Shock Effects in Meteorites II

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Determining Shock Pressure

The velocity and composition of the impacting materials determine the shock pressure.

Shock pressure can constrain impact velocities

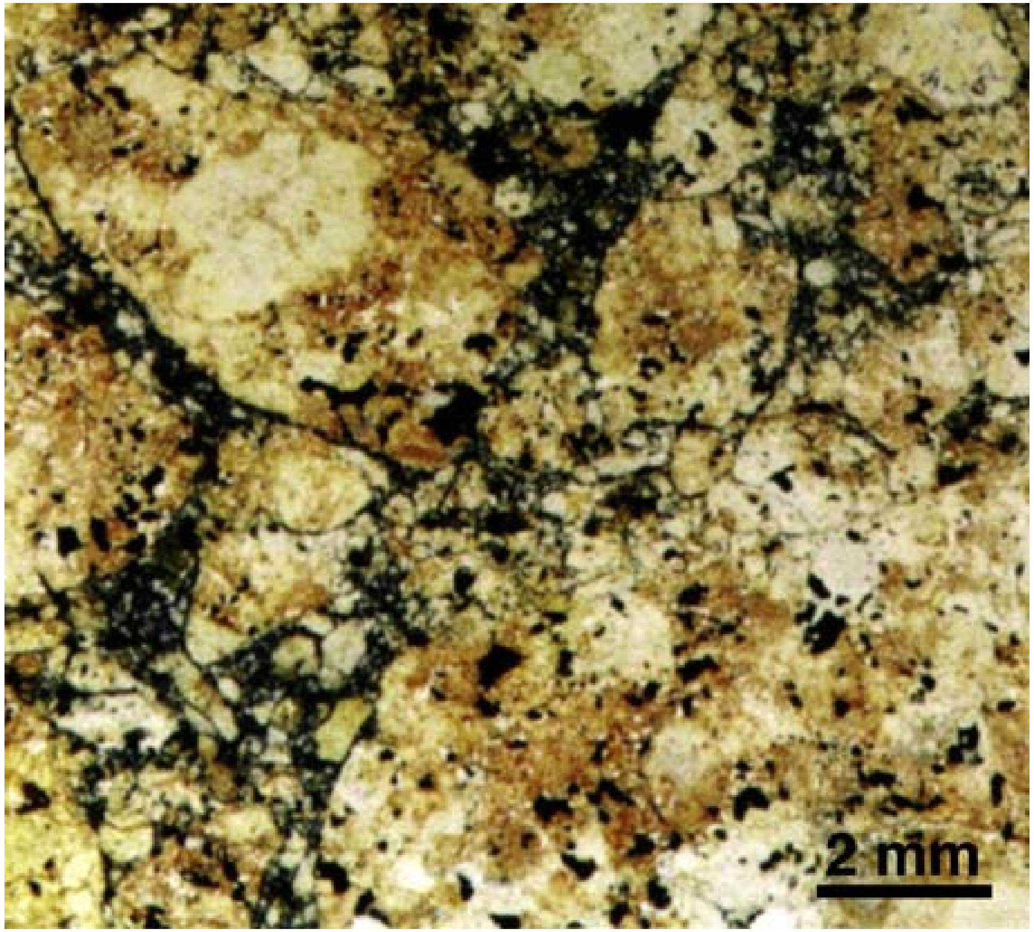
1. Calibrate the pressures required to produce specific shock features in shock-recovery experiments.
    - Use deformation and transformation processes in olivine, plagioclase (Stöffler et al. 1991)
2. Use pressure stabilities of high-pressure minerals to constrain pressure
    - High-P minerals formed by solid-state transformation
    - High-P minerals formed by melt-vein solidification

Introduction

- Meteorites represent the left-over materials form accretion and planet formation.
- Parent body assembly involved hyper-velocity collisions and shock
  - The record of early shock processes is commonly erased by subsequent heating
- Collisions between asteroids and on planetary surfaces cause shock metamorphism and ejection of samples that can make their way to earth.
- What can shock tell us about collision processes?

Shocked Chodrites

- Most chondrites are shocked
  - Shock-induced deformation and transformation
  - Shock-induced melting causes black shock veins
  - Phase transformations cause high-pressure minerals
- Impact shock is an important part of parent body processing.
  - It may be an important heat source for metamorphism (Rubin, 2004).



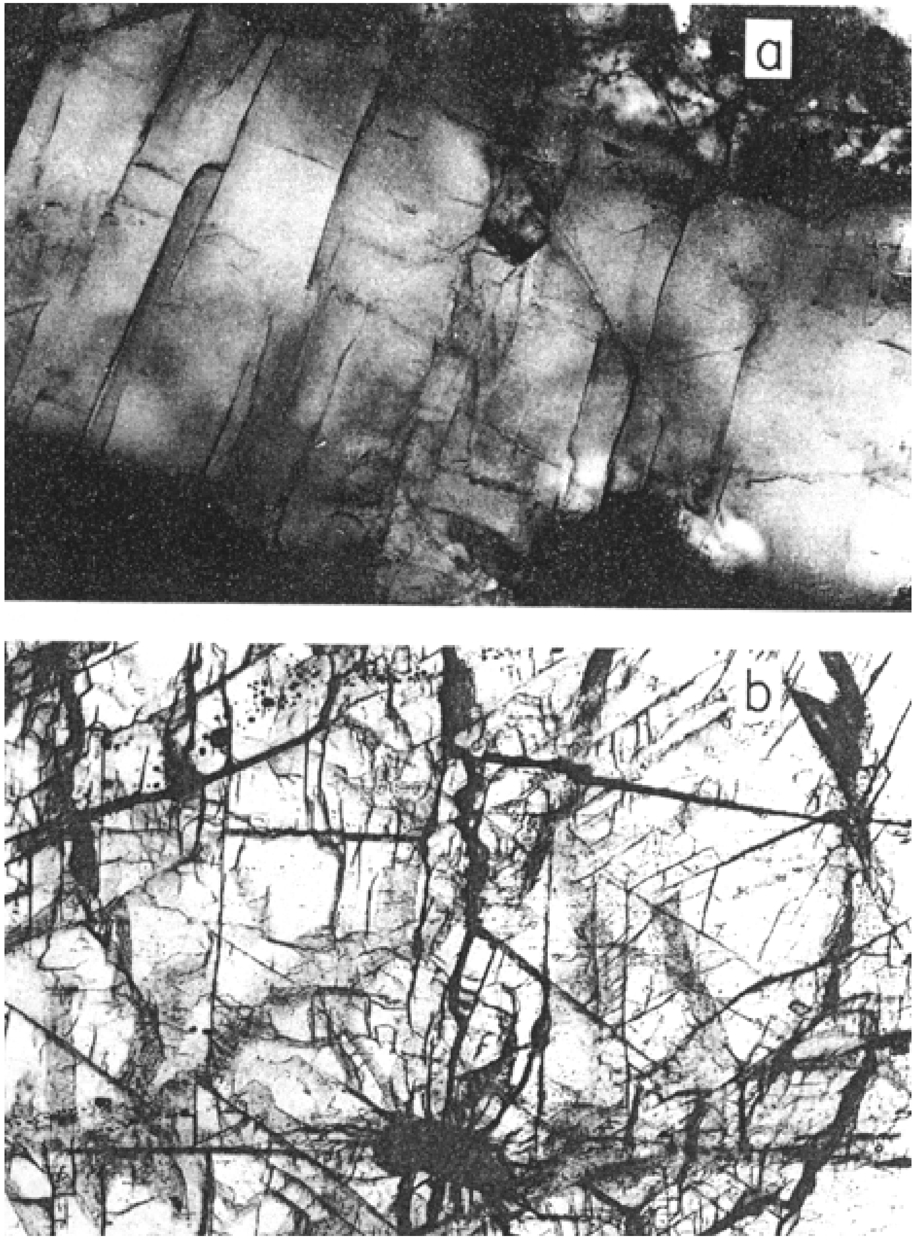
Acfer 040

Shock Deformation

- Major result of shock is plastic and brittle deformation of minerals.
  - Deformation effects have been studied carefully in terrestiral impact samples and in meteorites
  - Examples include fracturing, twinning, mozaicism and planar deformation features

Fracturing

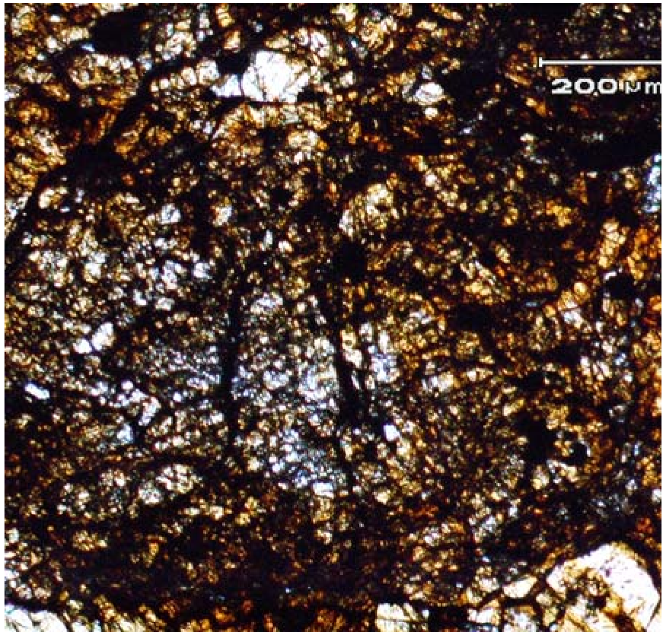
- Planar fracturing is common in shocked olivine
  - Moderate shock (a) produces {001} fractures
  - Higher pressures (b) produce {001} and {hk0} fractures

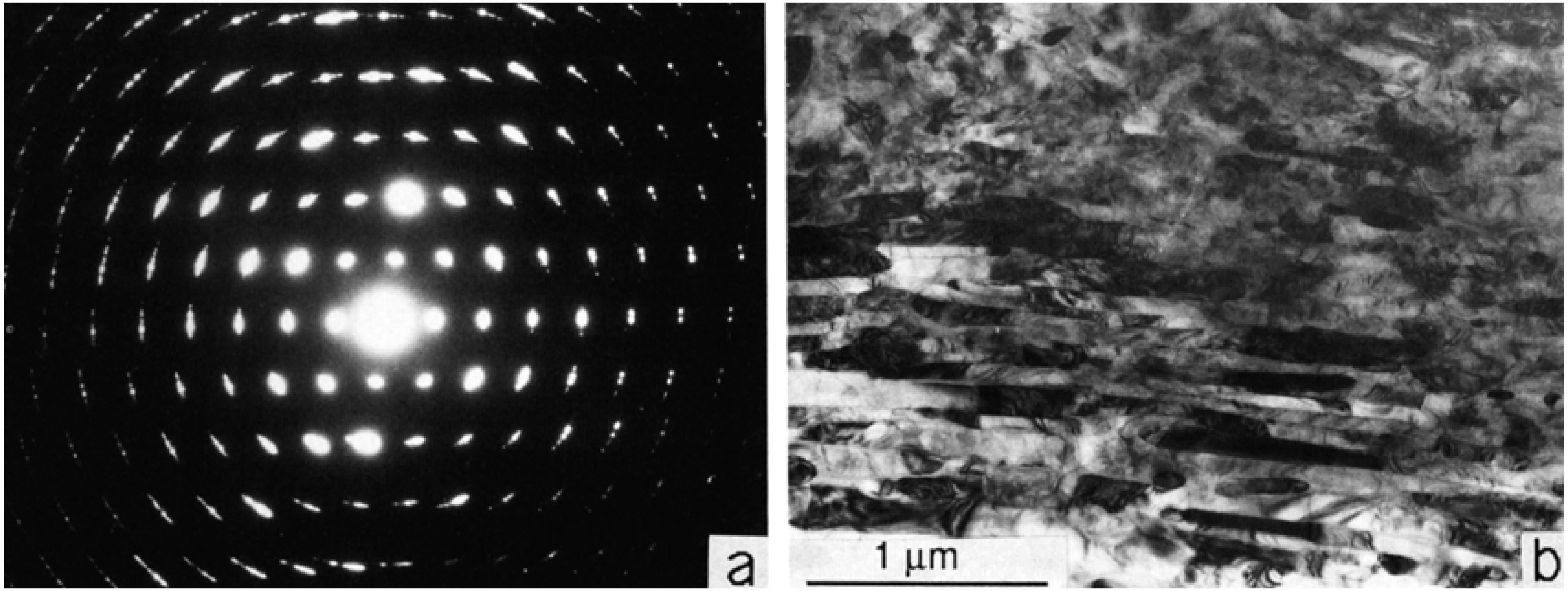


Stöffler et al. 1991

Mosaicism and recrystallization

- Highly deformed into small domains rotated by more than 3 - 5°
  - Fine scale fracturing and plastic deformation.
- Highly deformed samples near melt veins recrystallize into a fine grained aggregates



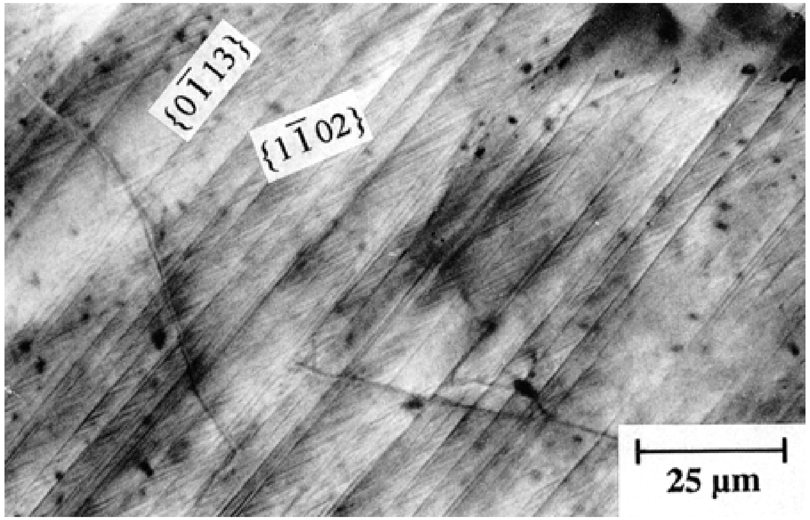


TEM image and diffraction pattern of diopside (Leroux etl. al 1994)

- Mosaicism produces astarism in X-ray and electron diffraction patterns.

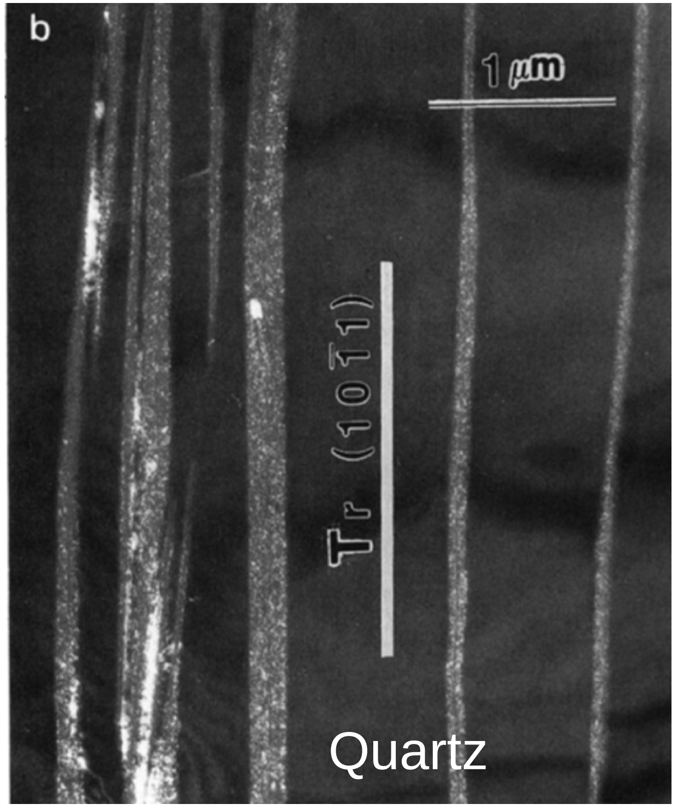
Planar Deformation Features

- Planar features found in quartz, feldspars and pyroxene
  - Occur on specific crystallographic planes
  - Orientations corellated to shock pressure
- Transformation feature!
  - Transformation to diaplectic glass.
- Kinetic process.
  - 18.8 GPa in Stainless steel vs. 10 GPa in polyethelene



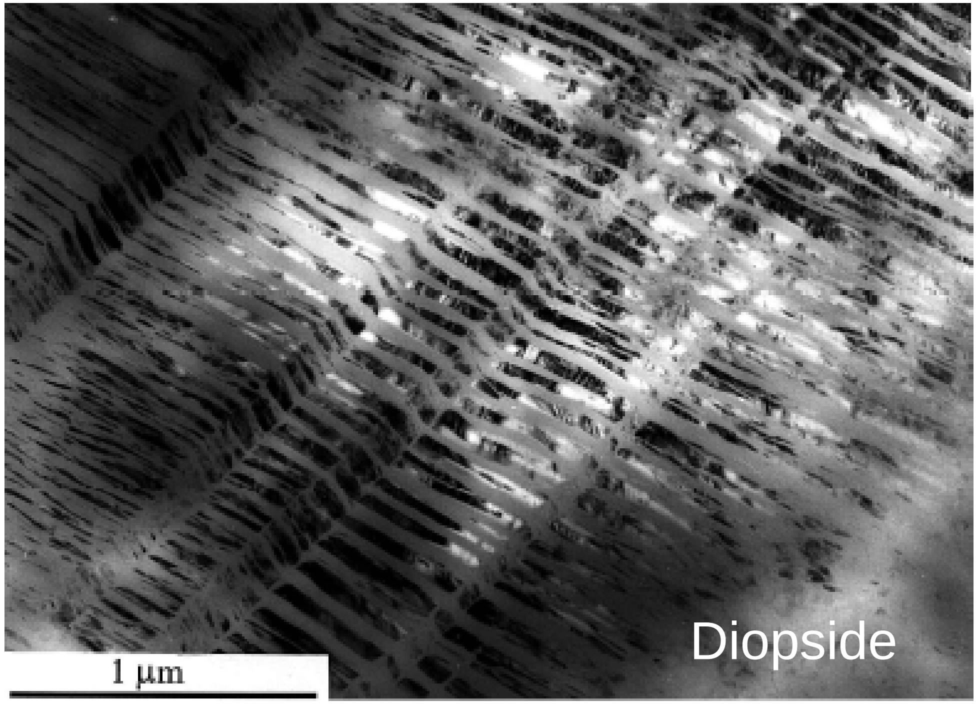
Stöffler and Langenhorst, (1994)

- Some TEM studies show nano-crystalline material in quartz PDFs.



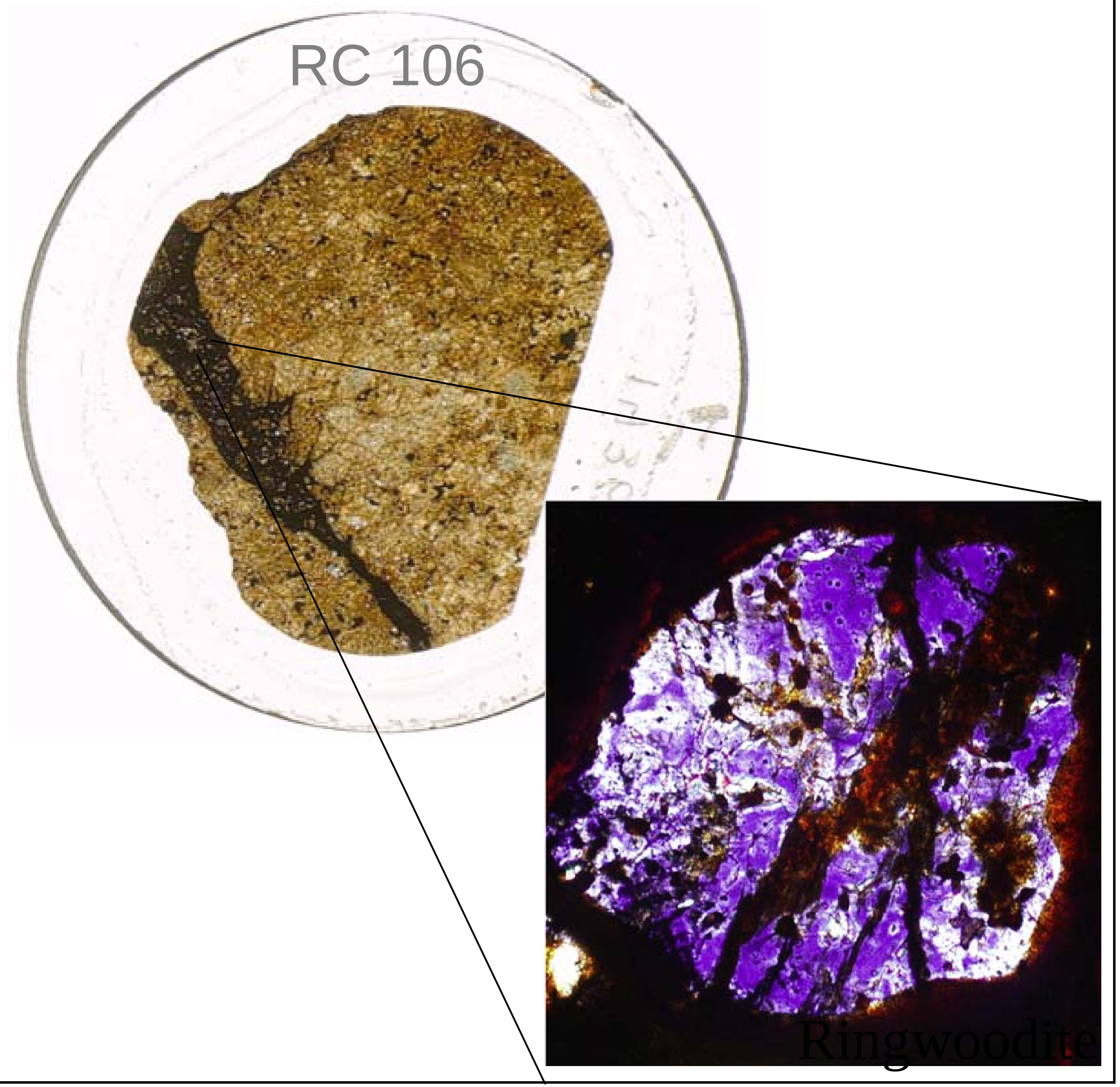
Goltrant et al. (1991)

Laroux, 2001



Melting and Phase Transformations

- The most highly shocked meteorites have localized shock-melt veins.
  - “Mixed melt” wich chondritic composition.
- High-pressure minerals in veins
  - Olivine and pyroxene transformation only occurs in or in contact with melt veins.



Shock Classification

- Many classification schemes.
- Most used is Stöffler et al. (1991)
  - Uses PLM-petrographic observations of deformation and transformation features in olivine and plagioclase
  - Relatively easy to use
  - Pressures of metamorphic effects are calibrated against shock-recovery experiments.

Stöffler et al. Classification

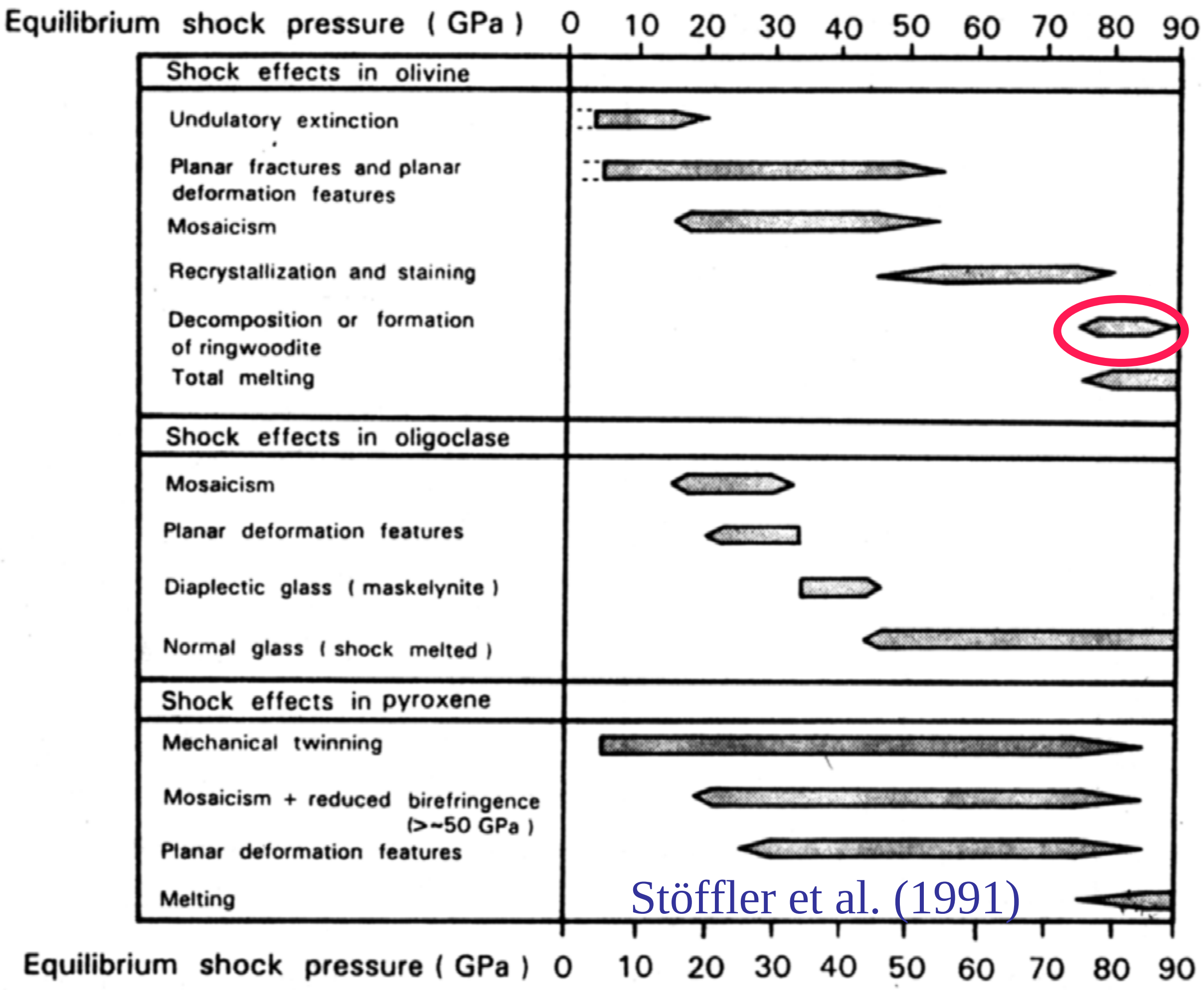
Shock Stage	Shock pressure GPa at upper stage boundaries	Shock features in Olivine and Plagioclase
Unshocked S1	< 4 – 5	Fractures and sharp optical extinction
Very weakly shocked S2	5 – 10	Fractures and undulatory extinction
Weakly shocked S3	15-20	Planar deformation features (PDF's) Melt veins
Moderately shocked S4	30-35	Mosaicism and PDFs Melt veins
Strongly shocked S5	45-55	Maskelynite, mosaicism and PDFs Melt veins
Very strongly shocked S6	75-90	Melt veins, solid-state transformation High-pressure minerals (at melt veins)
Whole rock melting		

- S6 features require "local P-T excursions" so S6 does not apply to the whole rock.

Calibrate Pressure with Shock-Recovery Experiments

Calibration problem

- No transformation of olivine or pyroxene in shock-recovery experiments.



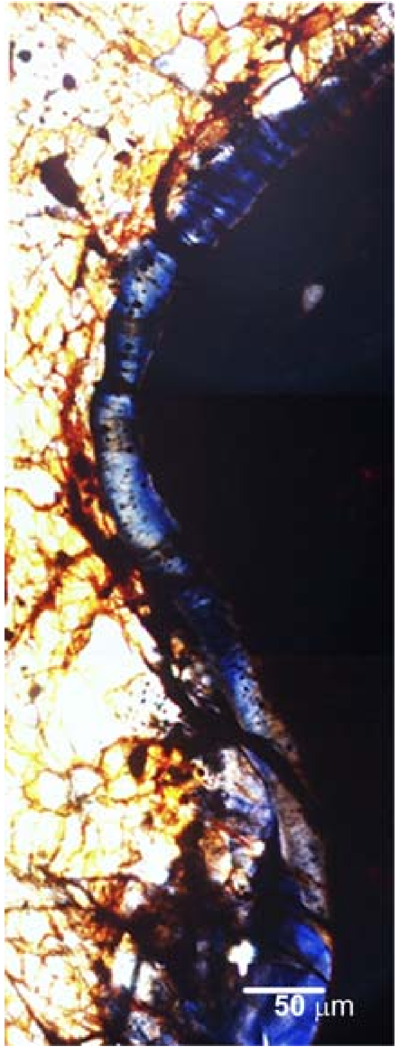
Pressure-Calibration Problems

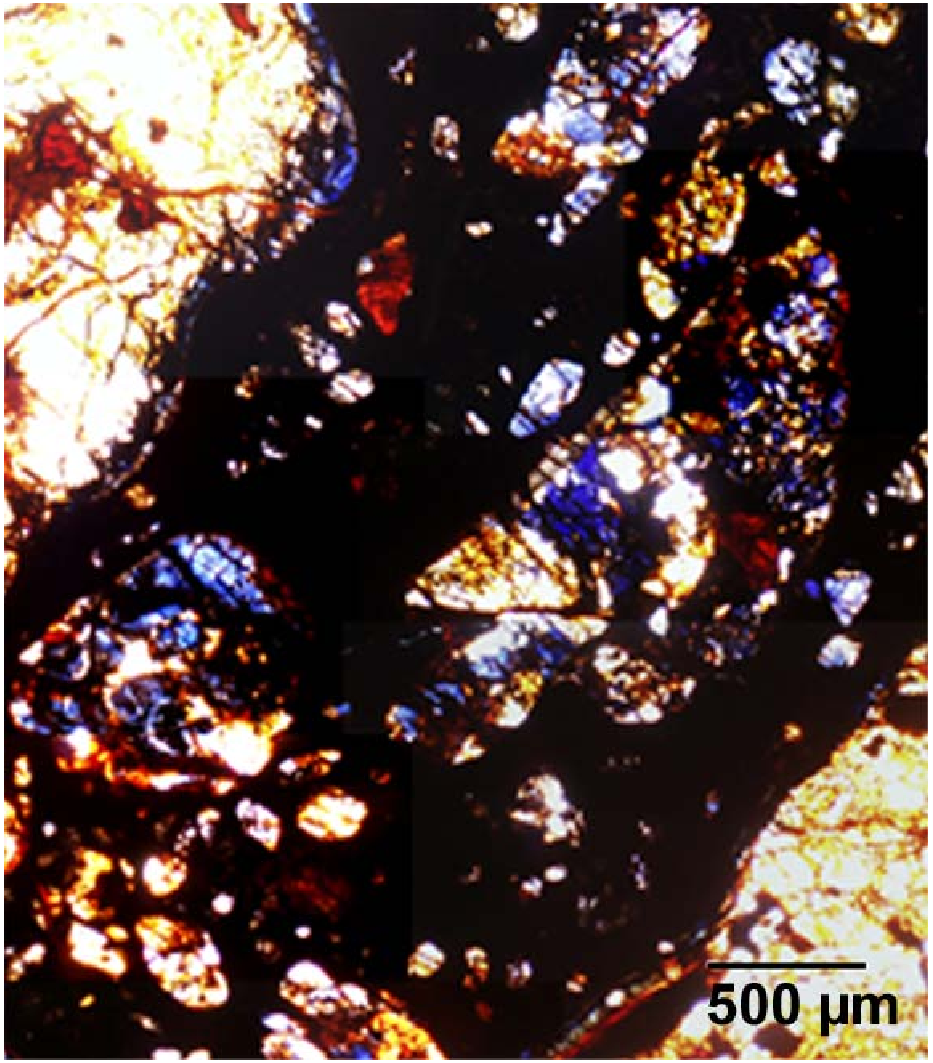
- Problem 1. Most shock-recovery experiments use a high-impedance metal containers.
  - Multiple-shock reverberation produce lower ΔE and therefore lower shock temperatures.
    - PDF sets in quartz that form at ~ 19 GPa in reverberation, form at ~ 10 GPa in single shock experiments (Bowden et al. 2001)

- Problem 2. Most shock recovery experiments are on non-porous samples (Schmitt, 2001).
  - Non-porous samples are heated much less than porous samples.
  - Most transformations are restricted to hot melted zones.

- Problem 3. μs duration experiments are used to model natural impact events of ms to s duration
  - May not be enough time for reconstructive transformations

High-Pressure Minerals





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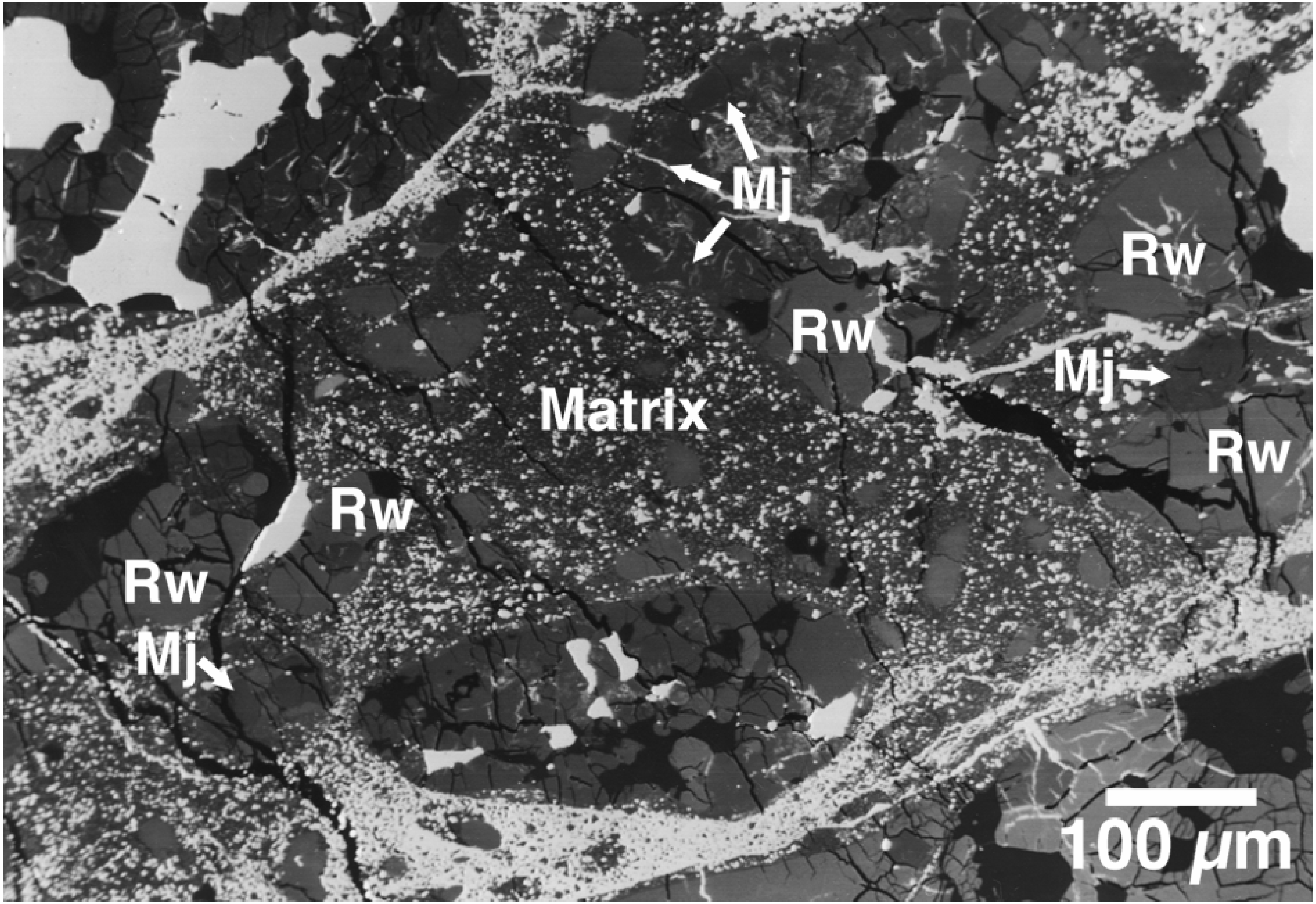
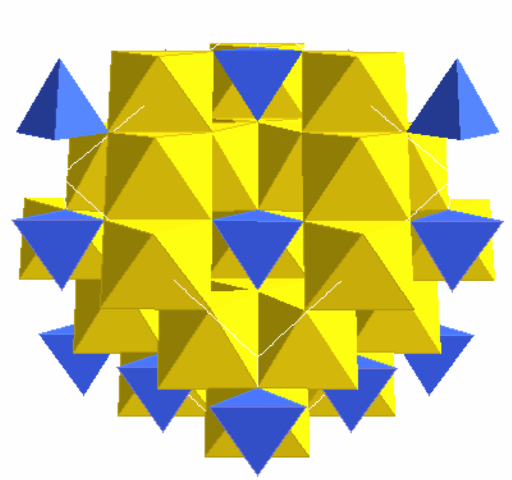
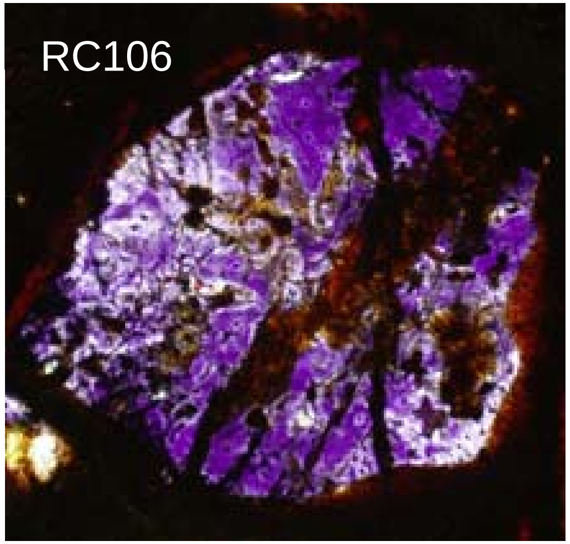


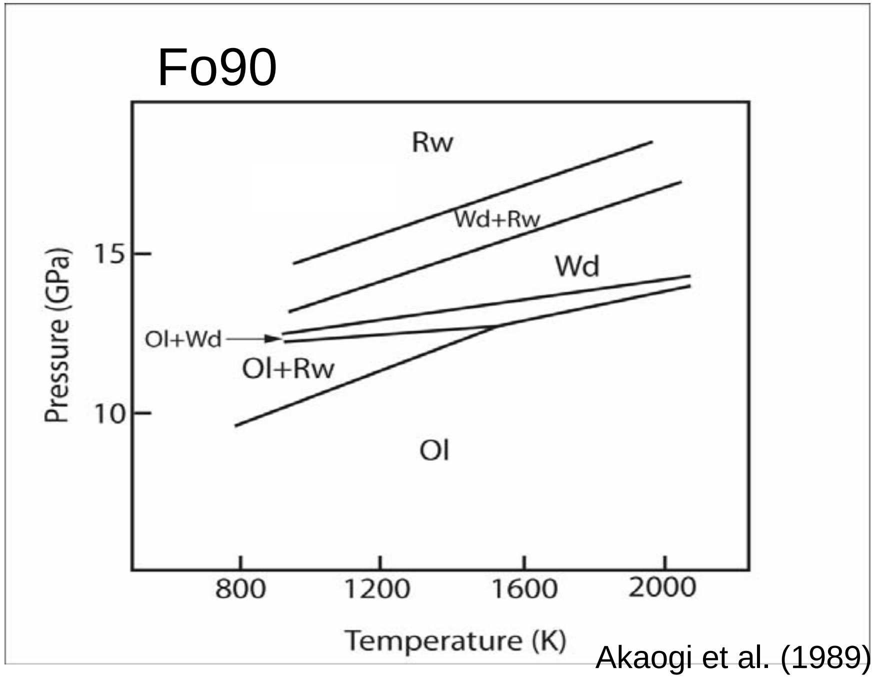
Sixiangkou

Ringwoodite

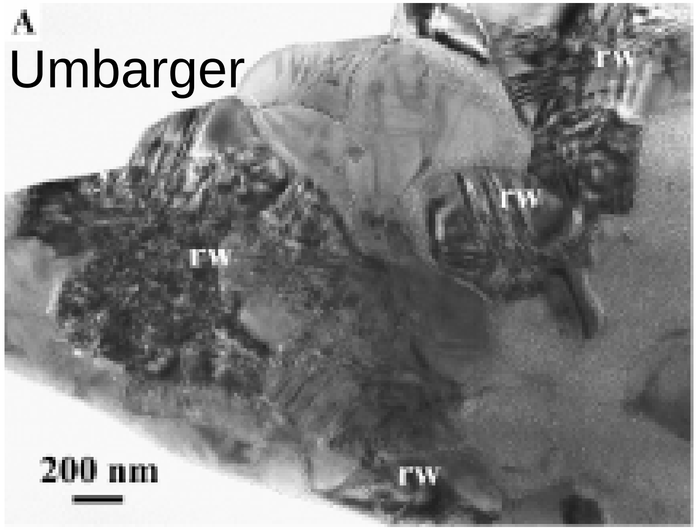
- Spinel-structured polymorph of olivine (γ-phase)
- Discovered in Tenham by Binns (1969) in Tenham
  - It was misidentified in Coorara by Mason et al. in 1968
- Distinctive purple-blue color
  - Can be colorless
  - Optically isotropic



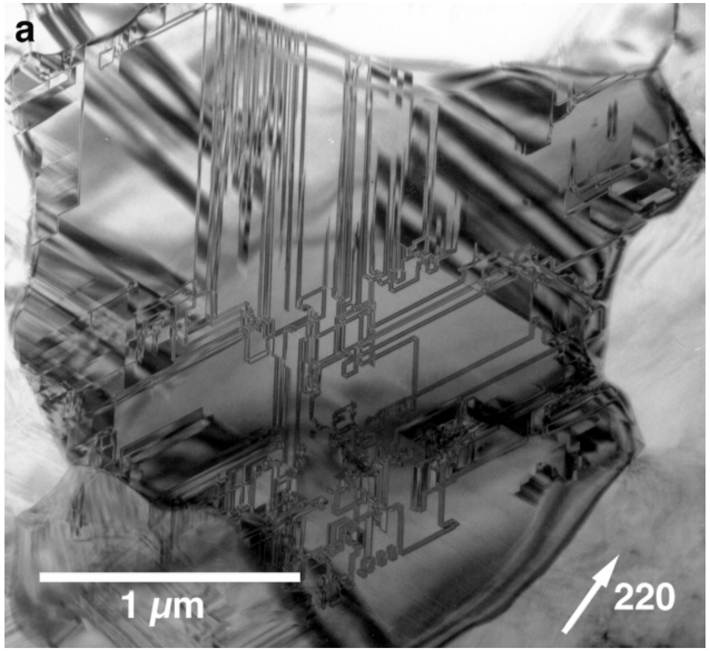




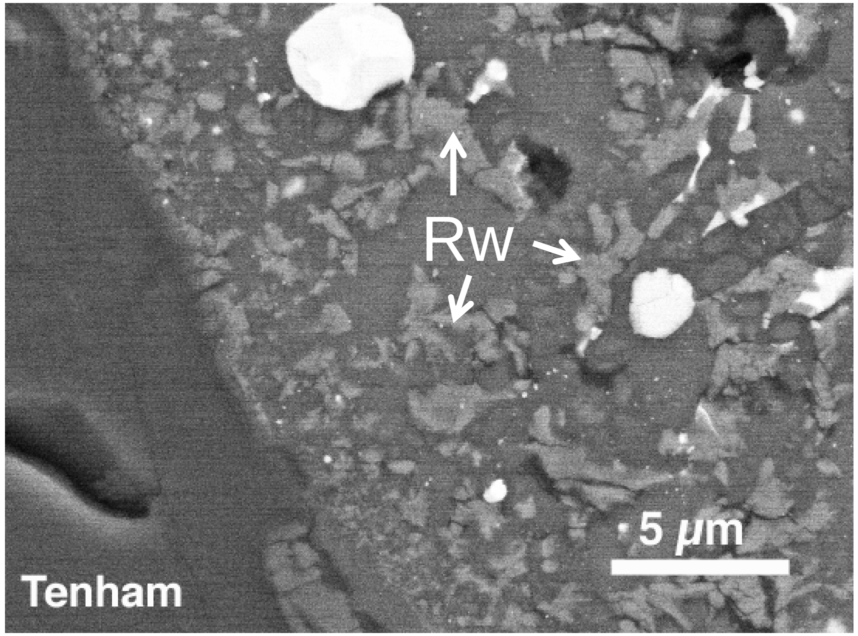
Akaogi et al. (1989)



Ringwoodite mostly occurs as polycrystalline aggregates after olivine (left), but also crystallizes from melt.

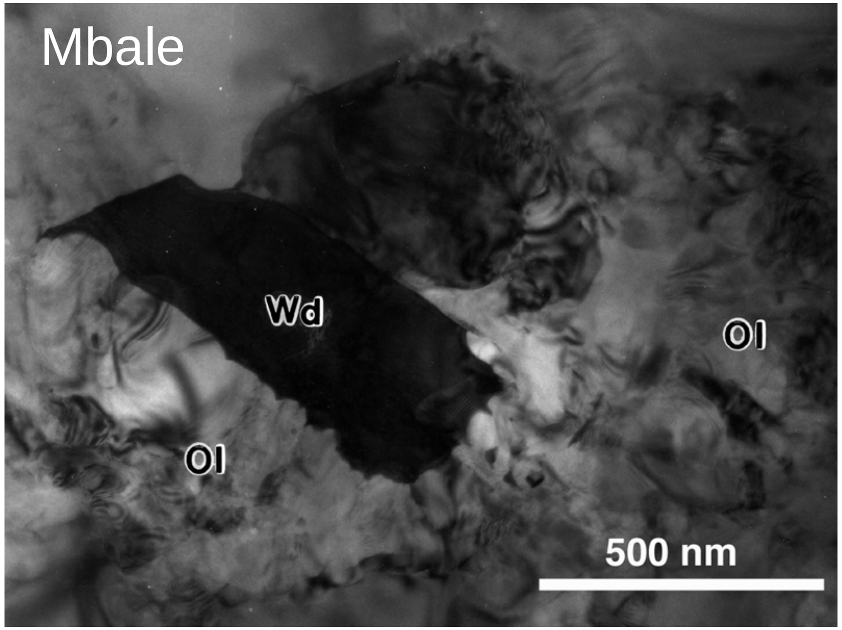


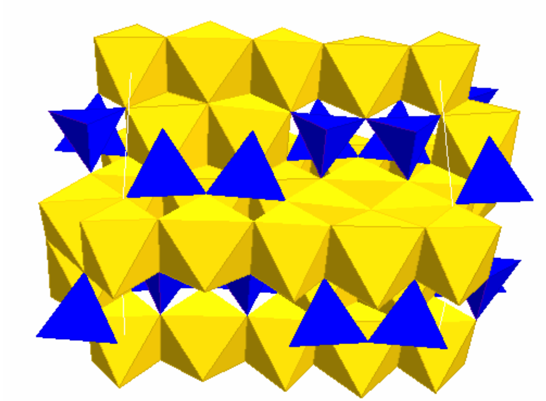
Sixiangkou

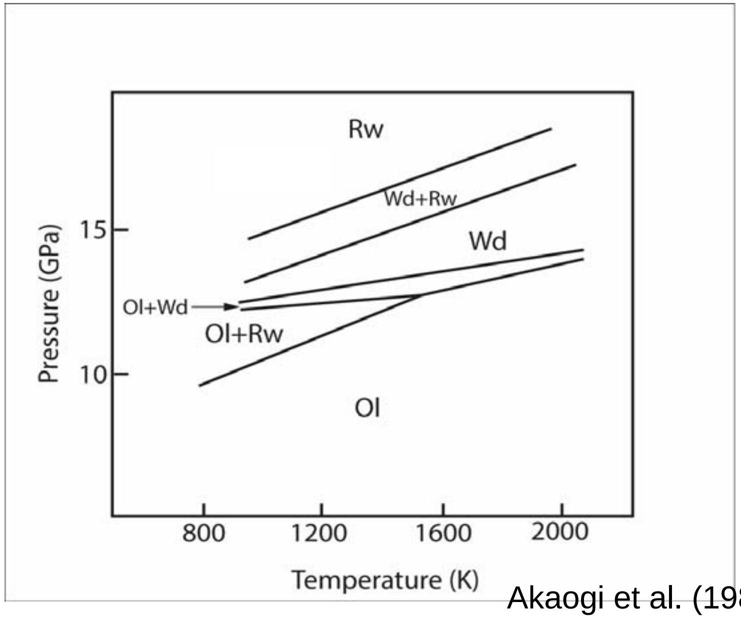


Wadsleyite

- 1979 - Putnis and Price use TEM to study Tenham and discover wadsleyite
  - Modified spinel structure (β).
  - Not as common as ringwoodite.



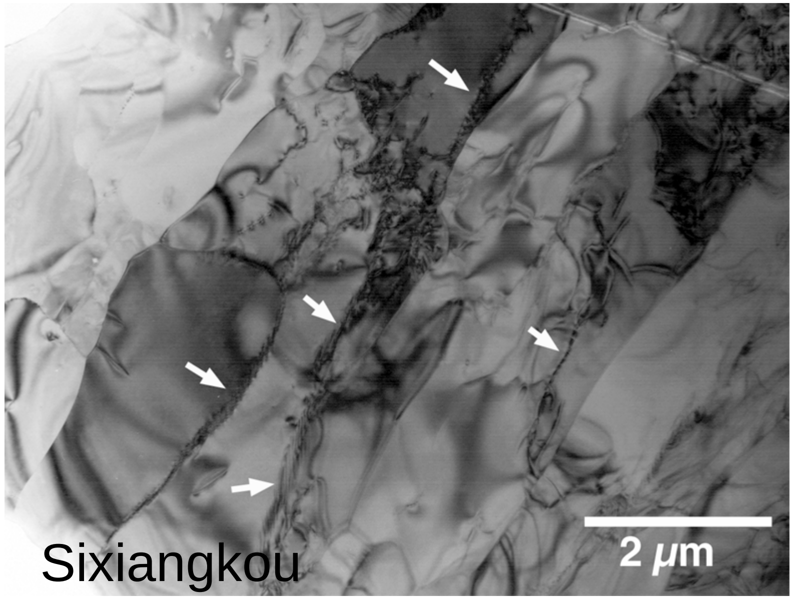


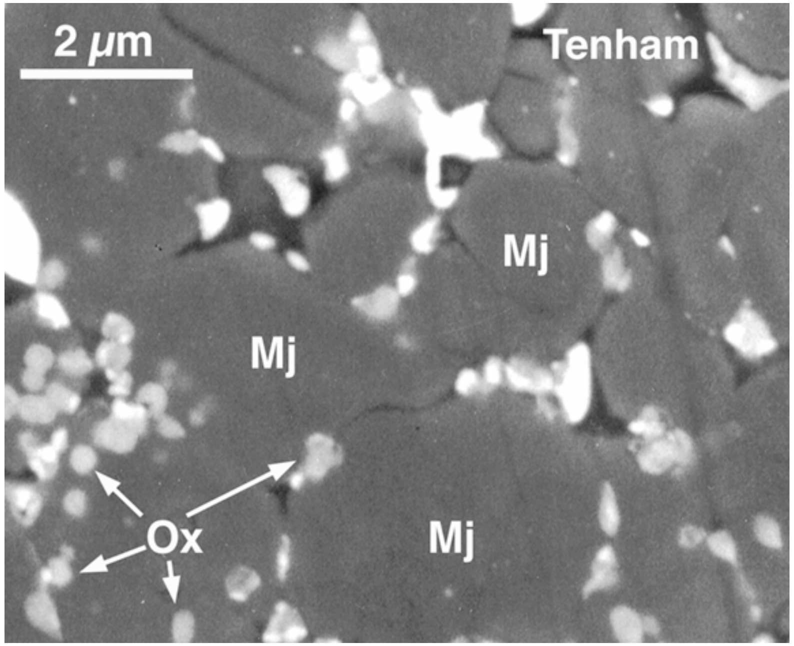


Akaogi et al. (1989

Majorite

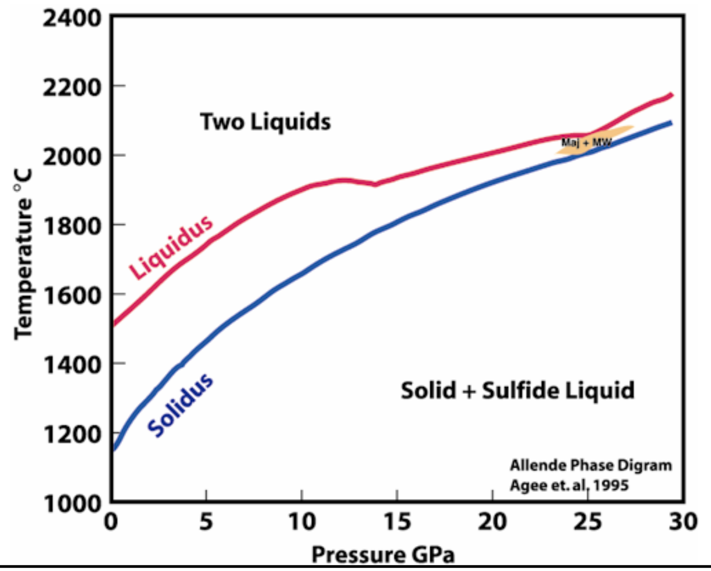
- 1970 - Smith and Mason discover majorite garnet in Coorara
  - Crystallized from the melt
- Pyroxene composition with a garnet structure
- Forms by transformation of enstatite
  - $Mg_3(MgSi)_2Si_3O_{12}$
- Or crystallization from melt.
  - $Mg_3(MgSi)_2Si_3O_{12}$-$Mg_3Al_2Si_3O_{12}$ with Ca, Na

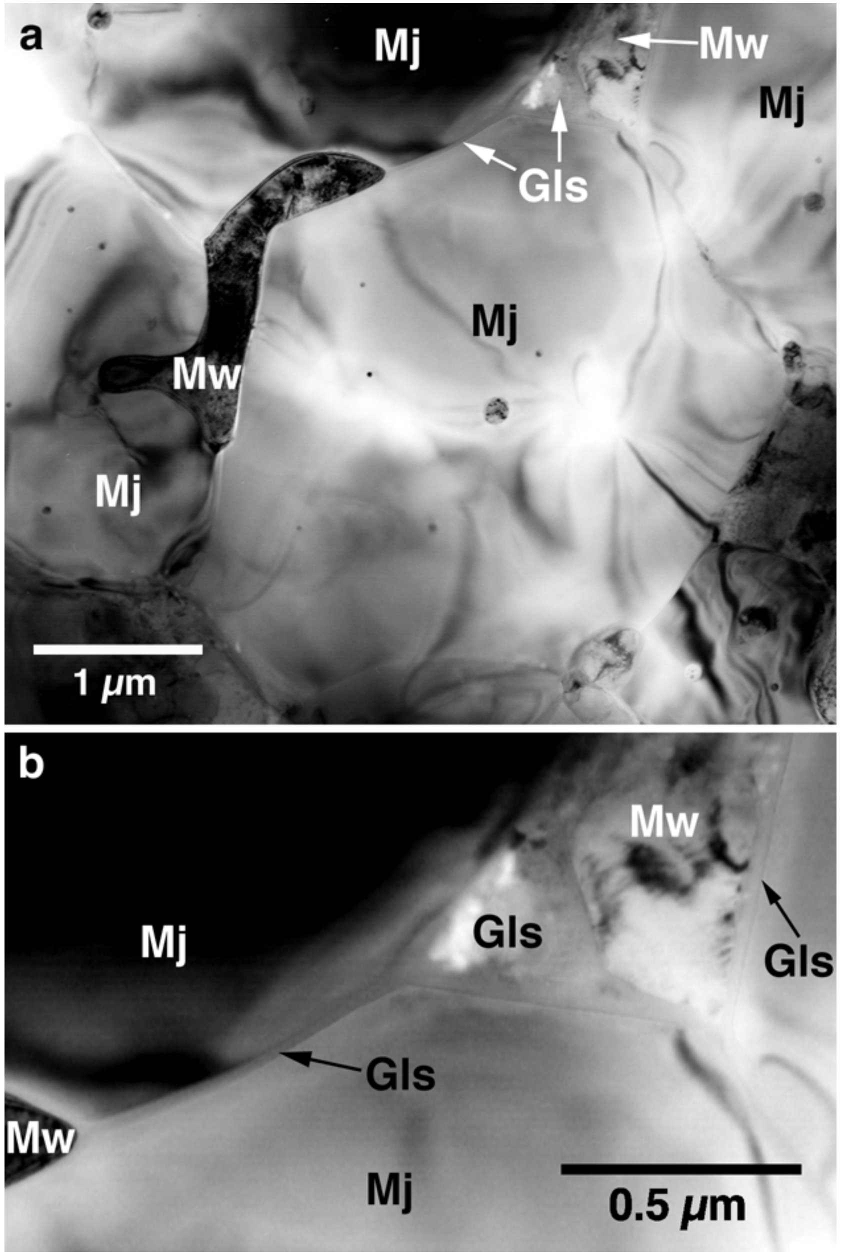




Magnesiowustite

- 1985 - Mori and Takeda discover magnesiowustite in melt veins.
- 1996 - Chen et al. discovered majorite + magnesiowüstite assemblage in melt veins
  - Crystallization at pressure of ~ 25 GPa



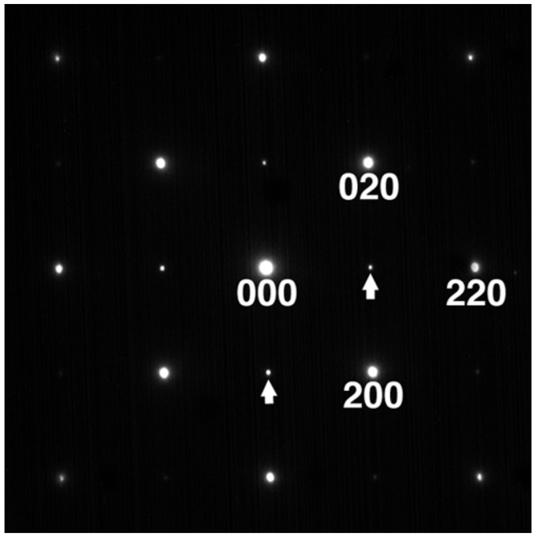


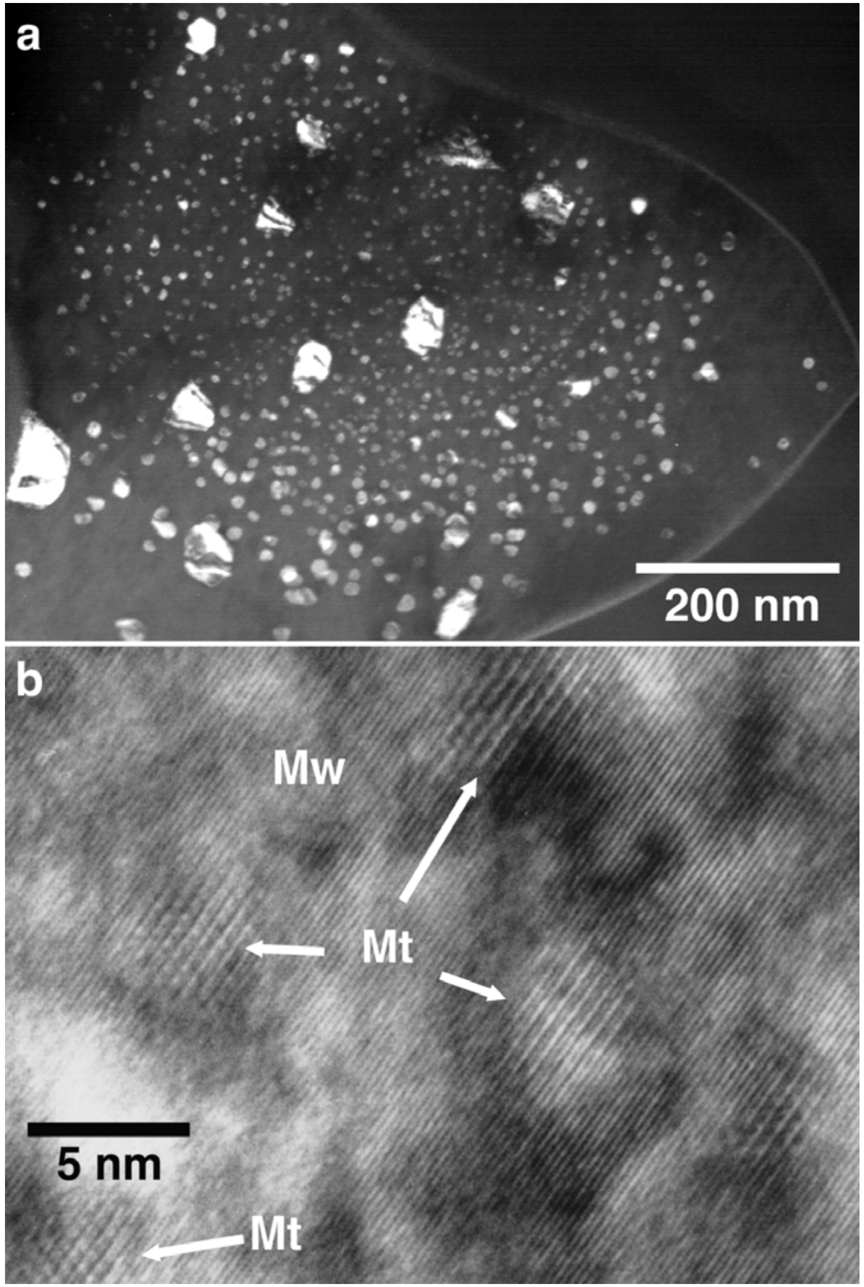
Magnetite

Magnesiowüstite contains exsolved magnetites

- Low-T breakdown
- Mw = Per + Mgt

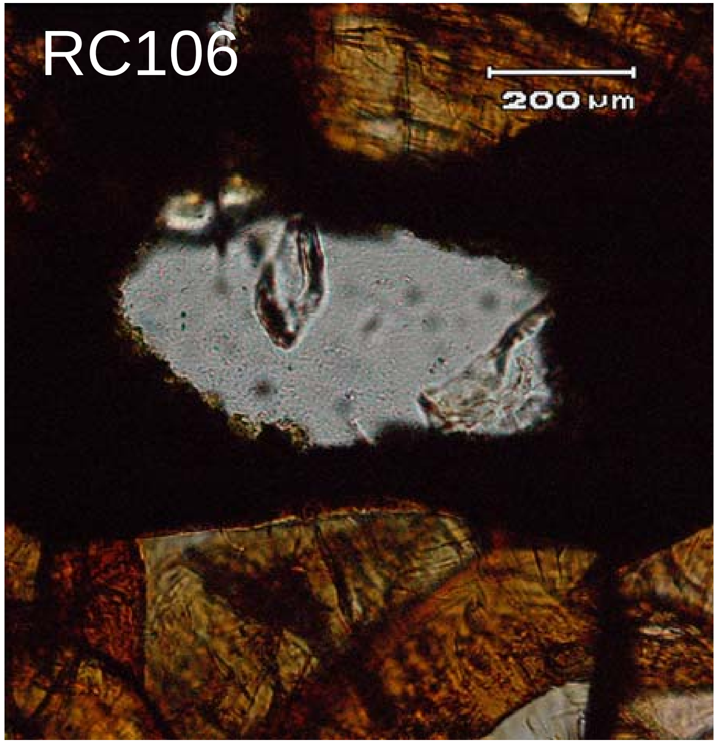
Implies that magnesiowustite was had Fe^{3+} + vacancies.‥



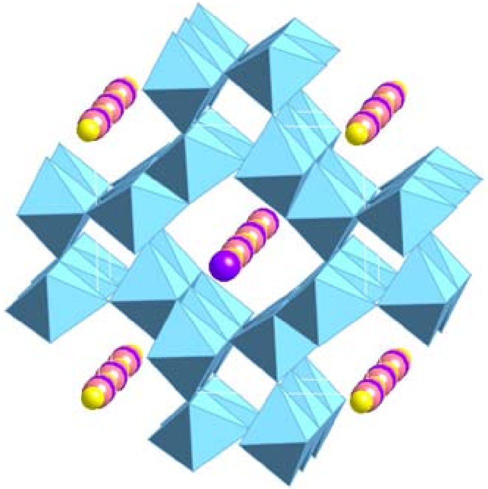


Maskelynite

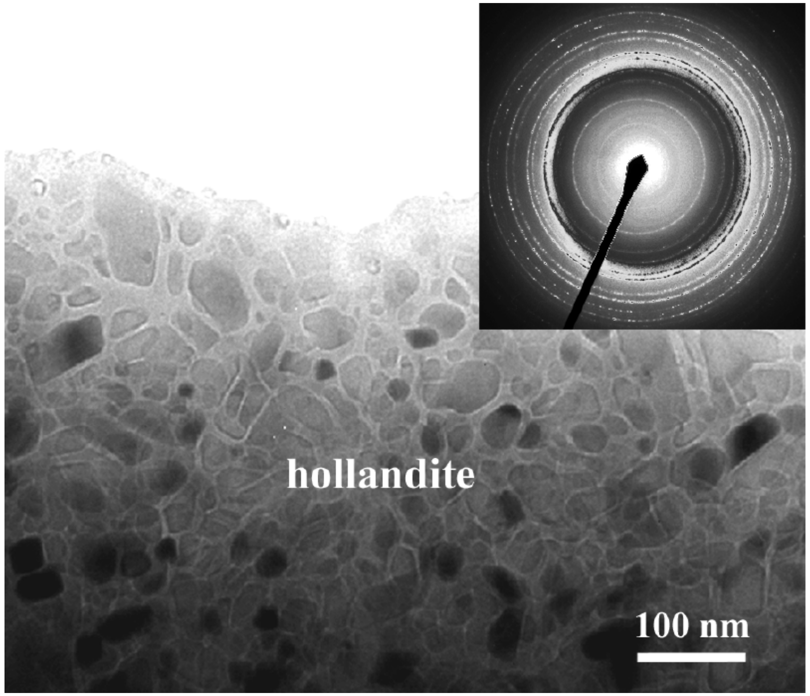
- 1967- Binns discovered maskelynite.
- Plagioclase transformed to a diaplectic glass
  - Near melt veins in S4-S5 samples
  - Throughout S6 samples.



Silicate Hollandite

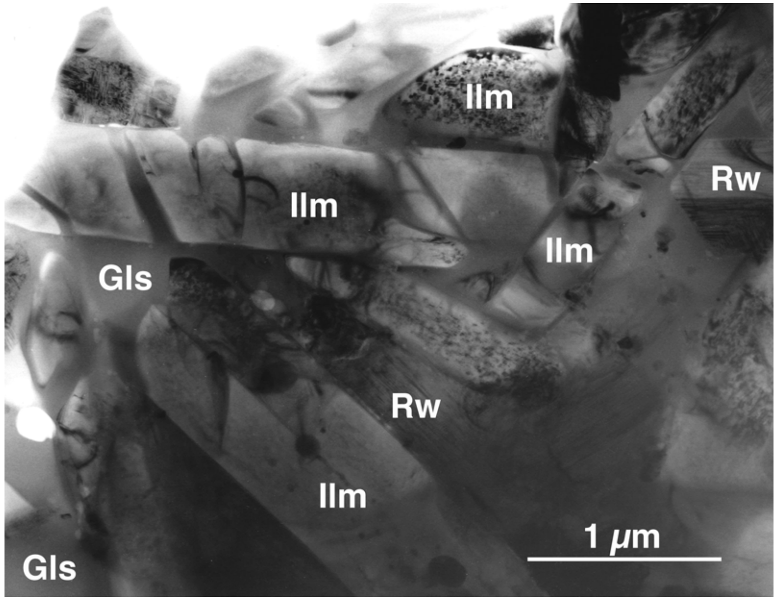


- 1990 - Mori reported $NaAlSi3O_8$-hollandite in Y790729
- 2000 - Gillet et al. and Tomiokka et al. rediscover $NaAlSi3O_8$-hollandite in in Sixiangkou and Tenham.
- 2000 - Langenhorst and Poirier find $KAlSi3O_8$-hollandite in Zagami.
- Nano-polycrystalline material in and adjacent to melt veins.
- Pressure stability from ~ 15 to 23 GPa.

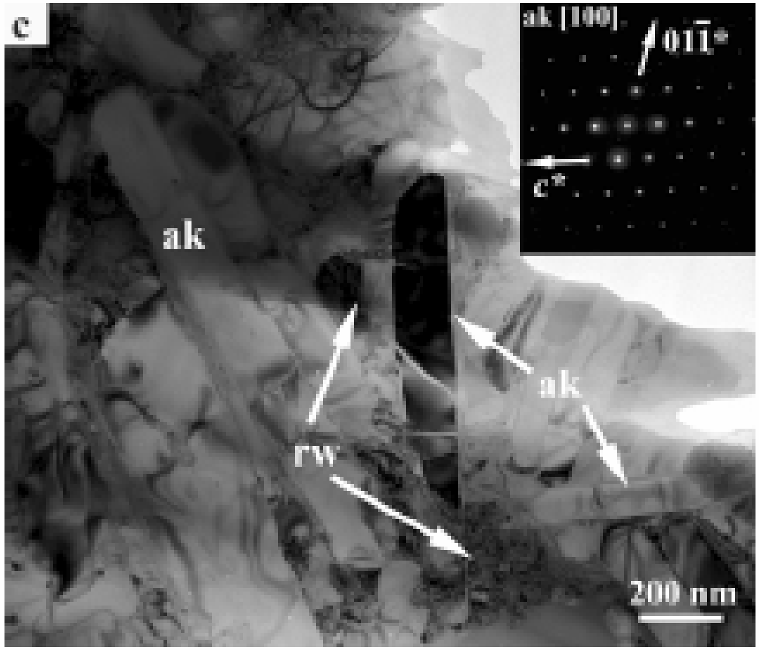


Akimotoite

- 1997 - Simultaneously, Sharp et al. and Tomioka and Fujino discover akimotoite ((Mg,Fe)SiO_3-ilemnite) in Acfer 040 and Tenham
  - Tomioka and Fujino (1997) Akimotite after enstatitie in Tenham describe
  - Sharp et al (1997): Akimotoite crystallized from melt in Acfer 040.
- Metastable crystallization in fast-quenched vein edges.



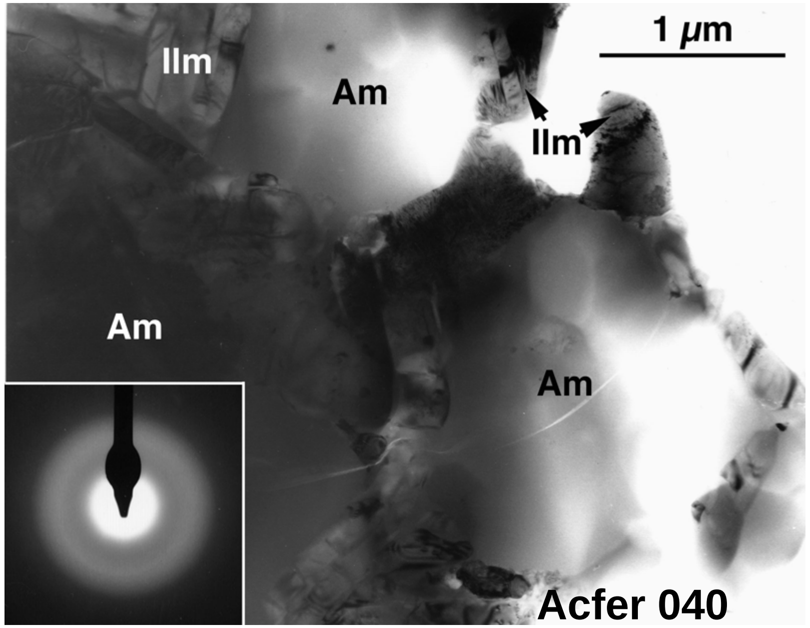
Acfer 040 Sharp et al, 1997



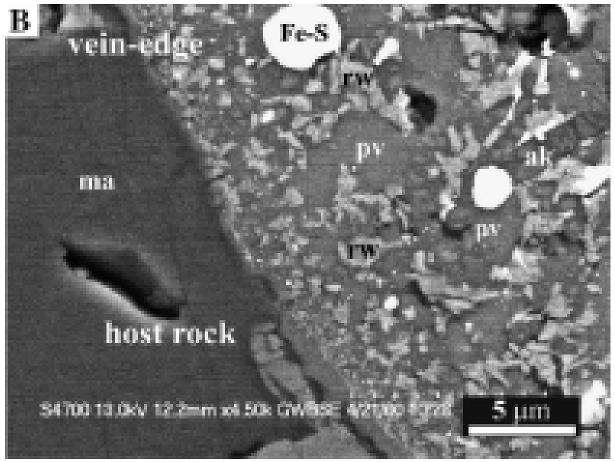
Umbarger Xie and Sharp 2005

Silicate Perovskite

- 1997 - Tomioka and Fujino discover $(Mg,Fe)SiO_3$-perovskite replacing enstatite in Tenham.
- 1997 - Sharp et al. describe vitrified silicate perovskite that crystallized from melt.
  - Also found in Zagami (Langenhorst and Poirier, 2000) and in Sixiangkou (Chen et al. 2004)



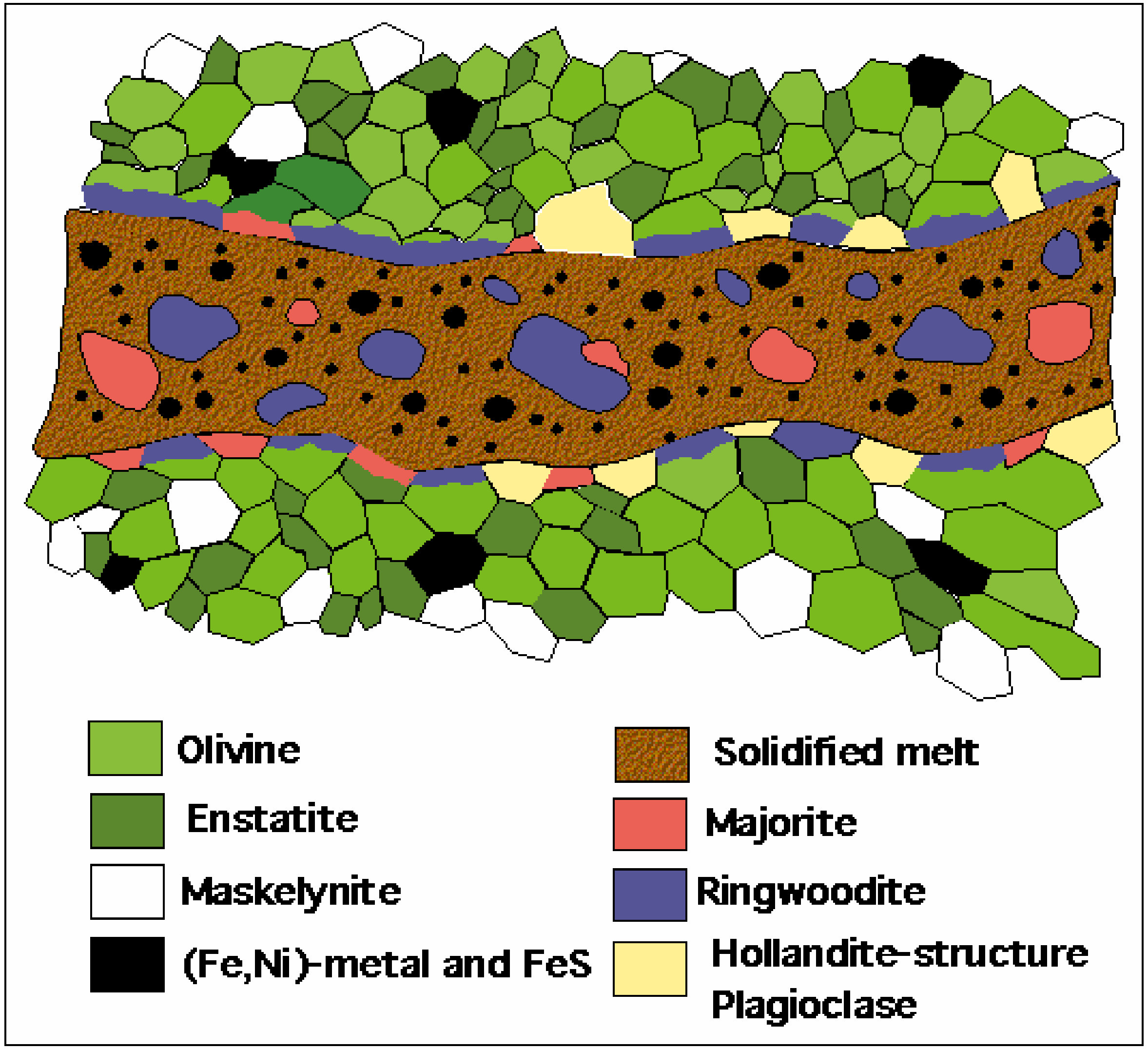
Sharp et al. 19997



Tenham, Xie et al. 2006

High-Pressure Minerals

- Metamorphic origin
  - Solid-state transformation of silicate fragments entrained in shock melt and some on vein margin.
  - Maskelynite can be distal to melt veins.
- Igneous origin
  - Crystallization of silicate and metal-sulfide liquids at high pressure.



So What? Who cares?

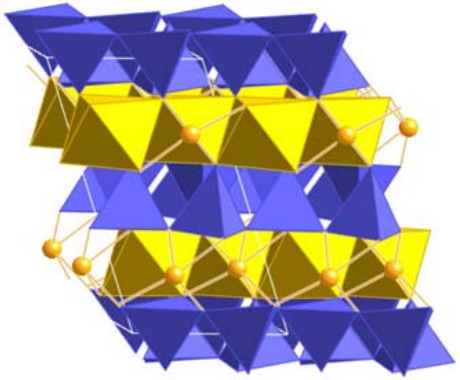
- The asteroid belt gives us natural samples of deep Earth minerals
  - We get to name them.
  - Useful for understanding Earth’s mantle?
- Do they help us constrain shock pressures?
  - Solid-state transformations suffer from large kinetic barriers.
    - Need to consider metastable phase boundaries
    - Phase boundaries may be significantly overstepped in pressure.
  - Melt-vein crystallization are kinetically easier because of higher temperatures.

Transformation Mechanisms

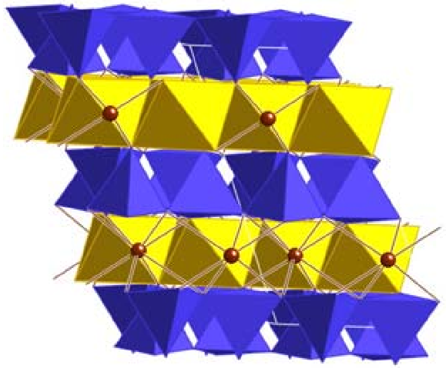
- Displacive
  - Symmetry change by small displacements of atom.
    - Kinetically fast - Nonquenchable
- Reconstructive
  - A major structural change that requires breaking and reforming bonds.
    - Kinetically slow - Nucleation, growth and diffusion - quenchable
    - The new phase may have a crystallographic relationship to parent.
- Martensitic
  - Rearrangement of atoms by shearing.
    - Motion of partial dislocations creates new structure
    - Crystallographic orientation required

Displacive

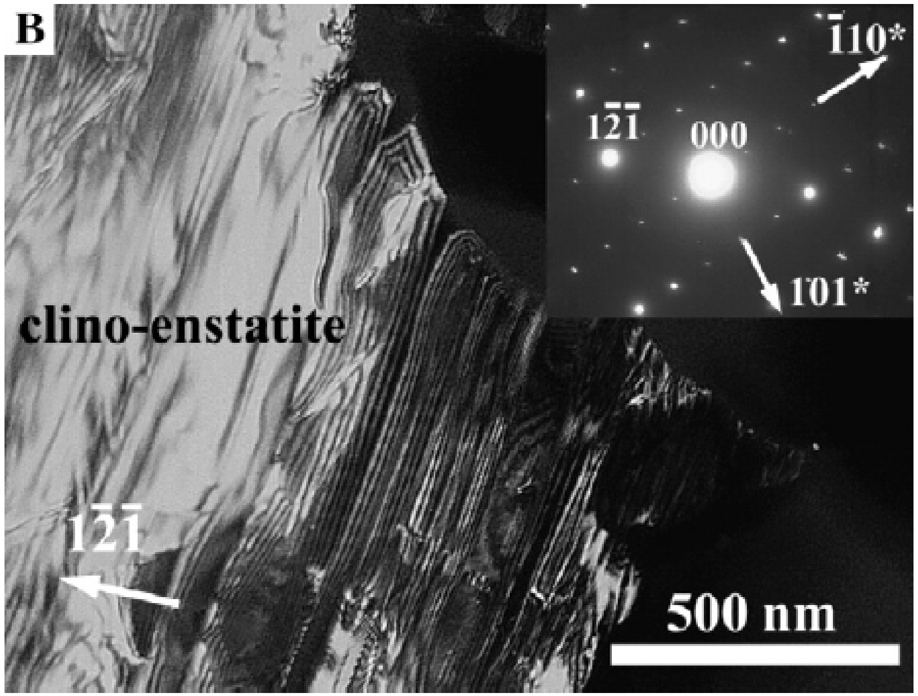
- At P> 10 GPa, a high-P clinoenstatite ($P2_1/c$) is stable.
  - During quench it transforms to clinoenstatite (C2/c)
  - If the low-Ca px in CEN, then HCEN will form.
  - If low-Ca px is OEN, reconstructive transition to HCEN forms during shock.
    - Need more TEM



$P2_1/c$

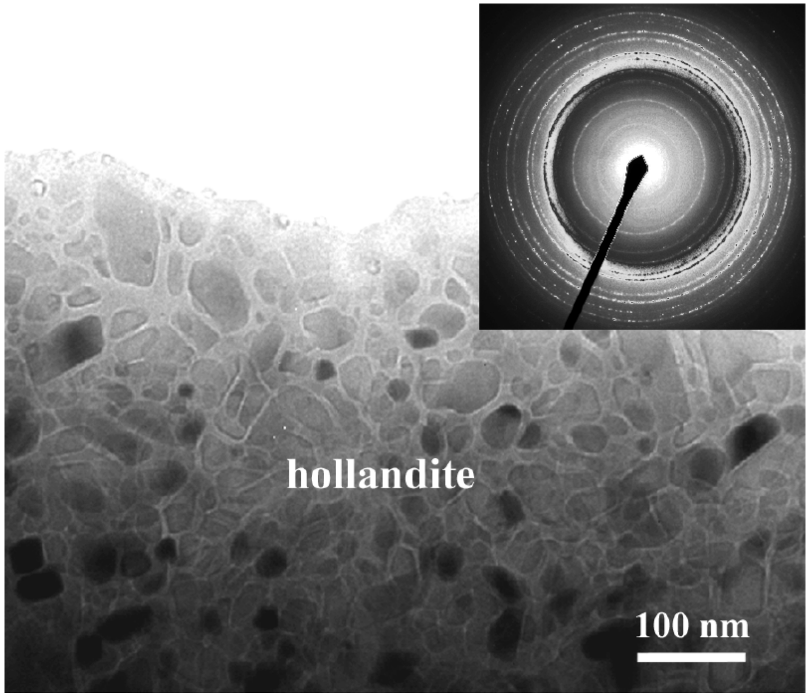


C2/c



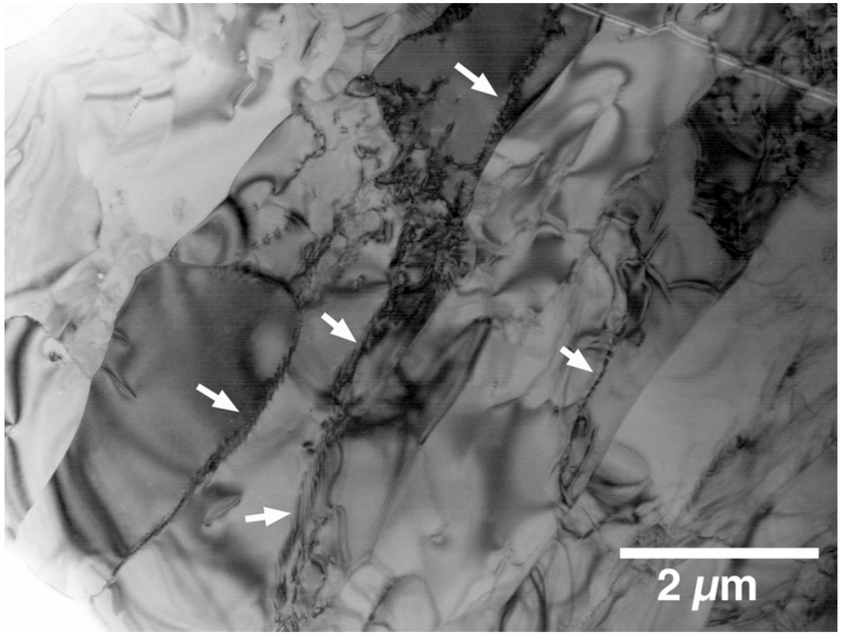
Plagioclase-Hollandite

- Only occurs in or next to melt veins.
  - Requires High T (1500 - 2000 ° C)
- Occurs as clasts in melt vein
  - Reconstructive mechanism
  - May involve melting or intermediate glassy state.
  - Hollandite-filled veins in Tehnham.



Enstatite -Majorite

- Enstatite transforms directly to (Mg,Fe)SiO_3-majortie.
  - Only in melt veins
  - Residual enstatite is common.
  - Much slower to react than olivine (Hogrefe et al. 1994)
- Polycrystalline aggregates consist of long (10-μm) crystallites separated by subgrain boundaries.
  - Suggests a reconstructive transformation with crystallographic control.
  - More work needed on partially transformed enstatite.



Olivine-Ringwoodite

- Ringwoodite usually consists of polycrystalline aggregates of sub -μm to μm crystallites
  - Crystallites appear to be randomly oriented
  - Intracrystalline mechanism with incoherent nucleation and growth until crystals impinge.
  - Growth rate data can constrain shock duration (Xie and Sharp, 2007)

$v = k_0 T \exp[-(\Delta H_a + PV^*)/RT][1-\exp(\Delta G_r/RT)]$

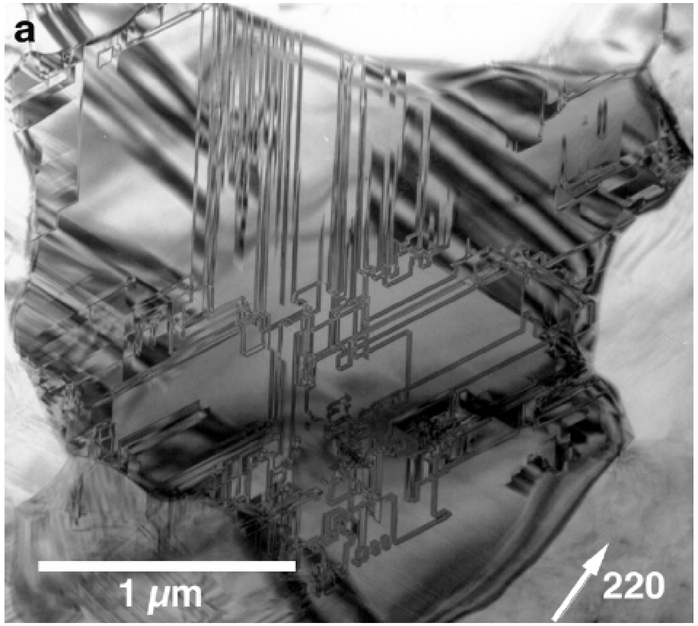
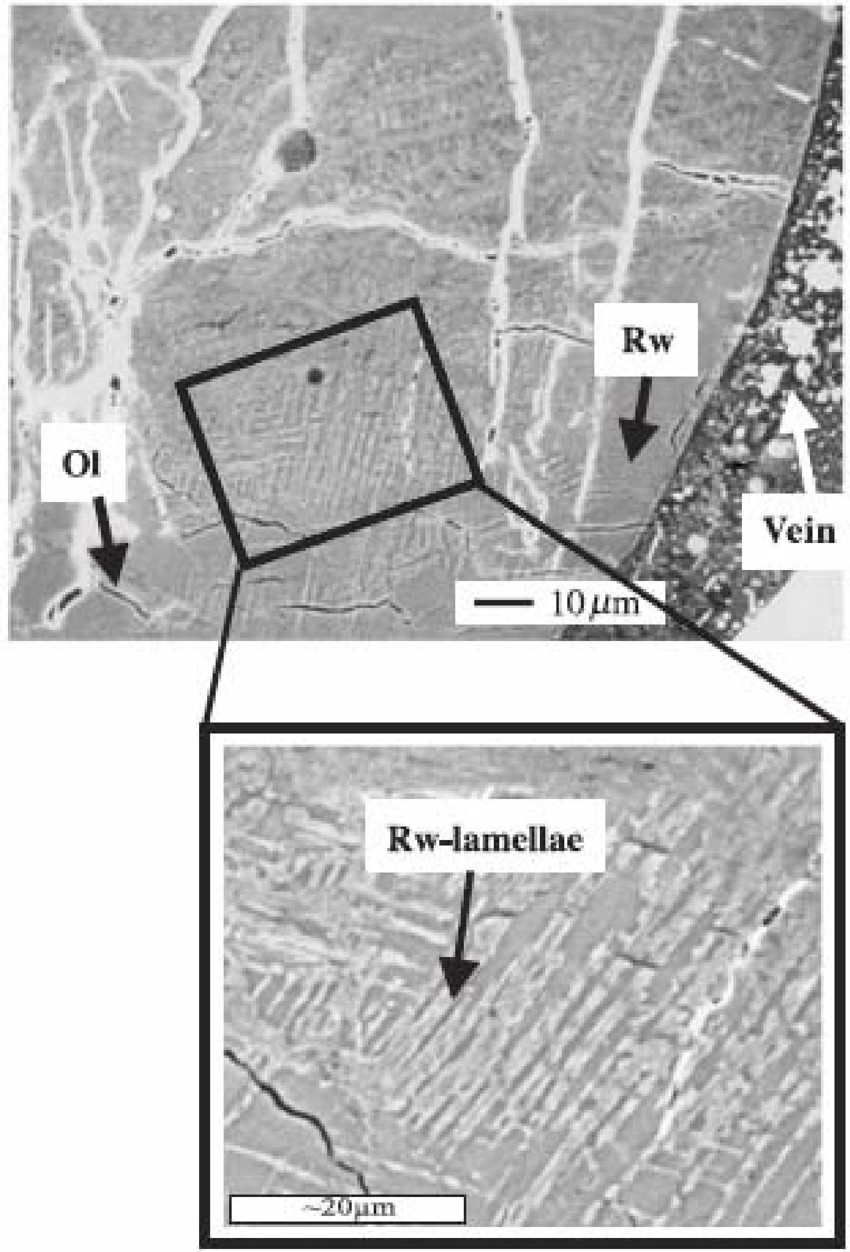


Table 3
Growth rate and duration as a function of temperature

T (*K*)	*V* (m/s)	*t* (s)
1200	1.4E−10	3.63E+03
1300	3.4E−09	1.49E+02
1400	5.2E−08	9.63E+00
1500	5.6E−07	8.93E−01
1600	4.5E−06	1.11E−01
1700	2.8E−05	1.77E−02
1800	0.00014	3.46E−03
1900	0.00062	8.02E−04
2000	0.00232	2.15E−04
2100	0.00761	6.57E−05
2200	0.02238	2.23E−05

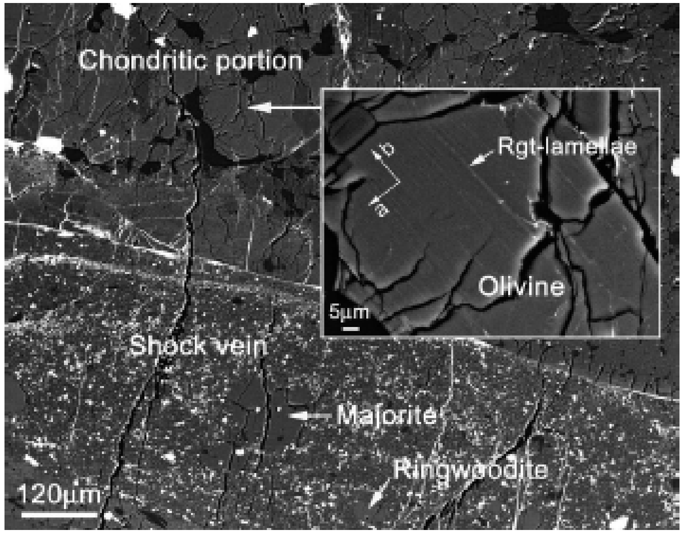
Ringwodite lamellae

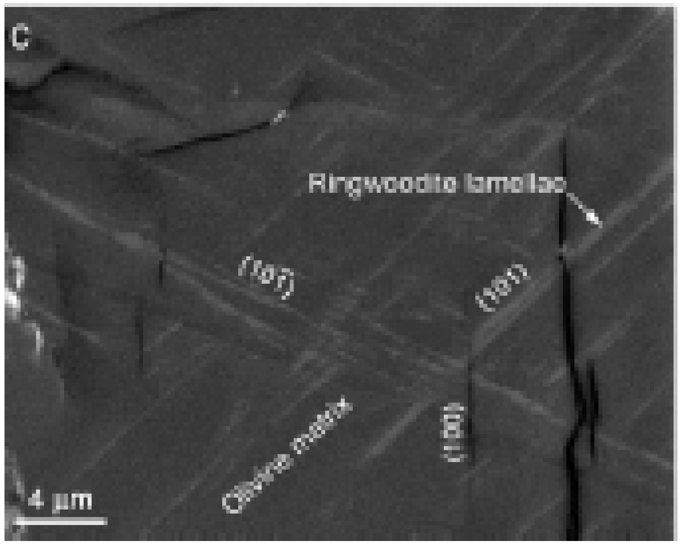
- Ohtani et al. (2004) found ringwoodite lamellae in olivines adjacent to melt veins in L6 chondrite Y791384.
  - Slower growth kinetics
  - Calculated shock pulse of 4s and impacting body > 10 km.

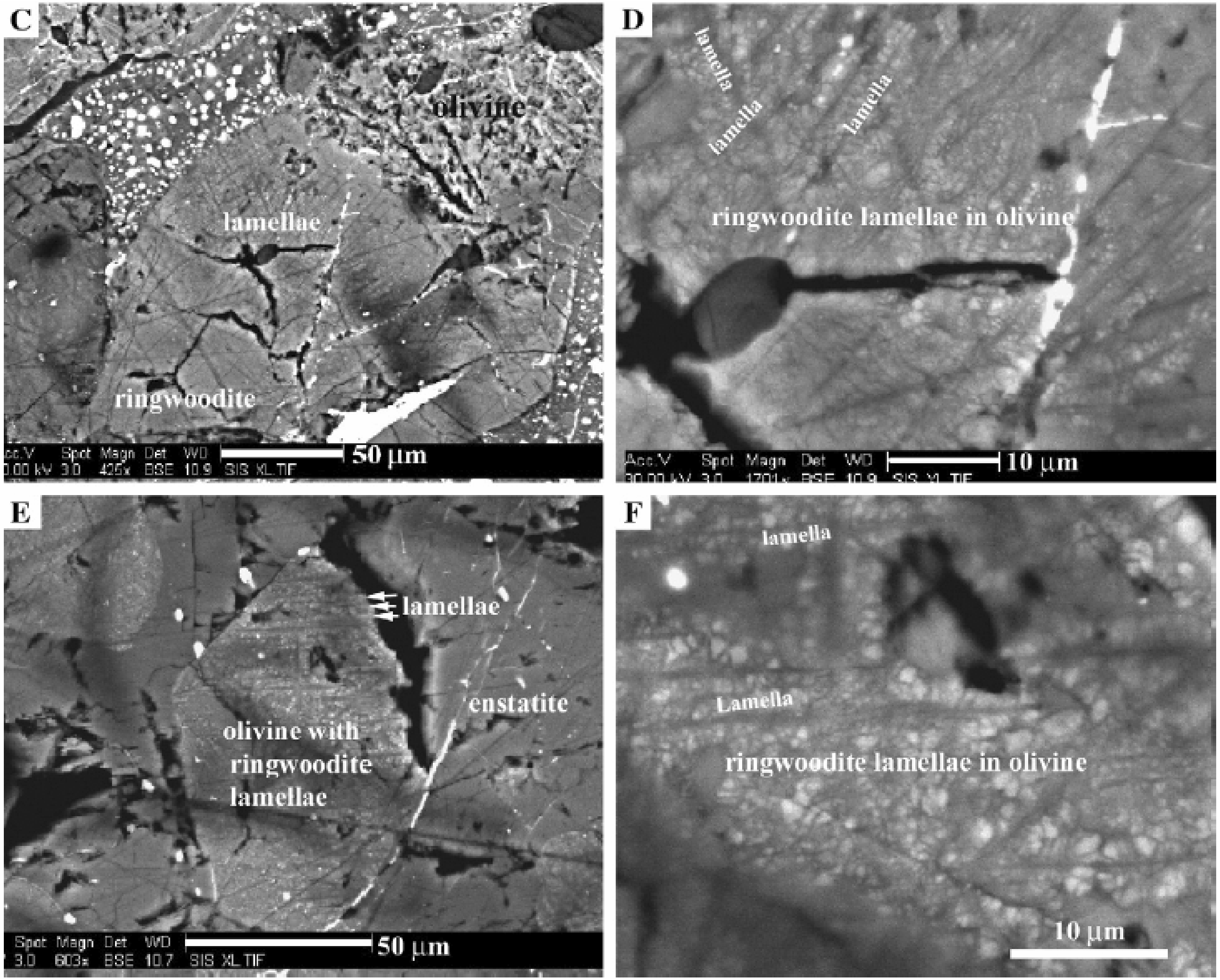


More Lamellae

- Chen et al. (2004, 2006)
  - Transformation by crystallographically controlled lamellae.
  - Argued for shock duration of 3 seconds (Chen et al. 2004)
  - and up to 3 minutes (Chen et al. 2006)
- Beck et al. (2005) used nano-SIMS to measure Mn and Ca profiles of ringwoodite lamellae in Tenham and Zagami.
  - Shock duration of 1s, and impactor of ~ 5km for L-chondrite parent body.
  - 10ms duration and 100m impactor for Mars



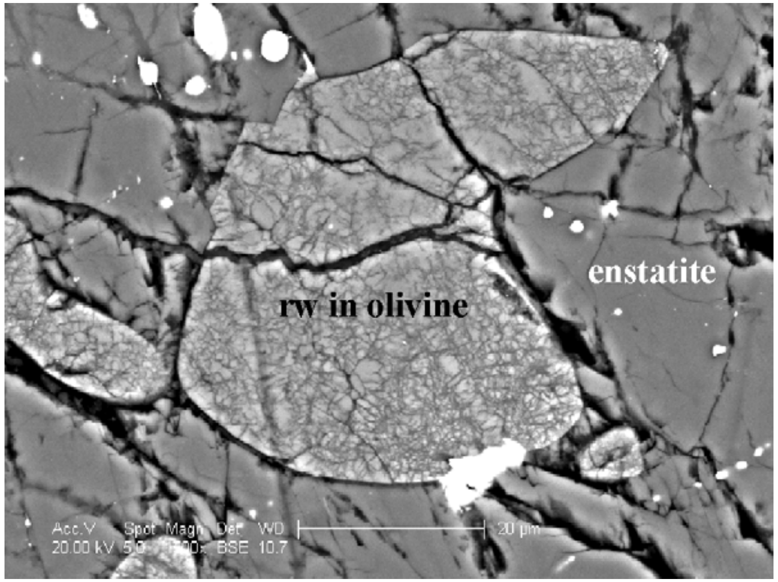


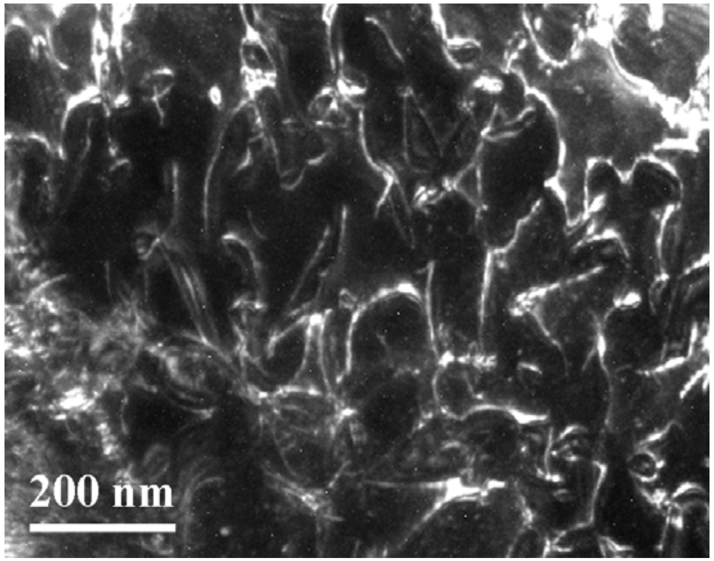


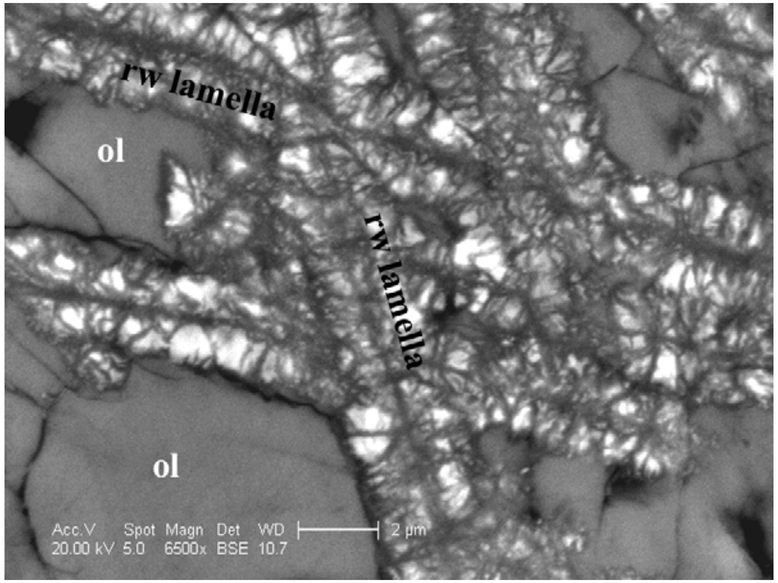
Ringwoodite lamellae in Tenham, Xie and Sharp 2007

Lamellae in Tenham

- Lamellae occur in cooler olivines
  - Paired lamellae suggest nucleation on a planar defect
  - Associate with highly deformed olivine.
  - Transformation may be enhanced by deformation

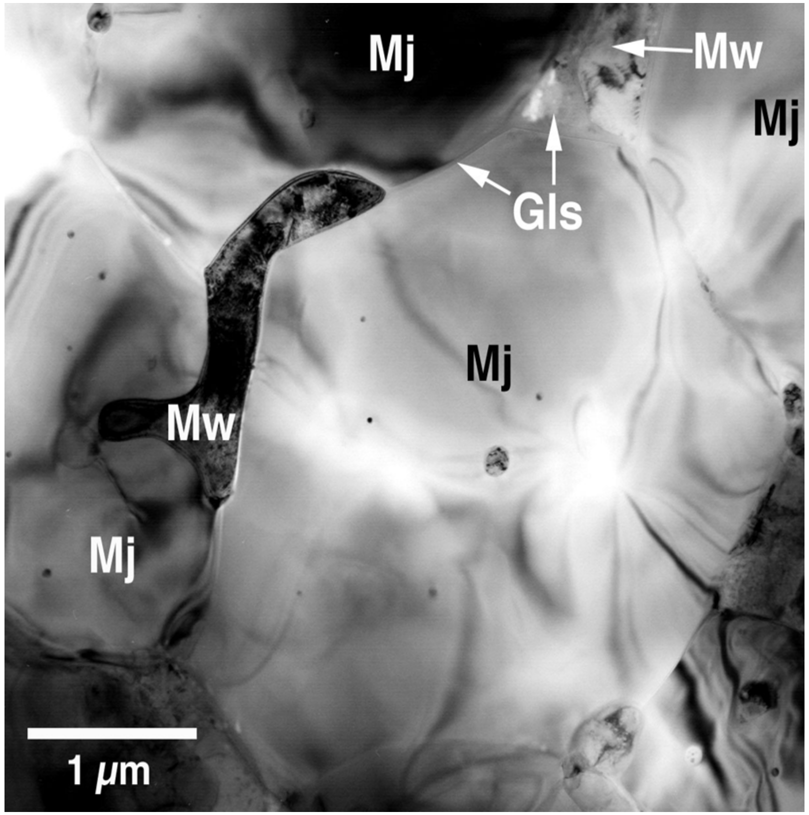


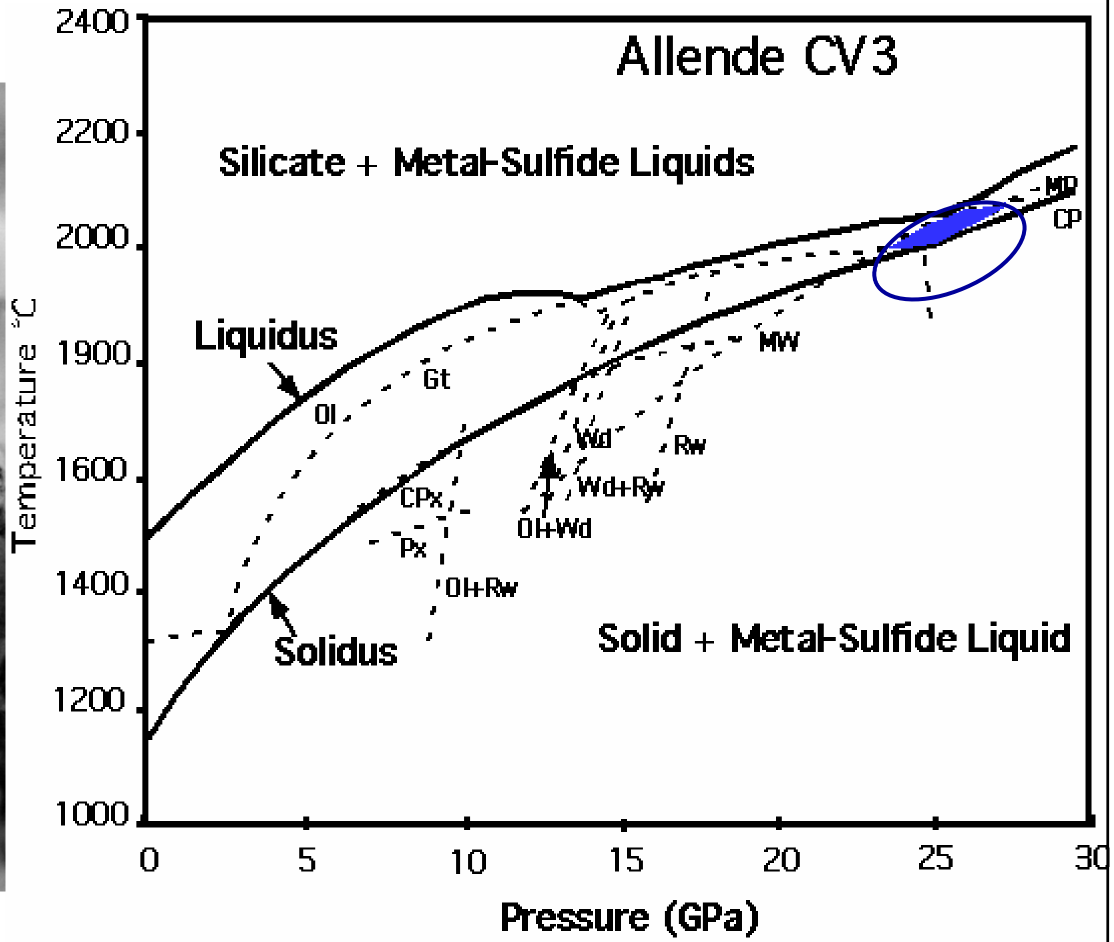




Estimating Crystallization Conditions

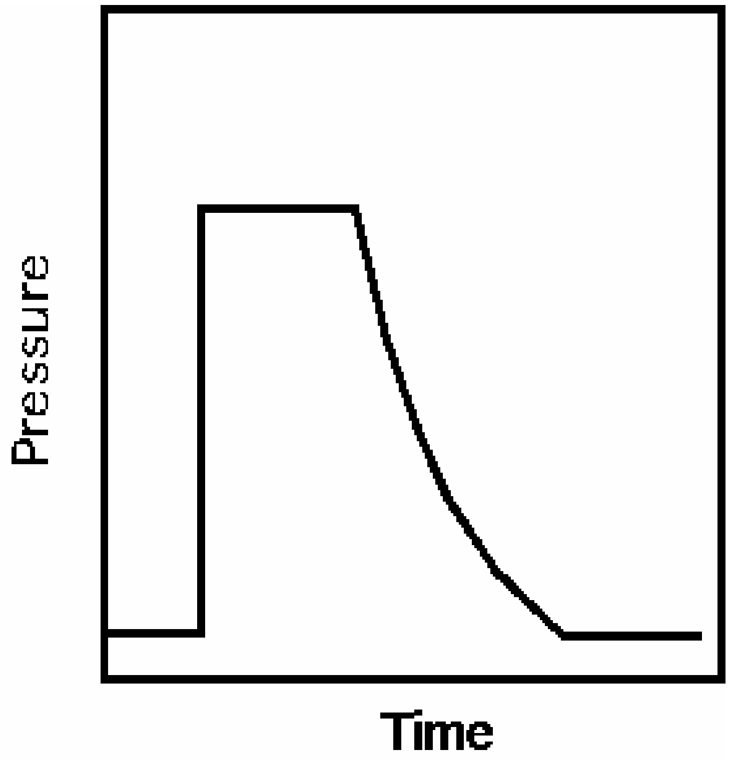
- Majorite-pyrope garnet + magnesiowüstite
- Crystallization at P≈ 23 to 27 GPa and T ≈ 2000 to 2100 ° C (Chen et al. 1996)
  - This is 1/2 the minimum pressure of the S6 Shock Stage of Stöffler et al. (1991)





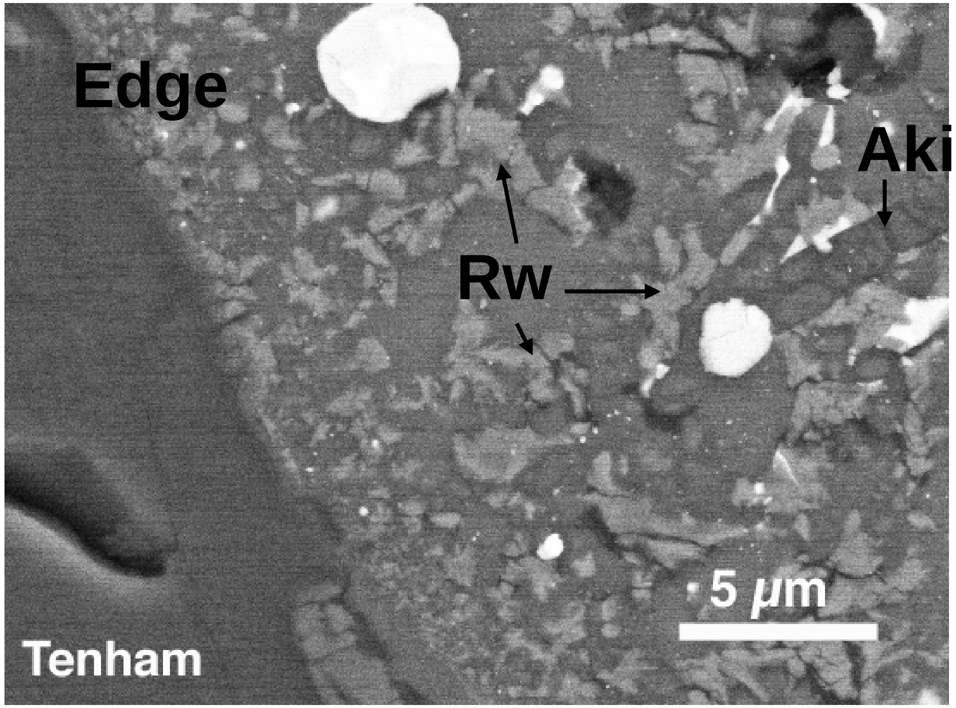
When do Melt Veins Crystallize?

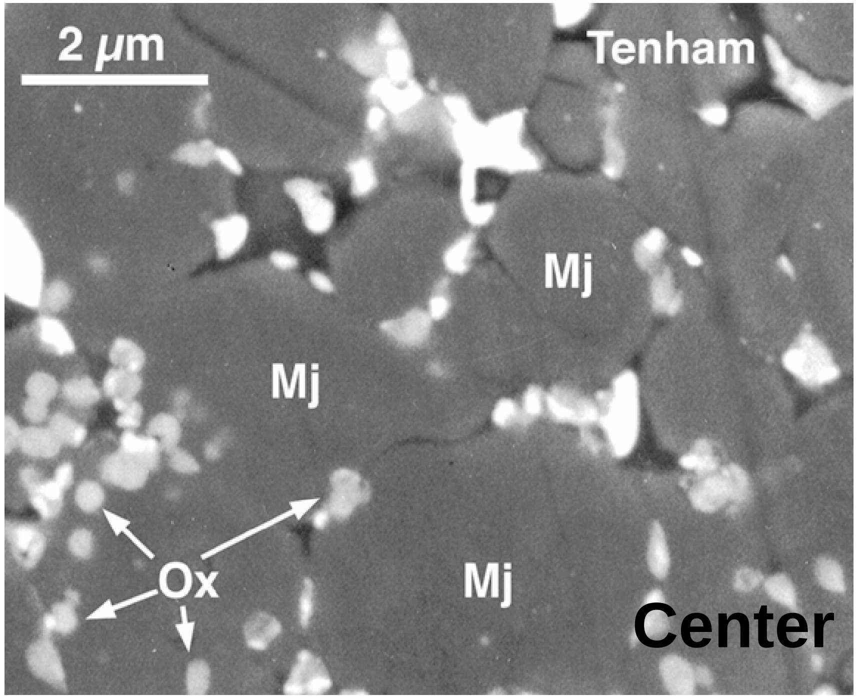
- Crystallization at equilibrium shock pressure?
  - Crystallization pressure should be nearly constant across a melt vein or pocket
  - Crystallization pressure is the shock pressure!
- Crystallization during adiabatic pressure release?
  - Crystallization starts at melt vein margins and ends in the center
  - Crystallization pressure should decrease from edge to center.



Tenham S6

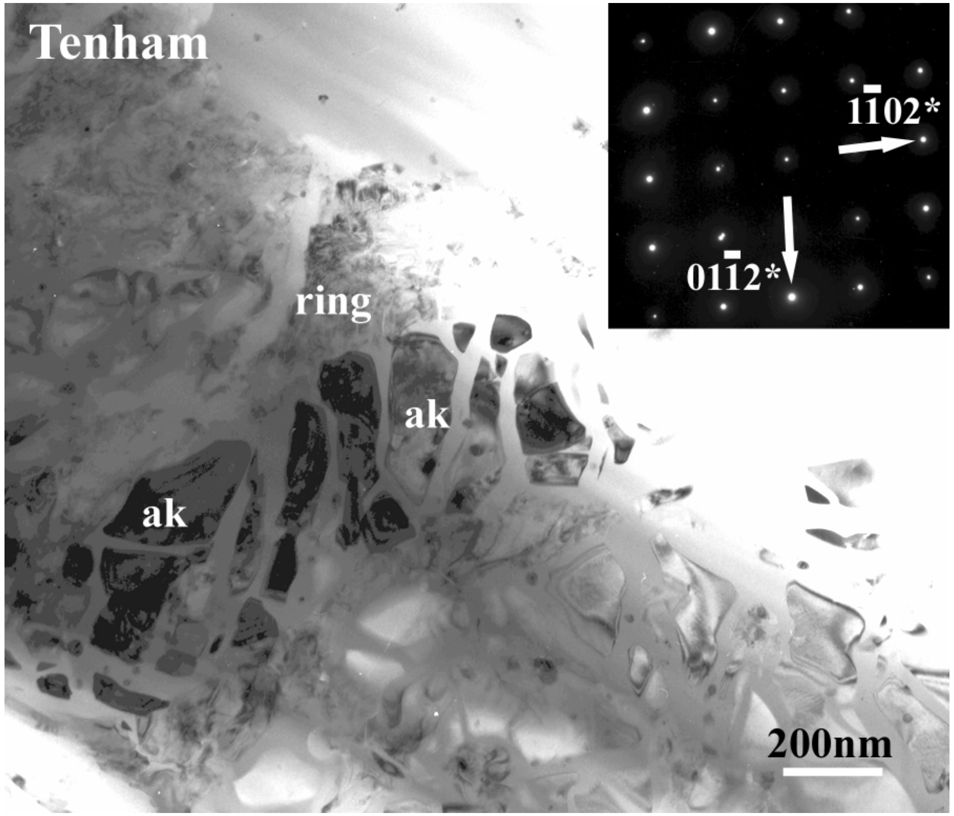
- Melt-vein texture and assemblage depends on position in the vein

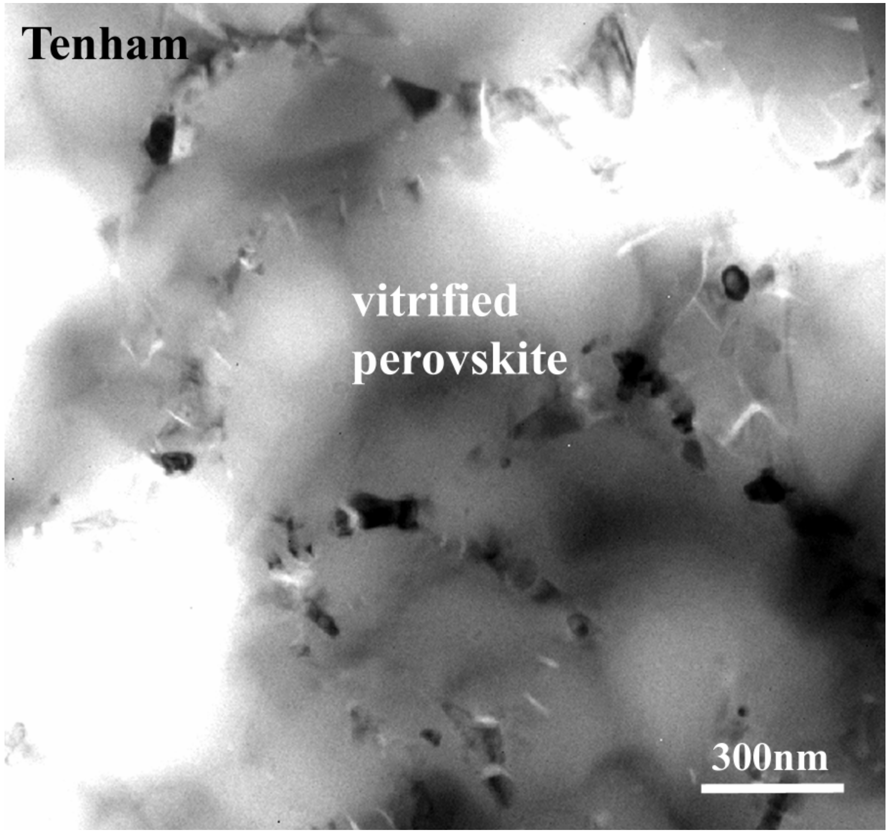




Tenham Vein Edge

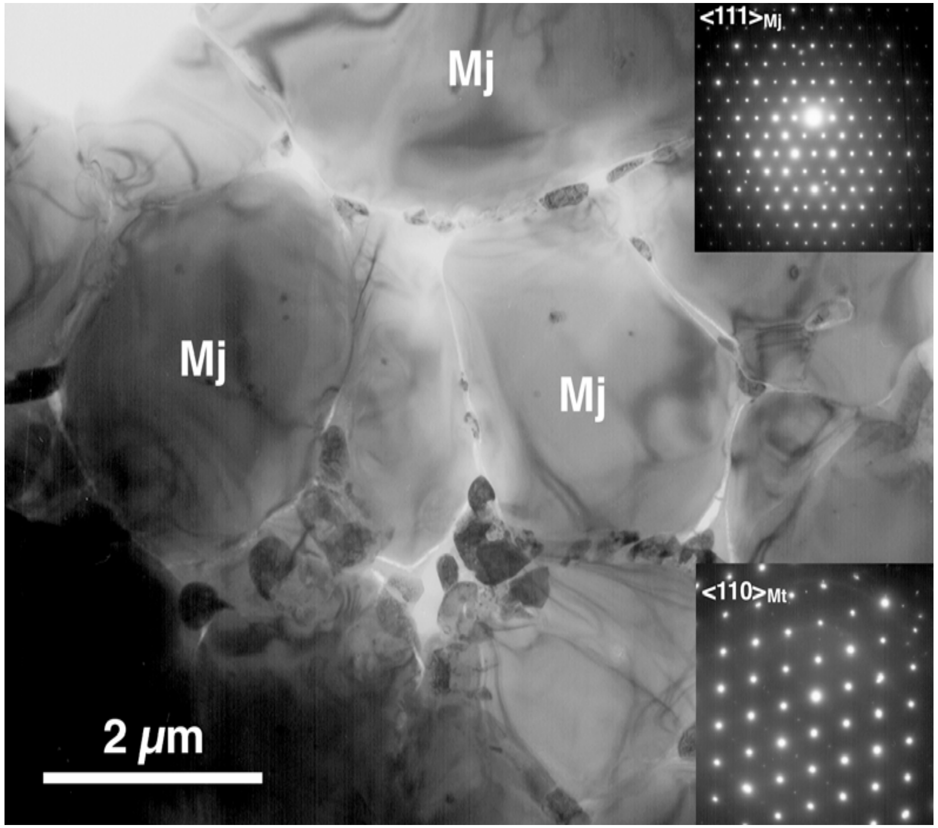
- $(Mg,Fe)SiO_3$-ilmenite “akimotoite” + ringwoodite
- Vitrified $(Mg,Fe)SiO_3$-perovskite + ringwoodite

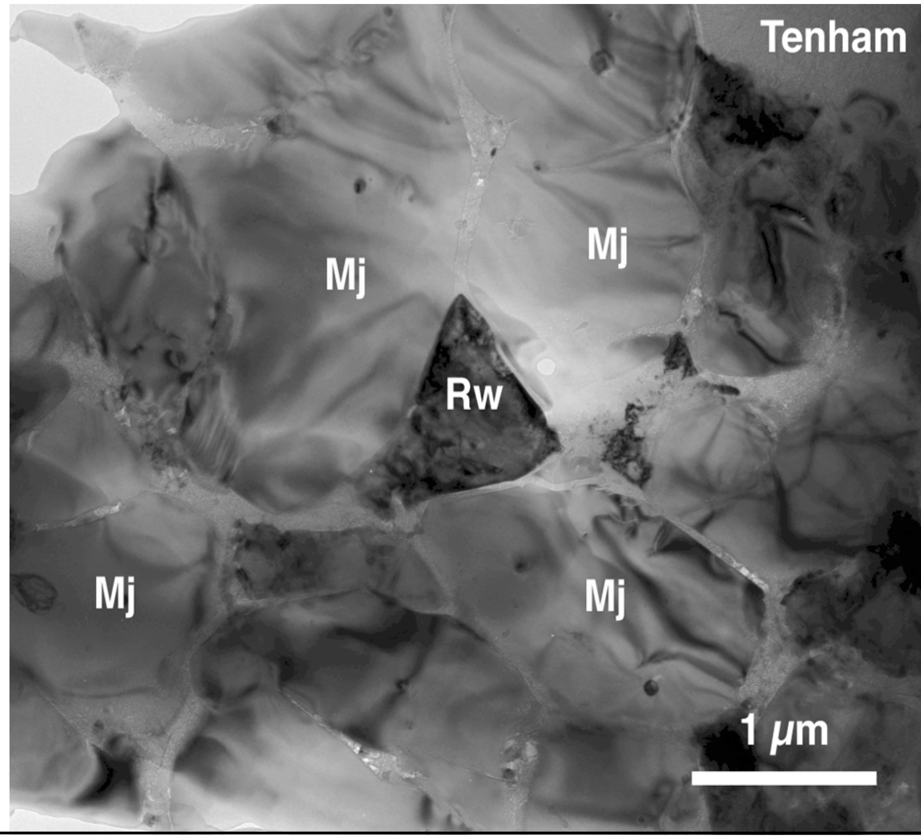




Tenham Vein Center

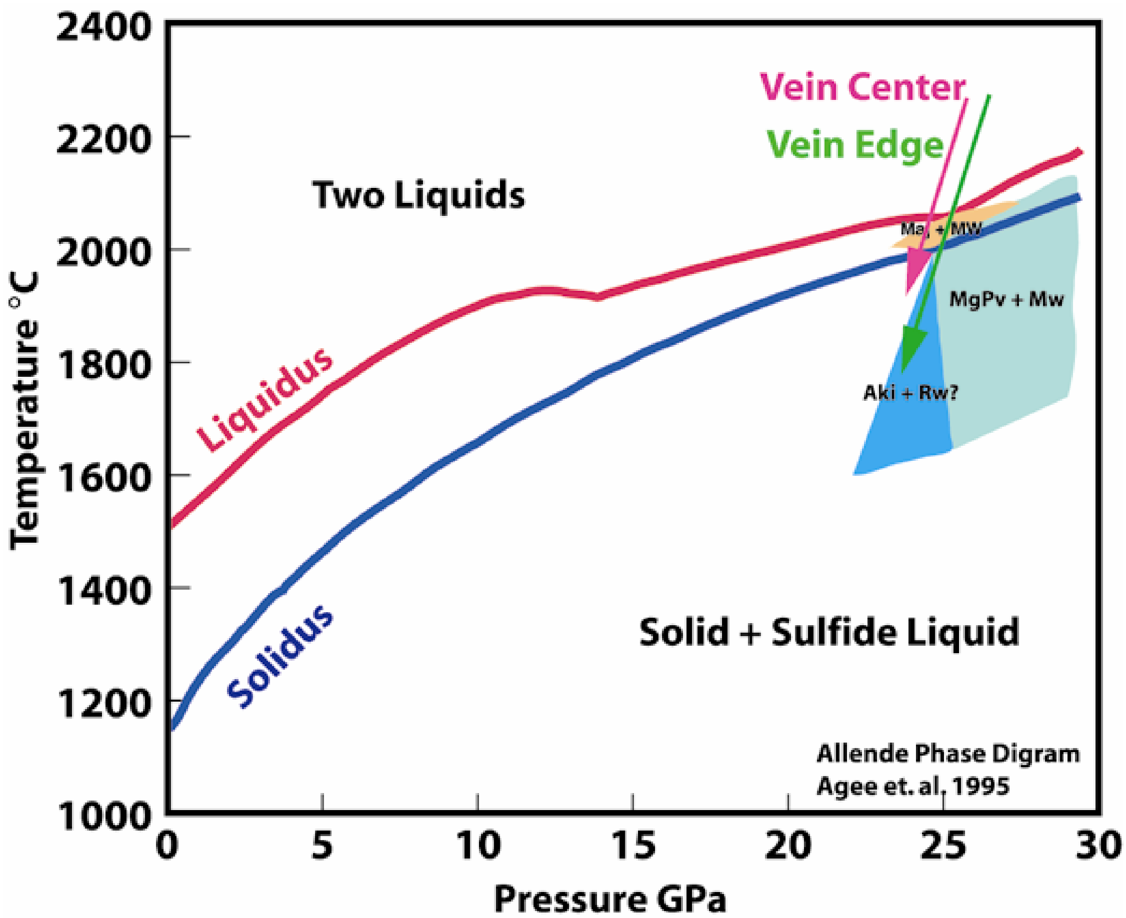
- Predominantly majorite + magnesiowüstite (partially altered to magnetite)





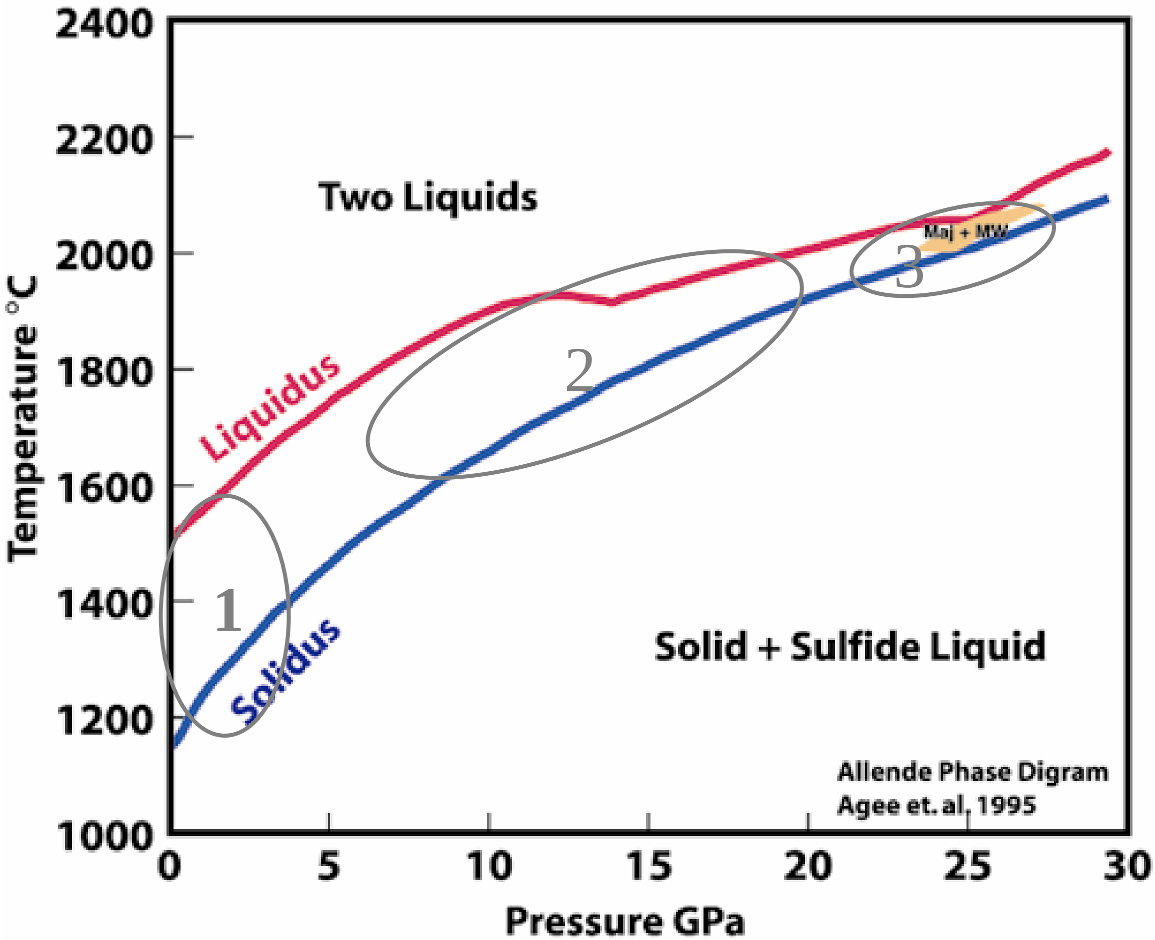
Tenham Crystallization

- Vein Center:
  - majorite + magnesiowüstite P ≈ 23 - 27 GPa
  - majorite + ringwoodite P ≈ 18 - 24 GPa
- Vein Edge
  - Akimotoite + vitrified perovskite + ringwoodite
  - Akimotoite-perovskite boundary at ≈ 25 Gpa
  - Super cooled liquid?



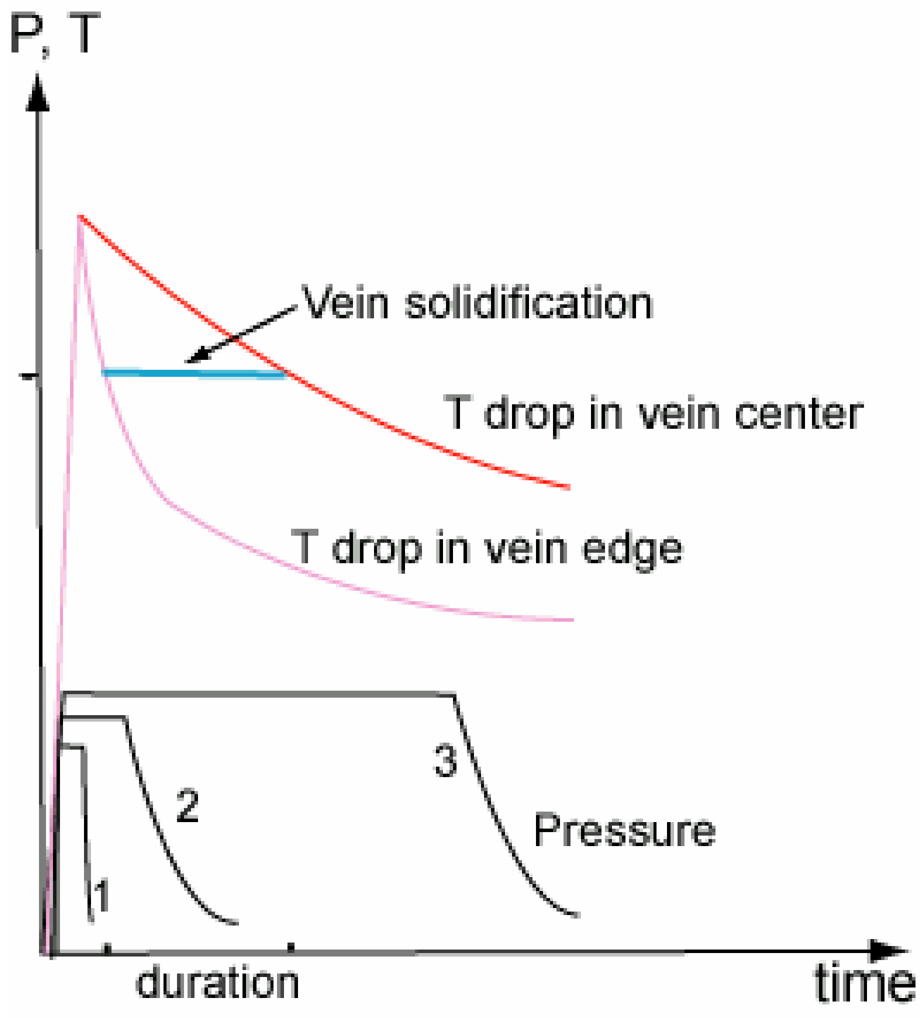
Crystallization Pressures

- Three pressure regimes.
  1. Post shock crystallization
  2. intermediate pressures 10 - 20 GPa
  3. 3 S6 23 -27 GPa



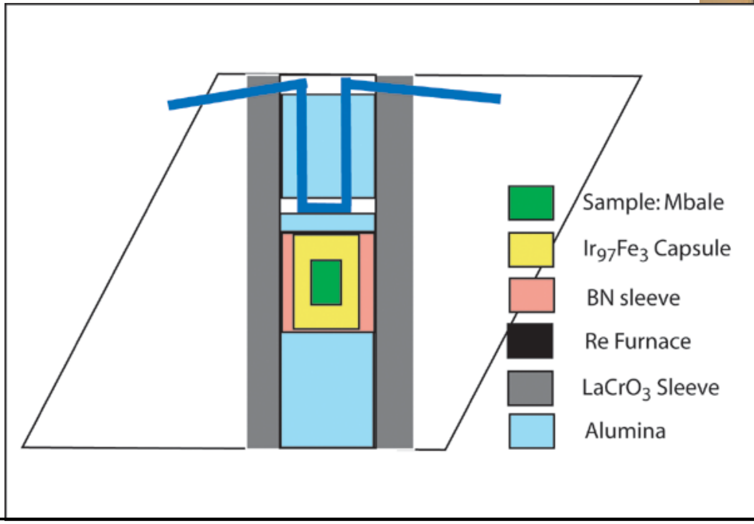
When do Melt Veins Crystallize?

- Depends on duration of quench vs. duration of pressure pulse.
  - 1) short P pulse - after release
  - 2) medium P pulse - during release
  - 3) long P pulse - equilibrium shock pressure



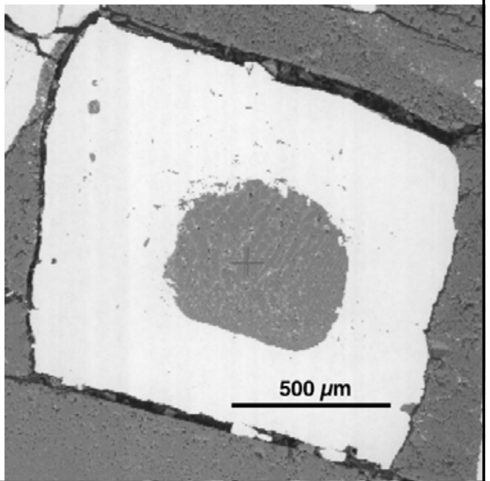
Super-liquidus quench experiments

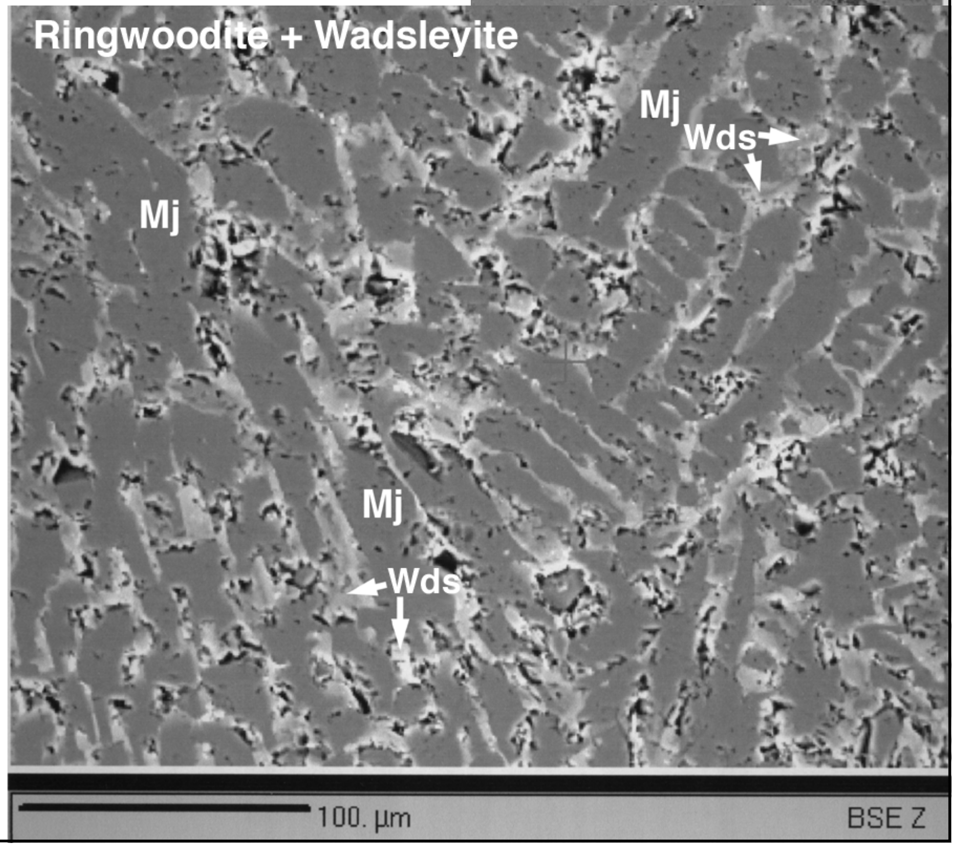
- Experiments at the ANU RSES and at ASU
- COMPRES 8/3 assembly
  - $Ir_{97}Fe_3$ and graphite capsules
  - Re foil furnaces
- P: 17 - 23 GPa and T: 2020 - 2440 ° C
- Quench by ramping power down or cutting power
- Phase ID by Raman Spectroscopy

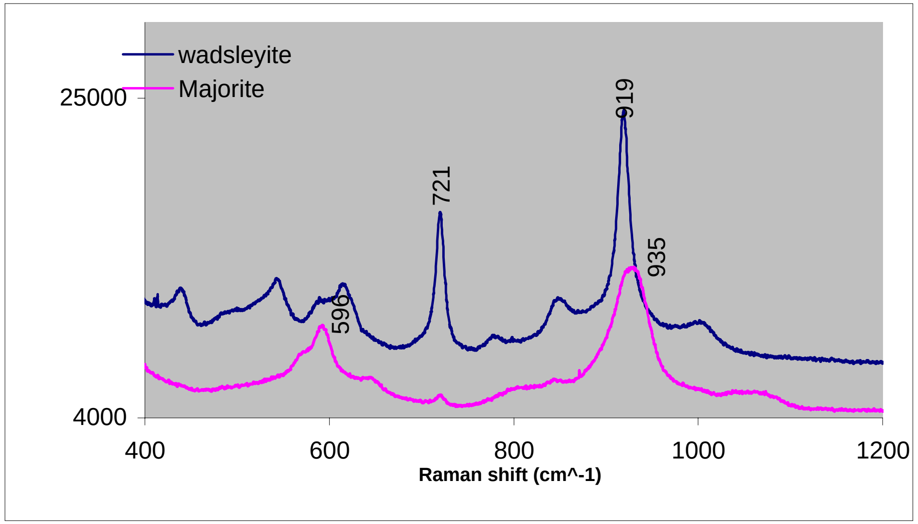


Majorite: 19.4 GPa

- 2360 ° C for 24s
  - Fast quench
- Majorite + wadsleyite
- Garnets up to ~ 50 μm long

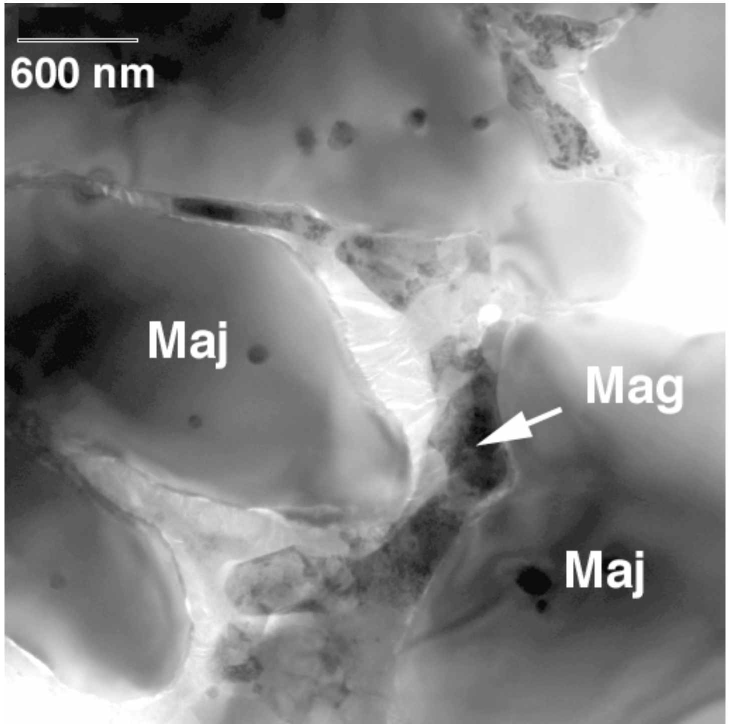


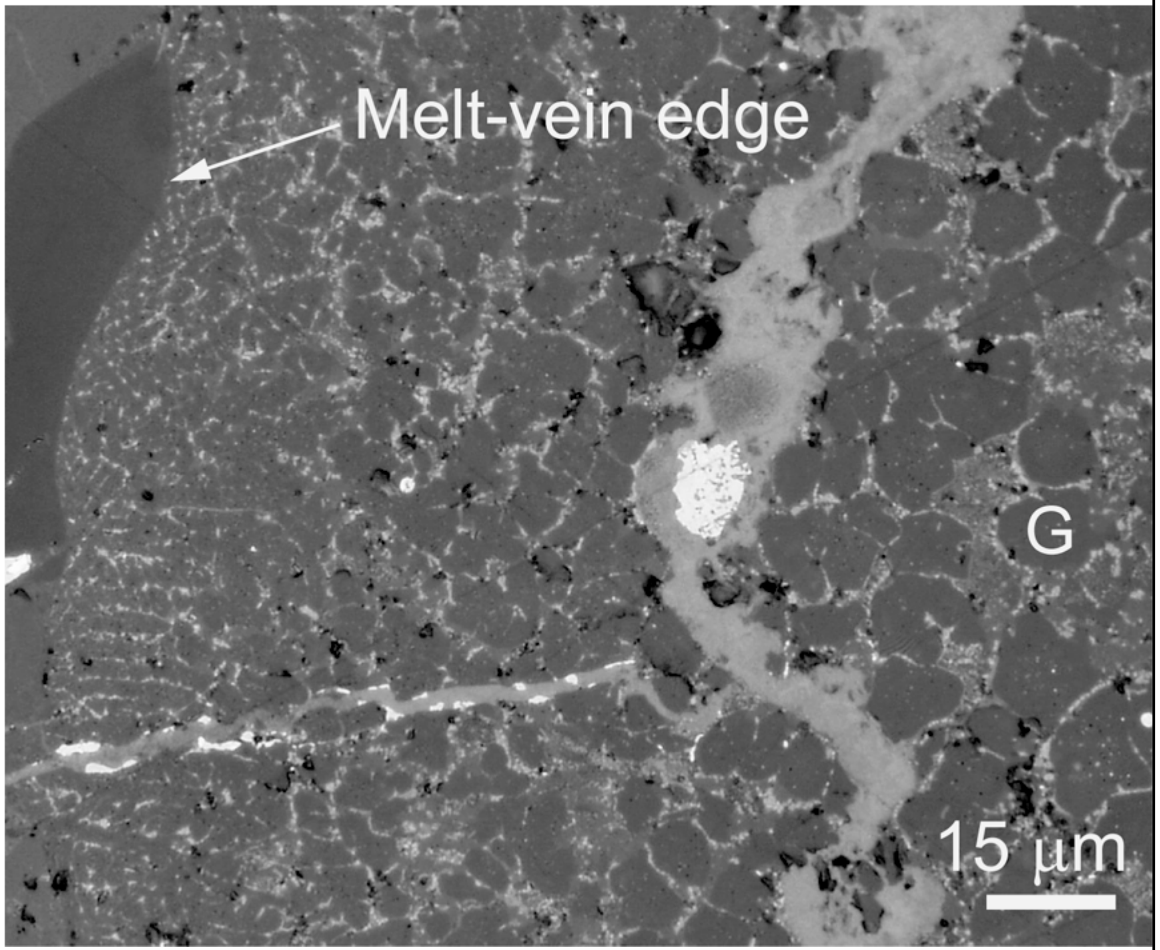




Majorite in melt veins

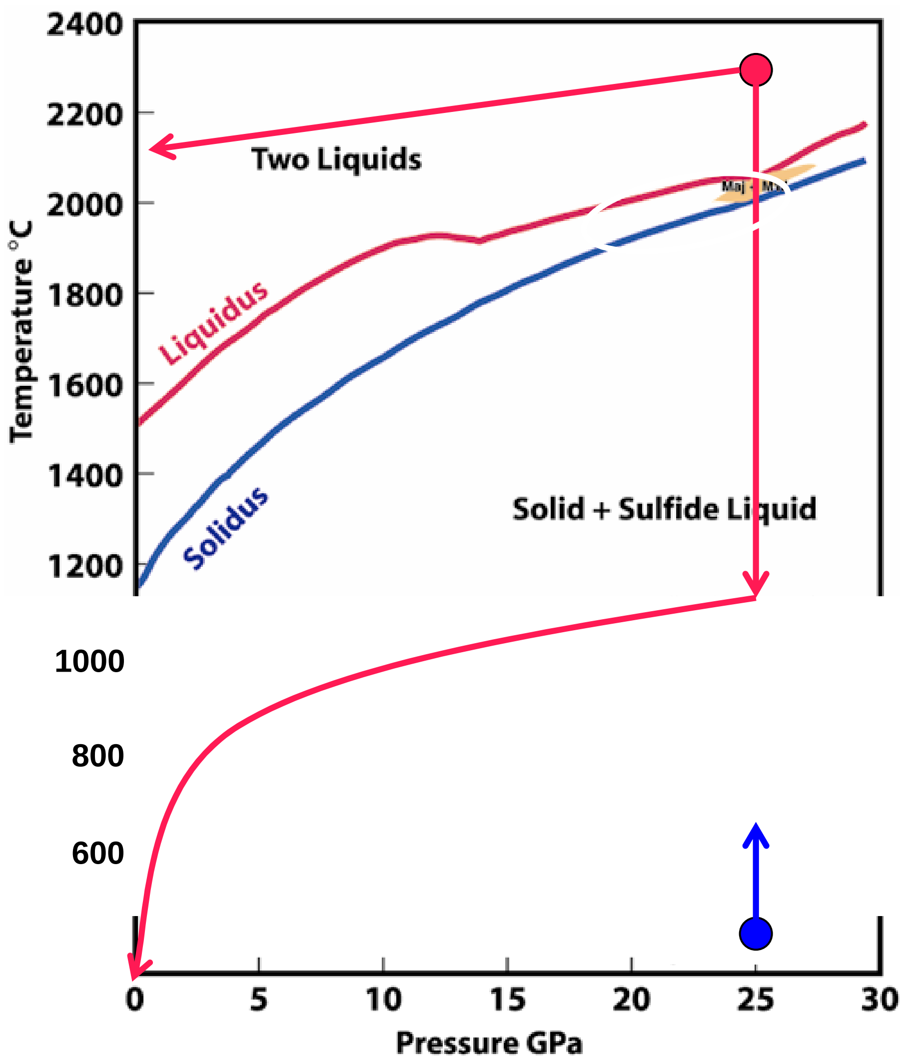
- Majorite + magnesiowüstite are very common in shock veins from L6 S6 chondrites
- RC 106: dendritic majorite near edges and large equant garnets in the interior
  - P ~ 20-23 GPa





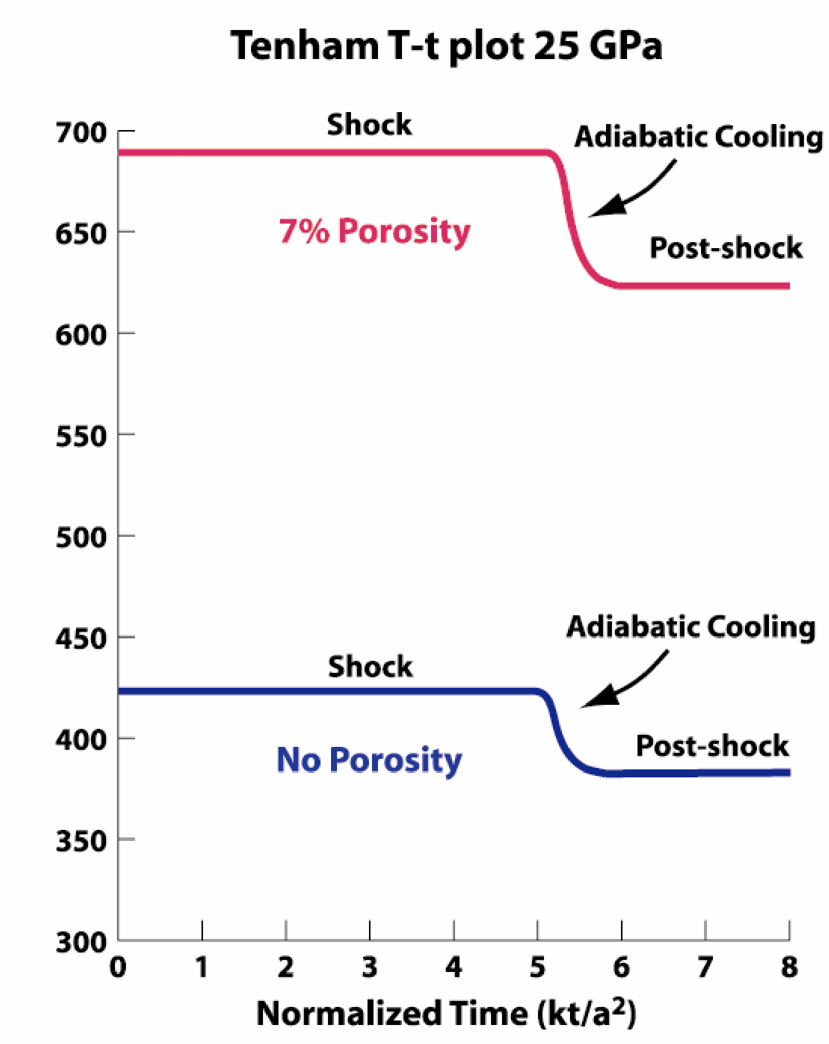
Melt-vein quench

- Melt vein assemblages in L6 S6 chondrites crystallized at 18 - 25 GPa.
  - What is the P-T path?
- For P = 25 GPa and 7% porosity, bulk shock T is ~ 400 ° C
- Adiabatic decompression of melt cools by only ~ 170° C
- Melt vein quench is driven by thermal conduction.
- If the pressure pulse was long (> 10s to 100s of ms), then quench would be nearly isobaric.



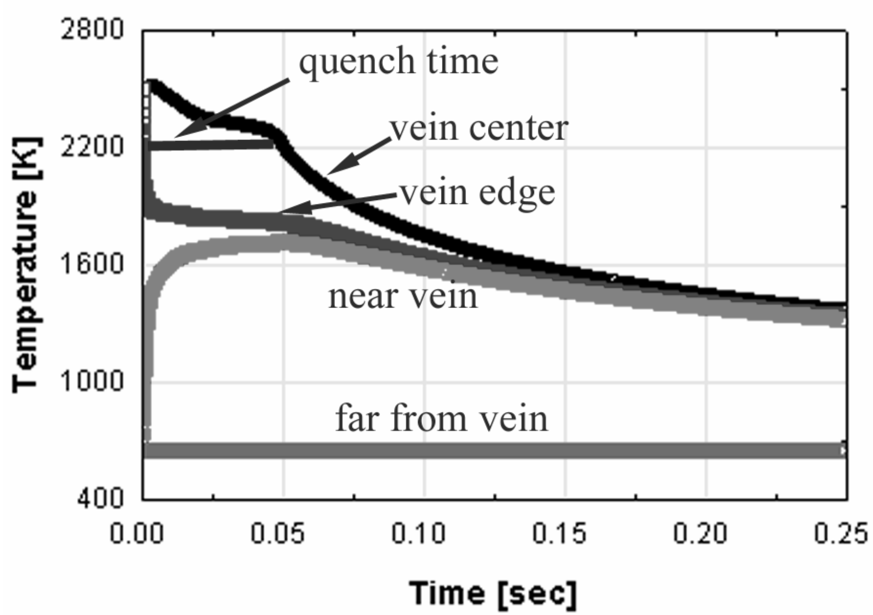
Shock and Post-Shock Temperatures

- Post-shock temperatures calculated from waste heat
  - C_p = 1J/gK
- Shock temperatures calculated using adiabatic compression
  - $T_s \sim T_o e^{\Gamma(Vo-V)}$
  - Γ = 0.5. 1, and 2
- Shock P = 25 Gpa and Γ = 1
  - Shock T = 423 & 687 K
  - Post-Shock T = 383 & 622 K



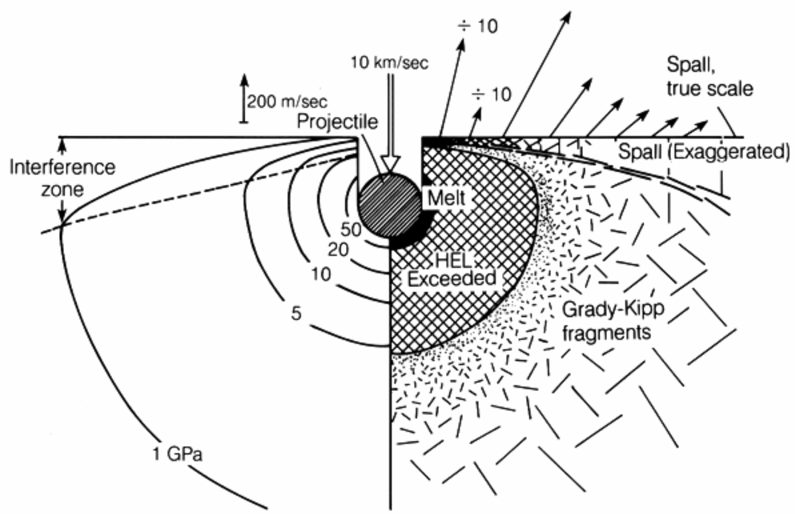
Modeling Melt-Vein Quenchin Tenham

- FEHT calculations of melt-vein cooling
  - Melt T_0 = 2700 K
  - Host T0 = 660 K
- Vein center quenches in 47 ms
  - Minimum duration of the shock pulse
- Silicate-perovskite decomposes at 973 K
  - This requires ~ 500 ms.



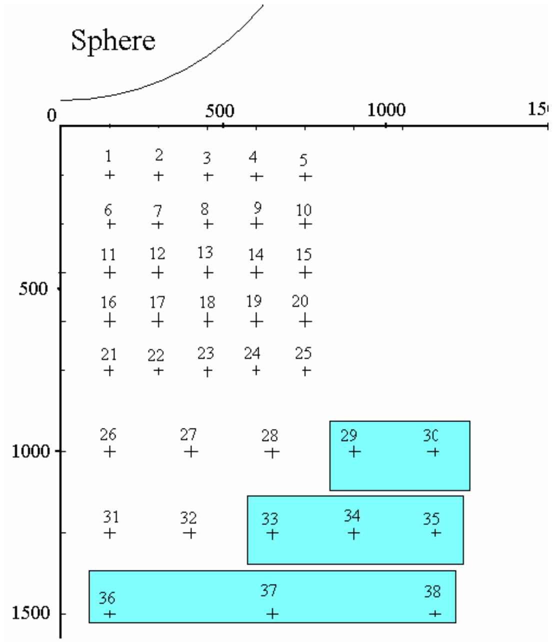
Imactor Size

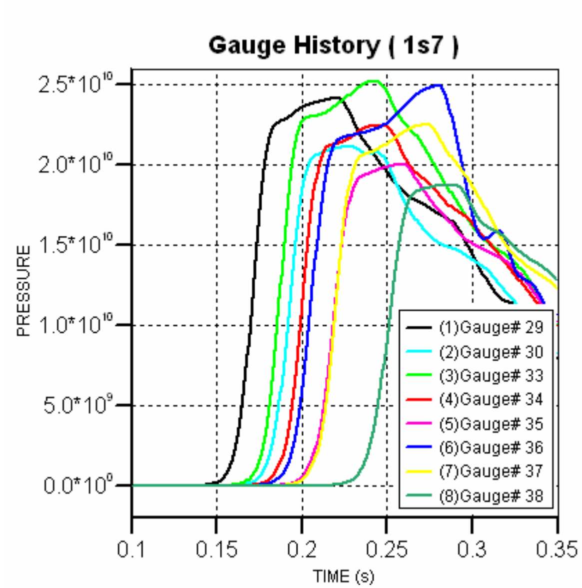
- L chondrite parent body impacted at 500 Ma
  - (Bogard 1995)
- What was the size of impacting body?
  - Shock duration estimates from 50 ms to 3 m.
  - Best estimates > .5 s to 4 s
  - Flat plate approximation gives size from 2 to 10 km.
  - However, reasonable geometries would require larger bodies.



Impact velocity

- Melt-vein crysallization gives shock pressures of 18 - 25 Gpa.
  - Phase diagrams not well calibrated, pressure could be lower.
- If samples came from impact site (surface) impact velocity is 2 km/s. (Xie et al. 2006)
- Higher velocity ~5 km/s is likely with excavation from depth.





Conclusions

- High-pressure minerals produced by crystallization of silicate melt and by solid-state transformations.
  - Use of transformations calibrated with shock experiments overestimates pressure.
  - Kinetics of transformations make poor candidates for quantitative pressure calibration using phase equilibrium data.
  - Kintetic data can be used to constrain shock duration if P-T conditions are known from melt veins.
- Melt-vein crystallization provides better constraints on shock pressure.
  - Shock veins crystallize at modest pressures P ~ 25 GPa
  - About half the lower bound for S6 Stöffler et al (1991)
  - Shock veins cool predominatnly by thermal conduction into the surrounding matrix.
  - Mineralogy and thermal modeling can provide P-t histories of veins
    - Large veins give long pulse history
    - Vein edges and small veins should record the shock pressure

More Conclusions

- No chondrites shocked to P > 25 Ga?
  - Implies low impact velocities or samples came from deep below the impact.
- Where are the really highly shocked chondrites?
  - Need to look for annealed or melted highly-shocked samples