STUDY OF THE MINERALOGICAL TRANSFORMATIONS OF GRANITE BY UNDERGROUND NUCLEAR EXPLOSIONS

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ABSTRACT

The object of the following communication is to prove new data about the petrographic effects of the underground nuclear explosions. It is founded on the results of french tests in granite rock. The samples are collected by drilling and the temperature of the rock was measured in the hole. Four types of melted rocks can be sorted, grey-green glass and pumices, beige to red-brown pumices, dark lavas, dark veinlets and crushed granite. The distribution of these rocks is studied. Optical microscopy, X-rays and chemical analysis, study by electron probe, are made. The results complete previously published data. They are interesting as far as the use of nuclear explosions for industrial applications is concerned.

1 - INTRODUCTION

The object of the following communication is to prove new data about the petrographic effects of the underground nuclear explosions. The knowledge of rock transformations is indeed necessary to define exactly the useful effects of the explosions and their possible applications.

This study is founded on the results of french tests on the HOGGAR test site (Central Sahara). The shots were fired in a very homogeneous granite mountain mass the composition of which is well known (see Table 1).

The explosions took place at the end of horizontal tunnels and after the shot, the surrounding rocks we explored by drilling.

A short first part of this report gives the outline of this exploration. The second part describes the petrographic features of the rocks collected. The third part gives the results of the special study techniques used.

TABLE 1

Composition of the granite of the HOGGAR Test Site (2)

Chemical Analyses

SiO_2	75,80	CaO	0,59
Al_2O_3	12,49	Na_2O	3,80
Fe_2O_3	1,30	K_2O	4,79
MnO	0,04	TiO_2	0,08
MgO	0,03	P_2O_5	0,01
	H_2O +	0,48	
	H_2O -	0,06	
	CO_2	0,13	

Mineralogical Analyses

Quartz	35	Chaye's index	64
Microcline	37		
Plagioclase	25		
Biotite	2,1		
Muscovite	0,6		

2 - GENERAL DATA ON THE EXPLORATION

Three drilling methods are used :

1) A conventional rotary drilling method when the length of the bore-holes was under one hundred and sixty meters. The recovery of cores is generally good.

2) A turbo-drilling method for larger lengths ; the turbo-drilling used allows a better control of direction because of its great accuracy (about one or two meters in four hundred meters). But the rate of recovery is often low.

3) A composite method combining turbo-drilling and coring by rotary drilling in the most interesting areas.

By means of those methods, the rocks surrounding the shot point are explored in nearly every way, at all levels and in all directions. But every cavity was rarely studied by more than five or six holes. The use of dimensional analysis allows us to show the similitudes between different underground nuclear explosions and facilitates the generalizing of the observations. This method simplifies the comparison between several shots and eliminates local anomalies.

Figure 1 is drawn along these principles. Holes crossing near the shot point are shown in scaled coordinates (r scaled length from the shot point is equal to the quotient of R the true length by $W^{1/3}$, W being the energy yield of the device in kilotons). It shows the recovery rate of holes crossing the cavity. This rate is very unsteady but the exact study shows that the variations are due to technical reasons (slope or size of the hole) and the samples are representative of the rocks surrounding the shot point.

From the very first holes, the existence of important thermic effects was confirmed and temperature was measured. The heating of boring bits and water around the cavity is quite high. In several cases, an artificial geyser regime was produced when the shape of one or several holes was suited. The drilling waters gathered in pockets. They progressively became overheated and vaporized at the rock contact. When the pressure gets to an adequate value, a steam jet can be produced at the head of the hole.

Measurement afterwards allows us to study the distribution of temperature in space and time (1). Some weeks after shot, the following facts are recorded. The temperature of the cavity rocks is relatively uniform, included between five hundred and six hundred degrees Celsius. In the surrounding crushed zone (at the wall of the cavity), there is a very big thermic drop. At ten meters in scaled length of the shot point, temperature is almost the same as the one of the rocks before the explosion. In the chimney, the temperature is about seventy-five degrees Celsius. Except this last field, the isothermal lines are fairly spherical (fig. 2). The temperature evolution in time is rather slow. The recorded changes are about a hundred degrees Celsius per year.

3 - CLASSIFICATION OF ROCKS PRODUCED BY THE EXPLOSIONS

The detailed geological logs show the large variety of aspect of the melted granite products. They are very generally radioactive samples and their observations require care. They must often be examined in protected areas through leadglass bulls-eyes. The direct comparison of two samples is in practice unrealizable. Those conditions of study might induce us to regard any attempt to classifying as useless. Doing it is however necessary for the report to be clear. The here used classification is founded on the core features resolved by the naked eye. It also reflects their relative positions to the shot point (fig. 3 and 4).

The following types can be sorted (see also table 2)

Type A - grey-green glass and pumices
Type B - beige to red-brown pumices
Type C - partially melted granite and dark lavas
Type D - dark veinlets and crushed granite.

Let us now look at them in detail.

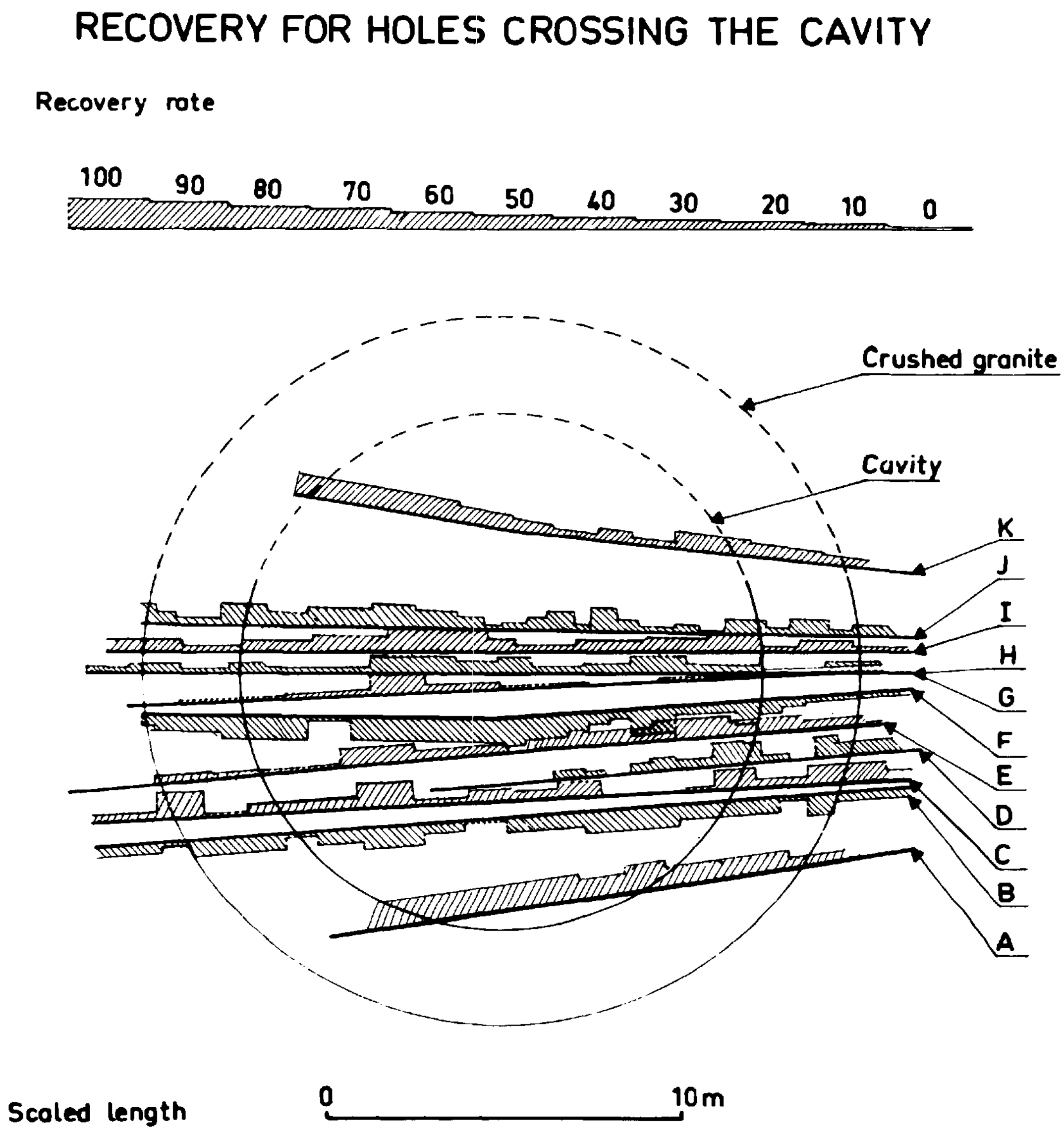

RECOVERY FOR HOLES CROSSING THE CAVITY
Recovery rate
100
90
80
70
60
50
40
30
20
10
0
Crushed granite
Cavity
K
J
I
H
G
F
E
D
C
B
A
Scaled length
0
10m

Fig. 1

EXAMPLE OF ISOTHERMS DRAWN ROUND A SHOT POINT

Results of C.E.N.G-degrees Celsius

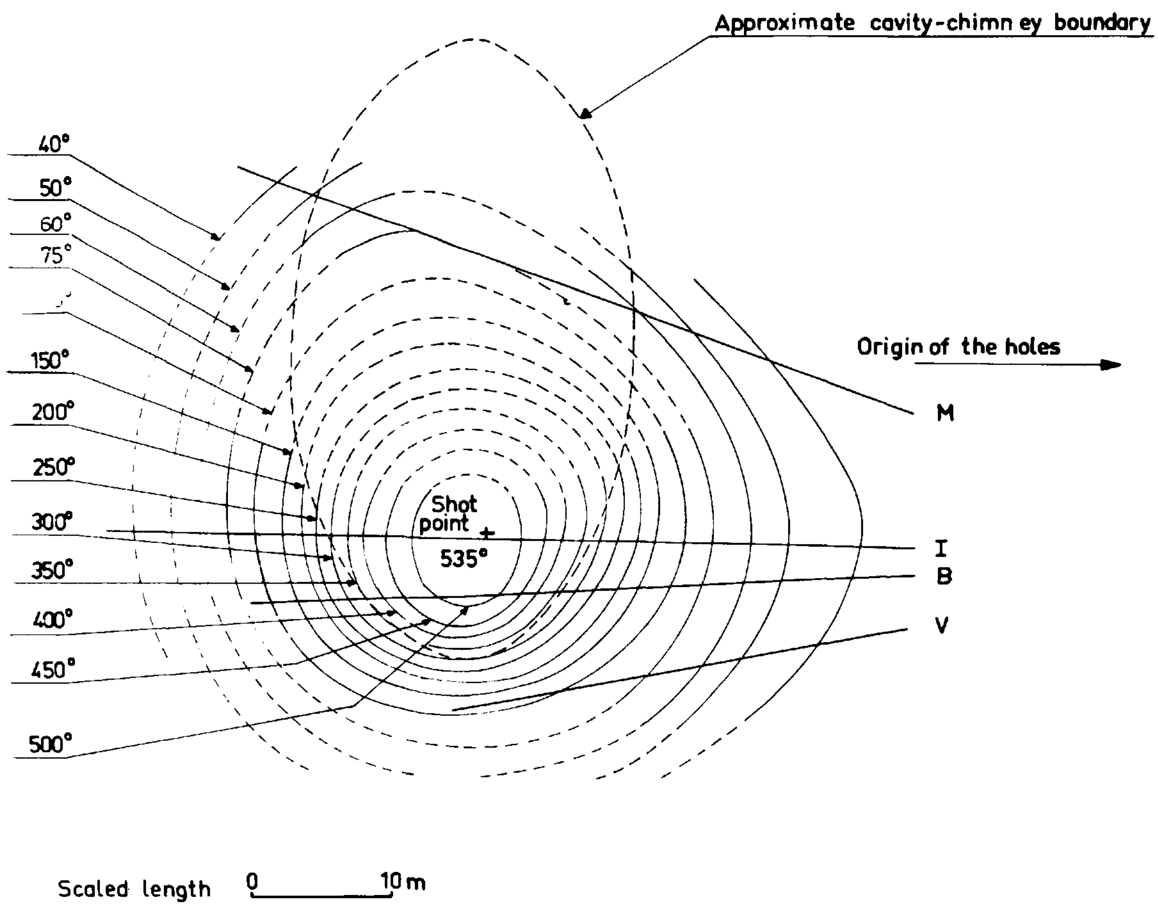


Fig. 2

GEOLOGICAL LOG OF A HOLE CROSSING THE CAVITY

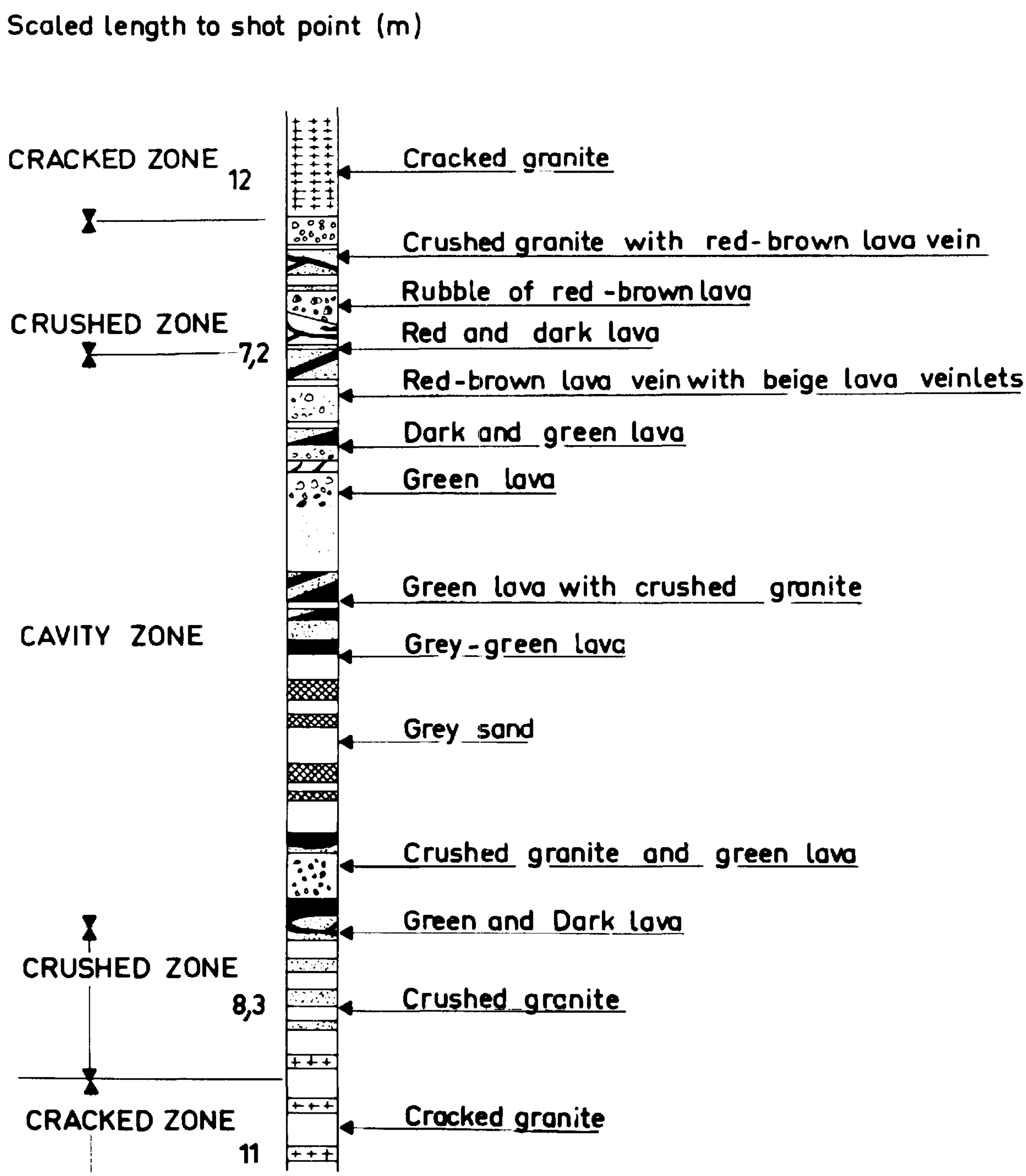


Fig. 3

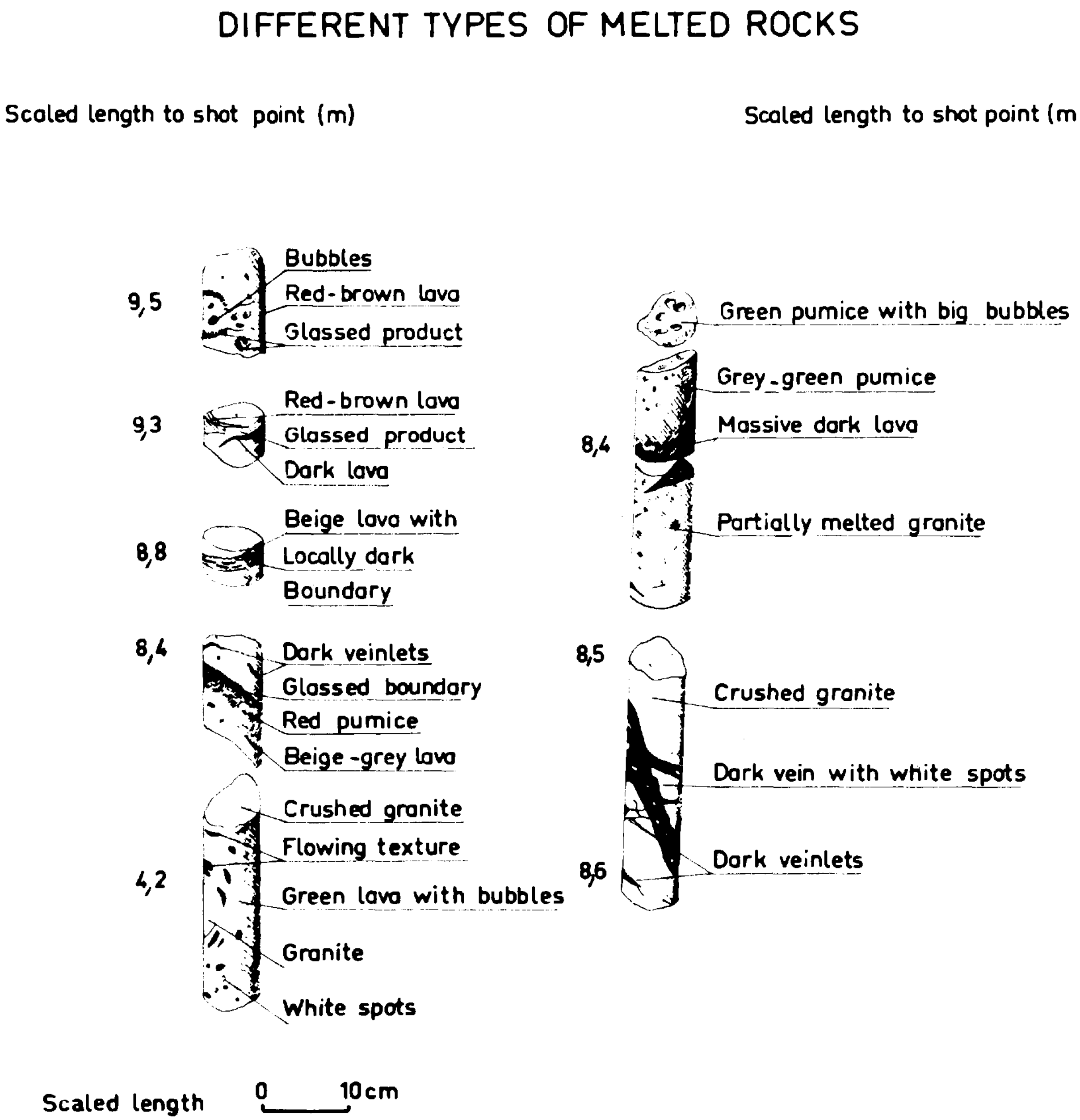

DIFFERENT TYPES OF MELTED ROCKS
Scaled length to shot point (m)
Scaled length to shot point (m)
9,5
Bubbles
Red-brown lava
Glassed product
9,3
Red-brown lava
Glassed product
Dark lava
8,8
Beige lava with
Locally dark
Boundary
8,4
Dark veinlets
Glassed boundary
Red pumice
Beige-grey lava
4,2
Crushed granite
Flowing texture
Green lava with bubbles
Granite
White spots
Green pumice with big bubbles
Grey-green pumice
Massive dark lava
8,4
Partially melted granite
8,5
Crushed granite
Dark vein with white spots
Dark veinlets
8,6
Scaled length
0
10 cm

Fig. 4

3.1 - Grey-green glass and pumices

These are the majority of the melted rocks obtained. They represent about one half of the total amount of lavas encountered near the shot point. On massive sample resolved by the naked eye, their colour varies from a fairly dark dull green to a dark iron grey. Sometimes massive and porcelain looking, they are in some cases semi-transparent glass (fig. 5a). Generally, they have bubbles which diameter varies with the samples from one to eight millimeters (fig. 5b), reaching exceptionally several centimeters. Around the blocks fallen from the roof which are not entirely melted, the bubbles are very elongated and give a flowing texture. Some samples show here and there rectangular whity spots (perhaps cristobalite crystals).

The grey-green lavas seem to be typical of the cavity where there are nearly exclusively found. Inversely, this criterion can be used, in case of doubt, to determine the limit of the cavity. The grey-green lavas are very seldom connected with the still cristalline granite. Dark lavas and half melted granite separate them most often. Among the grey-green lavas, there seems to exist a certain classification. Pumices are often found above the shot point. The bubbles are then well developped and very elongated. In the lower part of the cavity, massive melted rocks are mostly found.

TABLE 2

Types of melted rocks

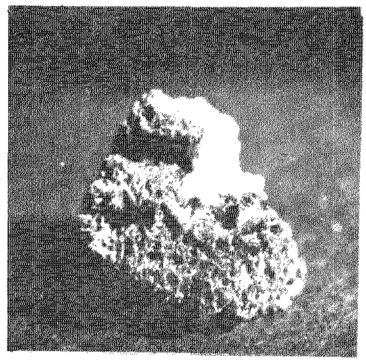
Type	Rock pattern	Color	Localisation
A	Lava (Pumice) (Glass)	grey-green	in the cavity
B	Lava (Pumice)	beige to red-brown	veins out the cavity
C	Lava	dark	boundaries of the cavity and half-melted granite near the other types A and B.
D	Breccia (veinlets)	dark	crushed granite near the cavity boundaries.

3.2 - Beige to red-brown pumices

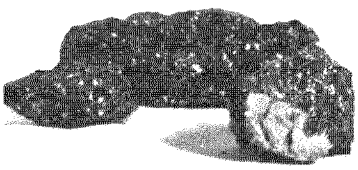
These rocks look like the grey-green lavas. They differentiate from them by their distribution since they are found outside cavity and especially because they have other colors ranging from beige to dark brown with all kinds of red in between.

MELTED SAMPLES OF GRANITE

5a GREEN GLASS TYPE A



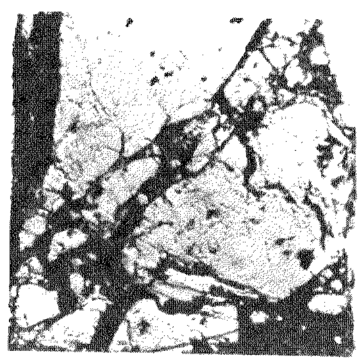
5b. GREY-GREEN PUMICE TYPE A



5c RED BROWN LAVA WITH WHITE SPOTS TYPE B

5d. RED-BROWN LAVA WITH LARGE BUBBLES

5e DARK LAVA TYPE C



5f. BRECCIA WITH DARK VEINLETS

Fig. 5

Sometimes, they give light pumices constitued of a fibrous aggregate. Their flowing texture is marked and often accentuated in the most massive patterns by a change of colour according to the beds. White mineralisations and transparent inclusions are encountered now and then (fig. 5c and 5d).

The chemical analysis showed that the colour scale is not in connection with large changes in composition. Although these rocks generally are recovered far from the cavity, this result seems to be incompatible with both following assumptions :

- hybridation of the melted silicates with fortuitously crossing products or

- natural distillation of the volatile parts.

The most likely assumption is that the change in colour proceeds from an iron oxydation. In the cavity, the atmosphere would be reducing and iron in the state Fe^{++}. In the cracks around, the atmosphere would be oxydizing and iron in the state Fe^{+++}.

3.3 - Partially melted granite and dark lavas

The dark lavas are the second large whole of melted rocks to be found in the cavity. They appear making the transition between the grey-green lavas and the still cristalline rocks. Generally, they lie at the boundary of the blocks fallen from the cavity roof or along its wall. They look remarkably like glass produced by the melting of granite in a furnace. The whole range of states between undamaged granite and glass is indeed found :

1 - granite may be only whitened. The iron oxydes naturally coloring the rocks pink, gradually combine with feldspars crystals which are whitened. In contrast, biotite micas appear darker and darker.

2 - In some areas, the crystal boundaries become fuzzy and colour observed with the naked eye turns blue grey and then darkens. The micas vanish.

3 - There are only whity spots on a darker glass giving a "salmon skin" aspect to the rock. Finally the rock turns to a very dark lava as an obsidian (fig. 5e).

With binocular lens, the glassed areas generally appear most transparent. Their colour scale is between smoked yellow and grey.

3.4 - Dark veinlets and crushed granite

Rocks of this pattern make a special variety of breccia rocks. Amid a whity aggregate created by crushed crystals which are not resolved by the naked eye, dark veinlets are very visible (fig. 5f). They are seldom alone but frequently dividing and crossing one another. When they are very numerous, the rock comes to look like dark lava of entirely melted granite as described above. Dark veinlets do not rise by chance in the crushed rock. They cross very frequently the biotite crystals.

The rocks with dark veinlets shape a rim round the cavity. May be some rubble from its roof recovered near the shot point are also of this pattern but they are undistinguishable from the other half-melted rubbles. The rocks with dark veinlets are the most original type among rocks transformed by the nuclear explosion. Therefore, a large part of the special studies which have been made, concerns them.

4 - GEOLOGICAL AND MINERALOGICAL STUDIES OF ROCKS

4.1 - Distribution of melted rocks

As mentioned above, there is a connection between the different melted rock types and their position along the borehole. Thus, grey-green lavas lie in the depth of the cavity and dark lavas shape big accumulations at the boundary of the crushed granite rim. The amount of each of these two patterns is about the same. The beige to red-brown products are much less common and are almost exclusively to be found in veins along the cracks far from the cavity. The farther from the cavity-wall, the more the rocks tend to be red. The dark veinlets the amount of which is proportionally very small, lie only in the zone of crushed granite around the cavity.

In the cavity (fig. 6) lavas and rubbles are not homogeneously distributed. Detailed survey shows a certain grading. The upper level of lavas reaches about half the radius of the cavity above the shot point (hole K). There, melted rocks and rubbles are about fifty-fifty. But rubbles progressively become larger when the hole is bored lower in the cavity. From this result, it is possible to make a rule of thumb between the melted rocks rate and the sampling level in the cavity. It is a linear law and an integration gives an approximate value to the amount of melted rocks in the cavity : nearly forty per cent of the cavity volume before collapse or about one thousand and three hundred tons melted rocks for a standard explosion yielding one kiloton.

4.2 - Laboratory analysis

The samples which are not or very weakly radioactive are studied by detailed laboratory analysis especially concerning the melting phenomenology of crushed granite (2).

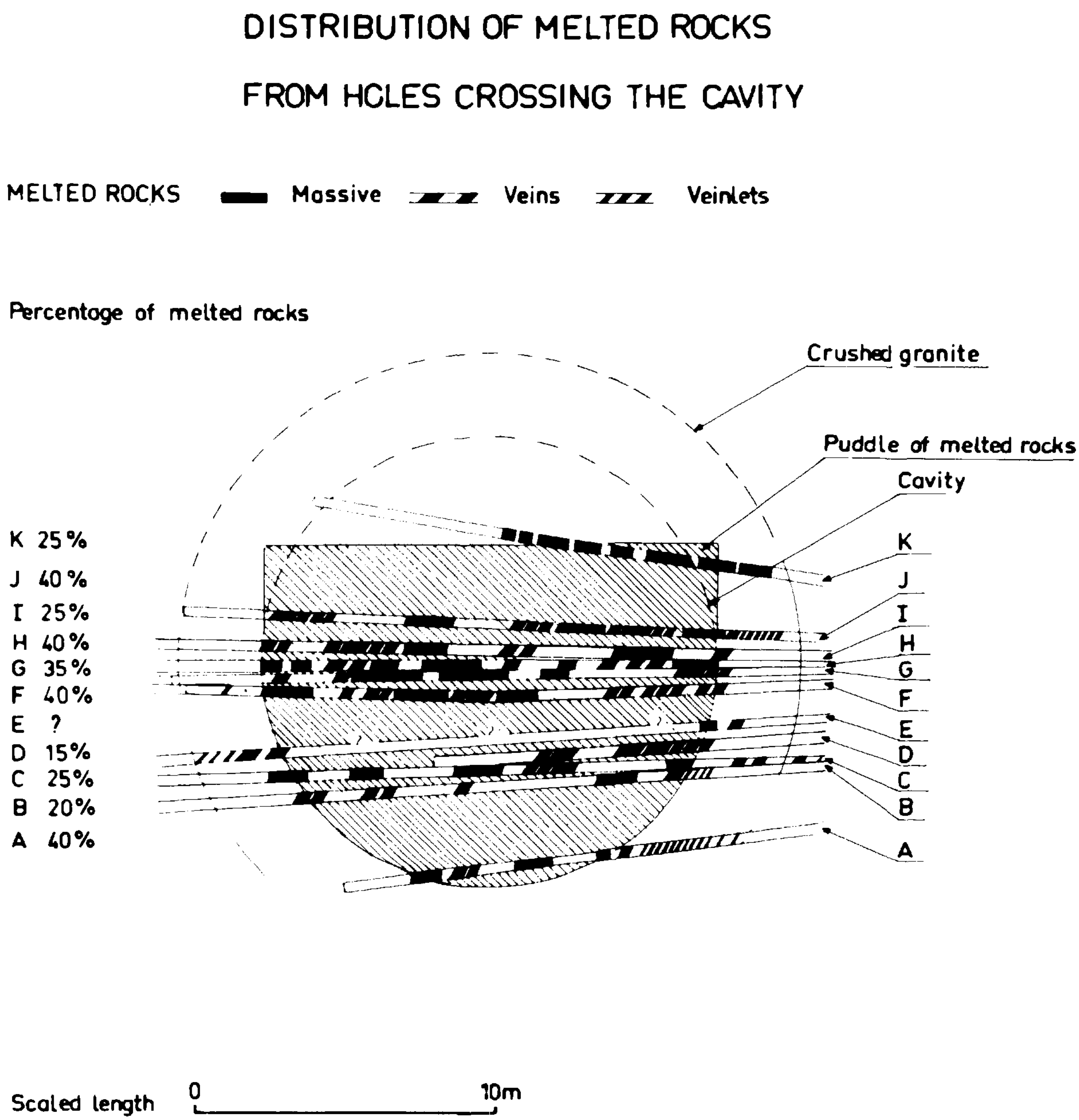

DISTRIBUTION OF MELTED ROCKS
FROM HOLES CROSSING THE CAVITY
MELTED ROCKS
Massive
Veins
Veinlets
Percentage of melted rocks
Crushed granite
Puddle of melted rocks
Cavity
K 25%
J 40%
I 25%
H 40%
G 35%
F 40%
E ?
D 15%
C 25%
B 20%
A 40%
K
J
I
H
G
F
E
D
C
B
A
Scaled length
0
10m

Fig. 6

4. 2. 1 - Optical microscopy

Thin plates survey shows that the glassed veinlets extend in a granite the crystals of which are profoundly altered. Quartz becomes optically biaxis and has many planar elements. Feldspars lose part of their lines of macle and of their birefringency. Biotite has many kink bands (fig. 7). In this aggregate, veinlets are constitued of a brownish glass matrix including many elements : little globular bubbles, round crystallizations, little white isotropic sticks, iron oxydes trails and clear minerals with often a marked relief. Crystals in connection with veinlets are sometimes corroded ; thus, on the boundary of a probably former microcline crystal, appears a big relief fringe. Biotites are surrounded by iron oxydes.

Under the microscope, it seems that grey-green lavas and pumices are made of homogeneous glass and dark lavas have an irregular distribution of the opaque iron oxydes.

4. 2. 2 - X-rays analysis

X-rays analysis was thought to allow :

- showing possible alteration of mineral lattices in granite
- establishing the identity of new mineral species created.

About the first point, no difference has been observed between undamaged granite samples and granite altered by the explosion effects. The crystals parameters of quartz are the very same to a 2. 10^{-4} A. Potash feldspars triclinism do not change : in all cases, it is a high microcline (α = 90° 39' γ = 87° 47'). No evolution is observed in the always pure albite perthites. Interreticular plagioclase lengths measurement always gives results corresponding to a five per cent anorthite plagioclase.

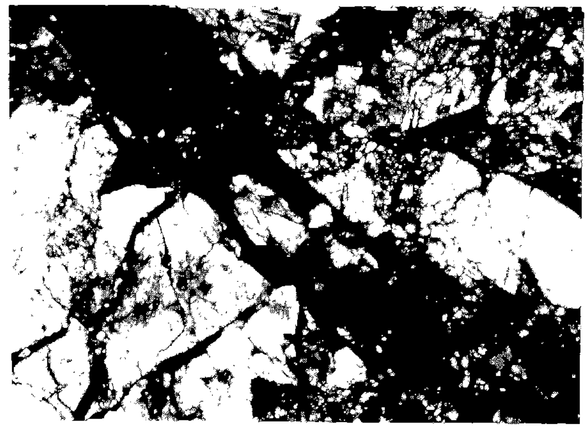
About the second point, X-rays analysis show the presence of two new species, sanidine and low cristobalite appearing in the crushed granite zone. At the cavity boundary the only minerals encountered are quartz, low cristobalite and sanidine. Low cristobalite is observed in small amounts in the white crushed granite part. Bigger amounts are to be found in the dark veinlets part and also in the totally melted samples. Sanidine is to be found in the crushed boundary but does not seem to appear in the cavity itself. Its concentration is also larger in dark veinlets than in white crushed granite (fig. 8).

MELTING OF GRANITE OBSERVED UNDER MICROSCOPE

(polarized light)

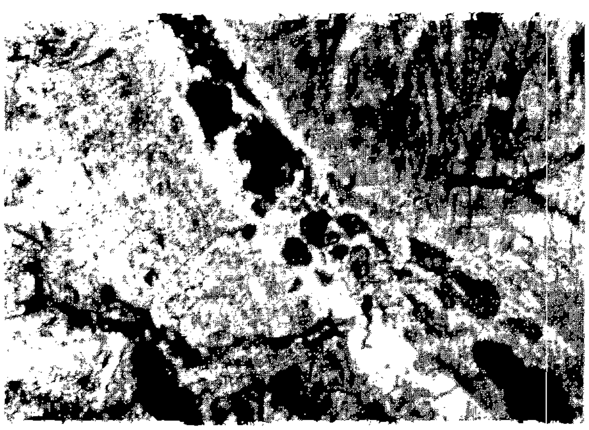
7a. CRUSHED GRANITE WITH KINK BANDS

0 ———— 1mm



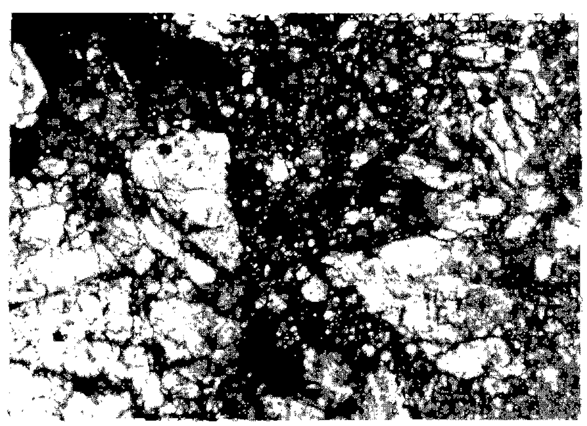
7b. VEINLET WITH MUCH GLASS

0 — 1mm



7c. VEINLET WITH RECRYSTALLIZED MATERIAL

0 —— 1mm



7d. HALF MELTED GRANITE (LEFT)

CONNECTED WITH DARK LAVA (RIGHT)

0 ———— 1mm

Fig. 7

REPRESENTATION OF MINERALOGICAL CHANGES AT THE CAVITY BOUNDARY

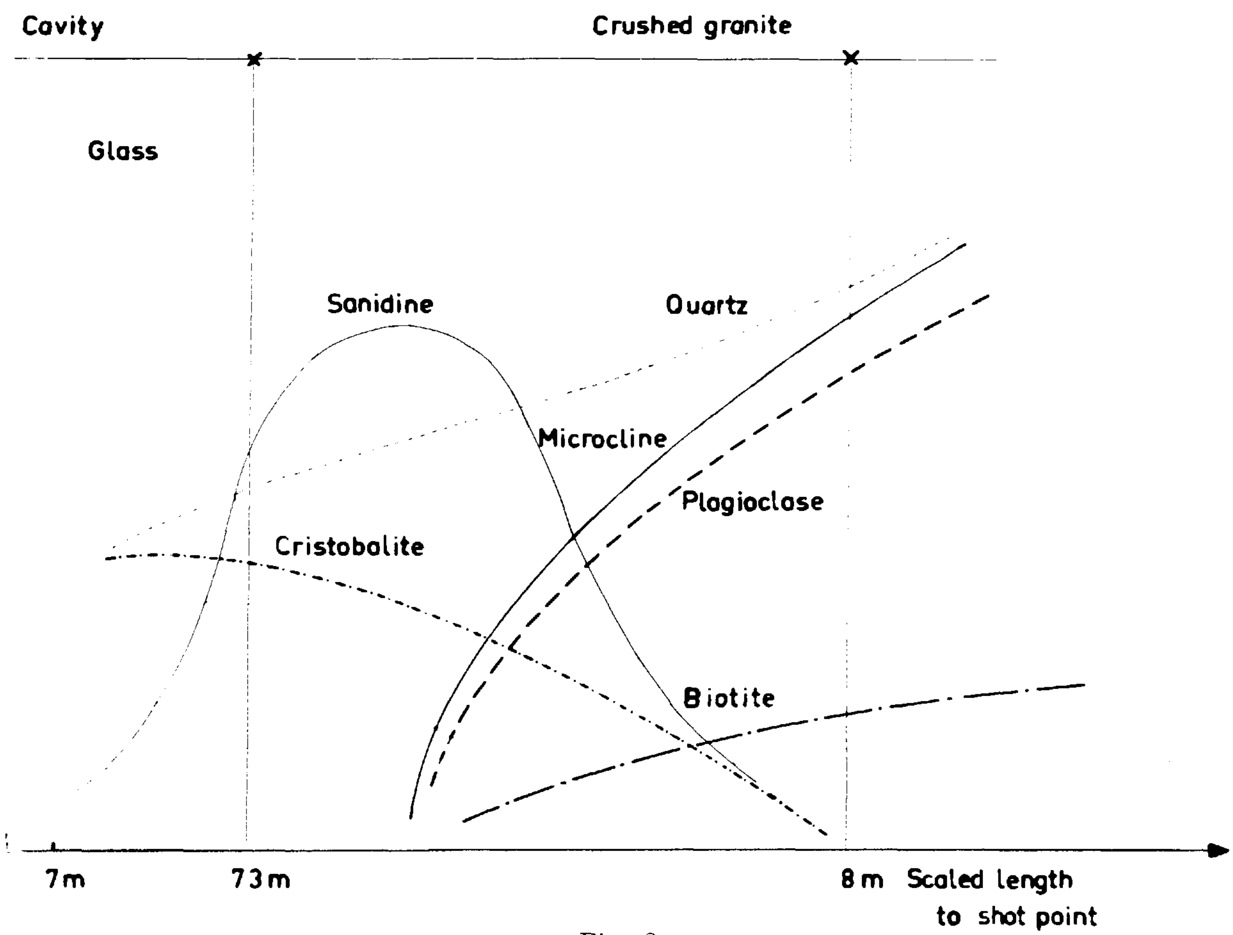


Fig. 8

The transformation pattern, in connection with the cavity boundary is typical of thermic effects. Shock effects are probably masked by them.

4.2.3 - Chemical study

In a parallel direction to the mineralogical analysis described above, granite samples have been studied by total chemical analysis. About one hundred chemical analysis were made on samples taken before explosion (see table 1). After shot, a first range of analysis were made on twenty-five samples recovered along the whole length of the explored areas. Figure 9 shows the results. There is no really significant change. But the survey of rocks bordering the cavity, is very interesting : samples can be divided in two parts. The white one is richer in silicium, the other one, which is created by the dark veinlets, has a higher rate in Al_2O_3, Fe_2O_3, MnO and K_2O. Thus, there is a kind of differenciation in this area.

The sanidine mineral which appears on the X-rays diagrams was analysed and this analysis shows that all the granite feldspars have newly crystallized creating a solid-solution potassium-sodium-calcium. There is also four point five per cent iron oxyde. This explains that sanidine did appear magnetic under mineral separation. But the parameters determined by X-rays show that the iron is not included in the lattice and may be in intergranulate state.

4.2.4 - Study by electron probe

The presence of a new mineral species as sanidine indicates a diffusion of the most volatile elements to reconstitue a new mineral. This induced us to try and find phenomena of element diffusion at microscope scale by observation with the electron probe. Using this instrument reveals that there is some iron oxyde in the cracks near the micas. Many analysis in the biotite specimens give large heterogeneity of iron, aluminium, silicium and potassium. But these changes can hardly be related to shock effect since the biotite of granite are already altering in the whole area. At the cavity boundary, for samples showing signs of a melting start, the electron probe still gives the mineral size. But in the same samples (fig. 10), some areas are clean whilst others show a more advanced stage of evolution. Potassium diffuses whilst iron, manganese or zirconium remain distinctly steady.

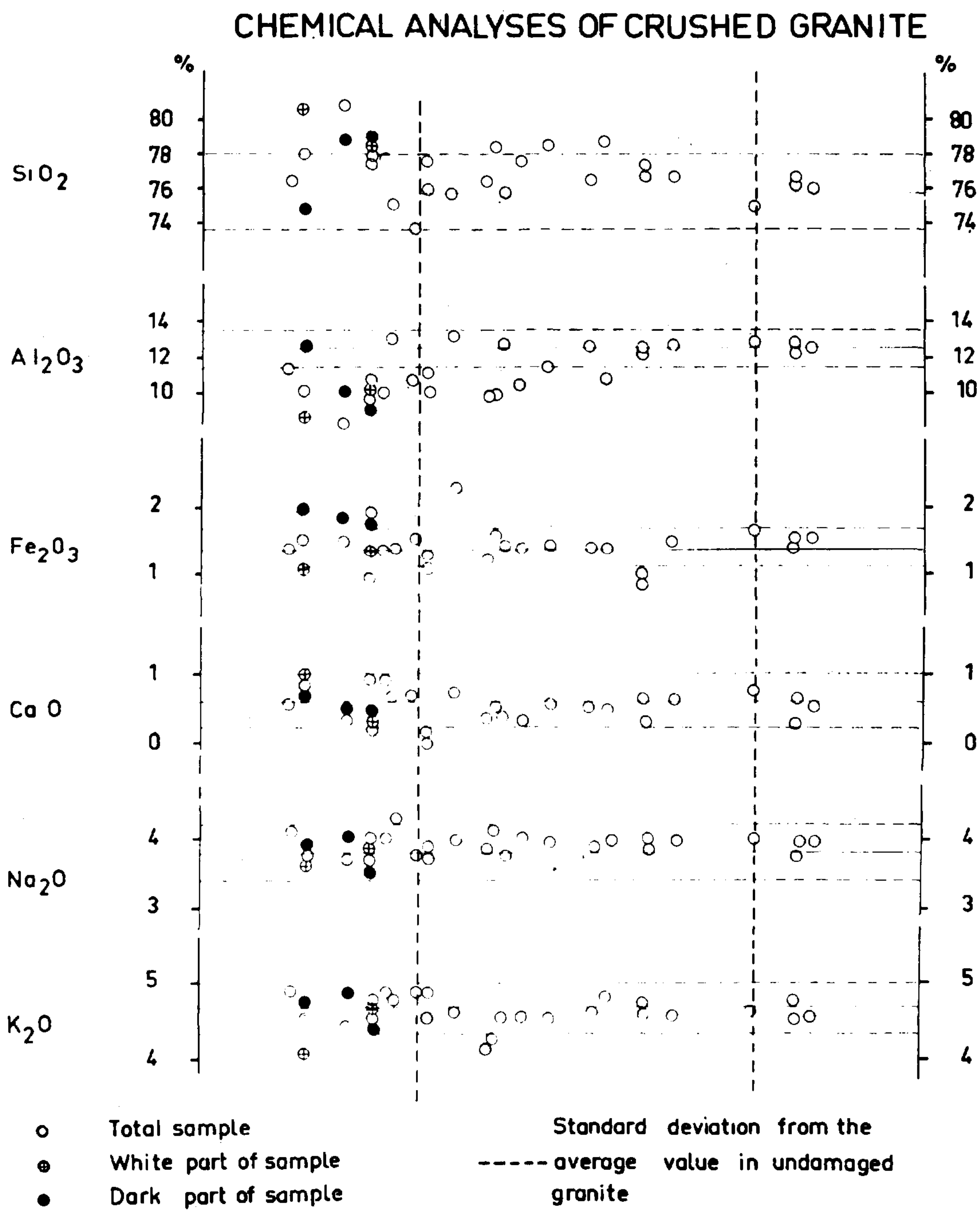

CHEMICAL ANALYSES OF CRUSHED GRANITE
%
%
80
78
76
74
14
12
10
2
1
1
0
4
3
5
4
SiO2
Al2O3
Fe2O3
Ca O
Na2O
K2O
Total sample
White part of sample
Dark part of sample
Standard deviation from the average value in undamaged granite

Fig. 9

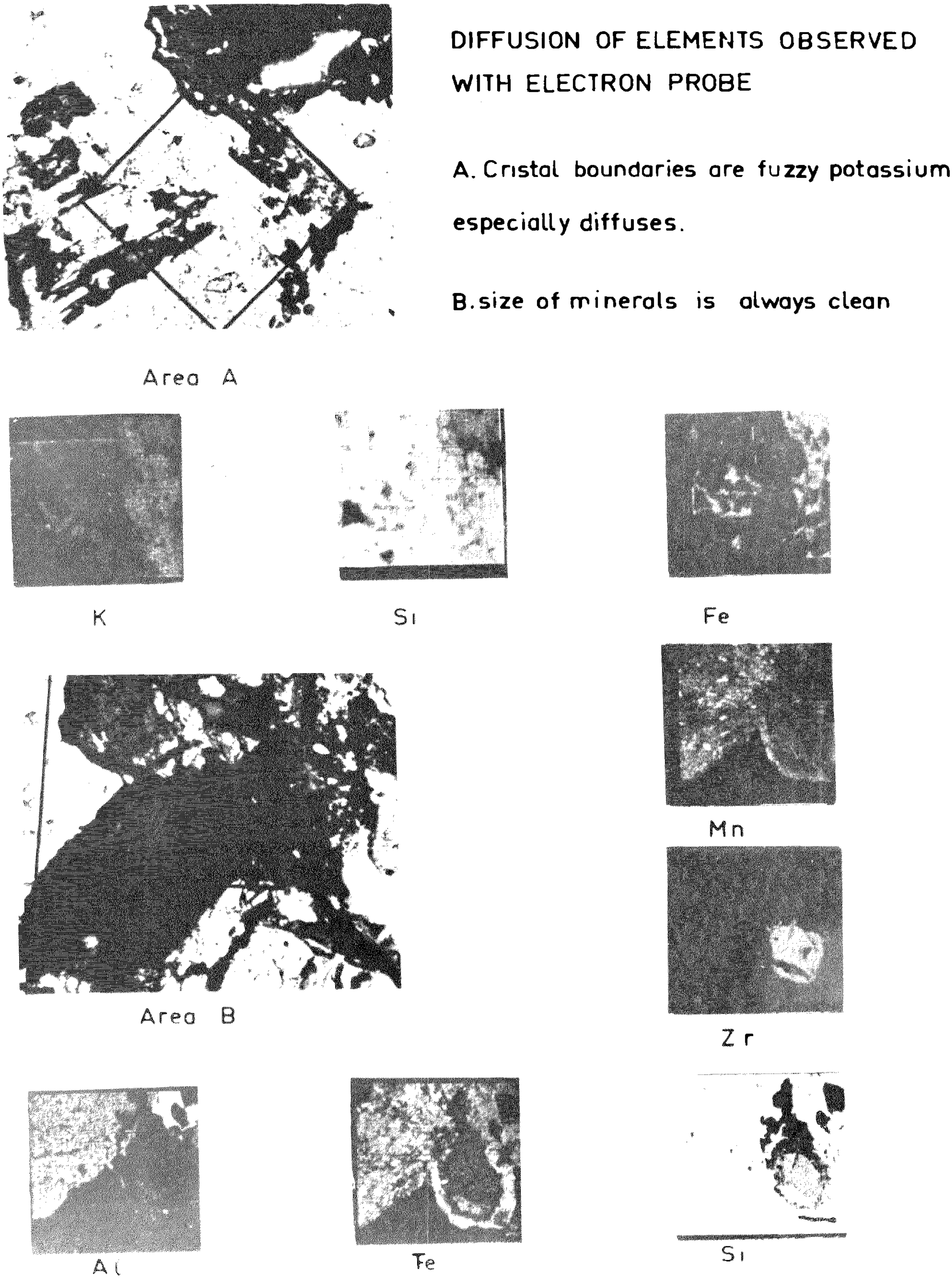

DIFFUSION OF ELEMENTS OBSERVED
WITH ELECTRON PROBE
A. Cristal boundaries are fuzzy potassium
especially diffuses.
B. size of minerals is always clean
Area A
K
Si
Fe
Mn
Area B
Zr
Al
Fe
Si

Fig. 10

TABLE 3

Comparison of different classifications of melted rocks

SHORT (1964)	RAWSON (1966)	FAURE (1966)
Type 1 (dense usually dark glass represents puddle accumulation)	1 - Predominant phase (accumulated puddle droplets and injection into cracks)	Type A (grey-green pumices and lavas
Type 5 (dense to vesicular melt injected into fractures)		Type B (beige to red-brown pumices).
Type 2 (light in color variably vesicular glass develops by super heat fusion)	2 - Border phase (interpreted as rep-presenting both rocks only partly melted by shock wave and melting by superheat	Type C (dark lavas)
Type 3 (globules, blebs smears along fracture)	3 - Gas leakage phase (along cracks in permeable regions 4 - Condensed vap-or phase (observed on the surface of rocks or other phases)	Type D (dark veinlets)
Type 4 (exclusive of craters shots).		

5 - CONCLUSIONS

The preceding results complete previously published data about the petrographic transformations in a granite under nuclear underground explosions. Account being taken of the different distribution of melted granite, temperature measurements are comparable in Nevada and in Hoggar. For the Shoal event, a six hundred degrees rocks puddle diffused the heat in the surrounding rocks (3).

Except for some particulars, the survey of melted products joins to the SHORT (4) and RAWSON (5) proposed classification after the Nevada test site nuclear explosions. The different rock patterns are in a fairly correct agreement save the radioactivity (table 3). However, the SHORT's type three and four are not commonly found in the Hoggar test site. The beige to red brown lavas belong to SHORT's type number five. One may wish to know whether there is a connection between RAWSON's phases three and four and the dark veinlets mentioned above.

In return, the distribution of melted products is clearly different on the two test sites (fig. 11). But calculation shows that most of these differences are due to the differences of cavity size and the respective amount of rubbles falling in the melt created by the shock wave.

The presence of low cristobalite (uncommon in the earth's natural materials, but found in the lunar samples collected by Apollo 11 (6) and sanidine and the diffusion of the elements in short length show the importance of thermic phenomena in rock tranformation by an underground nuclear explosion.

Finally, we hope these results will contribute to accurate explosion phenomenology. In this regard, the data about the position of lavas in the cavity chimney unity, appear different from the published figures. This may be important in connection with problems of engineering explosions : the lavas area is the radioactive products area. It may for instance have to be untouched in the case of possible mining applications.

The results also accurate the mineralogical and thermic effects of explosions. Thus, for example, the high pressure quartz polymorphes coesite and stishovite do not appear. This fact is probably in connection with the transformation into high temperature species as cristobalite. A similar process may bring the secondary transformation into graphite of diamond created by a shock wave.

COMPARISON OF PUDDLE POSITION FOR UNDERGROUND NUCLEAR EXPLOSIONS IN GRANITE (HOGGAR AND NEVADA TEST SITES)

Yield energy : 1 kt

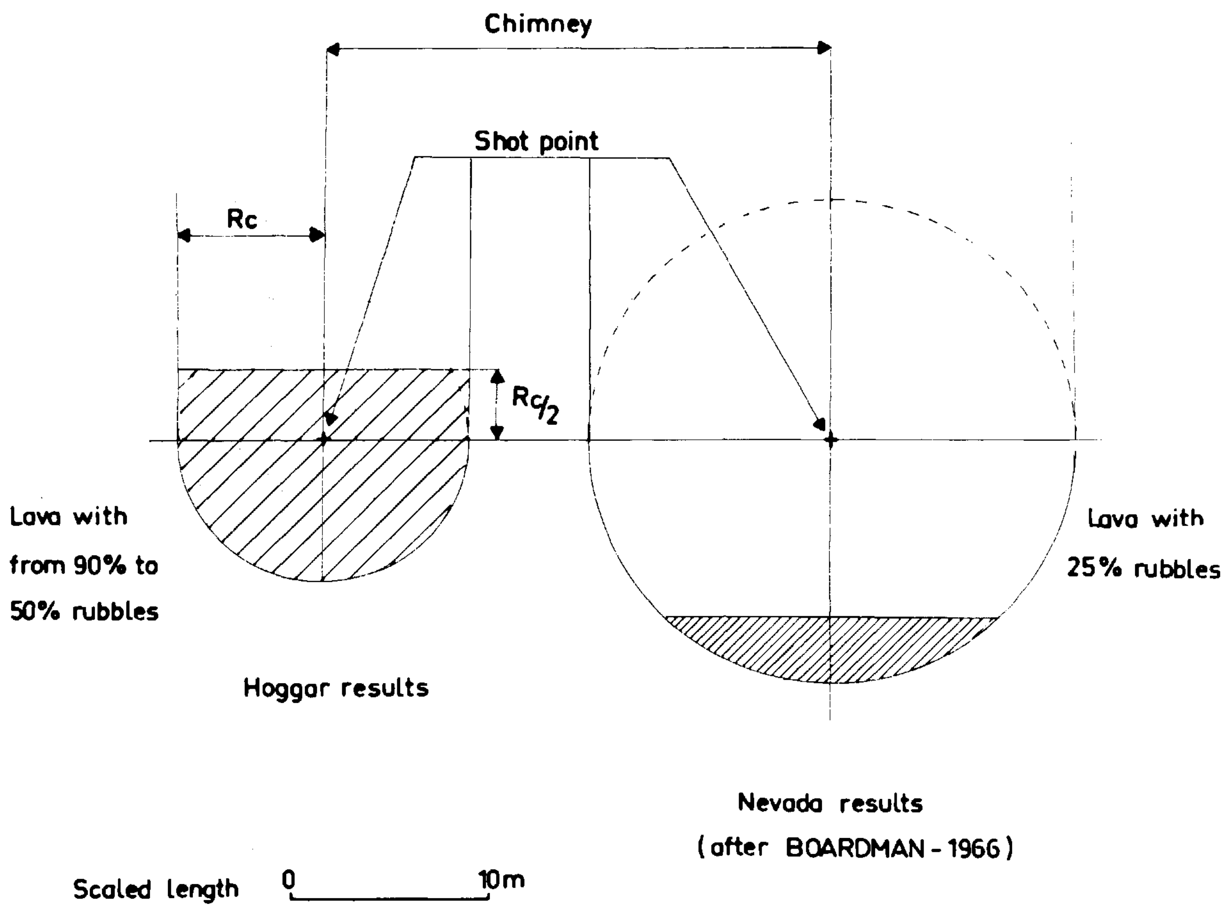


Fig. 11

6 - REFERENCES

(1) - Results from P. PERROUD (1965)
Centre d' Etudes Nucléaires de GRENOBLE.

(2) - Studies realized in collaboration with centre de Recherches Pétrographiques et Géochimiques de NANCY
Director : Professor M. ROUBAULT.

(3) - R. HECKMAN - Deposition of thermal energy by nuclear explosives.
California Univ. Livermore, Lawrence Radiation Lab.
Rept. - UCRL-7 801 (1964).

(4) - N. SHORT - Nuclear explosions craters, astroblemes and crypto-explosions structures.
California Univ. Livermore, Lawrence Radiation Lab.
Rept. - UCRL - 7 787 (1964).

(5) - D. RAWSON - Characteristics of glasses resulting from nuclear explosions in silicate rock.
Abstract in Shock metamorphism of natural materials
Proceedings of the first Conference held at NASA, Greenbelt (Maryland), April 1966.
Mono Book Corp. Baltimore - 1968.

(6) - The lunar Sample Preliminary Examination Team
Preliminary Examination of Lunar Samples from Apollo 11.
Sciences, 19-9-1969, Vol. 165, n° 3 899, pp. 1211-1227.