Why does it Crack?

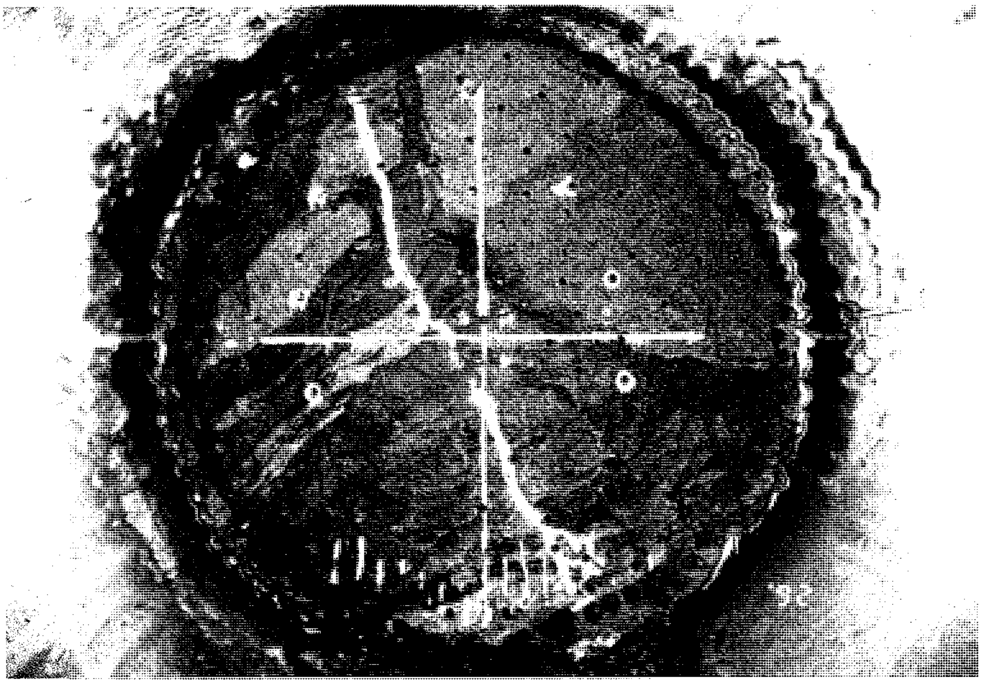
A 1.75-m-radius tunnel was excavated without explosives. A series of 100-mm diameter boreholes 1 m long were drilled to form the perimeter of the tunnel. The interior of the tunnel plug was then broken out using hydraulic rock splitters. The sequence of excavation was as follows:

1. Drill the perimeter holes as shown on the sketch below (time required about 6 hours).

2. Let the rock plug as shown on the sketch below stand for about 12 hours.

3. Break out the rock plug using the hydraulic rock splitters (time required about 6 hours).

A crack which extended to the depth of the plug was commonly observed as shown in the photogragh and the sketch. The crack occured shortly after the perimeter drilling was completed and after a fracture parallel to the tunnel face occured at the back of the rock plug.



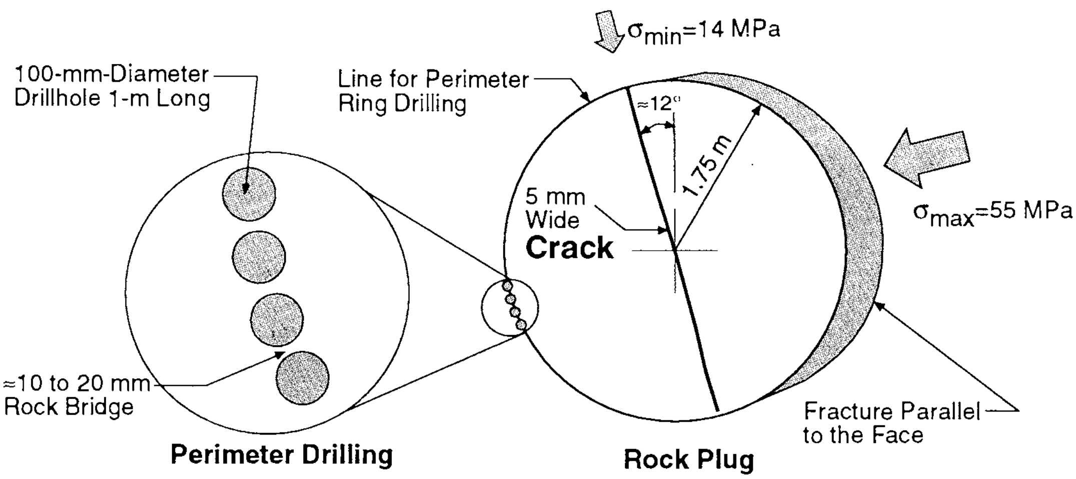


Illustration of perimeter drilling and the rock plug formed by the drilling

Please provide a short (1 page) explanation for the formation of the crack described above. Background information on the tunnel can be found in the article on the Underground Research Laboratory. Send your answer to Dr. P.K. Kaiser, Geomechanics Research Centre, Laurentian University, Fraser Building F217, Ramsey Lake Road, Sudbury, Ontario, Canada, P3E 2C6

Why does it crack?

The question posed on the back cover of Vol. 1, No. 1 provoked a number of responses. The answer which we believe to be the most correct and complete was submitted by former ISRM President, Professor Pierre Habib, of Ecole Polytechnique, Palaiseau, France. His explanation is reproduced below in French and English. The Editors have taken the liberty of adding a few details to the English version—the answer is unchanged.

Pourquoi est-ce que cela se fissure?

L'explication est extrêment simple.

Lorsque l'on fore les trous la contrainte σ_{max} = 55 MPa se reporte sur ce qui reste de matière entre les trous. Dans les cloisons orientées dans la direction de σ_{max} , la contrainte de compression est donc multipliée par le rapport des sections initiales (diamètre du trou + épaisseur de la cloison) aux sections finales (épaisseur de la cloison). Soit ici

$$\frac{100\text{ mm} + 20\text{ mm}}{20\text{ mm}} = 6 \quad \text{ou} \quad \frac{100\text{ mm} + 10\text{ mm}}{10\text{ mm}} = 11$$

selon que la cloison a 20mm ou 10 mm d'épaisseur. Vers le milieu de la cloison, il règne donc une contriante de compression simple de 330 MPa à 605 MPa. La granite de Pinawa est un excellent matériau mais il ne peut pas résister à une telle contrainte: il se casse, même si cela n'est pas très apparent, et le noyau est presque libre dans la direction de σ_{max}.

La situation est tout à fait différente dans la direction de σ_{min} = 14 MPa. La contrainte dans les cloisons est multiplié par les même facteurs, soit 6 σ_{min} = 84 MPa et 11 σ_{min} = 154MPa. D'après la courbe de la figure 12 (page 10) la cloison résiste. (Elle peut mème résister à plus de 200 MPa grâce à l'influence de la contrainte intermédiaire σ_2, car les cloisons sont longues par rapport à leur hauteur.)

Le noyau est alors soumis à un essai de type brésilien et il casse en traction sur une section diamétrale paralléle à σ_{min} ce qui paraît étonnant parce qu'on s'attendrait à une rupture dans une section diamétrale parallélle à σ_{max}.

Le fait que la fissure s'ouvre de 5 mm montre bien que le noyau était libre dans la direction de σ_{max}. De même, le fait qu'un discage se produise montre bien que le noyau était libre dans la direction de σ_{max} et a pu se dilater dans cette direciton permettant à une fissure de se produire en mode II (en cisaillement) détachant ainsi un disque de roche.

Le calcul **très approximatif** suivant (comme si la pression était uniforme) donne les déplacements disponibles suivants dans la direction de σ_{max}:

- Convergence de la galerie:

$$\frac{\Delta \Phi}{\Phi} = \frac{\sigma_{max}}{E}(1 + \nu) = 1{,}3.10^{-3};\ \Delta \Phi = 4{,}5\text{ mm}$$

- Dilation du noyau:

$$\frac{\Delta \Phi}{\Phi} = \frac{\sigma_{max}}{E}(1 + \nu) = 0{,}7.10^{-3};\ \Delta \Phi = 2{,}5\text{ mm}$$

Total: 7,0 mm

(La convergence de la galerie, m'a-t-on dit à Pinawa, a été de 7 mm—au lieu de 4,5 mm—ce qui doit être dû à la fissuration du granite.)

Dans la direction de σ_{min}, on aurait eu au total simplement 1,8 mm.

Si l'on admet que le disque de roche était chargé dans la direction de σ_{min} suivant un angle de $30 = \frac{\pi}{6}$, (Fig. 1) ce qui est une approximation grossière mais acceptable, la rèsistance en traction d'après l'essai brésilien serait, avec les notations habituelles:

$$R_T = \frac{2P}{2\pi RL} = \frac{2\pi}{6}\frac{RL\sigma_{min}}{2\pi RL} = \frac{14\text{ MPa}}{6} = 2{,}3\text{ MPa}$$

ce qui est très vraisemblable si l'on tient compte de la fissuration et de l'effet d'échelle.

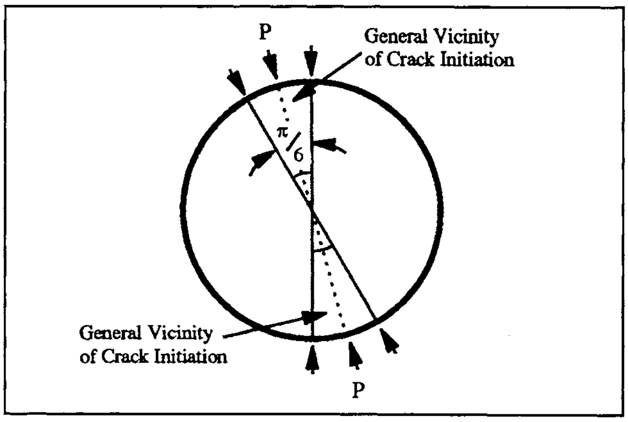


Figure 1.

Why does it crack?

The explanation is very simple. When the perimeter holes are drilled on the right and left quadrants of the tunnel periphery, the maximum stress smax=55 MPa is concentrated on the (10 mm 20 mm) wall of rock between the holes. The concentration is given by the ratio:
(wall thickness)/(hole diameter + wall thickness) i.e.

$$\frac{100\text{ mm} + 20\text{ mm}}{20\text{ mm}} = 6 \quad \text{to} \quad \frac{100\text{ mm} + 10\text{ mm}}{10\text{ mm}} = 11$$

Thus, the wall between the holes will be subjected to an average simple compression stress between 6 × 55 = 330 MPa, and 11 × 55=605 MPa. Pinawa granite is an excellent quality rock but it can not sustain such stresses; it breaks, although it may be difficult to see the failure, and the central (i.e. 3.5 m diameter) core is free (unloaded) in the σ_{max} direction.

The situation is much different in the σ_{min} = 14 MPa direction. The stress in the walls between the holes is multiplied by the same factors i.e. (6 to 11) σ_{min} = 84 MPa to 154 MPa. From Fig. 12 (page 10) it is seen that the rock can support such stresses (in fact, it can support even higher stresses because of (i) the influence of the intermediate stress σ_2, (ii) the wall length (1 m) is greater than the wall height (100 mm).

The central core is thus submitted to a kind of Brazilian test loading and it breaks in tension across a diametral section parallel to σ_{min}. At first glance, this seems strange since we usually expect a Brazilian type failure to occur across a diametral section parallel to σ_{max}.

The fact that the crack opened 5 mm shows that the rock core was free in the σ_{max} direction. The fact that discing (at the back of the 1 m drilled thickness) occurred before cracking shows that the rock core could dilate in the σ_{max} direction to allow a fracture to develop in mode II (shearing mode) to produce the (1 m thick) disc of rock.

The following **very approximate** calculation (which assumes that the stresses were uniform) gives the possible displacements in the σ_{max} direction.

- Tunnel convergence:

$$\frac{\Delta \Phi}{\Phi} = \frac{\sigma_{max}}{E}(1 + \nu) = 1{,}3.10^{-3};\ \Delta \Phi = 4{,}5 \text{ mm}$$

- Core dilation:

$$\frac{\Delta \Phi}{\Phi} = \frac{\sigma_{max}}{E}(1 + \nu) = 0{,}7.10^{-3};\ \Delta \Phi = 2{,}5 \text{ mm}$$

Total: 7,0 mm

where Φ is the tunnel diameter = 3,5 m; Poisson's ratio ν = 0,3; E is assumed to be approximately 55 GPa i.e. $\frac{\sigma_{max}}{E} = 1 \times 10^{-3}$

At Pinawa I was told the tunnel convergence was 7 mm—instead of 4.5 mm, as above—probably due to small-scale fracturing in the granite, causing a reduction in modulus, thereby increasing the convergence.

In the σ_{min} direction the maximum possible displacement should be approximately 1,8 mm.

If we assume that the rock disk was stressed in the σ_{min} direction of a $30^\circ = \frac{\pi}{6}$ angle, (Fig. 1) which is a rough but reasonable approximation, the tensile strength (R) from the Brazilian test formula is

$$R_T = \frac{2P}{2\pi RL} = \frac{2\pi}{6}\frac{RL\sigma_{min}}{2\pi RL} = \frac{14 \text{ MPa}}{6} = 2{,}3 \text{ MPa}$$

where P = total applied load over $\frac{\pi}{6}$ contact angle and thickness L (1m) of core disc

R = tunnel radius

This value seems reasonable if we take into account small-scale fracturing in the granite, and scale effects.

Comment

Professor Habib's explanation is very much in accord with ours. One fact that should be pointed out, which was omitted from the previous discussion, was that the crack was observed to start near the periphery i.e. essentially as two cracks growing towards each other, initiated by tension perpendicular to the diameter. Thus, the Brazilian formula, which calculates the tensile stress normal to the diametral axis of the disc at the center, should under-estimate the tensile strength of the granite in this situation since the strength was apparently not reached first at the center. It is not uncommon in laboratory Brazilian tests to observe that cracks are initiated near the periphery under the compressively loaded segment, rather than at the center.

Of the other replies received, Dr. Levent Tutluoglu (Middle East Technical Univ, Ankara, Turkey) and Luis Castro (Geomechanics Research Center, Laurentian Univ., Sudbury, Canada) suggested the same mechanism as Dr. Habib, but did not provide the detailed supporting computations.

Three contributors suggested a different mechanism, with varying degrees of numerical analyses offered in support. Essentially these assumed that the perimeter holes could be neglected (or had failed) so that the ring of holes could be approximated as a continuous slot, approximately 1 meter deep, with the maximum and minimum principal stresses (compression positive) of 55 MPa and 14 MPa respectively, acting normal to the axis of the tunnel, and intermediate principal stress of 48 MPa acting parallel to the axis. Concentration of these stresses due to the 1 m deep slot resulted in high compression stress concentration at the root of the slot itself, and a tension (σ_t) acting tangentially in the face of the tunnel. [See Fig. 2] Thus, the 1 m deep circular "stub" is essentially being "pinched" across the plane of the bottom of the slot, and bending as a circular plate or disc, with tension being induced in the face. This results in the development of a tensile fracture in the face which maximizes normal to the direction of σ_1 = 55 MPa.

Dr. T.R. Stacey, who supported the above explanation, noted that "in a higher stress situation (i.e. greater than at URL) the plate (disc) would be more likely to buckle with violence, to the extent of apparently exploding (it could also be that the thickness of the plate is less under these higher stress conditions, as in the case of core discing, and hence the plate is less stable)." Disc "exploding" behaviour occurred during mechanical mining of gold reef by large 600 mm diameter cored

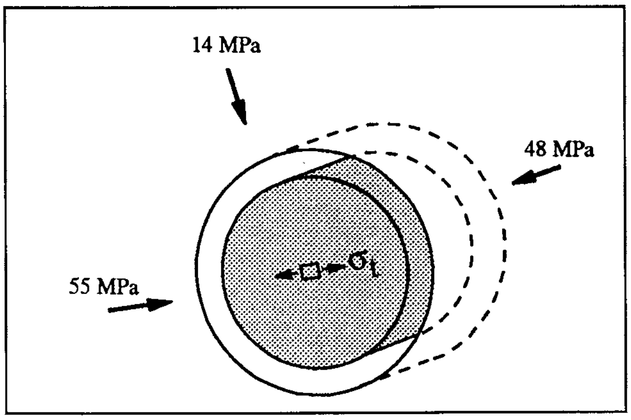


Figure 2.

holes. The buckling plate/disc behaviour is also suggested as the explanation of problems encountered during raise boring at depth.

The "buckling core" is plausible but the analyses presented by the various contributors involve different approximations to the three-dimensional field stress state, and obtain quite different results for the magnitudes and distributions of stresses induced in the core by the slotting operation. We plan to study this mechanism in more detail and will defer further comment until this study is completed. However, buckling, as described, would put the face in tension and would tend to augment the tension developed by the loading mechanism described by Professor Habib.

Another contributor took into consideration the fact that the perimeter holes were drilled sequentially and not instantaneously, suggesting, in effect that the right-hand side semicircle of perimeter holes was drilled first, starting 10° above the bottom of the tunnel and proceeding 10° past the top of the tunnel (i.e. the first and last holes lay on the diameter AC defined by the observed crack, σ_{min} see Fig. 3). This semicircle of holes created stress concentrations at the bottom of the perimeter holes, resulting in development of a partial (i.e. semicircular disc or half-moon fracture across the bottom of the 1 m perimeter holes). The disc fracture surface then dilated, as it detached from the rock mass, developing a bending stress across the base of the disc i.e. where the half-moon fractures terminated, and produced a tensile crack along the line ABC—but opening from the base of the stub rather than in the face of the tunnel. This explanation, while ingenious and having the merit of attempting to consider the sequence of perimeter hole drilling, does not seem to agree with the observed open crack in the face of the tunnel.

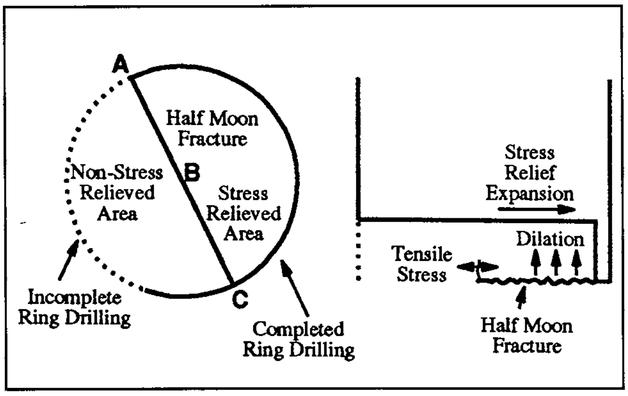


Figure 3

The remaining five contributions all attributed the crack to "maximum stress relief," "maximum extensional strain," or "maximum strain energy release" normal to the direction of maximum compression upon coring (i.e. perimeter drilling). While it is acknowledged that a micro-distribution of induced tension stresses and compression stresses [i.e. alternating on the scale of the rock grain size—but summing to a zero net force (but not zero strain energy) in (any of) the directions relieved of the σ_1 and σ_3 stresses by the perimeter holes] will result when the holes are drilled, this relief alone does not appear to produce fractures in the Lac du Bonnett granite. There are no examples of fractures developing in cores taken from the high stress environments of the U.R.L. underground.

We thank all contributors who took the time to prepare and submit their solutions to the problem, and hope that they and others will also consider submitting comments on the problem submitted by Mr. Ortlepp in this issue. [See page 66.]

Borehole breakout—large scale!

This photograph shows the shape developed by the periphery of the (initially) circular tunnel at the Underground Research Laboratory (See Cover photo in Vol. 1, No. 1), after careful removal of broken rock in the roof and floor. Note that the major and minor axes of the tunnel coincide with the 55 MPa and 14 MPa principal stress directions discussed in the "Why does it crack" problem. (Photo courtesy of R.D. Martin, URL, Pinawa, Canada)