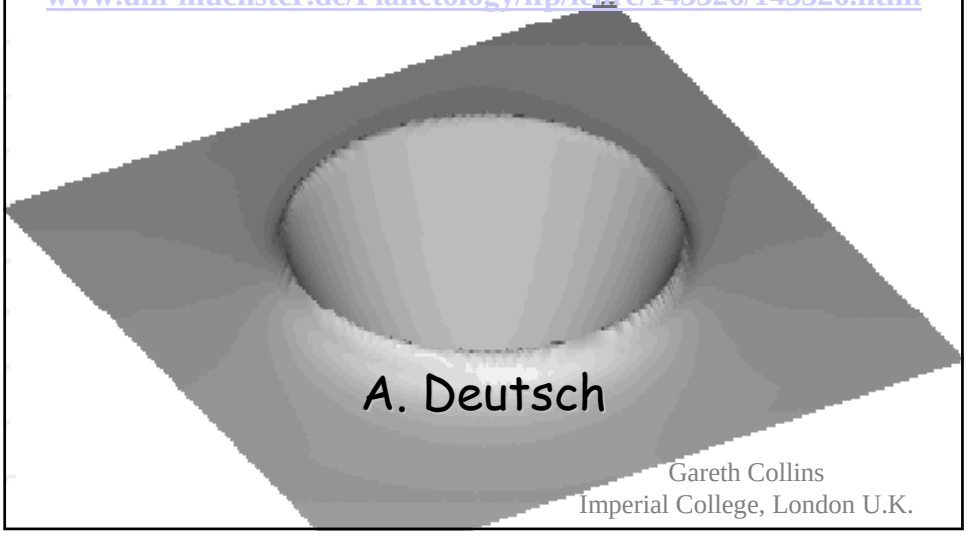
BSc – Impaktprozesse SS 14

User: 143326 **Passwort: 14Impakt**

www.uni-muenster.de/Planetology/ifp/lehre/143326/143326.html



A. Deutsch

Gareth Collins
Imperial College, London U.K.

Shock wave

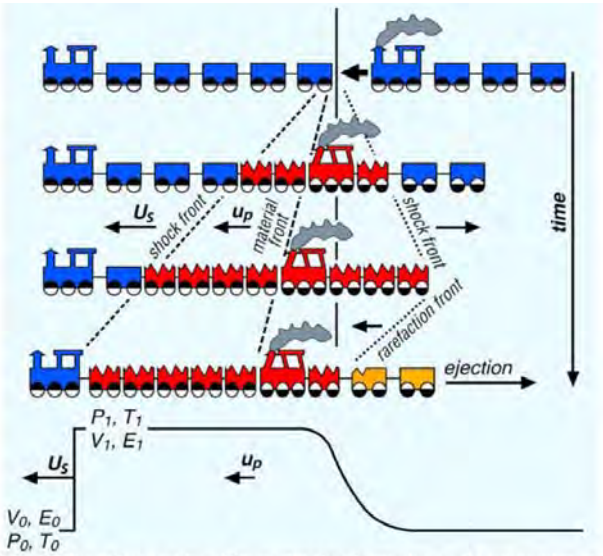
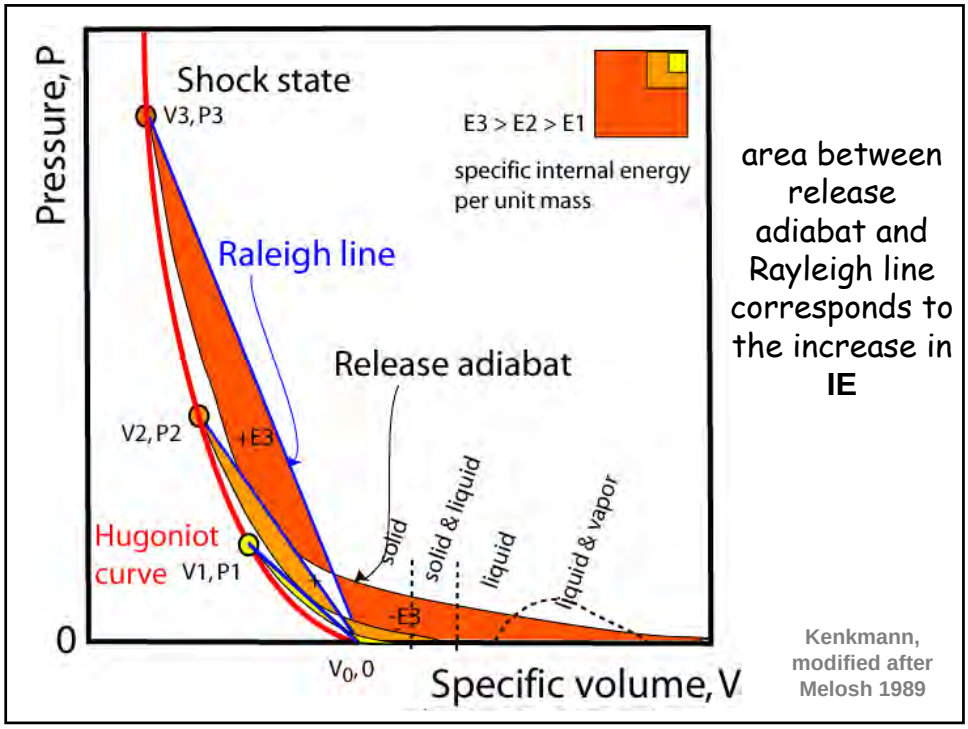


FIGURE 1. Sketch of the collision of two trains, illustrating the formation and propagation of shock and rarefaction waves (modified after Langenhorst 2002). P, T, E, and V are pressure, temperature, internal energy, and volume in the uncompressed (*0*) and compressed (*1*) matter.

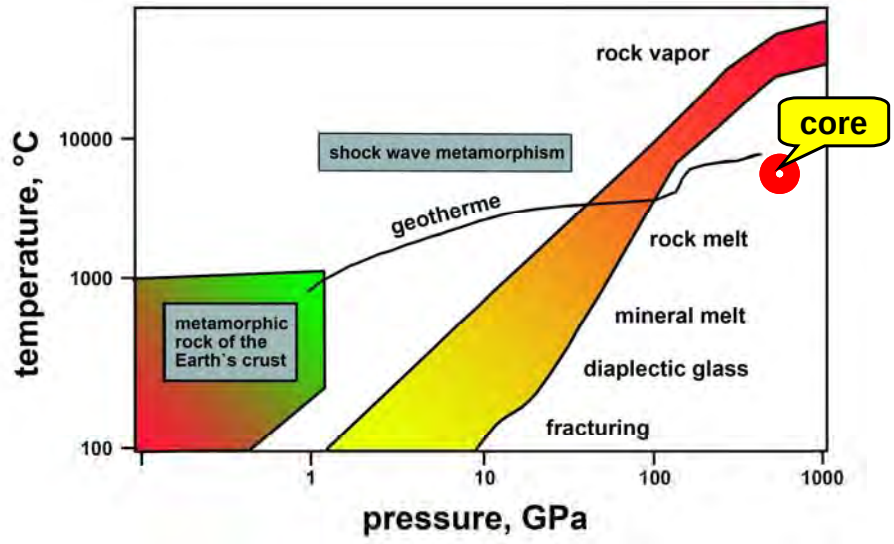
Langenhorst & Deutsch 2011



area between release adiabat and Rayleigh line corresponds to the increase in **IE**

Kenkmann, modified after Melosh 1989

Impact metamorphism



extreme pressure – temperature - strain rates

Impact metamorphism

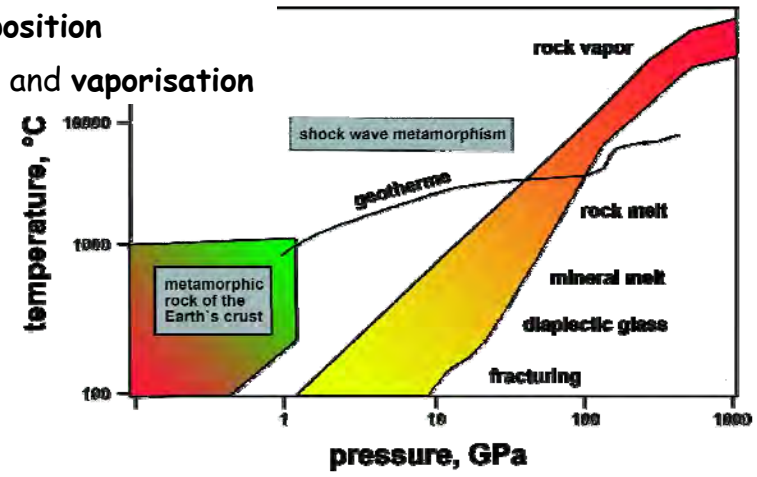
strain rates

- strain: measure of the amount of deformation that occurs when an object is placed under stress
- strain rate: change in strain over the change in time
- deformation caused by stress can be fully reversible (elastic)
  or (above the Hugoniot elastic limit HEL) permanent (plastic)
- earthquakes <10 s-1
- during shock compression strain range from 10^6 to 10^9 s-1

extreme - strain rates

"Shock effects"

- **deformation**
- **phase transformations**
- **decomposition**
- **melting** and **vaporisation**



Shock & post-shock effects

- **deformation**
- **phase transformations**
- **decomposition**
- **melting** and **vaporisation**

No single mineral shows all listed effects, as the shock behavior of a mineral largely depends on its composition and crystal structure.

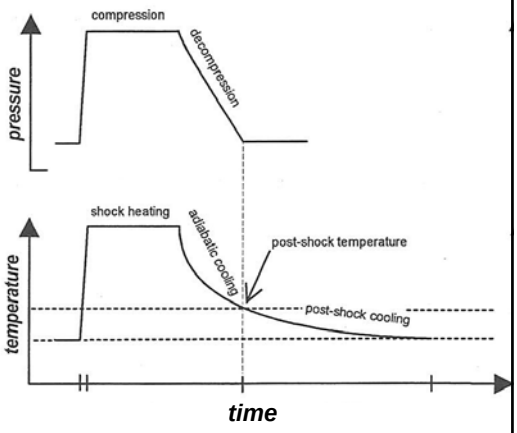
Shock & post-shock effects

- **deformation**
- **phase transformations**
- **decomposition**
- **melting** and **vaporisation**

Deformation and transformation features are caused by the transient shock compression.
Decomposition, melting and vaporisation, however, are temperature-dominated effects that develop during unloading to ambient pressure.

Shock & post-shock effects

- **deformation**
- **phase transformations**
- **decomposition**
- **melting** and **vaporisation**



Deutsch & Langenhorst 1998

Shock effects: deformation

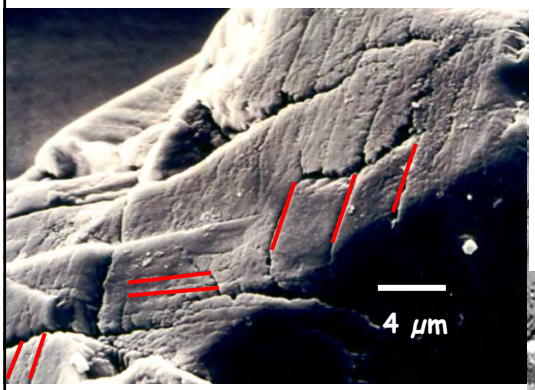
- dislocations
  linear lattice defect -> TEM
- feather features -> exact nature not yet determined
- planar microstructures
  PF – planar fractures
  PDF – planar deformation lamellae
- mechanical twins
- kink bands
  (resembles chevron folding in sedimentary rocks)
- mosaicism – optical phenomenon reflecting the internal fragmentation of a crystal into small domains

Shock effects: deformation

- planar microstructures
  - **PF – planar fractures**
  - PDF – planar deformation lamellae

PF form sets of parallel open fissures with a typical spacing of about 20 - 30 μm.
They are low-pressure (10-20 GPa) phenomena with an appearance that is identical to that of cleavage.
In quartz, PF are particularly diagnostic for an impact because quartz does not usually possess cleavage planes.

Shocked minerals – K-Pg boundary



zircon with planar fractures (PFs)

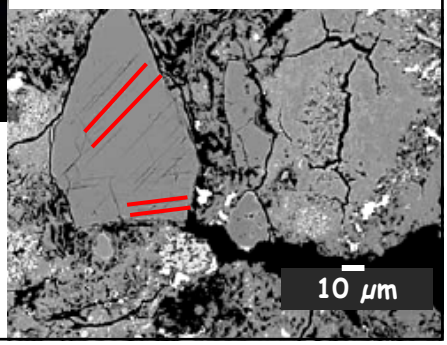
Baton Rouge

B. Bohor, USGS Denver

quartz with planar deformation features (PDFs)

ODP 207

Schulte et al. 2009



Shock effects: deformation

- planar microstructures
  - PF – planar fractures
  - **PDF – planar deformation lamellae**

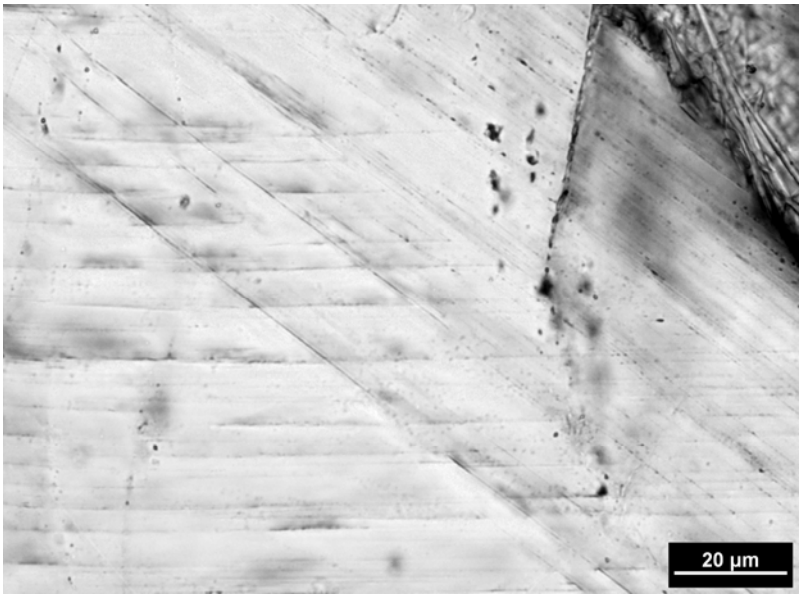
PDF are thin (< 1 μm) amorphous lamellae with the same composition as the host crystal, developed along rational crystallographic planes.

PDF occur in many silicates but are most typical for quartz and feldspars.

Orientation of PDF in quartz is sensitive to pressure (shock barometer at pressures between 15 and 35 GPa).

Annealing and alteration yield "decorated" PDF that preserve the original orientation.

Quartz – PF & PDF



Shocked and annealed gneiss bomb - Popigai

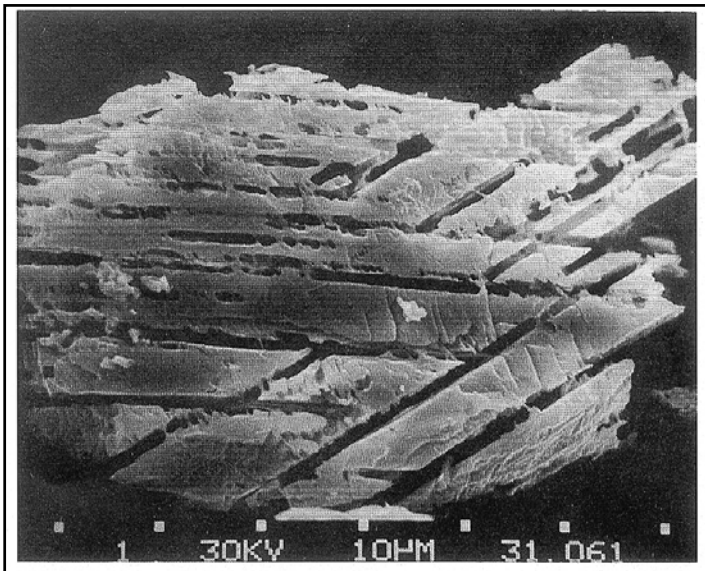
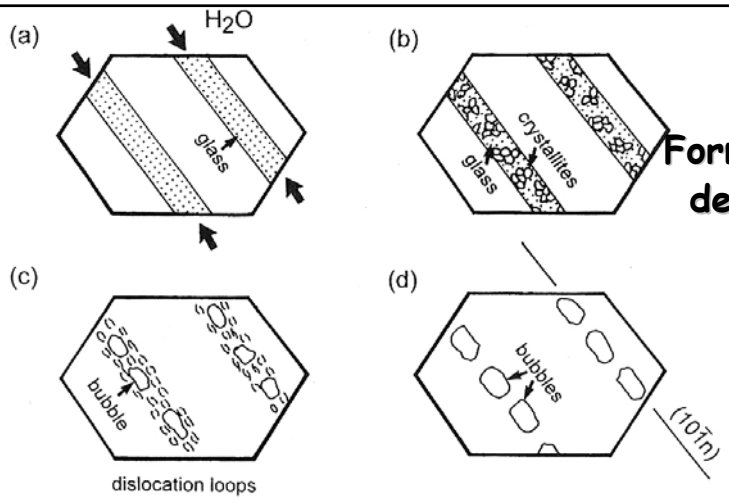


Fig. 6. SEM photograph of shocked quartz grain from the K–T boundary claystone at Brownie Butte, Montana, showing multiple sets of planar features (HF etched). Distance between scale marks = 10 μm. From Bohor et al. (1984).

Impact metamorphism of SiO_2

HF etched qtz grain with planar elements

K/T boundary

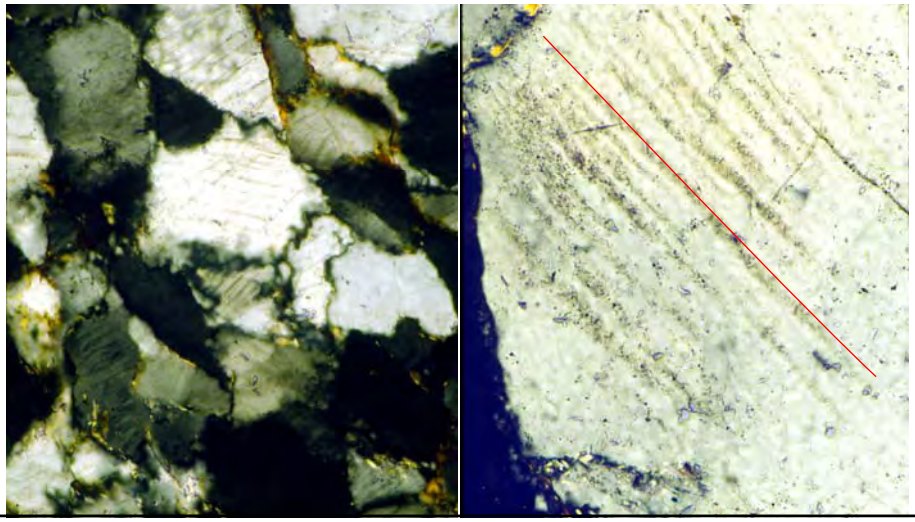


Formation of decorated PDF

FIG. 8. Schematic representation of the development of decorated PDFs. (a) Close to initial state with amorphous (glass) PDFs containing dissolved H_2O. (b) Initial recrystallization to a mixture of glass and quartz crystallites. (c) Exsolution of H_2O from recrystallizing quartz in PDFs in the form of bubbles and adjacent dislocation loops. (d) Final state with original PDF now represented as a series of bubbles aligned along a specific crystallographic orientation. See text for more details.

Tectonic deformation of quartz

Boehm lamellae



Tectonic deformation of quartz

Boehm lamellae

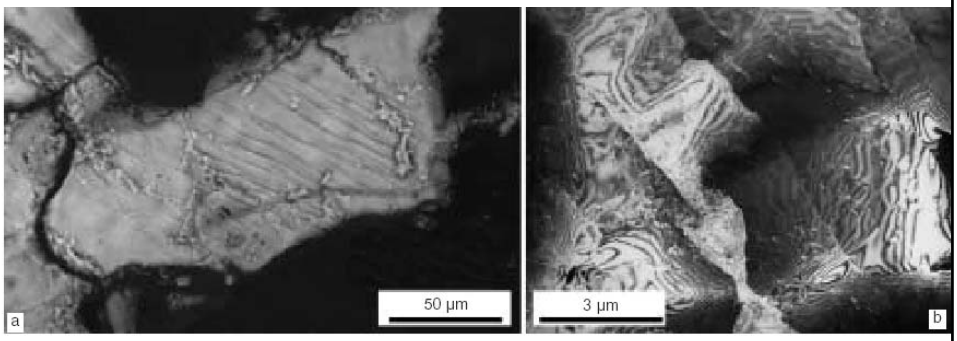
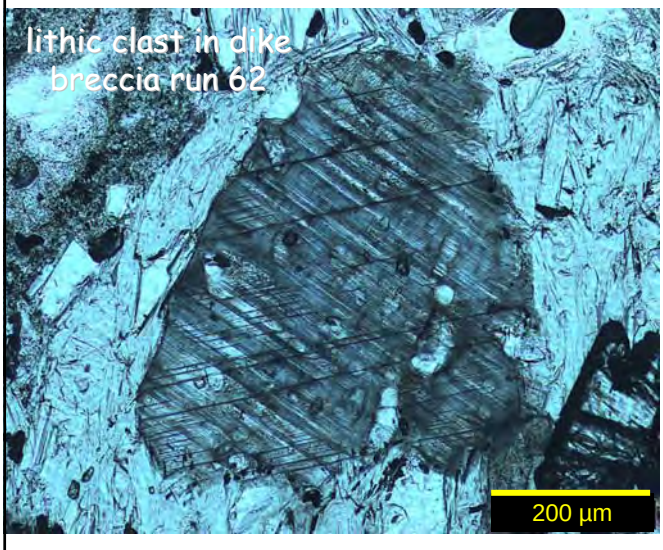


Fig. 8. (a) Optical micrograph and (b) corresponding bright-field TEM image of subgrain boundaries in a tectonically deformed quartz from Azuara, Spain (see Langenhorst and Deutsch 1996).

Shock effects: deformation

- mechanical twins
  crystal domains related by a point symmetry element (mirror, rotation or inversion axis) and produced by deformation

Calcite



- **multiple twinning**
- **planar elements**

Lake Bosumtwi
BCDP 8A

Shock effects: deformation

- kink bands
  (resembles chevron folding in sedimentary rocks)

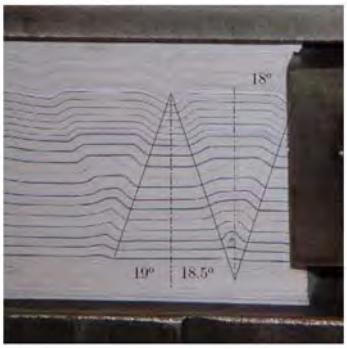


Fig. 2. Deformation under compression of approximately 625 sheets of paper from a sample of 800.

Wadee et al. 2003

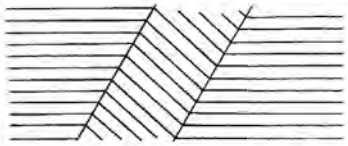


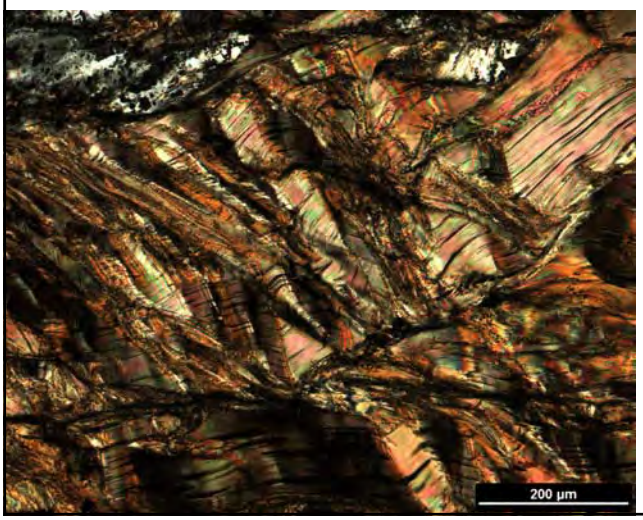
Fig. 1

Geological examples commonly occur in rocks with a strong planar anisotropy, in shales, slates and schists, and, on a microscopic scale, in mica crystals. Such examples have been described, usually briefly, from many different areas under a great variety of names (for example, joint-drags, knick-zones, conjugate folds, monoclinal conjugate folds, flexural folds, etc.). They have also been successfully imitated in the laboratory by Willis[3], by Kienow[4], and by Paterson and Weiss[6]. It seems generally agreed that kink-bands effect a shortening parallel to the original foliation. They may therefore be interpreted as a response

Anderson 1964

Shock effects: deformation

- kink bands



ICDP drilling Chesapeake

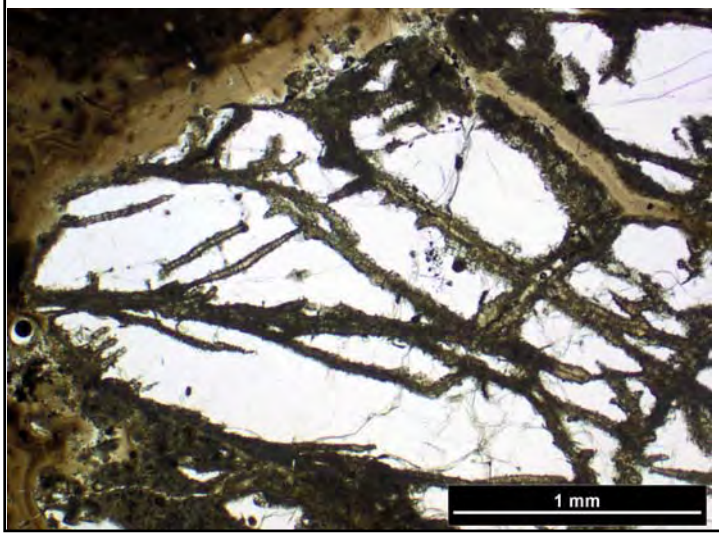
Shock effects: transformation

- diaplectic glass
- high-pressure phases

Diaplectic (thetomorphic) glass

- morphologic features of the crystalline precursor phase is retained (grain & twinning boundaries …)
- flow structures and bubbles (vesicles) are absent, refraction index and density are higher than that one of normal glasses of identical chemical composition
- diaplectic quartz glass may contain high pressure (hP) phases (coesite, stishovite)
- **diaplectic feldspar glass = maskelynite**

Diaplectic glass & high pressure phase



coesite in diaplectic SiO2 glass

Popigai
A007
//nicols

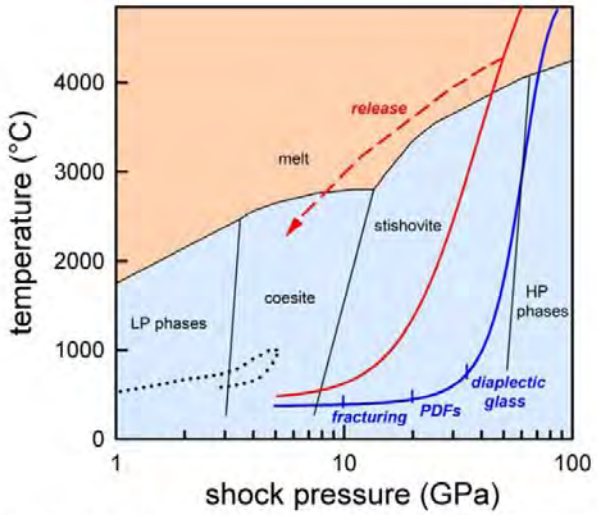
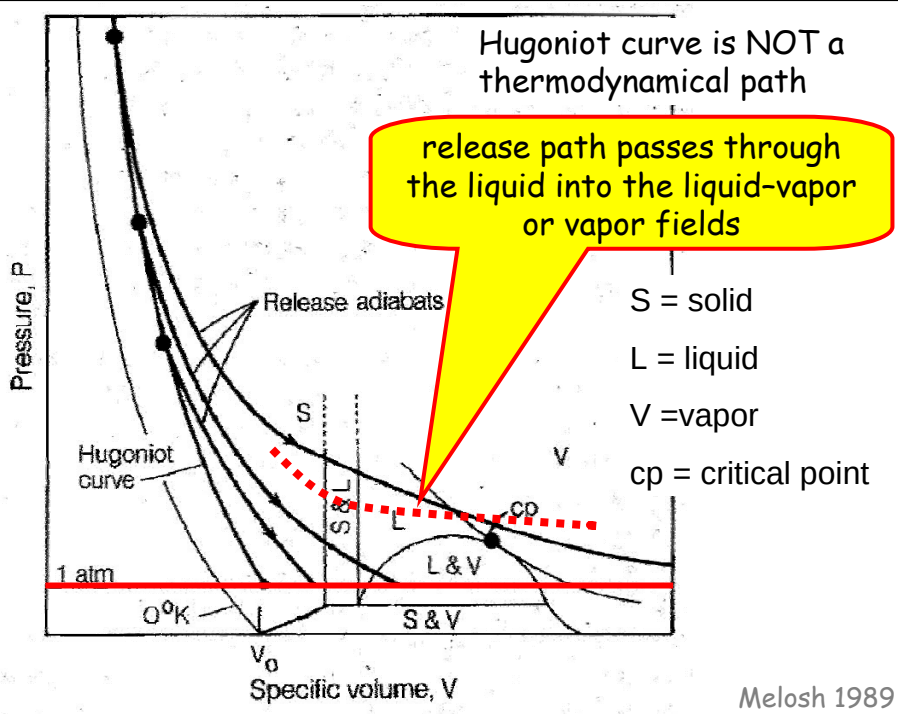


FIGURE 2. Phase diagram of silica showing the Hugoniot curves of quartz (blue) and sandstone (red). Hugoniot curves are non-isothermal equations of state, which depict all states that a material attains under shock compression. The Hugoniot curve of sandstone demonstrates that porous materials reach higher temperatures in the shock wave (Wünnemann et al. 2008). The dotted line corresponds to the *P-T* path of a diamond-bearing eclogite.

Shock & post-shock effects

- **deformation**: formation of
  - dislocations
  - planar microstructures (PFs and PDFs)
  - mechanical twins
  - kink bands
  - mosaicism
- **phase transformations** to
  - diaplectic glass
  - high-pressure phases
- **decomposition** into two or more phases (e.g., a solid residue and a gaseous phase)



Shock -> post-shock effects: decomposition

- decomposition into two or more phases (e.g., a solid residue and a gaseous phase)

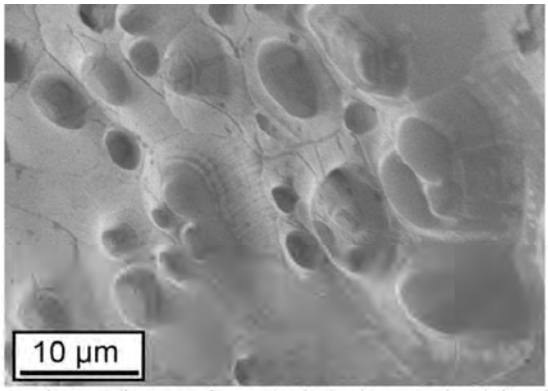


FIGURE 6. Secondary electron image of a melted single crystal calcite shocked in recovery experiment at a nominal pressure of 85 GPa. The bubbles indicate onset of dissociation which however was suppressed due to the confinement by the sample container.

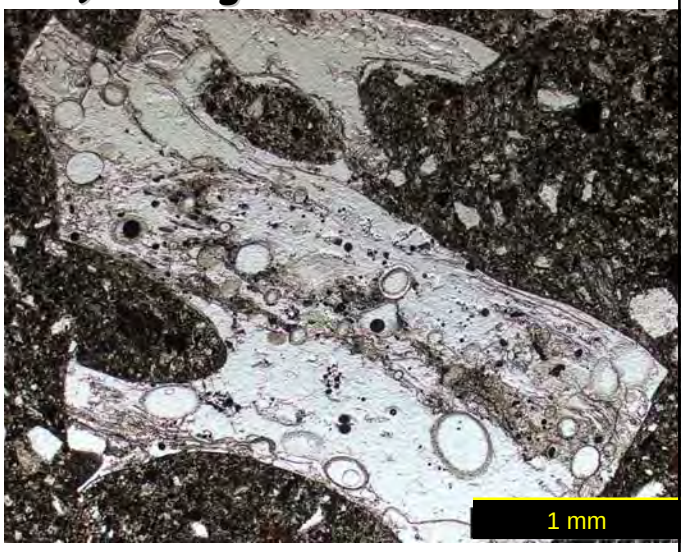
Langenhorst & Deutsch 2011

Shock & post-shock effects

- **deformation**: formation of
  - dislocations
  - planar microstructures (PFs and PDFs)
  - mechanical twins
  - kink bands
  - mosaicism
- **phase transformations** to
  - diaplectic glass
  - high-pressure phases
- **decomposition** into two or more phases (e.g., a solid residue and a gaseous phase)
- **melting** and **vaporisation** of the entire mineral/rock (subsequently quenched or condensed as glass or polycrystalline aggregates)

post-shock effects: melting

vesicular (rock) melt glass with schlieren



suevite

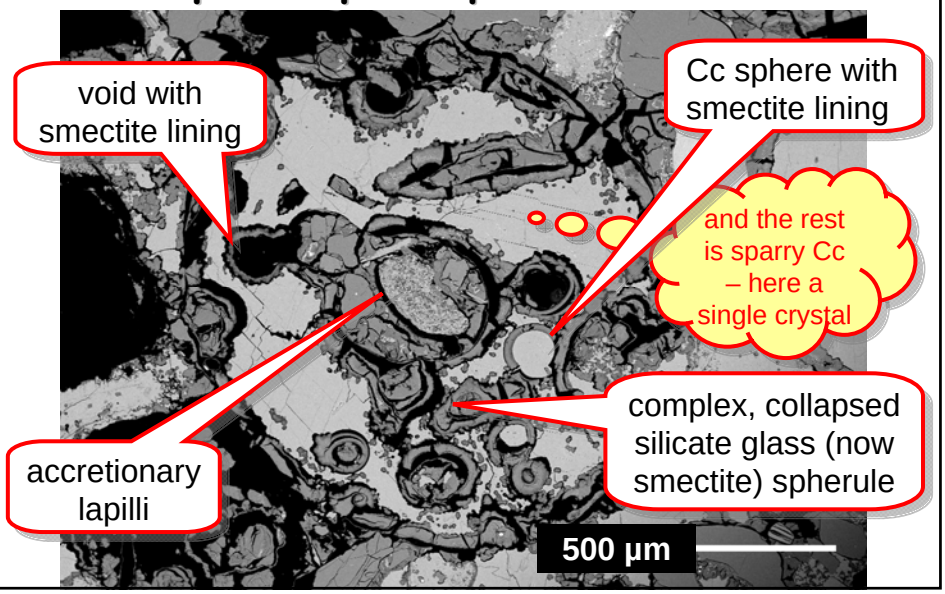
Lake Bosumtwi

W crater rim

post-shock effects: melting

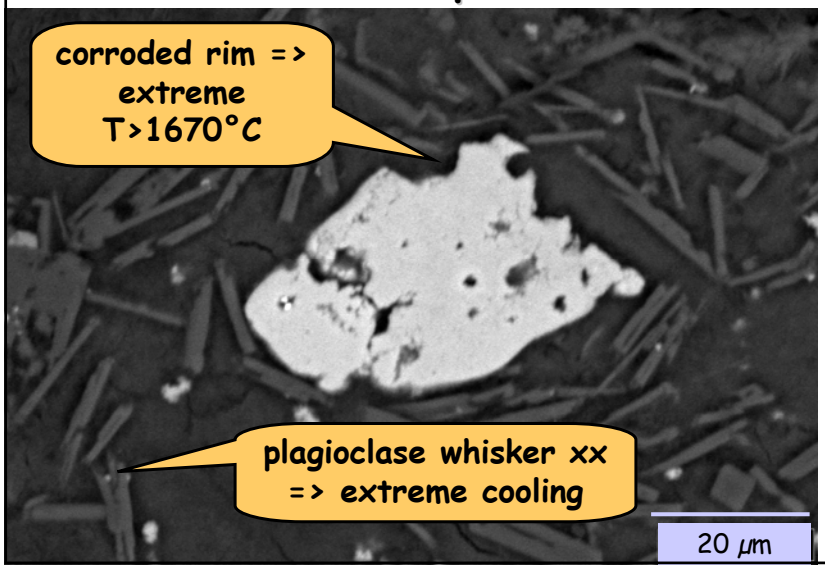
complex impact spherule

Shell Creek AL



post-shock effects: annealing

zircon in impact melt rock

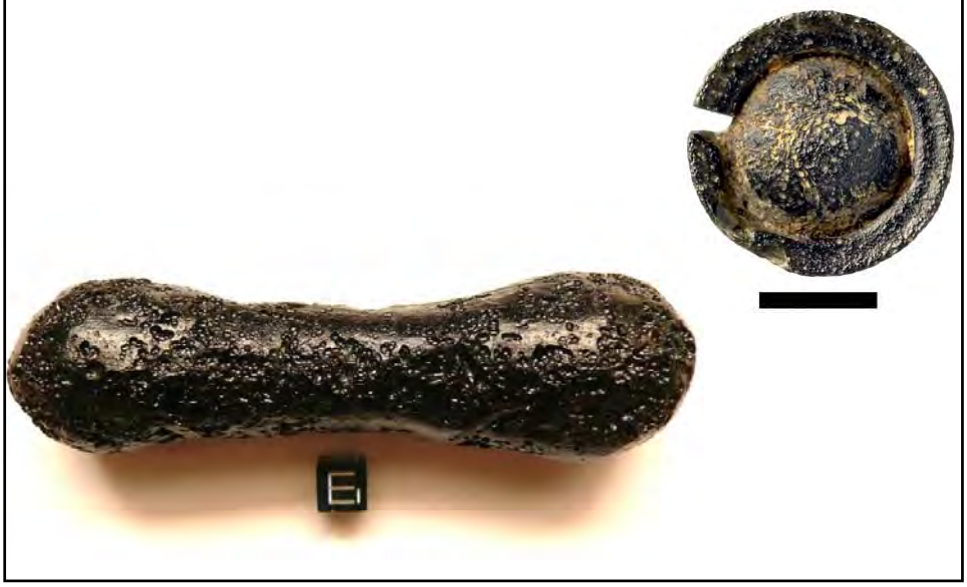


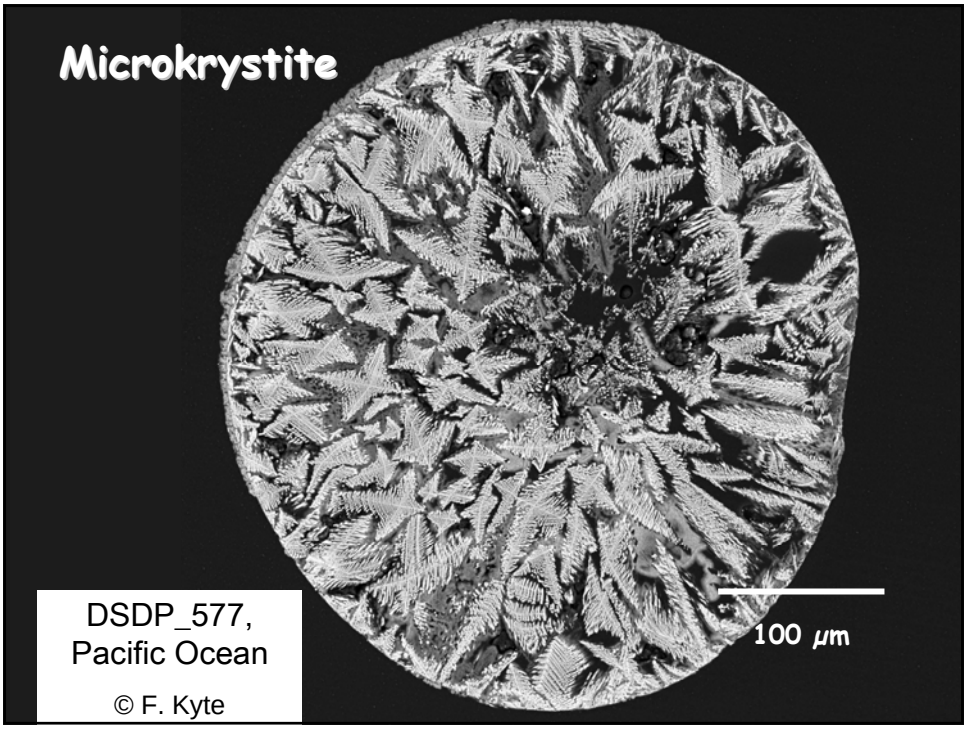
Chicxulub, YAX-1_835.77 m b.s.l.

Shock & post-shock effects

- **deformation**: formation of
  - dislocations
  - planar microstructures (PFs and PDFs)
  - mechanical twins
  - kink bands
  - mosaicism
- **phase transformations** to
  - diaplectic glass
  - high-pressure phases
- **decomposition** into two or more phases (e.g., a solid residue and a gaseous phase)
- **melting** and **vaporisation** of the entire mineral/rock (subsequently quenched or condensed as glass or polycrystalline aggregates)

Tektites "splash forms"

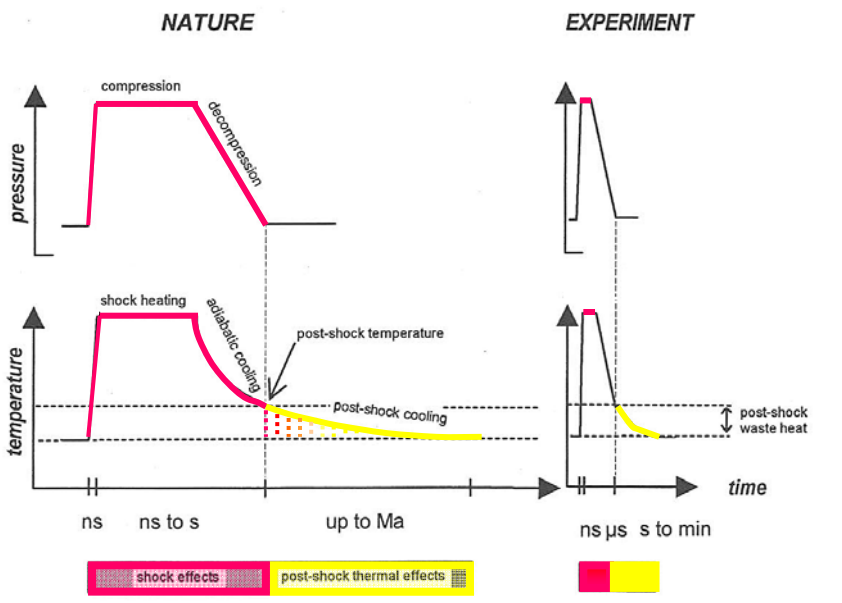




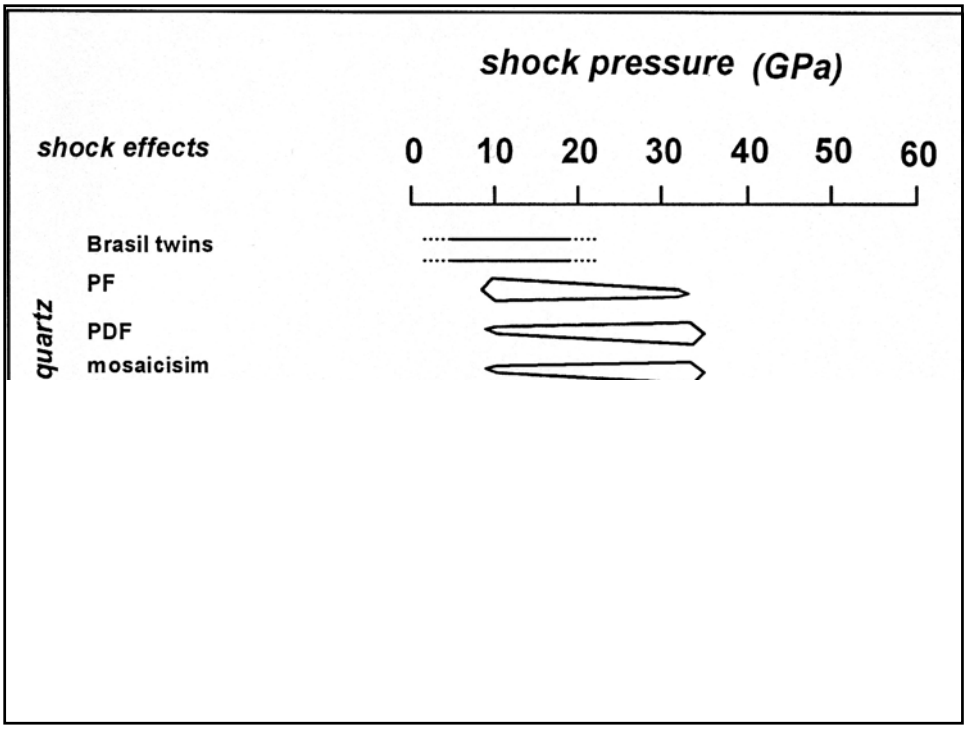
DSDP_577,
Pacific Ocean

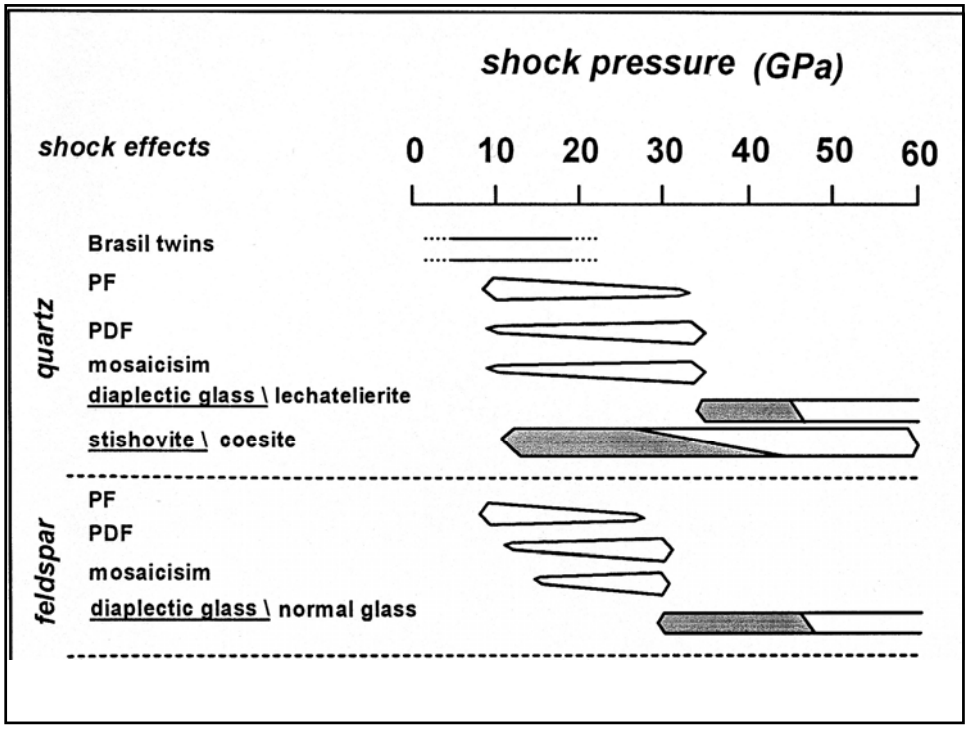
© F. Kyte

Shock/impact metamorphism



Deutsch & Langenhorst 1998





Impact breccias - impactites

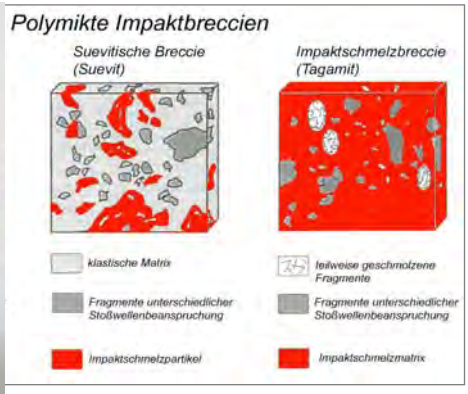
- Bunte Brekzie [clastic matrix breccia; fragmental breccia]
- suevite
- dike (dyke) breccias
  clastic – with melt particles – melt matrix
- (impact) melt breccias
- (impact) melt rock ≠ impact melt

Breccias

- monomict - polymict
- allochthon – authochthon – parauthochthon
- allogen - authogen
- Matrix-/Fragment-gestützt [matrix-/clast-supported]
- klastische – Schmelz-Matrix [clastic / melt matrix] glasig [glassy] – (holo)kristallin [crystalline]
  aphanitische Matrix – Pseudotachylit [pseudotachyly(i)te]

Impact breccias with melt particles & clasts suevite



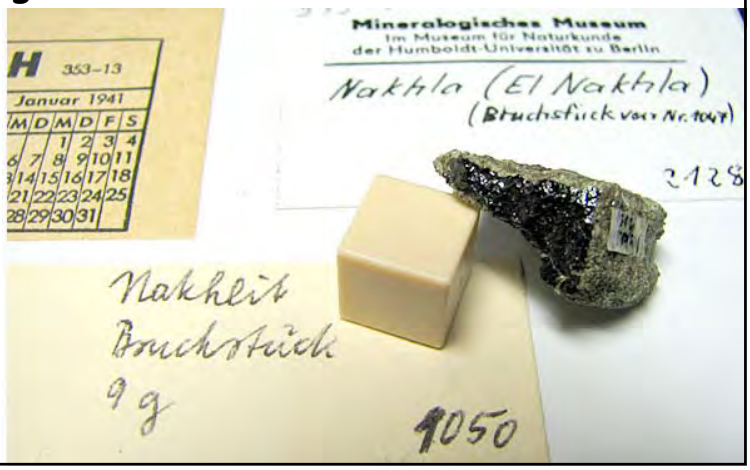


(impact) glass is not (impact) glass

- pseudotachylites – „shock veins" in meteorites
- impact melt rocks & breccias
- co-genetic glass shards & bombs in clastic matrix breccias (suevites)
- coating of lithic bombs & fallback particles

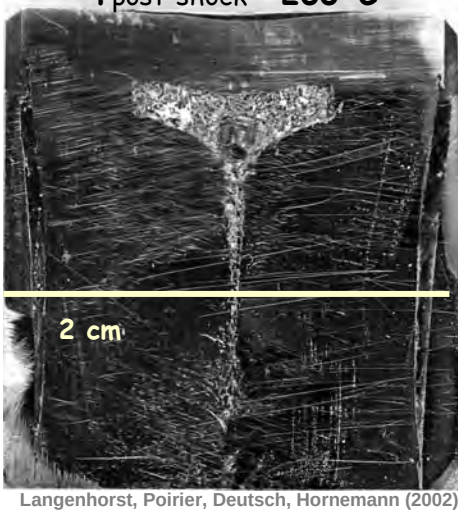
Origin of shock veins in meteorites

- pressure heterogeneities
- shearing



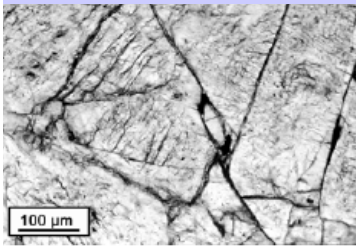
Single crystal olivine (San Carlos)

shearing at 41 GPa,
≤0.7 μs, Tshock ~500°C,
Tpost-shock ~200°C

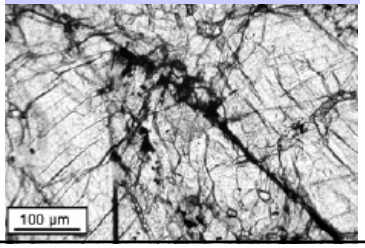


Langenhorst, Poirier, Deutsch, Hornemann (2002)

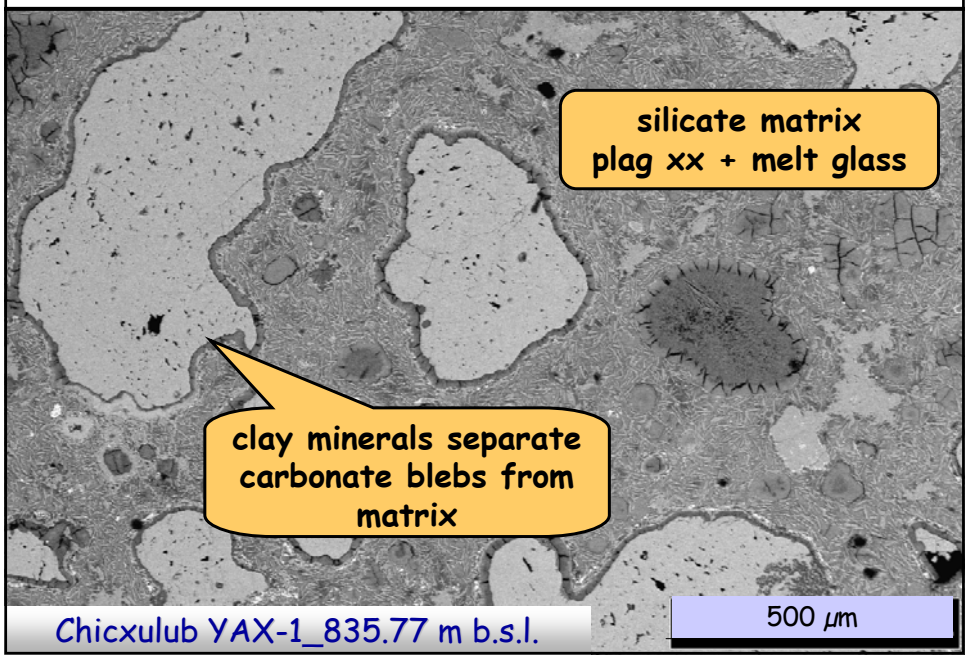
experimentally generated shock vein



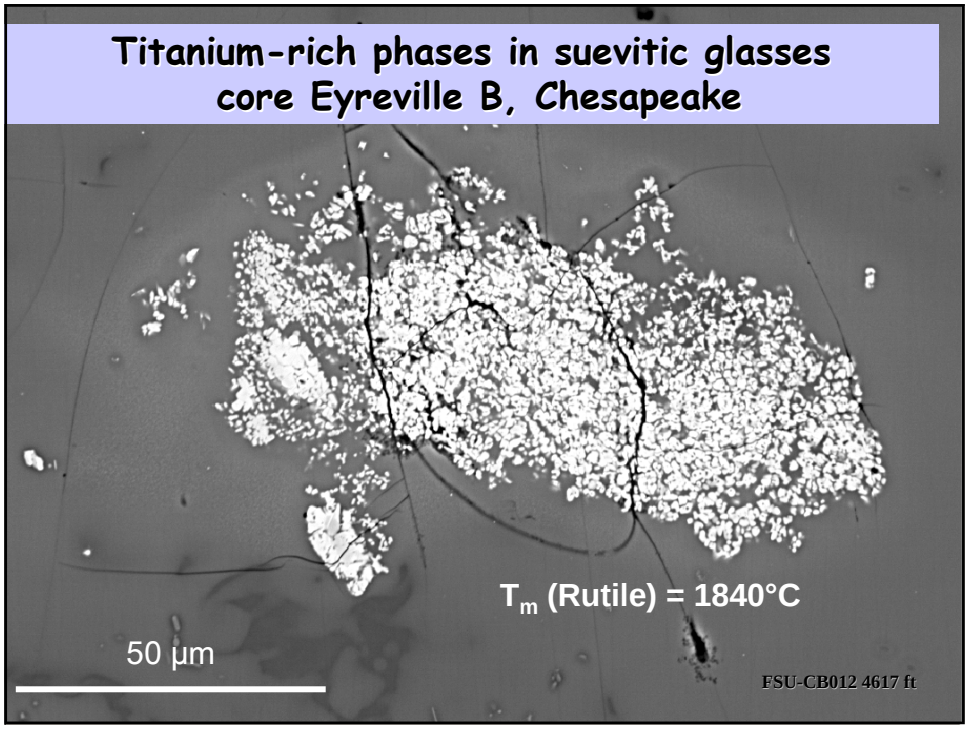
strongly shocked L5 ordinary chondrite Acfer 072



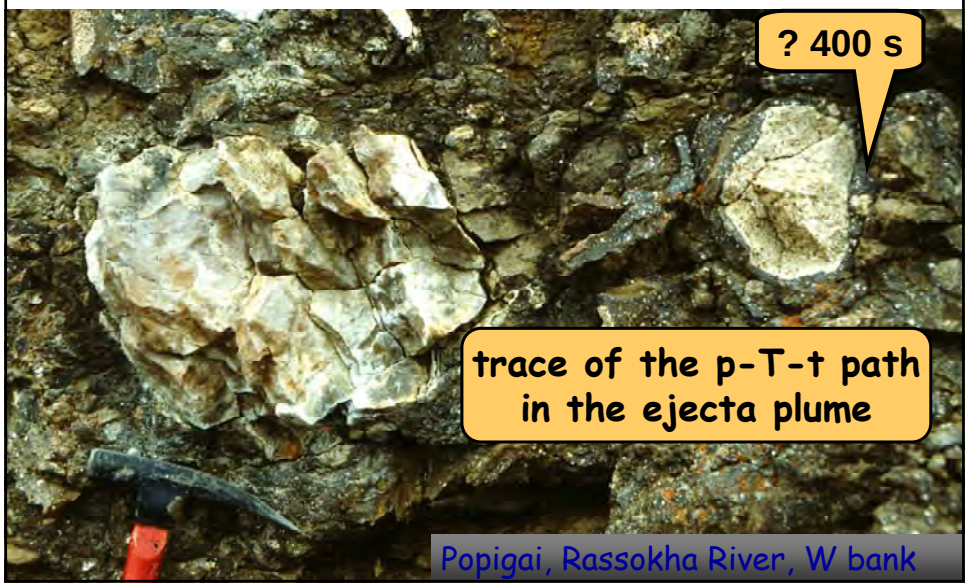
Carbonate melt in silicate melt



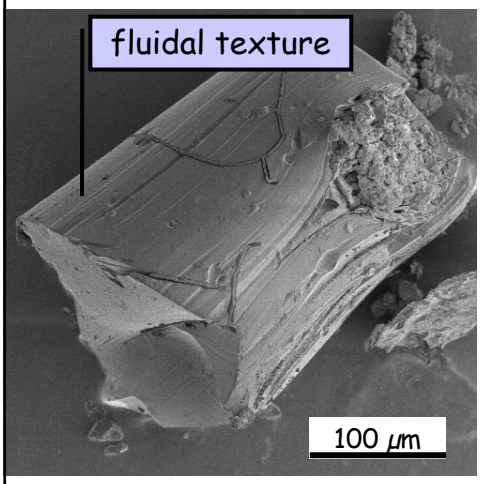
Titanium-rich phases in suevitic glasses core Eyreville B, Chesapeake

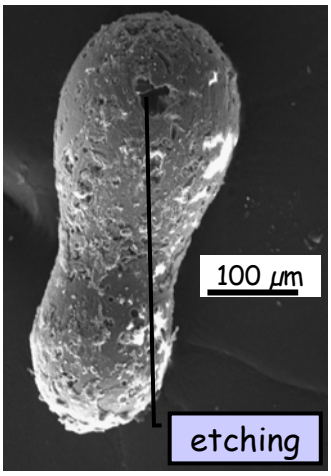


Gneiss bombs coated by various layers of impact melt (the flight recorder!!)



Glassy fallback material – Lake Bosumtwi





- glass probably originated by condensation of melt droplets in the vapor plume core LB 05

Tektites 1

- SiO_2-rich impact glass formed in early stage of terrestrial cratering from melted surface lithologies (^{10}Be)
- precursor lithologies have to be fine-grained, porous, silica-rich (e.g., sand, loess, soil, laterite)
- lack of meteoritic component (i.e., PGEs from the projectile) -> no contact between the incoming bolide and the target surface
- ⇨ melting by bow shock (compressed air) in front of the projectile? Best impact angle <30°

Tektites 2

- low H2O contents (10 – 100 ppm), CO may be present (45 ppm) extreme T in flash heating, reducing conditions
- the melt is ejected ballistically and deposited as aerodynamically shaped bodies in geographically defined strewn fields far off the continuous ejecta blanket (<3 crater radii)

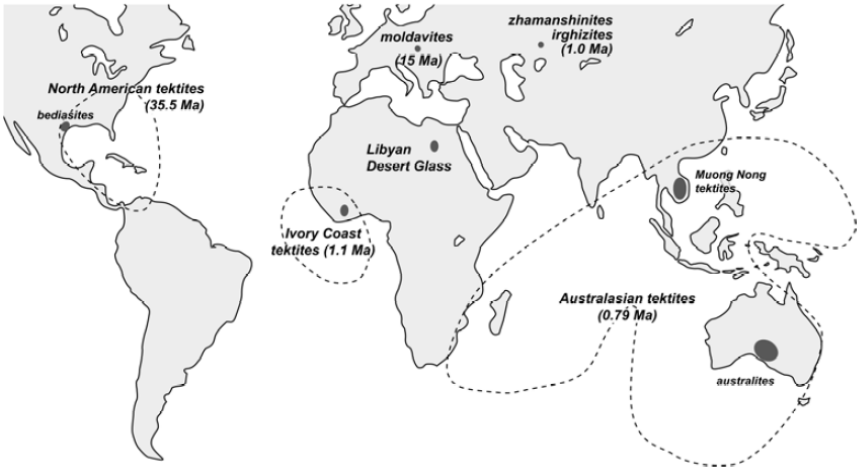
Tektites 3

- size ranges from sub-cm to sub-dm, rarely to dm
- Moung-Nong tektites: lumps of glass <24 kg found in N Thailand, Laos, Vietnam: melt stayed ± in place marking the impact site (i.e., melting directly below the incoming projectile)

Tektites 4 & tektite-like objects & impact glass spheres

- separate tektites have been described (Deutsch et al. 1997), e.g., urengoites, S-Ural tektite (1 object) - no source crater is known
- tektite-like objects cover wide areas in the N-African desert: Libyan Desert glass (>98 wt% SiO_2) – no crater is known
- microtektites (size in the sub-mm range) are generally found in marine sea sediments – may be associated to a tektite strewn field
- impact glass spheres (K-Pg boundary)

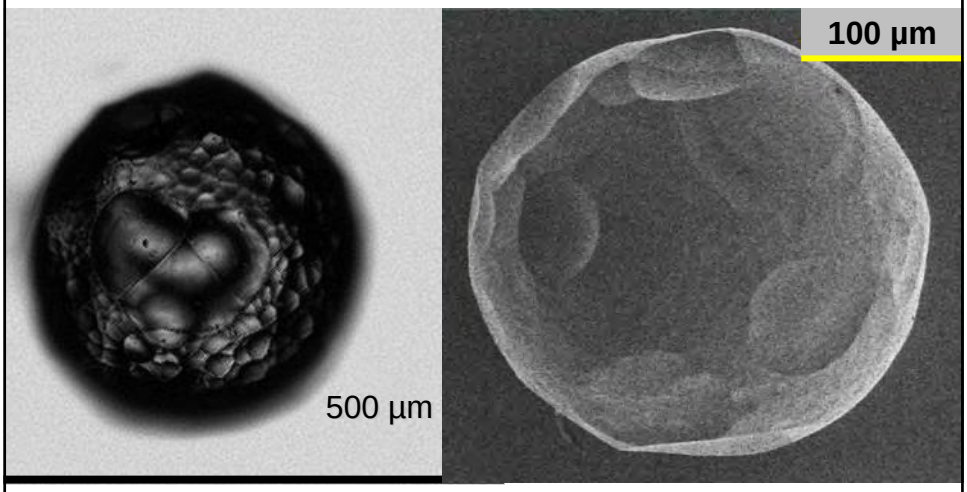
Tektite strewnfields



Ivory Coast tektite (IVC)
source crater Lake Bosumtwi

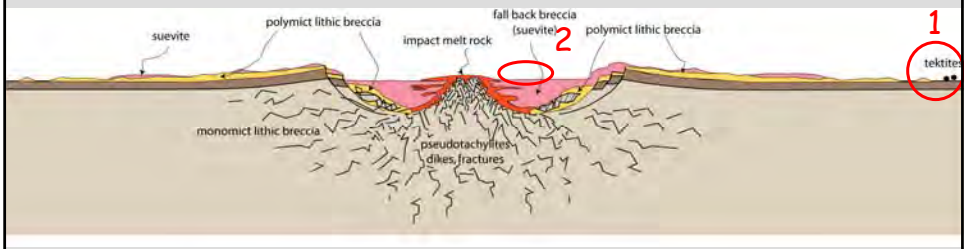


Microtektites
source crater Lake Bosumtwi

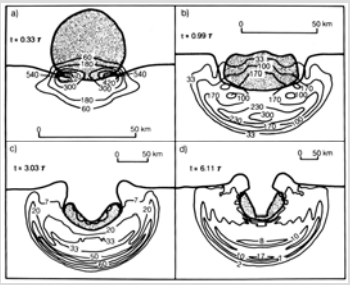


courtesy of B. Glass

1. Distal ejecta (tektites)
2. Vapor plume deposits



museum für naturkunde



O´Keefe & Ahrens, 1975; Melosh, 1989

Where do we find early cratering products?

1. **Distal ejecta (tektites)**
2. Vapor plume deposits
3. Impact melt rock

