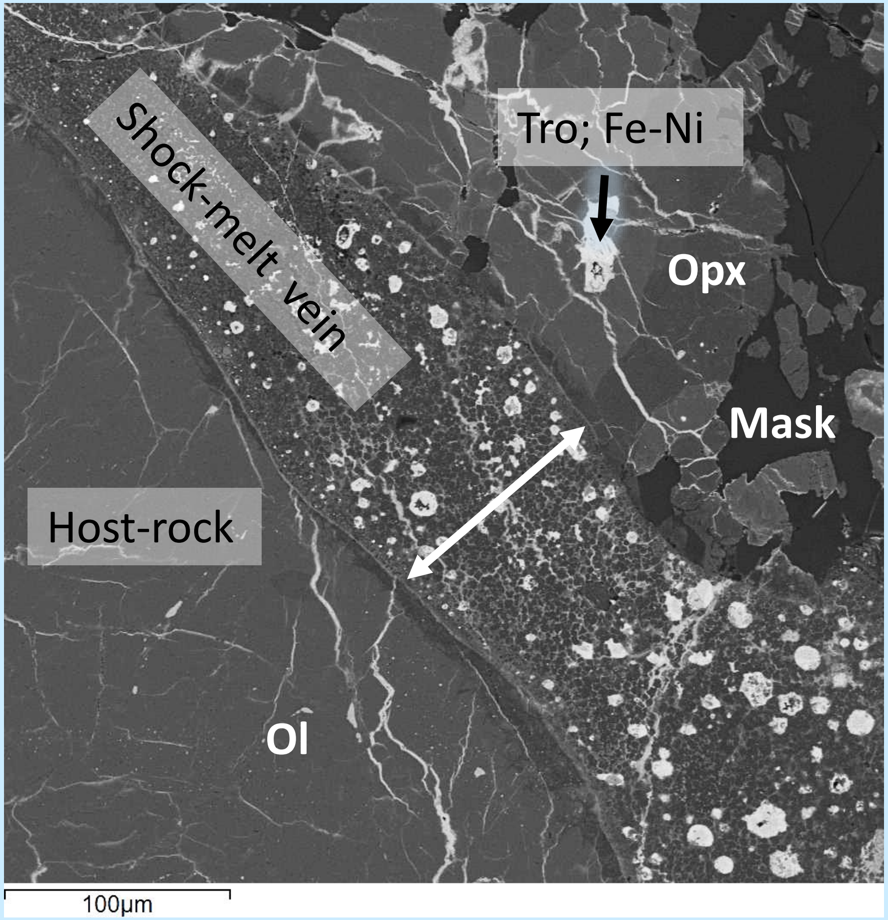
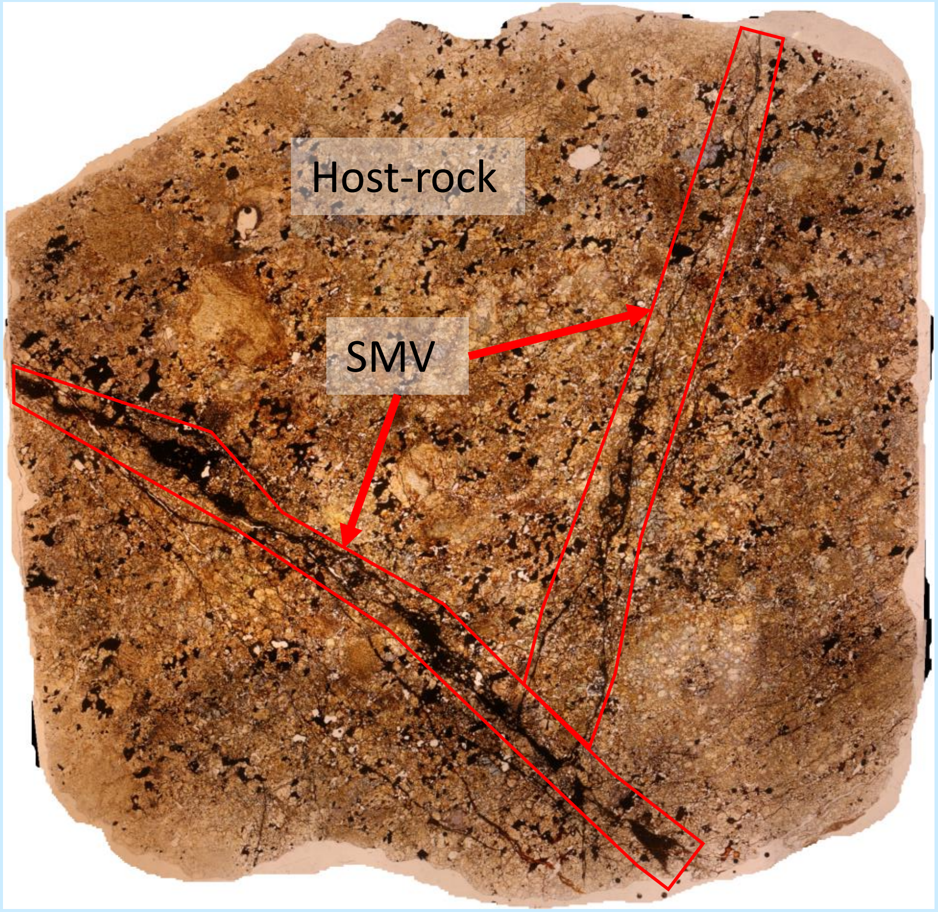
Impact events

Chondrite L6 Dhofar 922



BSE image of the Dhofar 922. Ol, olivine; Opx, ortopyroxene; Mask, maskelynite; Tro, troilite

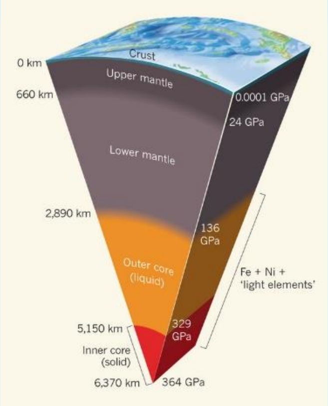


The host-rock with a black vein or shock-melt vein (SMV)

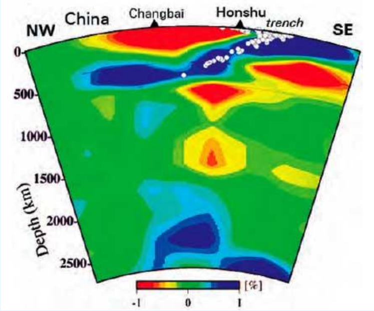
HP-minerals formation

How to get information about Earth interior, phase transformation of the rock forming minerals, mantle composition and phase relation with the depth etc.

1. Drilling? NO WAY…. Maximum 12.5 km in depth



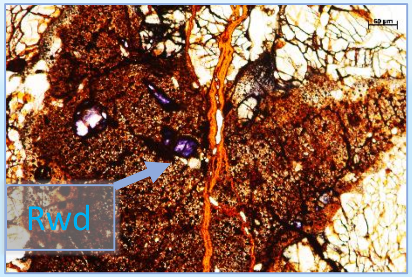
2. Geophysical investigation. YES of COURSE



3. High-pressure and high-temperature static experiment. YES

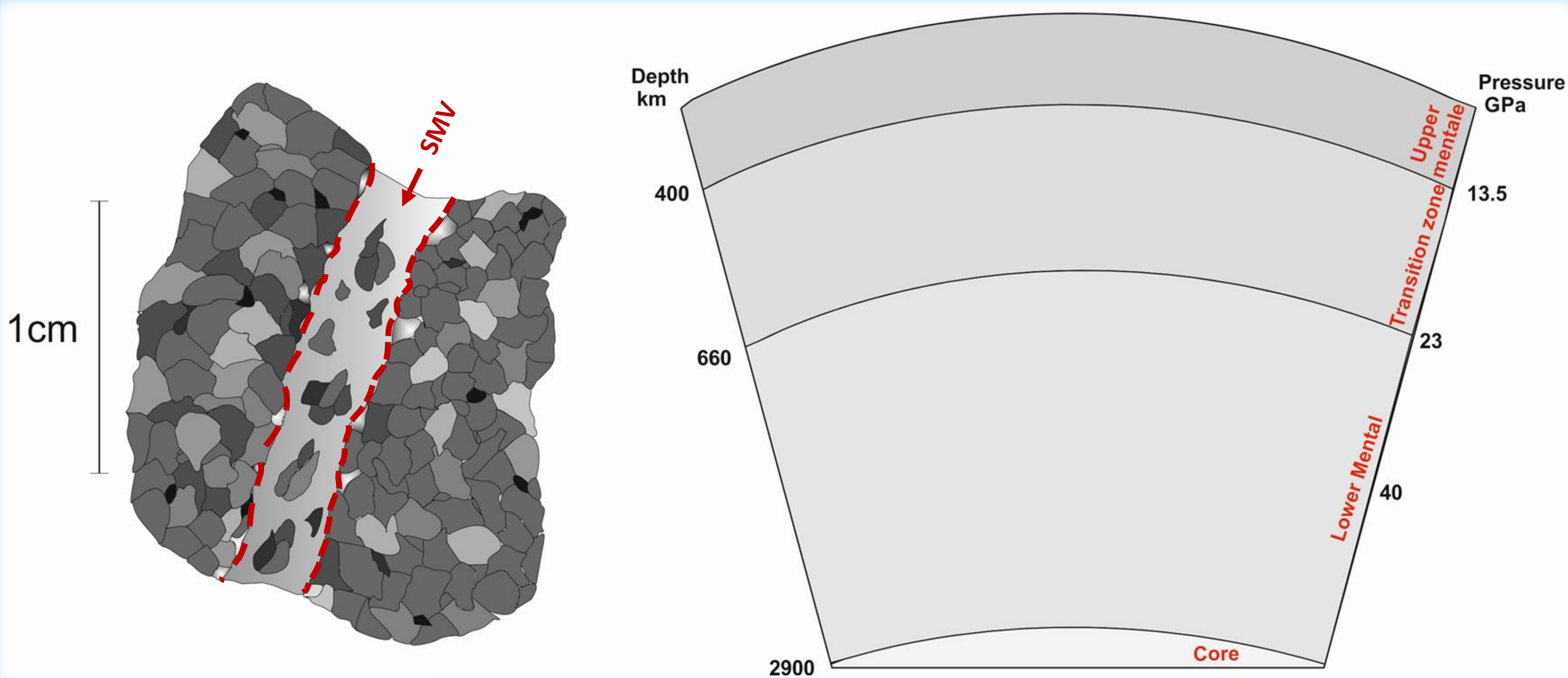
4. Diamond inclusions derived from deep mantle. YES

5. HP-minerals in chondrites (Binns et al. 1969)
All HP-minerales first were found in the heavily shocked chondrites



HP-minerals formation

A cross section schemes
of the shocked chondrite and Earth
(after D. Stoffler, 1997)



Minerals recording shock histories:
Silica minerals (coesite, stishovite, seifertite),
Feldspar (maskelynite, jadeite+silica, hollandite) ,
Olivine (wadsleyite, ringwoodite, bridgimanite + Mw)
Pyroxene (majorite, akimotoiite, bridgemenite)

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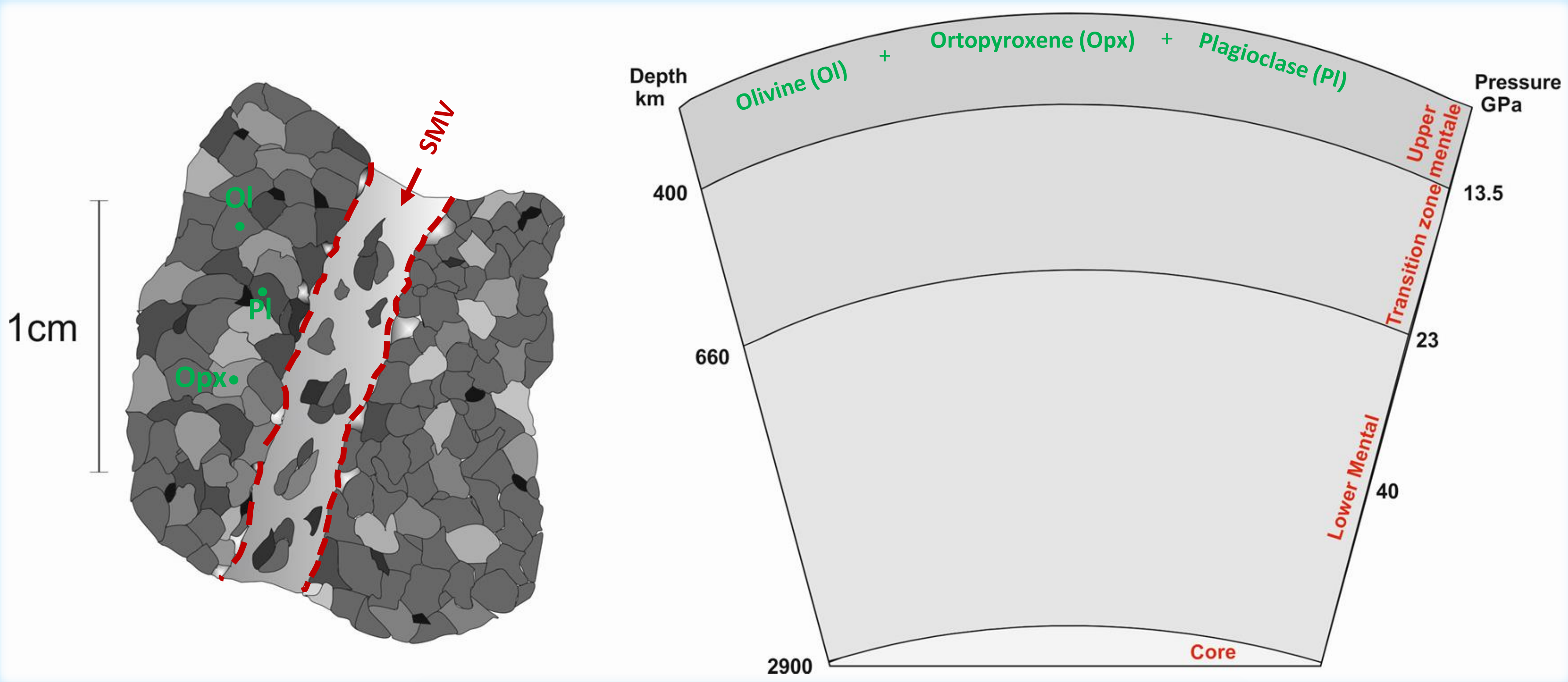

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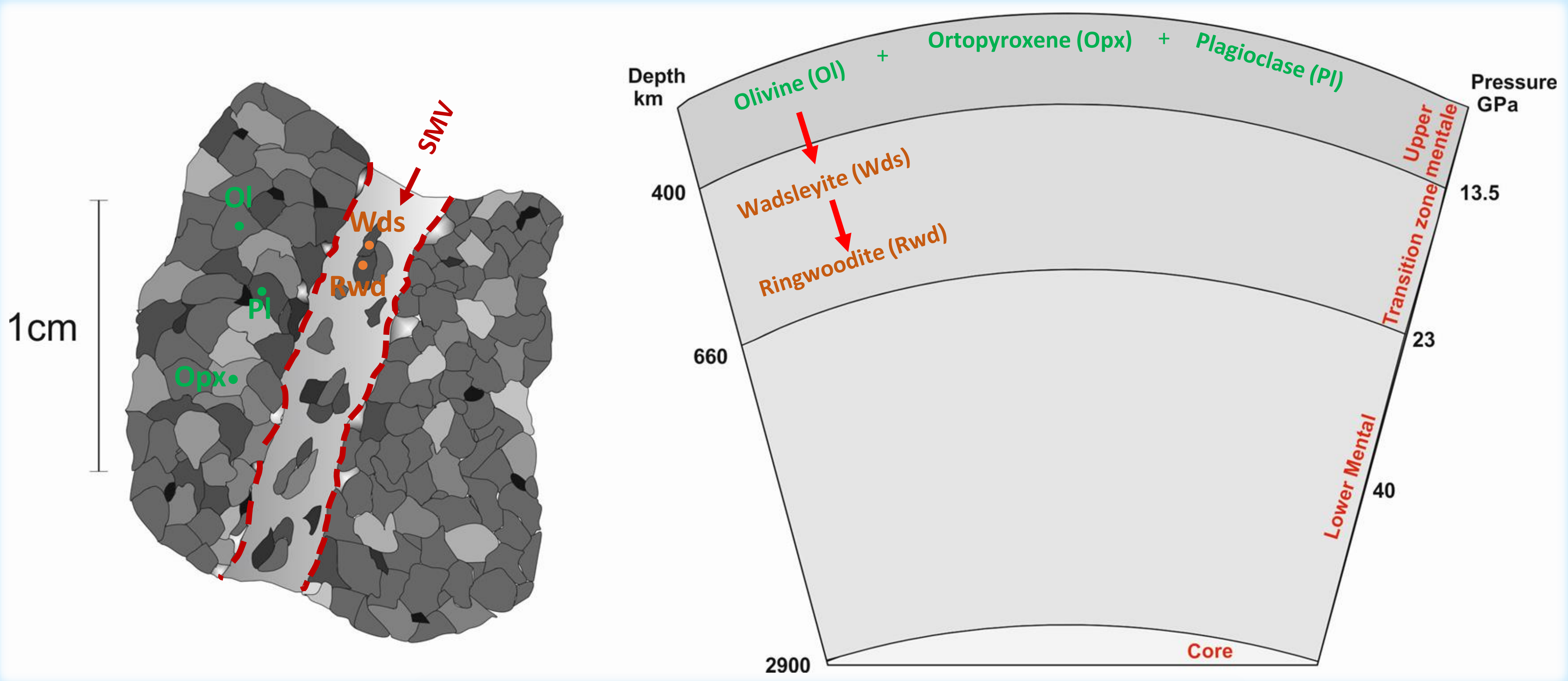

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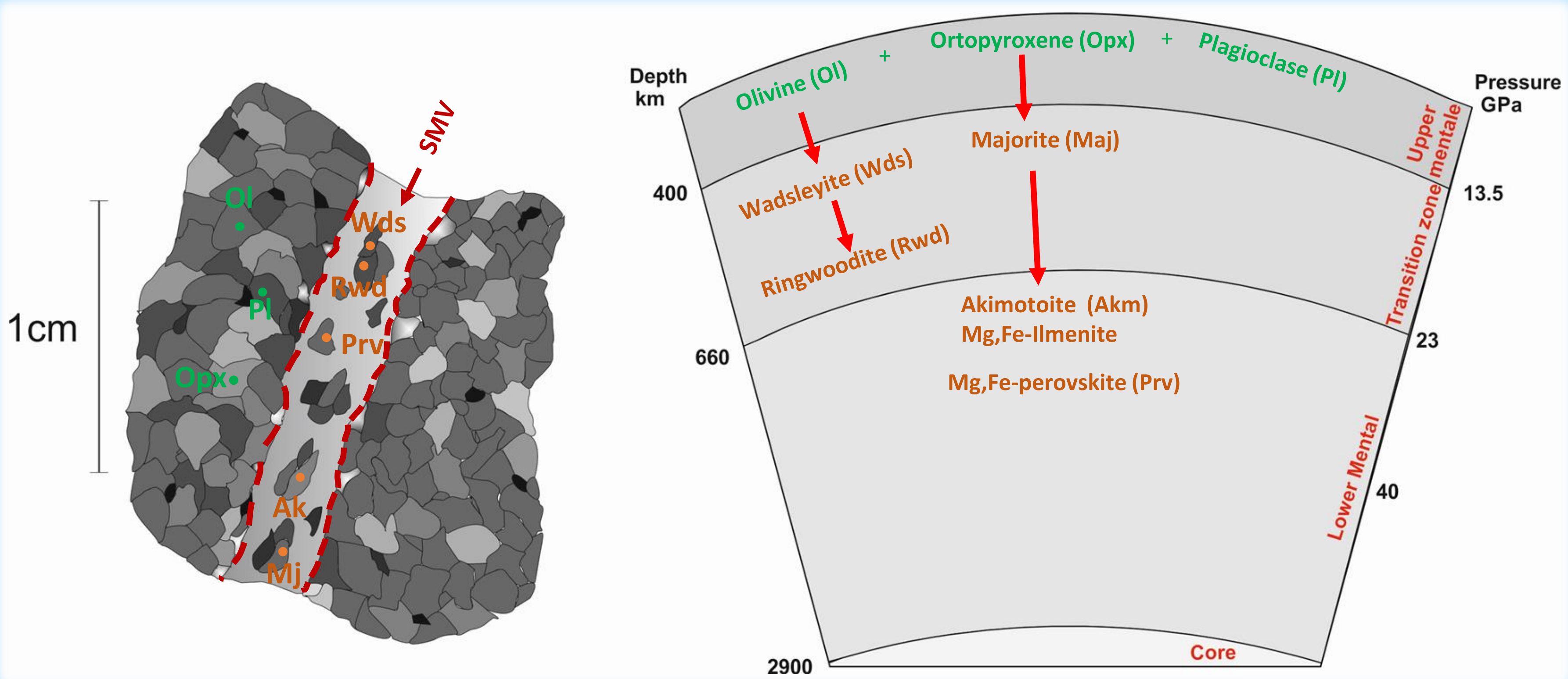

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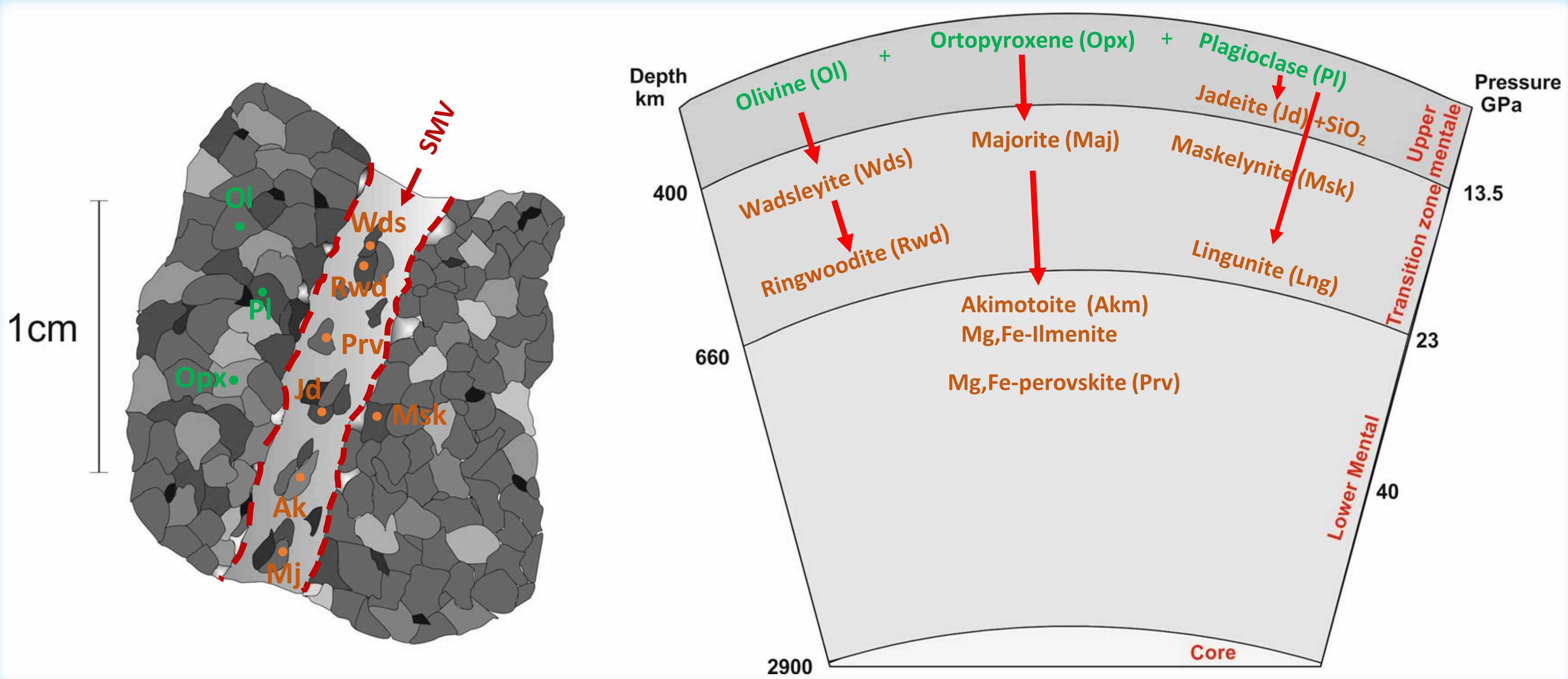

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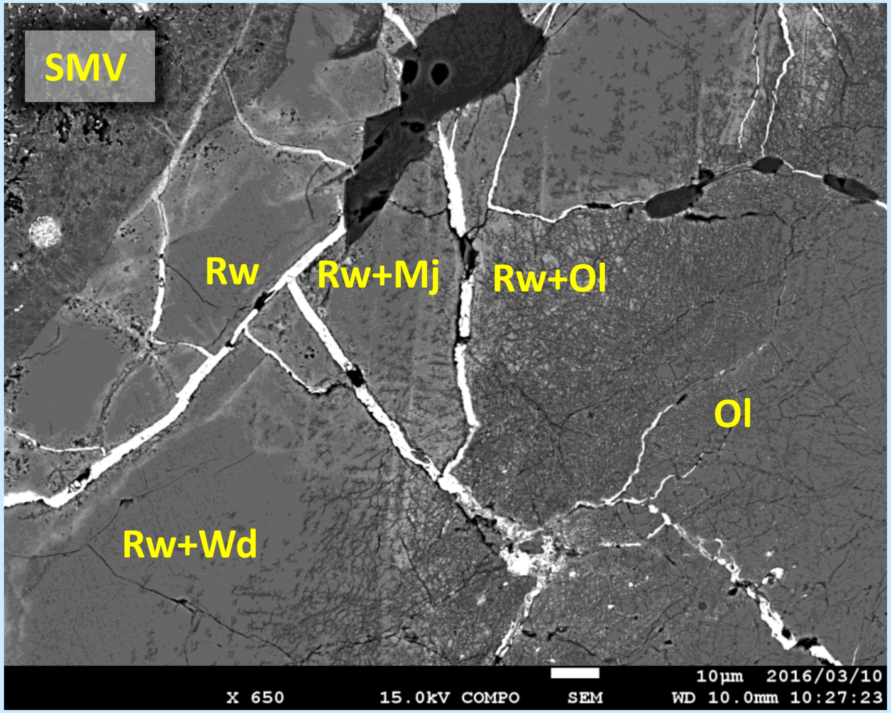
HP-minerals formation

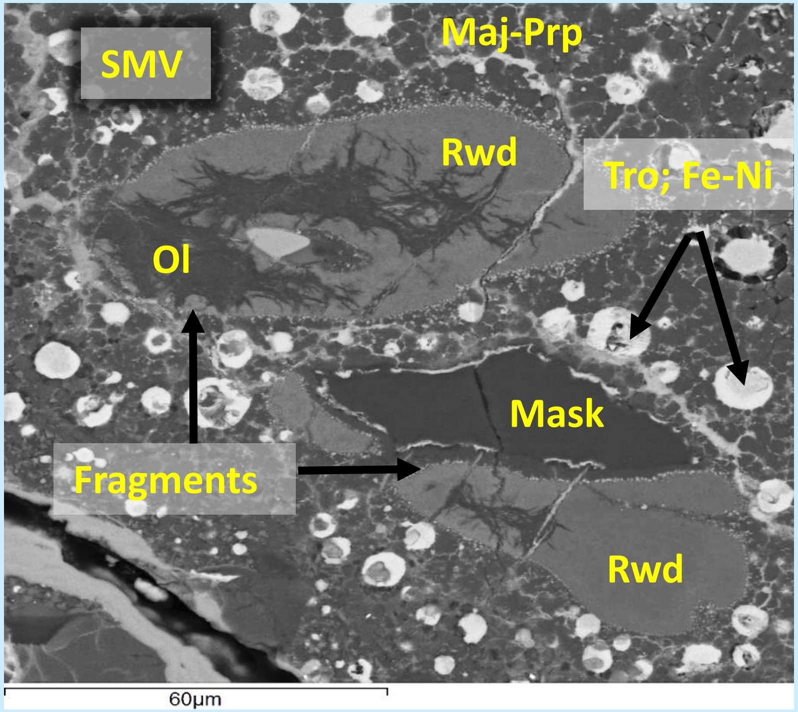
The SMV with the fragments of the host-rock.
Microstructures of high-pressure phases indicate two major types of modifications:

1. Solid state transformation



BSE image of the Dhofar 864
(Mg,Fe)SiO_3 – majorite (Maj) and akimotoite (Akm) Bridgmanite?

2. Crystal growth from shock melt



BSE image of Dhofar 922.
Ol, olivine; Mask, maskelynite; Rwd, ringwoodite Tro, troilite.

The key points

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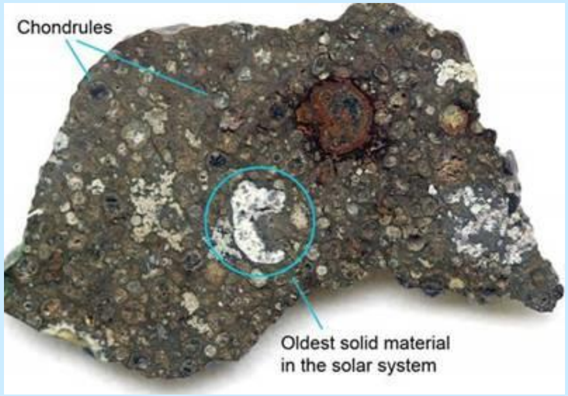

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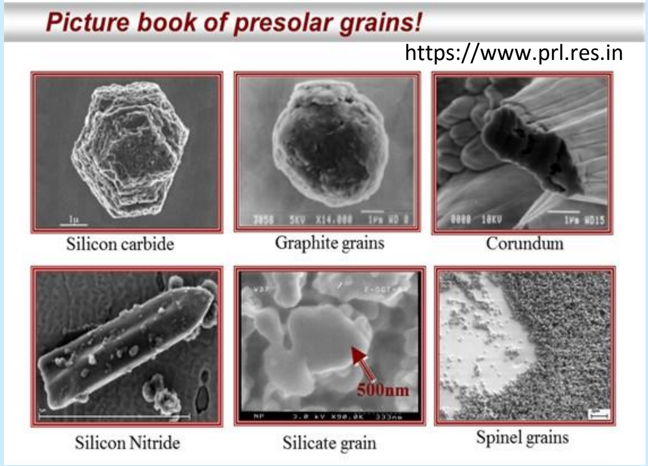
Presolar grains and chondrules are the build units of Solar System.



Iron meteorites good estimate of the composition of the Earth's core and the cores of other planets.

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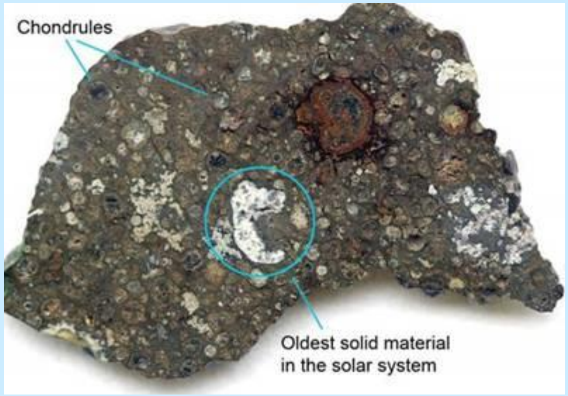

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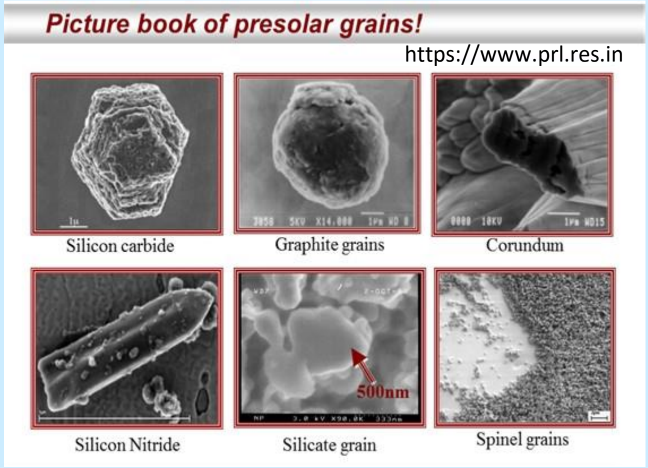

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3 The investigation of the Earth mantle HP-mineral assemblages

Formation of the HP-minerals. The shocked chondrites are a unique natural objects that contain wide range of the HP-minerals.

Methods of investigations

Low-vacuum scanning electron microscope (SEM)

Laser micro-Raman spectroscopy

Scanning Transmission Electron Microscope (STEM) with a EDS system

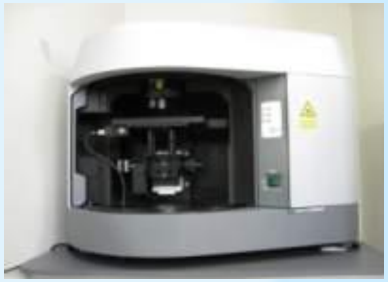
Focused ion beam (FIB) system

Transmission Electron Microscope (TEM)

Electron micro-probe analyzer (EMPA)

Nano-Secondary Ion Mass Spectrometry (SIMS)

Electron back-scattered diffraction (EBSD)



micro-Raman

SEM-EDS

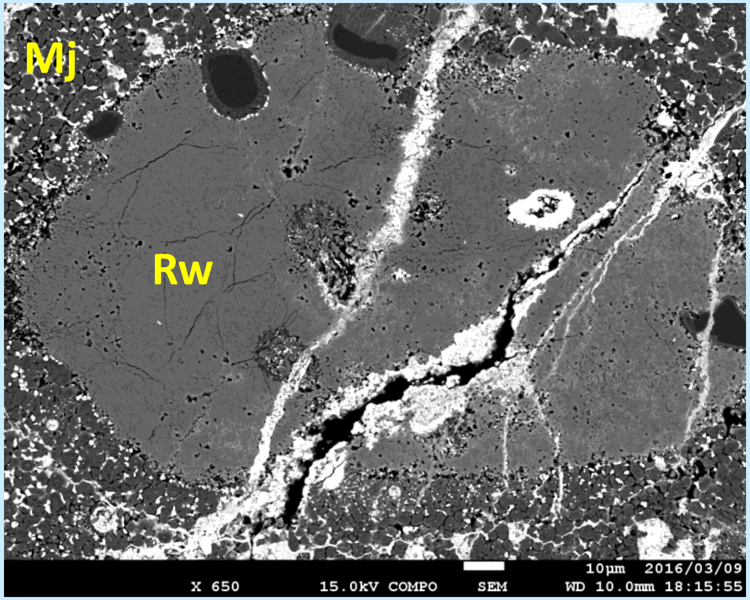
SIMS

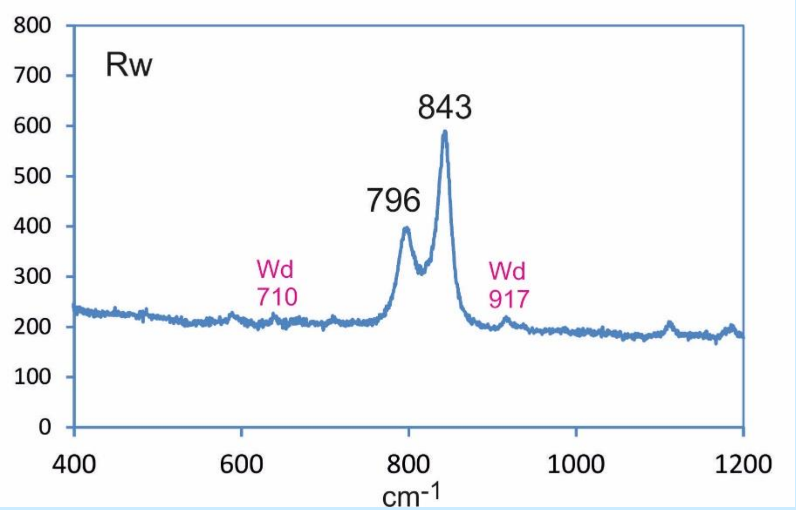
FIB

TEM

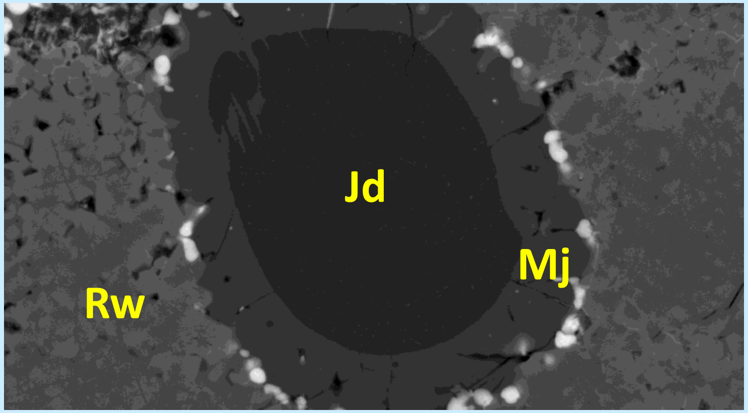
Raman between the key points

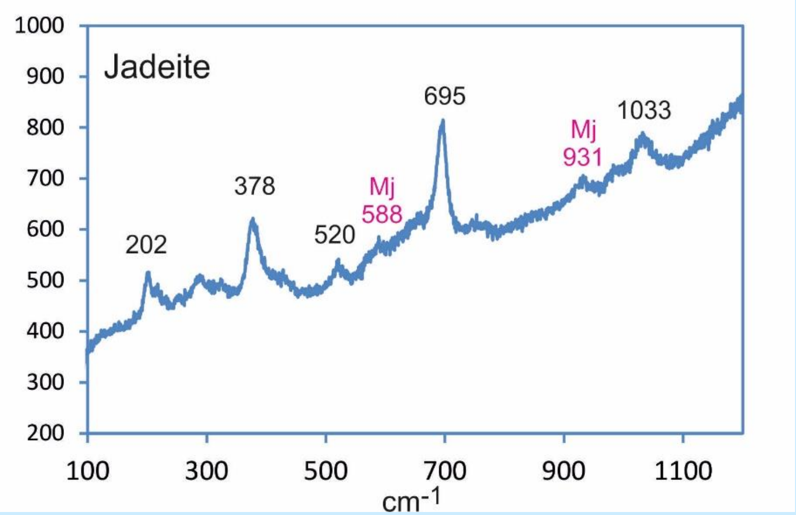
The fragments in the SMV of the Dhofar 864





Jadeite + minor majorite



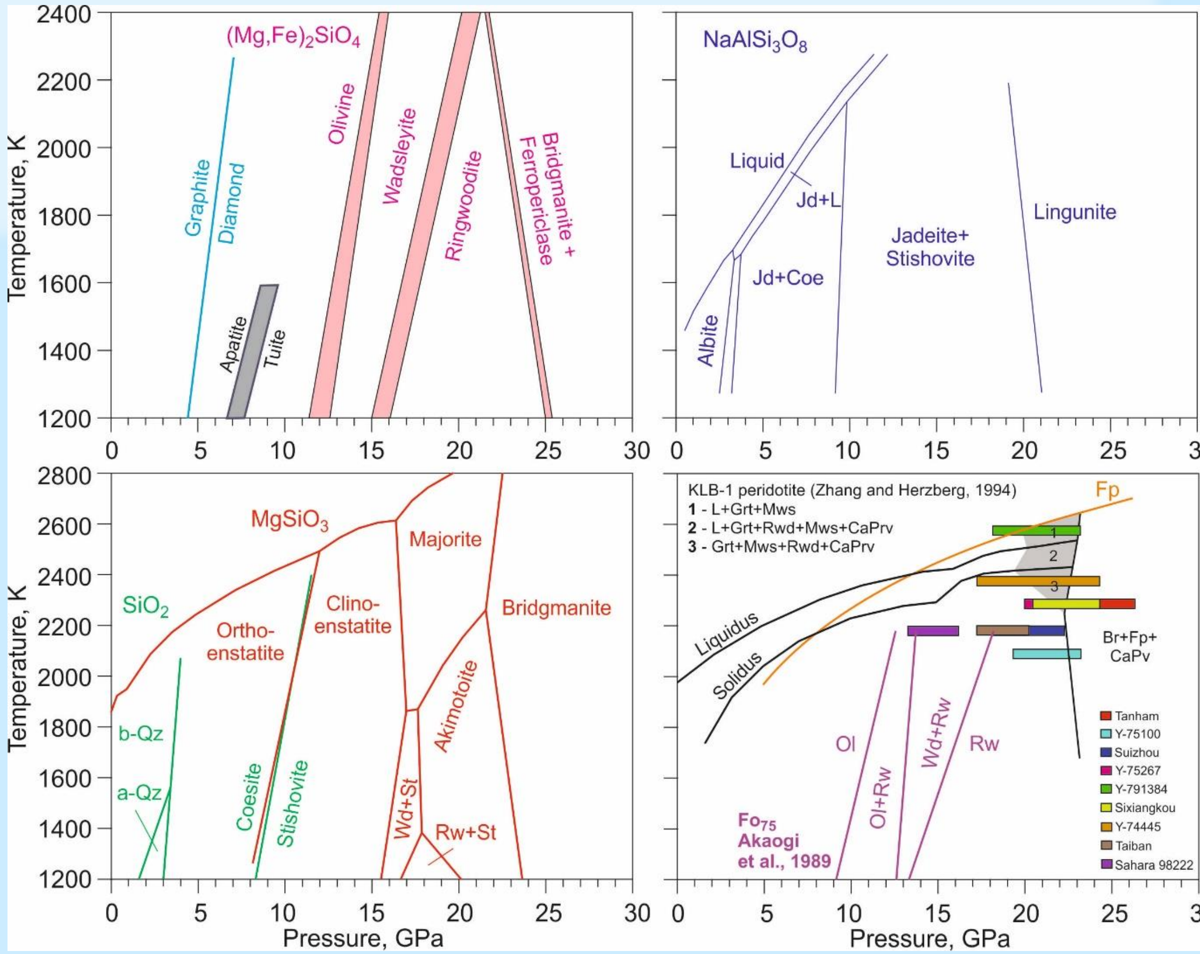


Pressure-temperature estimations

1. Static laboratory experiments

Important systems: Olivine, Enstatite, SiO_2, Albite, Carbon, Phosphates. Rarely TiO_2, chromite.

Duration of the experiments is several minutes.



Pressure-temperature estimations

2. Shock-wave laboratory experiments

The shock stages of the metamorphism from the shock- wave experiments base on the deformation features of the rock forming minerals.

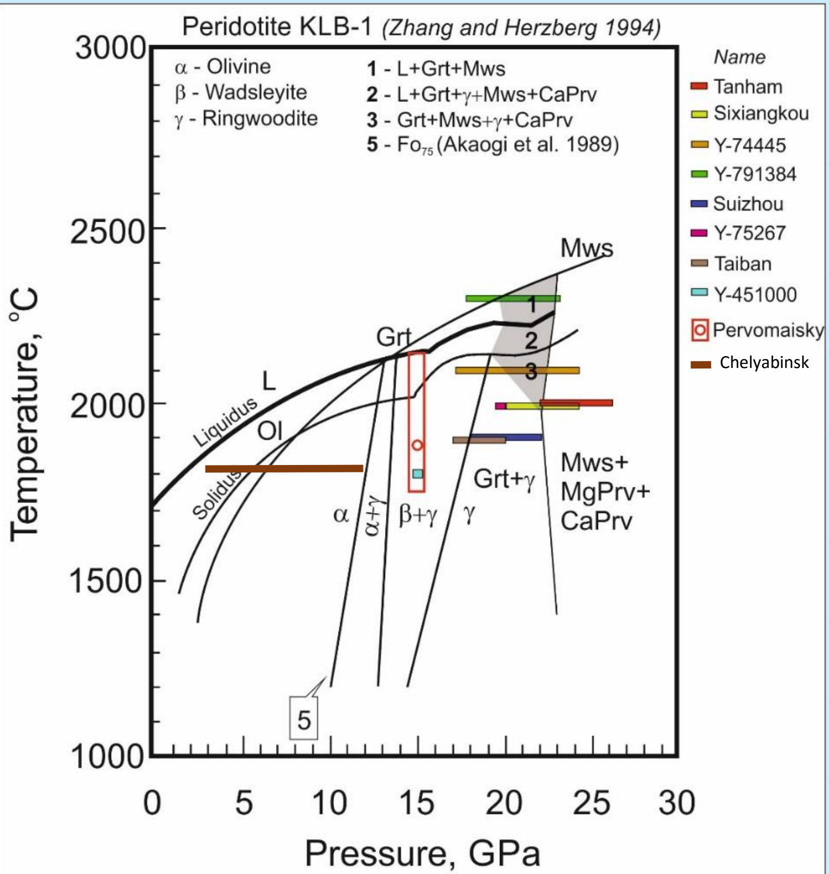
Duration of the experiments is 10^{-3} seconds

	Olivine	Plagioclase	Pressure (GPa)	Post-shock Temp. increase (K)
S1	Sharp extinction , Irregular fractures		<4 - 5	10 - 20
S2	Unduratory extinction , Irregular fractures		5 - 10	20 - 50
S3	Planar fractures	Same as S2	15 - 20	100 - 150
S4	Mosaicism (weak)	PDFs	30 - 35	250 - 350
S5	Mosaicism (strong) , PDFs	Maskelynite	45 - 55	600 - 850
S6	Ringwoodite, melting	melting	75 - 90	1500 - 1750
	Whole-rock melting			

* PDFs – planar deformation features

(Stöffler *et al.*, 1991)

Pressure-temperature estimations



PT-range of HP-minerals formation is 3-26 GPa and 1800-2300 ºC.

Meteorite	Type	High-pressure mineral assemblage	Formation condition		References
			Pressure	Temp	
Tenham	L6	Maj, Maj-Prp, Rwd, Akm, Prv	22-26 GPa	2000 ºC	Langenhorst et al. 1995; Tomioka, Fujino, 1999
Sixiangkou	L6	Maj, Maj-Prp, Rwd, Akm, Mws, Lng, Jd	20-24 GPa	2000 ºC	Zhang et al., 2006
Yamato 74445	L6	Maj, Wds, Rwd, Akm, Hol, Jd	17-24 GPa	2100 ºC	Ozawa et al., 2009
Yamato 791384	L6	Maj, Maj-Prp, Rwd, Akm, Hol, Jd	18-23 GPa	2300 ºC	Ohtani et al., 2004 Miyahara et al., 2011, 2013
Suizhou	L6	Maj, Maj-Prp, Mws, Hol	18-22 GPa	1900 ºC	Xie et al., 2001, 2002
Yamato 75267	H6	Maj-Prp, Wds, Rwd, Akm	20 Gpa	2000 ºC	Kimura et al., 2003
Taiban	L6	Maj+CPx , Wds, Rwd, Lng, Jd	17-20 GPa	1900 ºC	Acosta-Maeda et al., 2013
Yamato 75100	H6	Maj-Prp + Opx +Ol, Wds, Hol-Jd	18-24 GPa	1900 ºC	Kimura et al., 2000 Tomioka et al., 2003
Pervomaisky	L6	Maj-Prp+Ol+Cpx	15 GPa	1900 ºC	new data

Akm, akimotoite; Cpx, clinopyroxene ; Hol, hollandite; Jd, jadeite; Lng, lingunite; Maj-Prp, majorite-pyrope; Mws, magnesiowustite; Ol, olivine; Opx, orthopyroxene ; Rwd, ringwoodite ; Wds, wadsleyite (Whitney and Evans, 2010).

The key points of the meteorite investigations

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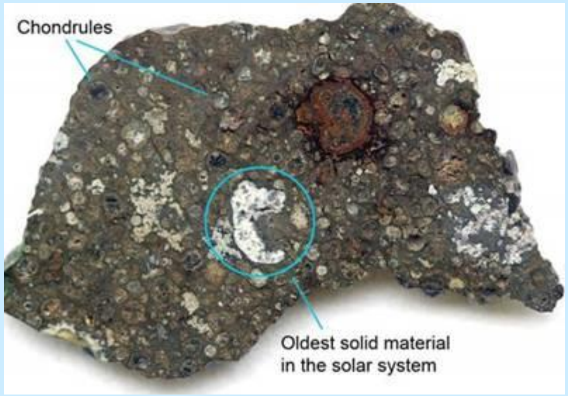

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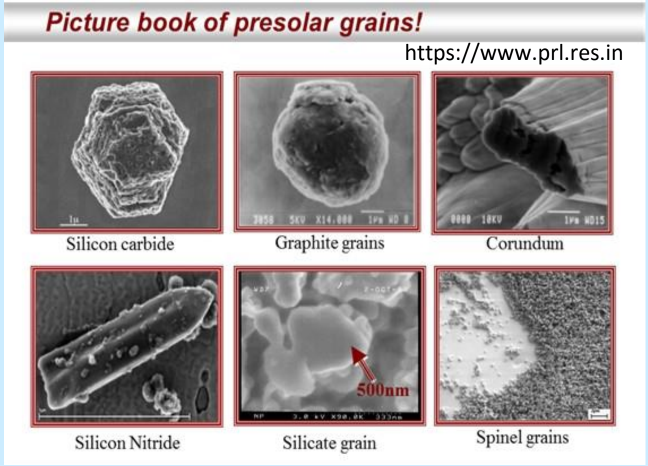

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3 The investigation of the Earth mantle HP-mineral assemblages

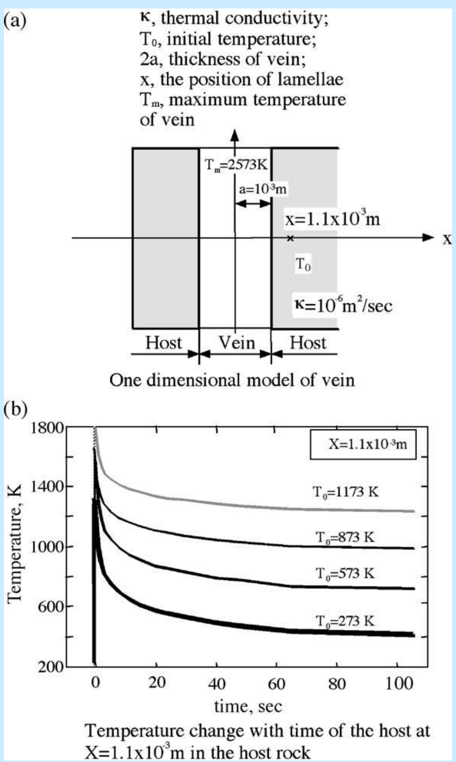
4 PT-estimation of HP-mineral formation at impact event

Shock event time estimation

1. **The duration of impact in a chondrites** *(Ohtani et al. 2004; Beck et al. 2005).*

Ohtani et al. (2004) estimated time of the crowth and quenching of the ringwoodite lamellae during the impact.

The result of estimation was **4 second**.



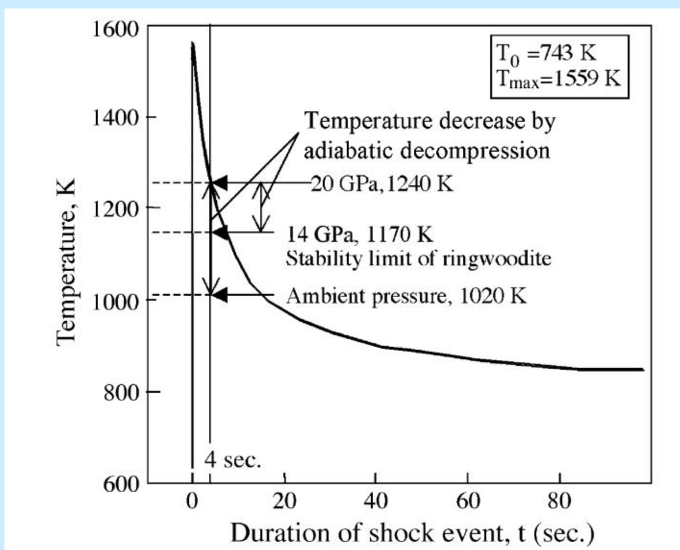
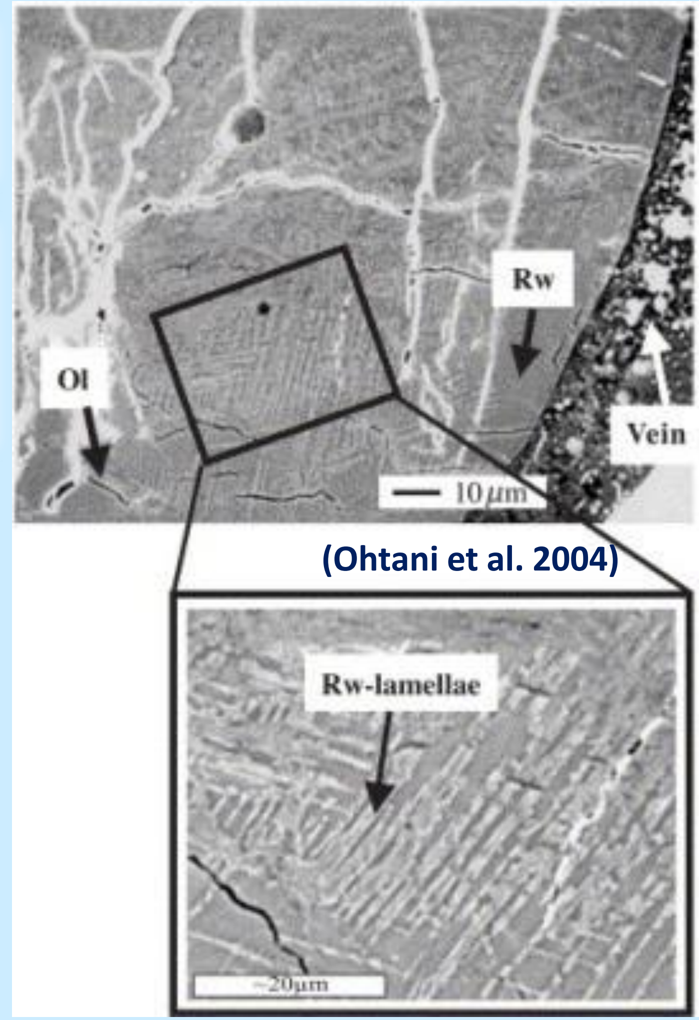


Fig. 8. The temperature change with time during the shock event at about 100 μm away from the vein for the initial temperature of T_0=743 K. The maximum temperature at this point is calculated to be 1559 K. The temperature drops due to the adiabatic decompression to the phase boundary and to the ambient pressure are given in the figure.



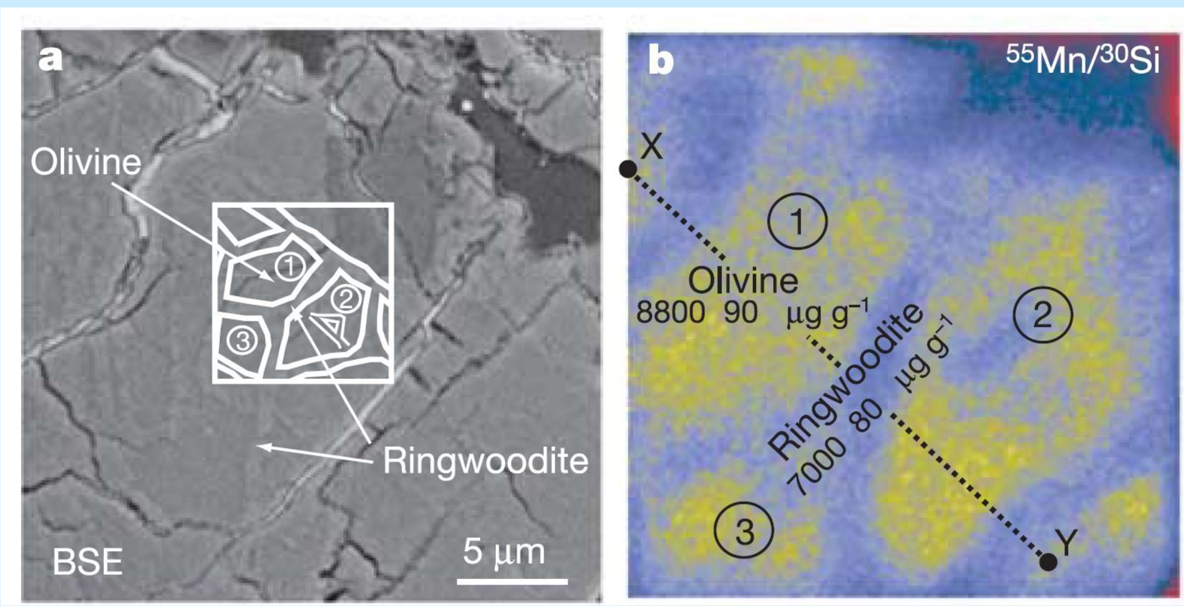
(Ohtani et al. 2004)

Shock event time estimation

1. **The duration of impact in a chondrites** (Ohtani et al. 2004; Beck et al. 2005).

Beck et al. (2005) The duration of shock events is inferred from trace element (Ca and Mn) distributions between the ringwoodite lamellae and host olivine.

The result of estimation was **1 second**.



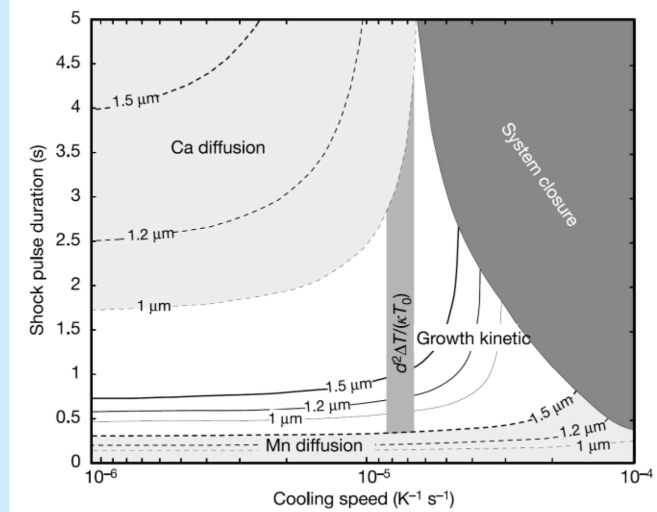


Figure 2 | Peak shock pressure duration as a function of the cooling speed for the Tenham meteorite. Three sets of curves are drawn, corresponding to the three methods used to constrain the shock pulse duration: Mn diffusion, Ca diffusion, and growth kinetics of ringwoodite laths within olivine[10]. The temperature dependence of both phenomena implies the knowledge of the cooling history of the system. Cooling was chosen to follow $1/T = at + (1/T_0)$ (ref. 26), where $a = d(1/T)/dt$ is the cooling speed and $T_0 = 2{,}500$ K is the starting temperature. Isopleths for Mn and Ca diffusion are calculated using:

Parent body size estimation

The size of impactor size were estimated in several reports:

Ohtani et al. 2004; Beck et al. 2005; Xie et al. 2006; Ozawa et al. 2014

(Ohtani et al. 2004)

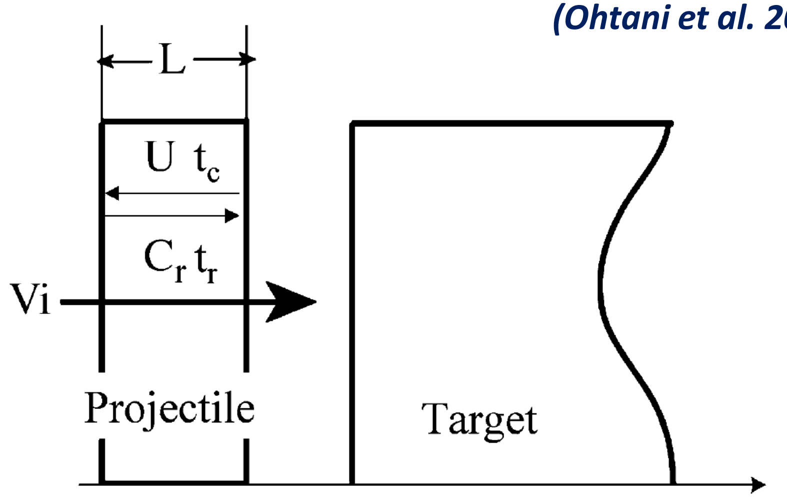


Fig. 9. One-dimensional model of the collision of the meteorite.

Shock wave is determined by

Runkine–Hugoniot relation:

$\mathbf{P=\rho_0 V_p U}$, where

P – the shock pressure = 20 GPa

ρ_0 – initial density = 3.26 g/cm3

V_p – particle velocity =

U – shock wave velocity

$\mathbf{U = c_0 + s\, V_p}$; (1)

$\mathbf{c_0}$ =4.82 km/s, s=1.33

$\mathbf{P=\rho_0 V_p(c_0 + s\, V_p)}$; (2)

;

$V_i = V_p$*2 ~2 km/s

V_i– impact velocity

U ~ 5 km/s

C_r~U~5 km/s –

velocity of the pressure release

Total time

t = t(compression) + t(expansion);

$t = t_c + t_r = L/U + (\rho_0 / \rho)L/C_r$

where

C_r = U (km/s) = L (km) / 2.5 (km/s)

The size of impactor L is 10 km/s

(Ohtani et al. 2004)

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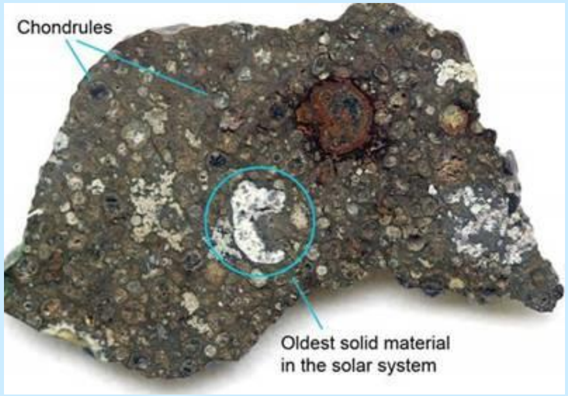

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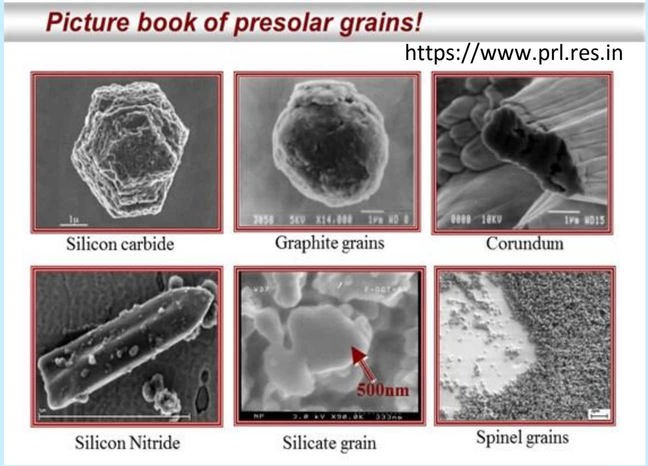

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5 Time estimation of the impact event

6 Size estimation of the chondrite parent body

Thank you

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Meteorite	Type	High-pressure mineral assemblage	Formation condition		References
			Pressure	Temp	
Tenham	L6	**Maj, Maj-Prp, Rwd, Akm, Prv**	22-26 GPa	2000 °C	Langenhorst et al. 1995; Tomioka, Fujino, 1999
Sixiangkou	L6	**Maj, Maj-Prp, Rwd, Akm, Mws, Lng, Jd**	20-24 GPa	2000 °C	Zhang et al., 2006
Yamato 74445	L6	**Maj, Wds, Rwd, Akm, Hol, Jd**	17-24 GPa	2100 °C	Ozawa et al., 2009
Yamato 791384	L6	**Maj, Maj-Prp, Rwd, Akm, Hol, Jd**	18-23 GPa	2300 °C	Ohtani et al., 2004 Miyahara et al., 2011, 2013
Suizhou	L6	**Maj, Maj-Prp, Mws, Hol**	18-22 GPa	1900 °C	Xie et al., 2001, 2002
Yamato 75267	H6	**Maj-Prp, Wds, Rwd, Akm**	20 Gpa	2000 °C	Kimura et al., 2003
Taiban	L6	**Maj+CPx , Wds, Rwd, Lng, Jd**	17-20 GPa	1900 °C	Acosta-Maeda et al., 2013
Yamato 75100	H6	**Maj-Prp + Opx +Ol, Wds, Hol-Jd**	18-24 GPa	1900 °C	Kimura et al., 2000 Tomioka et al., 2003
Pervomaisky	L6	Maj-Prp+Ol+Cpx	15 GPa	1900 °C	new data
Akm, akimotoite; Cpx, clinopyroxene ; Hol, hollandite; Jd, jadeite; Lng, lingunite; Maj-Prp, majorite-pyrope; Mws, magnesiowustite; Ol, olivine; Opx, orthopyroxene ; Rwd, ringwoodite ; Wds, wadsleyite (Whitney and Evans, 2010).					