Impact Cratering and the Formation of Shatter cones
The enigma remains

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Shatter cones in shale, Vredefort impact crater. See satellite image of the Vredefort dome (80 km in diameter).

Outline

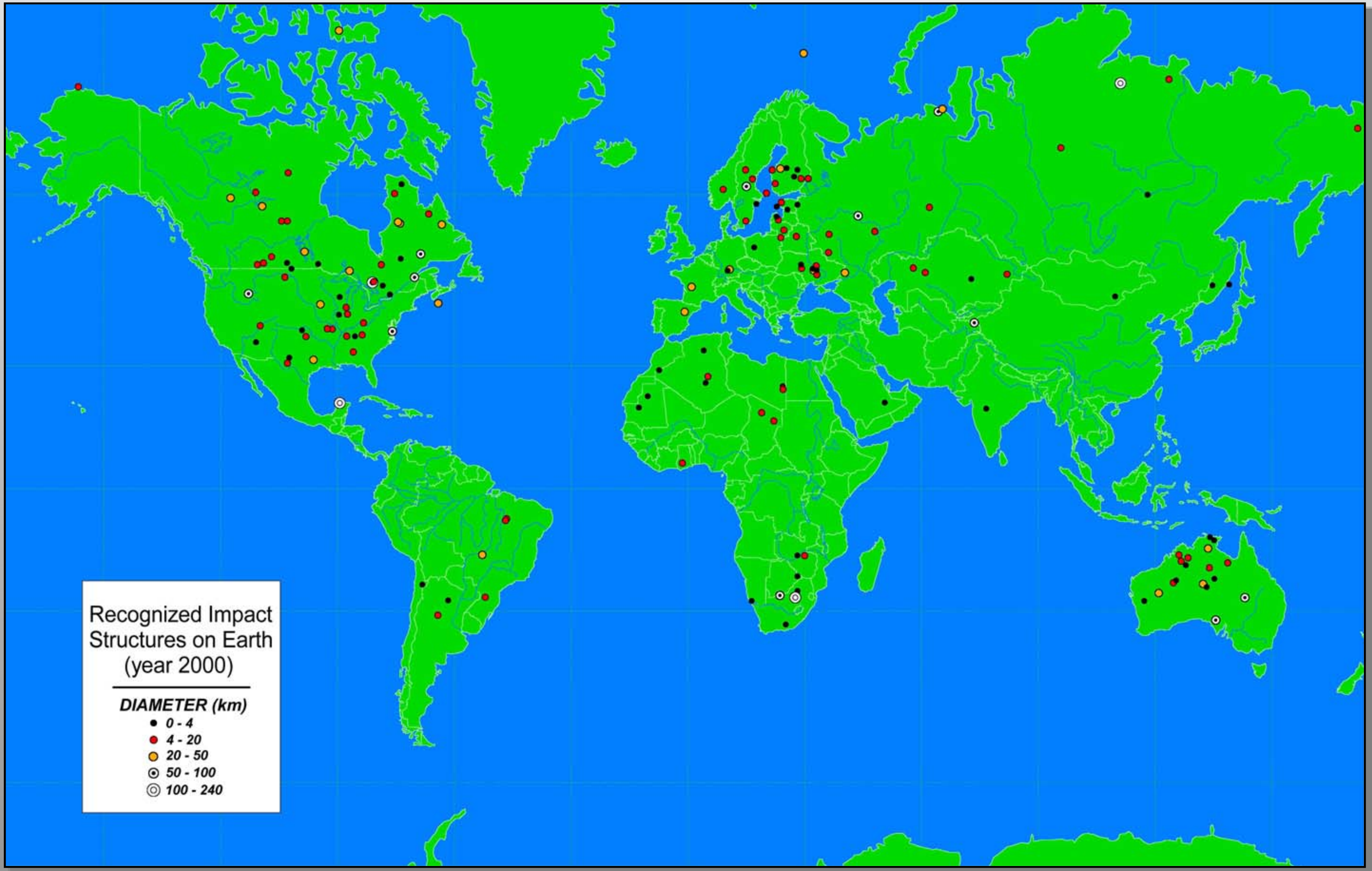
What is a shatter cone ?
Definition and criteria for identification

Where can you find shatter cones ?
Occurrence and distribution of shatter cones

Shape, orientation, size – what do we know ?

Model of shatter cone formation – The enigma remains…but what do we know ?

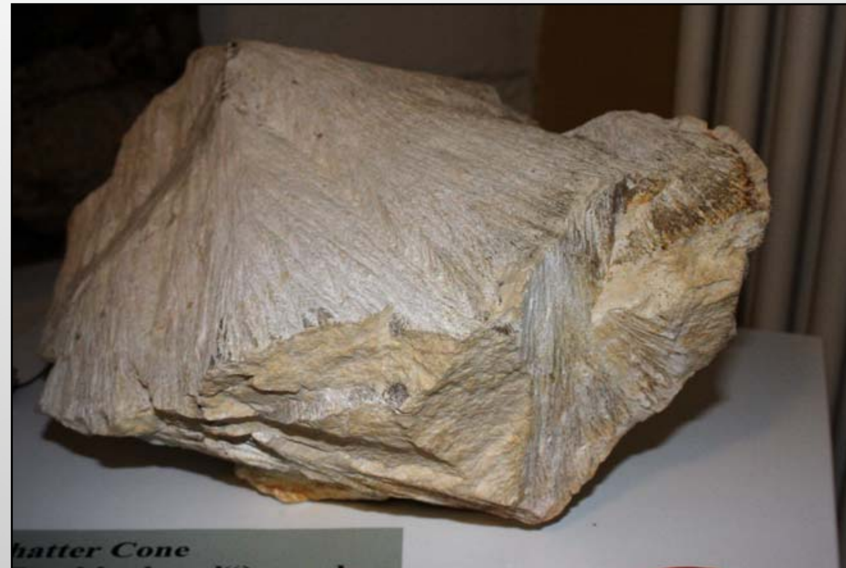
Map of the impact sites



What is a shatter cone ?

It looks like a cone (but actually the shape is rather curved or planar rather than conical).

Shatter cones in Shales, Vredefort impact crater.



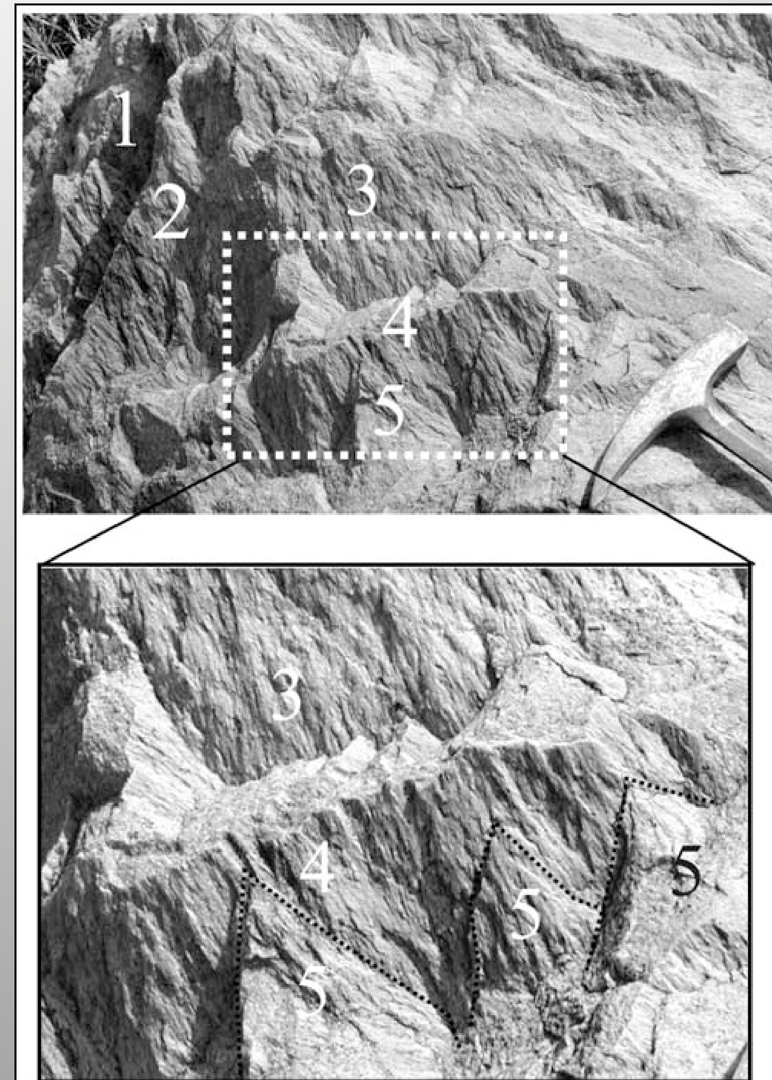
Shatter cones in limestone, Ries (Germany)

What is a shatter cone ?

Shape ? Conical, curvi-planar, planar ?

Haughton impact site, Canada, fine-grained limestones (Osinski, 2006)

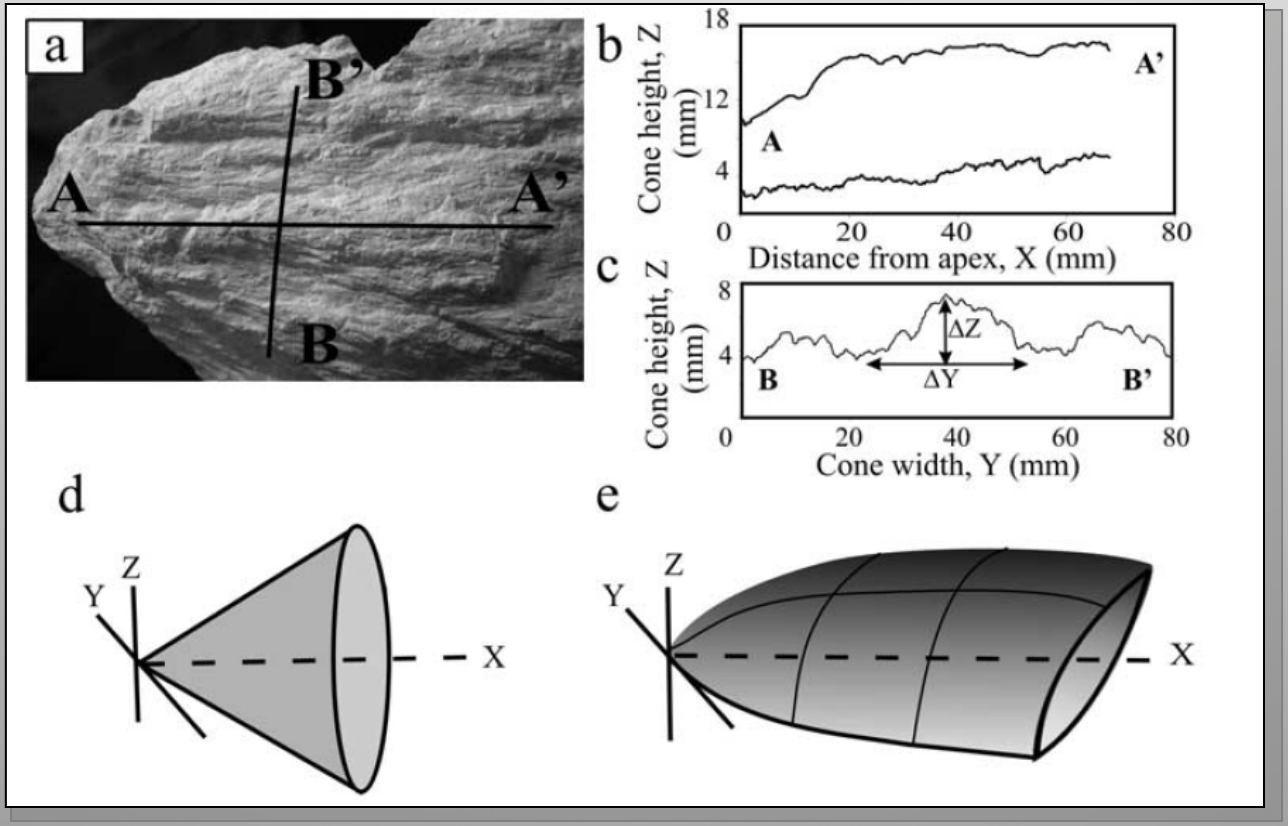
Vredefort impact site, quartzite, South Africa



Vredefort impact site, quartzite, South Africa. (Sagy et al. 2004)

What is a shatter cone ?
Shape

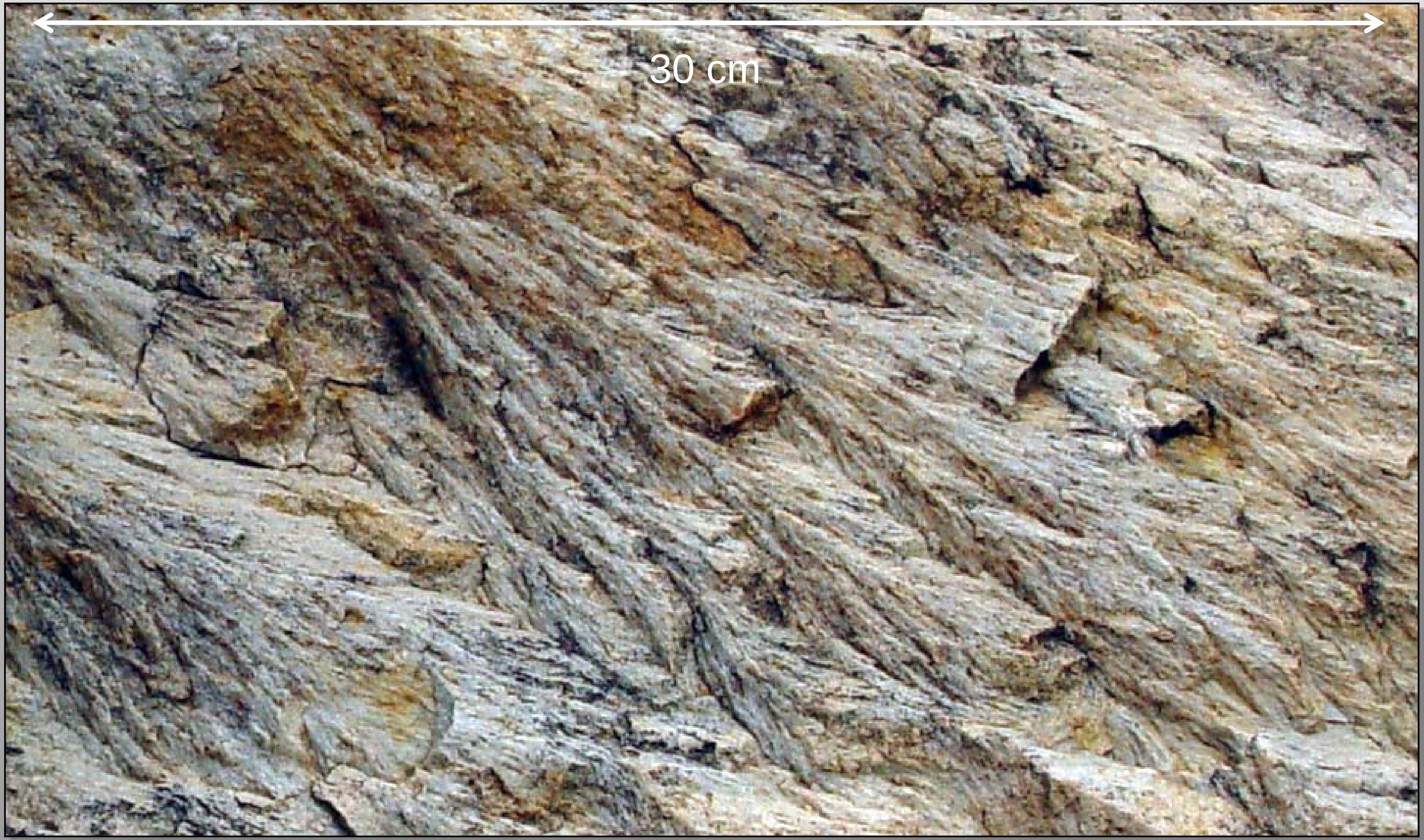
Unfortunately, measurement of the shapes of shatter cones are rare…



1-D topographic profile of shatter cones (Vredefort impact crater, Sagy et al. ,2002)

What is a shatter cone ?

It has characteristic striations on the surface



Shatter cones in quartzite, Vredefort impact crater.

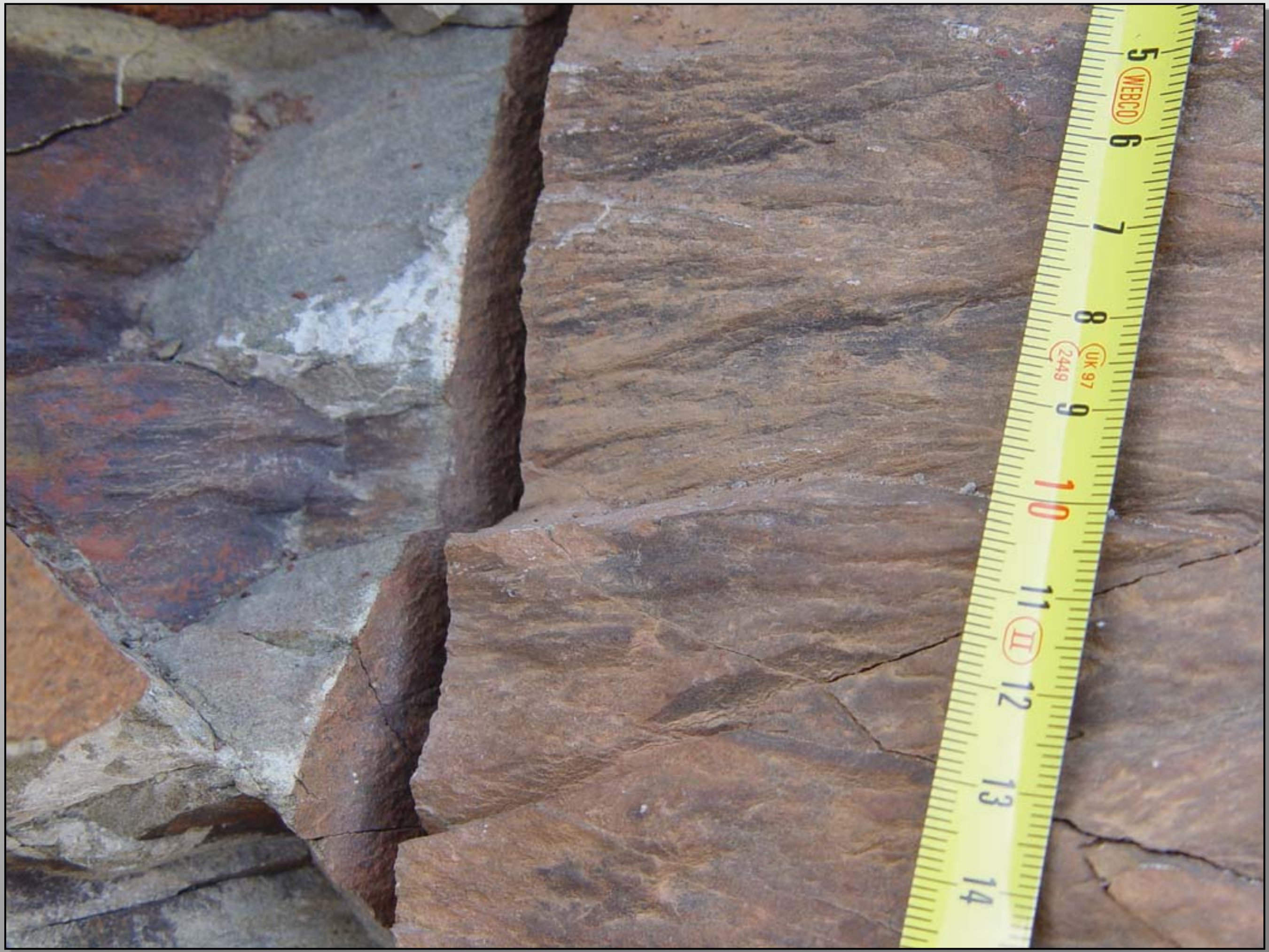
What is a shatter cone ?

It has characteristic striations on the surface

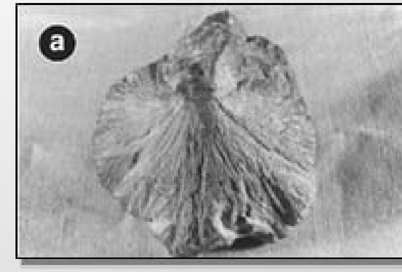
Shatter cones in shale, Vredefort impact crater.

What is a shatter cone ?

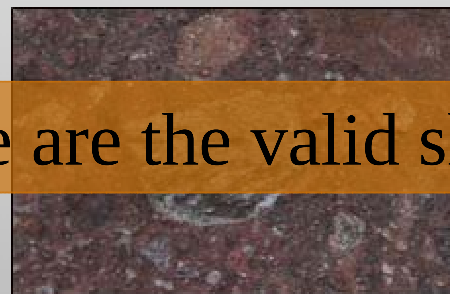
It is a pervasive fracture

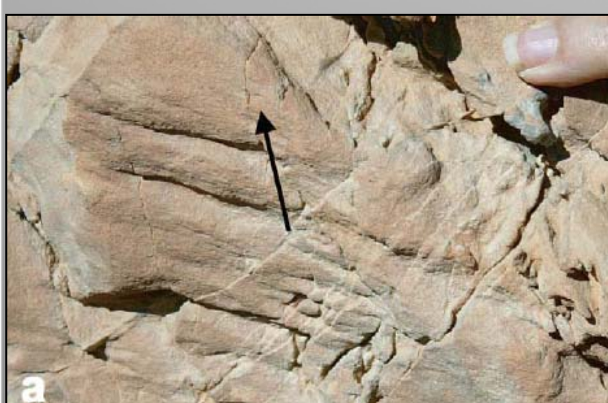


Shatter cones in shale, Vredefort impact crater.



Where are the valid shatter cones ?



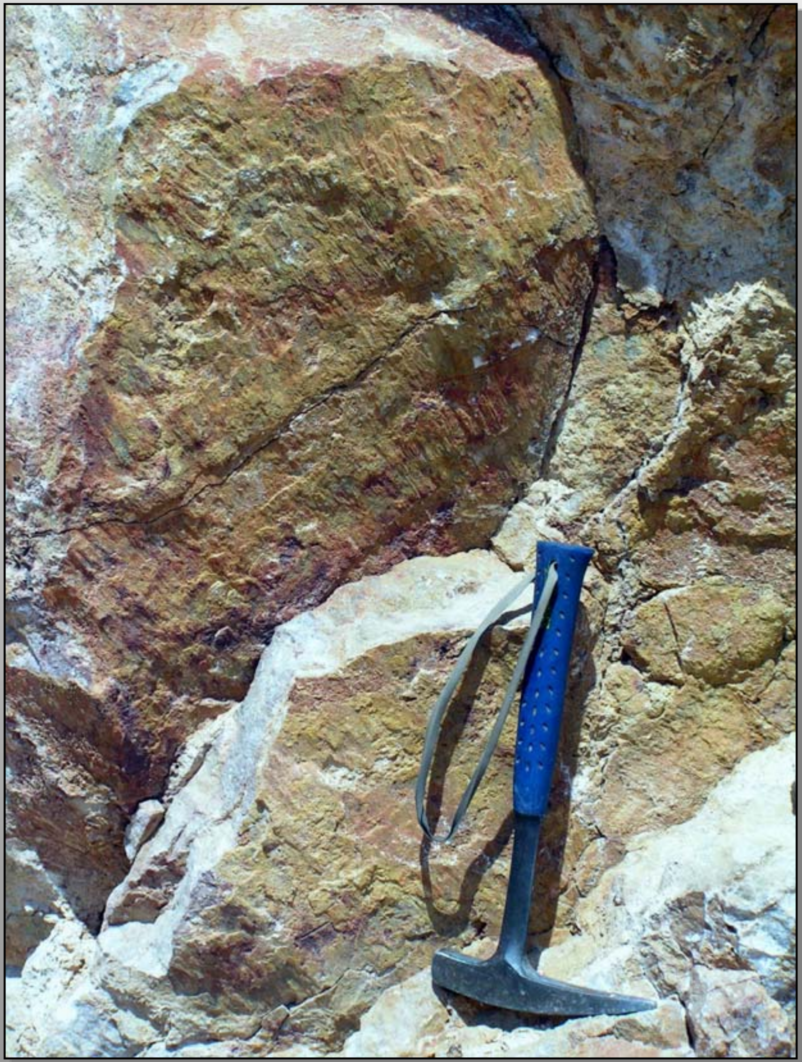


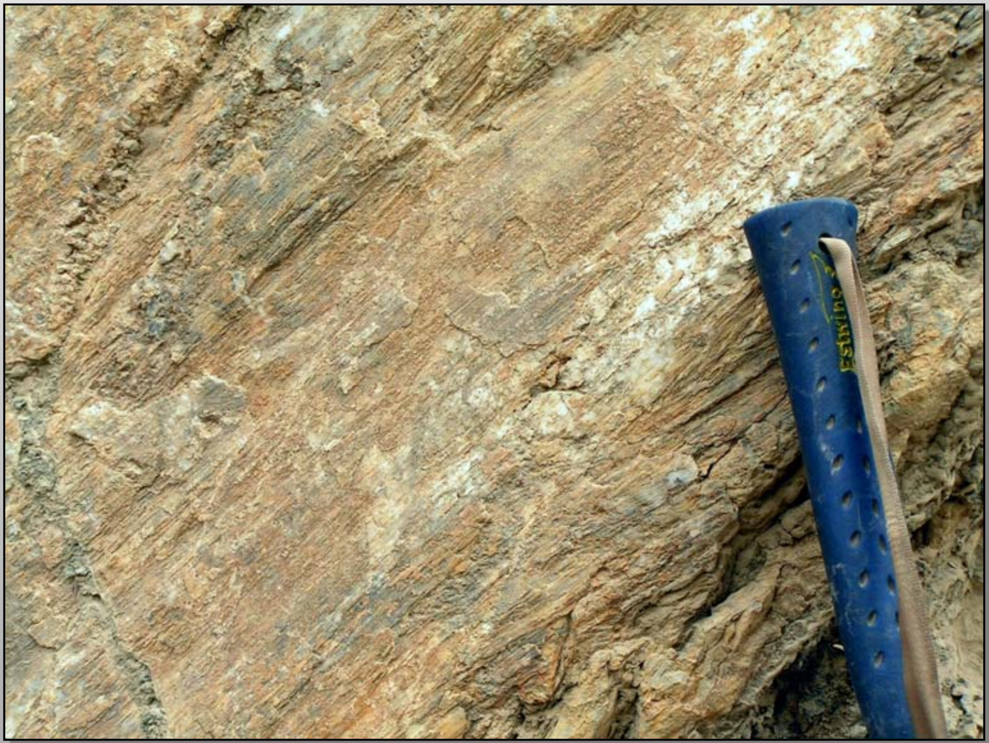

Canon
b
a

Is it possible to make a mistake ?

Example of possible confusions

Striations on surface faults - Slickenslides





Salvador, Limestone (Photo L. Baratoux)

Is it possible to make a mistake ?

Example of possible confusions

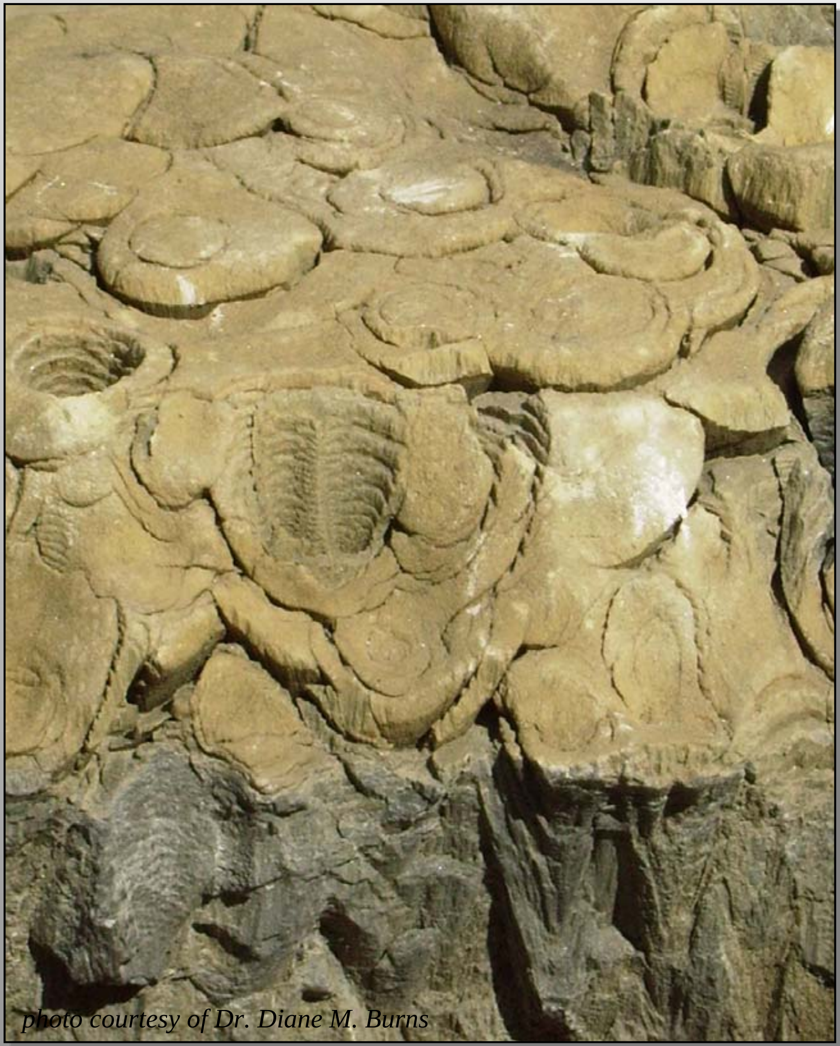
Quartzite at Vredefort impact crater

Slickensides and shatter cone striations can occur at the same outcrop

Is it possible to make a mistake ?

Example of possible confusions

Cone-in-cone structures (mostly in calcareous rocks)



Growth of calcareous fibers – exact mechanism (also) debated

Comparison after Lugli et al., 2005

Cone-in-Cone	Shatter Cones
Conical secondary growth features formed during diagenesis; found in undisturbed sedimentary rocks.	Conical fracture features formed by transient shock waves (P ~2 to >10 GPa) and found in meteorite impact structures, typically in uplifted central rocks.
Restricted to carbonate-bearing rocks (limestones, limy shales); associated with secondary carbonate.	Found in all rock types (sedimentary, igneous, metamorphic). Best developed in fine-grained rocks, especially limestones.
Cone axes normal to bedding planes.	Cone axes oriented at any angle to bedding, depending on orientation of rock at time of impact and on postimpact movements.
Cones oriented point-down.	Cones originally form pointing in direction of source of shock wave, i.e., inward and upward. Orientation varies over structure. Orientation further modified by development of central uplift or later postcrater deformation. When beds restored to original horizontal position, cones point toward a focus above original surface, indicating external source of shock wave.
Striations along cone surface generally continuous, uniform.	Striations along cone surface typically show development of divergent radiations ("horsetailing") along surface. Development of secondary (parasitic) cones on main cone is typical.
Cone surfaces are growth surfaces against other cones or fine matrix in rock.	Cone surfaces are actual fracture surfaces; rock splits into new shatter-coned surfaces along cone boundaries. Unlike *slickensides,* striated cone surfaces show no relative motion, fit together without displacement.
Rocks typically show no deformation, metamorphism.	Frequently contain kink-banded micas or quartz (coarser grains) with shock-produced planar deformation features (PDFs).

Conical crystallization texture (Stichtite, $Mg_6Cr_2CO_3(OH)_{16}$-4H2O)

Sedimentary Cone-in-cone structures

Is it possible to make a mistake ?

Example of possible confusions

Eolian features, ventifacts

Gilf Kebir plateau, Paillou et al., 2006

Is it possible to make a mistake ?

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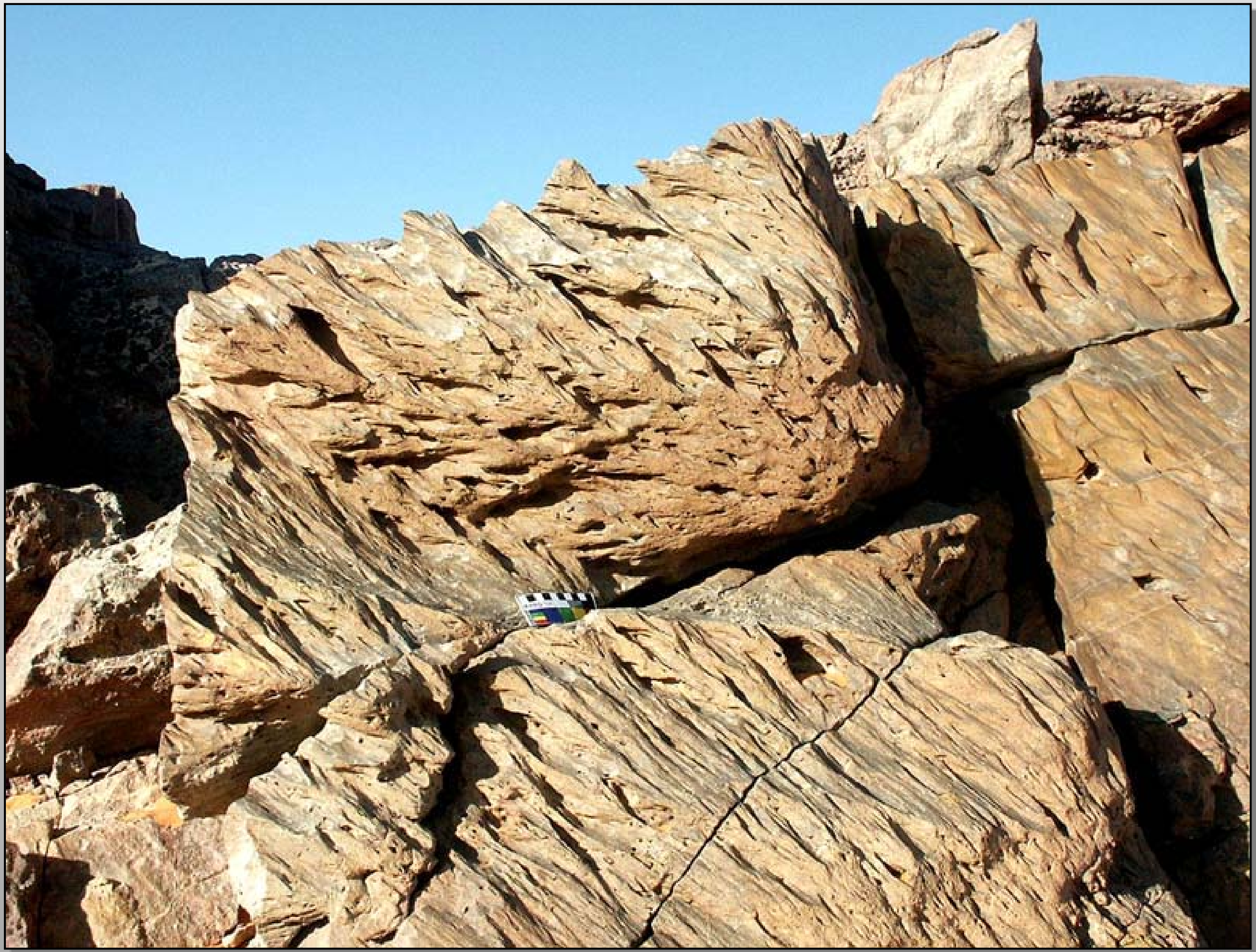
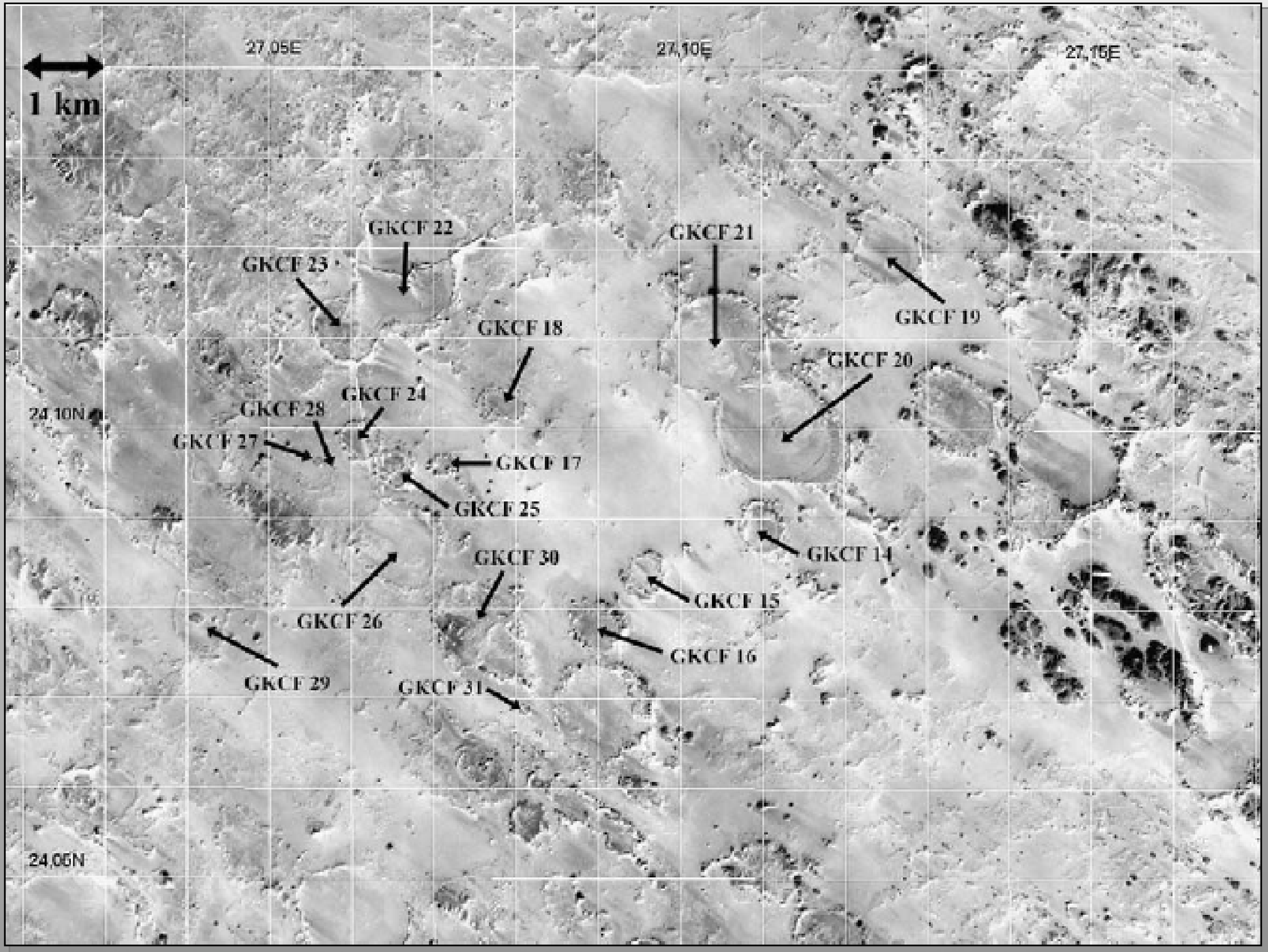


Gilf Kebir plateau, Paillou et al., 2006

Even if the sites look like impact craters…



Gilg Kebir plateau, Egypt, Paillou et al. 2006.

Even if the sites look like impact craters…

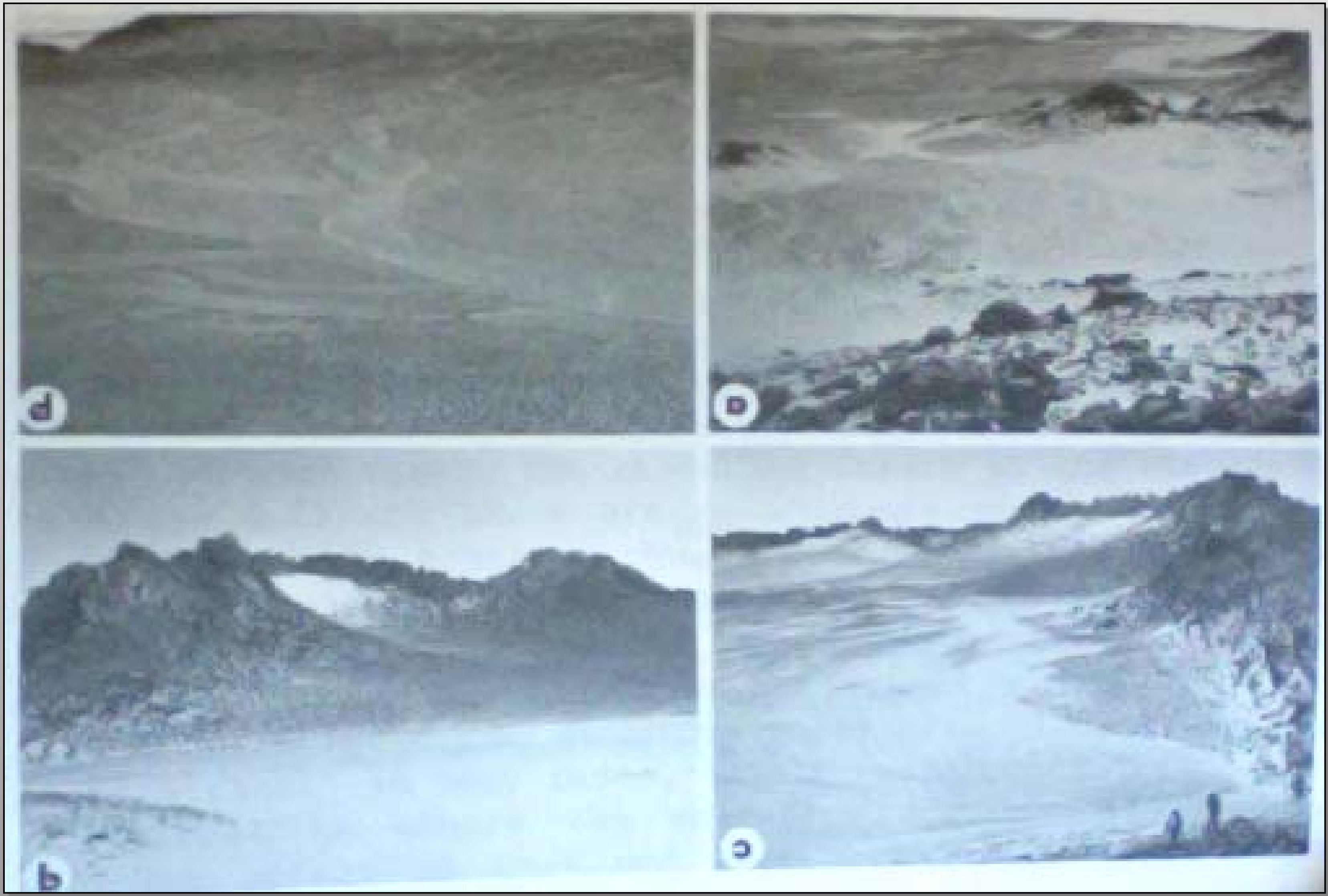
Gilg Kebir plateau, Egypt, Paillou et al. 2006.

To tell all the story…

Landsat image (1978)

From Desert Landforms of southwest Egypt: A basis from comparison with Mars. F. El Baz, T.A. Mawxell (editors)

To tell all the story…



From Desert Landforms of southwest Egypt: A basis from comparison with Mars. F. El Baz, T.A. Mawxell (editors), 1979.

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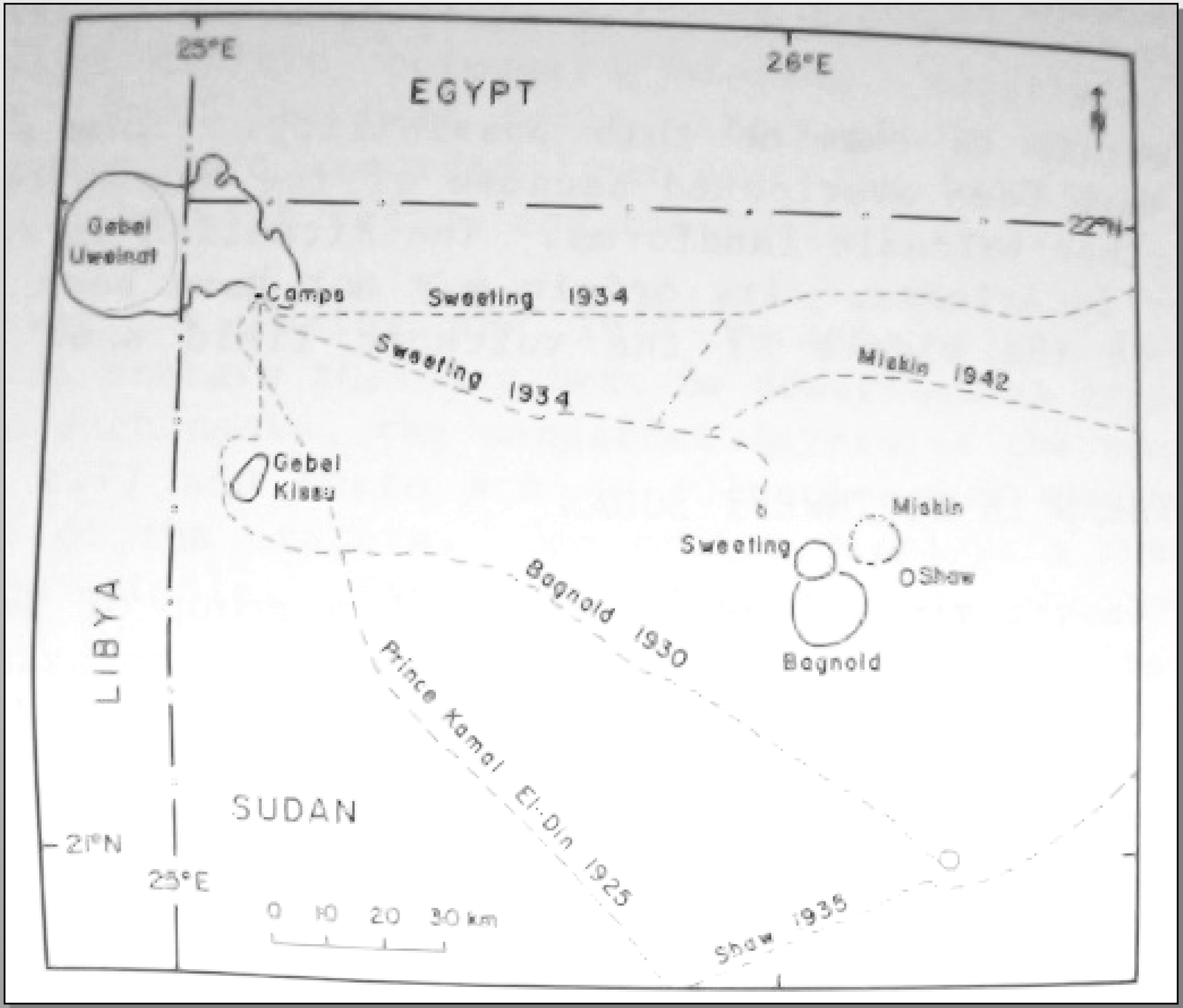

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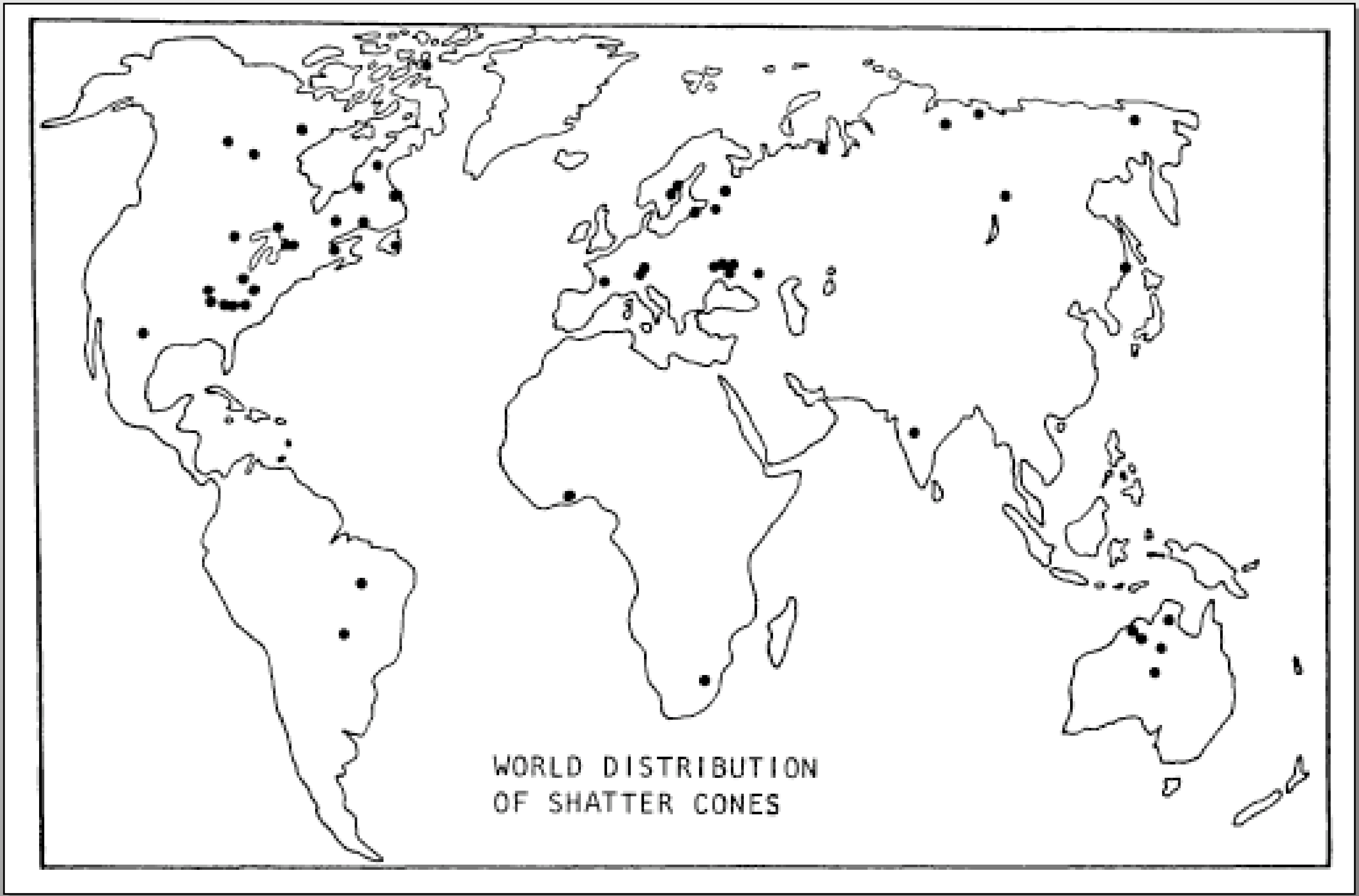
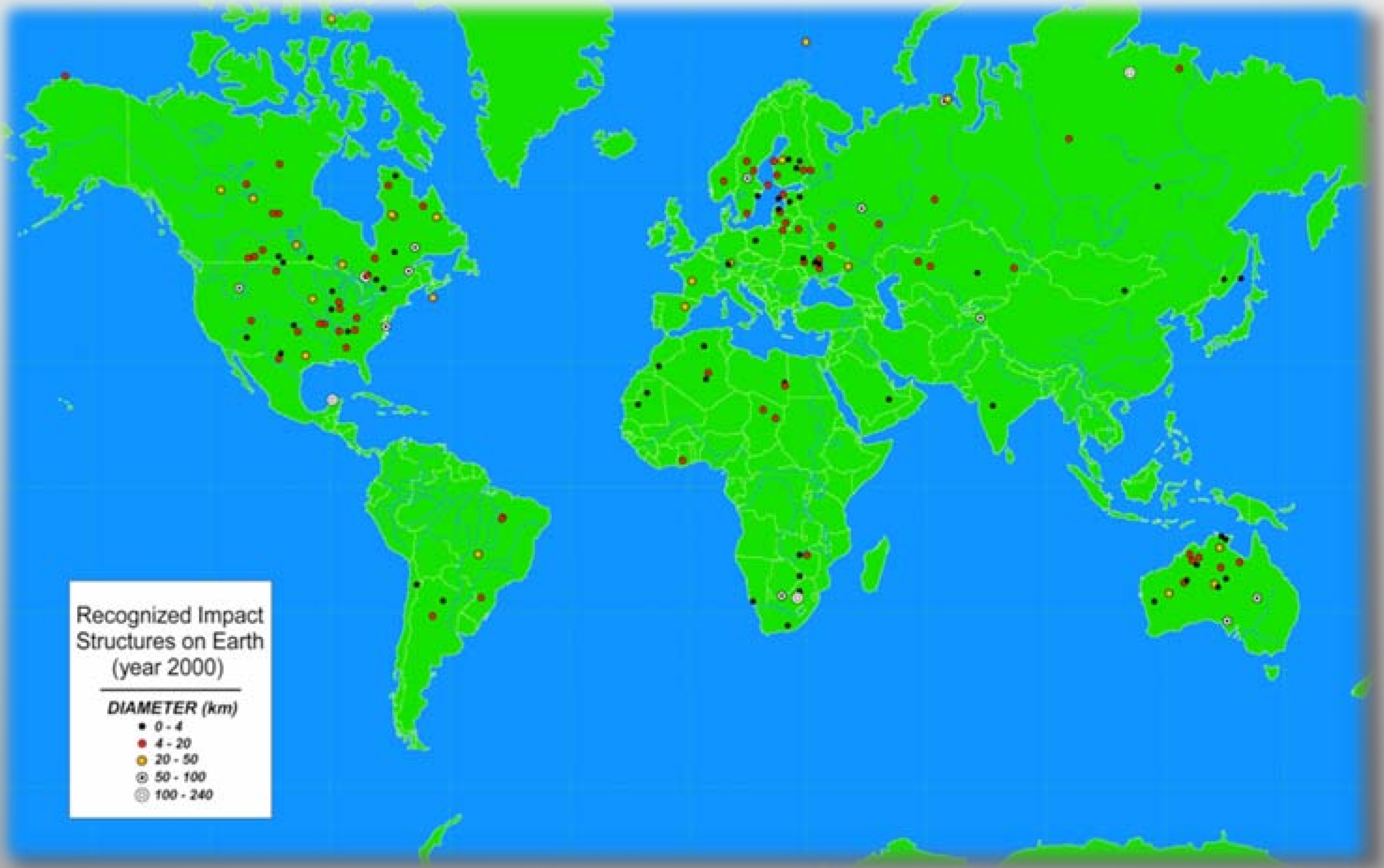
Shatter cones - Evidence for an impact crater



World map distribution of shatter cones, , Dietz, 1984, Meteoritics
Dietz, 1947 – Association of shatter cones with meteoritic impacts.

Since the 80’s, shatter cones have been clearly seen as one of the evidence on the field for an impact crater.

Shatter cones - Evidence for an impact crater



World map distribution impact crater

Since the 80's, shatter cones have been clearly seen as one of the evidence on the field for an impact crater.

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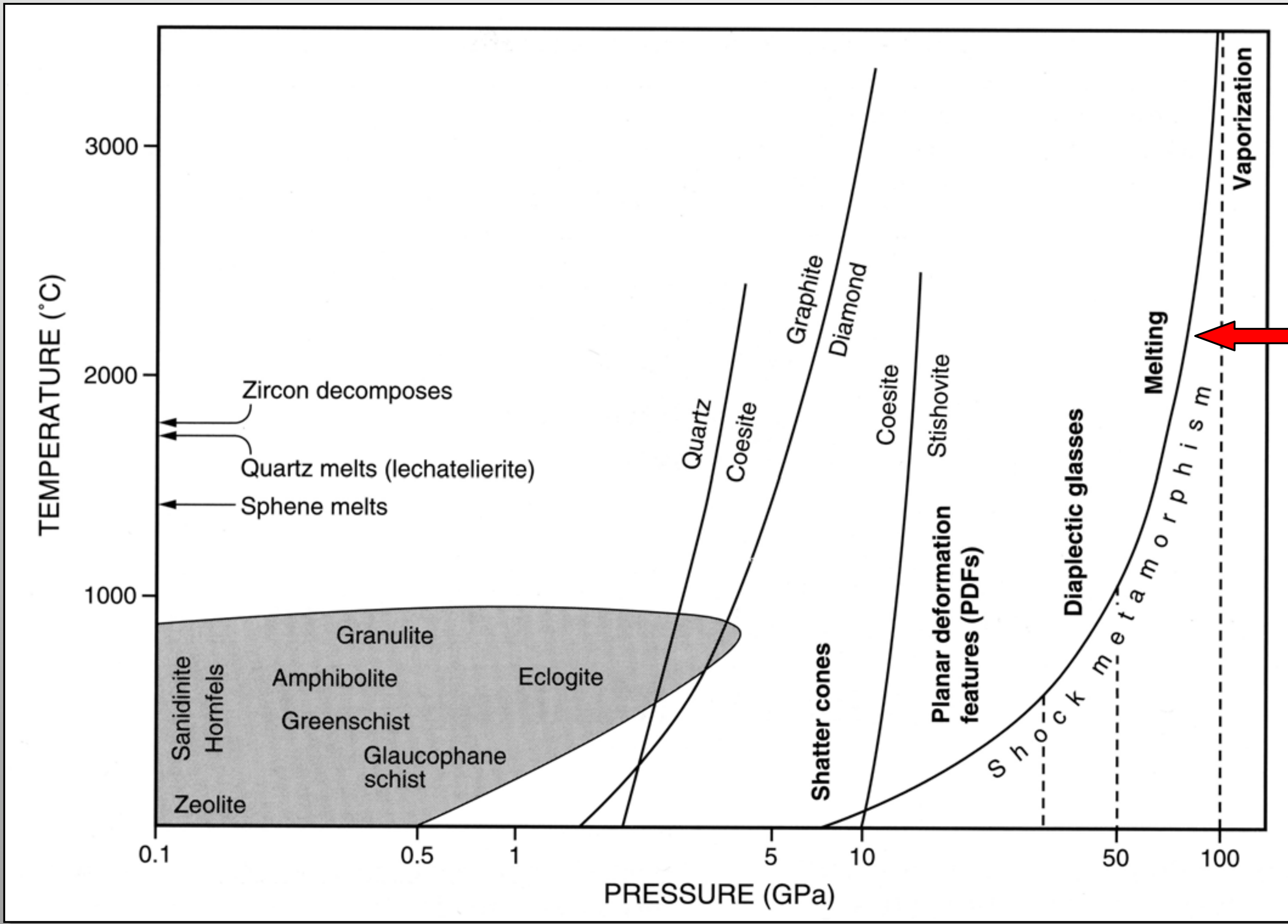
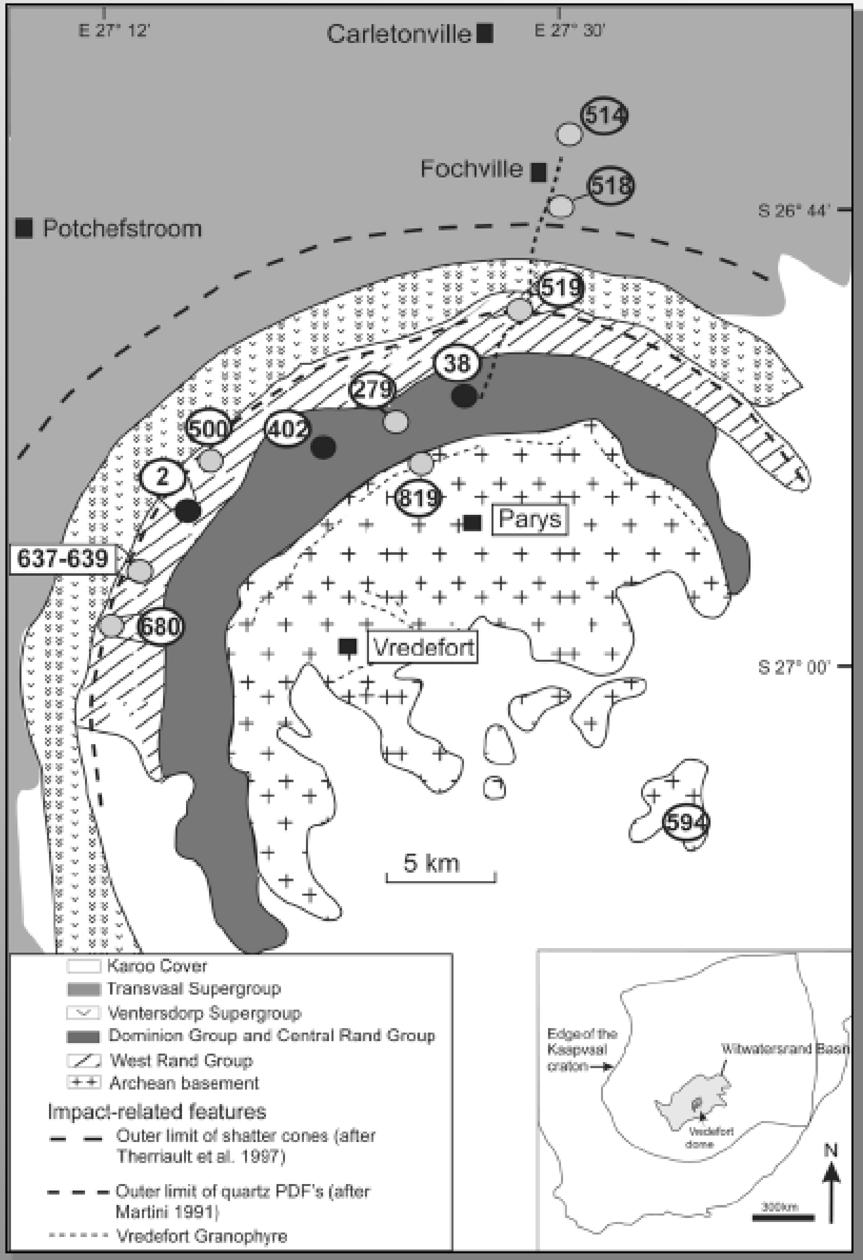
Impact metamorphism



Post – shock temperature

Impact metamorphism

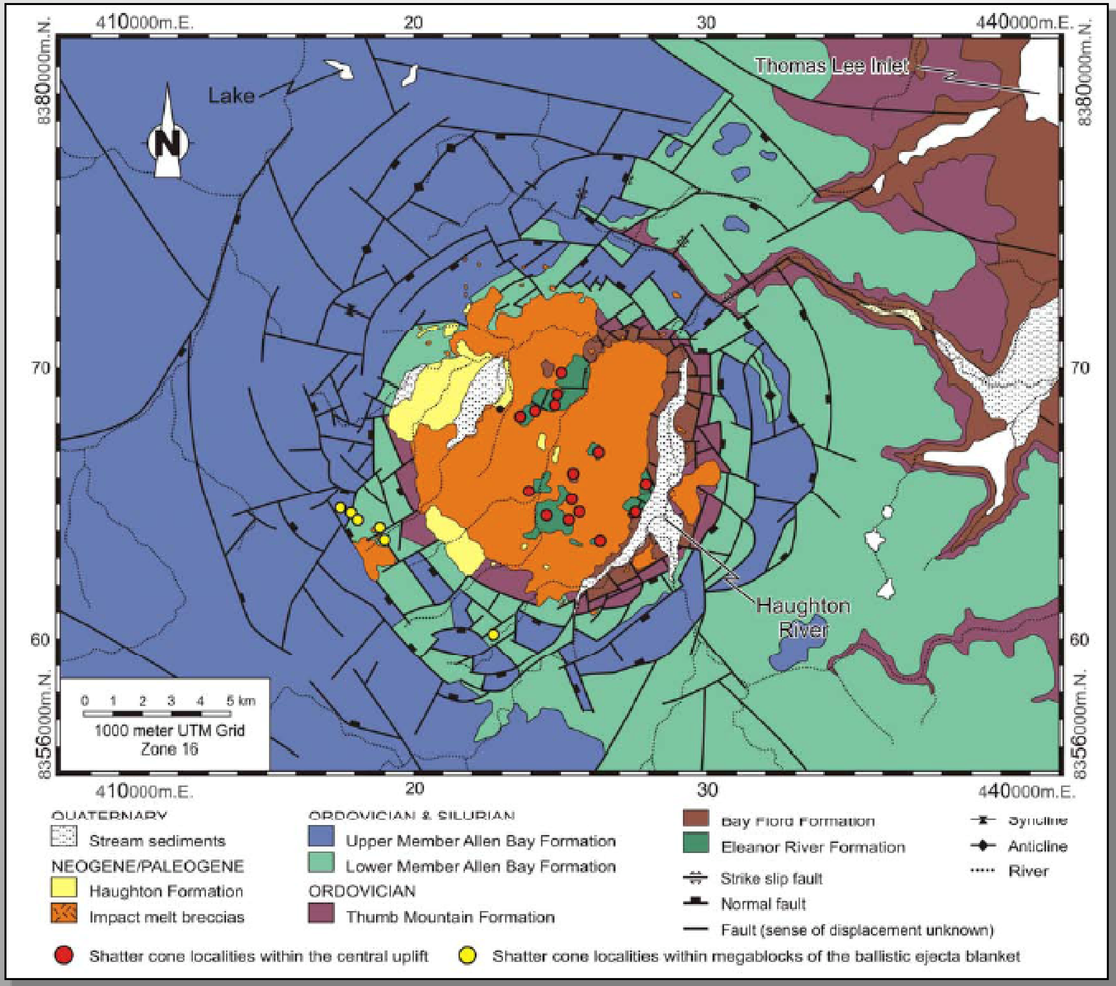
Where can you find shatter cones ?



Shatter cones at Vrederfort are found at distances ranging from 10 – 60 km from the center of the crater.

Shatter cones are generally found with a precise range from the center of the crater.

Where can you find shatter cones ?



Distribution of shatter cones in the Haughton impact structure, Canada.

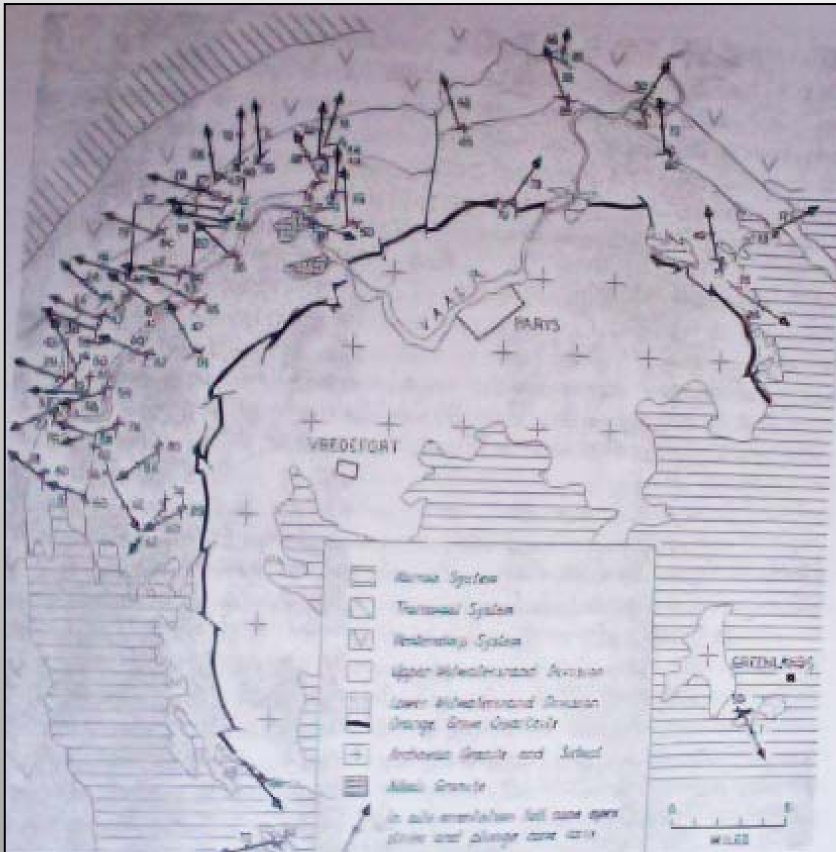
Shatter cones are found

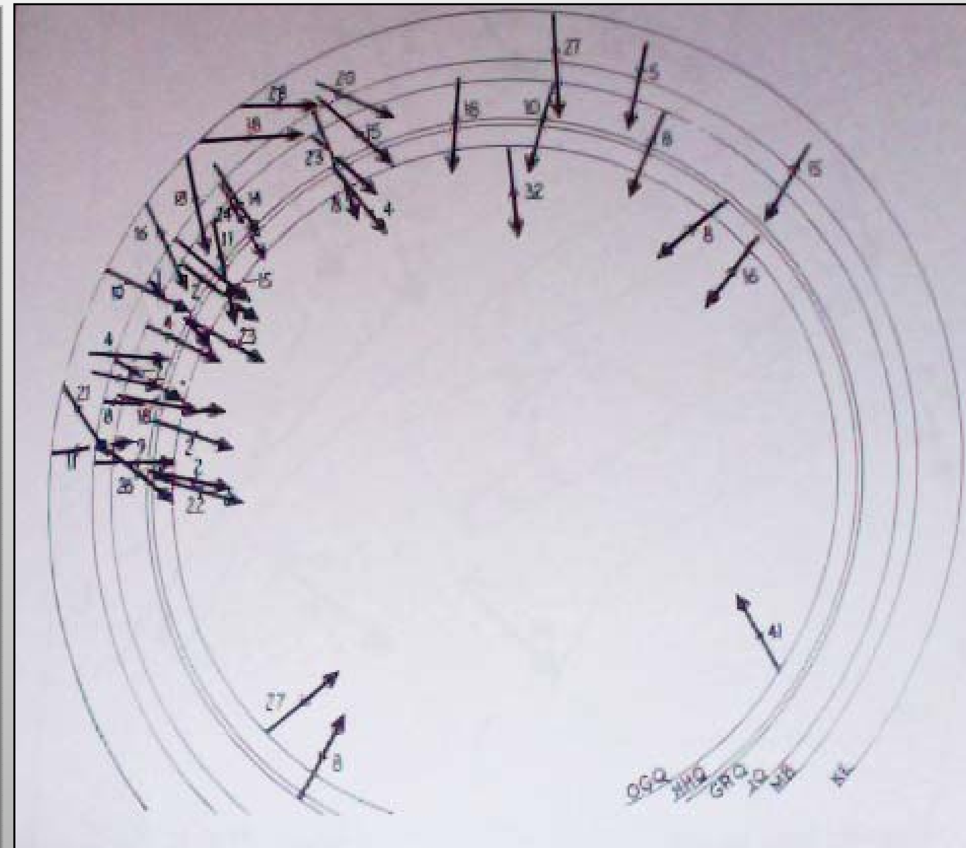
-In place in the central uplift
-Within ejecta blocks

Osinski and Spray, 2006 (ESA Conference)

Compilation of pressure ranges at various sites indicate values between 1 GPa (10kbars) and 20 GPa (200 kbars).

Orientation of shatter cones apices





Manton, 1977

Orientation of shatter cone apices point toward the center of the crater (after rotation of the bedding).

Shatter cones – how big ?

Sudbury, Ontario, Canada
12 meters high shatter cones

Shatter cones – how big ?

As small as few centimeter or even millimeters

Samples from Steinheim impact crater (Germany)

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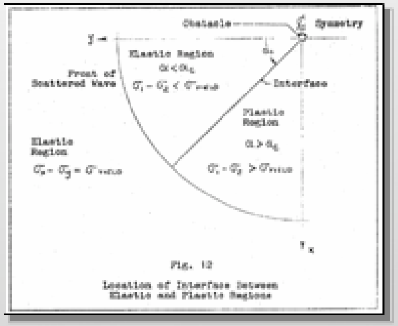
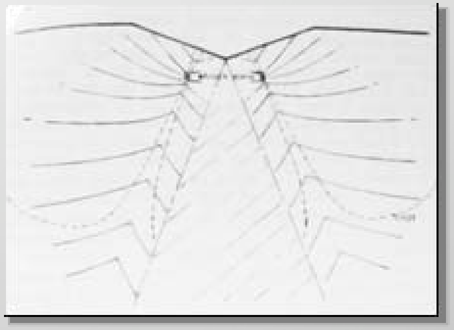
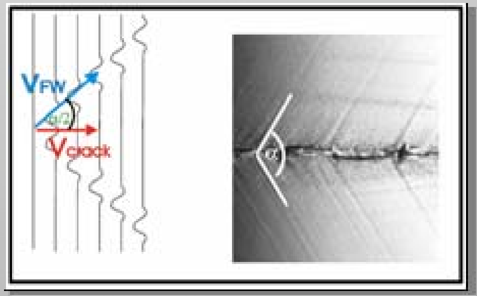
Models for the formation of shatter cones

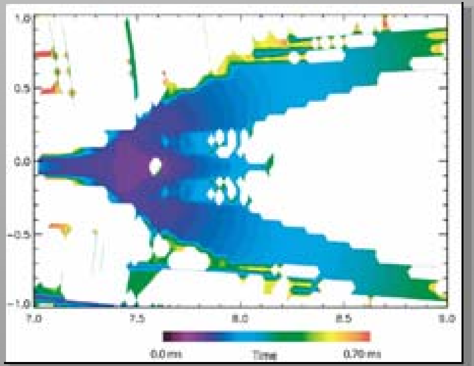




1) Previous ideas
   - Johnson and Talbot (1964)
   - Gash (1971)



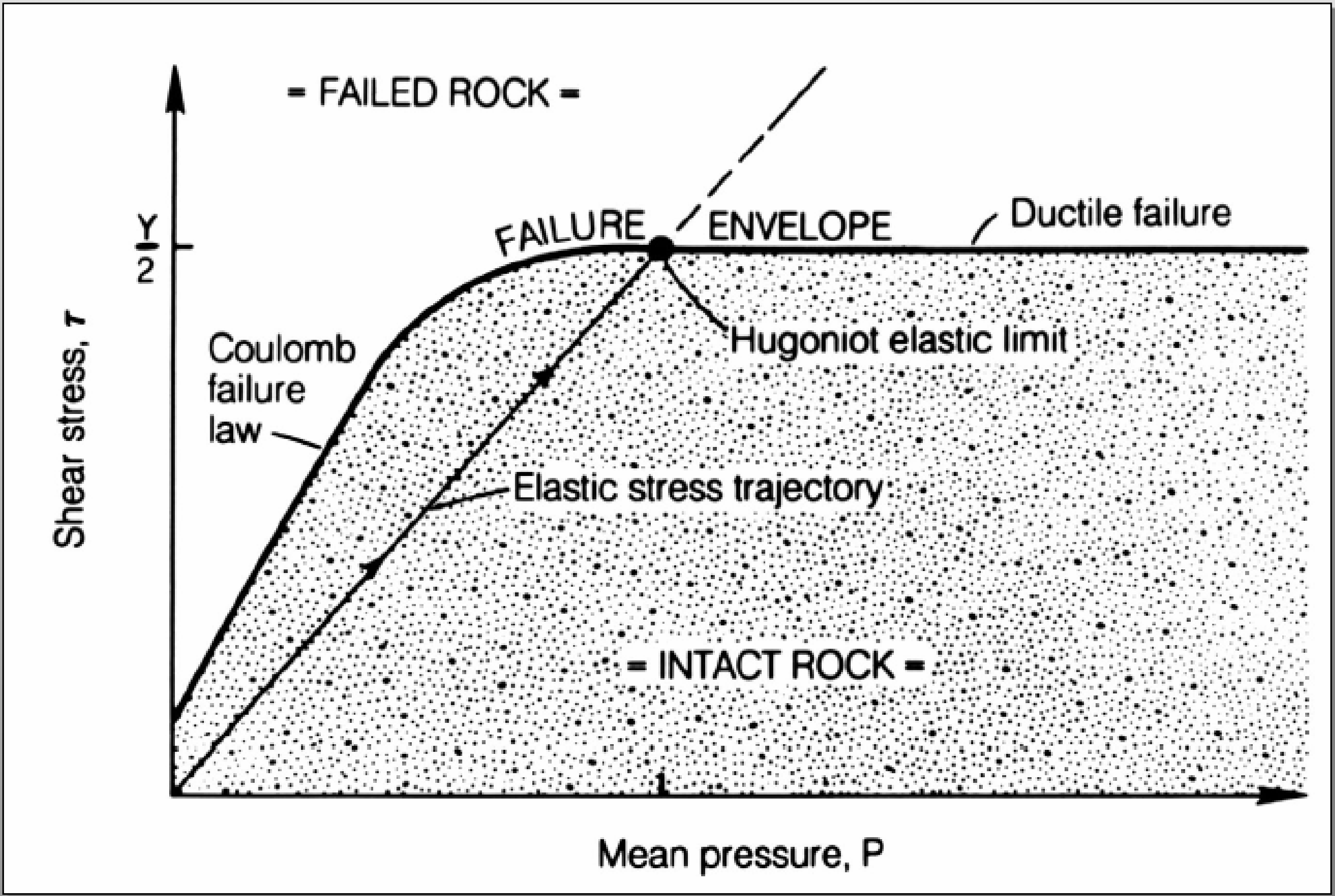
2) Front waves (Sagy and Reeches, 2002)



3) Baratoux and Melosh (2003)

Models for the formation of shatter cones

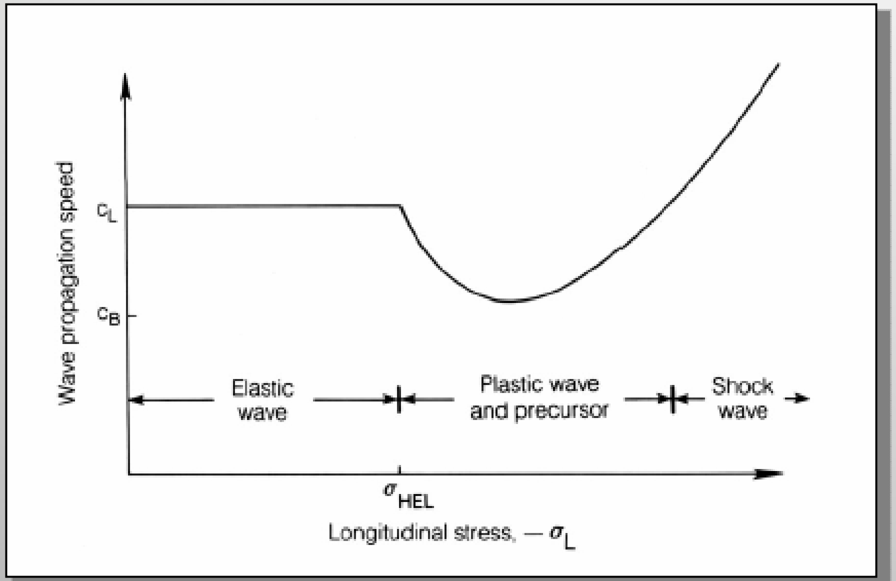
Some background about shock wave propagation

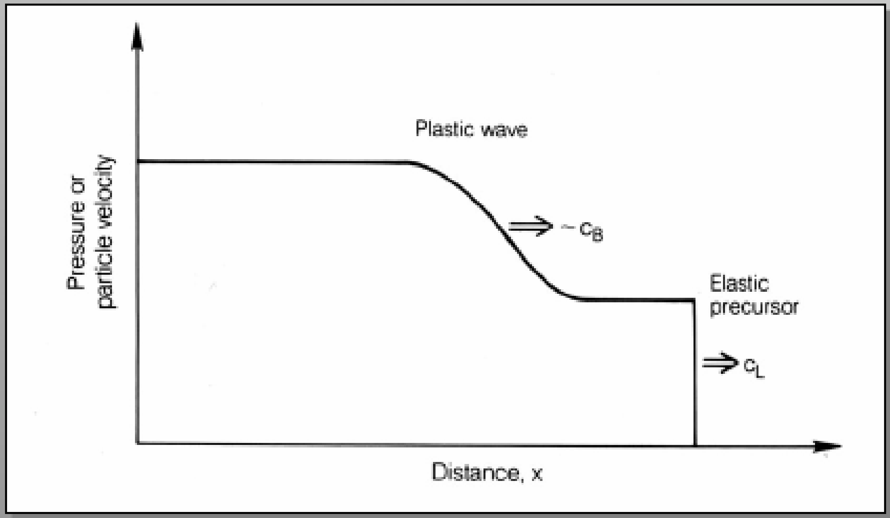


Melosh, 1989

Models for the formation of shatter cones

Some background about shock wave propagation





Melosh, 1989

Three regimes:

- Low pressure(< HEL) Elastic waves (speed: C_L)

- Intermediate pressure < Gpa Plastic wave with propagation speed lower than the elastic wave. Elastic precursor + plastic wave.

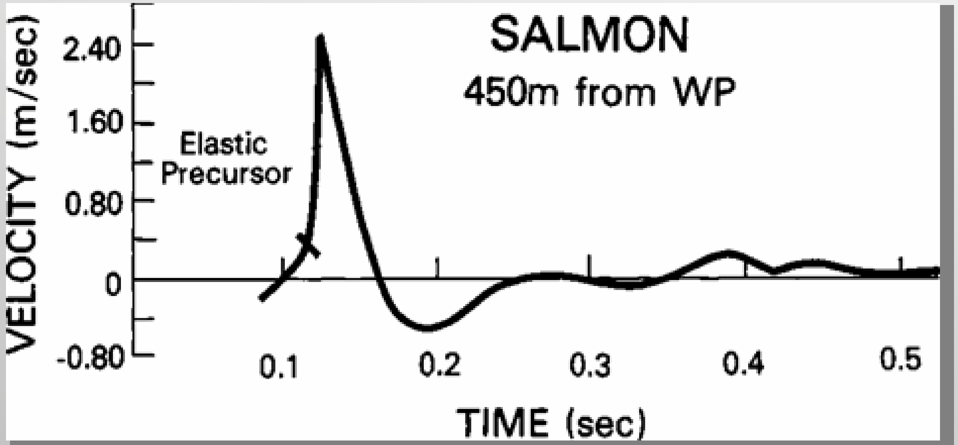
- High pressure >> GPa Shock wave propagating at a velocity greater than the elastic wave.

$$c_L = \sqrt{\frac{K_0 + \frac{4}{3}\mu}{\rho_0}}$$

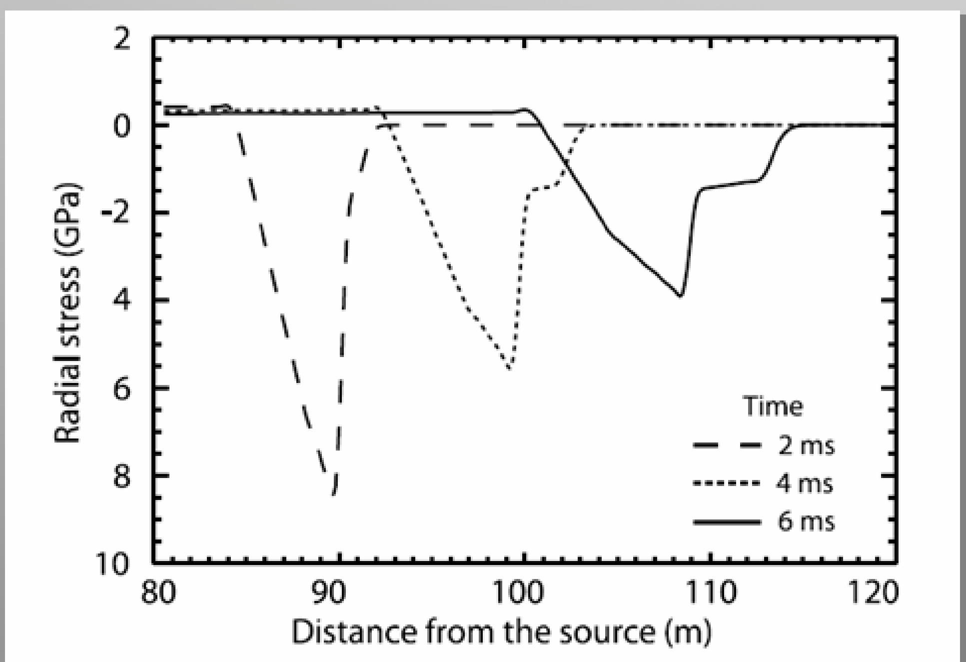
K_0: Bulk modulus
μ: Shear modulus

Models for the formation of shatter cones

Some background about shock wave propagation



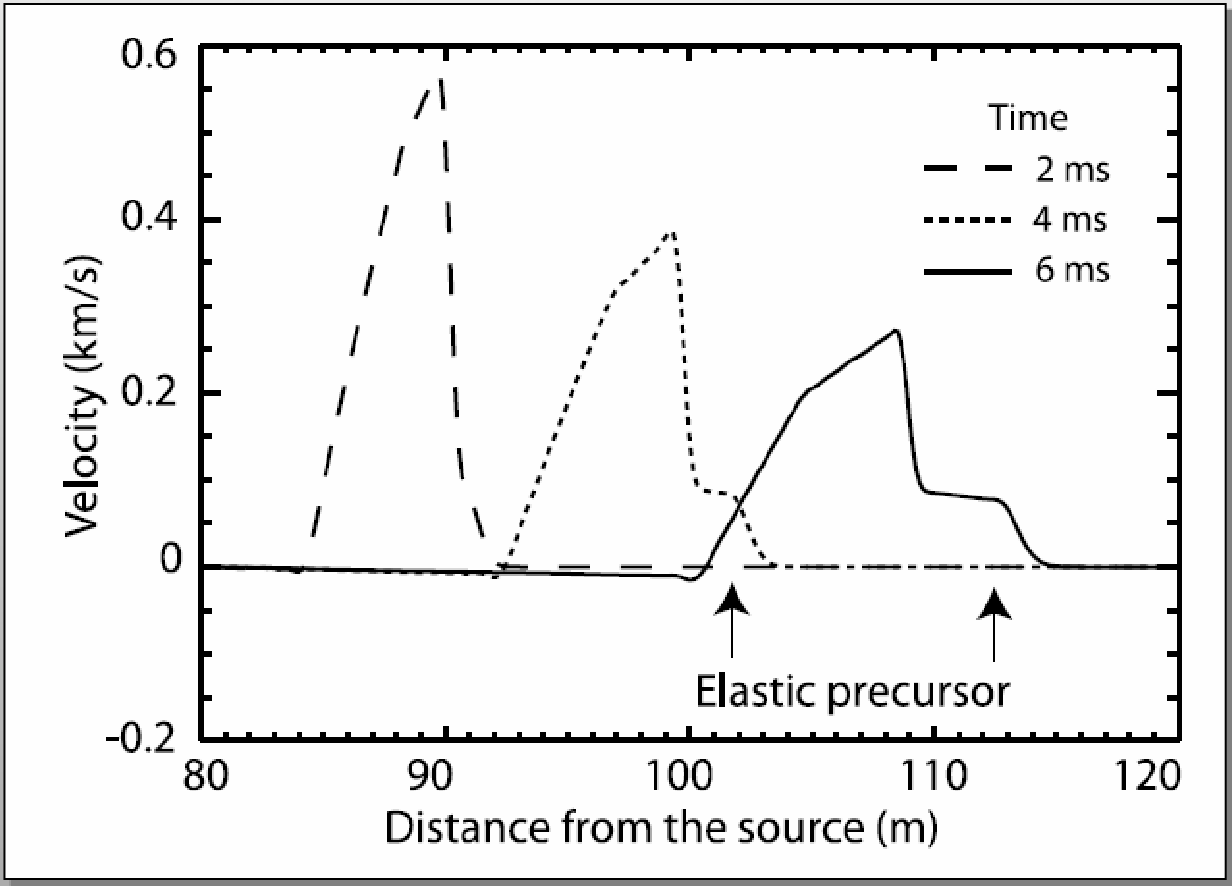
Elastic precursor in nuclear tests
Melosh, JAP, 2003.



Elastic precursor in numerical simulations
Baratoux and Melosh, EPSL, 2003.

Models for the formation of shatter cones

Stress distribution during the spherical propagation of a shock wave



Material properties in the one-dimensional simulation of the propagation of a spherical shock wave				
Density (kg/m^3)	Bulk modulus (GPa)	Shear modulus (GPa)	Murnhagan exponent	Hugoniot elastic limit (GPa)
3000	50	30	4	1

Baratoux and Melosh, 2003

Models for the formation of shatter cones

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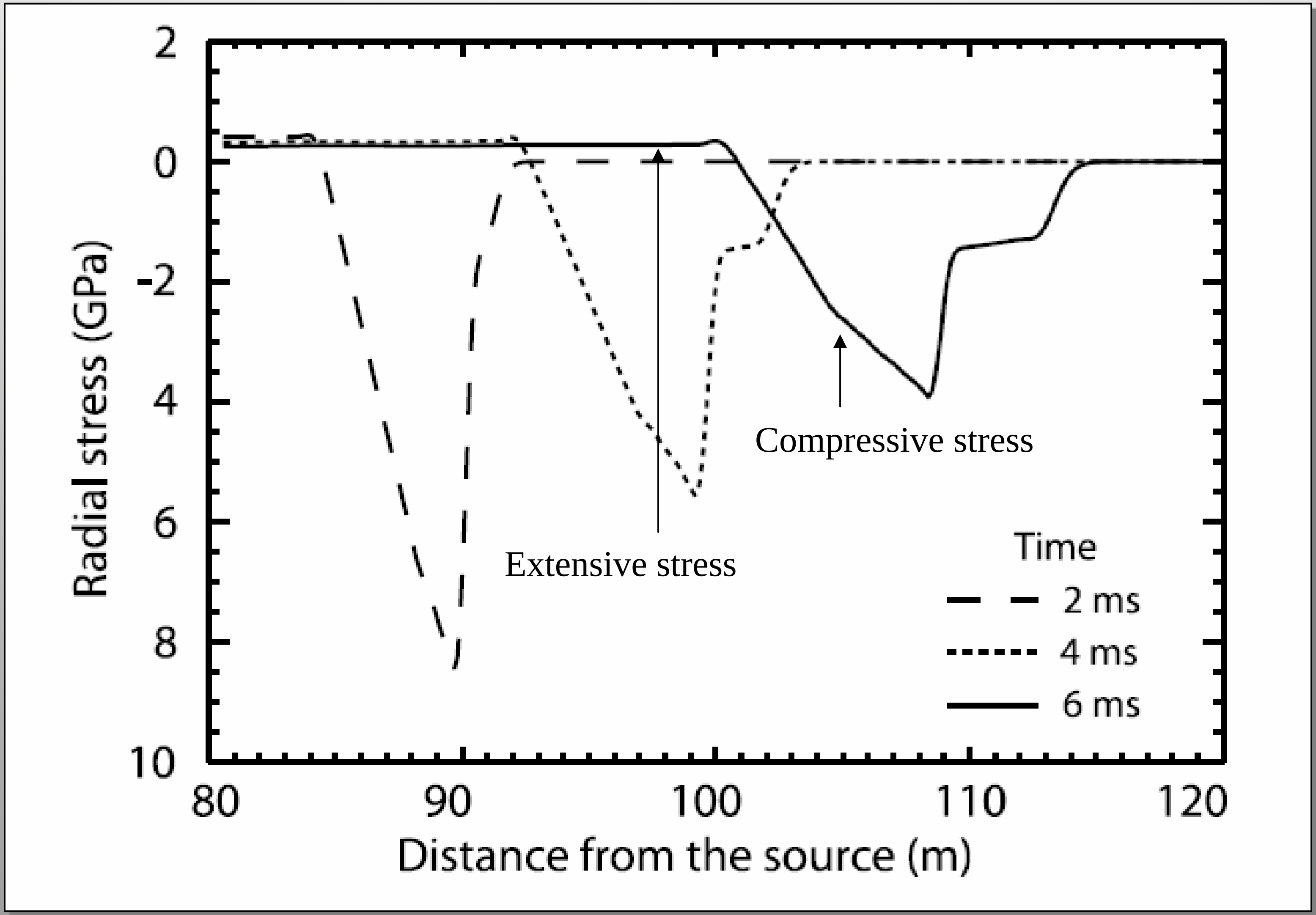

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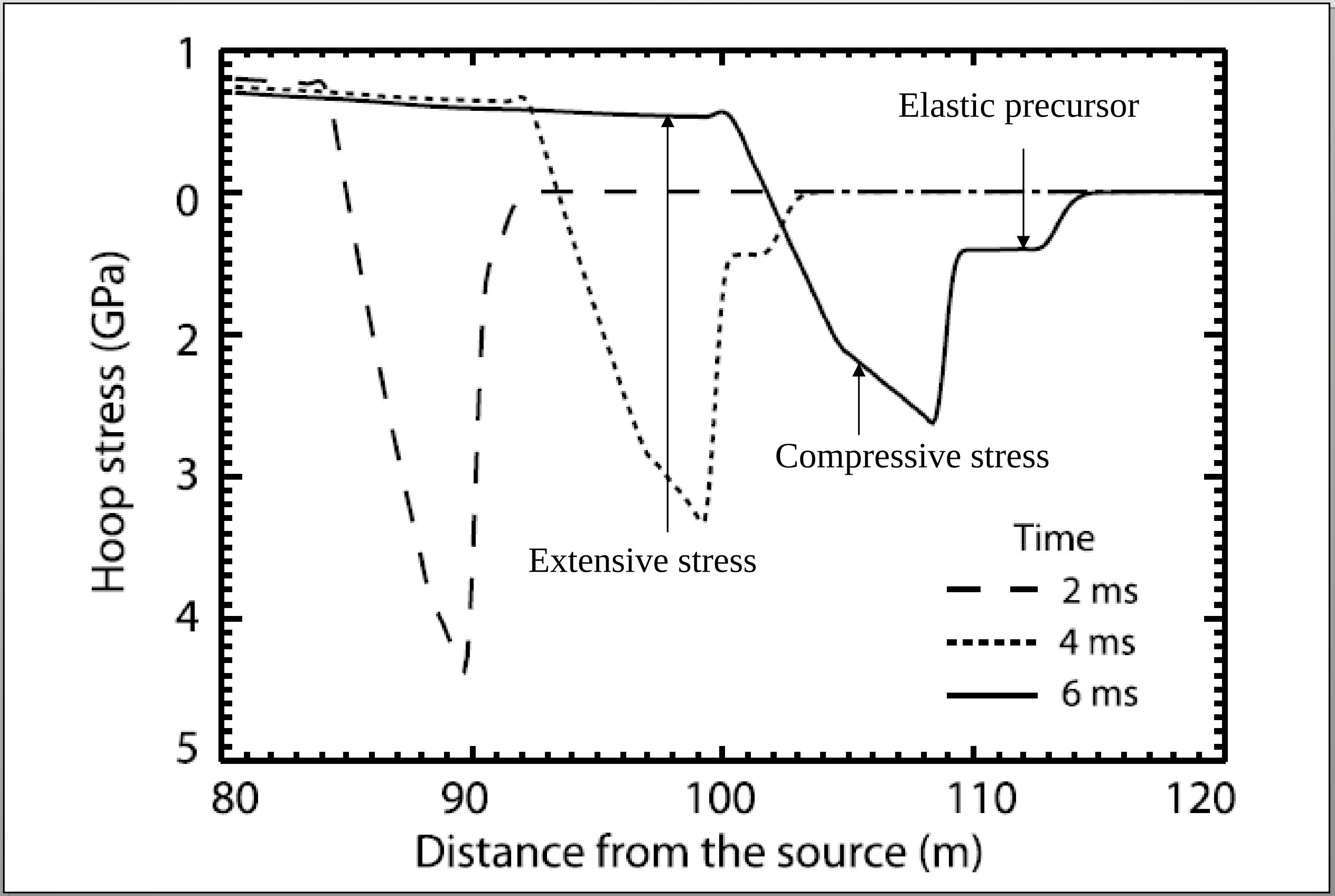
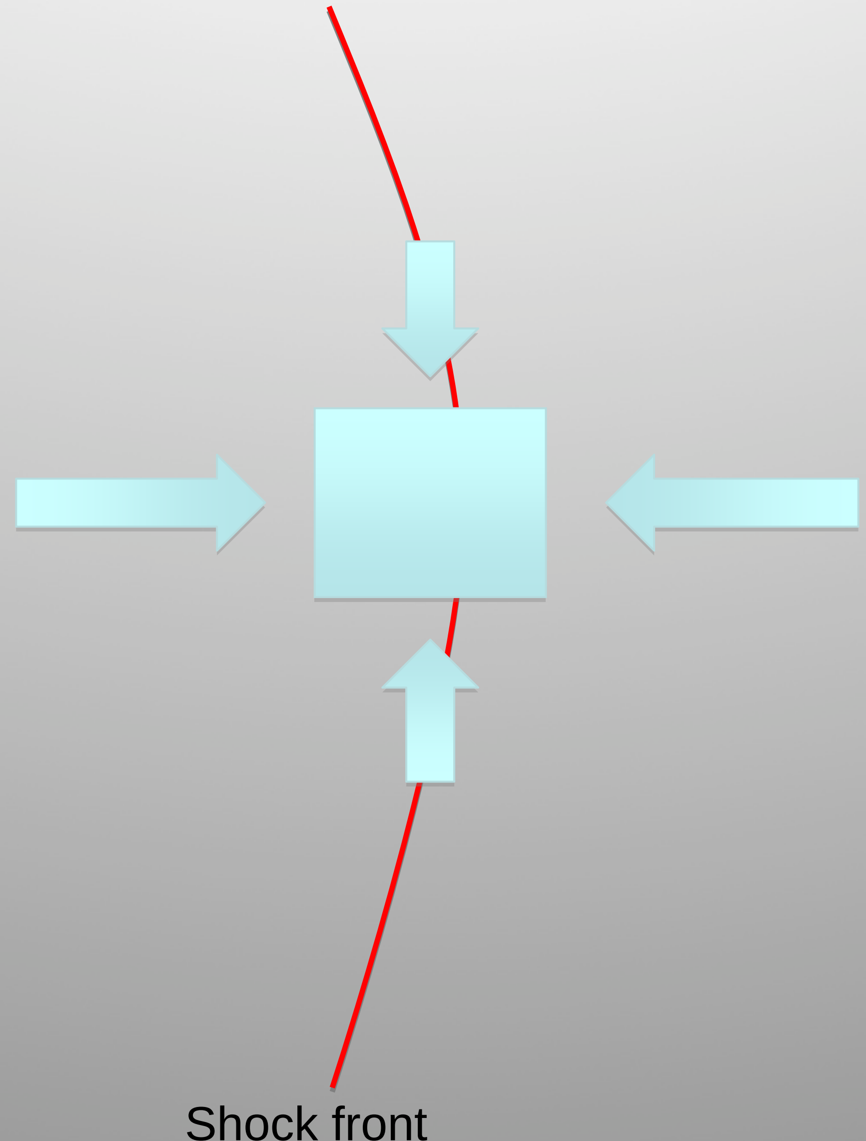


Baratoux and Melosh, 2003

Models for the formation of shatter cones

Stress distribution during the spherical propagation of a shock wave



Models for the formation of shatter cones

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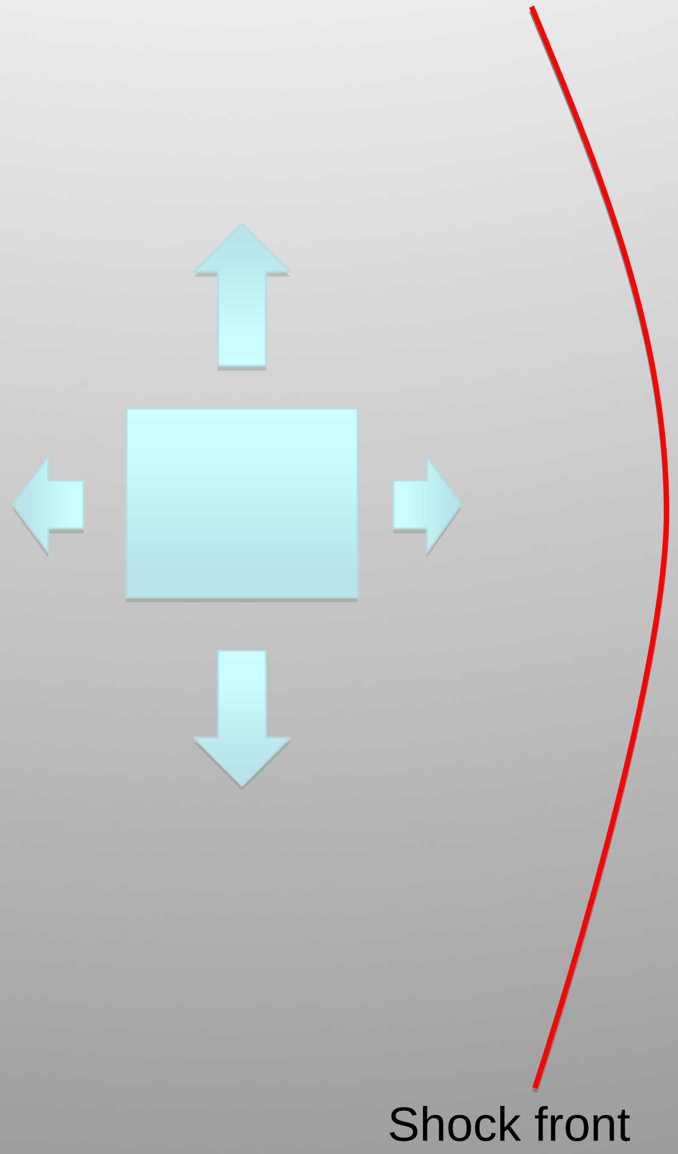
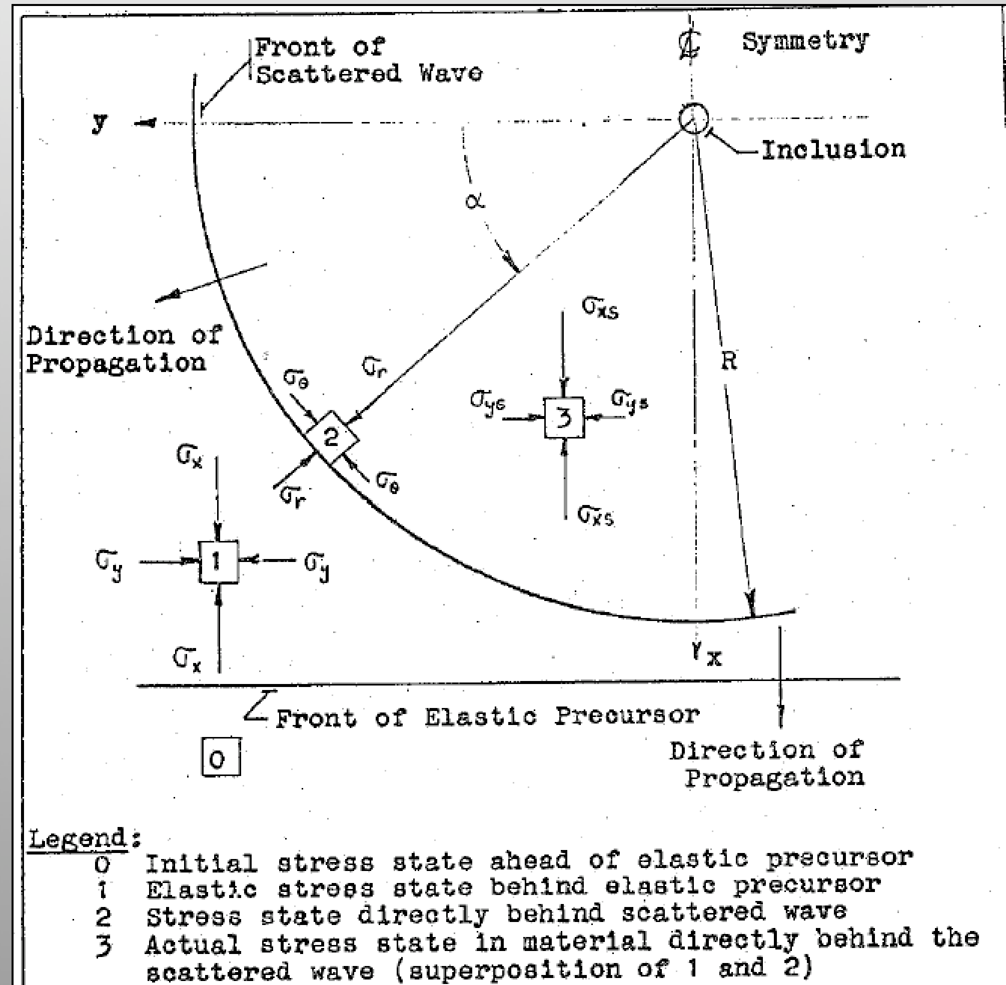


Johnson and Talbot (1964)

The elastic precursor

Starting point: Elastic precursor is scattered by a rock inclusion



Elastic stresses in the vicinity of an rock inclusion.

Johnson and Talbot (1964)
The elastic precursor

Consequence: Plastic yielding in a conical zone

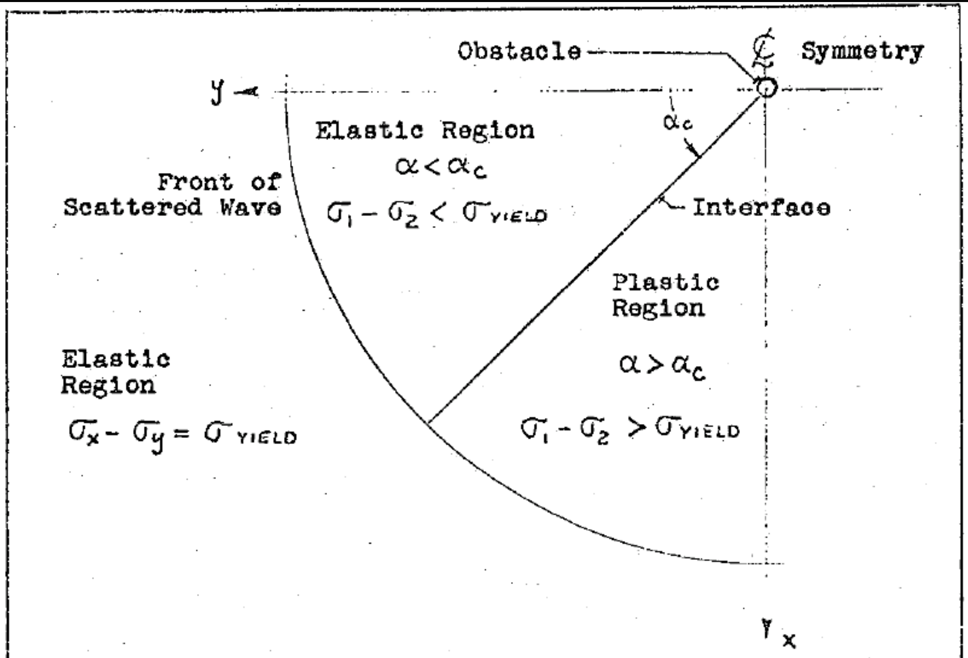


Fig. 12

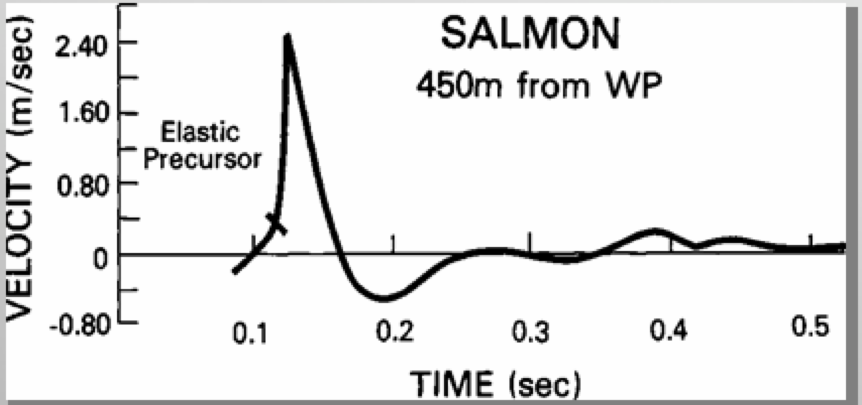
Location of Interface Between Elastic and Plastic Regions

Assumption : stress removal before the arrival of the main plastic wave
Elastic zone returns back to its initial state, but not the plastic zone
Separation or fracture occurs at the interface between the pastic zone and the elastic zone

Johnson and Talbot (1964)

The elastic precursor

Main problem: There is no stress removal before the arrival of the plastic wave. The whole rock will be exposed immediately after elastic precursor to higher stresses, and deformed plastically.



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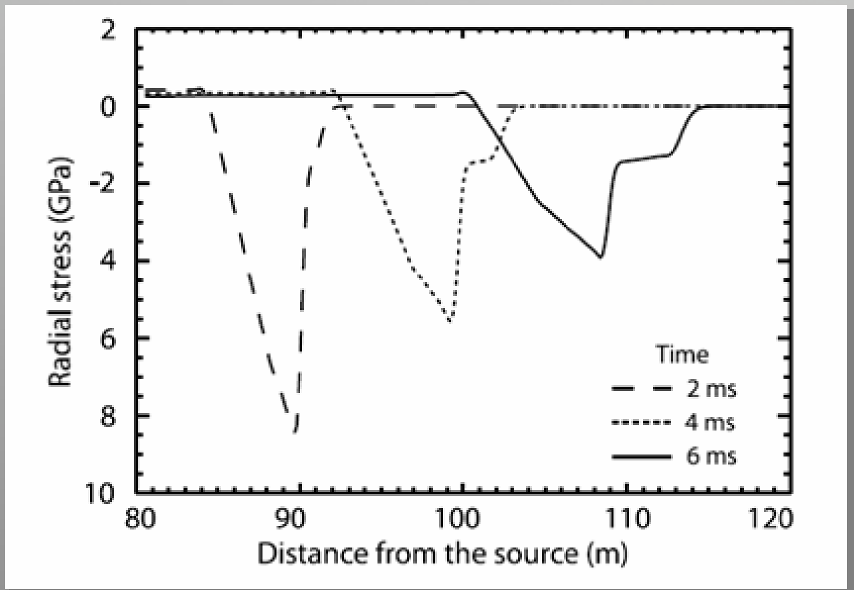
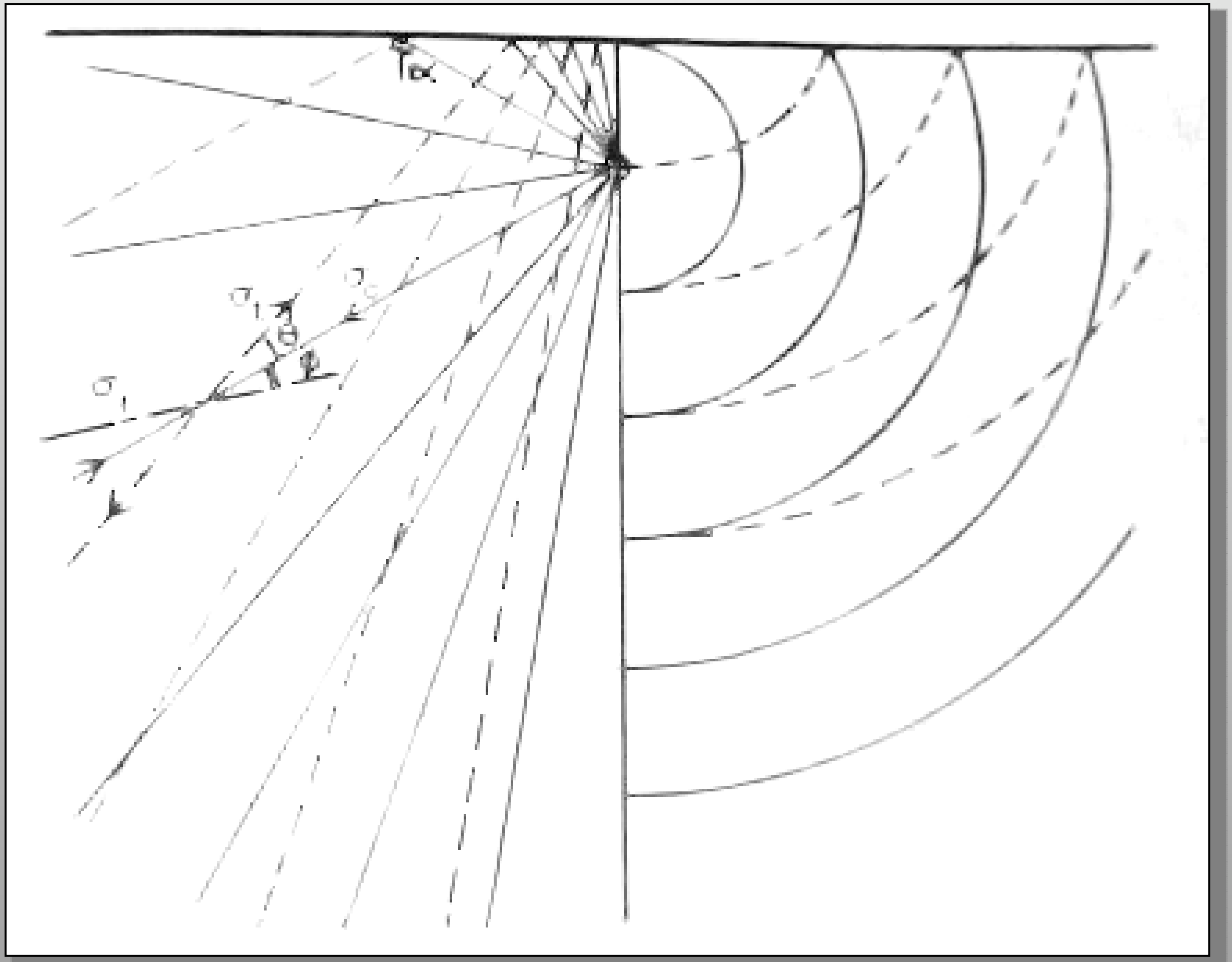


Elastic precursor in numerical simulations
Baratoux and Melosh, EPSL, 2003.

Gash - 1971

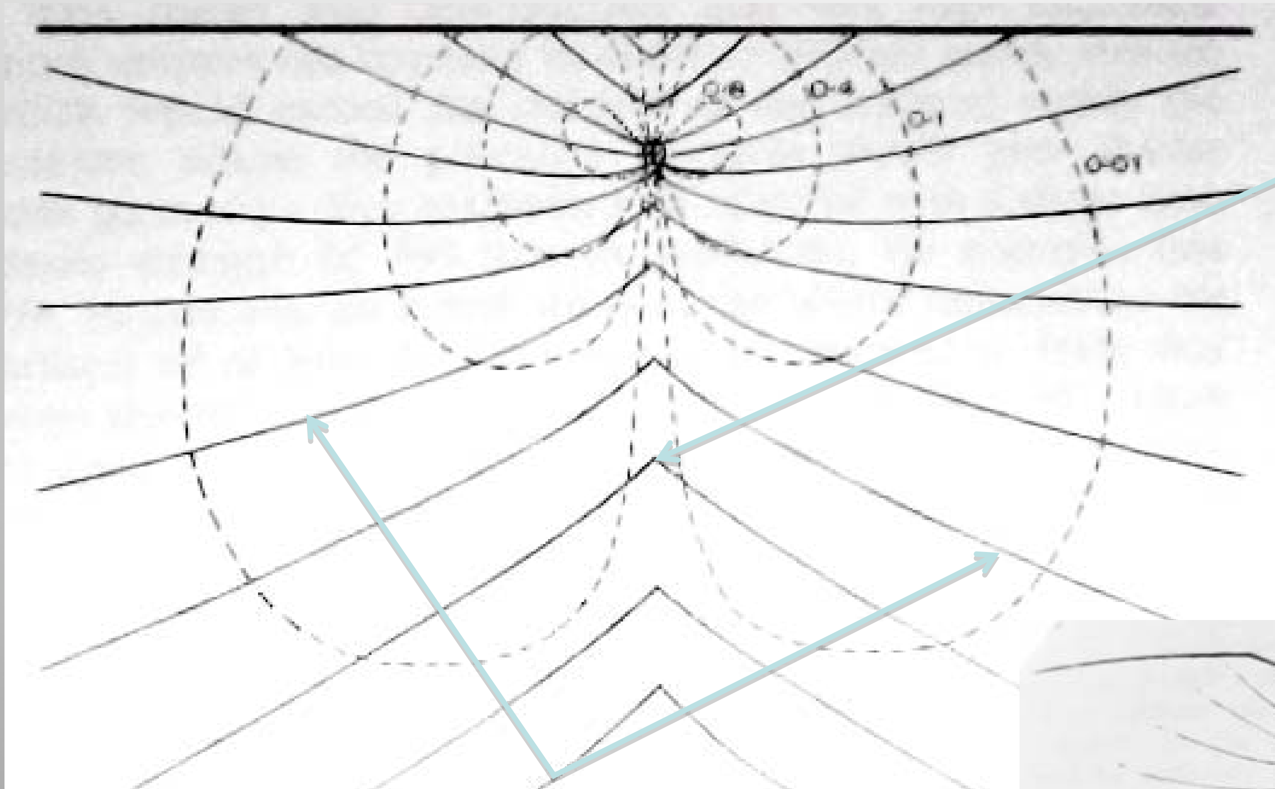
Interferences with reflected waves at the surface



Ray paths (left) and wave front (right) for a spherical wave stress emanating from a point source adjacent to a free surface. Incident stress (plain) and reflected stress (dashed)

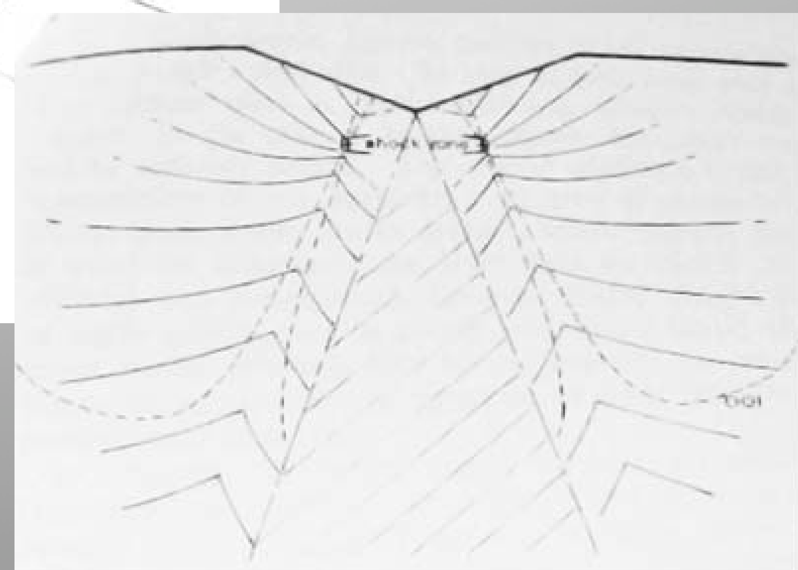
Gash - 1971

Interferences with reflected waves at the surface



"zero stress corridor"

Possible planes of fractures forming a (non complete) conical surface



σ_1 trajectories (fracture plane are // to σ_1 for fracture resulting from tensile stress)

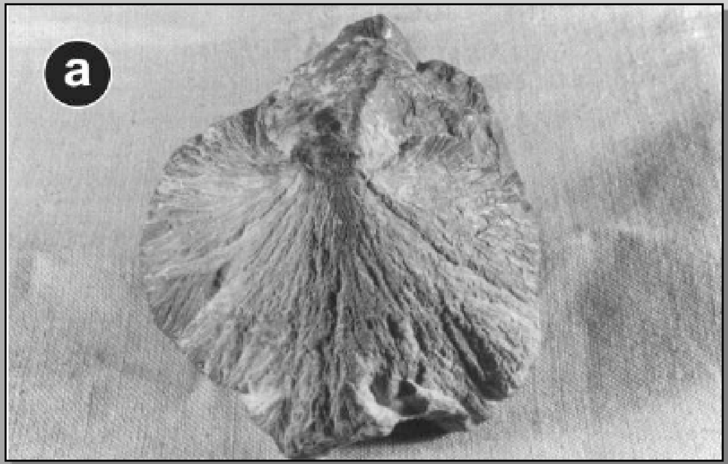
Contour for σ_3 values.

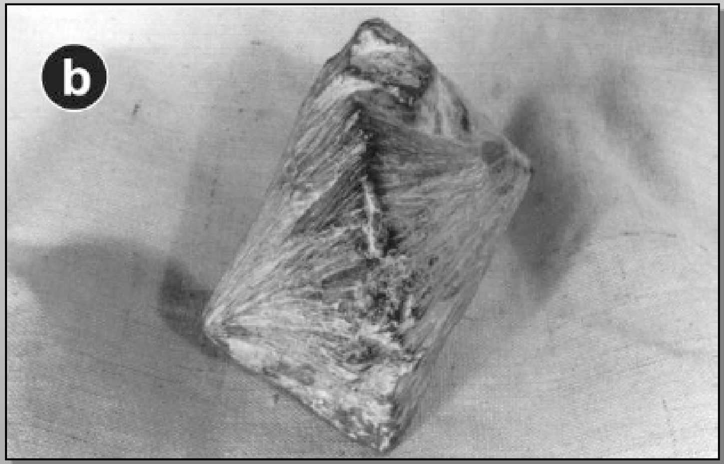
Gash - 1971

Interferences with reflected waves at the surface

This model has actually received little attention by other authors…
No real discussion of this model can be found in the literature.

I see two main problems :
Complete cones are impossible to form with this model, as there is no stress when the conical surface intercepts, as mentioned by the authors. Complete cones are rare indeed but they do exist!



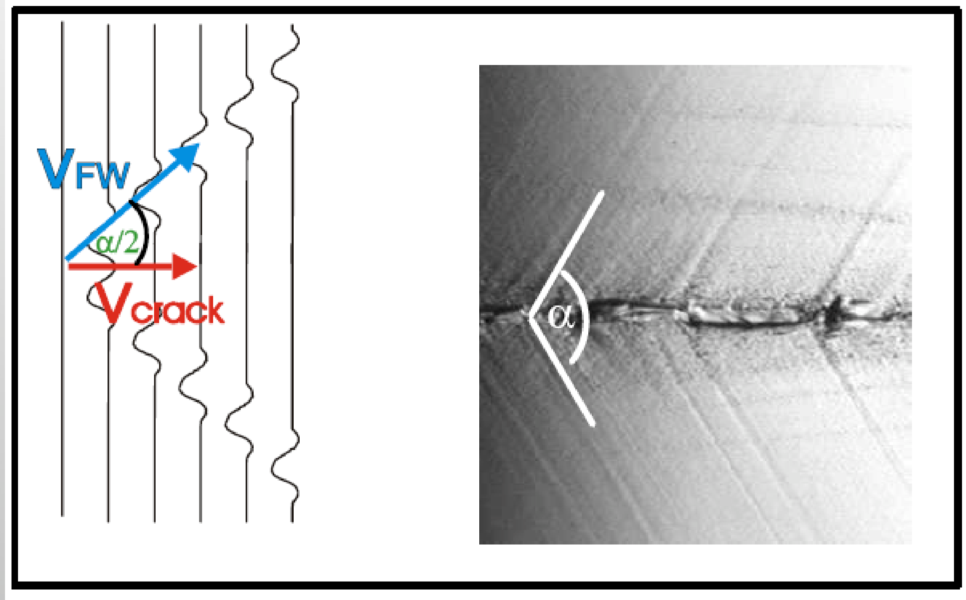


Orientations of shatter cones usually indicate that apices point toward the center of the crater, (ie, the source of the main shock wave) which is in contradiction with the prediction of this model.

Front wave

Sagy and Reeches, 2002, 2004

Theoretical studies [Ramanathan and Fisher, 1997; Morrissey and Rice, 1998, 2000], and experimental work [Sharon et al., 2001, 2002] have revealed a **new type of localized wave, termed a ‘‘front wave’’ (FW**), which is excited when a rapidly moving fracture front encounters an **inhomogeneity** in the material.



Inhomogeneity will induce a pair of propagating front waves that create **a pair of tracks** on the fracture surface emanating **from inhomogeneity** [Sharon et al., 2001, 2002].

V : Velocity of the fracture front

V_{FW} : Velocity of the front wave

= 0.96 – 1.0 Rayleigh wave velocity.

$$\cos(\alpha/2)=V/V_{FW}$$

Rayleigh wave velocity : maximum velocity at which a crack can propagate, independent of shock pressure).

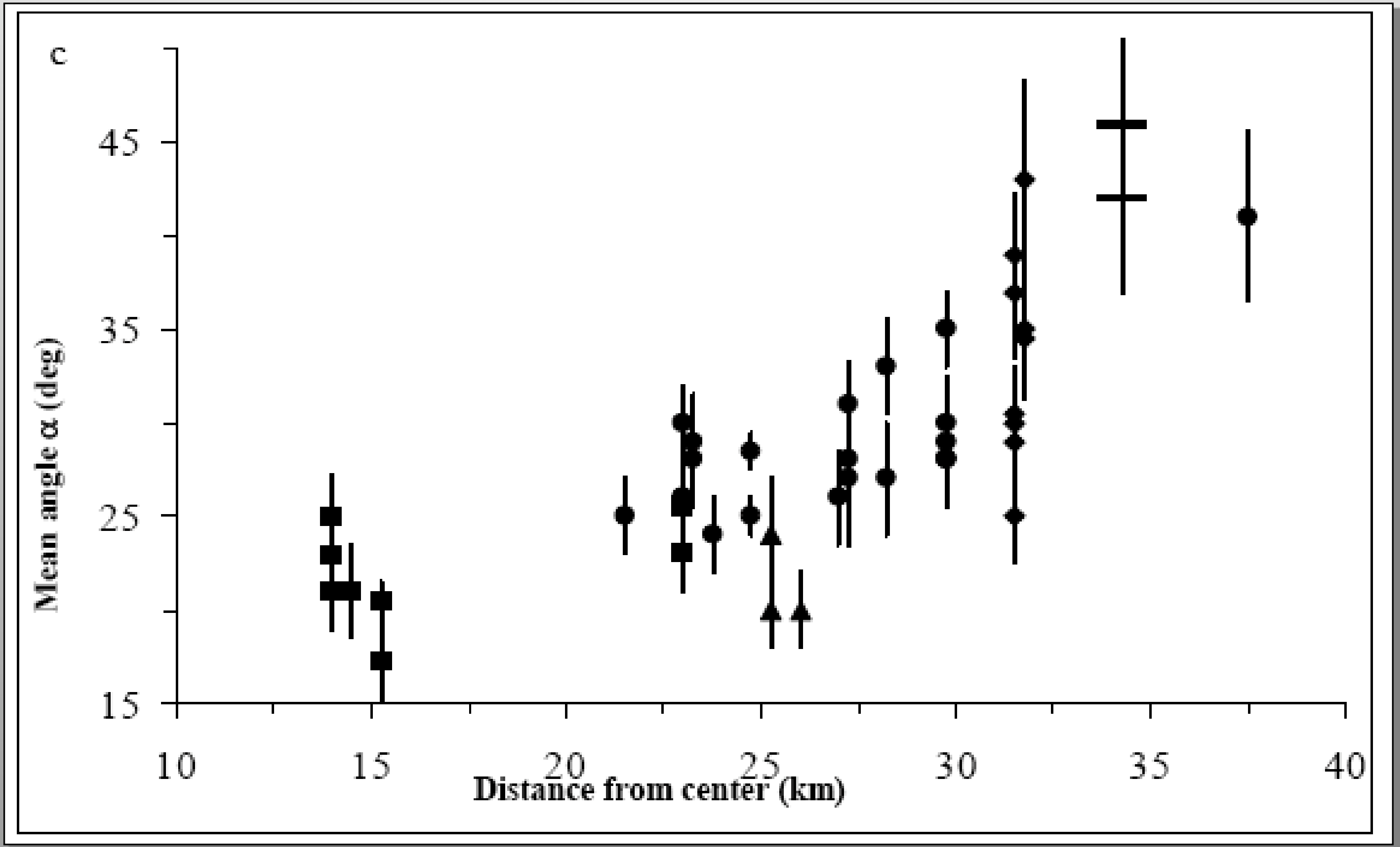
An important prediction of this model:

The fracture velocity will decrease with the decreasing stress away from the center

〈 should increase with the distance to the center of the crater

Front wave

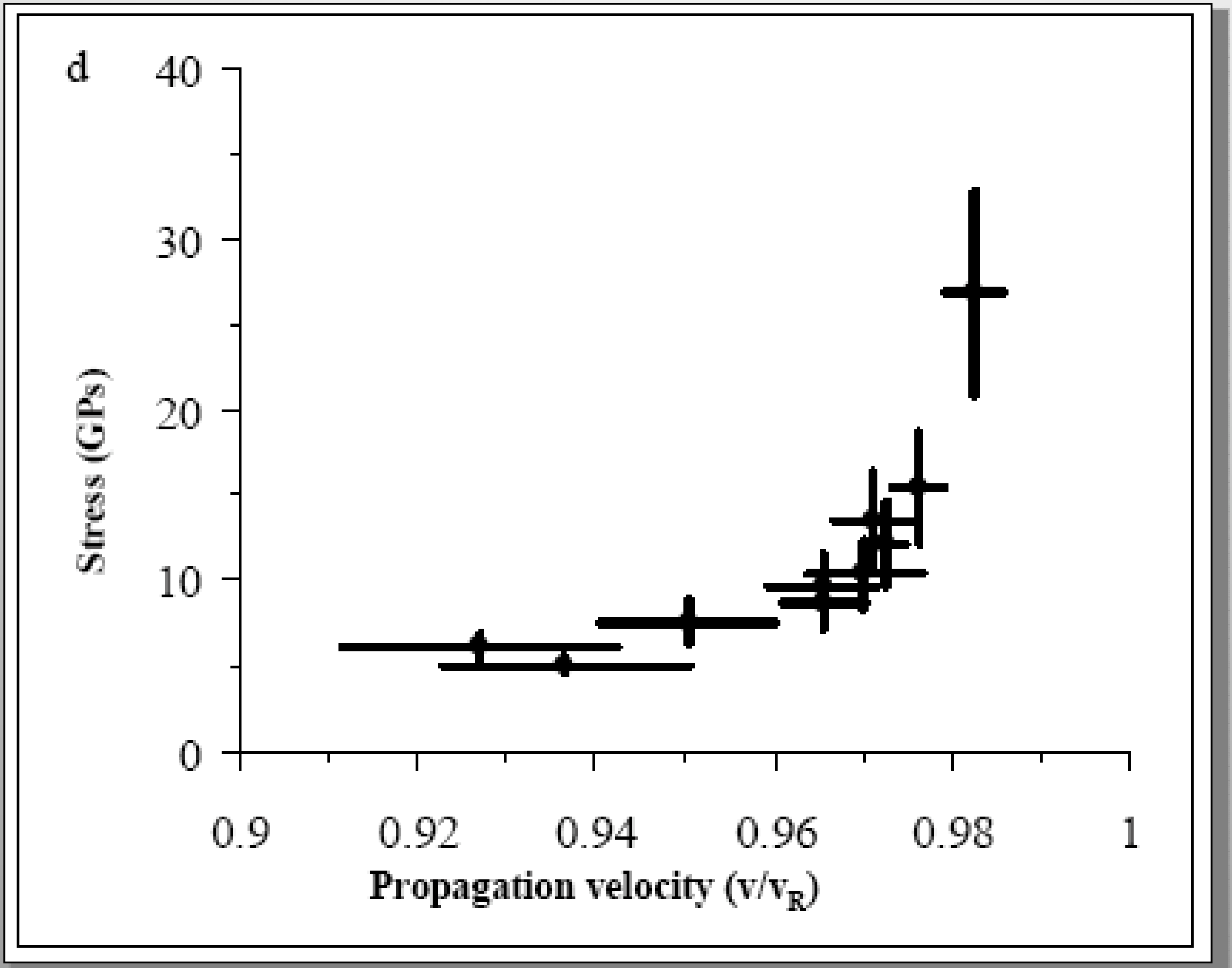
Sagy and Reeches, 2002, 2004



Observations: increase of the striation angle with the distance to the center of the crater (Sagy et al., 2002, 2004).

Front wave

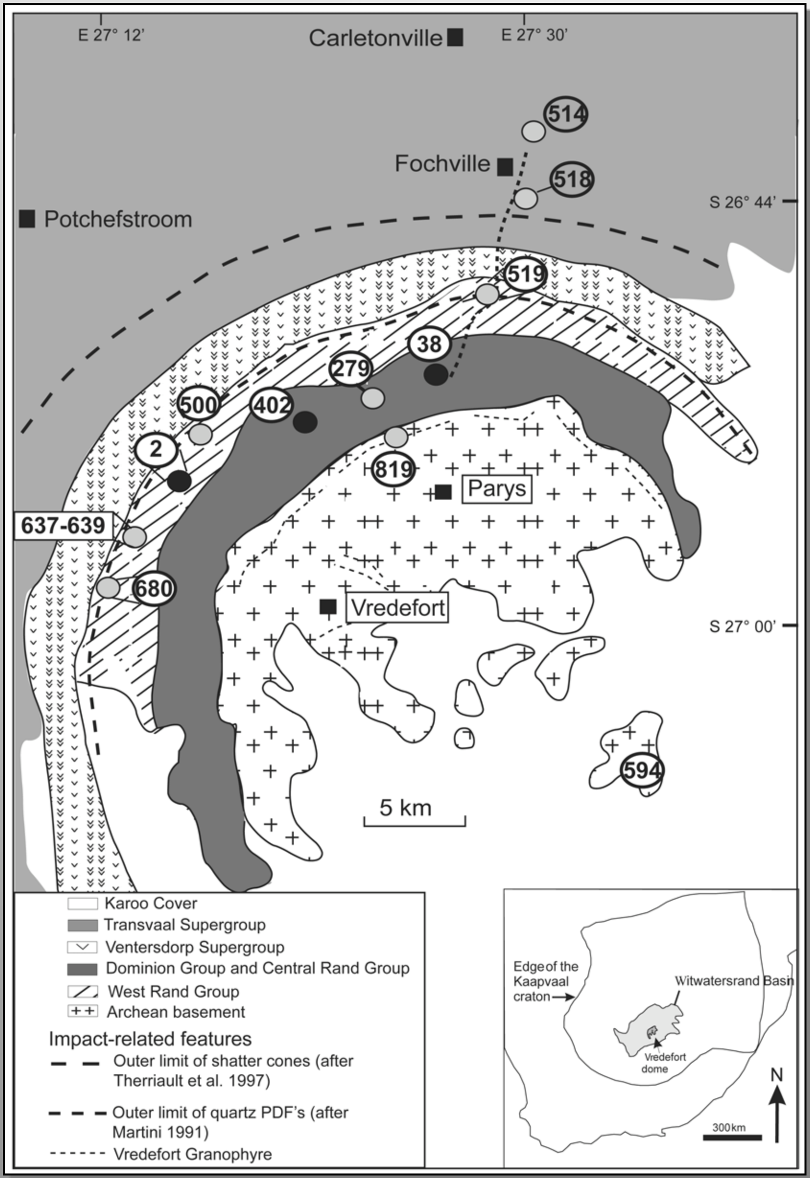
Sagy and Reeches, 2002, 2004



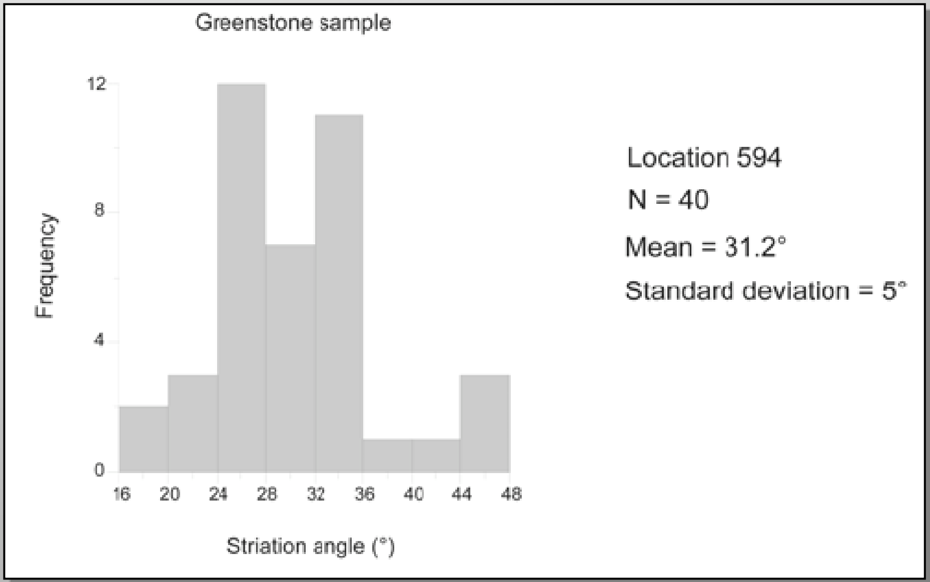
Internal consistency: Relation between crack velocity and compressive stress (estimated from numerical modeling of Vredefort impact crater). Sagy et al., 2004.

Front wave – Difficulties..

Sagy and Reeches, 2002, 2004



Careful analysis of the distribution of striation angles for each outcrop.

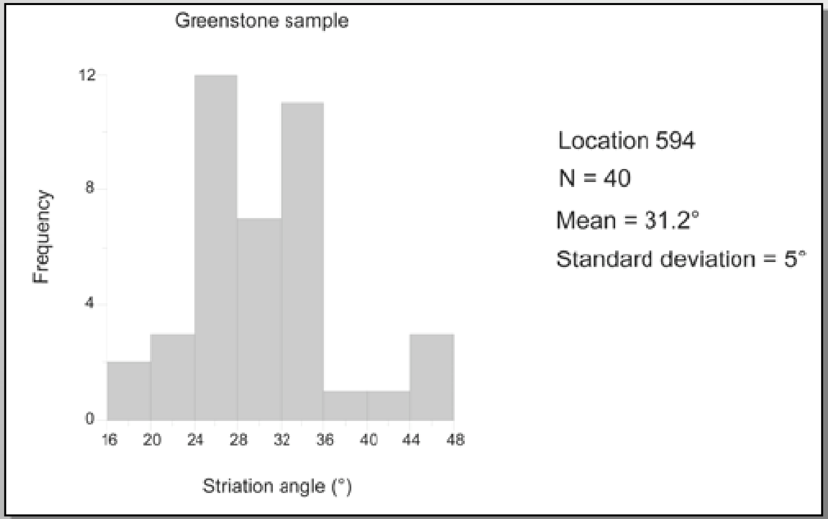


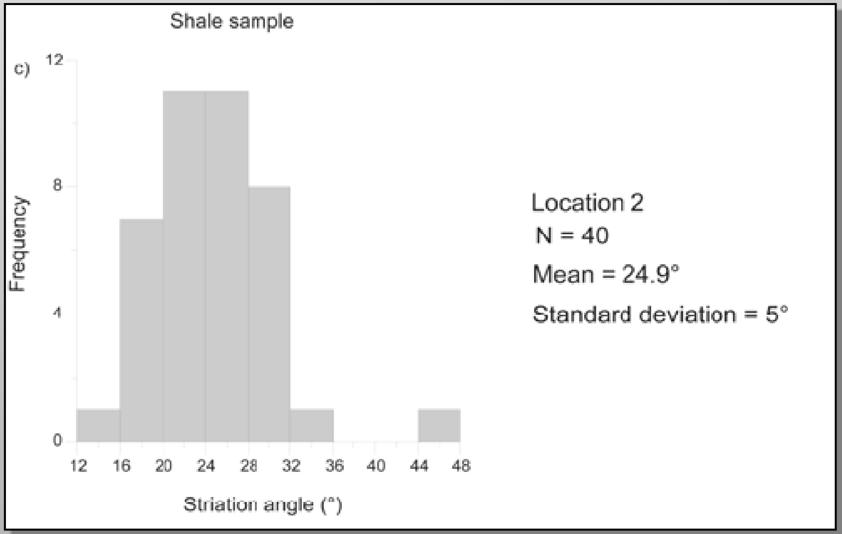
Wieland et al., 2006 (MAPS)

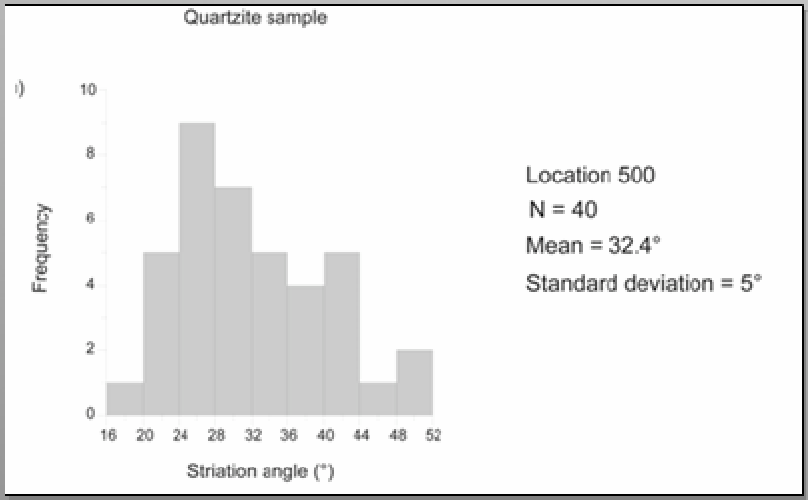
Front wave – Difficulties..

Sagy and Reeches, 2002, 2004

There are more variations at a given outcrop than between one outcrop and another!



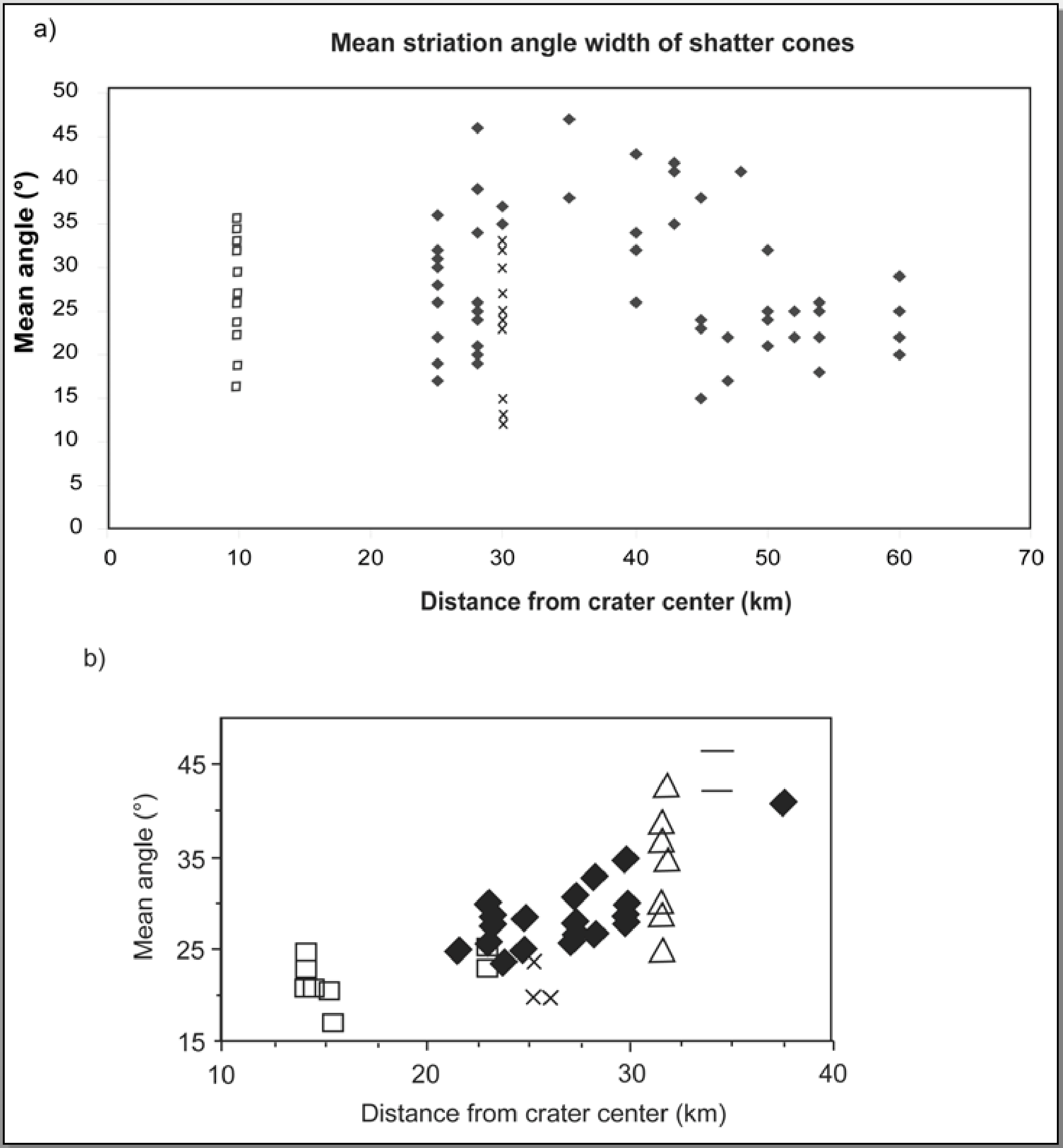




Wieland et al., 2006 (MAPS)

Front wave – Difficulties..

Sagy and Reeches, 2002, 2004



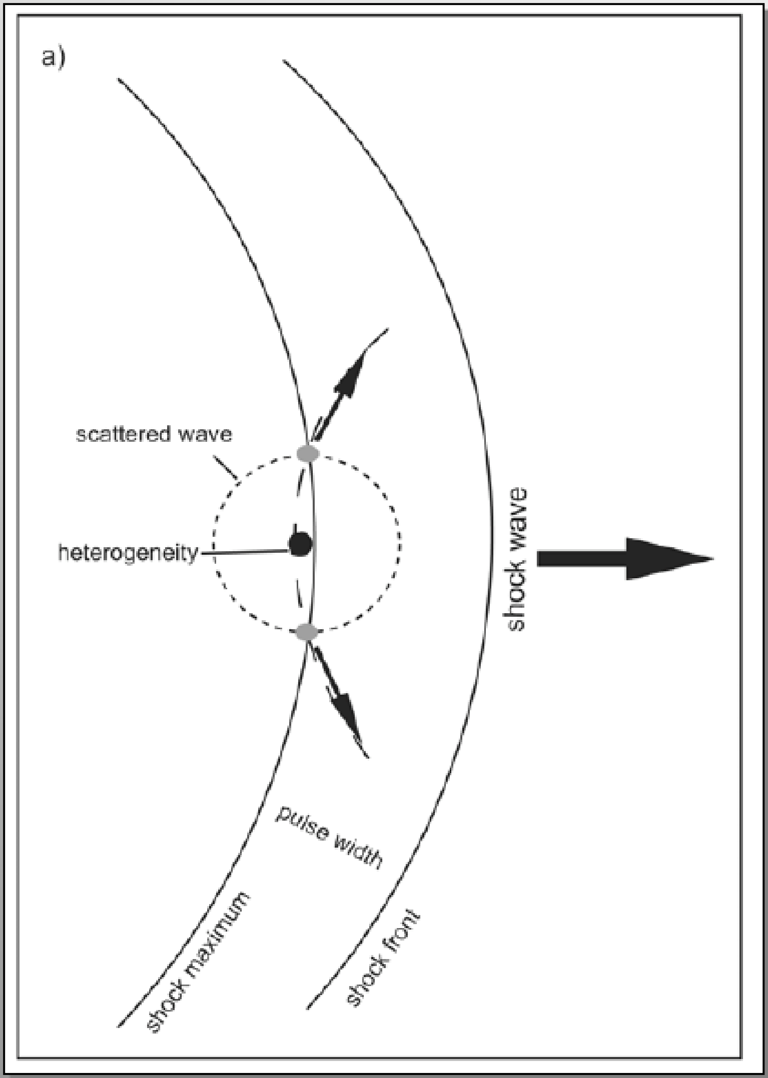
Comparison between Sagy et al. 2002, 2004 and Wieland et al., 2006 observations

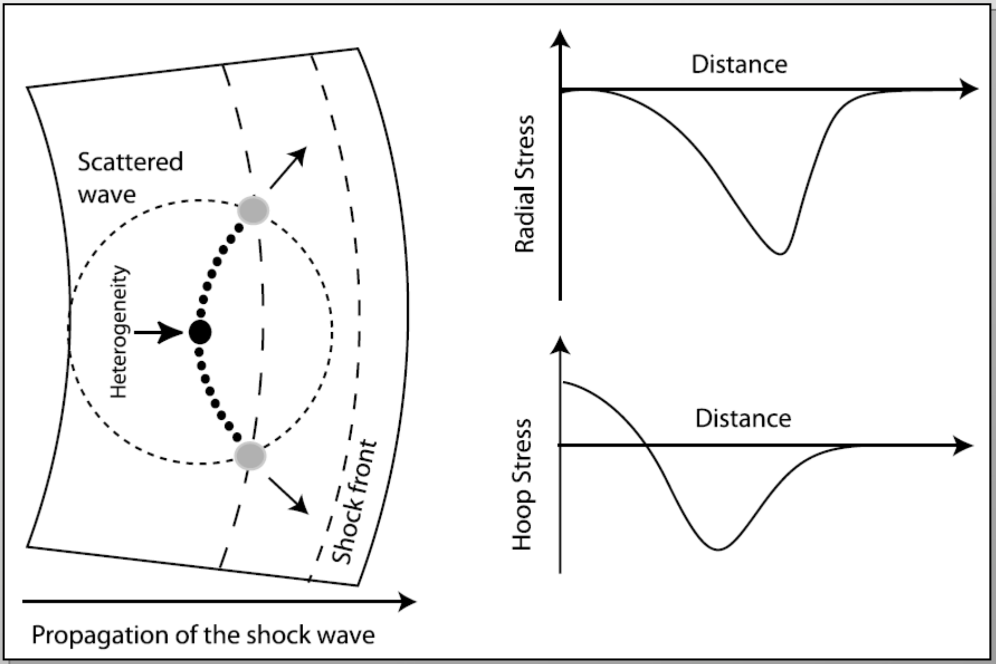
Dependence of striation angles with the distance to the center of the crater is seriously questionable.

Wieland et al., 2006 (MAPS)

Interferences at rock heterogeneities

Baratoux and Melosh, 2003





Interferences at rock heterogeneities

Numerical simulation of a shatter cone

S.A.L.E. (2D) Simplified Arbitrary Lagragian Eulerian

- Hydrocode: Navier Stokes equations
- Mass conservation
- Energy conservation
- Equation of state ($P = f(\rho,E)$) – Murnhagan EOS $P = K_0/n[(\rho/\rho_0)^n - 1]$

+ Artificial viscosity (to spread the shock wave over several cells of the grid, with Hugoniot equations satisfied)

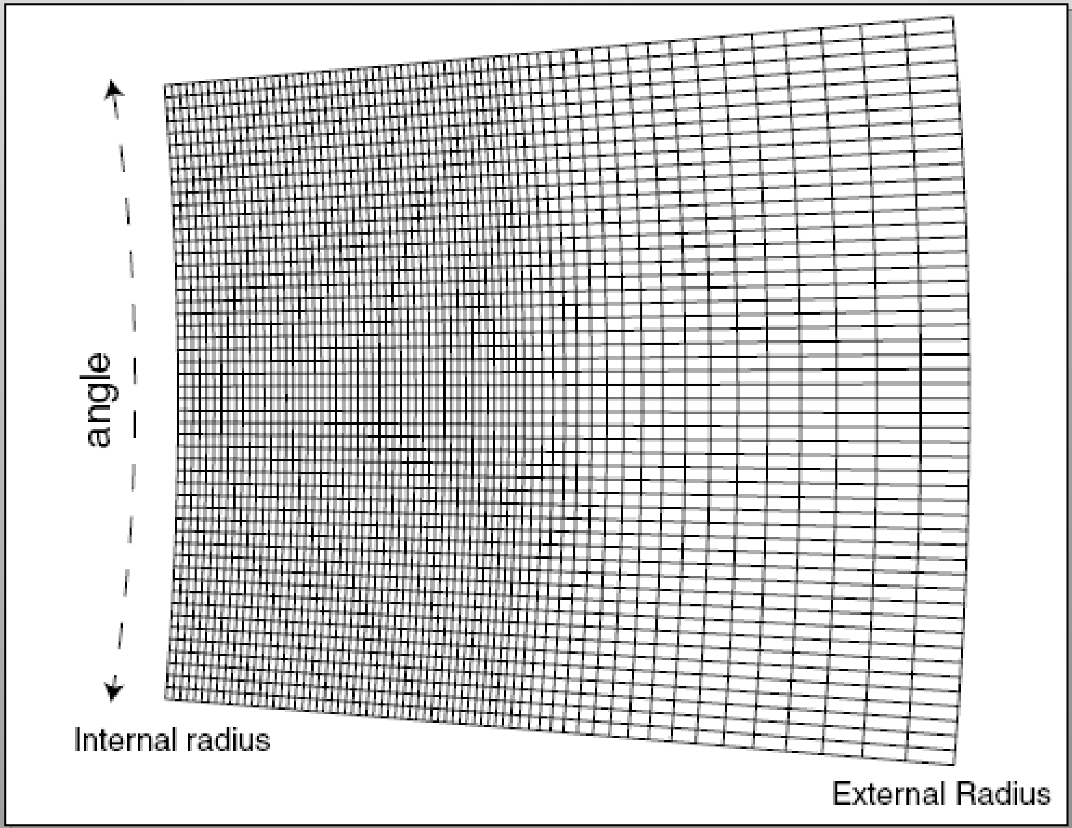
Baratoux and Melosh, 2003

Interferences at rock heterogeneities

Numerical simulation of a shatter cone

Goemetric parameters of the spherical shell

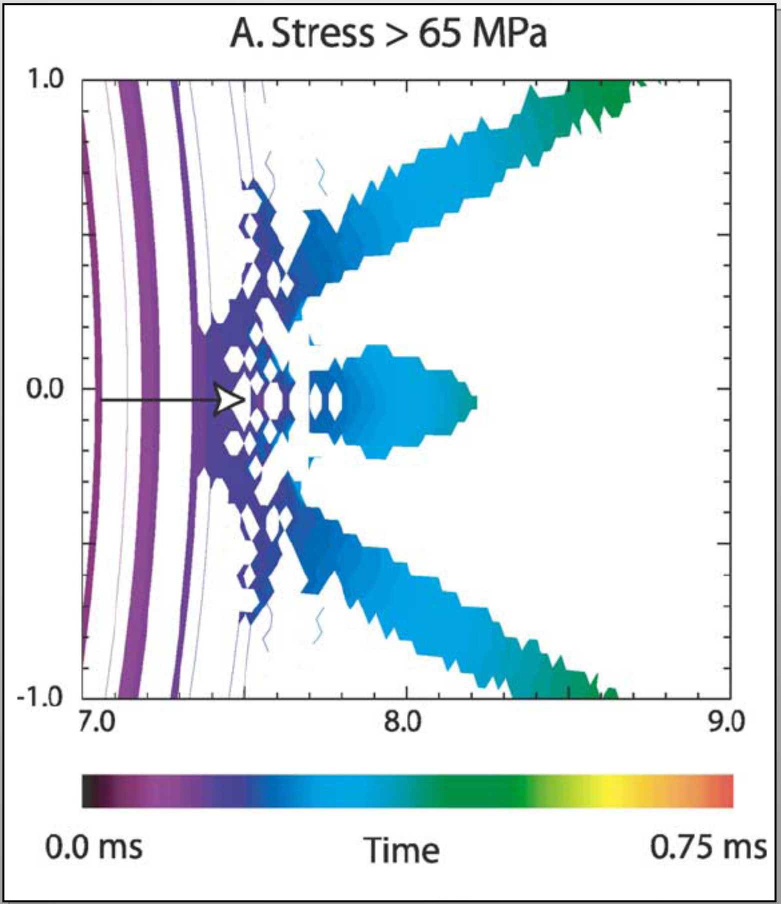
Internal radius : 7 m
Angle of the spherical shell : 30˚
Heterogeneity = 4 cells : 4 x 7.2 cm, at 7.60 m from the source



Baratoux and Melosh, 2003

Interferences at rock heterogeneities

Numerical simulation of a shatter cone



Material parameters		
	Material	Heterogeneity
Density (kg/m^3)	3000	3000
Bulk modulus (GPa)	50	5
Shear modulus (GPa)	30	3
Murnhagan exponent	4	4
Hugoniot elastic limit (GPa)	50	50

Size of the heterogeneity (1 cell) : 4 x 7.2 cm

For more information about Damage modeling see:
H.J. Melosh, E.V. Ryan, Dynamic fragmentation in impacts: Hydrocode simulation of laboratory impact, J. Geophys. Res. 97 (1992) 14735-14759.

Baratoux and Melosh, 2003

Interferences at rock heterogeneities

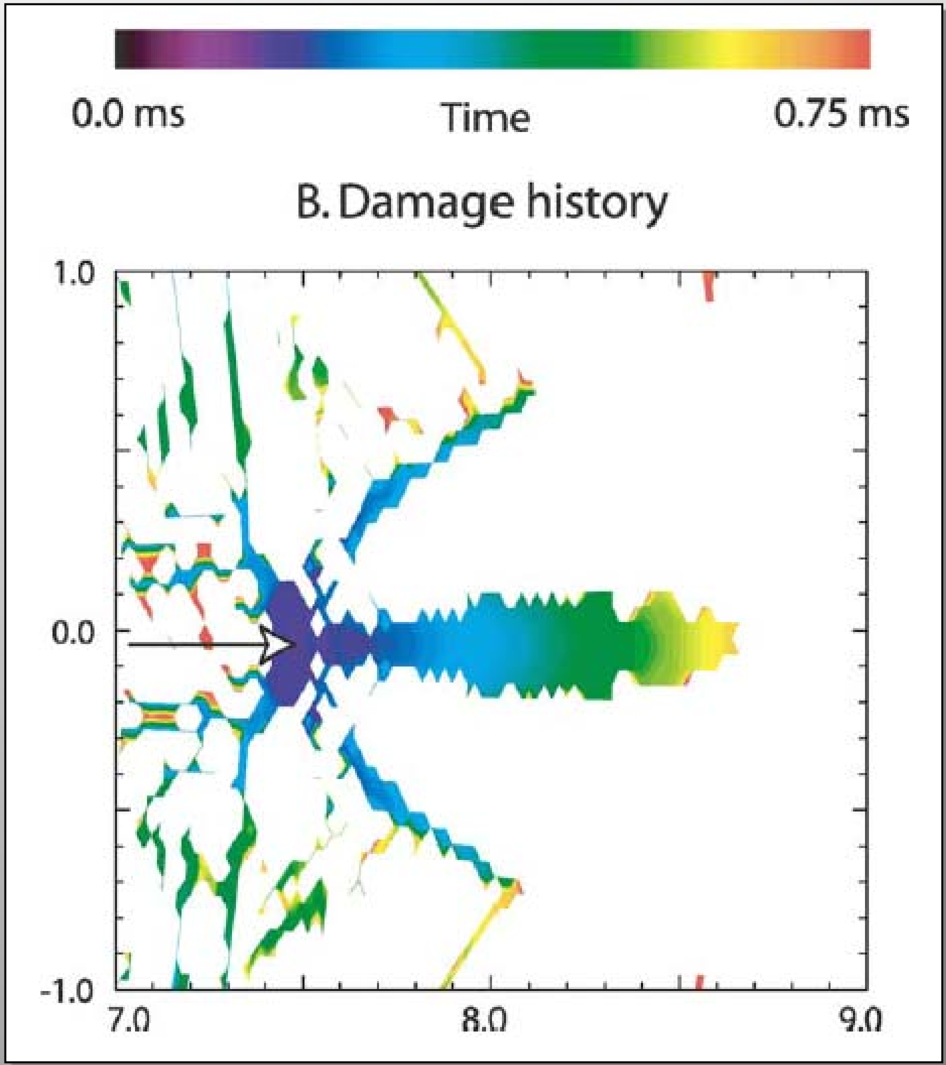
Numerical simulation of a shatter cone

Damage: Graddy-Kipp-Melosh fragmentation model

Fracturation is represented by a scalar parameter (D) for each cell decreasing the value of elastic modulii when stresses are tensional.

D = 0 : no damage
D =1 : Everything is damaged and tensile stresses are not transmitted

The parameter is responsible for a progressive (linear) decraese of elastic modulii of the media.

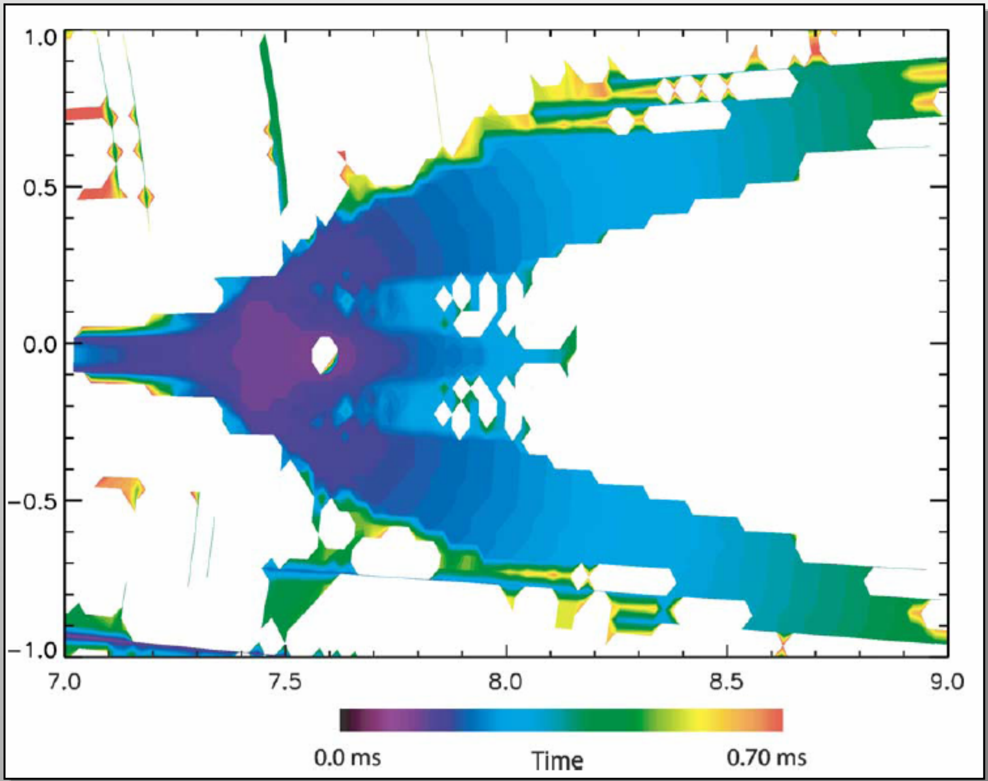


For more information about Damage modeling see:
H.J. Melosh, E.V. Ryan, Dynamic fragmentation in impacts: Hydrocode simulation of laboratory impact, J. Geophys. Res. 97 (1992) 14735-14759.

Baratoux and Melosh, 2003

Interferences at rock heterogeneities

Numerical simulation of a shatter cone



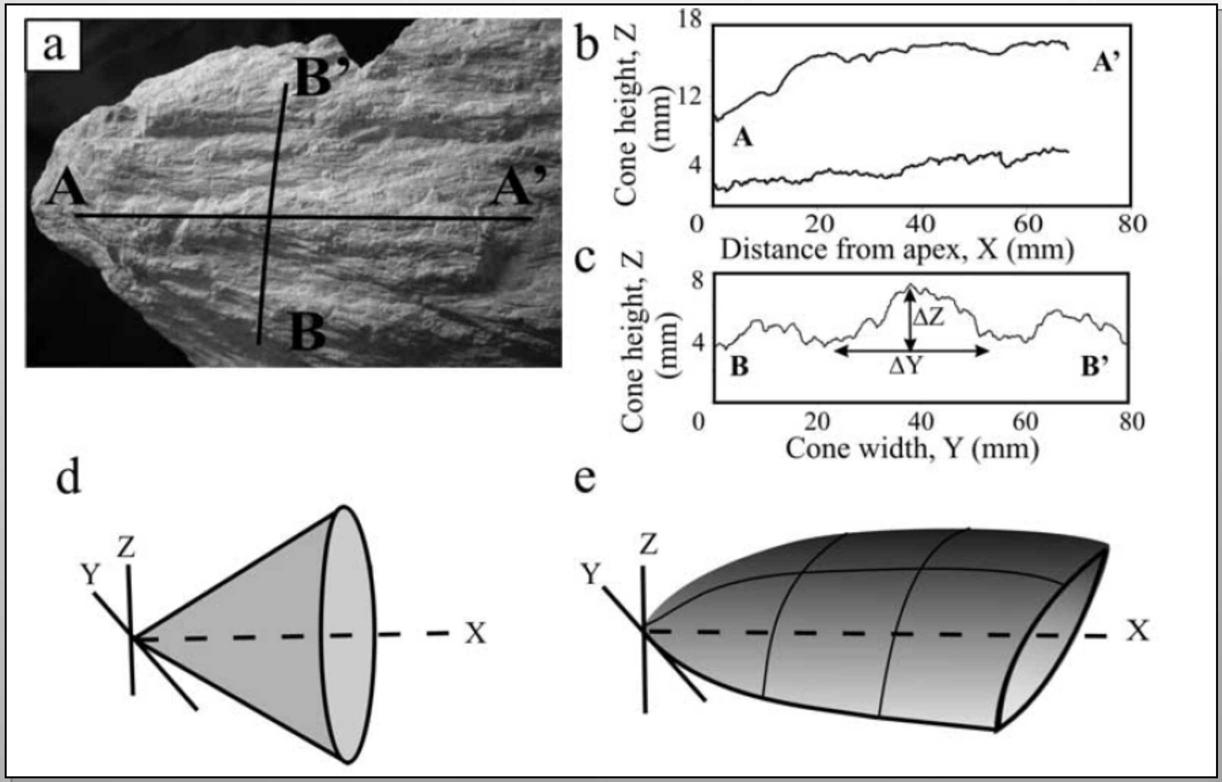
Shatter cone simulation for ice inclusion in a basaltic rock.

	Density (kg/m³)	Bulk modulus (GPa)	Shear modulus (GPa)	Murnhagan exponent	c_g (m/s)	pweib (m)	cweib (m^{-3})
Embedding material	2980	60.1	36.7	5.5	1790	9.05	3.05×10^{40}
Heterogeneity	900	0.2	0.12	5.23	7500	8.7	3.2×10^{44}

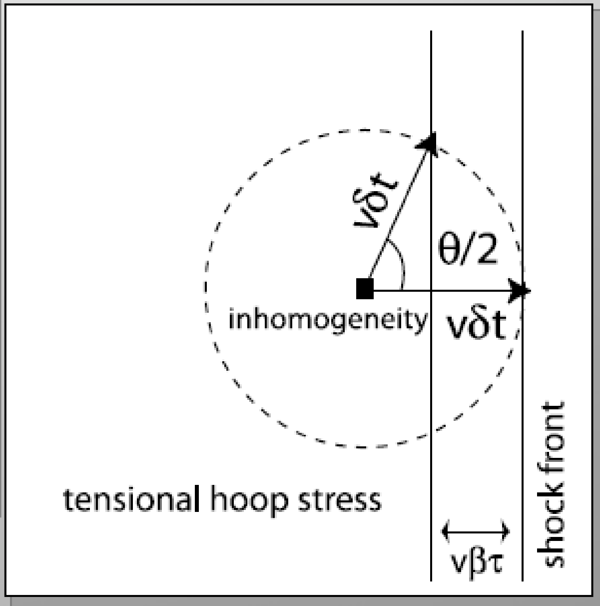
The fracture develop along a surface defining a pseudo-conical region. As the extensive stress is not transmitted once the fracture is formed the area within the cone is protected. Cells inside can be eventually partially fractured.

Baratoux and Melosh, 2003

The shape of shatter cones: determination of 3D required



Sagy and Reeches, 2004



Baratoux and Melosh, 2003

In Baratoux and Melosh, 2003, we predict that the shatter cone shape will result from the intersection of two expanding spheres. The exact shape will depend on the structure of the shock front (rise time) and of the parameters of the heterogeneities.

It would be possible to test the model with a 3D shatter cone shape measurement.

Implications

Range of pressures

Shatter cones are observed in numerical simulations for a range of pressure between 1 and 10 GPa, a range similar to the observed range of pressure in terrestrial impact craters. (~ structures d'impact terrestre).

The range of pressure for which shatter cones can occur is controlled by the resistance of the material in tension (and not by the Hugoniot Elastic limit, like in the Johson and Talbot model).

Duration of the rise time of the shock wave

Influence of the rise time and the size of the heterogeneity

Size of the heterogeneity (m)	0.04	0.04	0.04	0.08	0.08	0.08	0.16	0.16	0.16	0.4	0.4	0.4	0.8	0.8	0.8	1.6	1.6	1.6
Rise time of the stress wave (ms)	0.01	0.02	0.04	0.01	0.02	0.04	0.01	0.02	0.04	0.01	0.02	0.04	0.01	0.02	0.04	0.01	0.02	0.04
β (decay time factor)	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Time ratio[a]	1.37	2.73	5.47	0.68	1.37	2.73	0.34	0.68	1.37	1.37	2.73	5.47	0.68	1.37	2.73	0.34	0.68	1.37
Shatter cone	Yes	Yes	No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes	Yes

[a] Time ratio is the rise in time to the time necessary for the wave to travel through the heterogeneity.

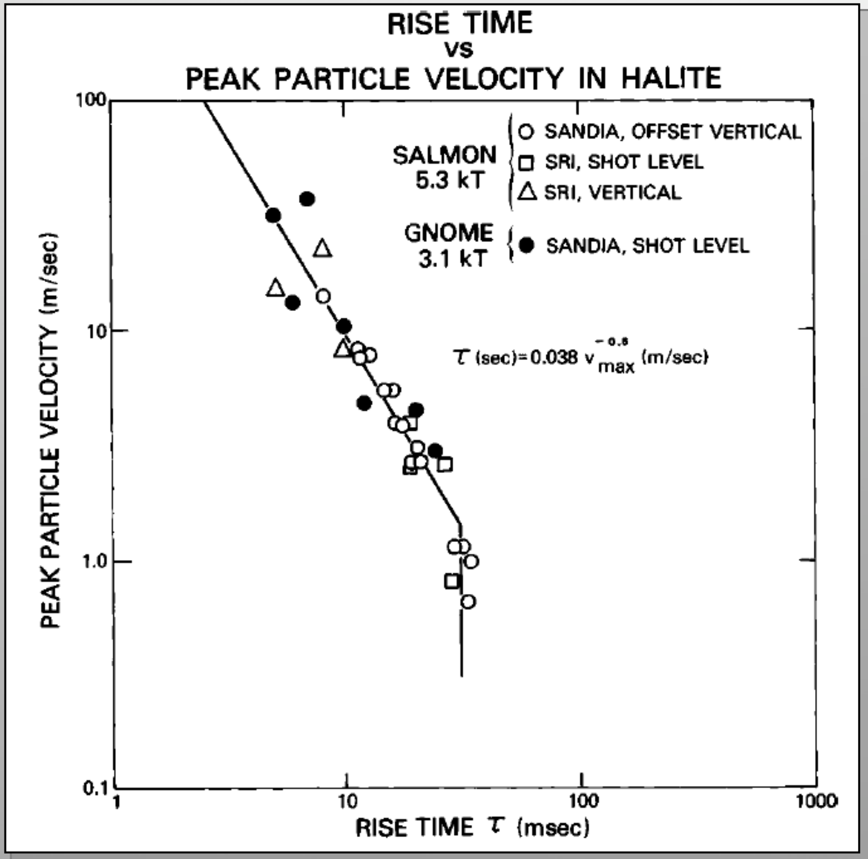
The rise times is should be short

What is the rise time of a shock wave in geological media ?

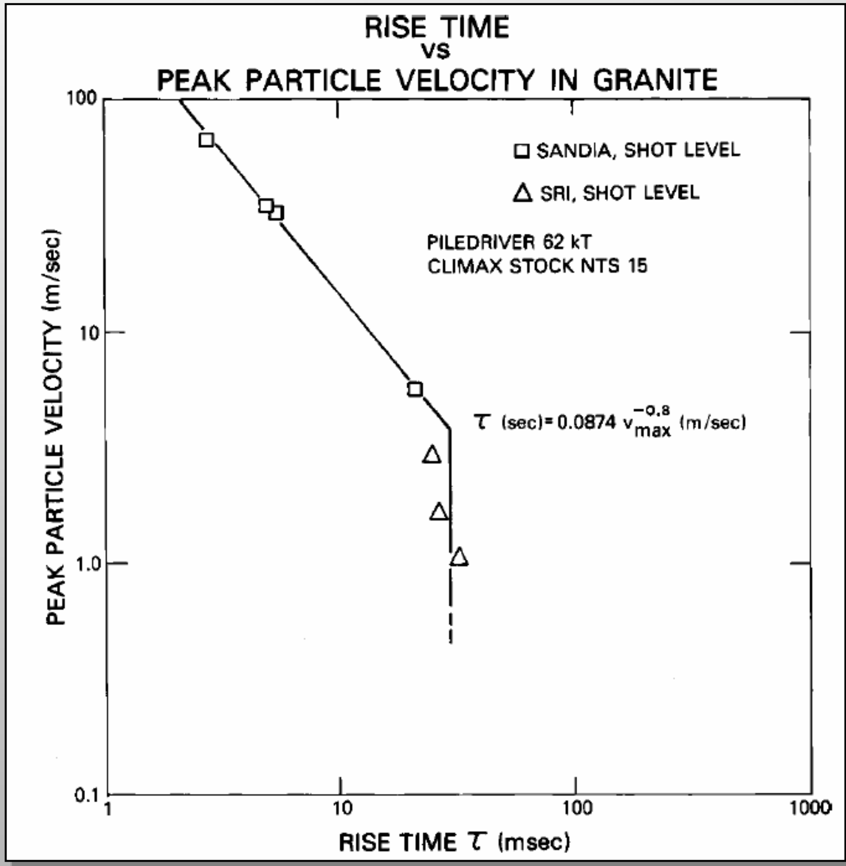
H.J. Melosh, 2003

Implications

The rise time of a shock wave in geological media: nuclear tests



Rise time as a function of particle velocity in halite (NaCl).



Rise time as a function of particle velocity in granite.

Rise time mostly depends on shock wave intensity.

→

The geometrical properties of shatter cones (size, apical angles) should depend on material affected by the shock waves.

H.J. Melosh, 2003

Implications

The rise time of a shock wave in geological media

$$\tau = 0.038\, v_{\max}^{-0.6}$$

Hugoniot equations

$$\tau = 0.038 \left(\frac{P}{\rho U} \right)^{-0.6} = 900\, P^{-0.6}$$

Extrapolation at 3 Gpa => 1 ms (still one or two orders of magnitude too long…).

What is the real rise time of strong shock waves in geological media ?

Conclusions

	Johnson and Talbot (1964)	Gash (1971)	Sagy at al., 2002, 2004	Baratoux and Melosh (2003)
Heterogeneities required	✔		✔	✔
Elastic wave interferences	✔	✔		✔
Tensile fracture		✔	✔	✔
Fractured linked with plastic yielding	✔			
Front waves			✔	

Important flaws

Conclusions

- Shatter cones are formed by extensive stresses

- Shatter cones are formed during the passage of the shock wave

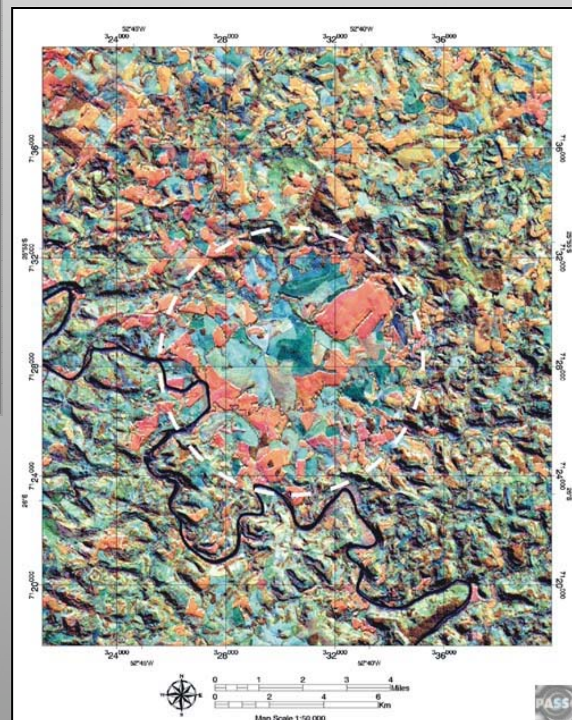
- Striations are explained by Sagy et al., 2002, 2004, but relationships between striations angle and distance to the center of the crater is not established.

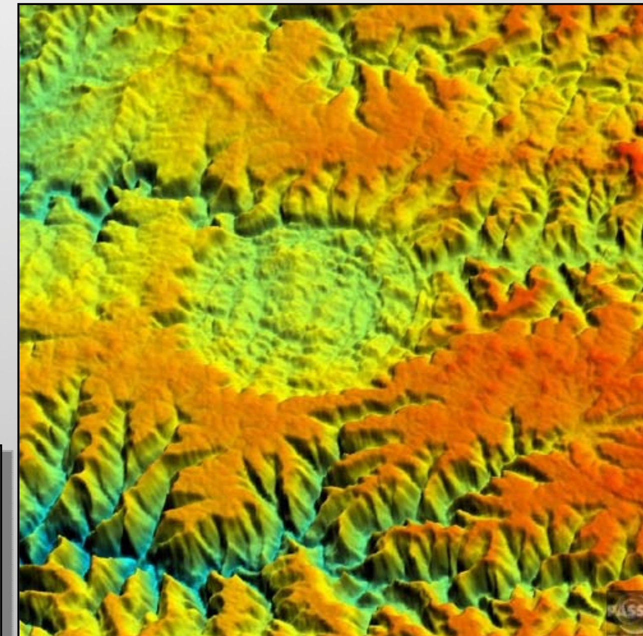
- Shapes and sizes are well explained by Baratoux and Melosh, 2003 (but the striations are not explained with this model).

Combination of the two models as proposed in Wieland et al., 2006 ?

Shatter cones in basalts – Craters in Brazil

Few words about Vargeão and Vista Allegre





R. Trinidade, E. Yokoyama, University of São Paolo

Shatter cones in basalts – Craters in Brazil

Few words about Vargeão and Vista Allegre

Parana trapps – overview of the basaltic pile

Shatter cones in basalts – Craters in Brazil

Few words about Vargeão and Vista Allegre

Parana trapps – contact with the Botucatu sandstone

Shatter cones in basalts – Craters in Brazil

First observations for a summer field campaign

Shatter cones in basalts – Craters in Brazil

First observations for a summer field campaign

Timing of the formation of shatter cones is clear!

Session proposal

The Meeting of the Americas

8 to13 August 2010, Foz do Iguassu, Brazil

Impact Cratering on Solid Planets - Shocks on Basalt

Baratoux, David[1], Crosta, Alvaro[2], Arakawa, Masahiko[3]

[1]Observatoire Midi-Pyrénées, Toulouse, France. [2]University of Campinas, Campinas, Brazil. [3]University of Nagoya, Nagoya, Japan.

Impact craters on solid planets are often formed on magmatic rocks. For the Moon and Mars, new magnetic, mineralogic and chemical data motivates a better quantification of shock effects on basalt. Recent analyses of craters on terrestrial igneous provinces offer the perspective of comparative studies. Contributions providing insights into the formation of impact craters on magmatic bodies, experimental or field studies (e.g., Vargeão and Cerro do Jarau, or Lonar), and analyses of extra-terrestrial impact structures will be appreciated. **A 2-day field trip to Vargeão and Vista Alegre craters is being proposed in association with this session.**

When stress becomes tensional the model employs Melosh-Graddy-Kipp's dynamic fragmentation model [Grady and Kipp, 1980, Melosh et al., 1992] implemented in SALE 2D. We describe here briefly the basics features of the model and its numerical implementation, the reader is referred to the complete description in [Melosh et al., 1992]. The graddy-Kipp model treats the damage as a continuum and the effect of the individual fractured is integrated in a scalar parameter called the damage which is responsible for a decrease of the elastic modulii when the material is in tension :

$$\sigma_{ij} = K(1-D)\epsilon\delta_{ij} + 2\mu(1-D)(\epsilon_{ij} - \frac{1}{3}\epsilon\delta_{ij}) \tag{1}$$

where σ_{ij} is the stress tensor, ϵ_{ij} the strain tensor, K and μ the bulk and shear mudulii respectively and ϵ the scalar volume strain equal to $\epsilon_{11}+\epsilon_{22}+\epsilon_{33}$. The damage D is related to the number and size of cracks in the rocks by the equation :

$$D = nV \tag{2}$$

where n is the number of idealized penny-shaped cracks per unit volume and V is the volume of the spherical stress-relieved region surrounding a crack. The damage at any time is an integral over the damage that has accumulated in the history of the material :

$$D(t) = \int_{-\infty}^{t} \frac{dn}{dt}(t')V(t-t')dt' \tag{3}$$

The number of flaws activated at any time is given by the two-parameters Weibull distribution [Jaeger, 1969] :

$$N = k\epsilon^{m} \tag{4}$$

where N is the number of flaws per unit volume activated at or below the tensile strain ϵ. Grady and Kipp assuming that cracks, once activated, grow at their maximum speed c_g derived the fundamental integral equation for damage accumulation :

$$D(t) = \frac{4}{3}\pi c_g^3 \int_{-\infty}^{t} \frac{dN}{d\epsilon}\frac{d\epsilon}{dt}(1-D)(t-t')^3 dt' \tag{5}$$

This equation provides a fundamental rationale basis for understanding dynamic fragmentation, however, the computation of the integral is prohibitive for numerical implementation. To avoid the problem, Grady and Kipp (1980) proposed an excellent alternative to (5)

$$\frac{dD^{1/3}}{dt} = \frac{m+3}{3}\alpha^{1/3}\epsilon^{1/3} \tag{6}$$

where α is given by :

$$\alpha = \frac{8\pi c_g^3 k}{(m+1)(m+2)(m+3)} \tag{7}$$

The equation (6) is exact in the limit of constant strain rate but allows the damage grow monotonically in the common situation of a non-constant strain rate. For all simulations presented here the velocity of the cracks is taken equal to 0.4 times the sou velocity in the material [Melosh et al., 1992].

While, the static failure regime is dominated by the growth of a single, weakest fl the dynamic regime is entered when the growth of this flaw cannot relieve the appl train. Stresses rise in adjacent material leading to the activation of new flaws. From Weibull distribution, the threshold strain is controlled by the size of the fragmenting bo [Melosh et al., 1992]. Indeed, for an infinite body a flaw can always be found that fails any small arbitrary strain. However, for a finite body of radius R, the activation of at le one flaw at a given small strain implies that the stress is greater than :

$$\epsilon_{min} = (\frac{4}{3}\pi k R^3)^{-1/m}$$

In the numerical simulations, we use a size-dependant minimum strain at which cracks initiate. The grady-Kipp model is extended for this purpose in higher dimensions. T algorithm implemented is described in [Melosh et al., 1992]. It involved the computat of an effective stress tensor :

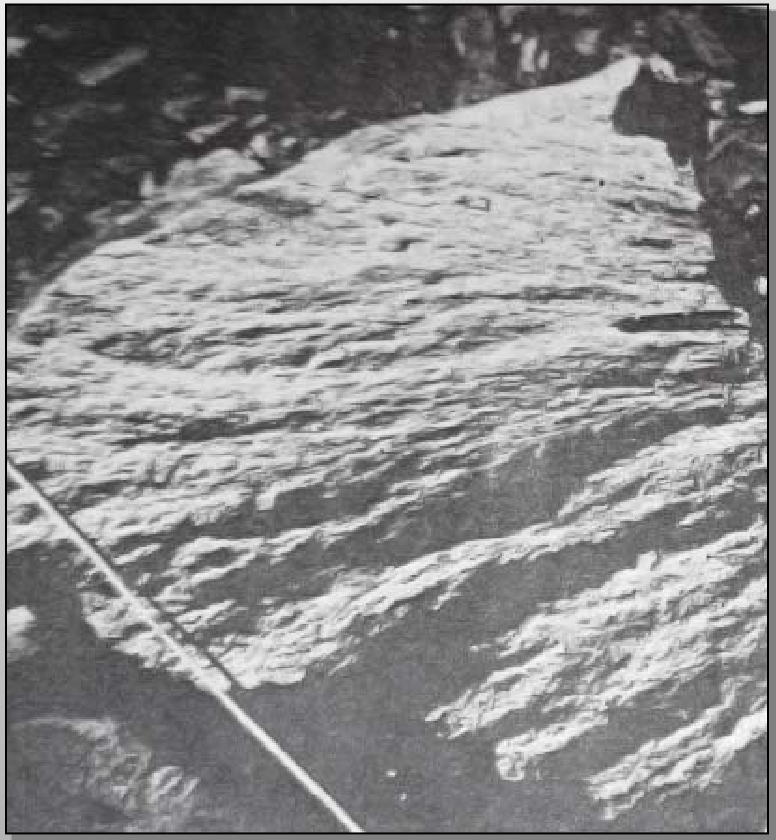
$$\sigma_{ij}^{eff} = B\epsilon\delta_{ij} + 2\mu(\epsilon_{ij} - \frac{1}{3}\epsilon\delta_{ij})$$

Then a principal axis transformation is performed in order to determine the most tensio axis $\sigma_{max} = max(\sigma_1^{eff}, \sigma_2^{eff}, \sigma_3^{eff})$. The effective strain that has to be compared to minimum strain (8) is given by

$$\epsilon = \frac{\sigma_{max}}{B + \frac{4}{3}\mu} \qquad ($$

a somewhat arbitrary choice to which the result are not very sensitive [Melosh et al., 19 however, this has to be checked for the specific simulations we achieved.

Can we produce shatter cones artificially ?



D.J. Roddy and Davis, 1977, Shatter cones in large scale experimental explosion craters.

Relationships between shatter cones and other fractures

Few words about the MSJS

Shatter cones are generally defined as curved fracture surfaces with striations. Entire or more often partial cones are found on the field.

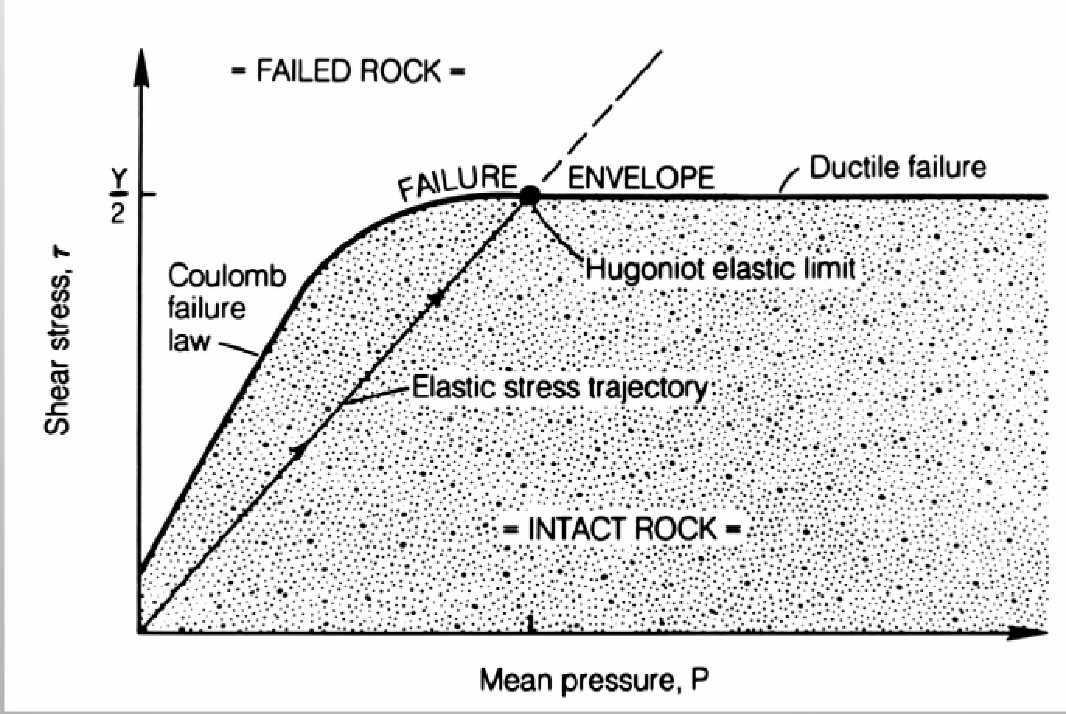
MSJS (Multipled-Striated-Joint-Set) are also fractured surfaces with striations
MSJS and shatter cones may be the expression of the same phenomenon, occurring **during the passage of the shock wave.**

MSJS at Vergeão impact crater in Brazil.

Limite élastique de Hugoniot

Les roches ne peuvent pas supporter des différences de contraintes au-delà d'une certaine valeur seuil

Fracture (critère de Coulomb) **Déformation plastique**

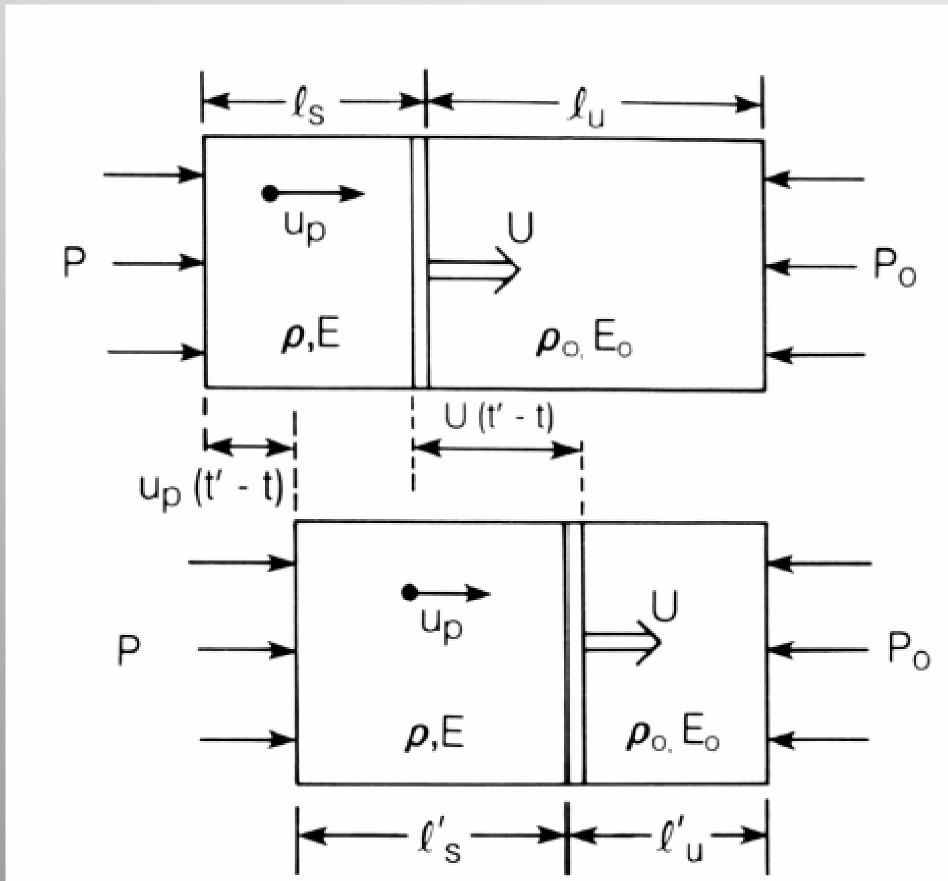


Différence de contrainte maximale : $\tau_{max} = \frac{Y}{2}$

Limite élastique de Hugoniot : $\sigma_{HEL} = (\frac{1-\nu}{1-2\nu})Y$

Melosh, 1989

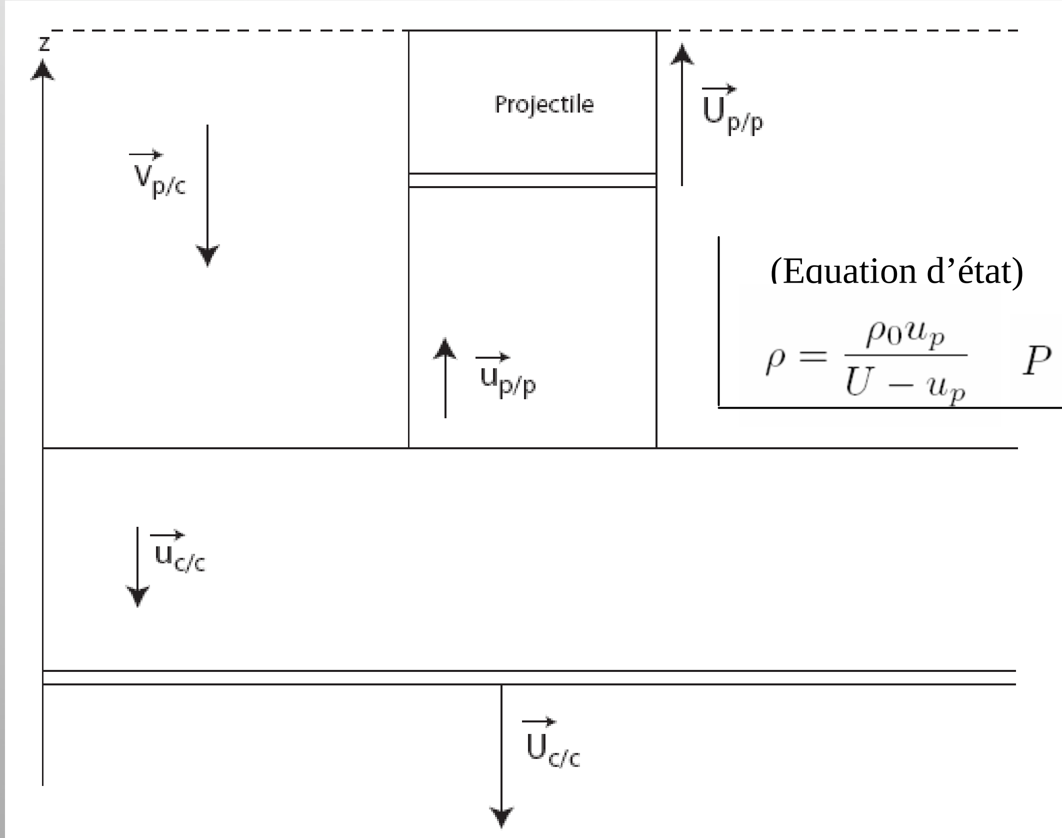
Traitement de l'onde de choc: Equation de Hugoniot



- Conservation de la masse
- Conservation de la quantité de mouvement
- Conservation de l'énergie

$$\begin{cases} \rho(U - u_p) = \rho_0 u \\ P - P_0 = \rho_0 u_p U \\ E - E_0 = (P + P_0)(V_0 - V) \end{cases}$$

Une première approximation des valeurs de pression: l'impact plan



Représentation du contact entre un projectile et la surface d'une planète dans l'approximation de l'impact plan. Le projectile se déplace à une vitesse Vp/c par rapport `a la cible. $U_{p/p}$ et $u_{p/p}$ représentent respectivement la vitesse du choc et d'un petit volume de matière relativement au projectile en mouvement. $U_{c/c}$ et $u_{c/c}$ représentent respectivement la vitesse du choc et d'un petit volume de matière relativement à la cible.

$$\vec{u}_{c/c} = \frac{\vec{V}_{p/c}}{2}$$

$$U_t = C_t + S_t u_p$$

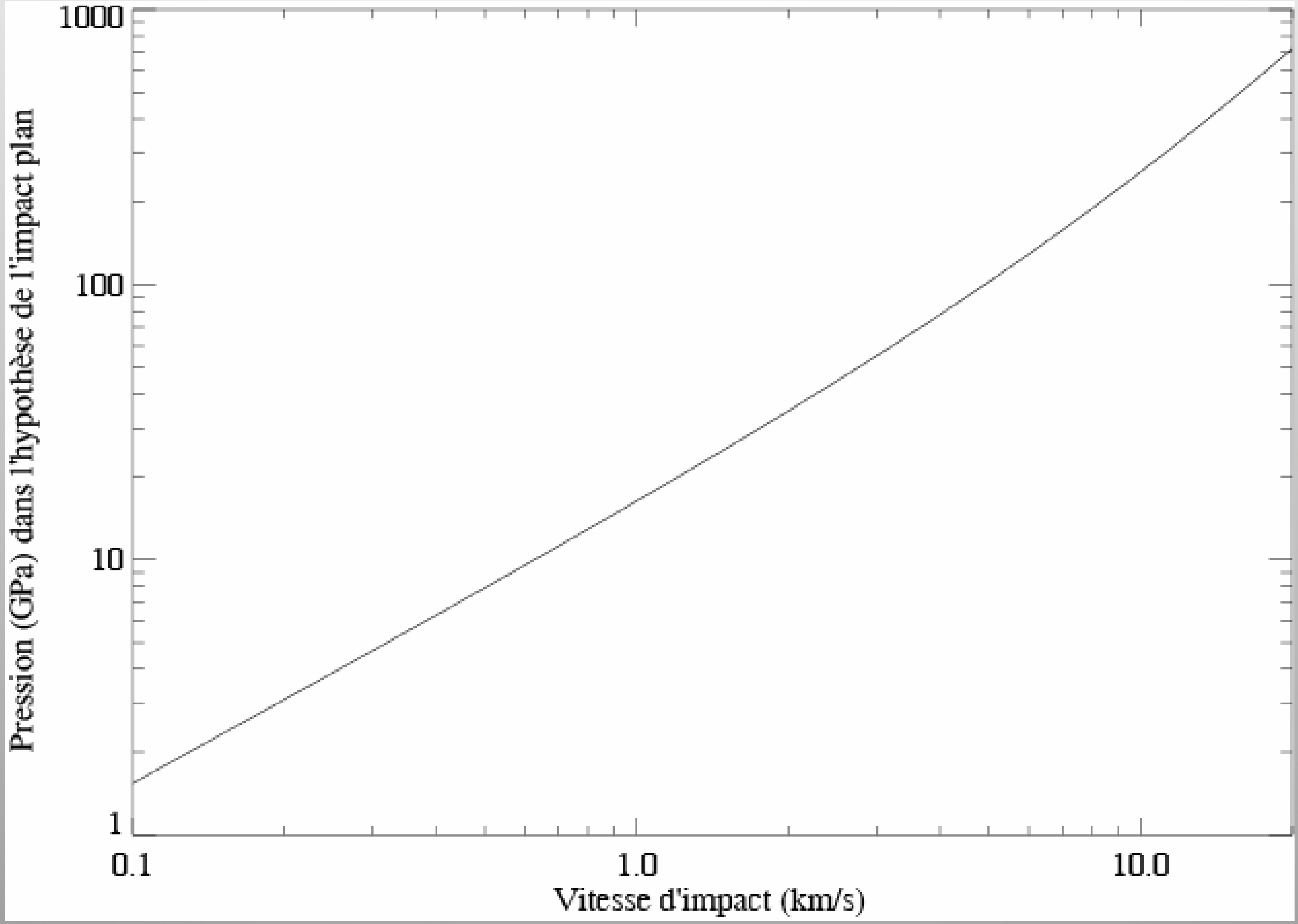
(Equation d'état)

$$\rho = \frac{\rho_0 u_p}{U - u_p} \qquad P = P + \rho_0 u_p U \qquad E = E_0 + (P + P_0)(V_0 - V)$$

$$P = \rho_0 \frac{V}{2}\left(C_t + S_t \frac{V}{2}\right)$$

$$\rho_0 = 3965\ kg/m^3$$
$$C_t = 7.71\ km/s$$
$$S_t = 1.05$$

Anorthosite (roche lunaire)


1000
100
10
1
0.1
1.0
10.0
Pression (GPa) dans l'hypothèse de l'impact plan
Vitesse d'impact (km/s)

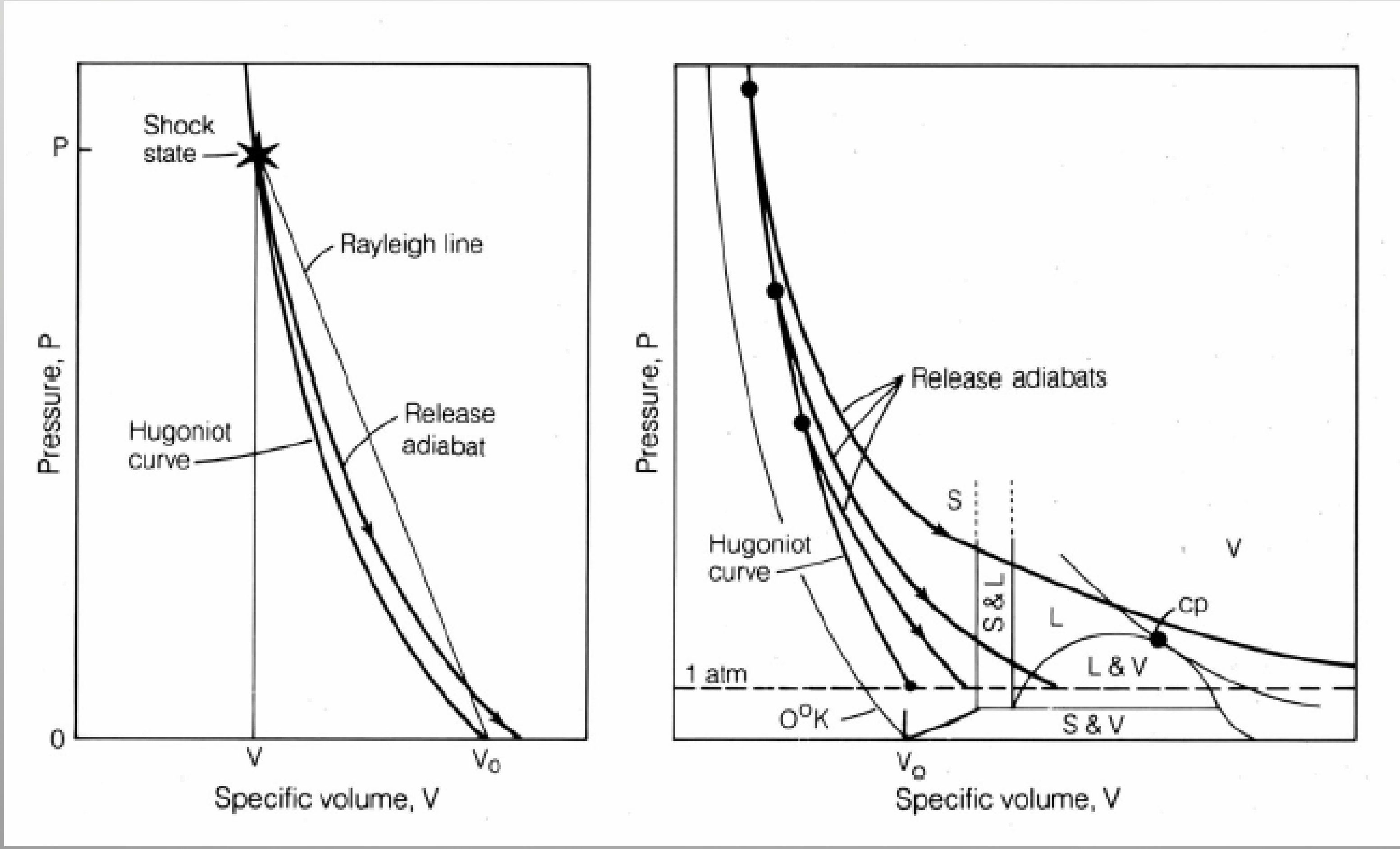
Limites de Hugoniot pour les roches terrestres (ou planétaires)

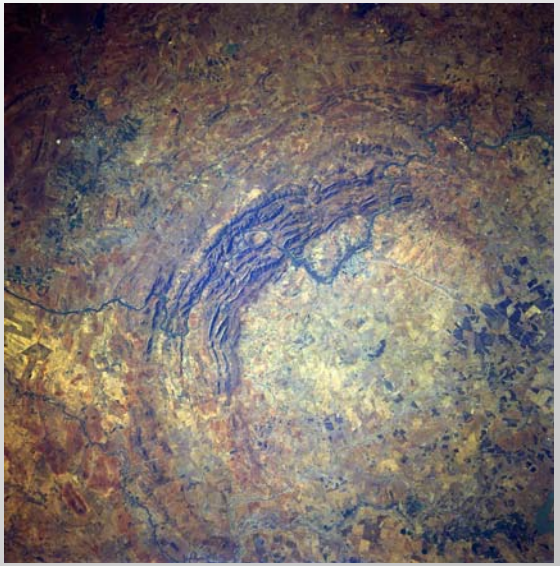
Material	Hugoniot Elastic Limit σ_{HEL} (GPa)	Source
Single Crystals:		
Periclase (MgO)	2.5	Grady (1977)
Feldspar	3.	Grady and Murri (1976)
Quartz (SiO_2)	4.5–14.5*	Duvall and Graham (1977)
Olivine (Mg_2SiO_4)	9.	Raikes and Ahrens(1979)
Corundum (Al_2O_3)	12–21*	Grady (1980)
Rocks:		
Halite	0.09	Larson (1982)
Blair Dolomite	0.26†	Larson (1977)
Vermont Marble	0.9	Grady (1977)
Westerly Granite	~ 3	Larson (1977)
Lunar Gabbroic Anorthosite	3.5	Ahrens et al. (1973)
Granodiorite	4.5	Borg (1972)
Metals:		
Armco Iron	0.6	Rice et al. (1958)
SAE 1040 Steel	1.2	Rice et al. (1958)

*HEL depends upon the crystal orientation.

†Rate dependence observed.

Après le passage de l'onde de choc:
- Décompression adiabatique
- Augmentation de température, changement de densité, transition de phase

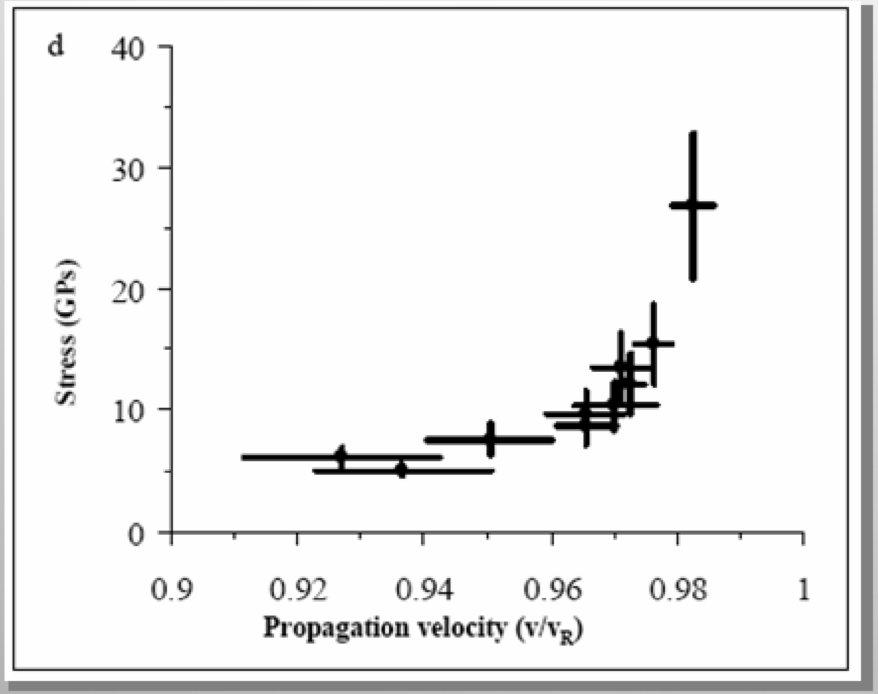


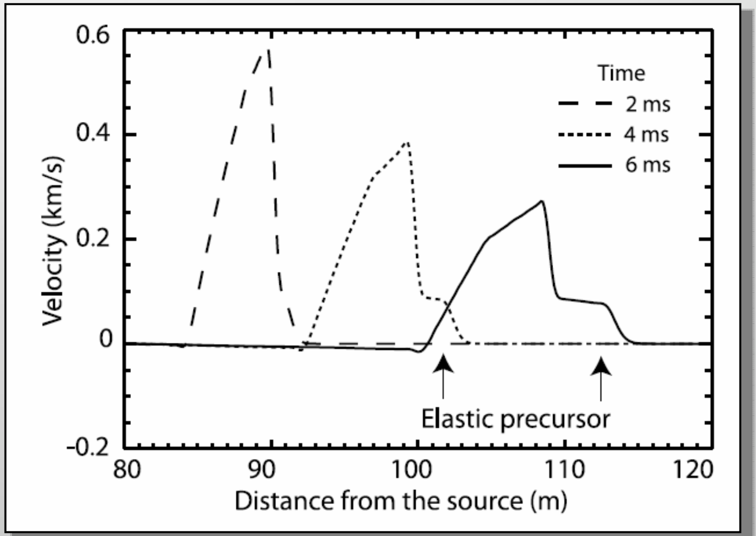


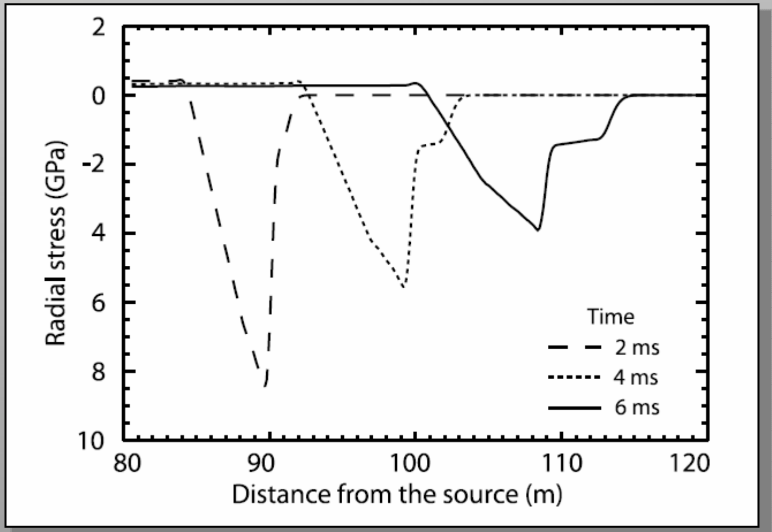
Cratère d'impact de Vredefort, 2.023 Gy, 280 km de diamètre

Front wave – Difficulties..

Sagy and Reeches, 2002, 2004







Assuming compressive stress equal tensile stresses.