ıe cracks propagate at 0.38 Vp the strain
. be tangential to the tip of a crack at an
69° from the normal between the charge and
face. This is in fact the average angle
cratering experiments. It has also been
simulating cratering experiments that if
:s are assumed to be orientated in the hole
.nsert the charge that the ends of many of
:s, assuming an appropriate dynamic tensile
strain, lie on a straight line. This can
.fied with the optimum crater. The critical
ın be identified as the distance to which
.n is sufficient to generate severe cracks.

: mechanisms would be expected to generate
ı all directions around the charge. It has
m that cracking is found all around the
› a distance which can be shown to be about
ıum depth in cratering experiments.

;train developed by spherical charges of
›s, as in cratering, and long cylindrical
as in bench blasting, can be calculated.
ılated strains when coupled with the
ıte dynamic tensile breaking strains show
›ench blasting the cracking does not extend
·ee face. The cracking extends only to
Lf the burden. This has some important
L implications which will be discussed

: the reflected strain wave has passed into
the explosion product gases still at a
ssure stream into the cracks at the local
Locity in the gas. The reflected strain
ed these cracks normal to it and opened
ıcks tangential to it so the gas will
tially stream into these cracks at an angle
er than 45° to the normal between the charge
free face. It can be shown that the time
r the gas to start escaping at the free
that calculated for the gas to stream into
ks of a length of $\sqrt{2}$ x burden. It has
ed experimentally that the gas does escape
om the side of the charge and the free face
ving when the gas starts to escape. The
g at high pressure compresses the rock and
to be taken into account in the calcula-
There is also as a result a pronounced
ıction which compresses the rock directly
of the hole.

gas streaming into the cracks also gives
mass an impulse forward. The calculated
gives the observed heave velocity of the
The gas streaming into the cracks is not
to extend the cracks in normal blast as
nentation observed is that to be expected
cracks induced by the strain wave.

evidence for these mechanisms has been
sewhere. (1)

AL CRACKING FROM A CONCENTRATED CHARGE -
ERING

mechanism proposed above would cause
all around the blasthole. This has been
perimentally in (2,3). The experiments in
re performed in the same quarry with the
losive. Using the upper damage zone
from (2) which were determined by seismic
measurements we find:

TABLE I

Hole Diameter 10^{-2} m	Charge Weight Kg	Upper Damage Zone m	Upper Damage Zone/Hole Radius
6.0	0.25	0.23	7.7
7.6	0.50	0.53 (0.61)	13.9 (16.0)
9.2	1.00	0.51 (0.56)	11.1 (12.2)
12.7	2.00	0.79 (0.94)	12.4 (14.8)

The unbracketed figures are the most probable figures and the bracketed figures the maximum values. The ratio (optimum crater depth)/(radius of equivalent spherical charge) found from an analysis of (4) in (1) is 13. This is very close to the ratio found experimentally from the seismic damage zone results which were obtained with spherical charges. This simply constructed array of radial cracks described in (1) gives a good account of cratering and the extent of the zone damaged by explosives.

4 RADIAL CRACKING FROM LONG CYLINDRICAL CHARGE - BENCH BLASTING

The same array of cracks orientated with respect to the free face is now applied to bench blasting.

Unlike cratering there is no pre-existing crack for the sets of radial cracks to align themselves on. The radial compressive wave strain after reflection at the free face has already been shown to have an influence on cratering. The interaction of the reflected tensile strain wave with the radial cracks will tend to orient the cracks towards the free face in the same manner as the cracks in cratering are orientated towards the free surface. In addition the cracking from the rear of previous blasts will influence the orientation and growth of the cracking of subsequent blasts. This effect will be cumulative. The cracking from previous blasts not only effects subsequent blasts on that bench but also, because of the effect of the explosive placed sub-grade, will effect the cracking particularly in the collars of lower benches.

The orientation proposed can only be considered as plausible. The only other reasonable alternative would be to use a completely random orientation.

In normal blasting practice a number of holes are fired together or in sequence. When the holes are fired together radial cracks are assumed to stop propagating where they touch. When holes are fired in sequence a radial crack is stopped where it meets an existing crack.

5 SINGLE ROW OF HOLES FIRED SIMULTANEOUSLY

A graphical representation of the radial cracking is given in Figure 1. It is obvious that the cracking from the previous blast has cut off much of the cracking from subsequent blasts. Firing the holes simultaneously has also reduced cracking where the cracks have collided. As a result, an uncracked area has been left between the holes. The analytical method of calculating maximum fragment length described elsewhere (8) gives a maximum fragment length of 3.6 ft. This

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graphical method gives virtually the same result as is shown by the circle diameter 3.6 ft drawn around the uncracked area.

6 SINGLE ROW OF HOLES FIRED IN SEQUENCE

Assuming the free face is initially flat, the first hole to be fired will see only the initial free surface.

The burden ejected will be wedge shaped and it is assumed that the rock will crack most easily along the diagonal between the holes. The radial cracking pattern when orientated in this manner is shown in Figure II. There is no improvement in fragmentation. It was found in the experiments reported in (5) that using delay detonators with this pattern gave no improvement in fragmentation compared with firing instantaneously.

7 SINGLE ROW OF HOLES STAGGERED WITH RESPECT TO PREVIOUS ROW AND FIRED IN SEQUENCE

Figure III has been constructed in the same manner as Figure II but the free face after the initial hole has fired is expected to appear along the diagonal connecting the two holes fired with the same delay. The fragmentation has improved compared to Figures I and II. This shows the importance of either drilling the holes in a staggered pattern or by using an appropriate delay pattern which develops a free face in which the holes are staggered. This is what the very popular echolon firing pattern does.

8 WIDE SPACING PATTERN

The product burden x spacing has been kept constant. In this particular example the ratio burden/spacing is 1/4. Each row is fired instantaneously. There is a marked improvement in regularity of cracking and the maximum fragment size is less than 2.5 ft as seen in Figure IV. Again, the holes are staggered as recommended by Langefors (7).

On comparing Figure I with Figures II and III, the face after blasting simultaneously, would be expected to be more even than blasting with delays as found by Bergmann Riggle and Wu (6). They also comment that "practically all observed cracks were related to the radial crack system emanating from each shothole".

There would seem to be very little doubt from these experiments that fragmentation is determined primarily by radial cracking and there is considerable scope for the improvement of blasting by using configurations of blastholes and delays which utilise the radial cracking as fully as possible.

This method gives an explanation of cratering, of the better fragmentation from delay blasting and wide spacing patterns. This is the first explanation of the fragmentation from delay blasting and wide spacing of which the writer is aware. The importance of staggering the hole with respect to the actual free face at the moment of firing has not apparently hitherto been recognised. This method makes possible the analysis of the fragmentation of any geometry of blasting.

This graphical method also makes it possible to incorporate into the analysis the effect of existing faults in the rock. If the faults are predominantly in one direction, it is easy to see that if the free face is parallel to these faults, that fragmentation is improved (if the spacing between the faults is the burden or greater) since much of the troublesome back cracking is cut off and the full cracking from the subsequent hole can now take place.

Cracks normal to the free face cause little trouble if the explosive is powerful enough to allow one hole to crack across the spacing. If this is not the case, toe will develop and, the spacing will have to be reduced.

If "in situ" seismic tests show considerable anisotropy due to the presence of faults, blasting should be arranged so that the free face is parallel to the direction of highest velocity.

Faulting will reduce the velocity and can, as shown above, make blasting in fact more difficult in this direction. Our experience of blasting in columnar basalt indicates that a burden > spacing gives best results. Blasting with spacing > burden gives an uneven face which cannot be easily mucked out and the bottom gradually creeps up. A smaller spacing which ensures that the face is split cleanly prevents this.

It seems to be a notable advance that we can at last begin to talk of rock as an inhomogeneous, anisotropic, faulted medium.

9 DELAY BLASTING

It has been pointed out above that the burden starts to move when the gas reaches the free surface. When the burden starts to move another free face is generated behind the burden. This second free face may not be parallel to the original free face. The gas streams into the cracks at a velocity of about 2000 m/s near the blasthole which falls to about 1000 m/s near the free face. The crack velocity determined in (6) is the average gas streaming velocity. It is only when the gas starts venting at the free face does the burden move so forming the next free face. The minimum delay time must be greater than this time. The experiments in (6) confirm that for any benefit to be obtained from delay blasting the time must be greater than the time taken for gas to reach the free surface and twice this time is ample.

10 CONCLUSION

This short paper attempts to show that the theory of blasting can now offer a reasonable explanation of many of the parameters affecting it. It is also feasible to incorporate into a graphical analysis some of the geological faults encountered in practice.

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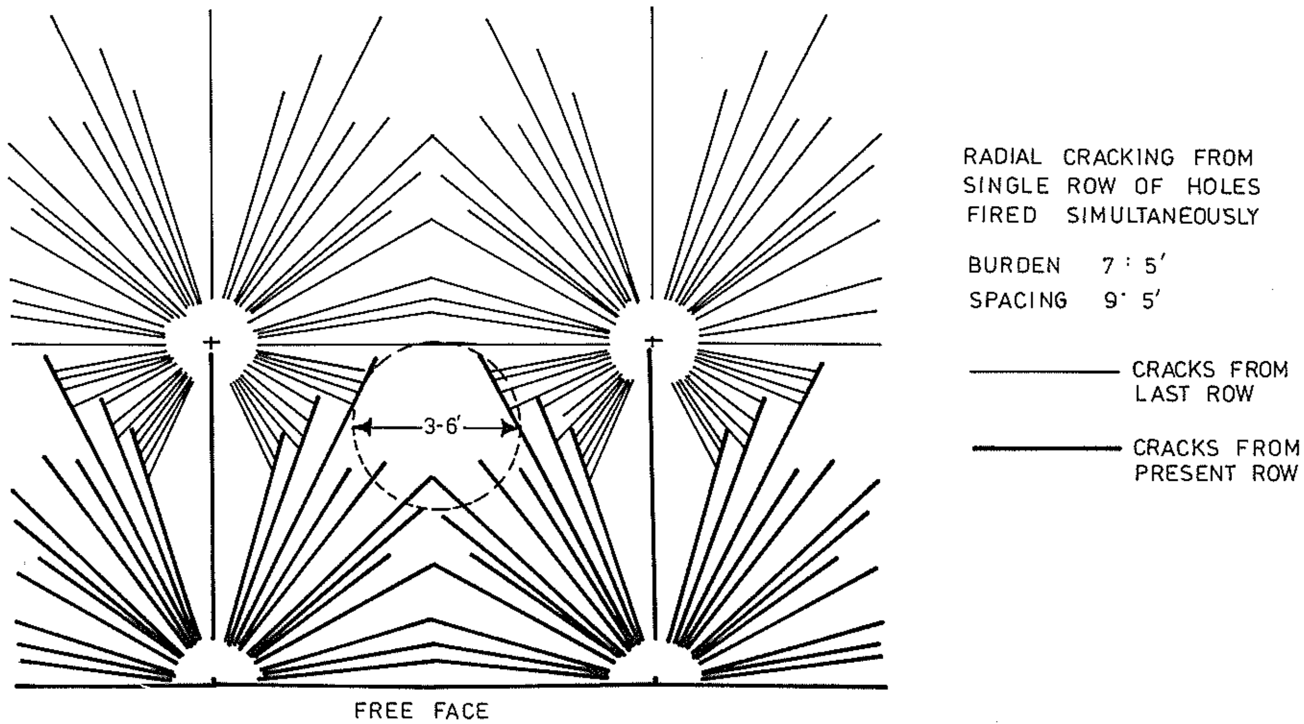

Figure 1

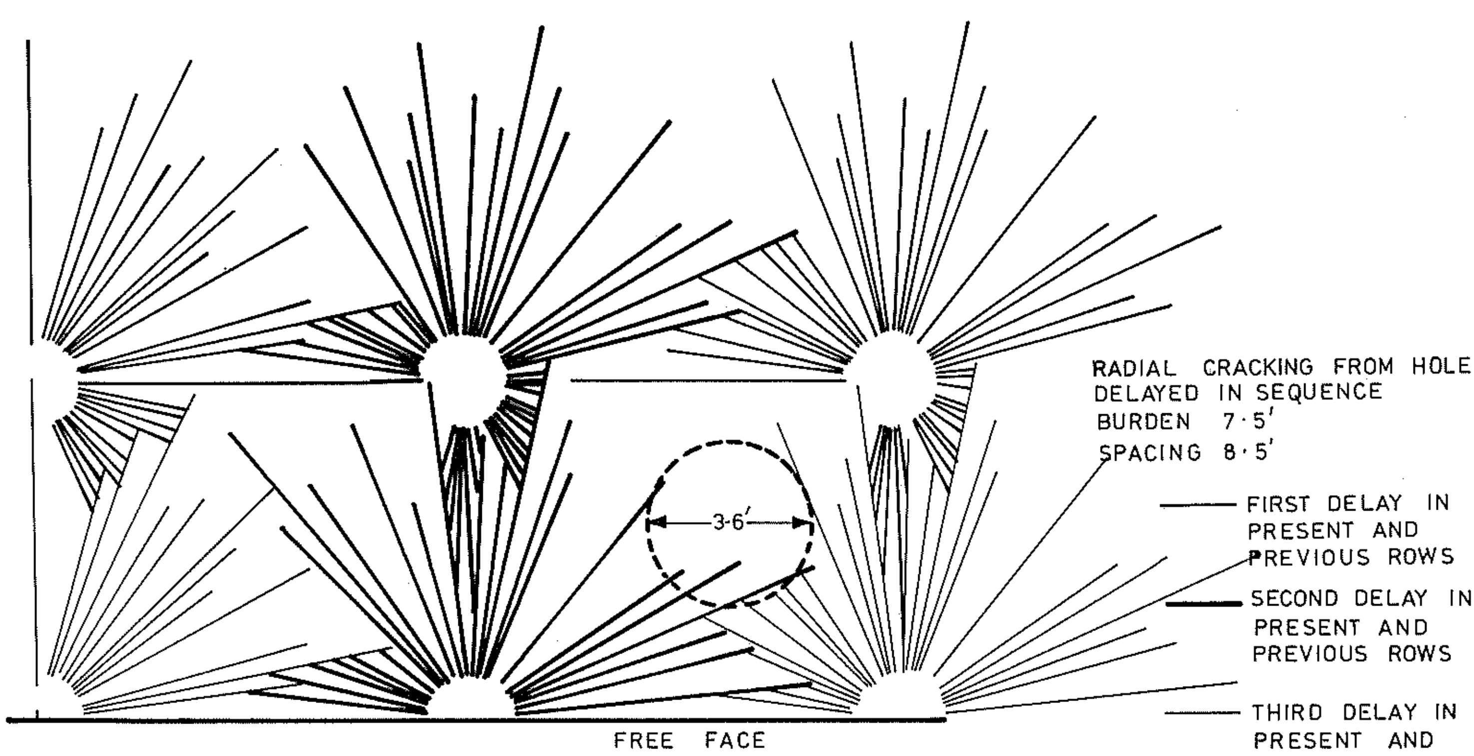

Figure 2

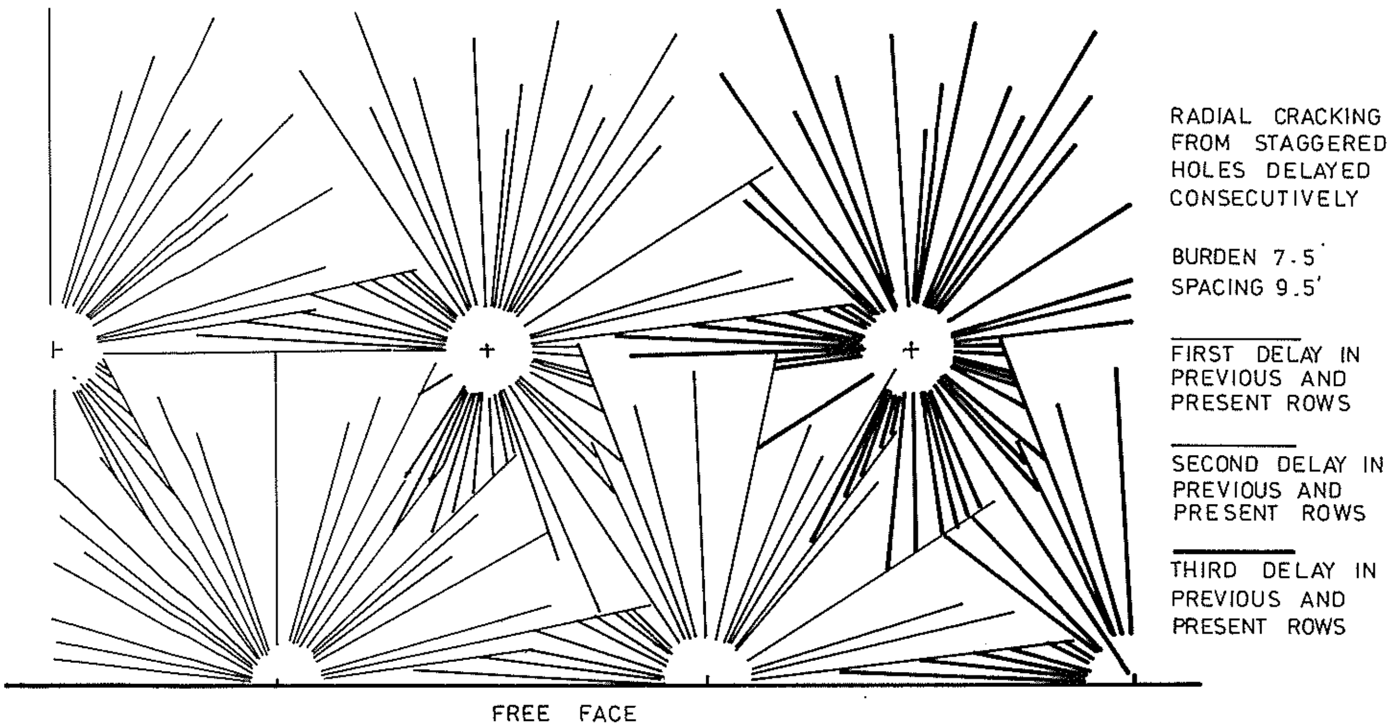

Figure 3

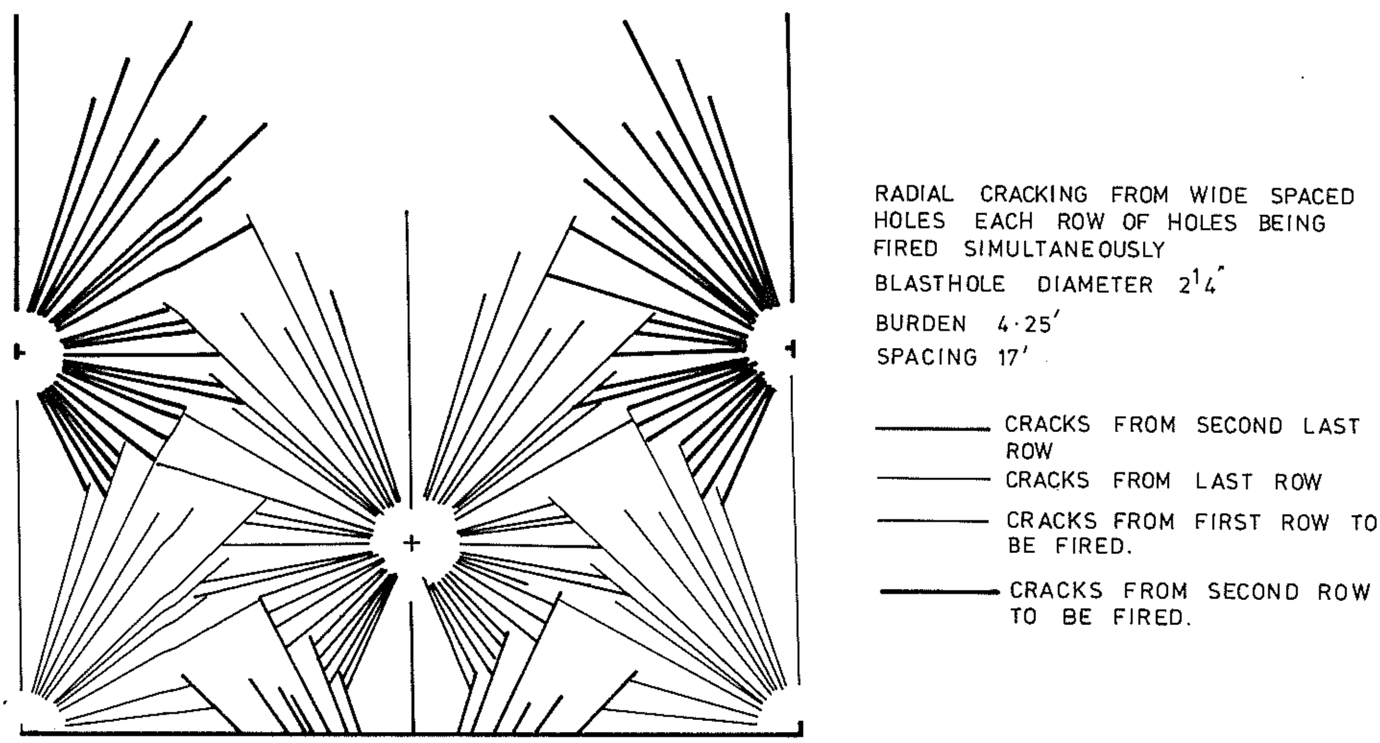

Figure 4

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