惑星科学的衝突過程における

物質強度・空隙モデル
と
数値シミュレーションと実験の関わり

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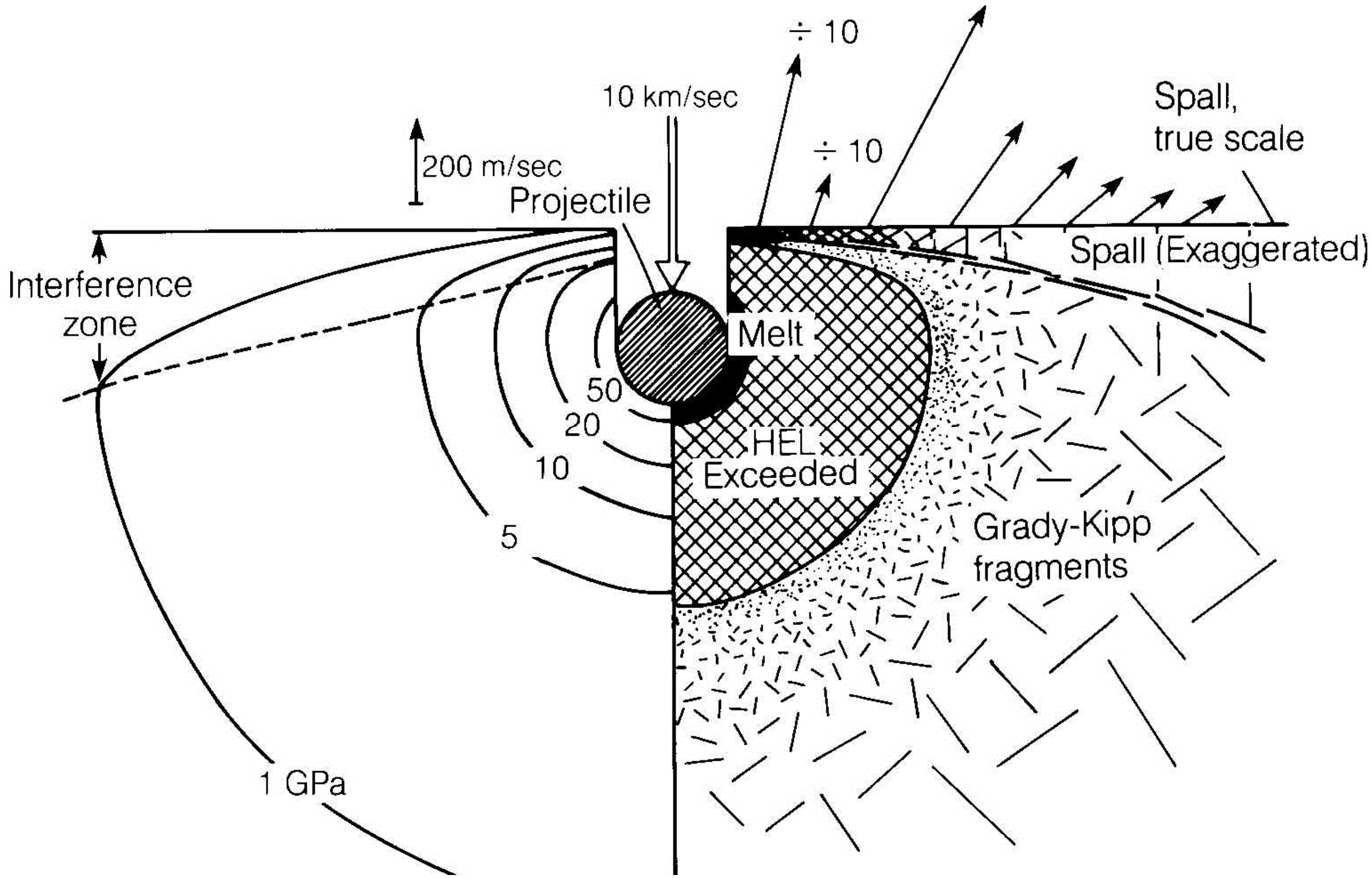
内容

1. 強度・空隙モデルが適用される問題
2. 強度モデル、空隙モデル
3. 数値シミュレーションと実験の関わり

1. 強度・空隙モデルが適用される問題

$$P \le \rho C^2$$



(Melosh, 1989)

小惑星帯の衝突進化とクレーター年代

O’Brien, Greenberg, and Richardson, 2006

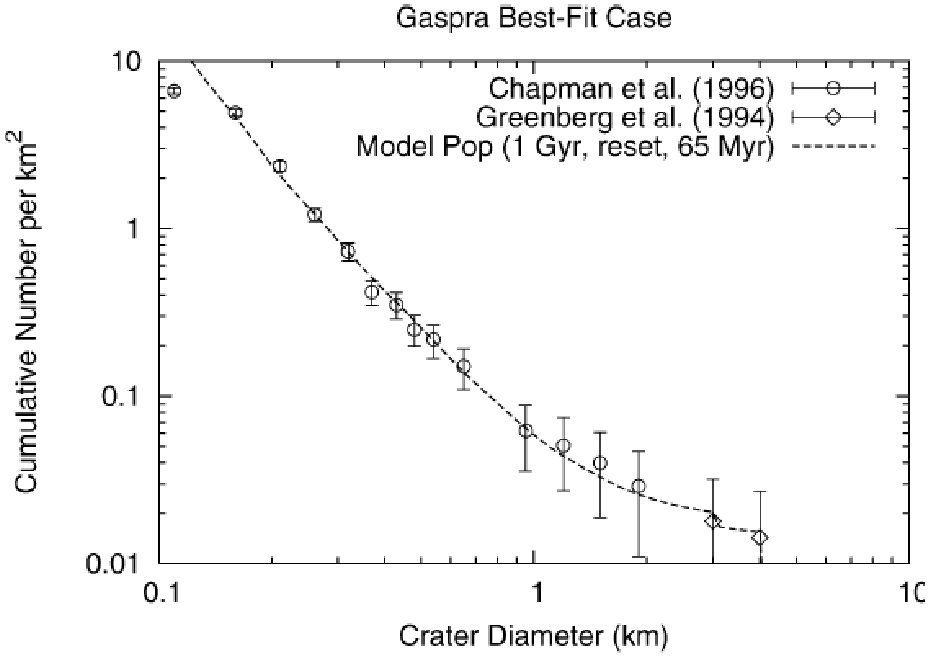
- **Gaspra** (**S**, 19x12x11 km)
- **Ida** (**S**, 56x24x21 km)
- **Mathilde** (**C**, 66x48x44 km) > 4Gyr
- **Eros** (**S**, 34x11x11 km)

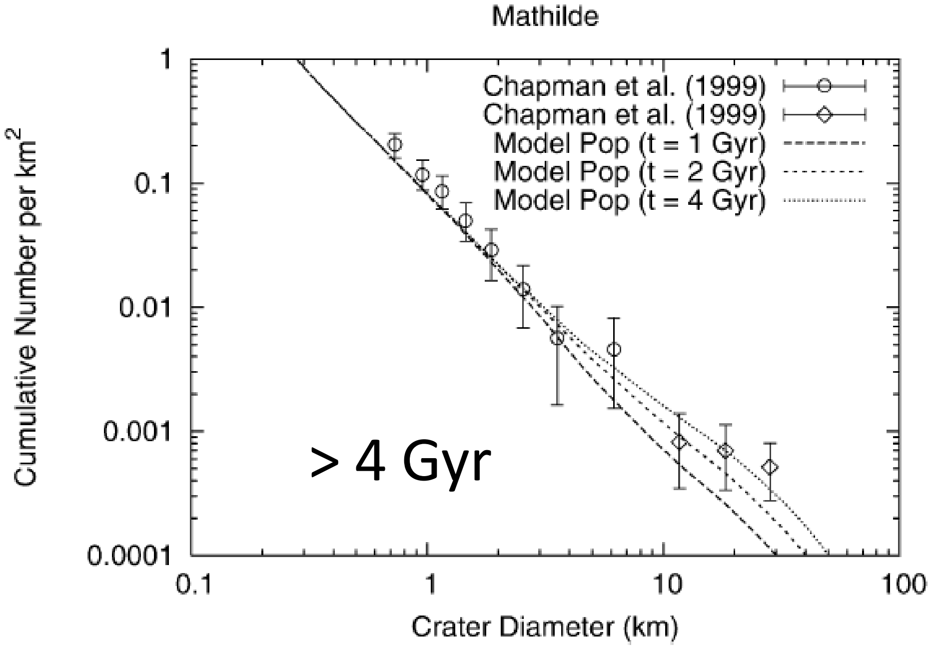
Michel, O’Brien, and Hirata, 2008

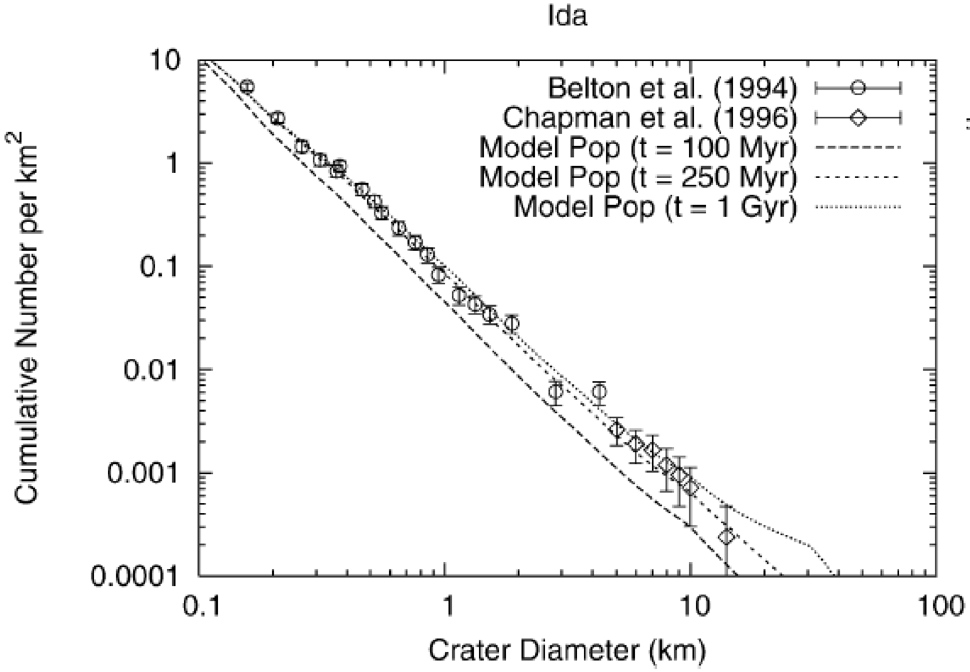
Itokawa (**S**, 0.45x0.29x0.21 km)   200 Myr <, < 2 Gyr

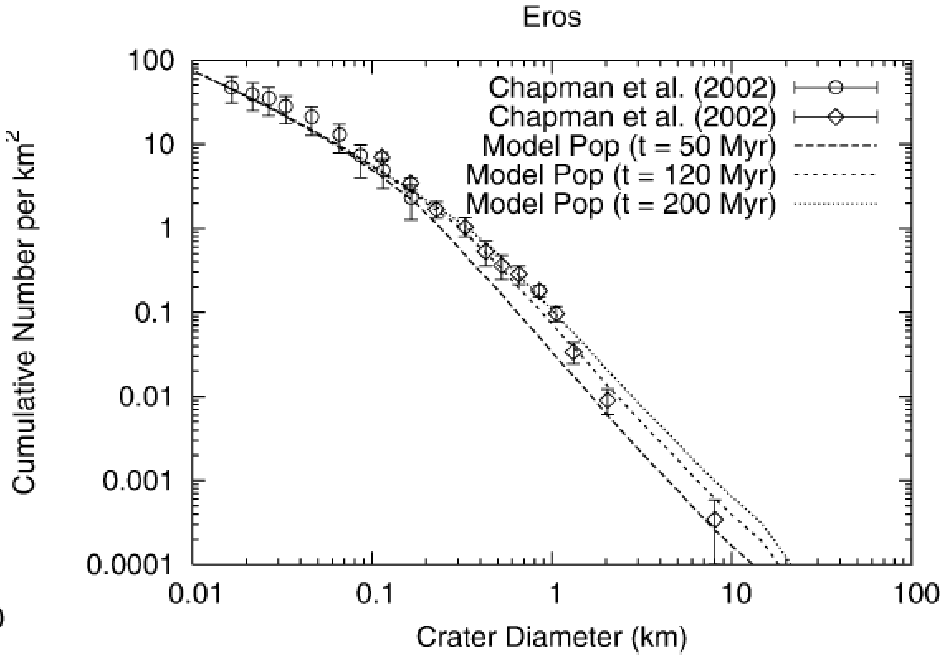
Eros

Lutetia,   Vesta, …

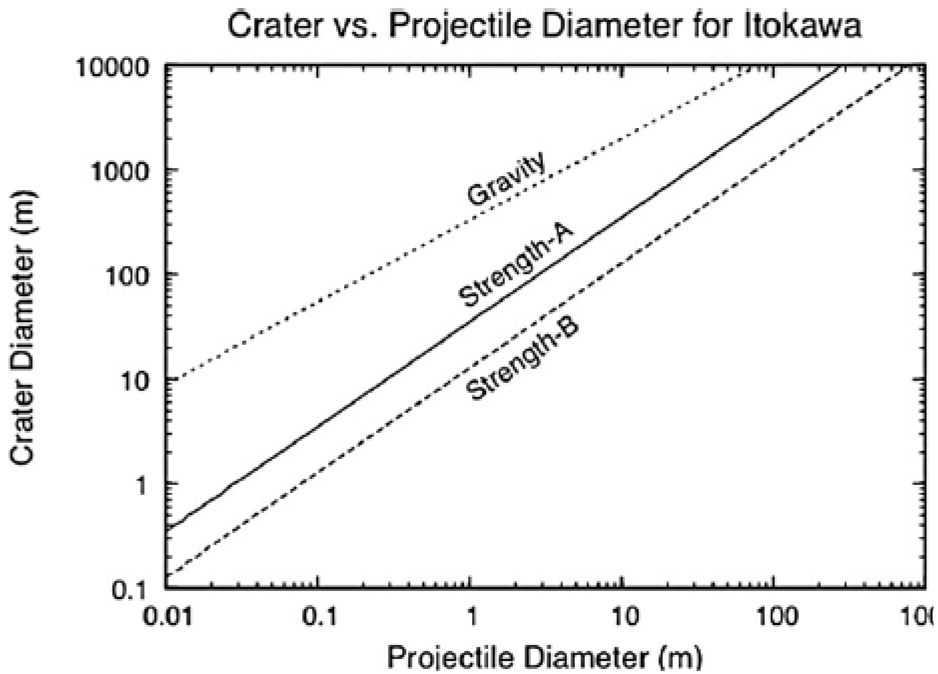

Gaspra Best-Fit Case
Chapman et al. (1996)
Greenberg et al. (1994)
Model Pop (1 Gyr, reset, 65 Myr)
Cumulative Number per km^2
Crater Diameter (km)

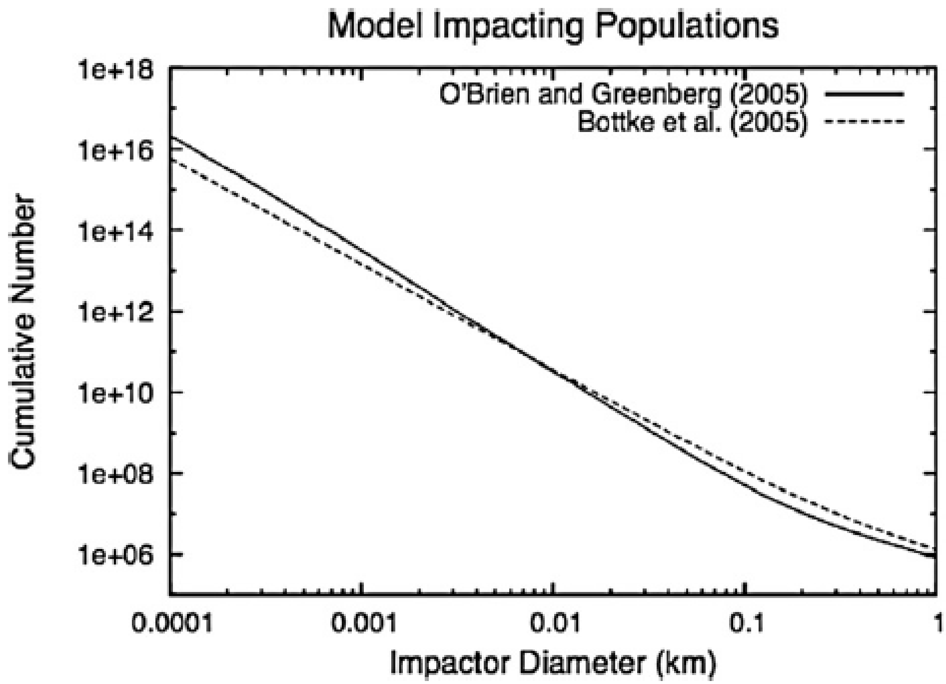

Mathilde
Chapman et al. (1999)
Chapman et al. (1999)
Model Pop (t = 1 Gyr)
Model Pop (t = 2 Gyr)
Model Pop (t = 4 Gyr)
> 4 Gyr
Cumulative Number per km^2
Crater Diameter (km)


Ida
Belton et al. (1994)
Chapman et al. (1996)
Model Pop (t = 100 Myr)
Model Pop (t = 250 Myr)
Model Pop (t = 1 Gyr)
Cumulative Number per km^2
Crater Diameter (km)


Eros
Chapman et al. (2002)
Chapman et al. (2002)
Model Pop (t = 50 Myr)
Model Pop (t = 120 Myr)
Model Pop (t = 200 Myr)
Cumulative Number per km^2
Crater Diameter (km)

(Michel, O’Brien, Hirata, 2008)





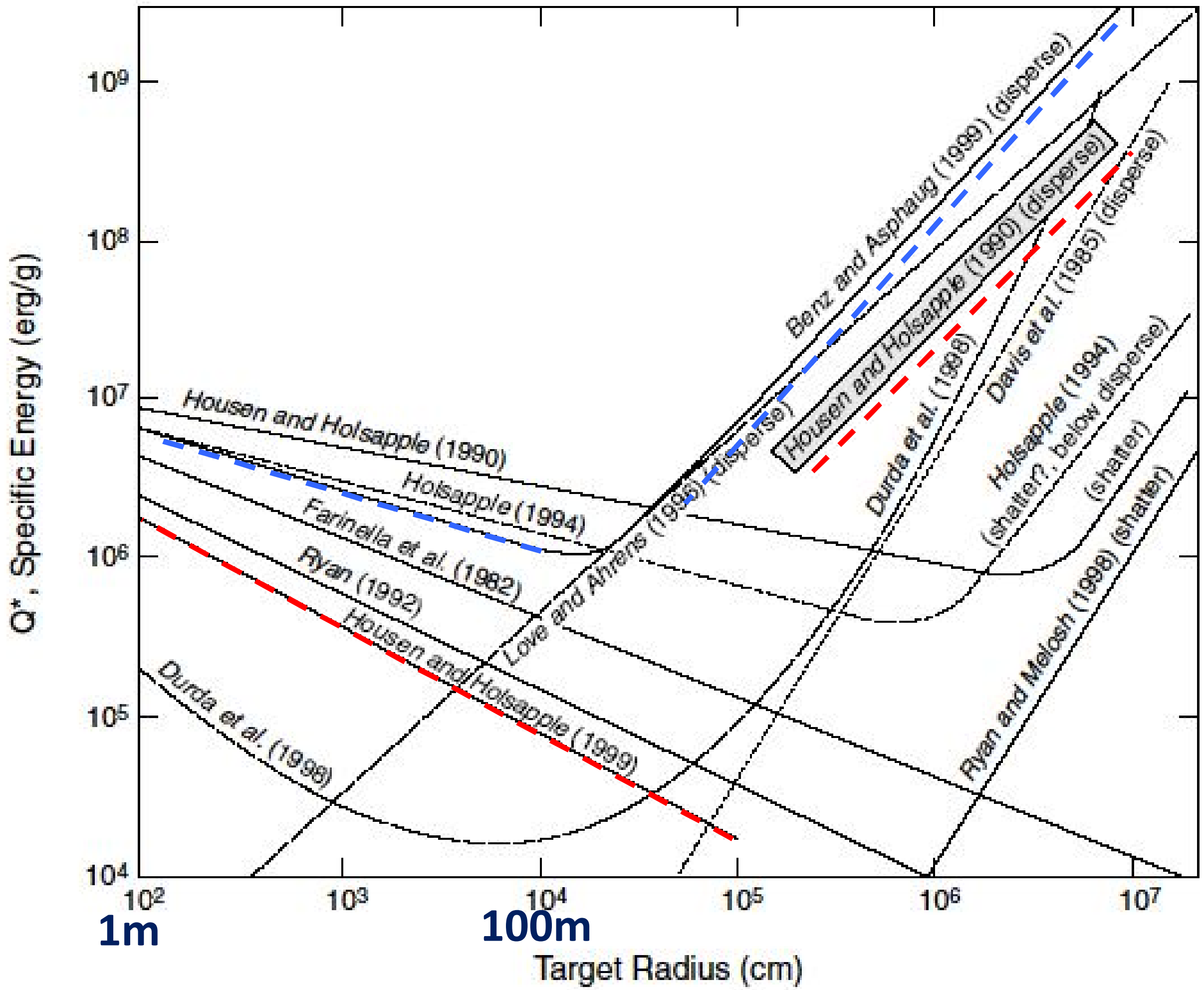
strength-A: hydrocode (**SALE**)
(Nolan, Asphaug, Melosh, and Greenberg, 1996)
gravity: pi-group hardrock (Holsapple, 1993)
strength-B: pi-group hardrock (Holsapple, 1993.)

O’Brien et al. (2006)
Mathilde に対して
（仕方なく）pi-group loose sand (Holsapple 1993)
を適用

小惑星帯の衝突進化モデル
O’Brien et al., 2005; Bottke et al., 2005

制約：
小惑星サイズ分布
・ベスタが壊れていないが大きなクレーター
・普通コンドライトの宇宙線照射年代
・小惑星（Gaspra, Ida, Mathilde, Eros）クレーターサイズ頻度分布
・小惑星の族の個数

スケーリング則や数値シミュレーションにより推定された衝突破壊のしきい値（*Q**）



(Holsapple et al., 2002)

2. 強度モデル、空隙モデル

流体

連続体　　　粉粒体

References: **Holsapple, K. A., 2009.**
On the‘‘strength’’of the small bodies of the solar system:
A review of strength theories and their implementation for analyses
of impact disruptions.
+ iSALE manual + ,,,

岩石強度・空隙モデルの入った数値シミュレーション

- Dynamic fragmentation in impacts - Hydrocode simulation of laboratory impacts, Melosh, Ryan, and Asphaug, 1992. **SALE + G-K モデル**

- Impact simulations with fracture.I-Method and tests, Benz and Asphaug, 1994. **G-K モデル + SPH**

-> Catastrophic disruptions revisited, Benz and Asphaug, 1999. ***Q****
（解像度に難あり、後にBenz自身がCD6(2003)かCD7(2007)で言及）

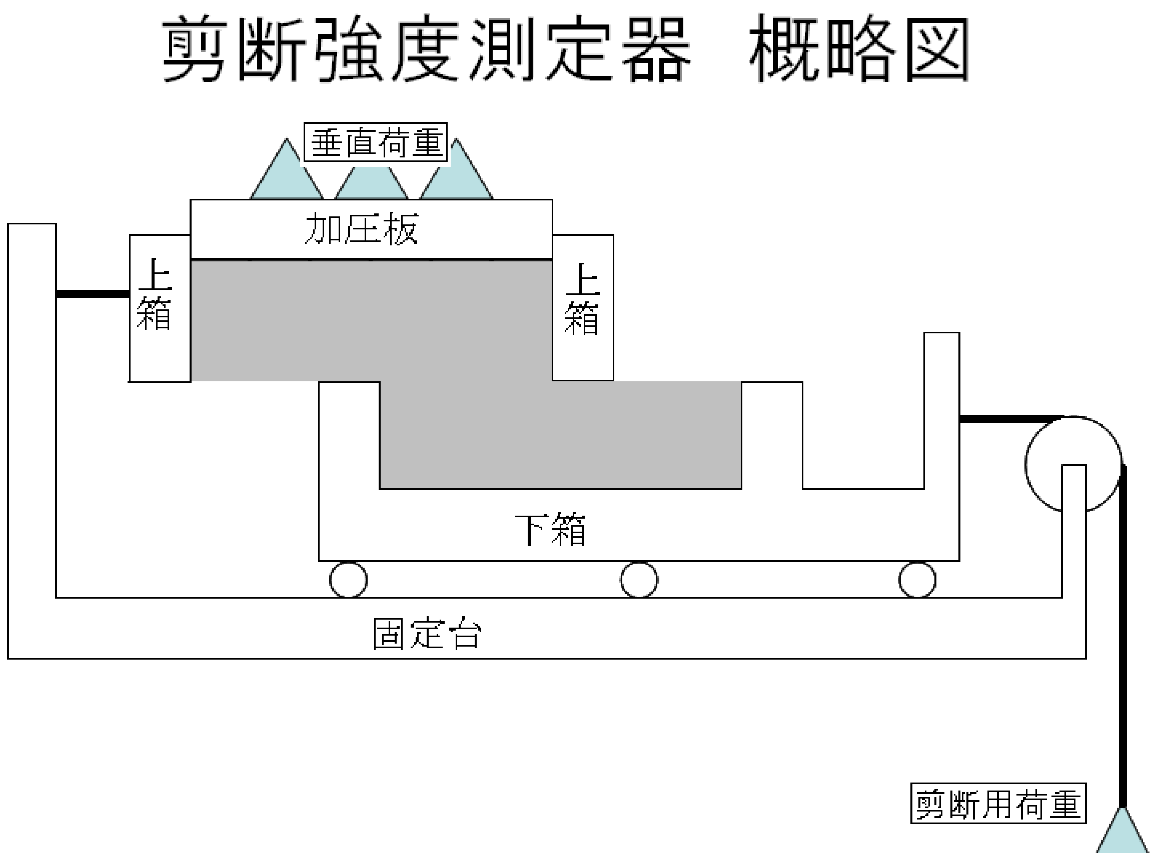
- Modeling damage and deformation in impact simulations, Collins, Melosh, and Ivanov, 2004. **SALE + Collins damage model**

“more comprehensive model (than the model in ‘92)” by Holsapple (2009)

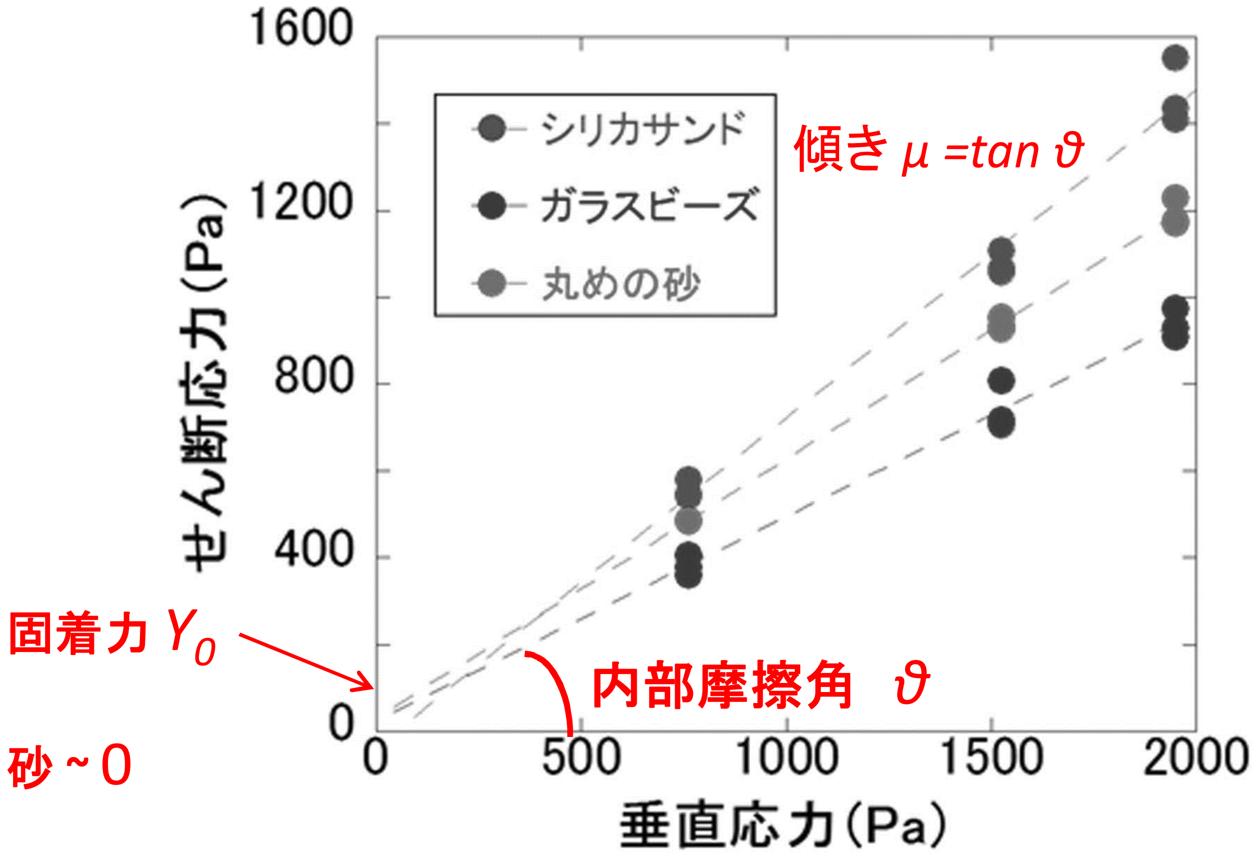
- A strain-based porosity model for use in hydrocode simulations of impacts and implications for transient crater growth in porous targets, Wunnenmann, Collins, and Melosh, 2006. **ε-α model**

- Numerical simulations of impacts involving porous bodies, Jutzi, Benz, and Michel, 2008. **P-α model**

粉粒体のせん断強度

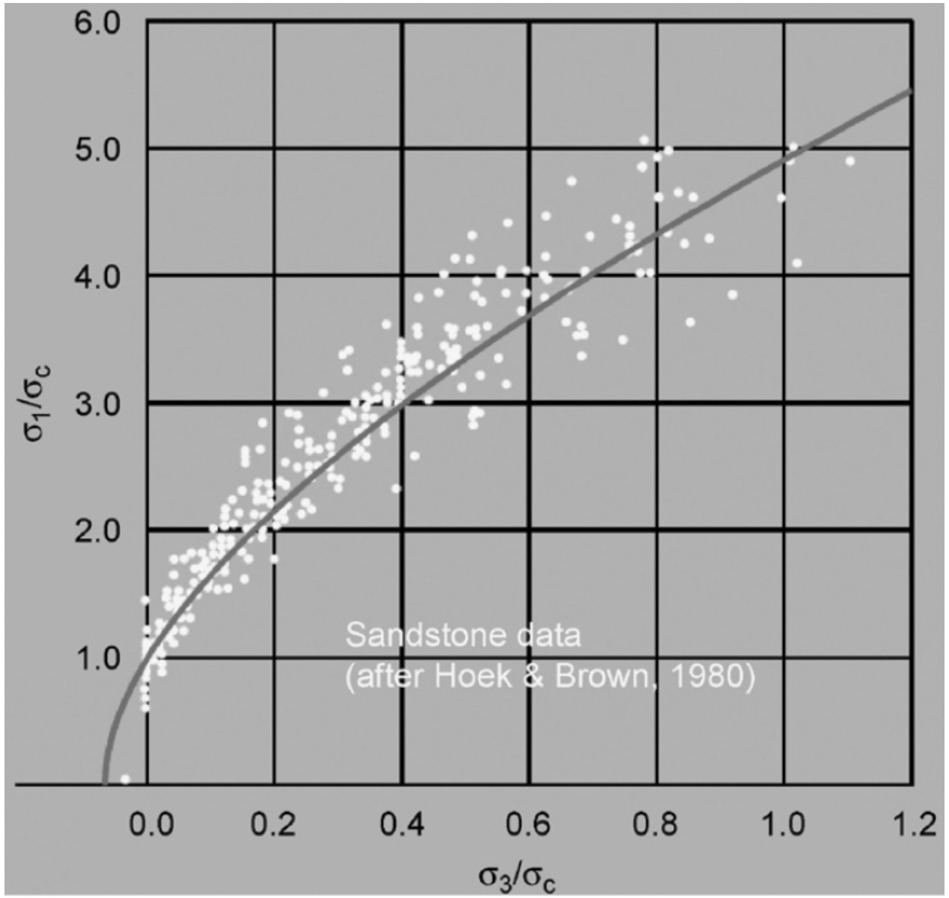


描画：Hakura, 2011による

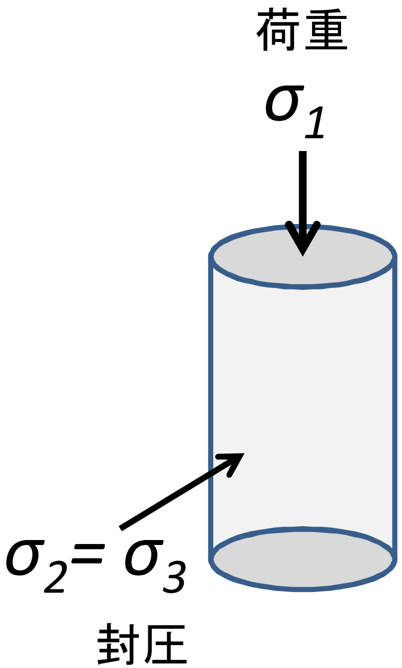

せん断応力(Pa)
垂直応力(Pa)
1600
1200
800
400
0
0
500
1000
1500
2000
シリカサンド
ガラスビーズ
丸めの砂
傾き μ =tan ϑ
固着力 Y_0
内部摩擦角 ϑ
砂 ~ 0

(Aoki, 2014)

砂岩の三軸圧縮試験結果



(Holsapple, 2009)



σ_1：最大主応力
σ_3：最小主応力

強度

それを超えると，変形が元に戻らない応力

$$f(\sigma) = C.$$

応力の不変量　J_1, J_2, J_3を用いて，

$$f(J_1, J_2, J_3) = f(P,\ J_2\ ,) = C.$$

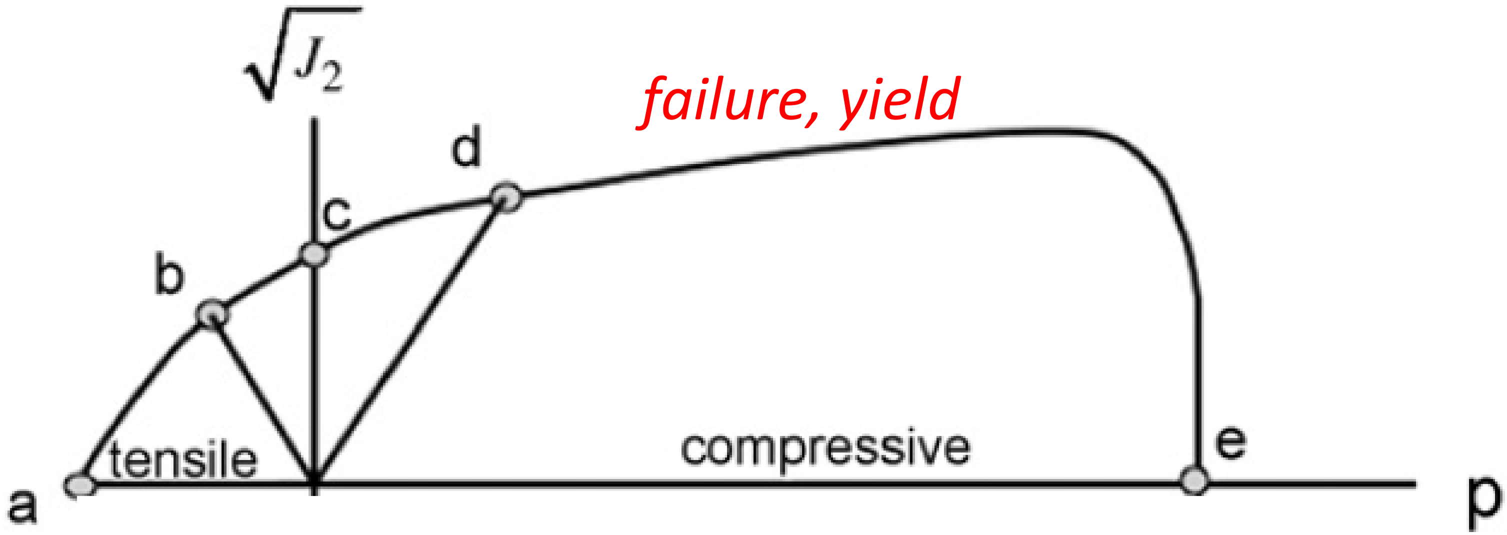
$$J_1 = \sigma_1 + \sigma_2 + \sigma_3 = -3P$$

$$J_2 = \frac{1}{6}\left((\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right)$$

$$f(P, J_2) = C \longrightarrow \sqrt{J_2} = Y$$

iSALE

Y: 強度モデル



b: 一軸引張強度（$\sigma_1=\sigma$, $\sigma_2=\sigma_3=0$）

$J_2 = \sigma/\sqrt{3}$,　$P = -\sigma/3$

c: 固着力

d: 一軸圧縮強度

(Holsapple, 2009)

iSALEの物質パラメタ (material.inp)

MATNAME	Material name	: mygrani
EOSNAME	EOS name	: granite
EOSTYPE	EOS type	: aneos
STRMOD	**Strength model**	**: ROCK**
DAMMOD	**Damage model**	**: COLLINS**
ACFL	Acoustic fluidisation	: BLOCK
PORMOD	**Porosity model**	**: NONE**
THSOFT	Thermal softening	: OHNAKA
LDWEAK	Low density weakening	: POLY

強度、ダメージ、空隙率

POIS	pois	: 3.D-01
TMELT0	tmelt0	: 1.673D+03
CHEAT	C_heat	: 1.D+03
TFRAC	tfrac	: 1.2D+00
ASIMON	a_simon	: 6.D+09
CSIMON	c_simon	: 3.D+00
YDAM0	ydam0 (ycoh)	: 1.D+04
FRICDAM	fricdam	: 8.D-01
YLIMDAM	ylimdam	: 2.D+09
YINT0	**yint0**	**: 1.D+07**
FRICINT	**fricint**	**: 1.1D+00**
YLIMINT	**ylimint**	**: 2.5D+09**
BDTPRES	bdt_pres	: -1.D+00
BPTPRES	bpt_pres	: -1.D+00
GAMETA	gam_eta	: 8.D-03
GAMBETA	gam_beta	: 1.15D+02

強度モデル（STRMOD）

ROCK Pressure- and damage-dependent strength model for rock-like materials.

DRPR Drucker-Prager: Linear pressure-dependent strength model for granular materials.

LUNDI Lundborg intact: Non-linear pressure-dependent strength model for intact rock.

LUNDD Lundborg damaged: Non-linear pressure-dependent strength model for damaged rock.

VNMS Von Mises: Constant yield-strength model for ductile materials.

JNCK Johnson and Cook: Strain and strain-rate dependent strength model for metals.

LIQU Liquid: Newtonian fluid model

HYDRO Hydrodynamic: Inviscid fluid model

DRPR Drucker-Prager:
Linear pressure-dependent strength model for granular materials.

$$Y = min(Y_0 + \mu p, Y_m)$$

Constant	Input parameter	Description
Y_0	YDAM0	Cohesion (yield strength at zero pressure)
μ	FRICDAM	Coefficient of internal friction for material
Y_m	YLIMDAM	Limiting strength at high pressure

LUIND Lundborg intact:
Non-linear pressure-dependent strength model for intact rock.

$$Y = Y_0 + \frac{\mu p}{1 + \frac{\mu p}{Y_m - Y_0}}$$

Constant	Input parameter	Description
Y_0	YINT0	Cohesion (yield strength at zero pressure)
μ	FRICINT	Coefficient of internal friction for material
Y_m	YLIMINT	Limiting strength at high pressure

ROCK Pressure- and damage-dependent strength model for rock-like materials.

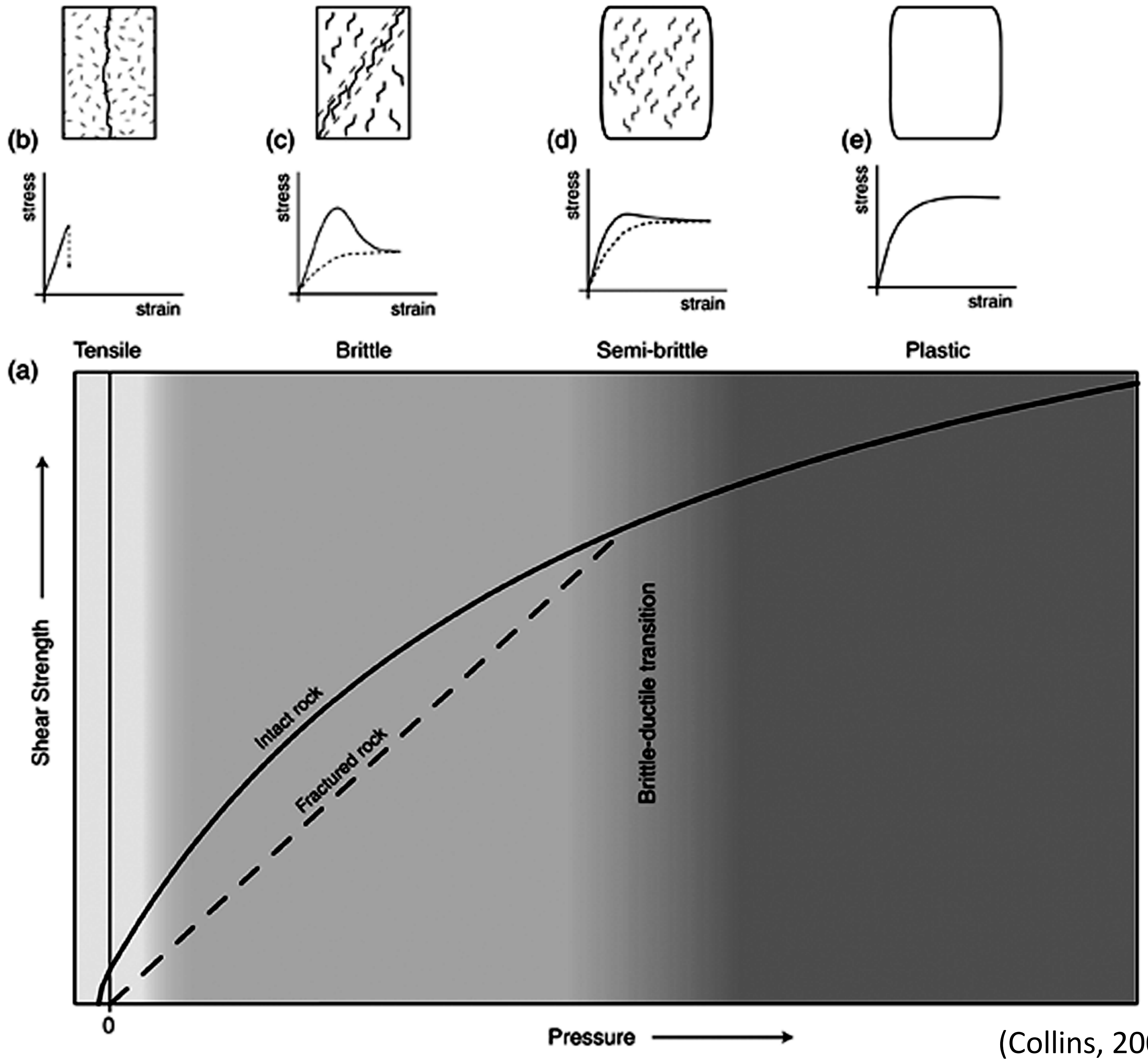
$$Y = Y_d D + Y_i (1. - D)$$

D: damage parameter, *D*=0: intact, *D*=1: fully-damaged

$$Y_d = min(Y_{d0} + \mu_d p, Y_{dm})$$

$$Y_i = Y_{i0} + \frac{\mu_i p}{1 + \frac{\mu_i p}{Y_{im} - Y_{i0}}}$$

Constant	Input parameter	Description
Y_{i0}	YINT0	Cohesion of intact material
μ_i	FRICINT	Coefficient of internal friction for intact material
Y_{im}	YLIMINT	Limiting strength at high pressure for intact material
Y_{d0}	YDAM0	Cohesion of damaged material
μ_d	FRICDAM	Coefficient of internal friction for damaged material
Y_{dm}	YLIMDAM	Limiting strength at high pressure for damaged material



(Collins, 2004)

ダメージモデル(DAMMOD)

COLLINS Combined shear and tensile failure model with brittle, semi-brittle and ductile shear failure regimes.

IVANOV Shear failure model with pressure-dependent failure strain.

SIMPLE Shear failure model with constant failure strain.

NONE No damage model; material remains intact.

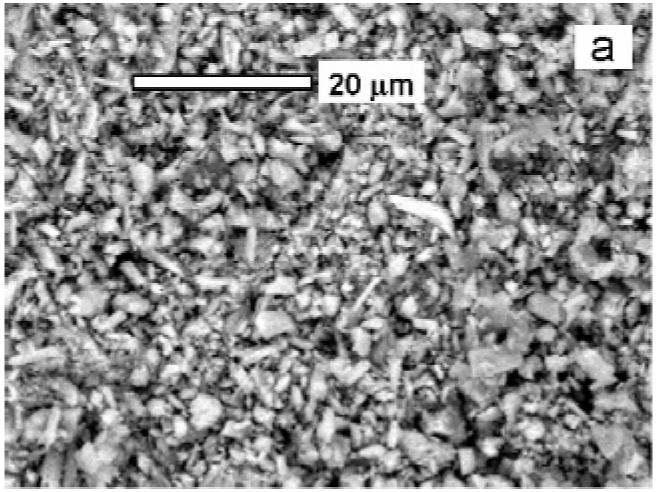
SIMPLE Shear failure model with constant failure strain.

$$D = \min\left(\frac{\epsilon_p}{\epsilon_f}, 1\right)$$

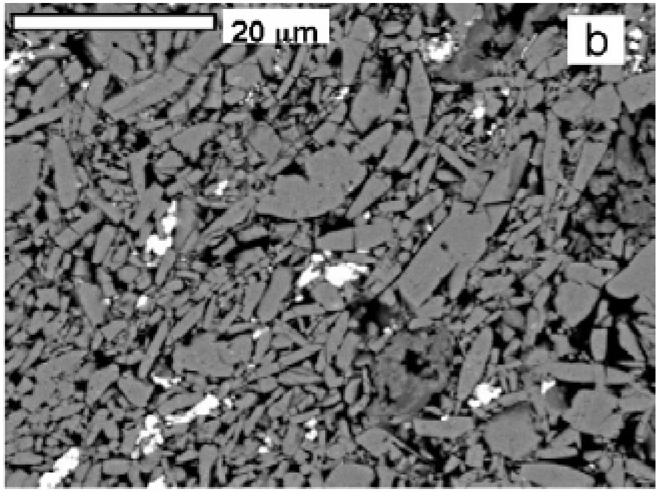
ϵ_p TPS - **Total plastic strain (shear)**

Constant	Input parameter	Description
ϵ_f	FAILSTRN	Constant plastic strain at failure

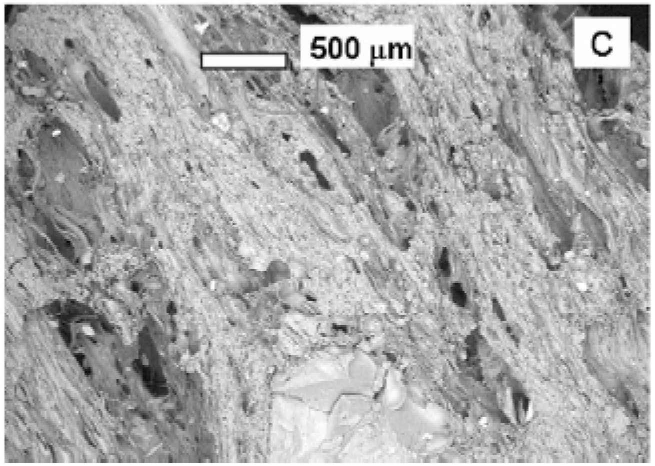
空隙モデル



石膏



Allende matrix



軽石

(Nakamura et al., 2009)

“distension (膨張パラメタ)” α を使って 1つの連続体で表す

α=物質の真密度ρ_s/バルク密度ρ

$$P = f(\rho, E, \alpha) = \frac{1}{\alpha} P_s(\alpha\rho, E) = \frac{1}{\alpha} P_s(\rho_s, E)$$

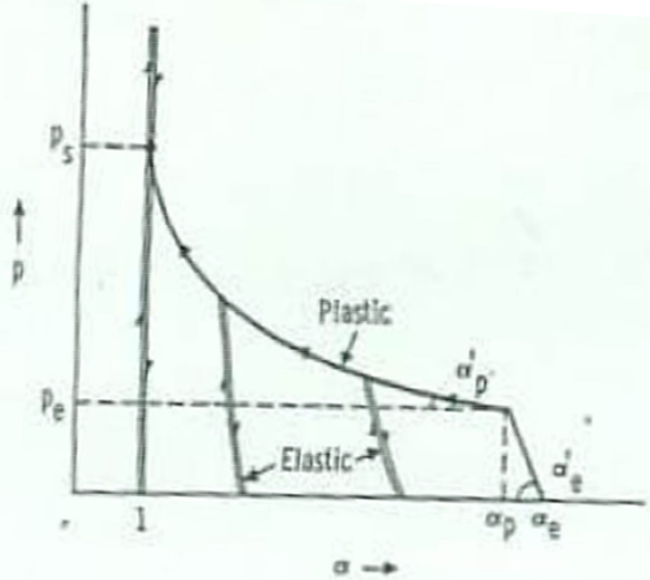
熱力学的説明　see Holsapple (2008)

P-α　モデル　(Hermann, 1969)

ε-α　モデル　(Wunnemann et al., 2006)

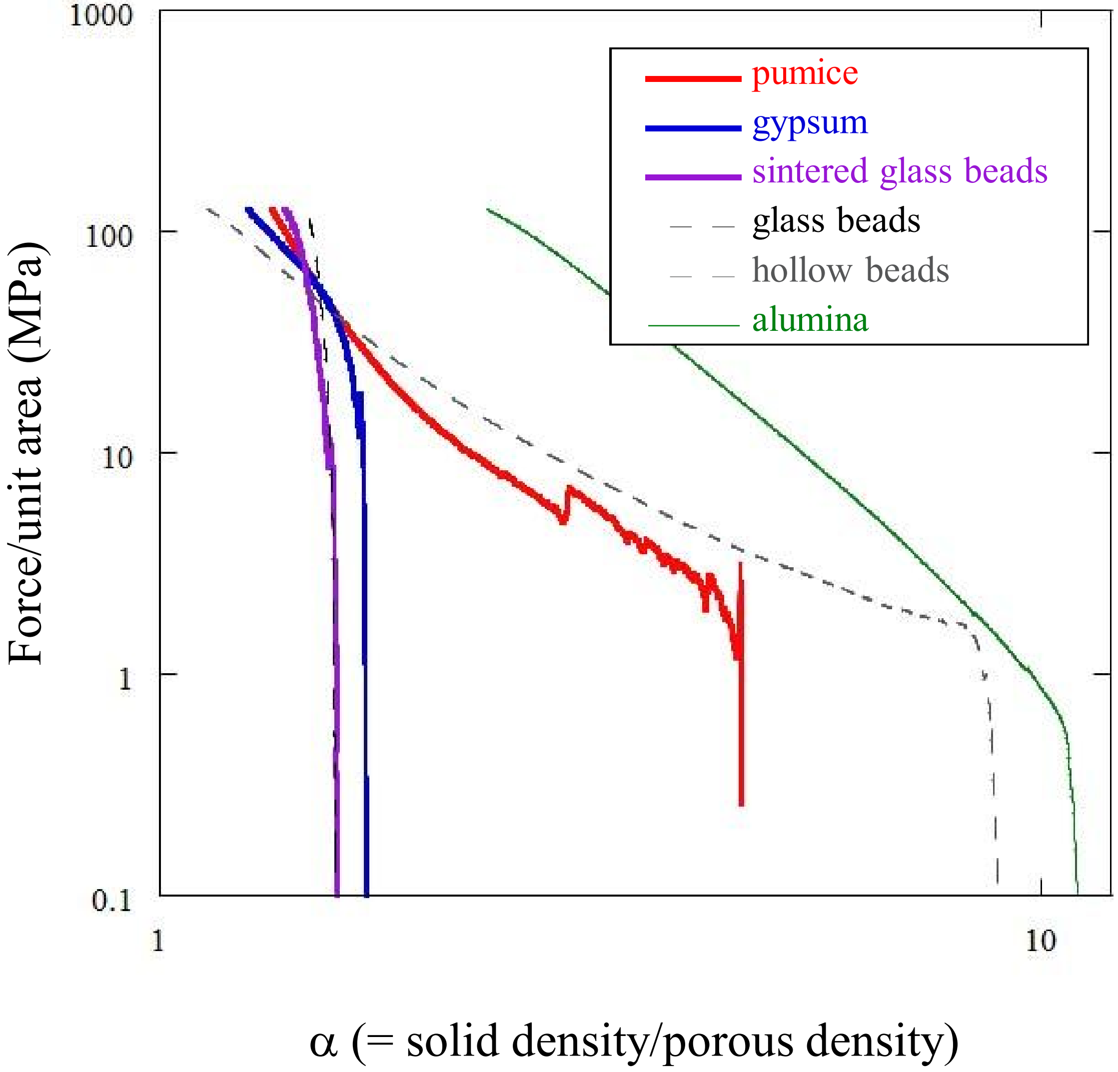
P-α モデル (Hermann, 1969)

FIG. 1. Schematic of the postulated compaction behavior of a ductile porous material.



$\alpha=\rho_s/\rho=F(P)$

多孔質物質の圧密曲線

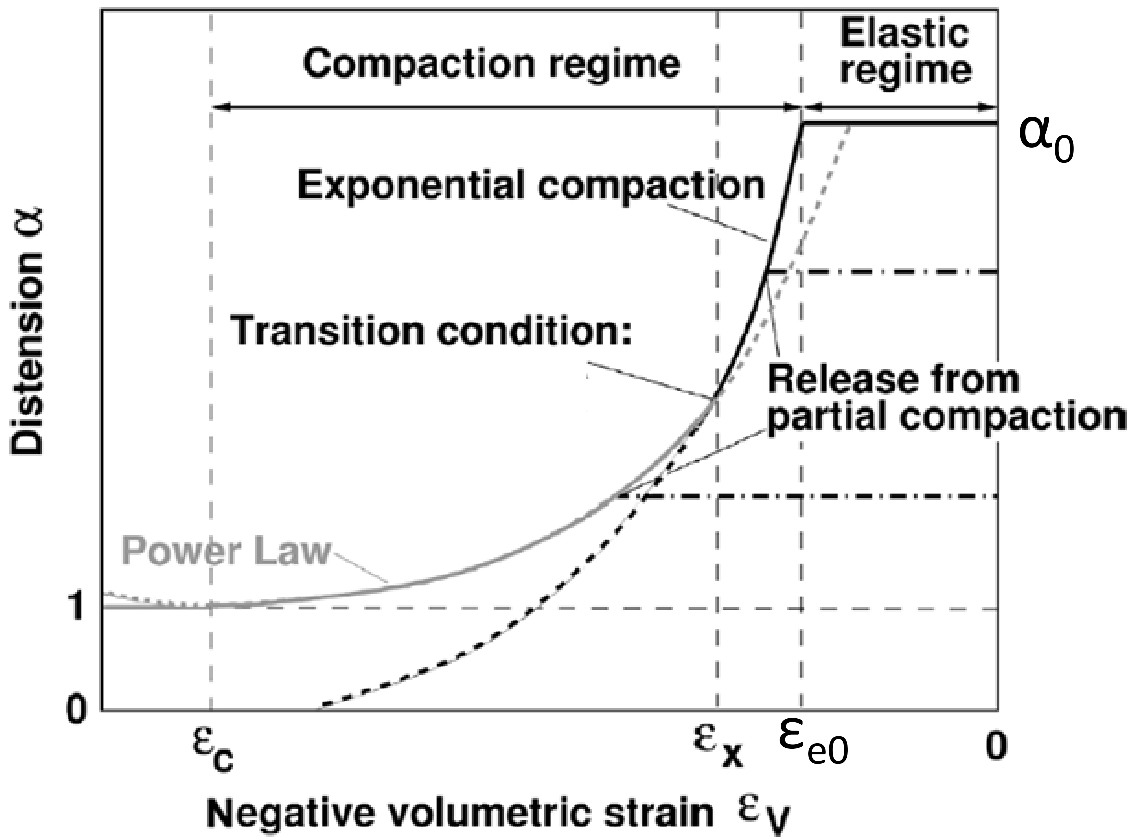


head speed=0.06mm/min

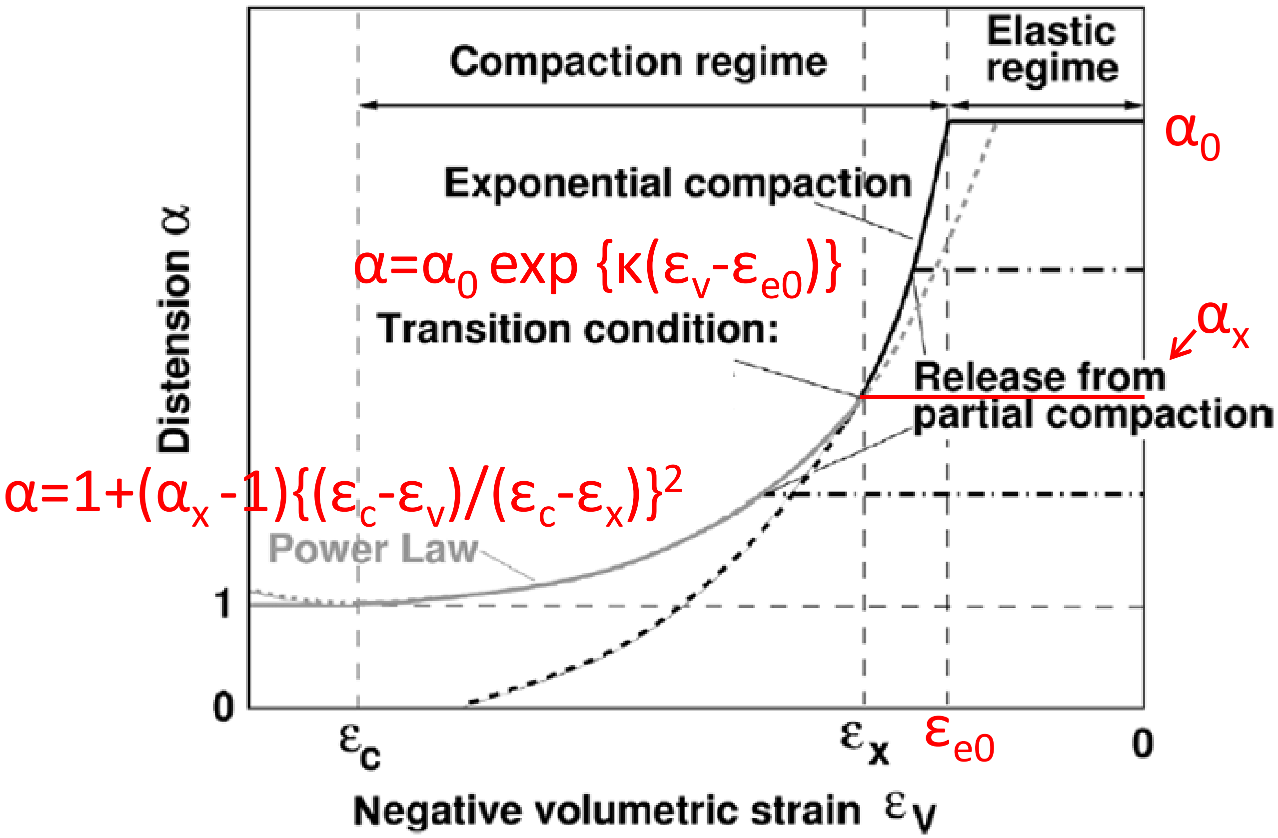
Hiraoka and Nakamura, 2007
(@CD8)

ε-α モデル

$$\varepsilon_V = \int_{V_0}^{V'} \frac{\mathrm{d}V}{V} = \ln\left(\frac{V'}{V_0}\right) = \ln\left(\frac{V'}{V_S}\frac{V_S}{V_0}\right) = \ln\left(\frac{\alpha}{\alpha_0}\right),$$



(Wünnemann et al, 2006)



Note that the behaviour of the original model can be regained by choosing $\chi = 1$.

Constant	Input parameter	Description
α_0	ALPHA0	Initial distension of porous material (1/(1-porosity))
ϵ_{e0}	EPSE0	Elastic volumetric strain threshold (-ve in compression)
α_x	ALPHAX	Distension at transtion from exponential to power-law compaction
κ	KAPPA	Compaction rate parameter in exponential compaction regime
χ	CHI	Ratio of porous to solid material sound speed at zero pressure

3. 数値シミュレーションと実験の関わり

Dynamic fragmentation in impacts - Hydrocode simulation of laboratory impacts, Melosh, Ryan, and Asphaug, 1992. SALE + G-K

- Impact simulations with fracture.I-Method and tests, Benz and Asphaug, 1994. *G-K + SPH*

  ref. Nakamura and Fujiwara, 1991; Nakamura 1993

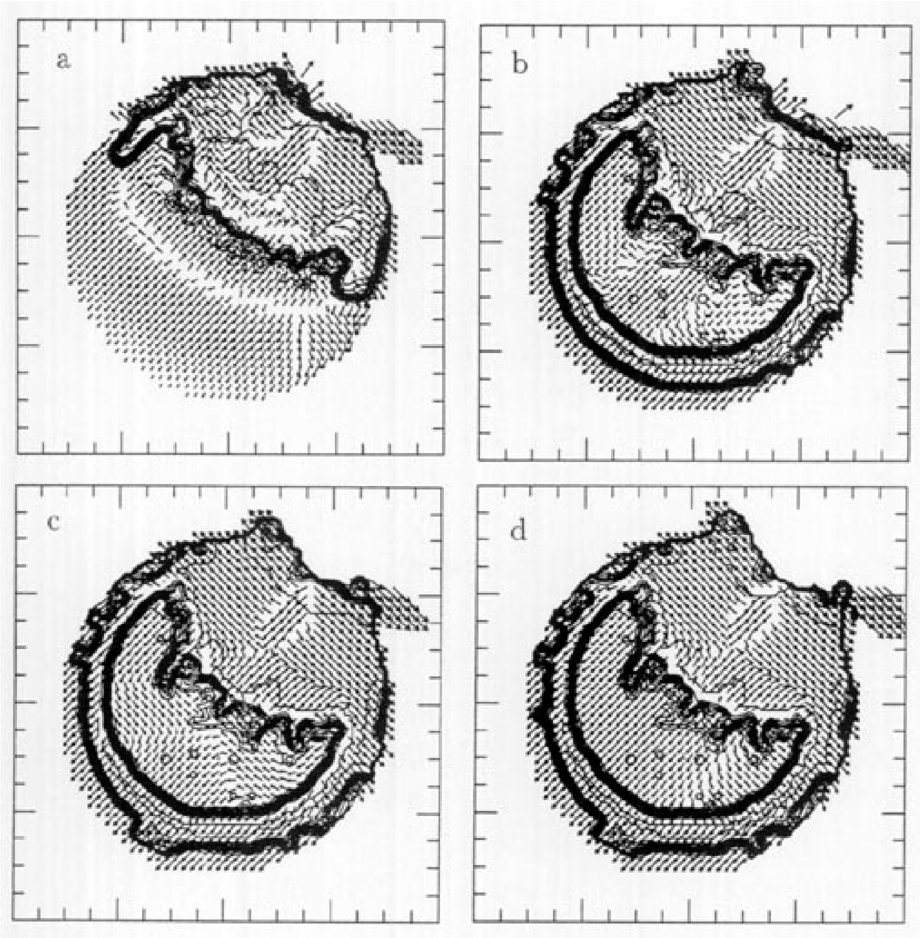
- Weibull parameters of Yakuno basalt targets used in documented high-velocity impact experiments, Nakamura, Michel, and Setoh, 2007. G-KのWeuibull 定数

- Numerical simulations of impacts involving porous bodies,

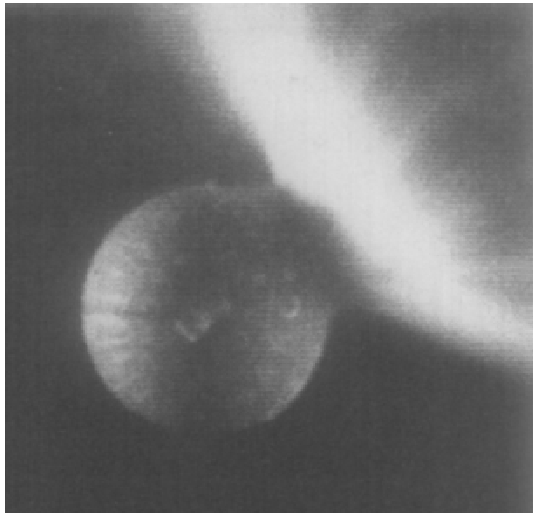
  Jutzi, Benz, and Michel, 2008. *P-α model*

  Numerical simulations of impacts involving porous bodies II. Comparison with laboratory experiments, Jutzi, Michel, Hiraoka, Nakamura, Benz, 2009.

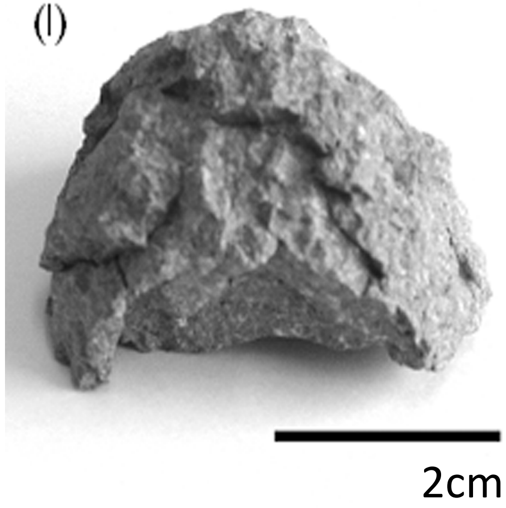
玄武岩へのナイロン球衝突



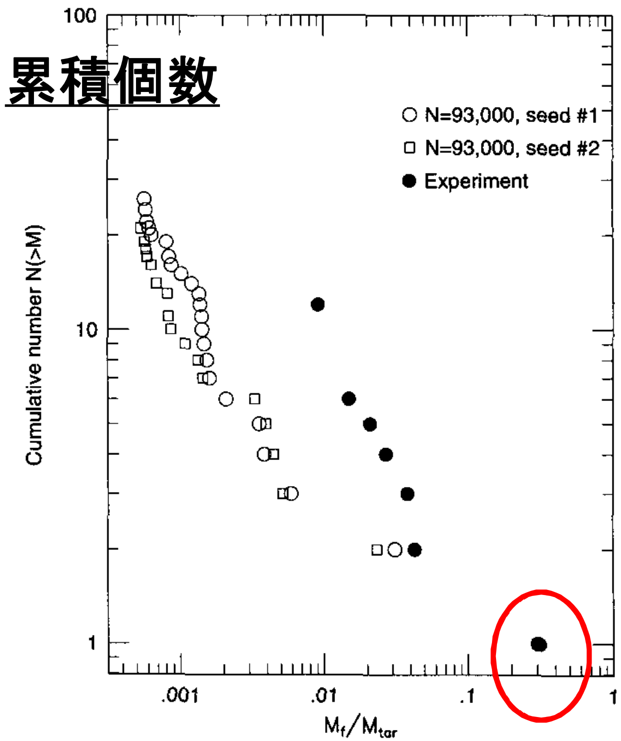
衝突から10、20、30、40 μsの等ダメージ線と粒子速度ベクトル (Benz and Aphaug, 1994)



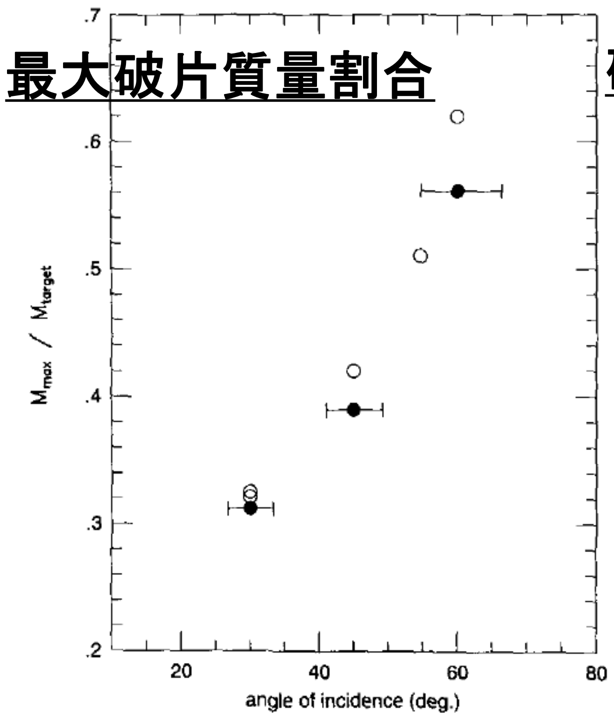
衝突から100 μs (Nakamura and Fujiwara, 1991; Nakamura, 1993)



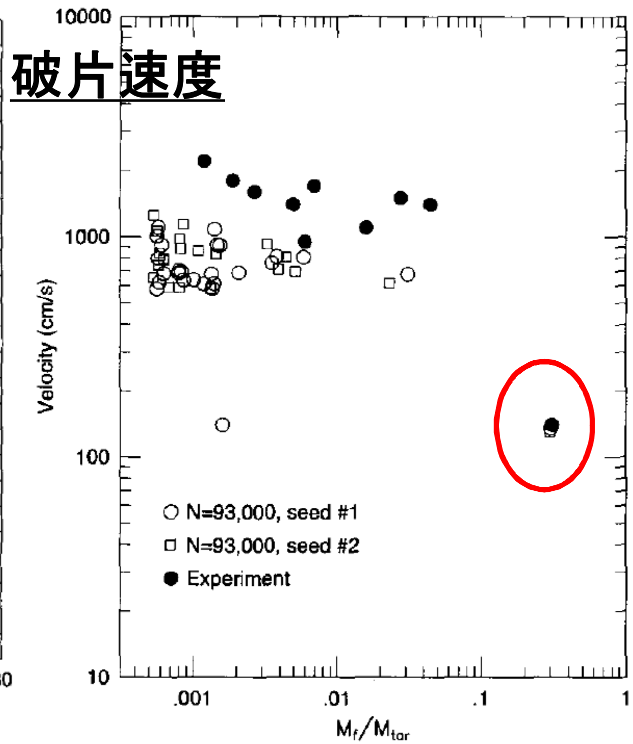
Benz and Asphaug 1994数値シミュレーションと実験との比較



破片質量/標的質量



衝突角度



破片質量/標的質量

Weibullパラメタ (m,k) の値

TABLE 1. Weibull dynamic fracture coefficients for various rocks.

Material	Reference	m	k (cm^{-3})	ln(k)/m
Basalt*	*Melosh et al.* (1992)	9.5	1.0×10^{27}	6.54
Basalt*	*Benz and Asphaug* (1995)	9.0	4.0×10^{29}	7.17
Basalt†	*Lindholm et al.* (1974)	9.5	1.59×10^{30}	7.32
Granite†	*Grady and Lipkin* (1980)	6.2	4.14×10^{17}	6.54
Water Ice*,†,‡	*Benz and Asphaug* (1999)	9.6	1.4×10^{32}	7.71
30% Sand + Water Ice†	*Stewart et al.* (1999)	9.57	1.34×10^{30}	7.25
Concrete†	*Grady and Lipkin* (1980)	5.3	5.27×10^{12}	5.53
Oil Shale†	*Grady and Kipp* (1980)	8.1	1.70×10^{21}	6.04
Limestone†	*Grady and Lipkin* (1980)	57.0	4.26×10^{167}	6.77

* Determined from simulation fits to laboratory data. The two-dimensional axisymmetric simulations of *Melosh et al.* (1992) require stronger fracture parameters than the nonsymmetric three-dimensional simulations of *Benz and Asphaug* (1995) for the same impact experiment.

† Determined experimentally through measurements of tensile strength vs. strain rate.

‡ Earlier published values of $m = 8.7$, $k = 3.2 \times 10^{38}$ (*Lange and Ahrens,* 1983) were later corrected to similar values [$m = 9.57$, $k = 1.28 \times 10^{32}$ (*Stewart et al.*, 1999)].

(Asphaug et al., 2002)

Weibull (1939)分布

応力σ以下で成長し始めるひびの数密度を

$$n(\sigma) = k\sigma^m$$

とすると、ランダムに選んだ体積vの中に、応力σ以下で成長し始めるひびを含む確率は、

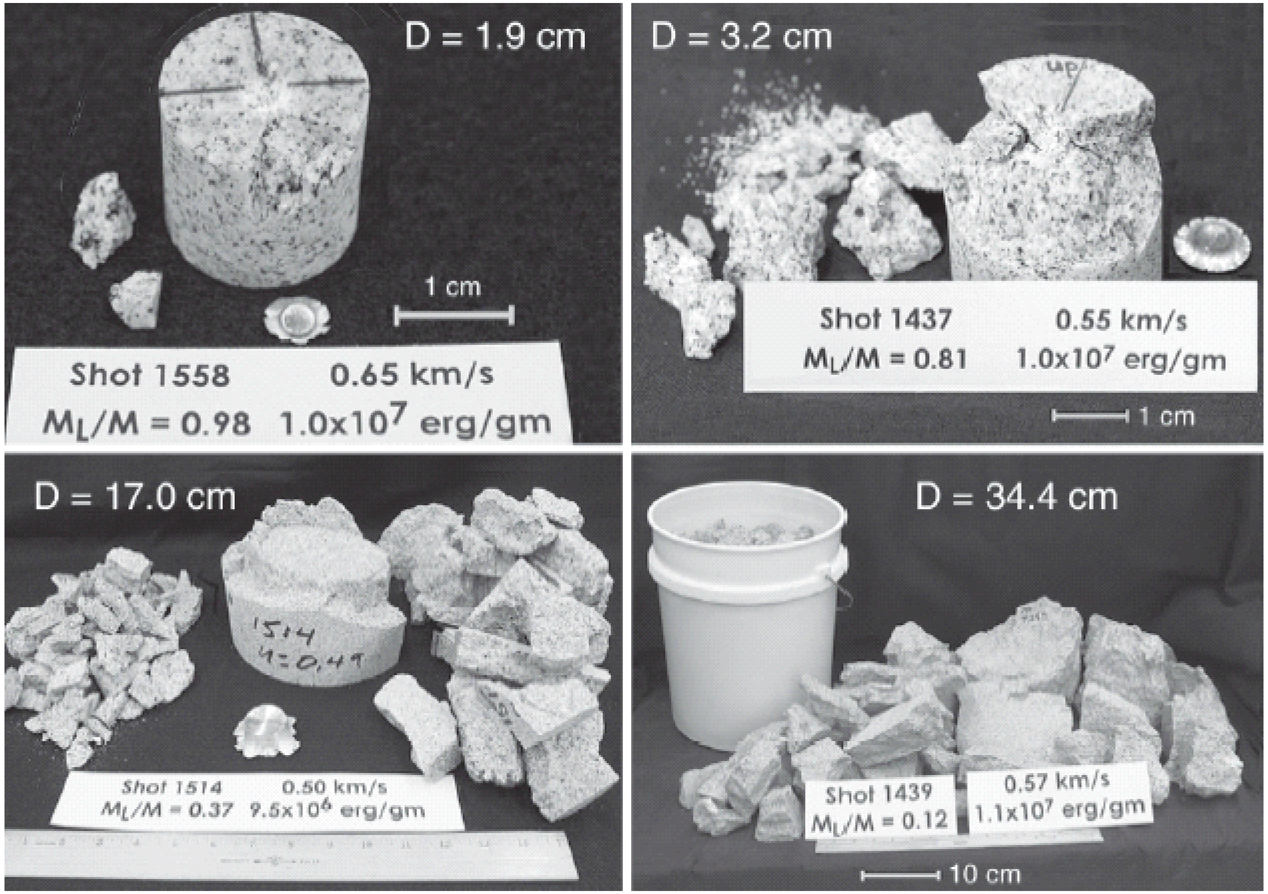
$$1 - exp[-(\sigma/\sigma_{min})^m]$$

ただし、

$$\sigma_{min} = (kV)^{-(1/m)}$$

← 強度のサイズ効果

ターゲットサイズ効果



(Housen and Holsapple, 1999)

標的/弾丸比を固定して速度も（ほぼ）一定で系の大きさだけ変化させた衝突実験

大きいものほど壊れやすい、細かく壊れる

Grady-Kippの破壊モデル (1980)

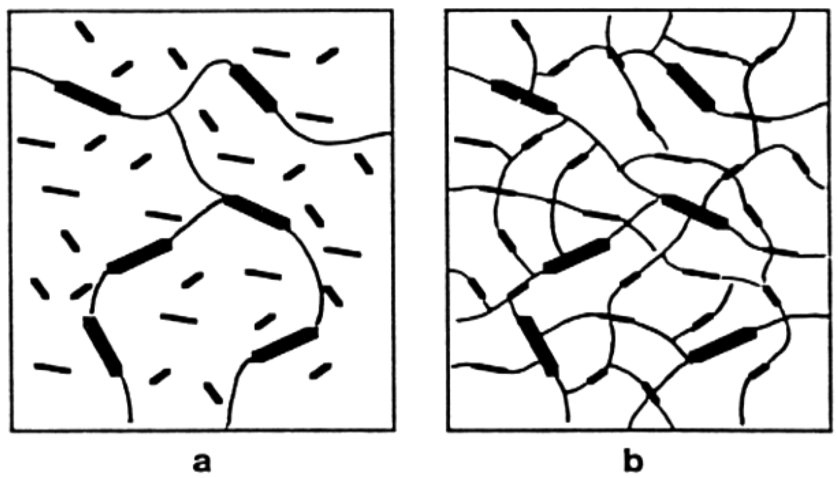
- 脆性物質は、内在するひび（のもと）が成長して、引張りで壊れる。

$n(\sigma) = k\sigma^m$

歪ε以下で活性化するひびの個数 $n(\varepsilon)$は $n(\varepsilon) = k\varepsilon^m$ とかかれる。

- ひびは、一定速度Cgで時間とともに成長する。
- ひびの空間密度により定義されるdamage "D", $\sigma_D = \sigma(1 - D)$

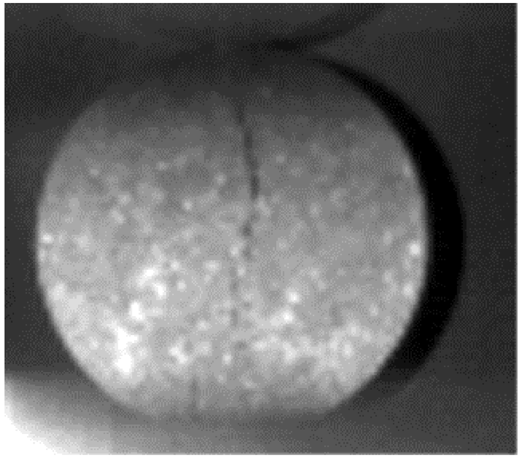
歪速度小



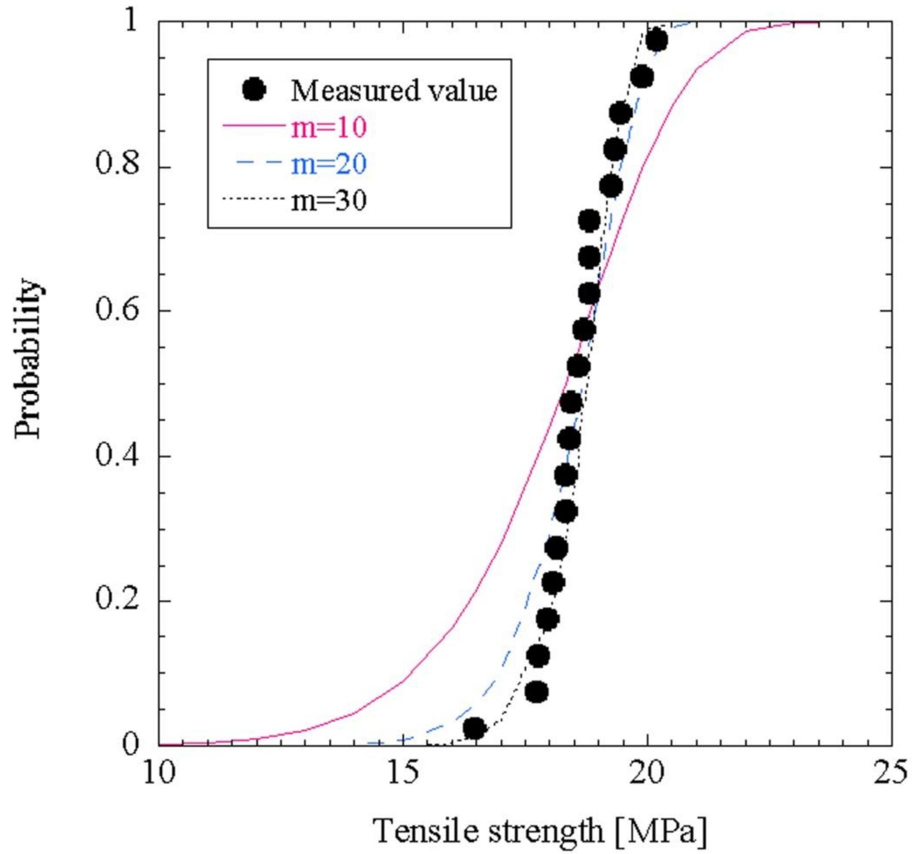
歪速度大

破片サイズ∝(歪速度)$^{-m/(m+3)}$

Weibull (1939) の手法による



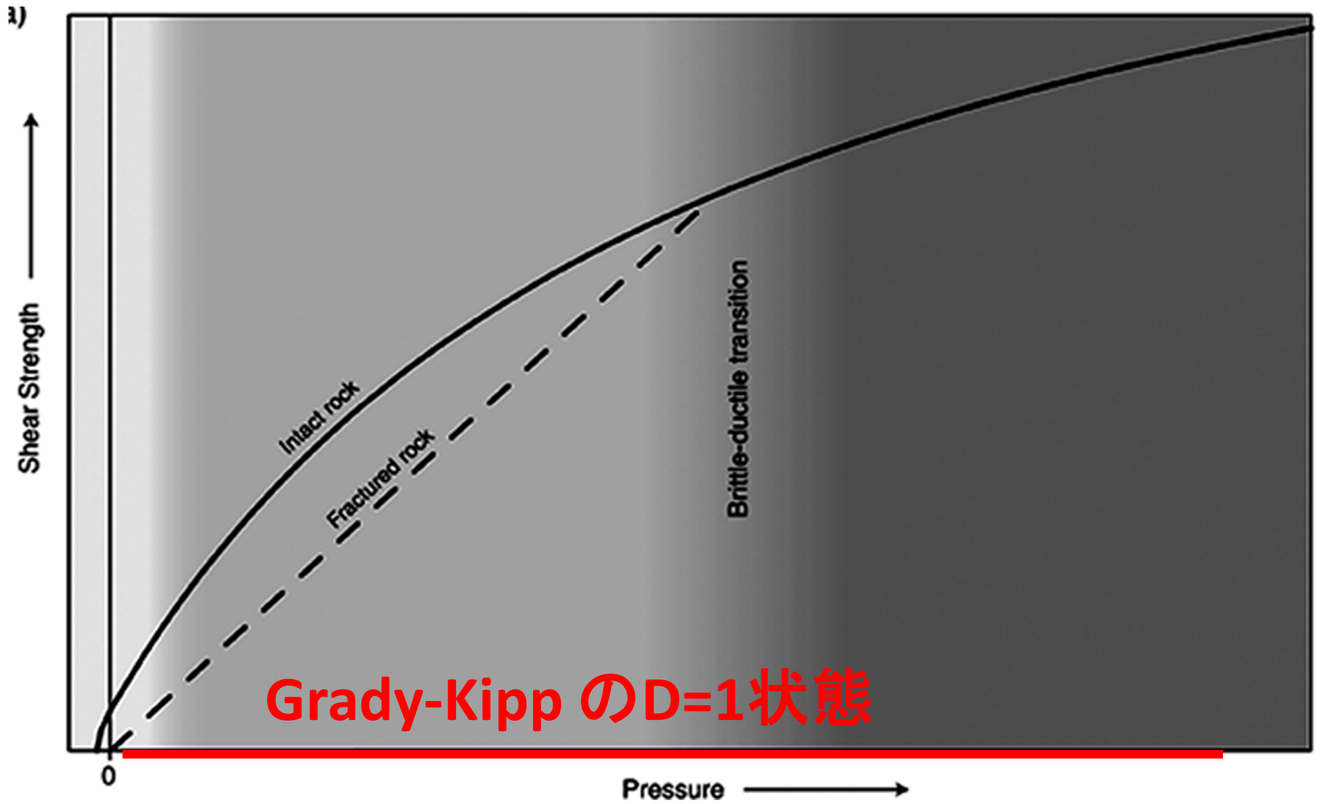
直径10 mm、厚み5 mm の
円板 20 個の圧裂引張強度測定



$$1-\exp(-\sigma/\sigma_0)^m$$

$$m = 15 - 17$$

(Nakamura, Michel, and Setoh, 2007)

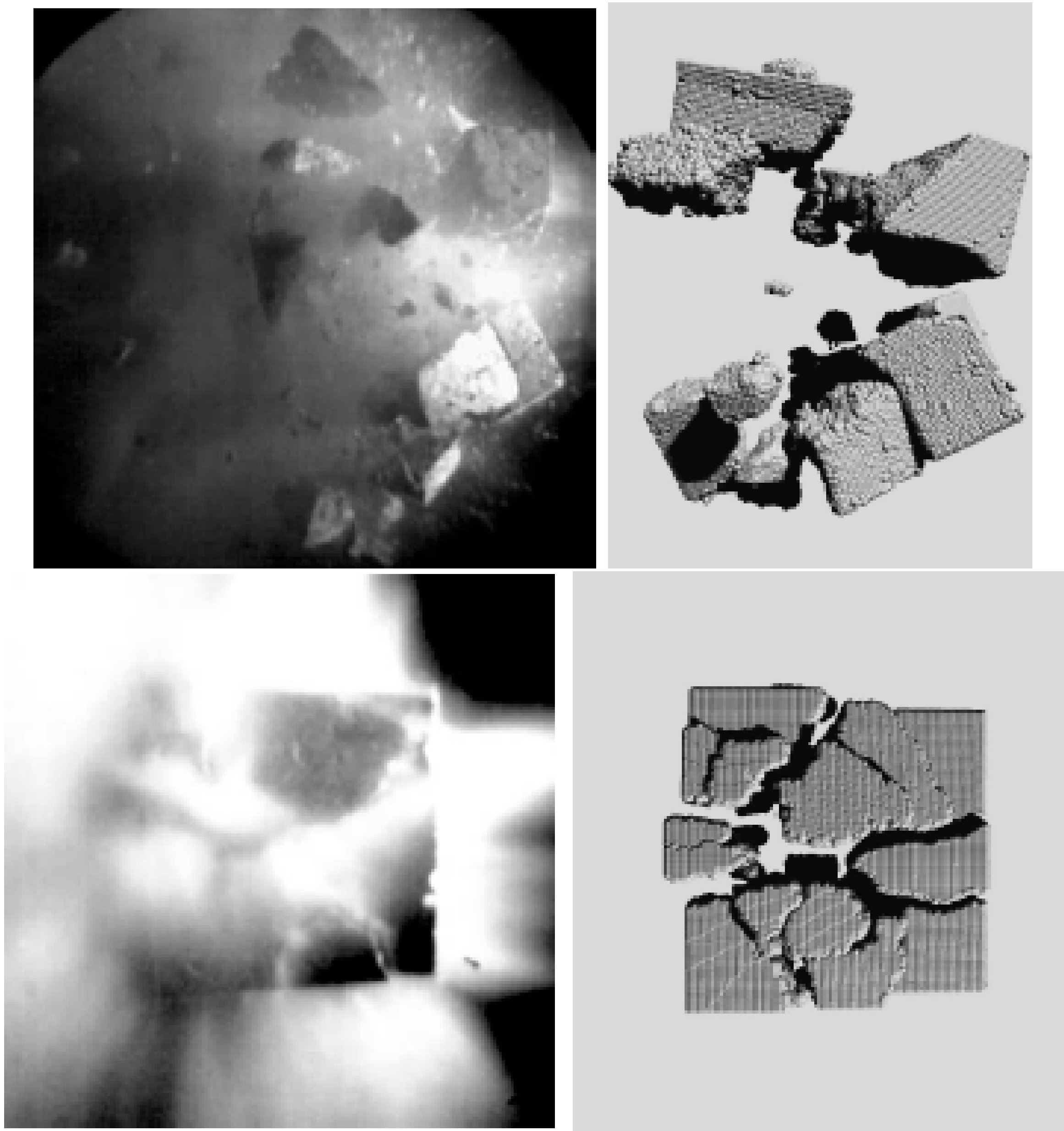


G-Kモデルを採用した数値計算　破壊された部分が流体として振る舞う

⇒　Shear が重要なクレーター形成過程のシミュレーションには向かない

(Holsapple)

引張破壊が支配的な Disruption向け



(Jutzi et al., 2009)

シミュレーションと実験の共同研究への道

1. 出会い・タイミング
2. 少なくとも片方に強い熱意・わくわく感
3. 互いの言語を理解しようとする姿勢