V. Introduction to the Mechanics of Rock Excavation

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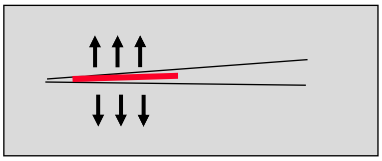
Assistance of Prof. L.N. Germanovich and Mr. H.C. Khor is acknowledged

Learning objectives

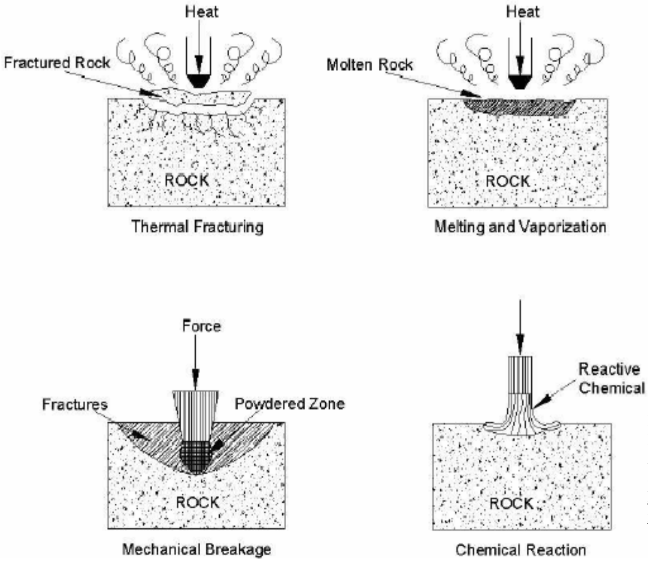
- To familiarise with the possible methods of rock breakage, both existing and potential
- To understand the mechanics of production blasting
- To understand the mechanics of perimeter blasting and the influence of rock mass structure
- To understand the mechanism of thermal fracturing and spallation

Methods of rock excavation

- Mechanical
  - Drilling
    - Rotary drilling
    - Percussive drilling (vibrations)
  - Cutting
- **Blasting (drill and blast)**
- **Thermal fracturing (spallation)**
- Melting
- Chemical
  - Bulk dissolving
  - Fracturing
- Biological



Methods of rock excavation

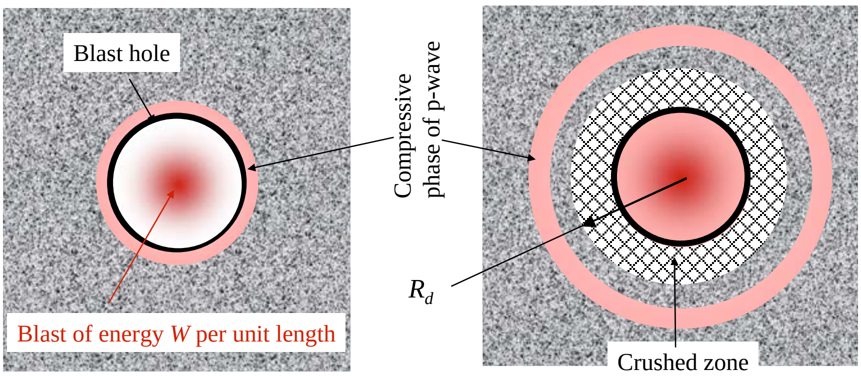


Kris Zacnyy, Michael Quayle, Mara McFadden, Adam Neugebauer, Kenji Huang and George Cooper, 2002 http://www.lpi.usra.edu/publications/reports/CB-1152/berkeley-2.pdf

Blasting

- Blasting methods
  - Production blasting
  - Perimeter blasting
- Mechanics of breakage by blasting
- Perimeter blasting
- Non-explosive rock breaking systems

Stage I of blasting. Crushed zone



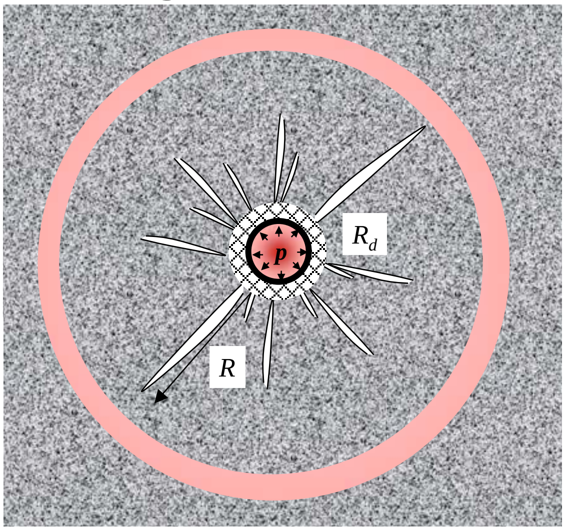
•Plastic crushed zone: $W^{-1}\sigma_y R_d^2$=const; σ_y is the yield stress
•Brittle crushed zone: $W^{-1}K_{Ic}R_d^{3/2}$=const; K_{Ic} is the fracture toughness

Stage II of blasting. Radial cracks

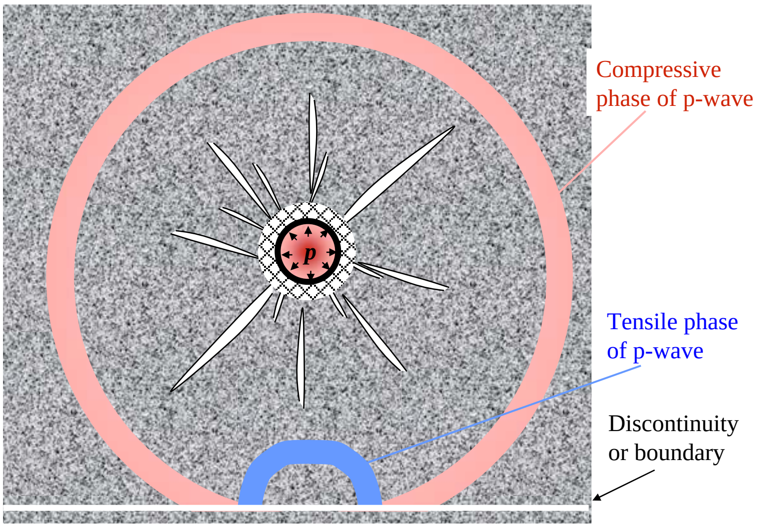
$$R = \frac{C}{\pi}\left(\frac{2prk_d}{K_{Ic}}\right)^2, \quad C \cong 1$$

$$k_d = \frac{2(1-\nu_d)\frac{r}{R_d}}{1-2\nu_d+\frac{\mu_d}{\mu}+\left(1-\frac{\mu_d}{\mu}\right)\frac{r^2}{R_d^{\,2}}}$$

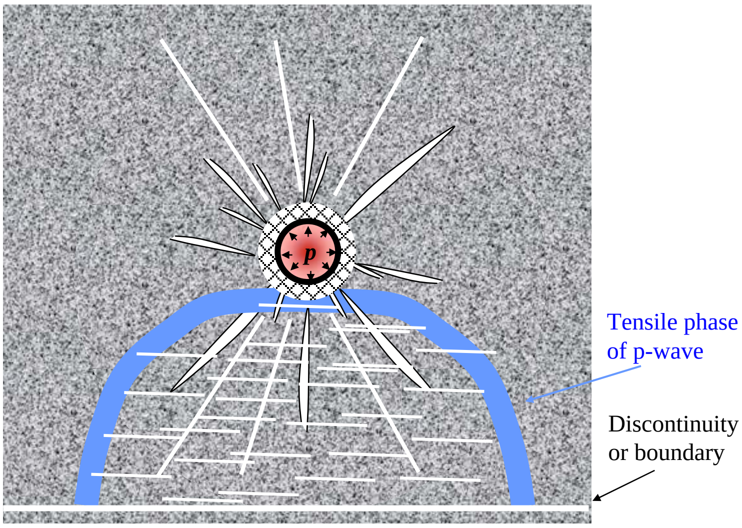
r is blast hole radius
p is gas pressure
μ_d, ν_d R_d are shear modulus, Poisson's ratio and radius of crushed zone
μ is shear modulus of rock
K_{Ic} is the fracture toughness



Stage III. Wave reflection



Stage III. Rock fragmentation



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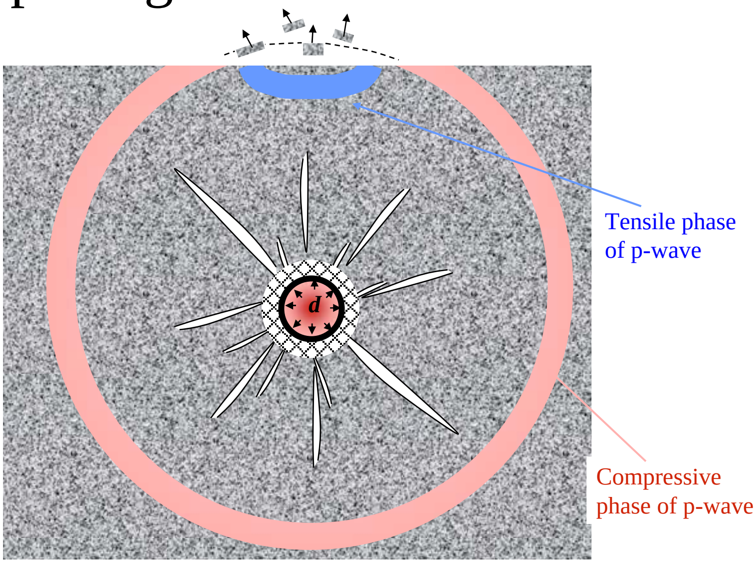
Spalling due to wave reflection



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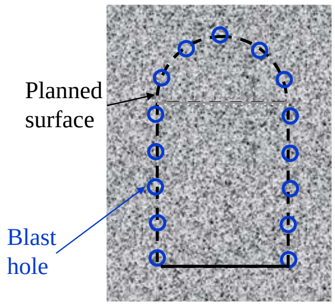
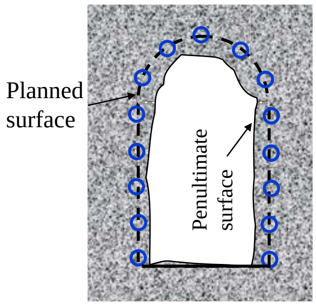
Perimeter blasting

- ◆ Pre-split blasting
  - Absence of local free surface

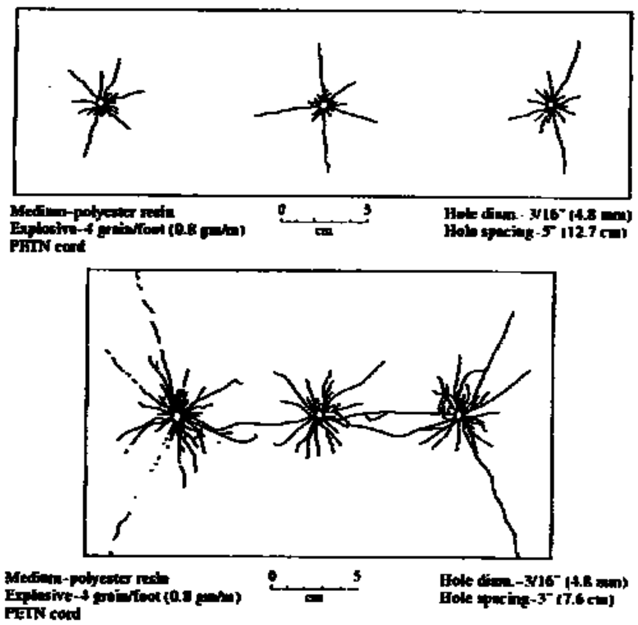


- ◆ Smooth wall blasting
  - Near a penultimate surface

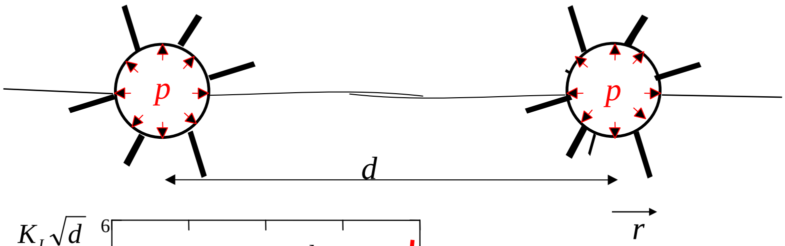


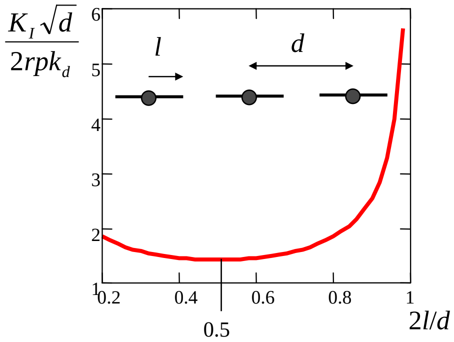
Pre-split blasting

Hudson and Harrison (1997)



Mechanics of pre-split blasting

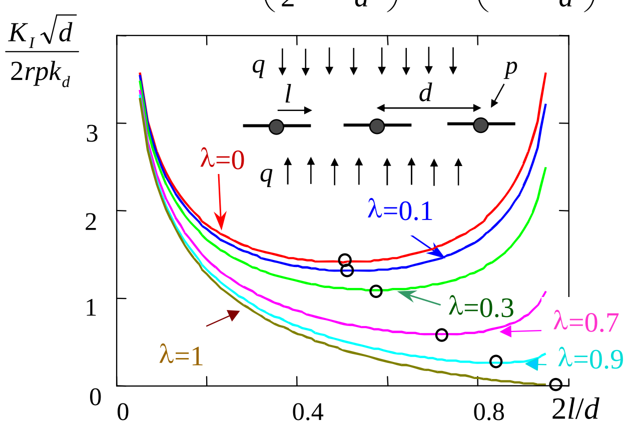




$$d_{cr} = 2\left(\frac{2pk_d r}{K_{Ic}}\right)^2$$

Influence of lateral *in-situ* pressure

$$K_I = 2rp\left(\frac{d}{2}\sin\frac{2\pi l}{d}\right)^{-1/2} - q\left(d\tan\frac{\pi l}{d}\right)^{1/2}$$



$$\lambda = \frac{qd}{2prk_d}$$

The lateral pressure severely hampers crack growth

⇨ Pre-split blasting is best if sub-parallel to a free surface

Effect of discontinuities

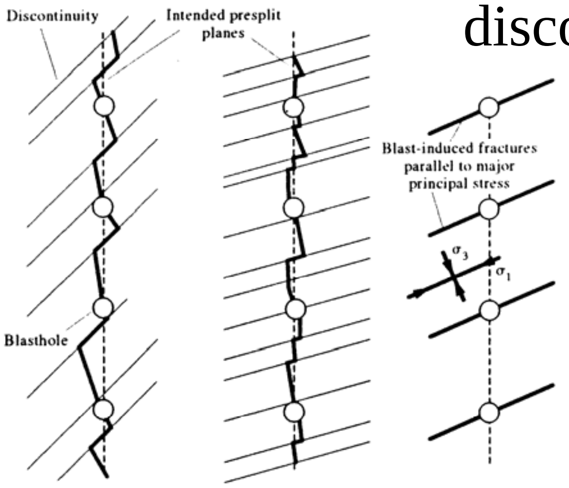


Figure 15.13 The effects of discontinuities and *in situ* stress on the creation of the pre-split plane. (a) Low-angle discontinuities. (b) High-angle discontinuities. (c) *In situ* stress.

Hudson and Harrison (1997)

Discontinuities can distort the pre-split crack resulting in very rough surface

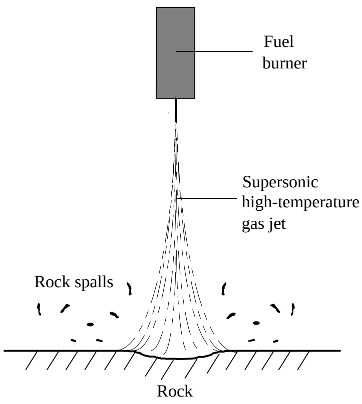
Non-explosive rock breaking

Elimination of the crushed zone

- ◆ Discharge of gas/fluid pressure
  - Hydro Fracturing
    - “Boulder Buster”: A pressure impulse is generated in the tool by a cartridge filled with a propellant. The pressure impulse is directed through the Boulder Buster barrel into an incompressible fluid column (water or gel) introduced into a pre-drilled hole in the rock (http://www.amquip.com.au/page16.html)
- ◆ Mechanical systems
  - Wedges
  - Expanding grouts
    - (“Katrock”: http://www.amquip.com.au/page14.html)

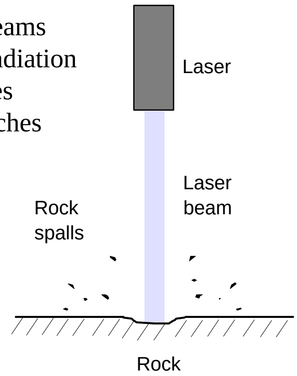
Dunn, P.G. 1992

Thermal Fracturing (Spallation)



Flame jet spallation

Lasers
Electron beams
Infra-red radiation
Microwaves
Plasma torches

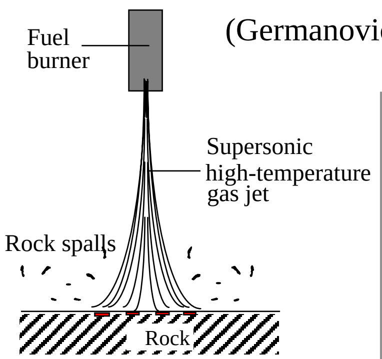


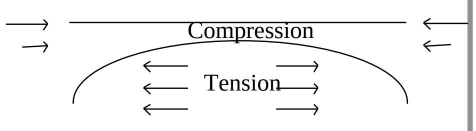
Energy flux spallation

Typical energy intensity is 1-100 MWt/m^2

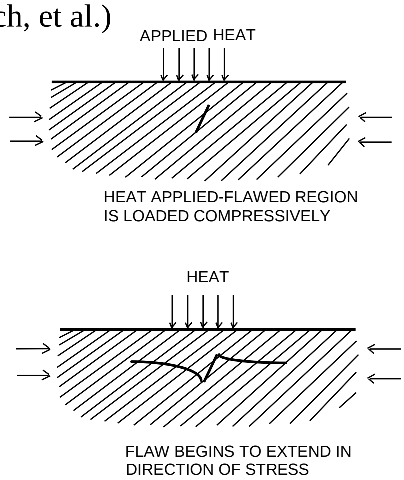
Mechanism of Thermal Fracturing

(Germanovich, et al.)





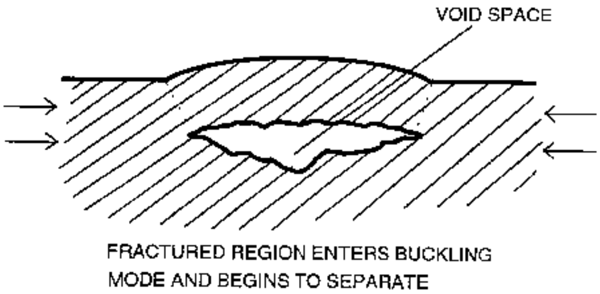
Thermal stresses



Mechanism of spalling

Thermal Spallation

- Two profile mechanisms of spallation:
  - –Crack growth in thermally induced compression
  - –Crack growth due to water vapour pressure



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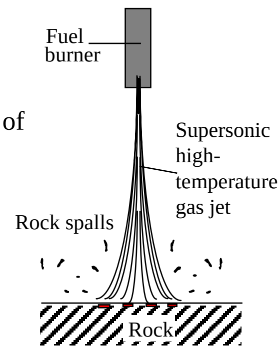
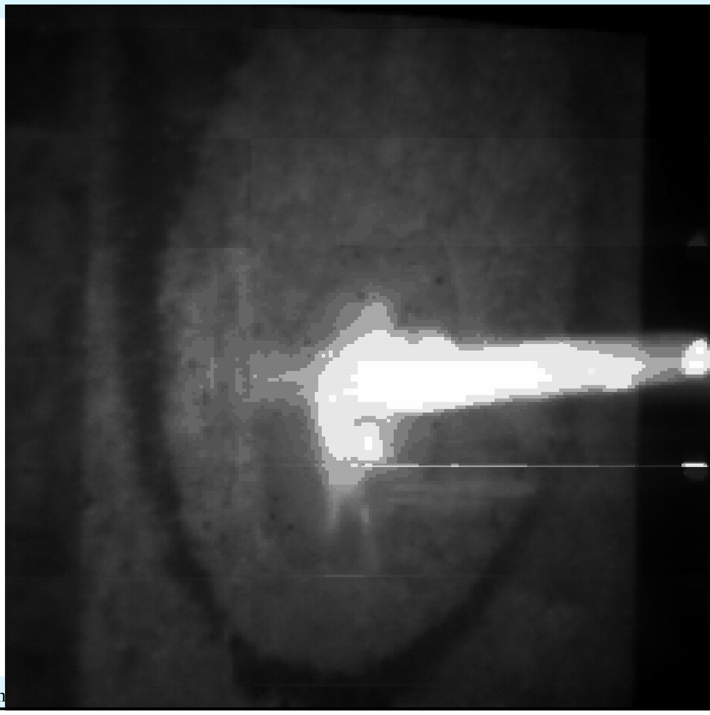
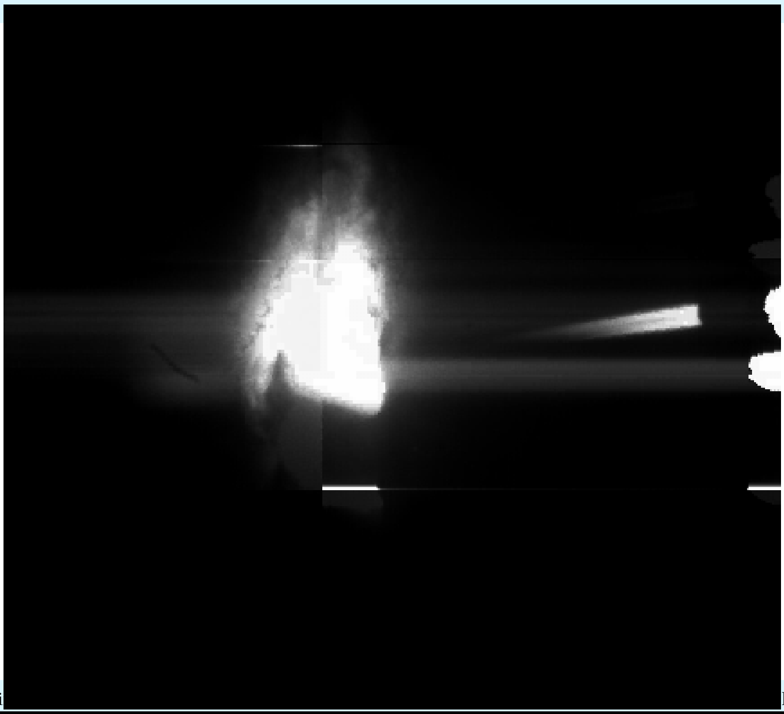
Some Observations on Rock Thermal Spallation

- ◆ Flame jet temperature: 500-5000°C
- ◆ Heat transfer coefficient: κ~100-10,000 Wt/(m^2 °C)
- ◆ Jet is supersonic: ~1,000 m/sec
- ◆ Rock surface temperature at the moment of spallation: 100-1000 °C
- ◆ Surface temperature right after spallation: first tens of °C
- ◆ Spallation time: 0.01-1000 sec
- ◆ Spall thicknesses: 0.1 mm-10 cm
- ◆ Mosaic character of spallation process
- ◆ The more intensive heat impact, ie., the higher jet temperature or heat transfer coefficient, the smaller typical spall thickness and spallation time
- ◆ Rock weakening under spallation zone

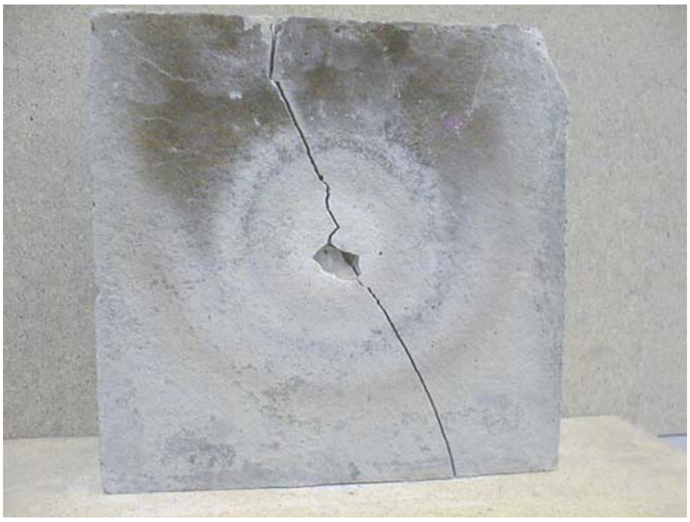


Flame Jet Test Apparatus

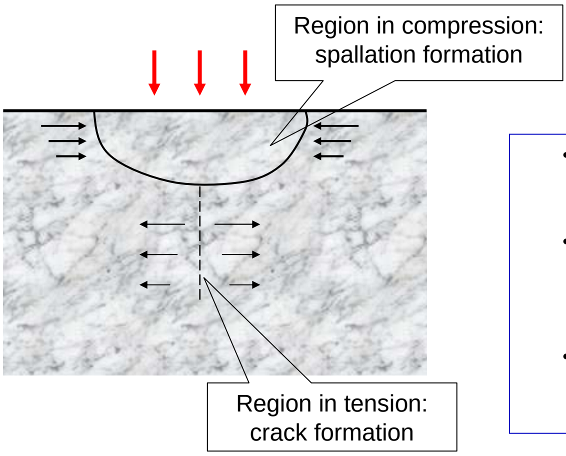




Cracking

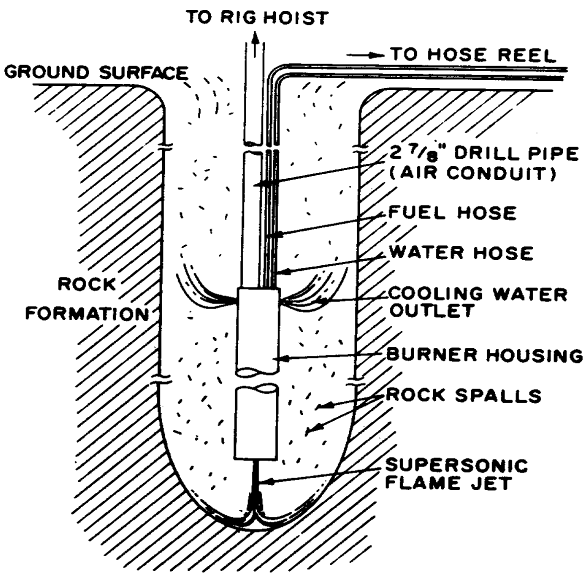


Cracking vs. Spallation
Role of water



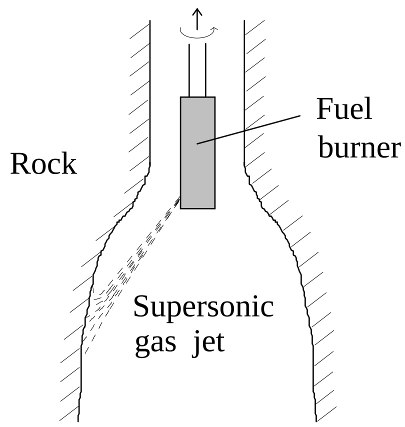
- High tensile strength is a necessary condition for spallation
- Water vapour plays an important role in spallation for materials with low permeability.
- The higher temperature the deeper and smaller the spalling area

Flame Drilling of Blast-Holes



(after Williams et al., 1988)

Flame Expansion of Blast-Holes



Summary

- Methods of rock breakage
  - Major: Mechanical and Blasting
  - Potential: Thermal and Chemical/Biological
- Production blasting
  - Damaged zone new the blasthole
  - Radial cracks
  - Fragmentation by the tensile component of the wave reflected from a discontinuity
  - The role of the reflecting discontinuities can be played by radial cracks produced by neighbouring blastholes. Hence the importance of correct blast sequencing
- Perimeter blasting
  - Relatively smooth surface
  - The distance between the blastholes should be small enough to ensure the formation of splitting crack
  - The charge has little influence on the distance between the blastholes
  - Lateral pressure is detrimental (free surface is needed)
- Thermal spallation
  - Caused by compression created in the surface layers by heating
  - Temperature should be below the melting point
  - Water affects fracture propagation

Literature

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