INGEOKRING SYMPOSIUM- 23 NOV 2018

EFFECT OF HIGH HYPERBARIC PRESSURE ON ROCK CUTTING PROCESS

A tribute to **Peter Verhoef**: Engineering Geology as an eye-opener for Civil Engineering

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OUTLINE

- Background information
- Hyperbaric cutting process – hypothesis
- Laboratory investigation
- Experimental results and observations
- Hyperbaric cutting models
- Conclusions

BACKGROUND – DEEP SEA MINING

- History
  - HMS Challenger, 1874: polymetallic nodules (manganese nodules)

- Why Deep Sea Mining interest recently?
  - Growing demand for resources
  - Depletion of onshore easy accessible deposits
  - Independent from other countries

Source: NOAA Photo Library

Onshore

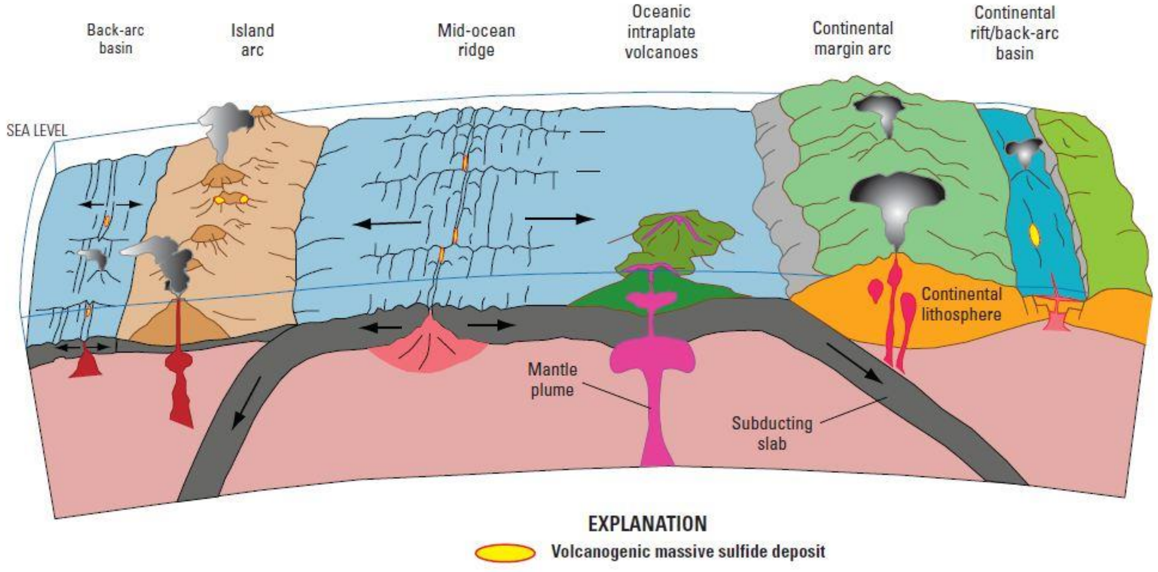
Offshore

Source: Mining Technology, 2012

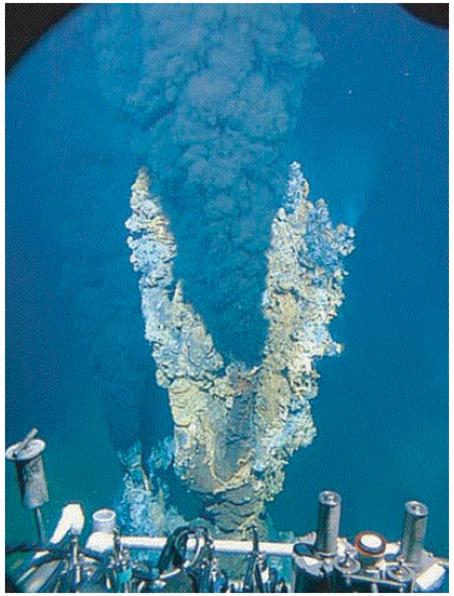
BACKGROUND – DEEP SEA MINING (SMS)

- High grades of Cu, Zn, Au, and Ag
- Hydrothermal origin
- ‘Black Smokers’

Parameter	Min	Max
Wet bulk density [kg/m^3]	$2.4 \cdot 10^3$	$4.0 \cdot 10^3$
Solid density [kg/m^3]	$3.6 \cdot 10^3$	$5.5 \cdot 10^3$
Porosity [-]	0.15	0.53
Unconfined compressive strength [MPa]	3.1	38
Tensile strength [MPa]	0.14	5.2
Typical water depth [m]	> 1000	



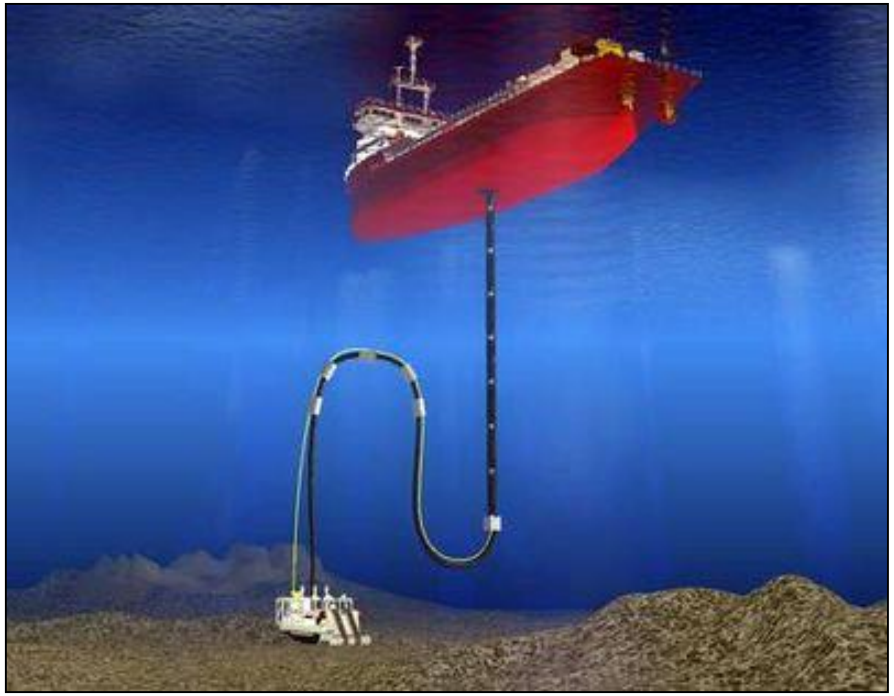
Source: Shanks and Thurston, 2012



Source: Tivey, 2007

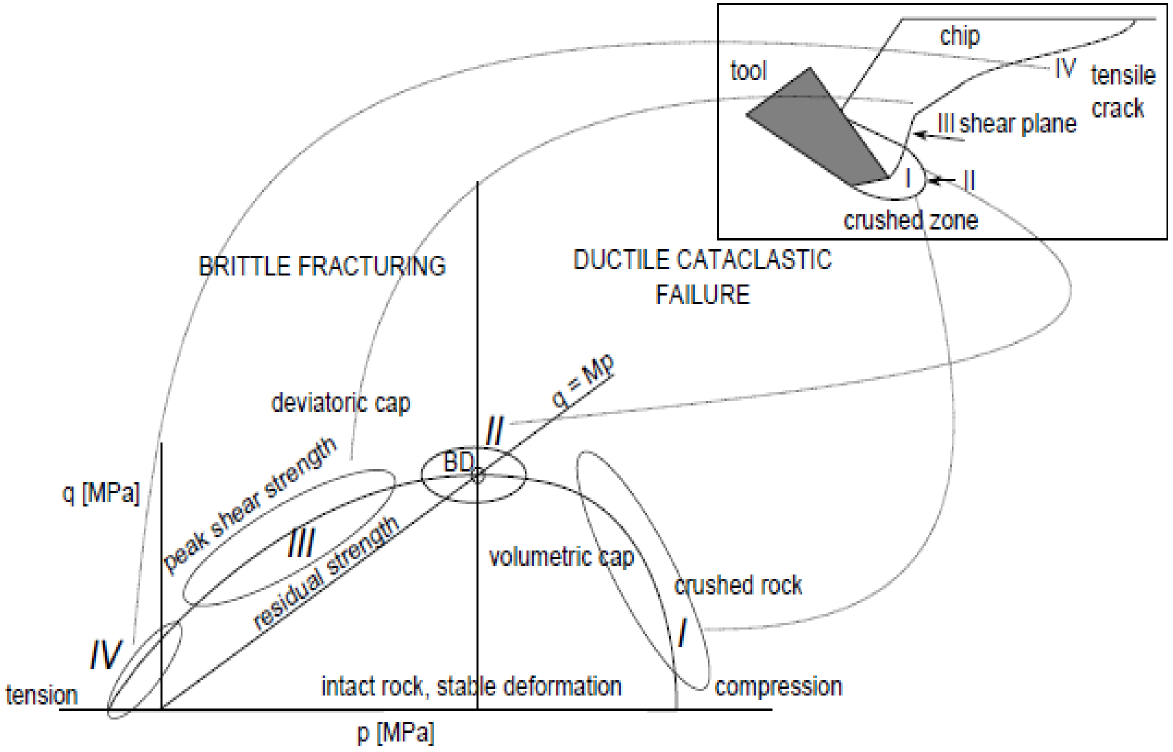
EXCAVATION OF DEEP SEA DEPOSITS?

- **How to excavate sea mining deposits ?**
  - Up to 4000 m below sea level and even deeper
  - Ore in veins and chimneys such as the case of SMS deposits
  - Which excavation tool needs to be used for each deposit?
  - What is the effect of hyperbaric pressure on cutting forces?



(Source: IHC Merwede, 2011)

PHENOMENOLOGICAL MODEL ROCK CUTTING PROCESS

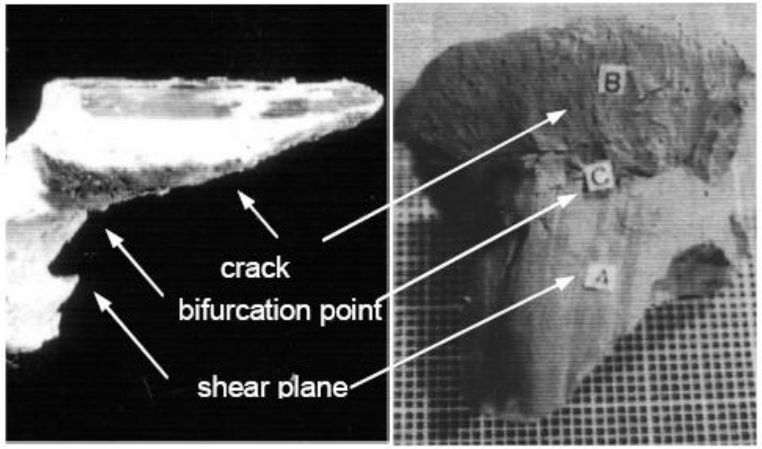


P – Q DIAGRAM

Verhoef (1997)

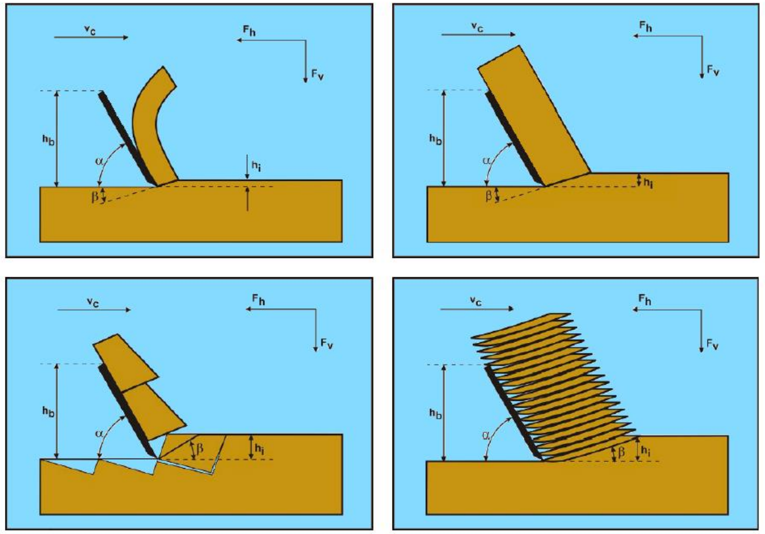
Tensile crack occurs when $K_I > K_{IC}$

K_{IC}: Critical stress intensity factor



EXISTING ROCK CUTTING MODELS

MODELS	MECHANISM
• Evans (1965)	– tensile failure
• Nishimatsu (1972)	– brittle shear failure
• Goktan & Gunes (2005)	– tensile failure
• Miedema (2014)	– tensile/ brittle shear failure



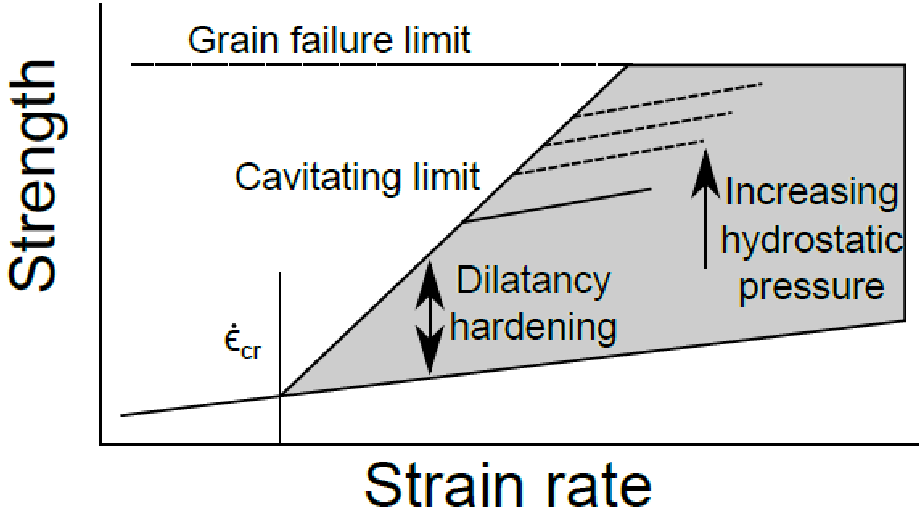
Source: Miedema (2018)

Models were developed mainly for dry and/or saturated conditions at shallow water depth!!

HYDRO- MECHANICAL EFFECTS IN ROCK DEFORMATION

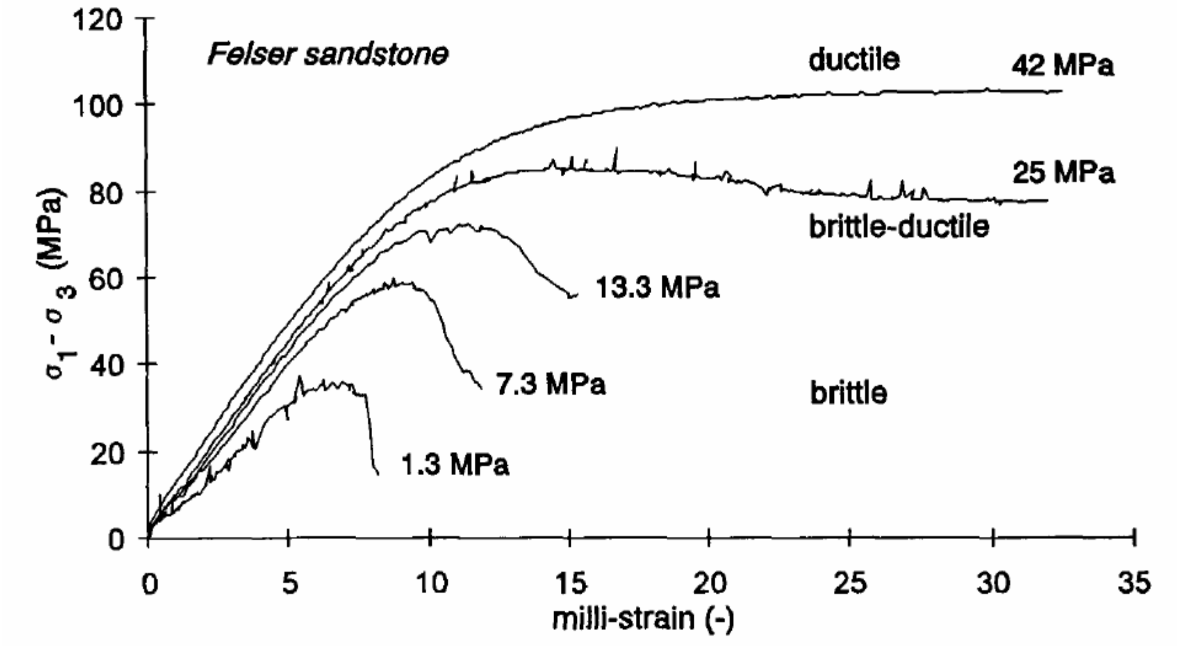
$$\zeta_{Pe} = \frac{v_c t_c}{D} = \frac{v_c t_c \eta \left(C_f - \alpha C_s + n\left(C_p - C_s\right)\right)}{\kappa}$$

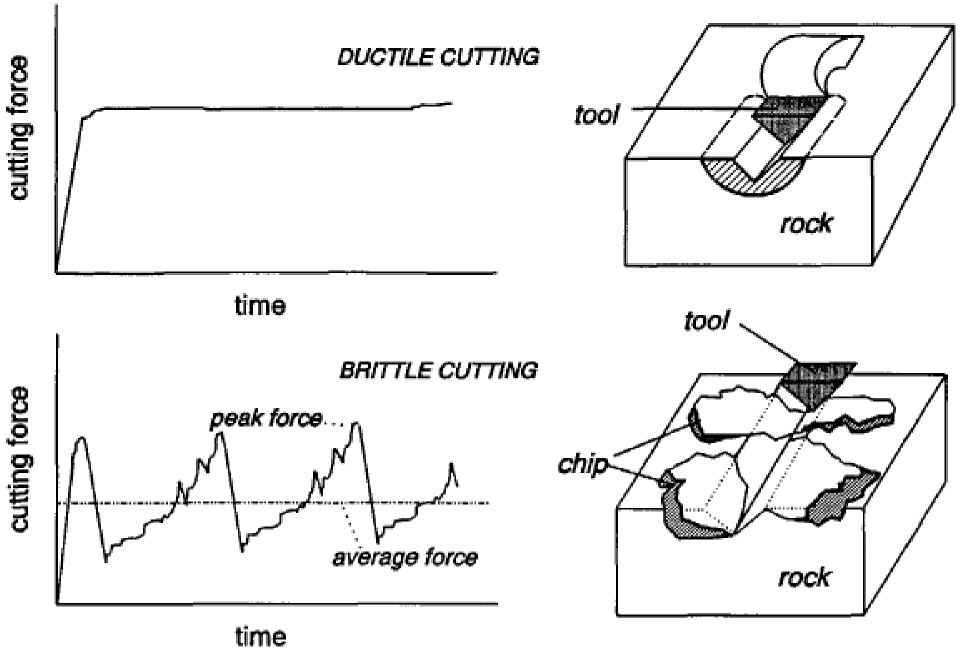
- Pe < 1 drained behavior
- Pe > 10 undrained behavior



Van Kesteren, 1995

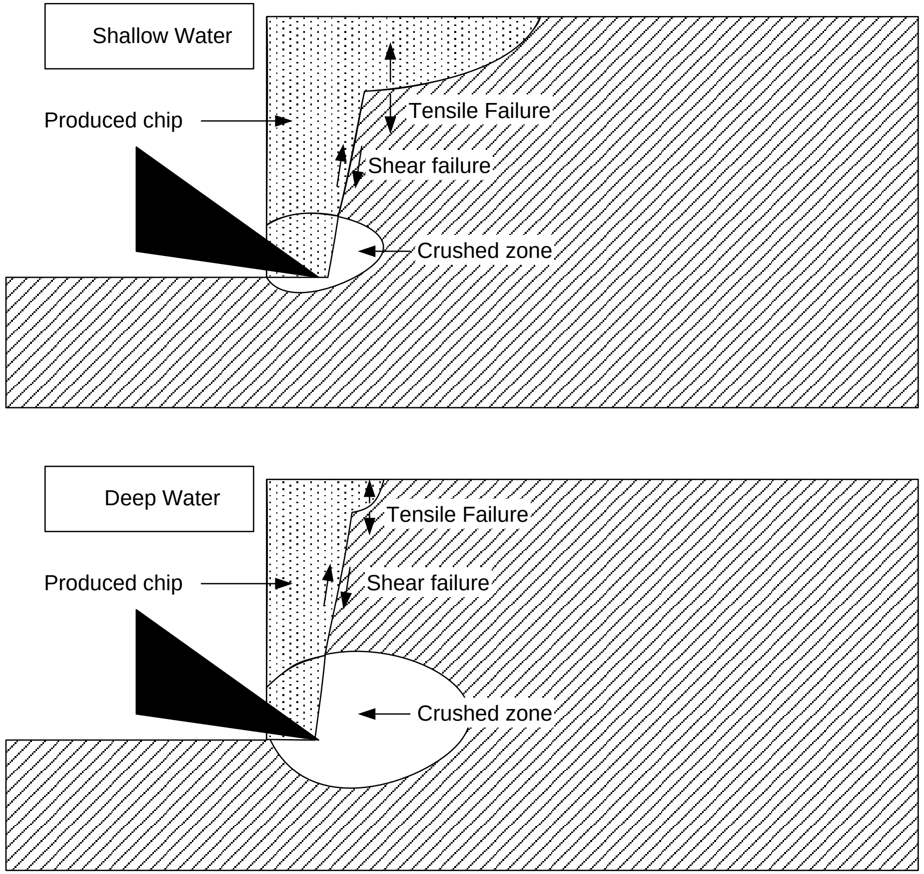
BRITTLE – DUCTILE TRANSITION





Verhoef, 1997

PHENOMENOLOGICAL DESCRIPTION – ROCK CHIP FORMING PROCESS: HYPERBARIC - HYPOTHESIS



SHALLOW WATER (Verhoef, 1997)

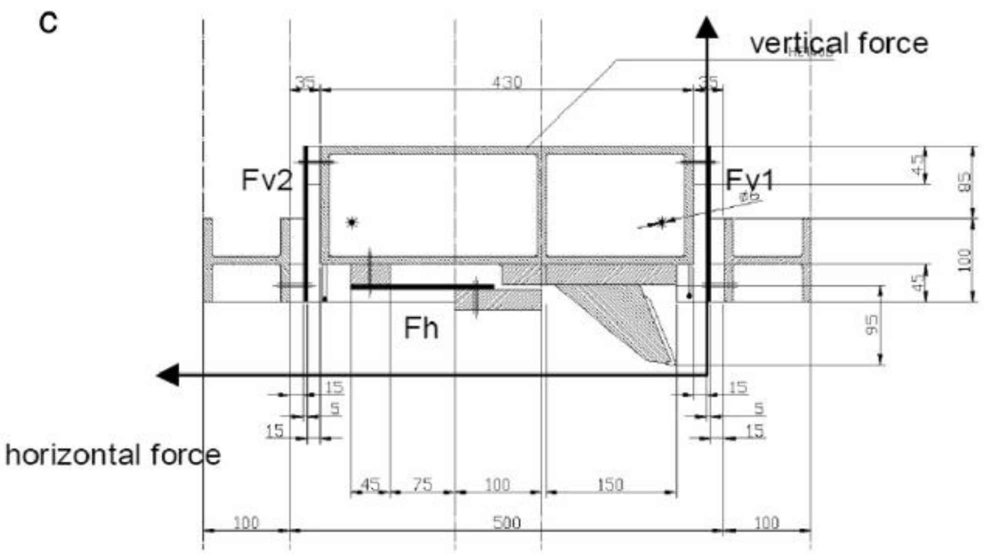
DEEP WATER (> 1000 m)

From Brittle to Ductile behavior

EXPERIMENTAL INVESTIGATION

Linear cutting tests of hyperbaric experiments focused on:

- Effect of hyperbaric pressure: from atmospheric conditions to 18 MPa (1800 m water depth)
- Effect of cutting speed: from 0.01 m/s to 2 m/s
- Cutting depth 20 mm
- Tooth with 21 mm
- Cutting angle 68 deg.



ROCK PROPERTIES AT ATMOSPHERIC CONDITIONS

Rock properties at atmospheric conditions.

Test no.	UCS MPa	E (GPa)	ν (−)	BTS (MPa)	k liquid (m/s)	n (%)	ρ_s (Mg/m^3)
1	7.92	5.95	0.31	0.88	3.1E−06	37.86	2.78
2	7.92	5.95	0.31	0.88	3.1E−06	37.86	2.78
3	7.92	5.95	0.31	0.88	3.1E−06	37.86	2.78
4	8.75	7.53	0.25	1.09	8.5E−07	34.64	2.76
5	8.75	7.53	0.25	1.09	8.5E−07	34.64	2.76
6	8.75	7.53	0.25	1.09	8.5E−07	34.64	2.76
7	8.75	7.53	0.25	1.09	8.5E−07	34.64	2.76
8	9.29	5.89	0.27	1.15	1.4E−07	33.17	2.76
9	10.62	8.32	0.23	1.05	2.8E−07	31.66	2.78
10	10.64	9.01	0.27	1.13	2.2E−08	33.92	2.79
11	8.86	8.20	0.31	0.86	1.5E−07	35.12	2.77
12	8.86	8.20	0.31	0.86	1.5E−07	35.12	2.77
13	8.86	8.20	0.31	0.86	1.5E−07	35.12	2.77
14	10.54	9.98	0.33	x	3.4E−09	35.89	2.80
15	10.54	9.98	0.33	x	x	x	x

Rock type: Savonnieres limestone

- **UCS values between 7.92 – 10.64 MPa**
- **BTS values between 0.86 – 1.15 MPa**

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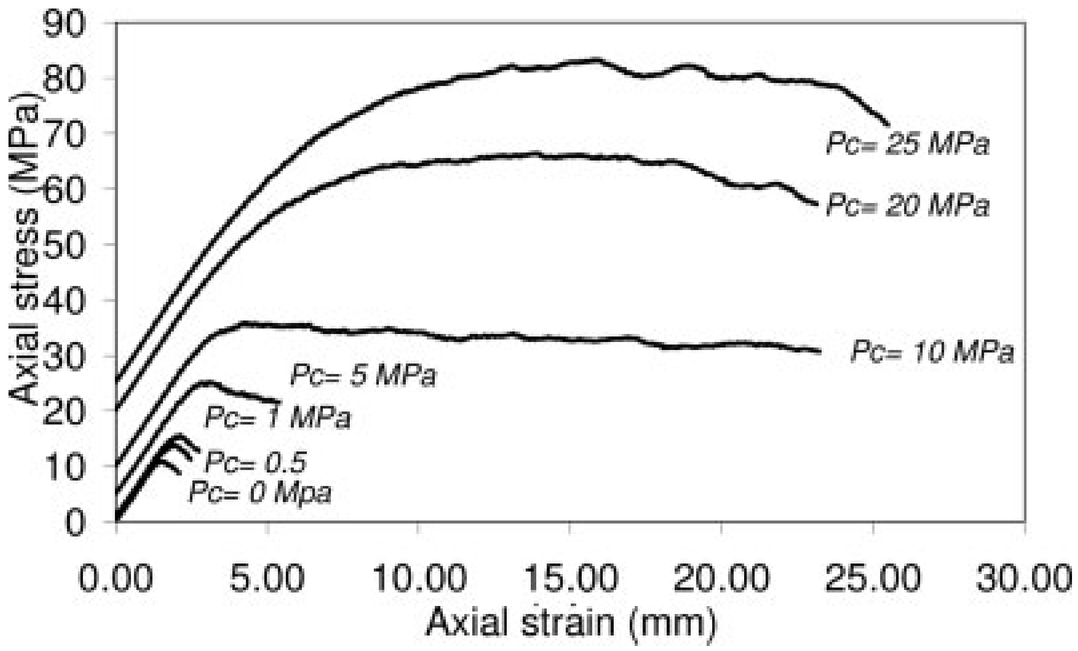
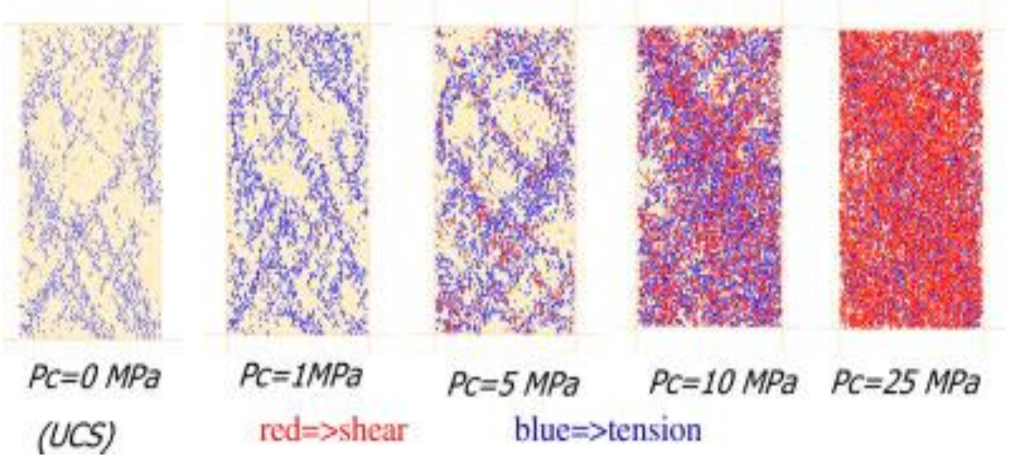
NUMERICAL SIMULATIONS – BRITTLE DUCTILE TRANSITION – PFC2D

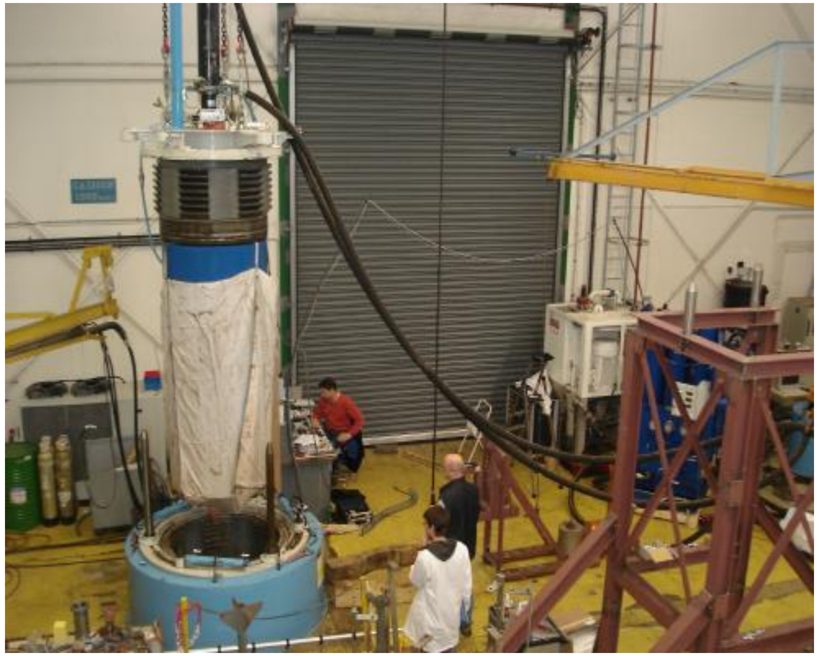




Brittle-ductile transition found at about 5 MPa confining pressure

Ref. Yenigul; Alvarez Grima, 2010

HYPERBARIC LAB TEST SET-UP



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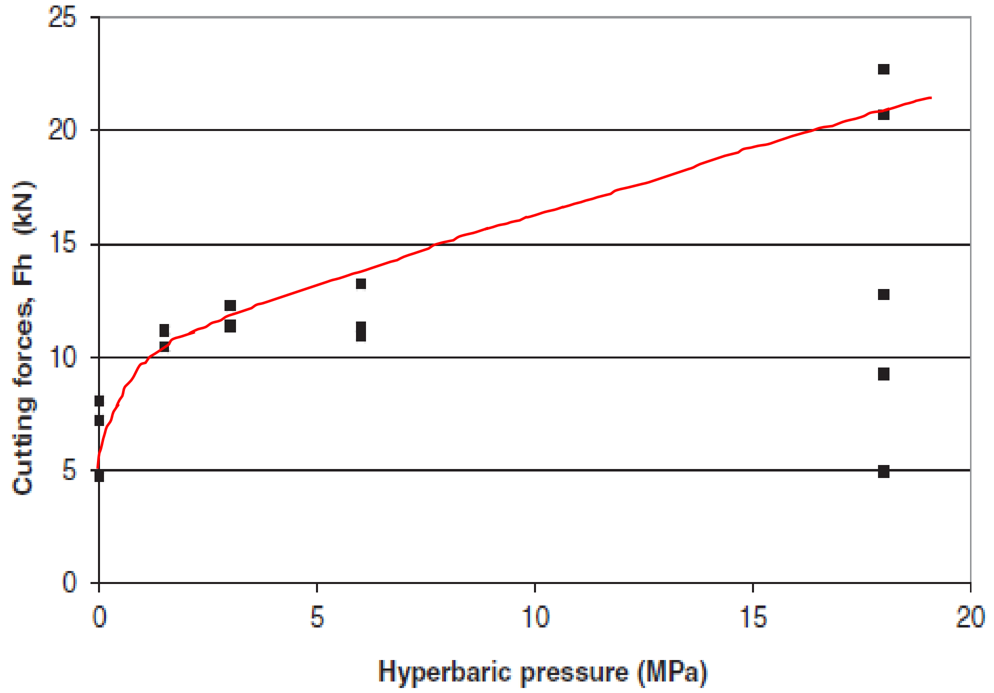
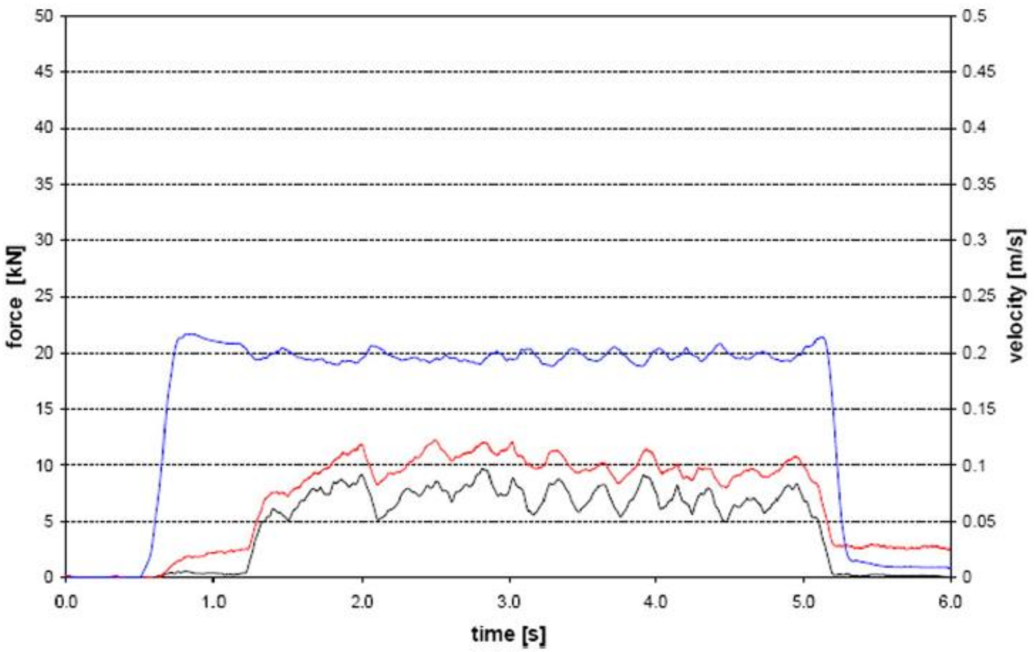
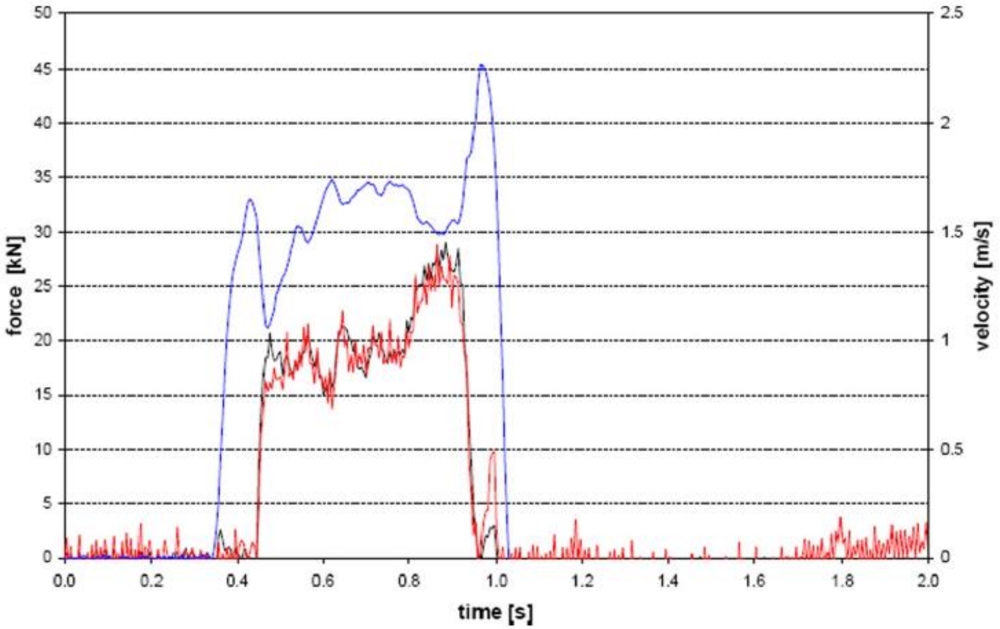
CUTTING FORCES VS HYPERBARIC PRESSURE



- Minimum cutting force measured, Fh = 4.7 kN (atmospheric conditions)
- Maximum cutting force measured, Fh = 22.7 kN (hyperbaric conditions)

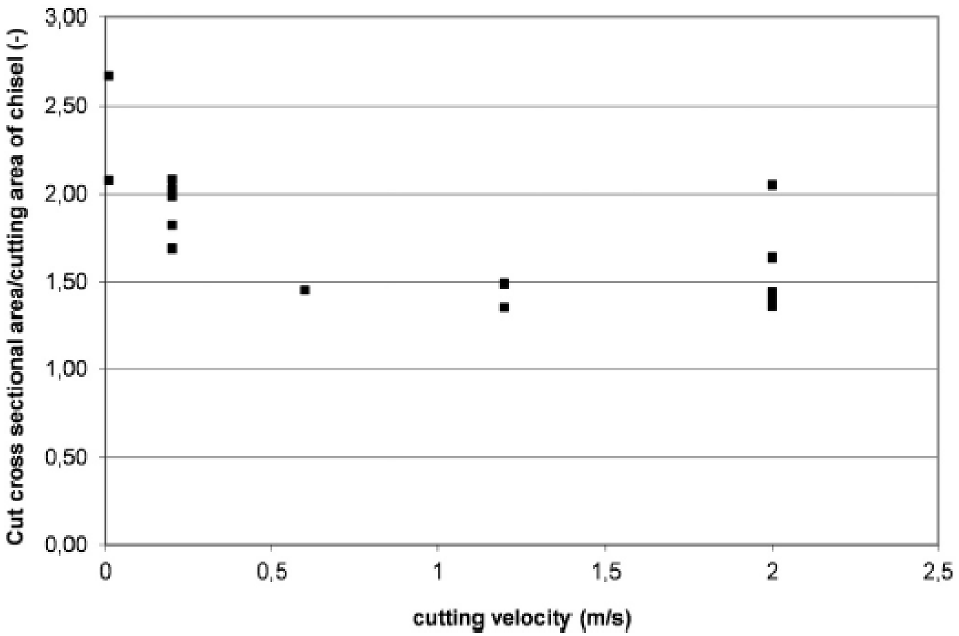
CUTTING FORCES VS TIME - EXAMPLE

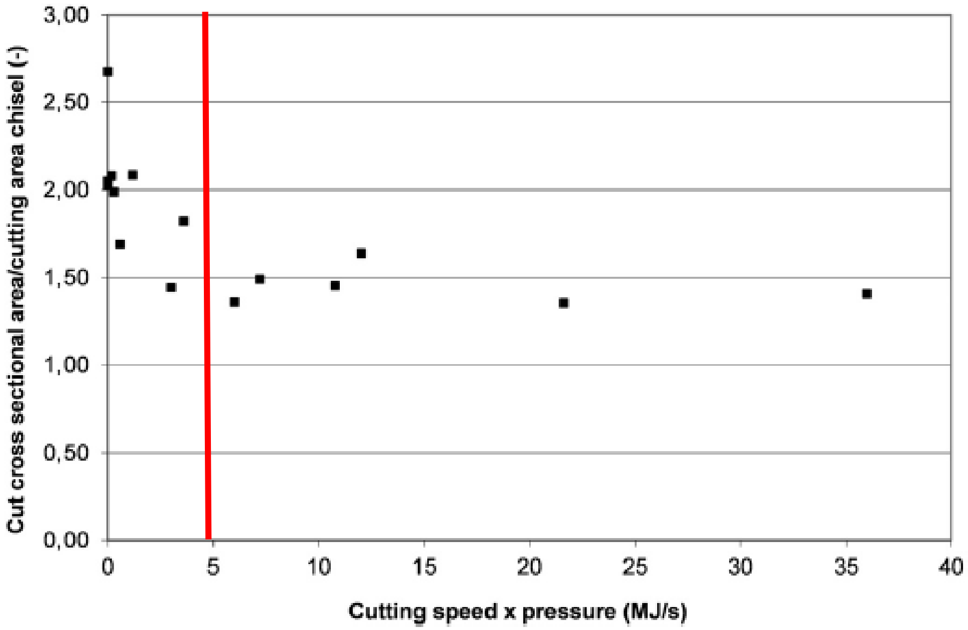




- atmospheric condition – speed 0.2 m/s
- 18 MPa – speed 2 m/s

RATIO CUT CROSS SECTIONAL AREA/CUTTING AREA VS CUTTING VELOCITY AND PRESSURE

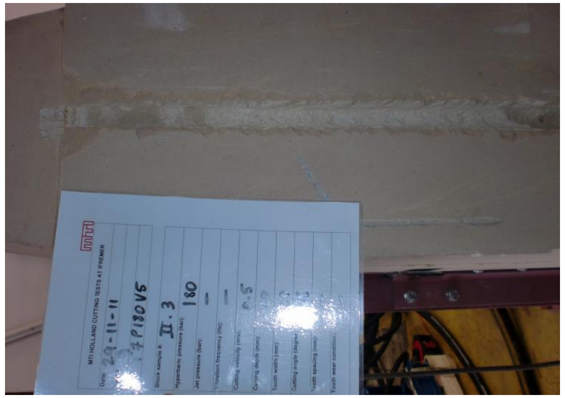




SHALLOW CUTTING VS HYPERBARIC CUTTING

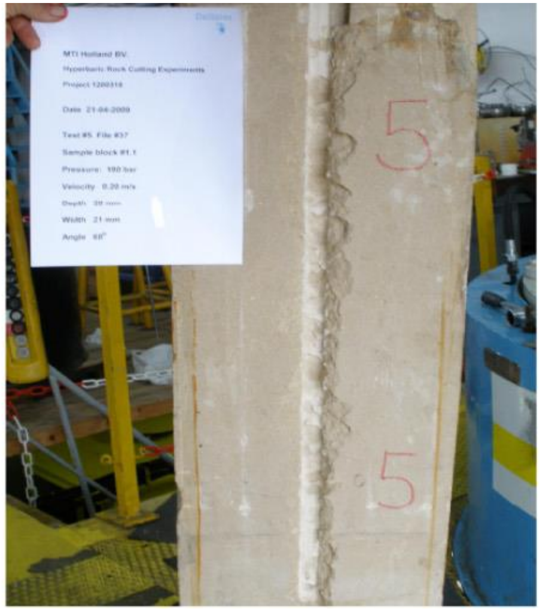
- Shallow water (atm.)

- Deep water (18 MPa)

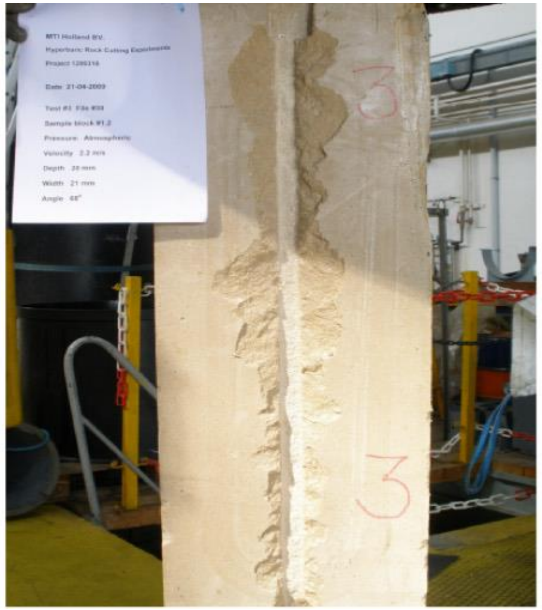


OVERVIEW OF COMPLETE CUT

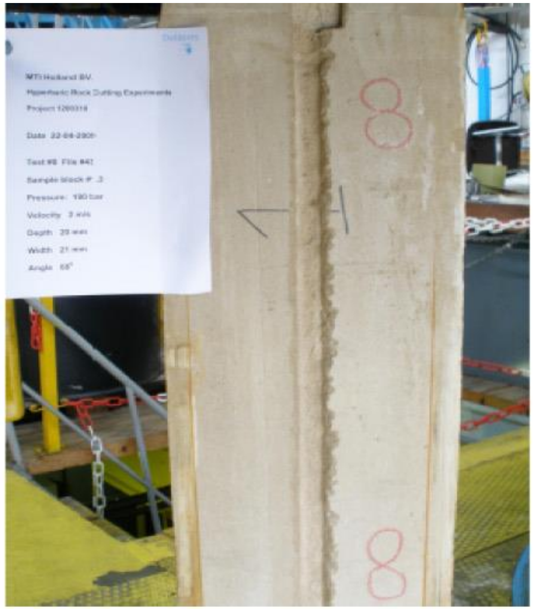
- a) P= atm & v = 0.2 m/s



- b) P = 18 MPa & v = 0.2 m/s

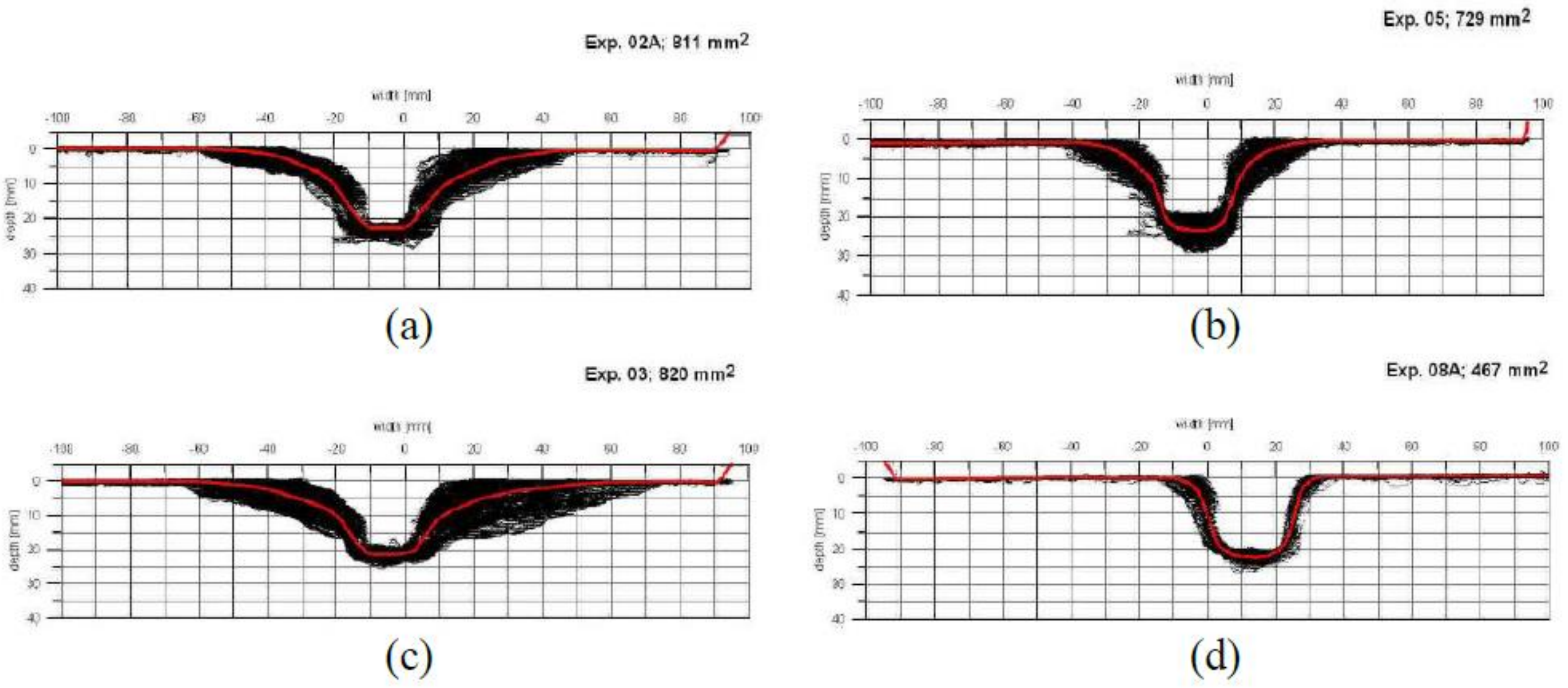


- a) P= atm & v = 2 m/s



- a) P= 18 MPa & v = 2 m/s

COMPOSITION OF LASER SCAN CUT GEOMETRY



a) **Atmospheric with low cutting velocity (0.2 m/s)**
b) **High hyperbaric pressure (18 MPa) with low cutting velocity (0.2 m/s)**
c) **Atmospheric with high cutting velocity (2 m/s)**
d) **High hyperbaric pressure (18 MPa) with high cutting velocity (2 m/s)**

IHC

EFFECT OF PRESSURE ON PRODUCTION

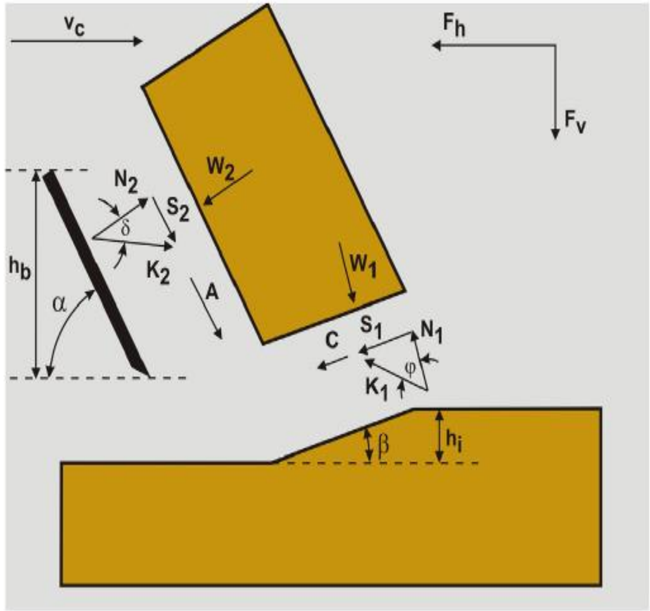
(a) (b) (c) (d)

- a) P= atm & v = 0.2 m/s
- b) P = 18 MPa & v = 0.2 m/s
- a) P= atm & v = 2 m/s
- a) P= 18 MPa & v = 2 m/s

HYPERBARIC CUTTING MODEL

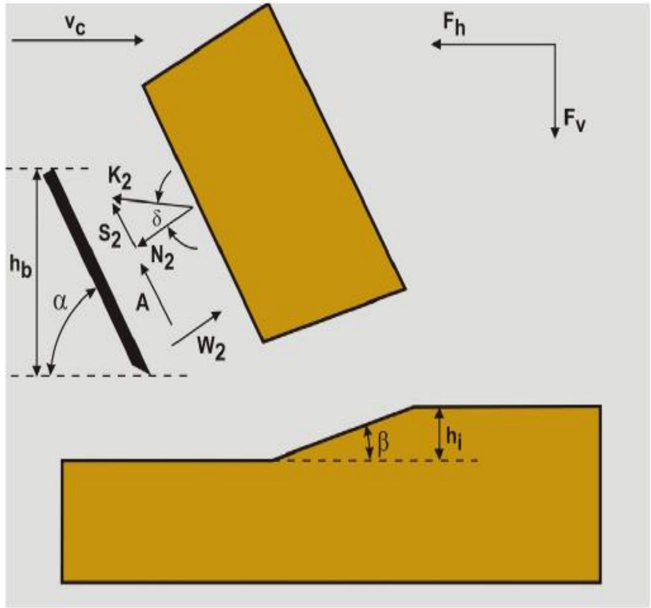
HYPERBARIC CONDITIONS

FORCES ON THE LAYER CUT



$$W_1 = \frac{\rho_w \cdot g \cdot (z+10) \cdot h_i \cdot w}{\sin(\beta)} \quad \text{or} \quad W_1 = \frac{P_{1m} \cdot h_i \cdot w}{\sin(\beta)}$$

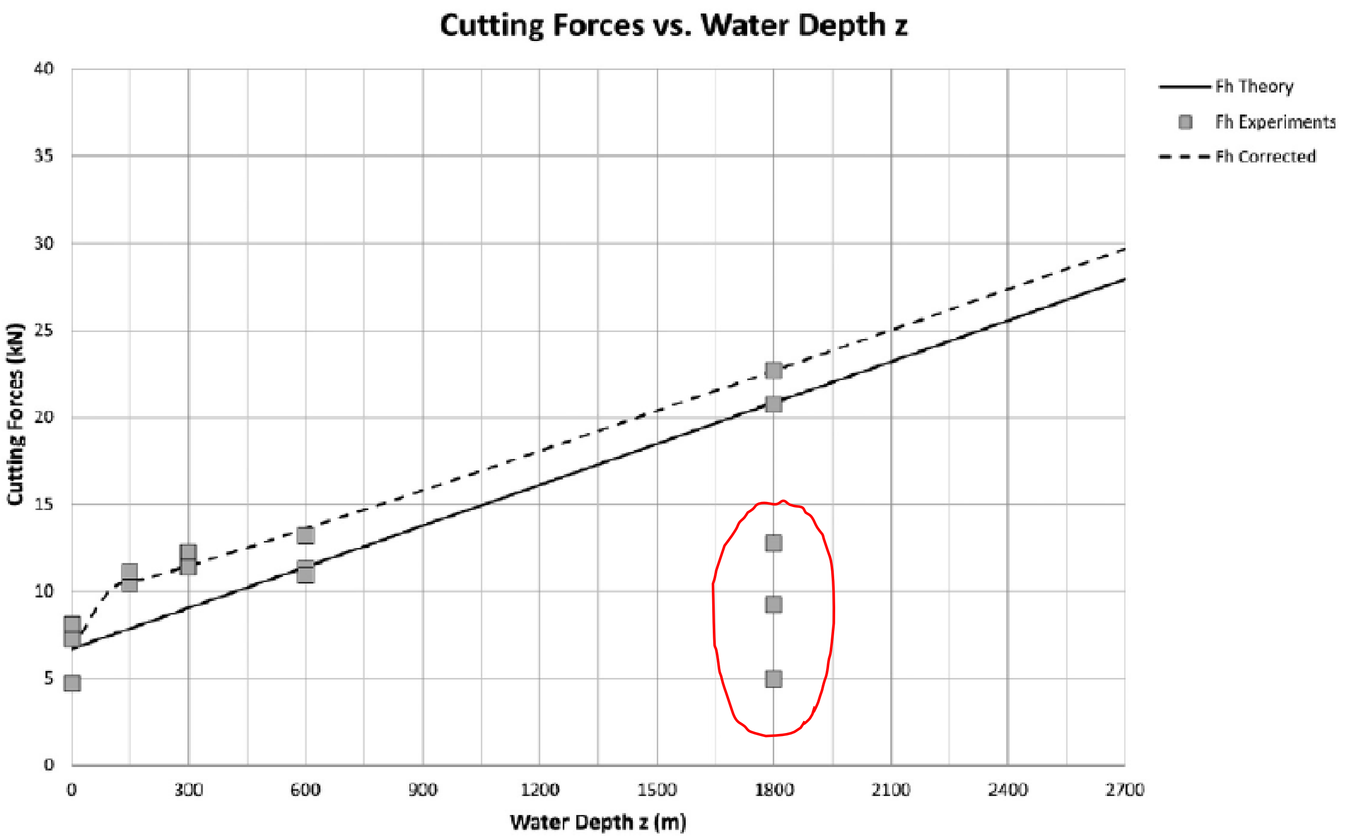
FORCES ON THE BLADE



$$W_2 = \frac{\rho_w \cdot g \cdot (z+10) \cdot h_b \cdot w}{\sin(\alpha)} \quad \text{or} \quad W_2 = \frac{P_{2m} \cdot h_b \cdot w}{\sin(\alpha)}$$

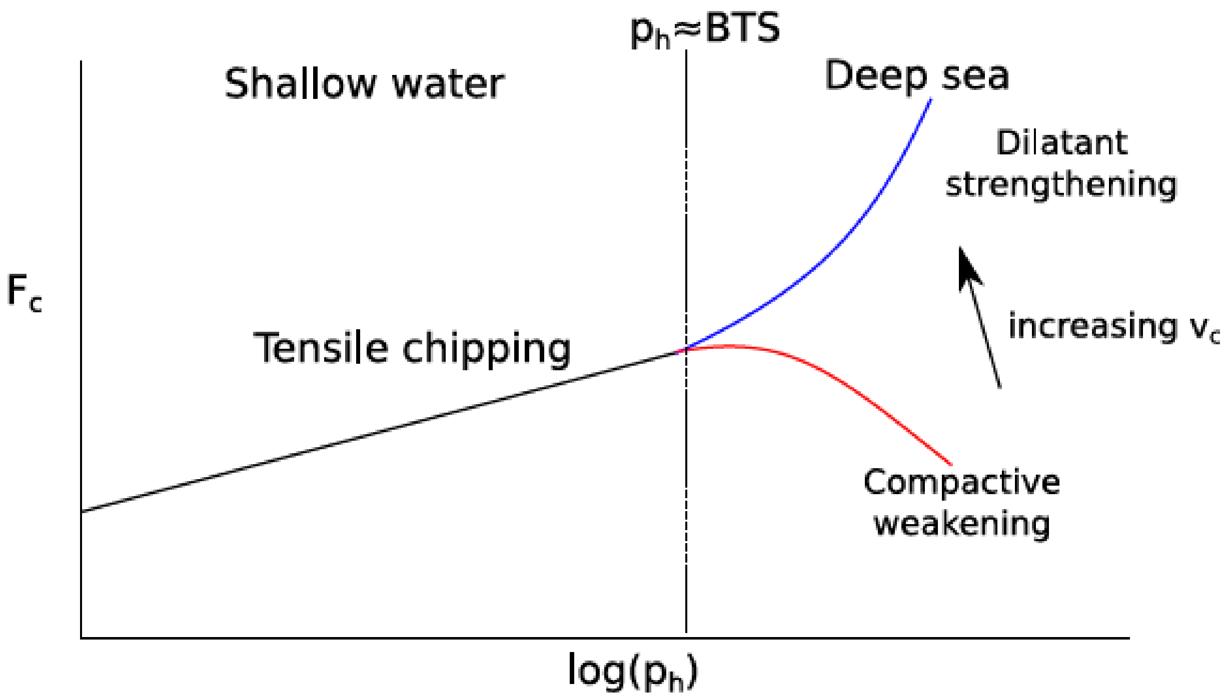
Extension of Miedema shear cutting model (1987)

HYPERBARIC CUTTING MODEL - RESULTS



Model assumes full cavitation

EFFECT OF WATER DEPTH ON CUTTING FORCES: POSSIBLE EXPLANATION

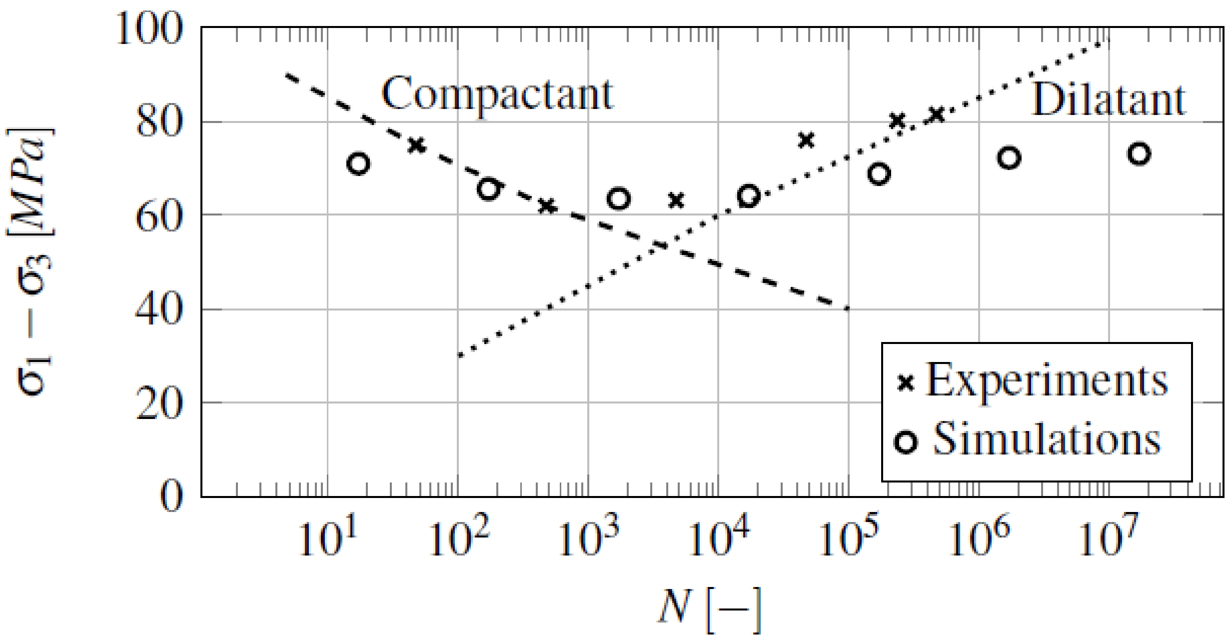


- $\zeta_{Pe} < 1$: Compactant weakening regime
- $1 < \zeta_{Pe} < 10$: Transitional regime
- $\zeta_{Pe} > 10$: Dilatant strengthening regime

Ref. Helmon's et. al. 2018

WEAKENING AND STRENGTHENING VS STRAIN RATE

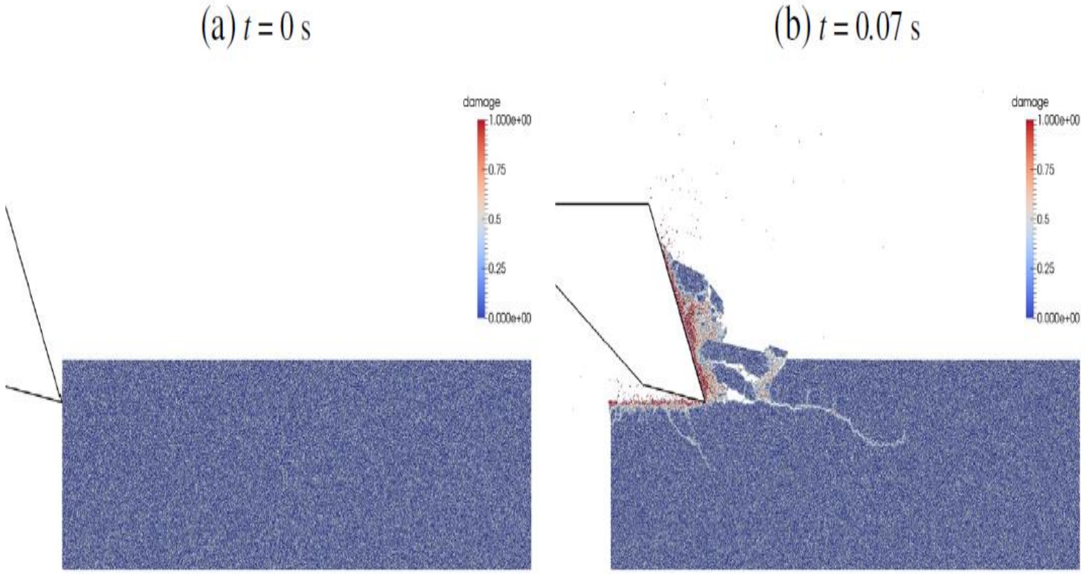
Undrained Triaxial test at 50 MPa on Kimmeridge Bay shale (Swan et. al. 1989)



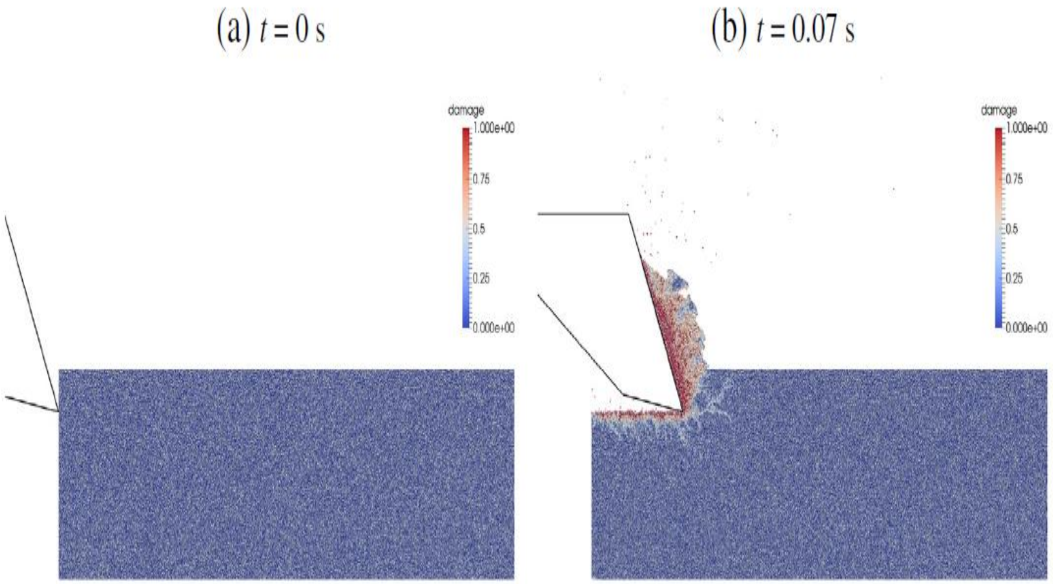
Ref. Helmons 2017 (PhD Thesis); Helmons et. al. 2016

NUMERICAL SIMULATIONS – 2D DEM-SPH

Damage for rock cutting at atm. conditions

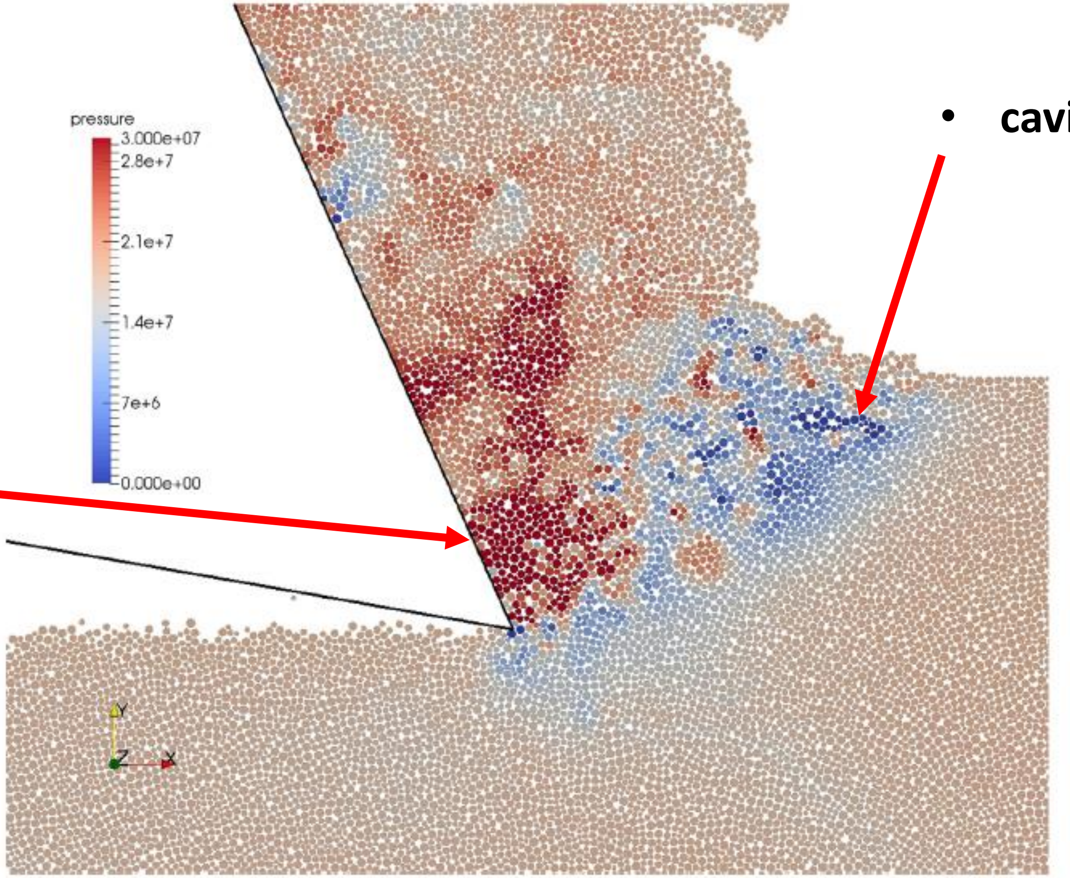


Damage for rock cutting at pressure of 10 MPa



Ref. Helmons 2017 (PhD Thesis); Helmons et. al. 2016

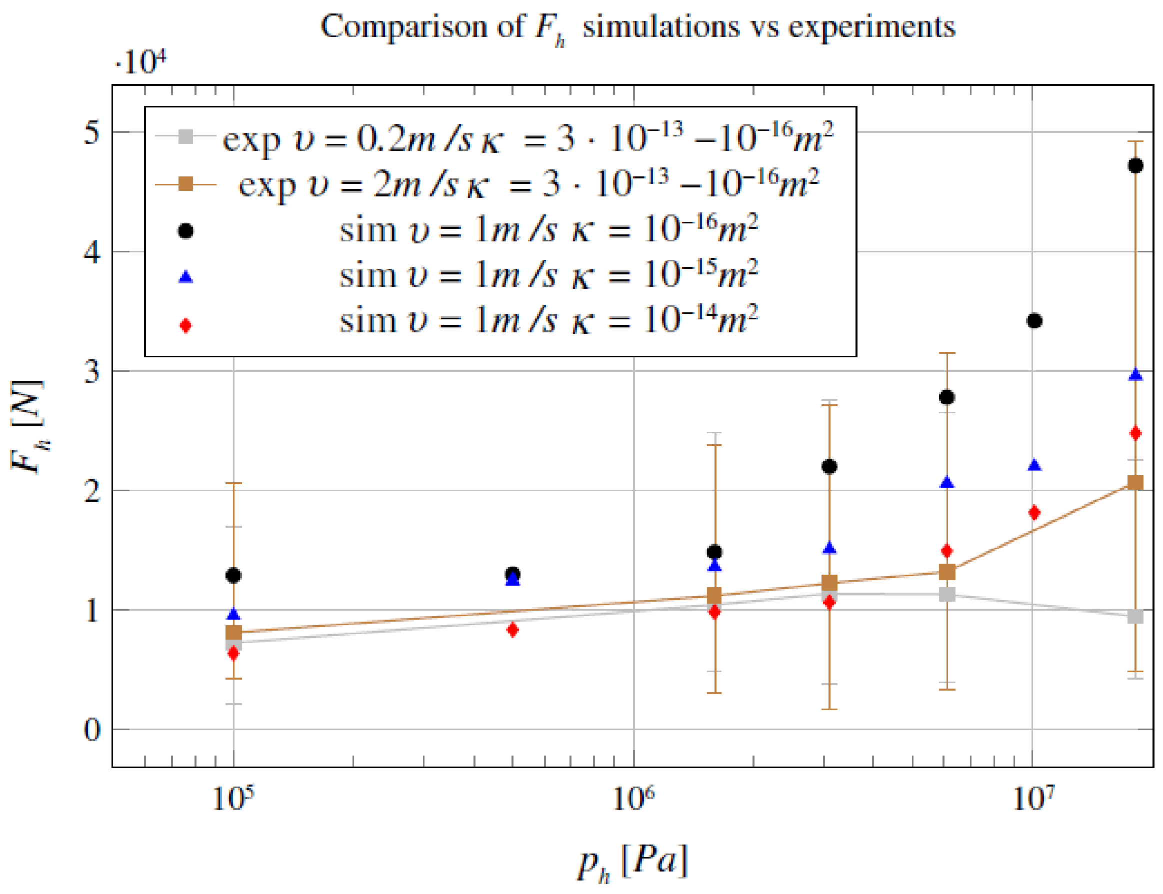
PORE PRESSURE DISTRIBUTION – 2D SIMULATIONS



- cavitation on shear zone (dark blue)
- crushed zone – (dark red)

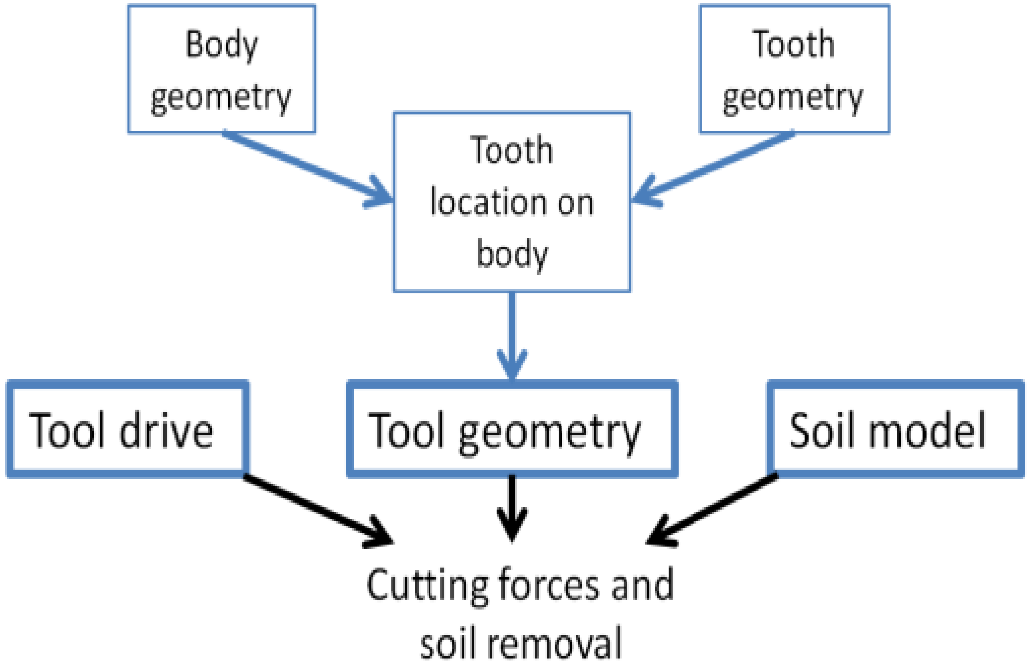
Ref. Helmons 2017 (PhD Thesis); Helmons et. al. 2016

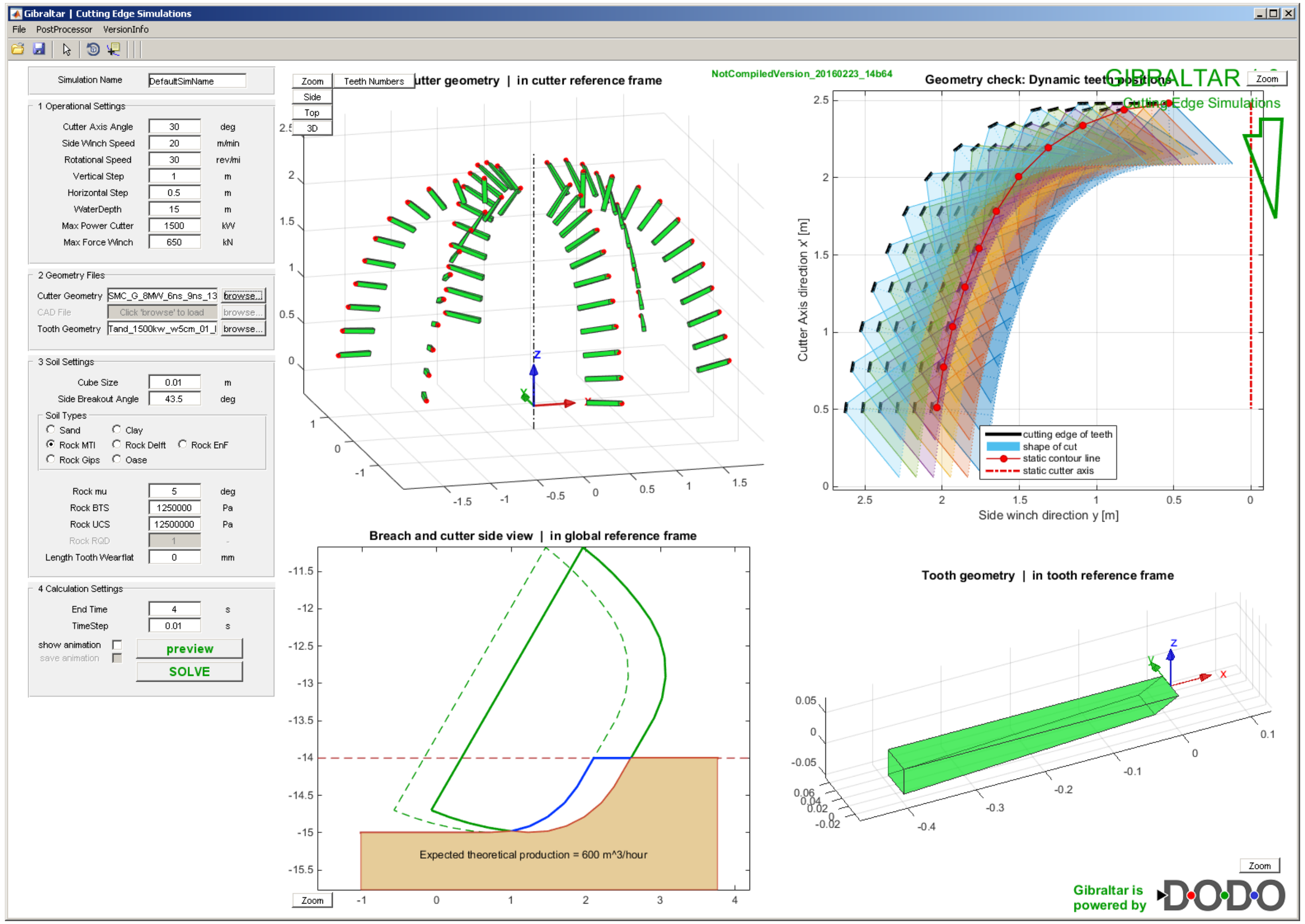
COMPARISON OF SIMULATION AND EXPERIMENTS



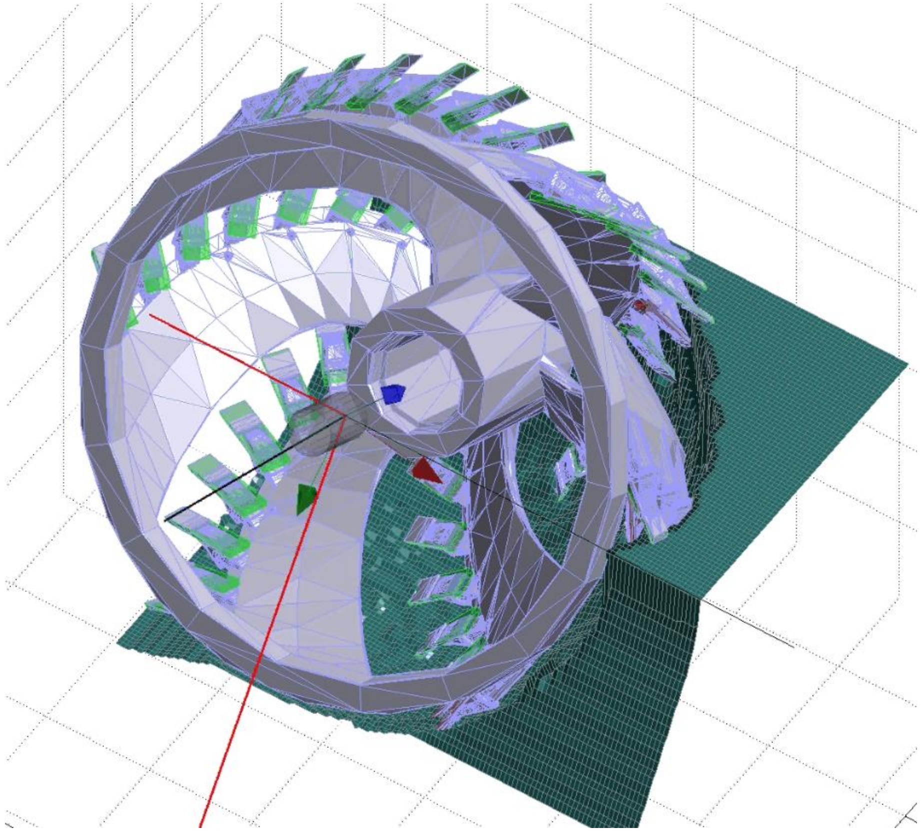
Ref. Helmons 2017 (PhD Thesis); Helmons et. al. 2016

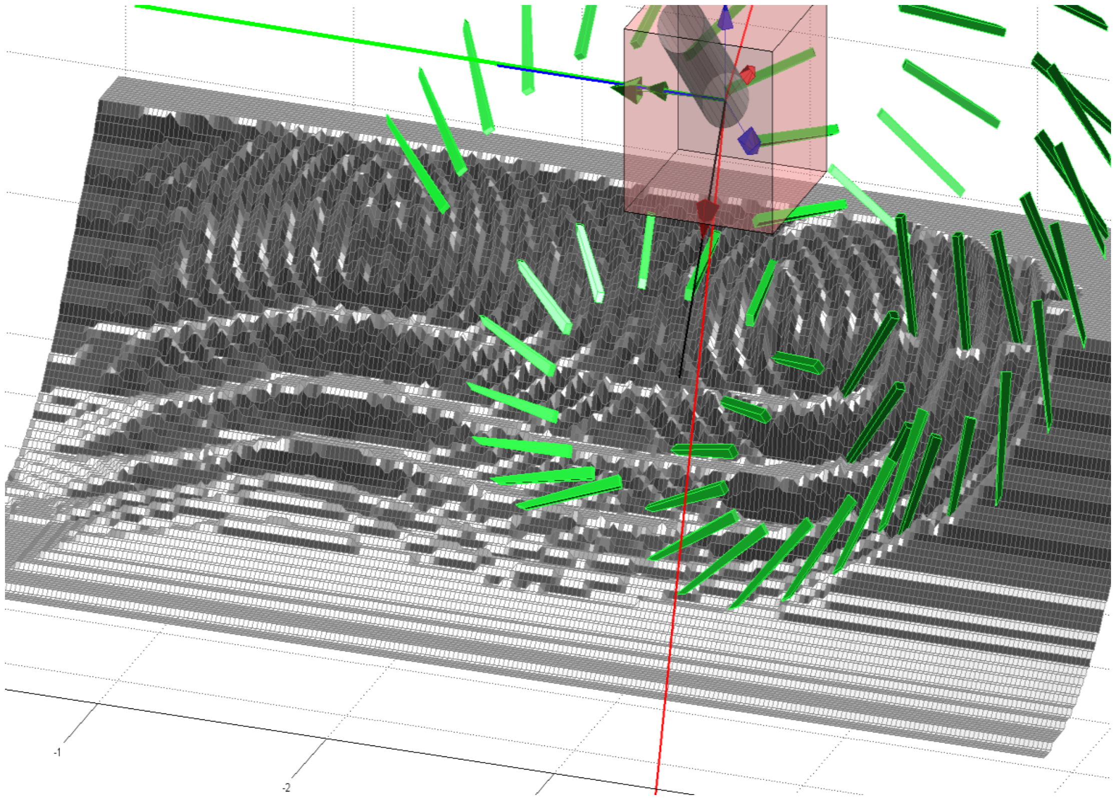
SIMULATION TOOL: GIBRALTAR



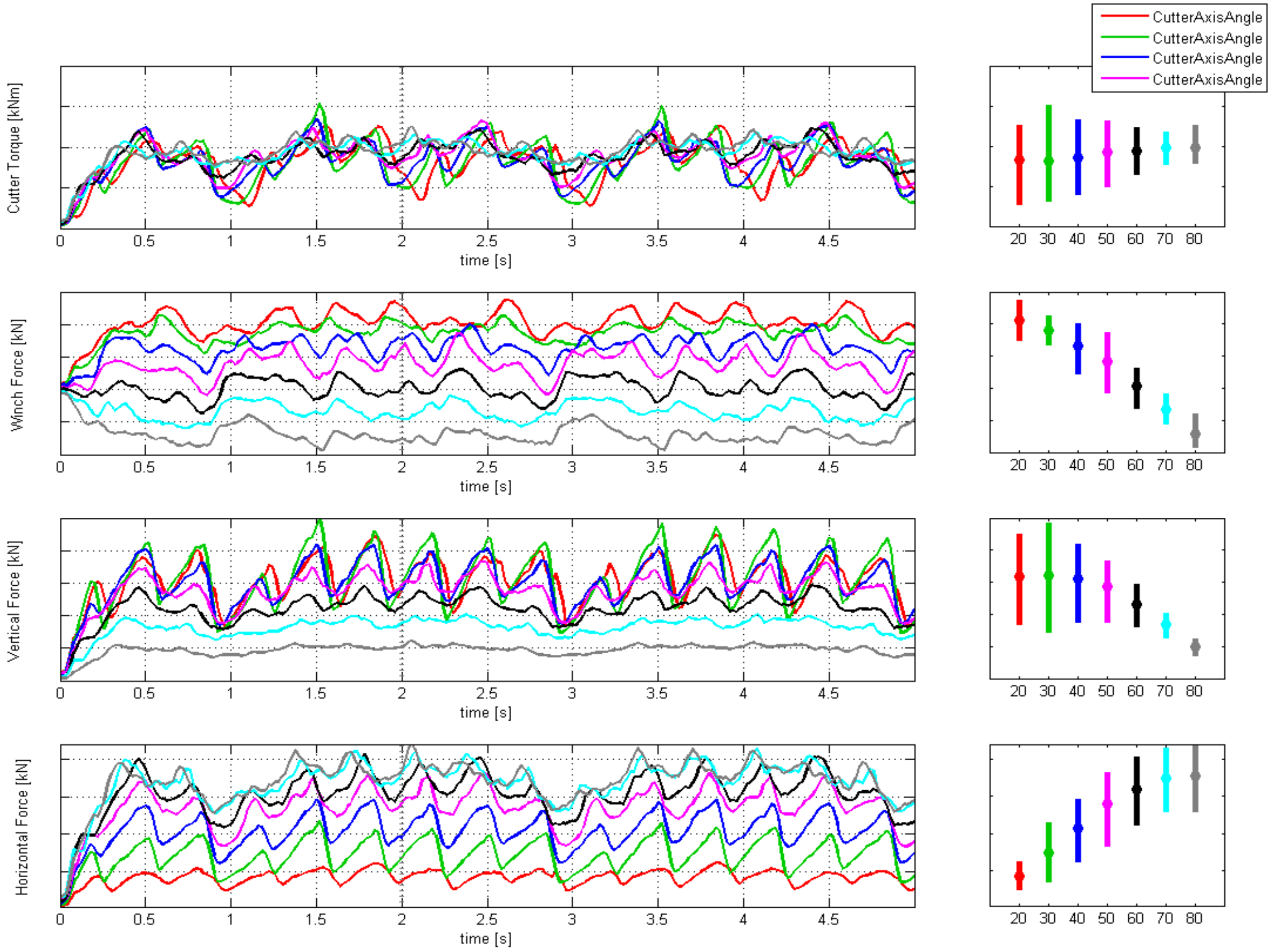


SIMULATION TOOL: CUTTER AND BREACH





SIMULATION TOOL: CUTTING FORCES EXAMPLE



CONCLUSIONS

- In general the cutting forces and specific energy increases as the hyperbaric pressure increases.
- The brittle behavior of the material and the brittle cutting process changes into an apparent ductile mode.
- Cutting forces at high hyperbaric pressure (18 MPa) were found to be **4 to 6 times higher** than at atmospheric conditions.
- Side-break out angle at high hyperbaric pressures is much narrow than the side-break out angle at atmospheric conditions. **Less tooth production.**
- Depending on the combination of hydrostatic pressure, cutting velocity and rock properties - **compactive weakening** or **dilative strengthening** might dominate the cutting process. This is a theory that needs to be confirmed with more experiments.
- The hyperbaric cutting model proposed can reproduce the measured values rather well. However, the calculations done with the model assume full cavitation.
- The numerical framework proposed by Helmon's (PhD thesis) offers a possibility to study the **build up and dissipation of pore water pressure** when cutting rock at high pressures. The results agree rather well with the lab experiments.

Thank You!

Artists impression of rock cutting – deep sea ROV, source: IHC

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