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EXPERIMENTAL STUDIES RELATING MINERALOGICAL AND PETROGRAPHIC FEATURES TO THE THERMAL PIERCING OF ROCKS

by

James A. Soles* and Lorant B. Geller**

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SYNOPSIS

The mineralogical relations, petrographic features and certain other physical properties of several classical rock types are compared with the results of laboratory scale jet-flame piercing tests on large samples of the rocks. The comparison has provided information which may be used to assess the potential usefulness of jet-flame rock drills in areas where the geology is known.

The compressive strength and specific heat of a rock cannot be used to predict its pierceability by a jet flame. Linear thermal expansion is an unreliable indicator of a rock's pierceability. Textural, structural and, particularly, mineralogical information, however, can be used to predict how a rock will respond to thermal shock. The rocks examined and their respective piercing characteristics are described.

Quartz, nepheline and dolomite favour the spalling process; thus, rocks of the granite, quartz-rich metamorphic, nepheline syenite and dolostone classes should be pierced easily. Micas and mafic minerals tend to reduce the efficiency of the spalling process. Certain textural relationships of minerals, such as graphic intergrowth, may favour disintegration of a rock. Structural weaknesses, soft materials, and schistosity in rocks retard the piercing process.

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ÉTUDES EXPÉRIMENTALES SUR LES CARACTÈRES MINÉRALOGIQUES ET PÉTROGRAPHIQUES DES ROCHES, PAR RAPPORT À LEUR PERCEMENT THERMIQUE

par

James A. Soles* et Lorant B. Geller**

RÉSUMÉ

Les auteurs comparent les rapports minéralogiques, les caractères pétrographiques et certaines autres propriétés physiques de plusieurs types ordinaires de roches, avec les résultats, obtenus en laboratoire, d'essais de percement à la torche, effectués sur de gros échantillons de roches. Ils en tirent des renseignements qui peuvent servir à évaluer l'utilité que pourraient avoir des perforatrices à jet de feu dans des terrains dont la géologie est connue.

La résistance à la compression et la chaleur spécifique d'une roche donnée ne permettent pas de prévoir si l'on peut la percer à l'aide du feu. Sa perçabilité n'est pas indiquée sûrement par la courbe de la dilatation sous l'influence de la chaleur. Les données sur la texture, la structure et surtout la minéralogie, peuvent cependant servir à prévoir comment une roche réagira à une violente attaque thermique. Les auteurs décrivent les roches étudiées et leurs caractéristiques respectives de percement.

Le quartz, la néphéline et la dolomie se prêtent bien à l'effritement; donc, le granit, les roches métamorphiques riches en quartz, la syénite à néphéline et les roches fortement dolomitiques devraient tous se percer facilement. Les micas et les minéraux ferromagnésiens tendent à réduire l'efficacité du procédé de l'effritement. Certaines rélations texturales des minéraux, tel l'enchevêtrement graphique, peuvent favoriser la désagrégation des roches. Les faiblesses structurales, les matériaux tendres et la schistosité des roches ont pour effet de ralentir le percement des roches.

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INTRODUCTION

Thermal piercing of rocks has become popular in the last decade because certain rock types are drilled more economically and rapidly with jet-flame drills than with conventional equipment.

The mechanics of rock spalling caused by thermal shock is but poorly understood. In an attempt to determine the processes involved, Mr. W.A. Duncan of the Linde Gases Division of Union Carbide Canada Limited, Toronto, initiated a joint research project with the Mines Branch of the Department of Mines and Technical Surveys at Ottawa in 1958.

A primary objective of the program was to determine which physical and chemical properties of rocks affect their susceptibility to disintegration by a jet flame, in particular:

1) specific heat; 2) mechanical strength; 3) linear thermal expansion;
4) texture; 5) structure; 6) mineralogy.

The rocks were selected to provide variation in these properties. The influence of each feature or property was judged according to the results of piercing tests which were made on samples of the rocks chosen.

MATERIALS

Standard commercial testing equipment was used whenever possible in this investigation, but special apparatus was custom built when necessary. Various commercial hydraulic presses were used to obtain information on rock strength; specific heat values of rock specimens were determined in a special large-volume calorimeter; and linear thermal expansion was measured directly on a heating apparatus designed for the purpose. The jet-flame blowpipe used was an experimental hand model modified by one of the authors (L.B.G.) from a prototype supplied by Union Carbide Canada Ltd., Linde Gases Division, shown operating in Figure 1.

Twenty-two rock types were examined and tested in the investigation. They comprised three main groups, shown in Table 1: (1) megascopically homogeneous igneous rocks of various compositions and textures; (2) quartzose rocks which differed texturally or structurally as well as compositionally; and (3) carbonate rocks which differed texturally and compositionally. Two silica bricks were also subjected to certain tests.

The samples of rock used for piercing tests were large, having a minimum face area of 8 square feet to eliminate possible boundary effects. Specimens used to obtain detailed petrographic information and other mechanical or thermal properties were cut from fragments of the large samples.

EXPERIMENTAL PROCEDURES AND CONSIDERATIONS

The most important measurement to be obtained in the investigation was, of course, the rate at which a rock would be pierced by a high-temperature jet flame. The 'ideal' experimental conditions imposed would perhaps give misleading results—primarily because the scaled-down experimental blowpipe does not produce the same thermal conditions as do field models, and secondarily because natural environmental conditions, always variable, could not be duplicated in these tests. We assumed, however, that the inherent properties of rocks themselves should control the rate of thermal piercing far more than environmental changes; hence, the experimental tests should indicate, in relative terms at least, what could be expected from a thermal drill. Next, we considered that the experimental rate of excavation would indicate the pierceability of a rock somewhat more accurately than would the rate of linear advance of the hole; therefore, the pierceability ratings were established by measuring the amount of rock dislodged from the samples in a given length of time under specified test conditions.

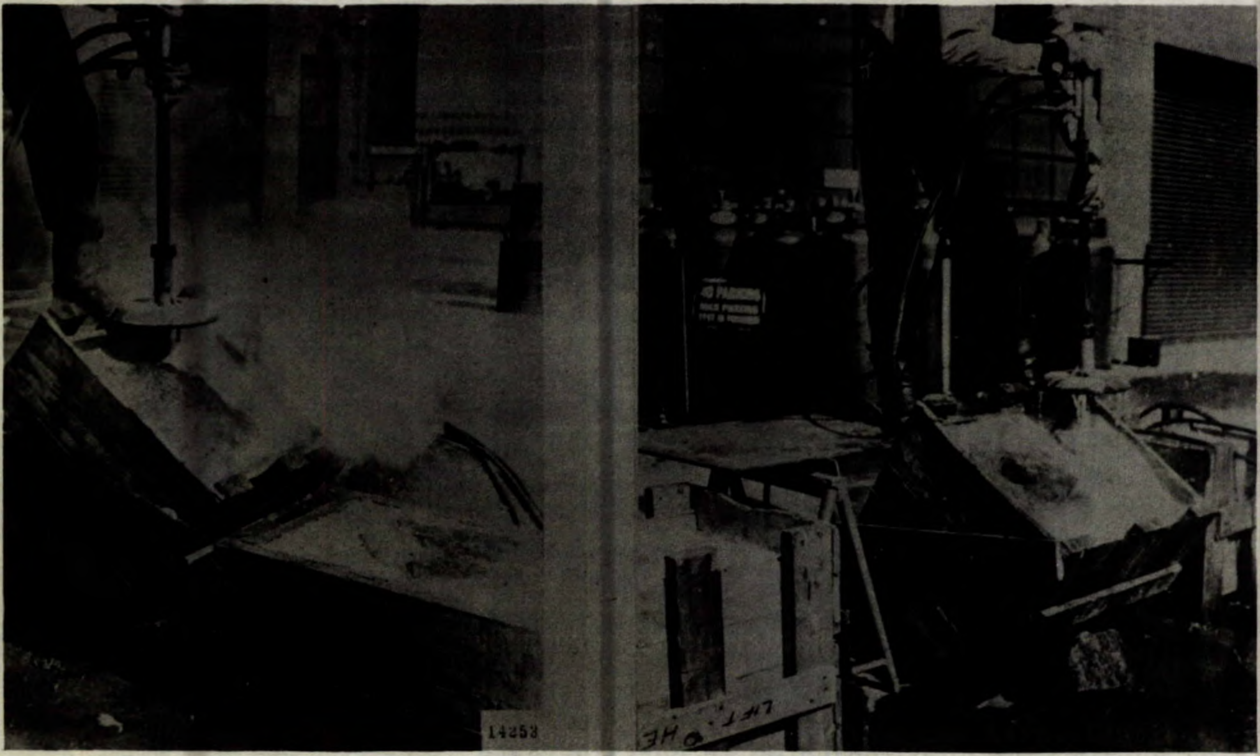

Figure 1. Experimental jet-flame apparatus in operation.
Left - rapid piercing with effective spalling.
Right - slow piercing with fusion.
(Courtesy of Union Carbide Canada Ltd.)

Dependable strength properties are difficult to obtain on rocks because of structural heterogeneities, particularly planes of weakness. To examine the influence of rock strength on pierceability, however, the compressive, tensile and shear strengths were obtained on eight of these rocks; the specimens were carefully selected to avoid visible fractures, and in many cases were cut in two directions perpendicular to each other.

The linear thermal expansion of a rock is likewise influenced greatly by structural variation, but mineralogical change rather than planes of weakness is the dominant factor to be considered. A mica schist, for example, will expand more perpendicular to the schistosity than parallel to it. Thermal expansion tests were therefore made on several specimens when compositional differences were observed in a rock, and the values were averaged to plot the expansion curves. The total expansion of each specimen was measured up to 1000°C.

Mean specific heat values were obtained for the temperature range 26° to 625°C. As the mineralogy of a specimen governs its specific heat, great care was exercised when selecting specimens from heterogeneous rocks, in order to obtain fair representation. The results given are the average of three tests on each rock type. The deviation from the mean was less than 1 per cent in every test.

Detailed petrographic work supported all other studies. The rocks were selected to represent certain petrographic groups having distinctive structures, textures or compositions, so that the influence of these features on pierceability could be determined. Thin sections were cut and selectively stained for microscopic examination. Accurate mineralogical compositions were obtained by counting grains, the textural relations of minerals were studied, and megascopic and microscopic structures were noted.

TEST RESULTS AND DISCUSSION

Tabulation of Test Results

A close examination of Table 1 will show that rock composition was the controlling factor in tabulating the results of tests. The igneous rocks are listed roughly according to decreasing quartz content and increasing Ca-Mg-Fe minerals content, the first six being quartz-rich and the remainder quartz-poor. The miscellaneous quartzose rocks are also listed according to decreasing quartz content and increasing Ca-Mg-Fe content (silica bricks excepted). Carbonate rocks are tabled according to decreasing dolomite content, or decreasing grain size.

Results of Piercing Tests

The piercing ratings given are arbitrary values based upon the amount of rock displaced from the test hole in a given period of time. They provide certain information as to the nature of the products and the piercing characteristics, as follows:

TABLE I

Composition, Classification, and Piercing Rating of Rocks Used in Thermal Piercing Investigation

Piercing Rating	Sample No.	Rock Class	Mineral Composition, Per Cent Qtz	K-Felds	Na-Felds	Ca-Felds	Ferromagnesians & Miscellaneous	
					1. Igneous Rocks			
10	M-190	Rhyolite	23	52	21	--	3 Magnetite	--
9	M-194	Granite	34	31	31	--	3 Biotite	--
8	M-209	Granite	33	29	23	--	10 Biotite	--
5	M-195	Albite Granite	29	21	45	--	3 Biotite	2 Muscovite
7	M-210	Qtz Monzonite	27	20	--	42(An_{28})	10 Biotite	1 Muscovite
6	M-208	Granodiorite	21	4	--	51(An_{30})	12 Hbde; 9 Biot; 3 Epidote + Sphene	
5	M-192	Nordmarkite	9	73(Perthite)	8	--	7 Hbde; 2 Aug; 1 Mag + Hematite	
4	M-191	Hbde Syenite		69(Perthite)	17	--	9 Hornblende; 2 Biot; 3 Mag	
2	M-193	Anorthosite	--	1	--	97(An_{50})	1 Augite; 1 Magnetite	
2	M-178	Gabbro (Diabase)	←--- 12 (Graphic) ---→			46(An_{50})	24 Aug; 11 Hbde, Biot; 7 Mag	
1	M-189	Basalt (Saussurite)	← - - - - - - 25 - - - - - - - - →				40 Epid; 20 Aug; 10 Chlorite; 5 Mag	
9	M-188	Nepheline Syenite	--	23	52	--	2 Magnetite	23 Nepheline
					2. Miscellaneous Quartzose Rocks			
10	M-179	Quartz	100	--	--	--	--	--
10	M-176	Sandstone	92	8	--	--	--	--
9	M-207	Quartzite	93	--	--	--	--	7 Muscovite
6	M-200	'Taconite'	60	--	--	--	23 Grunerite	17 Magnetite
5	M-199	Hbde-Qtz Gneiss	25 (Incl. Feldspar ?)				70 Hornblende	5 Calcite
10	'A'	Silica Brick	--	--	--	--	Cristobalite + minor Tridymite	
0	'B'	Silica Brick	--	--	--	--	" + " "	
					3. Carbonate Rocks			
			Quartz		Calcite	Dolomite	Others	
10	M-168	Dolostone (Recryst.)	--		--	98	2 Tremolite	
10	M-186	Dolostone	--		--	80	1 Sulphides, Oxides; 19 Voids	
3	M-187	Dolomitic Limestone	--		72	27	1 Dark impurities	
0	M-185	Limestone (Recryst.)	<1		88	10	1 Diopside; 1 Graphite	
0	M-184	Limestone	≪1		94	4	2 Clay, impurities	

Hbde: Hornblende Biot: Biotite Aug: Augite Mag: Magnetite

TABLE 2

Texture, Structure, Strength, Linear Thermal Expansion, and Mean Specific Heat of Rocks Used in Piercing Investigation

Piercing Rating	Sample No.	Rock Class	Texture	Gross Structure	Ult. Compr. Str. (psi)	Lin. Thermal Exp'n, 573°C	Mn. Sp. Ht. Cal/g/°C
				1. Igneous Rocks			
10	M-190	Rhyolite	F-gr, allotriomorphic	Homogeneous	--	1.1 %	0.238
9	M-194	Granite	M-gr, hypidiomorphic	"	--	1.2	0.238
8	M-209	Granite	M-gr, "	Coarsely gneissic	--	1.2	0.238
5	M-195	Albite Granite	M-gr, "	Homogeneous	--	1.1	0.241
7	M-210	Qtz Monzonite	C-gr, panidiomorphic	"	21-23,000	1.2	0.240
6	M-208	Granodiorite	M-gr, hypidiomorphic	"	--	1.4	0.239
5	M-192	Nordmarkite	C-gr, panidiomorphic	"	--	0.9	0.231
4	M-191	Hbde Syenite	M-gr, hypidiomorphic	"	26-28,000	0.77	0.229
2	M-193	Anorthosite	C-gr, "	"	22-25,000	0.8	0.234
2	M-178	Gabbro (Diabase)	M-gr, diabasic-hypidio.	"	49-50,000	0.65	0.226
1	M-189	Basalt (Saussur.)	F-gr, altered	Irregular banding	--	0.48	0.236
9	M-188	Neph. Syenite	M-gr, hypidiomorphic	Homogeneous	31-33,000	1.0	0.237
				2. Miscellaneous Quartzose Rocks			
10	M-179	Quartz	Coarse crystals	Homogeneous	--	1.25	0.250
10	M-176	Sandstone	F-gr, friable	Slight banding	--	1.3	0.246
9	M-207	Quartzite	F-gr, strained crystals	Local foliation	50-58,000	1.2	0.249
6	M-200	'Taconite'	M-gr, metamorphic	Banded, gneissic	--	1.0 +	0.228
5	M-199	Hbde-Qtz Gneiss	M-gr, metamorphic	" "	--	0.7	0.231
10	'A'	Silica Brick	Porous	Homogeneous	1280	--	
0	'B'	Silica Brick	"	"	600	--	
				3. Carbonate Rocks			
10	M-168	Dolostone	Coarse crystals	Homogeneous	--	1.1	0.253
10	M-186	Dolostone	M-gr, porous	Large voids	15-16,000	1.0	0.251
3	M-187	Dolomitic Ls.	F-gr, fossiliferous	Homog. (exc. fossils)	--	1.2	0.243
0	M-185	Limestone	Coarse crystals	Homogeneous	--	0.55	0.241
0.	M-184	Limestone	F-gr, sedimentary	Local banding	26-31,000	0.74	0.241

10-8: Excellent
8-6: Good
6-4: Fair
4-0: Poor
0: Unpierceable

F-gr: fine-grained (<1 mm) M-gr: medium-grained (1-5 mm) C-gr: coarse-grained (>5 mm)

Pierceability Rating	Features
10-8 Excellent	Clean spalls; continuous, rapid piercing
8-6 Good	Evident fusion; continuous, slower piercing
6-4 Fair	Abundant fusion; slow piercing, intermittent blockage
4-1 Poor	Abundant fusion; frequent blockage
0 Non-piercing	Does not spall; calcines or melts

Influence of Specific Rock Properties on Pierceability

Specific Heat

The mean specific heat values of the rocks between 26° and 625°C bear little relation to their pierceabilities (Table 2). The variation in specific heat is small, even between totally different rocks; therefore specific heat is unsuitable as a parameter for predicting a rock's reaction to thermal shock.

Mechanical Strength

The strength of a rock also does not seem to reflect its tendency to spall under the influence of a jet flame. Tensile and shear strengths ranged widely on different specimens of the same rock; therefore a reliable datum could not be established for a comparison, and the test results have not been included. Compressive strengths were fairly reproducible (Table 2), but were inconsistent with the piercing ratings of the 8 rocks tested; for example, the rock pairs M-207 and M-178, M-184 and M-188, and M-193 and M-210 compare favourably in compressive strengths, but have entirely dissimilar piercing characteristics. The comparison of data from tests on these few rocks does not indicate that compressive strength by itself can be used to predict the pierceability of rocks.

Linear Thermal Expansion

The total per cent linear expansion of the rocks at 573°C are given in Table 2. This temperature, the inversion temperature of quartz, was chosen because the expansion rates of different rock types begin to vary greatly at higher temperatures, and a comparison of results with piercing ratings becomes less meaningful. The averaged thermal elongation curves, included in Figure 2, reveal this clearly; the variations often reflect mineralogy, or reactions and mineral phase changes caused by heating certain minerals. An abrupt levelling of an expansion curve around 600°C invariably indicates quartz; carbonate rocks often shrink after 900°C, or earlier if dolomite is present; and a high biotite content causes a high expansion rate after 650°C.

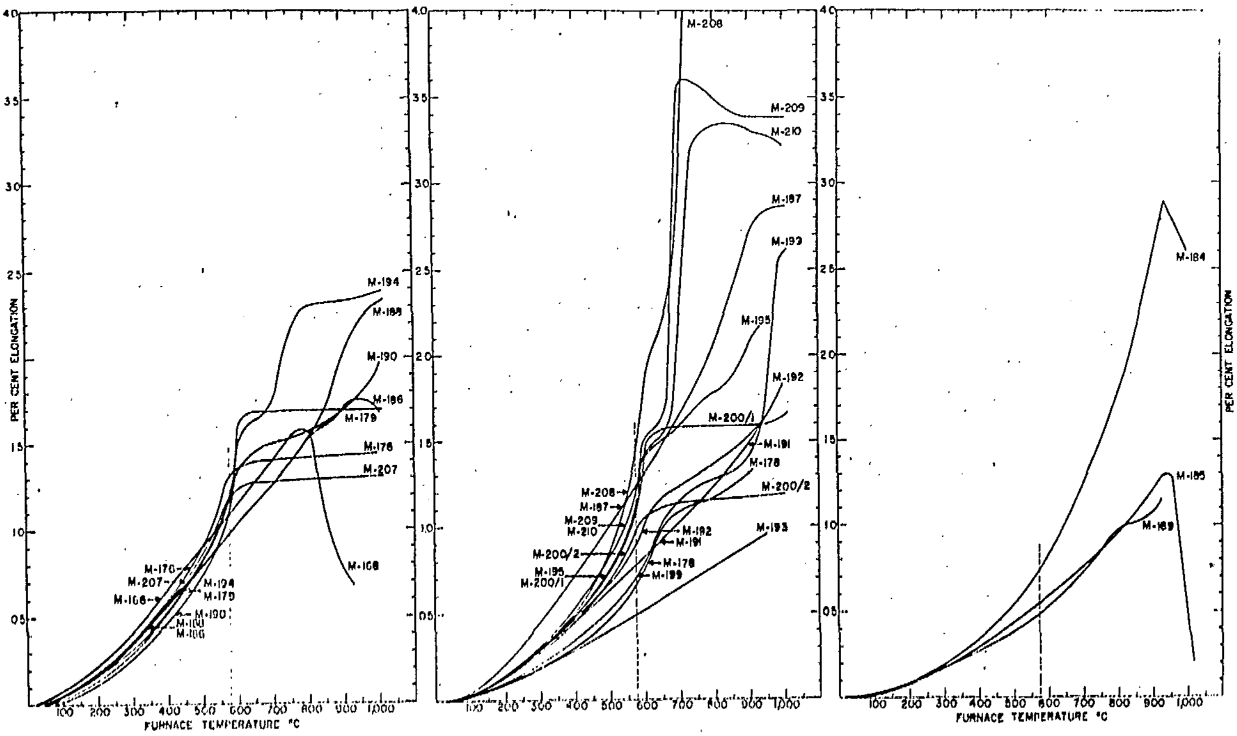

Figure 2. Linear thermal expansion curves of different rocks.
Left - rocks of 'excellent' pierceability.
Centre - rocks of 'good' to 'fair' pierceability.
Right - rocks of 'poor' pierceability or 'non-pierceable' rocks.

The average per cent linear thermal expansion of a rock at 573°C could perhaps be used to indicate whether or not it can be pierced by thermal means. Rocks having thermal expansions of less than 0.75% will generally be pierced with difficulty, while those expanding more than 1% will mostly be pierced easily; M-199 and M-187 are exceptions. Thermal elongation will not assist, however, in deciding whether a rock will be pierced rapidly or only moderately well, a difference which should be known when estimating costs of drilling.

Critical Temperature Parameter

Manson and Smith(1) have demonstrated the dependence of the thermal shock resistance of ceramic discs on the temperature at which the thermal stress at the surface is equal to the fracture strength. An analogous critical temperature parameter can be calculated for the case of spalling by equating the expression for the surface thermal stress given by Gray(3) to the compressive strength. The critical temperature parameter in this case is:

$$T_c = \frac{P_u(1 - \nu)}{E \alpha},$$

where

P_u = ultimate compressive strength
E = Young's modulus
ν = Poisson's ratio, and
α = coefficient of linear thermal expansion

T_c was calculated for eight rock types using values of P_u from Table 2, of α derived from Figure 2, and of E and ν given by Larocque(4). No definite dependence of piercing rating on T_c was found.

Rock Texture

The texture of a rock--that is, the size, form and relationship of the constituent minerals--appears to influence its pierceability only to a minor extent. The massive quartz rock M-179, for example, is pierced as readily as the fine-grained, partly indurated quartz sandstone M-176, which might be expected to disintegrate more easily because of yielding along grain boundaries. Inversely, the texturally similar carbonate rocks M-168 and M-185 have totally dissimilar piercing characteristics. The rhyolite M-190 is pierced slightly more easily than its coarser-grained, more siliceous counterparts M-194 and M-209; this may be attributed to its complex, graphic quartz-feldspar intergrowth. It is likely that graphic or perthitic intergrowths in igneous rocks favour disintegration to some extent because intragranular rupture from differential thermal stresses generated by heating would initiate spalling; however, the effect could be easily nullified by a mineralogical change (compare M-191 with M-192). Relatively plastic material (e.g. soft alteration products) at grain boundaries will yield rather than transmit stresses, and inhibit spalling.

Rock Structure

Most of the igneous rocks tested were structurally homogeneous, and the influence of structure on pierceability could not be determined from them. Field tests, however, show conclusively that rock structures strongly influence piercing; for example, holes change direction abruptly where slip and foliation planes are encountered. Quartzite M-207 may be cited as a special example in which piercing difficulties arose because of its structural character. Intensely deformed and internally stressed, it commonly shattered under the jet flame, producing megascopic and microscopic fissures which retarded piercing; the schistosity associated with muscovite bands also decreased the piercing rate locally.

Structure in a rock is usually revealed by preferred orientation of minerals, a change in mineralogy, a change in grain size, and shear or fracture surfaces. Most often, the mineralogical changes accompanying structural variation in rocks will have the greatest influence on their thermal pierceability.

Rock Composition

It is well known that certain rocks are more amenable to thermal disintegration than others. The differences are usually explained by compositional differences, and indeed the pierceability of a rock may often be predicted from a knowledge of its mineralogy. Table 1 reveals the profound influence that mineralogical composition exerts on rock pierceability.

Quartz is distinctly favourable to the piercing process, and rocks of the granite and quartz-rich metamorphic classes usually are pierced readily. The increase in volume effected by the inversion of α-quartz to β-quartz at 573°C has been considered by many investigators to be responsible for much of the efficiency in spalling of quartz-rich rocks. This may be questioned, as petrographic study suggests that the surface temperature of the spalling rock is below the inversion temperature of quartz*. Perhaps the high resistance of quartz to deformation is a major cause of failure. The piercing rating of a rock does not vary in direct proportion to its quartz content, and other factors—chiefly texture and associated minerals—must be considered even when quartz is abundant. M-190, for example, has a lower quartz content than M-194, yet it was pierced more rapidly; apparently its complex graphic texture promoted spalling. The low pierceability rating of albite granite (M-195) is distinctly anomalous relative to that of the other granites; no reason for this is evident.

Nepheline is almost as effective as quartz in promoting spalling, for a reason not yet understood. As an example, the nepheline syenite M-188 was pierced as readily as M-194, a near counterpart in the granite class. No phase change, with attendant volume increase, occurs in nepheline to generate stresses; however, the linear thermal expansion of M-188 below 500°C is noticeably high. Further studies of the thermal disintegration of the feldspathoid rocks should be undertaken.

Micas inhibit spalling, a fact which is quite evident from the protrusion of mica books on the pebbly surface of a pierced biotite granite (e.g. M-209), and from the abrupt decrease of piercing rate in schistose rocks (e.g. M-207) when a micaceous layer is reached.

An increasing content of mafic (Mg,Fe) minerals tends to reduce the efficiency of the piercing process. This was most evident from tests on M-199 and M-200, where progressively greater amounts of grunerite, hornblende, or magnetite progressively lowered the rate of penetration. The effect is less apparent with the igneous rocks, but all of those having a high proportion of mafic minerals were pierced with some difficulty; melting was common. Rocks having a high K-feldspar/plagioclase ratio appear to be pierced more easily than those with a low ratio, e.g., M-191 vs. M-193. Sodic plagioclase seems to inhibit piercing more than calcic plagioclase (M-195 vs. M-210), but the former rock has an anomalously low piercing rate for its quartz content. Further tests should be carried out on rocks which vary only in the

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*It may also be noted that for 8 rocks the calculated values of the critical temperature parameter T_c (see page 6) were all below 573°C, the average being 250°C.

composition and degree of alteration of their feldspars. Collectively, the more silicic rocks are pierced more easily than the more basic (Ca-Mg-Fe-rich) rocks.

Carbonate rocks show the greatest extremes in their piercing characteristics. High-calcite limestones are not pierceable, whereas high-dolomite rocks are pierced with ease; the rate of piercing is dependent on the proportion of dolomite in the rock, and those rocks with less than 30% are pierced with difficulty. Perhaps the structural changes which accompany the early 750° stage of dolomite decomposition as opposed to the 850°C stage of calcite decomposition* favour the spalling, but it is doubtful that such temperatures are reached when spalling is rapid except for calcination of small fragments; there is no petrographic evidence of inversion, and no significant decrease in dolomite content according to differential thermal analysis of spalls from dolostone.

The two silica bricks require special mention. Although manufactured from similar quartz sand under the same conditions, they have completely opposite piercing characteristics. X-ray and thin section study showed that both bricks consisted of cristobalite with minor tridymite in similar proportions and textural relationships. The only visible difference is that brick 'B' is whiter. Its strength is less than that of brick 'A' however, suggesting there is a slightly weaker bonding of the grains. It is suspected that the thermal stresses are transmitted from grain to grain in the more resistant brick 'A', whereas intergranular stress relief occurs in brick 'B'.

The Spalling Process

Rocks are pierced thermally in two ways: by melting, which is a slow, costly process; and by spalling, a rapid, piecemeal disintegration process apparently initiated by localized stresses resulting from heating.

A careful study was made of the fragments ejected during the piercing tests, and certain distinctive features were noted which could be helpful in understanding the spalling process. The fragments ranged from large 3-cm flakes to dust, the latter predominating deeper in a hole. Regardless of rock type or hole depth, the flakes, when formed, were similar: thin, curved, occasionally beveled on the edges, predominantly polycrystalline (excepting spalls from very coarse-grained rocks), and multi-mineralic if the rock contained different minerals. The rupture surface of a typical spall crossed all brittle minerals, following cleavage planes or weak grain boundaries when their attitudes were close to that of the rupture surface. Most of these features are illustrated in Figure 3. The locus of potential rupture within a rock for the present test conditions evidently is a plane extending as far as 1 to 3 mm below the surface facing the jet flame; the stresses created locally along this plane by heating the rock surface appear to be sufficiently great to break the crystals of most mineral species, when the heat flux is high and the heated surface is confined.

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*Shown by differential thermal and thermogravimetric analyses.

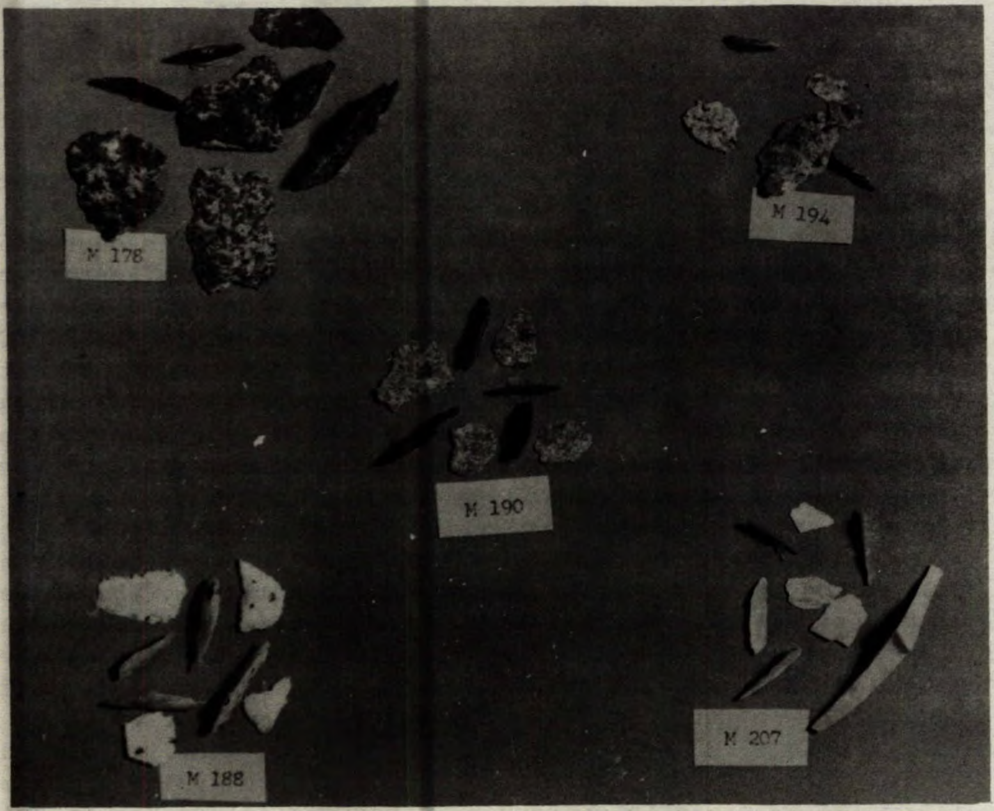

Figure 3. Spall products from the piercing of different rocks. Note the thin, lenslike, multicrystalline flakes.

The spalling of readily pierceable rocks, such as M-194, takes place at a relatively low surface temperature, apparently below 573°C for quartzose rocks. When particles spall continuously from the freshly exposed face, the temperature below the breaking surface is little higher than that of the unheated rock. The spalls themselves at the instant of breaking are usually free of melted particles, even though the temperature of the flame greatly exceeds their melting point. The linear expansion curves indicate that rocks with a high expansion coefficient below about 600°C are pierced more readily than rocks with a low coefficient; a high expansion coefficient above 650°C does not appear to produce a high rate of piercing. Rock composition, texture, or structure influence the stress conditions at the face, and the temperature may rise to the point where spalling is inhibited and fusion begins.

The results of mathematical studies of thermal disintegration of rocks and other solids have been published by several authors(2), and the theory of thermal stresses has been reviewed by Gray(3) in relation to the present experimental observations. The general nature of the stresses involved is understood, but detailed knowledge of the exact mechanism by which a spall is formed must await further experimental studies using high speed photography and other techniques. At the present time, the evidence suggests that a spall is initiated at the outer surface of the rock, either at an irregularity or where an inclined fracture has been formed by high thermal stresses. This initial crack permits stresses to develop approximately parallel to the surface, and a flake-like spall forms by propagation of the fracture along a plane of potential rupture. Cross-fractures, weak zones, or deformable materials terminate the spalling process. The thickness of a spall would be partly controlled by the temperature gradient, a steep gradient causing a thin spall.

The present series of tests investigated only one type of thermal failure, namely spalling of rocks under the influence of a sonic velocity jet flame. It is evident that the spalling characteristics of a rock for such an environment cannot be predicted from any single physical rock property measurement. Further work, particularly on rock strength measurements at elevated temperatures and on thermal diffusivity measurements, is required to establish whether a grouping of parameters such as $\frac{\sigma_f}{E\alpha}$ and K* as suggested by Manson and Smith may provide information for predicting spallability. The fact that most rock properties vary with rising temperatures, and that these changes cannot usually be reversed by lowering the temperatures, will also have to be considered. Finally, more data on the thermal expansion and strength of specific minerals are greatly needed; the reason for one mineral favouring and another inhibiting spalling may be explainable with this information.

No theoretical curve will likely be produced to indicate the pierceability of rocks, mostly for the reason that heterogeneities always exist in rocks and therefore no single curve is applicable. A petrographic study would be necessary, in any case, to provide data for the application of a curve. The petrographic information alone would indicate the pierceability to be expected.

SUMMARY

Linear thermal expansion, mechanical strength, specific heat values, and petrographic data were obtained on many different types of rock so that the influence of each on the pierceability of rocks by a high-temperature jet flame could be assessed. The different test results were compared with experimental piercing rates obtained on the rocks, and the following conclusions were reached:

(1) The specific heat or ambient temperature strength of a rock cannot be used alone to determine whether or not it will spall under the influence of thermal shock.

(2) Rocks having linear thermal expansion of less than 0.75% at 573°C will generally be pierced with difficulty, while those expanding more than 1% will mostly be pierced readily. Thermal expansion will not predict, however, whether a rock will be pierced rapidly or only moderately well.

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* σ_f = Fracture strength.
K = Thermal conductivity.

(3) The texture of a rock does not influence greatly the rate at which it will be pierced. Graphic and perthitic intergrowths of minerals appear to promote spalling to some extent in igneous rocks. Intermittent bonding of grains in quartzites evidently favours their disintegration, but the intergranular bonds must be sufficiently strong to transmit stresses. Lack of intergranular cohesion inhibits spalling because the energy required to cause rupture is dissipated.

(4) The influence of rock structure on pierceability may be great. For example, slip and foliation planes retard piercing. Highly deformed rocks may rupture extensively under thermal shock, and the cracks formed will reduce the piercing rate. Mineralogical changes must be treated independently when assessing the influence of structure on pierceability.

(5) Mineralogical composition affects the rate of piercing of rocks more than any other factor. A high quartz or nepheline content favours piercing; micas inhibit spalling; mafic (Mg,Fe) minerals reduce the rate of piercing; rocks containing K-feldspars appear to be pierced more easily than rocks containing Na,Ca-feldspars; and carbonate rocks are not pierced unless dolomite is present in excess of 30 per cent. Soft, pliable minerals relieve stresses and prevent spalling.

(6) Different types of rocks spall in a similar fashion, producing thin, curved, polycrystalline flakes whose rupture surfaces cross all brittle mineral species. The locus of potential rupture within a rock evidently is a plane lying 1 to 3 mm below the surface facing the jet flame; the differential stresses developed locally along this plane appear to be sufficiently great to break the crystals of most minerals.

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