MELTING OF GRANITE UNDER EFFECTIVE CONFINING PRESSURE

by

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ABSTRACT

Preliminary experiments, concerned with the shape and location of the first liquid to form when Westerly granite is melted in the presence of water, have been carried out on solid granite cores under effective confining pressures of from ½ to 1 kilobar. Thin-section examination of the partially melted rock shows that the liquid is localized in thin sheets, predominately along quartz-quartz, quartz-feldspar, and feldspar-feldspar boundaries. These observations are important when considering the effect that partial melting in the crust will have on the mechanical properties of rock such as granite.

INTRODUCTION

Triaxial compression experiments using high confining pressure have been done by Griggs et al. [1960] and others in an attempt to duplicate conditions under which rocks are deformed in the earth. However, these experiments have been carried out either at room temperature or at temperatures below the melting point of the rock being tested. The effect of partial melting on the strength and the physical properties of a rock is not well known and is of interest not only to the structural geologist who studies how rocks deform under different conditions of applied stress but also to the seismologist who studies the propagation of elastic waves through rocks. Both are interested in how partial melting might affect processes which take place deep in the earth. Since the experiments which would give the effect of partial melting on the physical properties of the rock are difficult to perform, at this point we must utilize indirect methods of finding these effects. As a first step, we can gain some knowledge from simply looking at a partially melted rock and drawing implications of the mechanical behavior of the rock. The experiments described in this paper were not done under conditions of differential stress but were done only with an effective confining pressure present on the rock sample -- the first step before triaxial experiments are done.

The experiments to be described were designed to detect the location and shape of the first liquid to form when solid cores of granite are melted under effective confining pressure. By observing the glass formed when the partially melted rock is quenched, one can visualize the three dimensional shape of the liquid present in the partially melted rock.

Tuttle and Bowen [1958], Luth et al. [1964], and Oja [1959] have investigated the melting of granite under water pressure. All of the investigators except Oja did their experiments using samples of powdered granite rather than solid cores and obtained the solidus of granite as a function of temperature and water pressure up to ten kilobars (Figure 1). In the experiments performed by Oja the cores of rock were wrapped in platinum foil and were open to the pressure medium. Since the foil capsule was not an effective seal against the pressure medium, there was no effective stress present on the rock. The purpose of the platinum wrapping was to prevent intense corrosion of the specimen which otherwise occurred when the cores were placed in the vessel unjacketed under conditions of temperature and pressure above the solidus of granite. Oja noted that there was still visible corrosion of the specimen due to some of the minerals having dissolved in the pressure medium (also see Tuttle and Bowen, 1958). Oja's determination of the solidus using solid cores was within 10°C of the curve found by Tuttle and Bowen at any given pressure.

In all the experiments done by Tuttle and Bowen and by Luth et al., there was an excess of water placed inside the sealed capsule along with the sample, and the external pressure acted only on the steam present in the capsule during the experiment. Therefore, there was no effective confining pressure producing grain to grain contact between the minerals, and the external pressure was equal to the water pressure inside the capsule (Figure 2). However, if the amount of water and the total volume of void space present in the capsule are known, it is possible to control the water pressure inside the capsule. In the experiments described in this paper the internal water pressure is known and is always less than the external pressure. Therefore, the mineral grains have an effective stress acting upon them (Figure 3). It seems reasonable to assume that rocks in the crust are under an effective confining pressure or that any pore pressure which might be present is less than the lithostatic pressure. For this reason, a number of experiments were carried out to melt solid cores of granite under an effective confining pressure.

PROCEDURE

Cores of Westerly granite and Mount Katahdin aplite (Table 1) were ground to right circular cylinders with diameters of 15.88 mm and lengths of about 12.5 mm, were soaked in acetone for about 24 hours to remove the cutting oil used, and then were placed in a vacuum at 80°C for a few hours to remove the acetone. After each was weighed, the rock specimen and a measured amount of water, along with the two piece end plug, were placed in a 0.25 mm thick copper jacket which was then sealed by welding on the copper end cap (Figure 4). The jacket and end caps were made of seamless copper, and one end cap was welded on before the sample was placed in the jacket. When the second cap was welded on, all but the top 6½ mm of the jacket was submerged in a water heat sink in order to assure that there would be no loss of water from the end plug inside. The purpose of the end plug reservoir was to form a known volume inside the jacket which was much larger than the supposed total porosity (0.009) of the rock and which would be constant during the experiment [Brace et al., 1965]. The volume of the reservoir in the two piece end plug was calculated from accurate measurements of the outside dimensions of the plug and from weighing the plug both dry and immersed in carbon tetrachloride. Then knowing the volume of the reservoir in the end plug, the initial volume of water put inside the jacket, and the equation of state of water (Figure 5), it was easy to calculate what the water pressure would be inside the capsule after the temperature had been increased to the desired value. Table 2 shows the conditions under which the rock was placed during the different experiments (refer to Figure 3).

The errors involved in calculating the internal water pressures and the effective pressures listed in Table 2 include all of the uncertainties in the experiment and would be of interest to note at this time. In calculating the error there are two major types of uncertainties which must be considered. The first is the error in the measured quantities such as the volume of water used, the volume of the end plug reservoir, and the value of the temperature inside the jacket during the experiment. The second is the error caused by neglecting the porosity of the rock. The effect of these variations combined with negligable uncertainty in using Figure 5 [<u>Kennedy et al.</u>, 1958] gives the value of the internal water pressure to ±10 bars of the value listed in Table 2. When combined with an uncertainty of ±7.5 bars for the total external pressure (Heise gauge), this gives an uncertainty of ±17.5 bars for the effective pressure applied to the sample. However, during some of the experiments slow leaks developed in the pressure system and the external pressure varied ±150 bars of the value in

Table 2. In addition to the above-mentioned errors is the error in the internal pressure caused by some of the water dissolving in the melt. At the pressure of these experiments the melt will contain a maximum 6% water [Tuttle and Bowen, 1958]. When combined with the amount of glass observed in the quenched rock, this means that the water pressure varied at most to a value 40 bars less than the tabulated value.

The pressure vessel used is internally heated and designed for use up to 10 kb. The outside of the vessel is cooled by cold water circulating through copper tubing. The pressure medium used was argon gas, compressed from a tank pressure of about 150 bars to 1 kb by means of a hydraulic intensifier. Pressure in the vessel was monitored by a Heise gauge which had an uncertainty of 0.1% of full scale reading or ±7.5 bars.

The furnace was constructed by winding 0.76 mm diameter molybdenum wire concentrically around an alundum tube approximately 30 mm in diameter. It was heated by a 60 cycle AC voltage regulated by a motor driven variac. Temperature control was achieved by using a West "Gardsmen" Controller to switch on a "bucking" transformer which decreased the output power of the variac by about 6% when on the cooling cycle. With the high efficiency of the water cooled jacket around the pressure vessel this small decrease (6%) of power was all that was necessary to cause the temperature to decrease. The controller is capable of keeping the temperature within ±5°C of the desired value. The signal to the controller and to the potentiometer used to measure the temperature in the sample holder was supplied by a Pt, Pt-10 percent Rh thermocouple.

The sample was sealed in the pressure vessel, and the system was brought up to a pressure of about 1 kb to check for leaks. When it was evident that the pressure was constant, power was applied to the furnace in order to raise the temperature to a value above the solidus of granite at the water pressure present in the jacket. As the temperature was increased, there was an increase in the pressure in the vessel due to the heating of the argon. A pressure release valve was used to maintain the desired external gas pressure. The controller was initially set about 20 degrees below the desired temperature, and then was increased slowly when the lower temperature was reached. Close monitoring of the system showed that temperature and pressure could be maintained at their desired values without any drift for the duration of the experiment (about 20 hours). However, if there was a very slow pressure leak, the temperature rose slightly due to the decreased mass of gas that had to be heated, (about 10 degrees Centigrade for 300 bars pressure drop). At the termination of the experiment the power was turned off, and the external pressure increased to maintain a minimum value of 1 kb in the vessel as it cooled (15-20 minutes). The pressure was then slowly (50 bars/minute) reduced to room pressure and the sample removed. The sealed jacket and its contents were weighed, and the rock was dried and reweighed separately. The granite was then thin sectioned and examined under a polarizing microscope to determine the presence of glass.

Previous to the work described above, a series of experiments was done using solid cores of aplite in which there was no effective stress present on the specimen (Figure 2). Aplite was chosen because the apparatus used in these experiments necessitated the employment of small cores of rock (<4 mm), and the aplite was the only available rock with a granitic composition and a very fine grain size.

The cores of aplite used were about 2.8 mm in diameter and about 25 mm in length. The specimen was placed inside a gold tube 4 mm in diameter with 0.12 mm wall thickness along with a measured amount of water. The tube was then welded closed and placed inside an externally heated cold seal pressure vessel as described by <u>Luth et al</u>. The pressure medium used was water, and the apparatus was suitable for use up to 2 kb.

After being quenched, the small cores were thin sectioned and examined for glass in the same manner as the granite.

OBSERVATIONS

Thin section examination of the quenched specimen showed that the melt formed principally in thin sheets along grain boundaries and along cracks in individual grains. Mod~~e~~al analyses of partially melted granite and aplite are shown in Table 3. Table 4 shows the percentage of available grain boundaries along which glass was found. The grain boundaries were categorized depending upon what two minerals formed them. The value for a given type of grain boundary as listed in Table 4 was determined by multiplying the percentage of glass that occurred along the grain boundary by the fraction of glass in the specimen and then dividing by the frequency of the particular grain boundary. This gives the percentage of the grain boundaries of that type which contained glass. It is evident from Table 4 and from microscopic observations that the melt forms in about the same location and shape regardless of the type of rock or the presence of an effective stress. However, the aplite which was melted under effective stress appeared to have much more hematite contamination in its glass than the aplite melted in experiments done without an effective stress. The reason for this difference is not yet fully understood.

Figures 6 through 10 are photomicrographs of thin sections of quenched granite with crossed Nichols and with plane polarized light. The glass is easily identified since it is isotropic. When viewed with plane polarized light, some of the glass is found to contain opaque inclusions (Figure 7). These inclusions are thought to be tiny grains of hematite which perhaps originated from the breakdown of biotite grains in the virgin granite.

The relative relief of the glass showed that its index of refraction was less than that of the rest of the minerals in the granite and less than the index of refraction of balsam cement. In particular, the index of the glass was found to be less than the index of microcline ($\alpha = 1.522$, $\beta = 1.518$, $\gamma = 1.525$), the index of this mineral being less than the index of balsam cement ($N = 1.537$). These observations agree well with the results obtained by Khitarov et al. [1959] who found that the glass formed by quenching melted granite had an index of refraction, $N = 1.486 - 1.501$. The thickness of the glass shown in the photographs can be considered to be indicative of the glass found elsewhere in the section. However, some variation in the thickness of the glass was found to exist, which may be explicable by the "apparent dip" of the glass sheet to the plane of the section, but it was observed that the thickest glass occurred most frequently at quartz-quartz interfaces.

At the termination of an experiment the copper jackets showed no sign of deterioration, but the steel end plug had a thin, less than 0.020 mm, coating of black iron oxide on its surface. The general appearance of the interior of the quenched sample was unchanged, but the holes on the top of the end plug made imprints on the end of the rock cylinder because of the effective stress. Also, when the specimen was removed from the jacket after being quenched, it was covered with a thin layer of water and was wet to the touch. The quenched granite appeared to be less competent than the starting material, but no quantitative strength measurements were made. However, the thin section examination showed that many of the mineral grains in the quenched rock were cracked as compared to the virgin granite which has no cracked grains.

DISCUSSION

Our present understanding of the mechanical properties of materials can show us how elastic materials such as rock and how viscous liquids such as silicate melts behave separately under conditions of differential stresses similar to those thought to exist in the crust. In trying to better understand the behavior of a substance such as a partially melted rock, the shape and location of the liquid-solid interfaces becomes a very important consideration. For instance, if the liquid part of the composite takes the form of small (less than ¼ grain size) pseudospherical inclusions distributed throughout the solid elastic matrix, this type of solid-liquid aggregate would have quite different mechanical properties than a material in which the liquid formed thin sheets between all or most of the grains. The experiments reported in this paper have shown that the thin sheet model seems to be the one which best fits a partially melted granite.

Besides the above experiments of the partial melting of granite under effective confining pressure, there are some indirect considerations which lead to the conclusion that the thin sheet model is a valid one for partially melted granite. The first of these considerations concerns the equilibrium shape of the liquid-solid interface as a function of the ratio of the solid-solid (F_{ss}) and liquid-solid (F_{sl}) surface energies of the solid and liquid components. *Smith* [1948] gave the relation between what he called the dihedral angle (θ) and the above-mentioned ratio:

$$\frac{F_{sl}}{F_{ss}} = \frac{1}{2\cos\frac{\theta}{2}} \qquad (1)$$

He found the above relationship to hold for the materials with which he was concerned -- metal alloys. The surface energies of a few solid silicate minerals are fairly well known [*Brace and Walsh*, 1962], but the only values for solid-liquid interface energies come from studies of the silicate materials used in ceramics [*Kingery*, 1960]. It would therefore seem that Smith's theory would be of little value in the present study. Even so, approximate calculations show that the dihedral angle should not be more than a few degrees for liquid silicate material in contact with quartz and feldspar. This means that the liquid would "wet" the solid material along the grain boundaries. The fact that melt is found along quartz-quartz and feldspar-feldspar grain boundaries in the above experiments indicates that the liquid present is capable of "wetting" the mineral grains. This conclusion is made because the conditions of the experiments were below the solidus of both quartz and water, and feldspar and water [*Tuttle and Bowen*, 1958]. One of the by-products of further experiments with the melting of silicate rocks in which some sort of equilibrium is thought to have been reached between the liquid and solid is that a better value of the liquid-solid surface energy might be obtained by careful determination of the dihedral angles. In the experiments described in this paper the shape of the interfaces as found in the quenched granite correspond to a dihedral angle of approximately 0^{o}. If some other experiment is designed to obtain accurate values for the solid-liquid surface energy of granite melt, then the shape of the liquid-solid interfaces could be more precisely predicted from Smith's theory.

In addition to the previous consideration concerned with surface energies is another possible explanation for the first liquid forming where it is observed. If we examine the grain boundary region on an atomic scale, the structure between two crystals will actually be amorphous over some short distance and therefore disordered and more like a liquid than a solid over the region. This means that not as much energy will have to be expended to form melt along the boundary as it would take to form two new solid-liquid surfaces between the grains. Chalmers [1940] found that the same solid material may have different melting points according to whether it is within a grain or forms a grain boundary. He attributed this difference to the differing atomic arrangements of the atoms at the boundary or to the fact that the boundary material itself forms a separate phase in which the atoms are disposed at random about the normal atomic spacings, i.e., as in a liquid. An alternative explanation which has been offered [Pumphrey and Lyons, 1949] is that the atoms are in their geometrically determined positions in the lattices of the two crystals but are distorted by their mutual proximity.

A third consideration which seems to point to the formation of a sheet of liquid at the grain boundaries in a partially melted granite is that the material along the grain boundary will have a lower melting point than the rest of the rock due to its different composition. This becomes more evident when we consider that the material around the grains was the last to solidify when the granite was formed from liquid magma. Therefore, for simplicity's sake, we can consider the material along the grain boundaries to contain a small concentration of impurities which would give it a lower melting temperature than the rest of the rock.

The three above considerations all further substantiate the findings of the experiments described earlier in this paper. We will now assume that partially melted granite can be described by a model consisting of solid grains of the minerals of the rock partially surrounded by thin sheets of melt which may be interconnected (Figure 11). Walsh (personal communication) has found the attenuation versus frequency relationship for an elastic matrix which contains viscous inclusions of various shapes. He finds that this relationship is different depending on the shape of the inclusion. Specifically, the relationship for pseudo-spherical inclusions in an elastic matrix is different than that for high aspect ratio cracks or thin sheets of viscous material in an elastic matrix. This analysis is valuable for work concerned with attenuation of seismic waves in the earth where partially melted rock is thought to exist.

The model of partially melted granite presented in this paper would have unique physical properties. As soon as a small amount of melt has formed, the strength of the material in compression would begin to decrease. When the liquid comprises 20-25% of the volume of the rock, it can deform without becoming dilatant, and the only resistence to shearing would be due to the viscosity of the melt. This would imply that the shear strength of partially melted rocks is reduced when the percentage of liquid is lower than was previously thought by Tuttle and Bowen and others. The reduction of shear strength means that the material would be able to deform in compression without becoming dilatant if the deformation takes place in the liquid.

The exact manner in which smaller amounts of melt affect the mechanical properties of granite will only be precisely known after triaxial compression experiments have been done on this material with the liquid present. For instance, partially melted granite with a small amount of liquid present might fail as a brittle material at high confining pressures as granite without any melt present does at high confining pressures. Then, we must find when the "brittle-viscous" transition in the behavior of rock in compression takes place as the amount of melt is increased.

Let us now examine the possibility of granite beginning to melt in the crust. Lithostatic pressure at the base of the crust (35 km) is likely not to exceed 10 kb. If there is an effective confining pressure on the rock, then the water pressure will have some value less than the total lithostatic pressure. The actual value of the effective pressure present in the crust will depend upon two principal unknowns: the volume of pore space present and the amount of water available. The manner in which temperature varies with depth is much less well known, and therefore will also be assumed to be one of the variables in the following discussion. Tuttle and Bowen [1958] give an excellent compilation of data concerning measured geothermal gradients in the crust. When the most likely gradients are superimposed on the first melting curve for granite, several interesting facts are noticed (Figure 12). Taking the extremes of the 15°/km and 40°/km geotherms, we see that they intersect the granite solidus at a value of about 650°C, which corresponds to a depth of about 21 km.

Using the extremes of the possible geothermal gradient, we can find values ranging from 12 - 30 km for the depth at which first melting of granite might occur. However, the difference between the lithostatic and the hydrostatic (water) pressures would mean that the depth at which first melting takes place is lower than would be indicated by Figure 12. *Tuttle and Bowen* again give an excellent analysis of the conditions when the granite may become completely melted and of the possibility of the formation of a zone of partially melted granite in the crust. Besides the composition of the granite, the temperature and pressure at which complete melting will occur depends upon the amount of water and other volatiles available to act as fluxes. Once melting has begun in rocks of granitic composition, the only obstacle to complete melting is the amount of volatiles present. The anhydrous composition of the bulk of the granites is such that given the required amount of volatiles, granite would melt completely or nearly completely at the temperature of the beginning of melting. However, the melt formed has up to 17% water dissolved in it (*Luth et al.*) and as more and more melt is formed the water pressure in the vicinity of the melting rock may be lowered sufficiently so that the rock would no longer be in the region where melting occurs. If the permeability of the rock around the melted volume is large enough, then perhaps the water pressure would again increase so that more melting could occur or perhaps is even great enough so that complete melting may take place continuously at some rate controlled by both the activation energy of the liquid silicate and the permeability of the rock. If partially melted rock, when cooled below the solidus, becomes impervious, then melting would only occur as long as the water pressure was high enough. However, the experiments in this paper suggest that the partially melted granite is relatively permeable, although no quantitative measurements of its permeability were made. Work by <u>Frangos</u> [1967] indicates that the permeability of water in granite under high (4kb) effective confining pressure at room temperature is small but still finite (about 4×10^{-9} darcies). It is not known what the effect of high temperature would be on the permeability at high confining pressure.

FIGURE 1

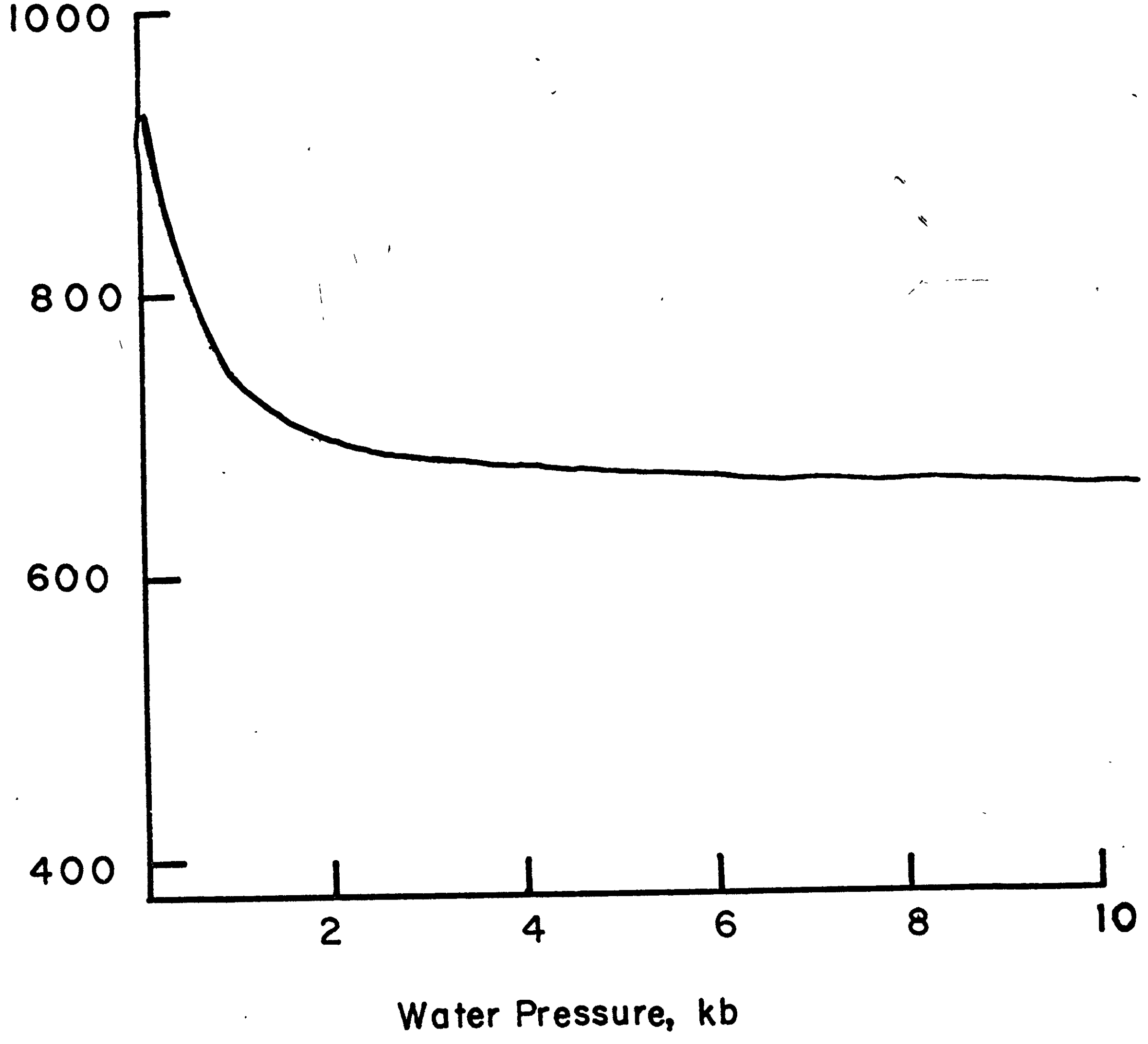
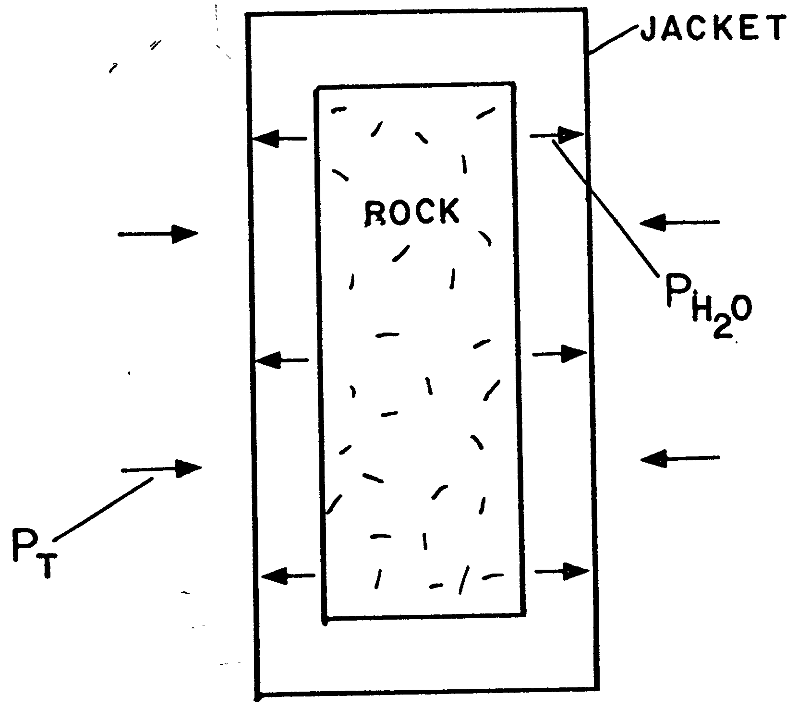


FIGURE 2



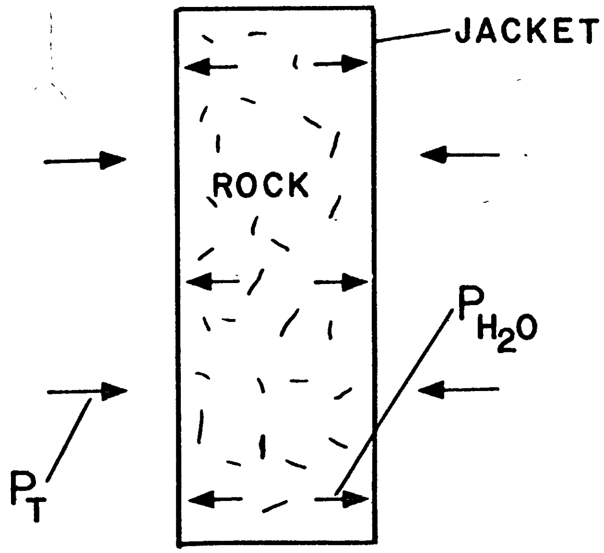


FIGURE 3

FIGURE 4

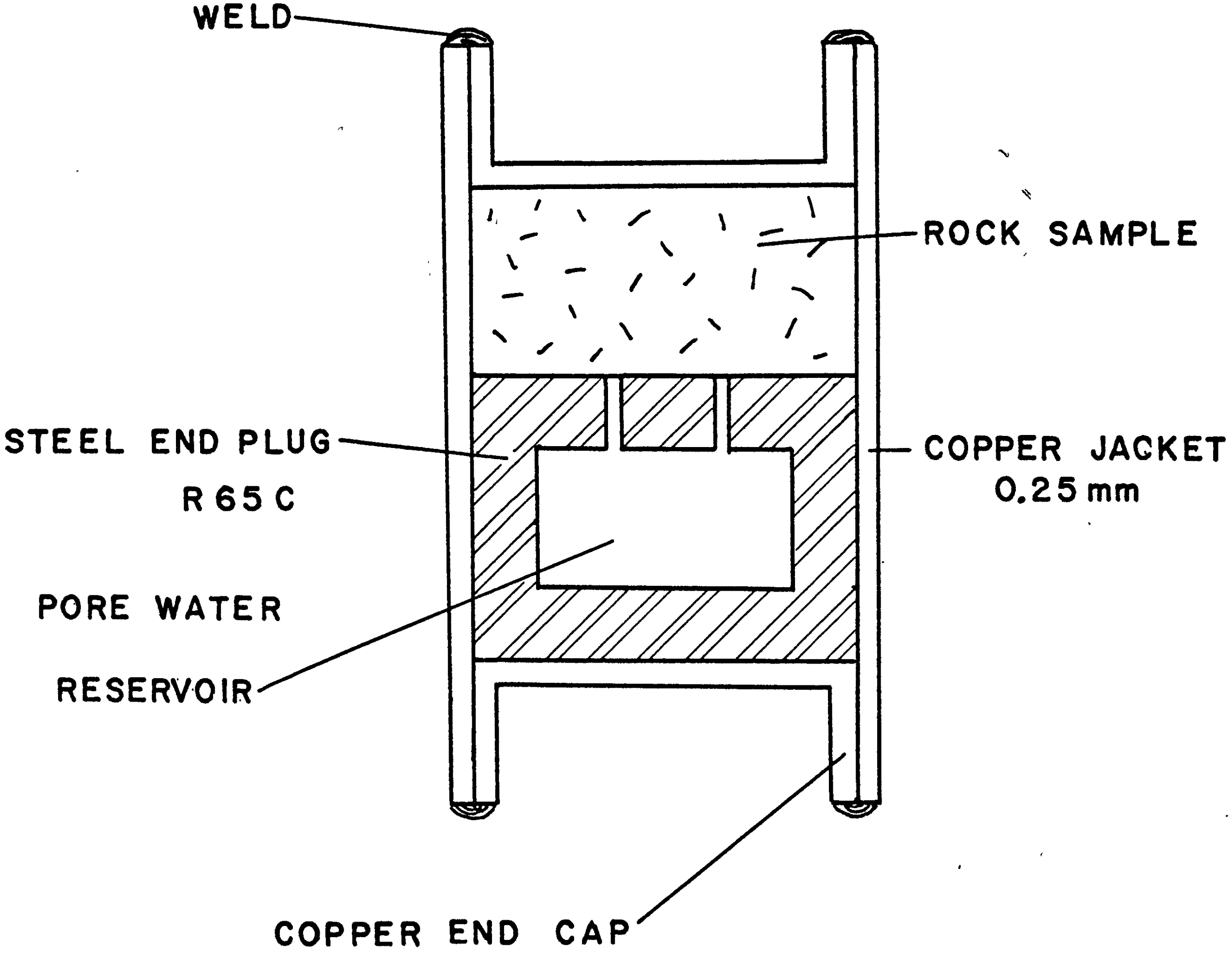

WELD
ROCK SAMPLE
STEEL END PLUG
R 65 C
COPPER JACKET
0.25 mm
PORE WATER
RESERVOIR
COPPER END CAP

FIGURE 5

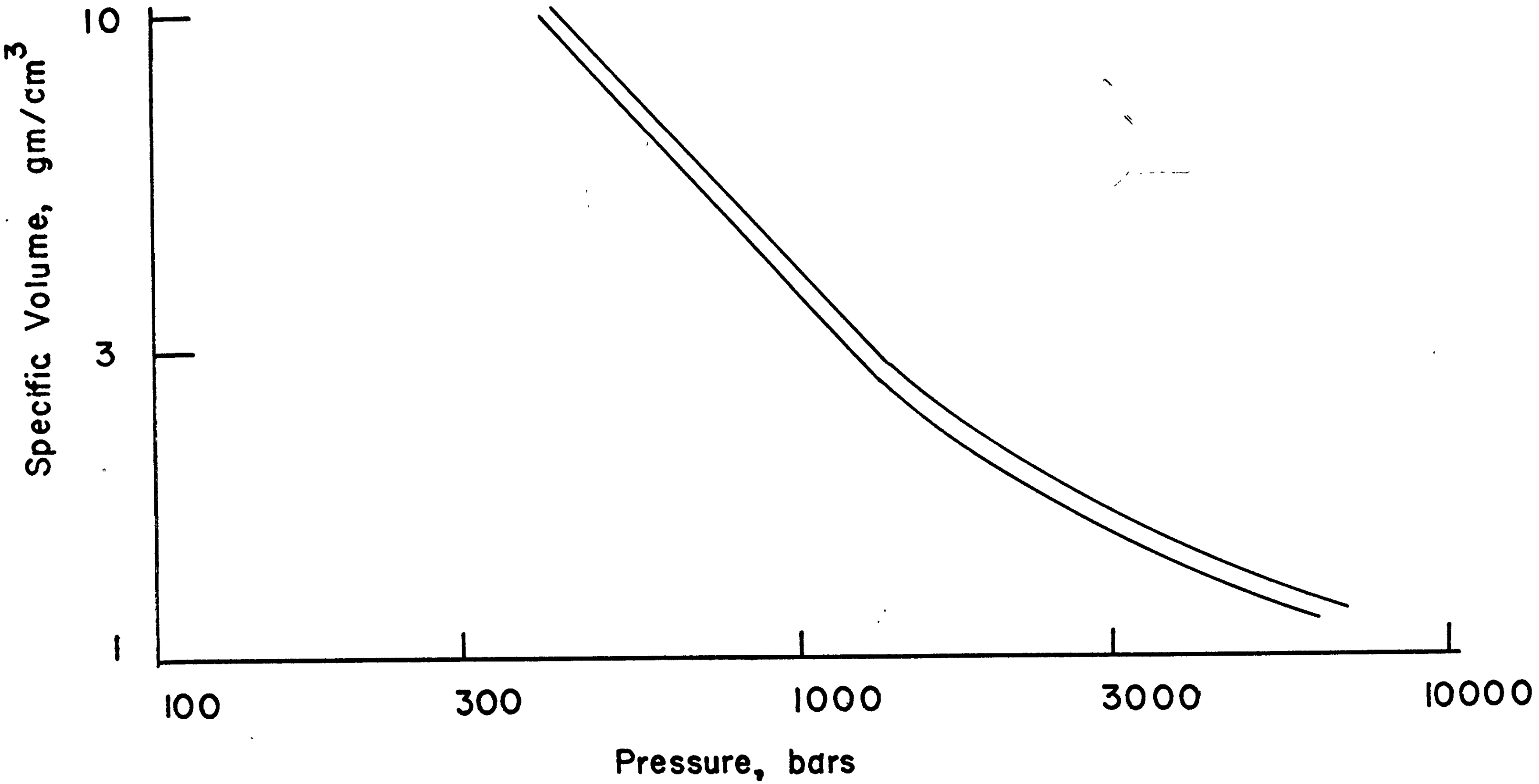

10
3
1
Specific Volume, gm/cm³
100
300
1000
3000
10000
Pressure, bars

FIGURE 6

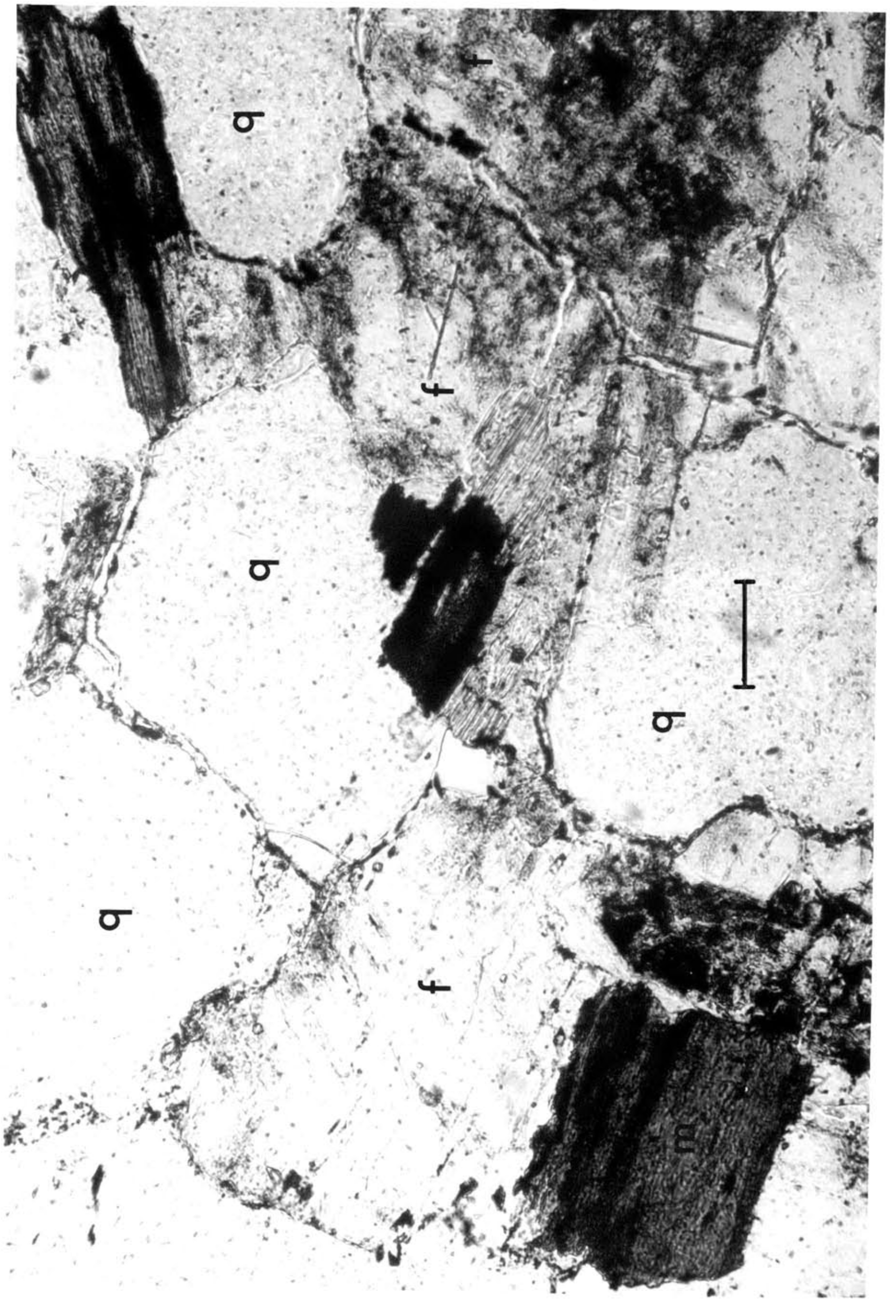


FIGURE 7

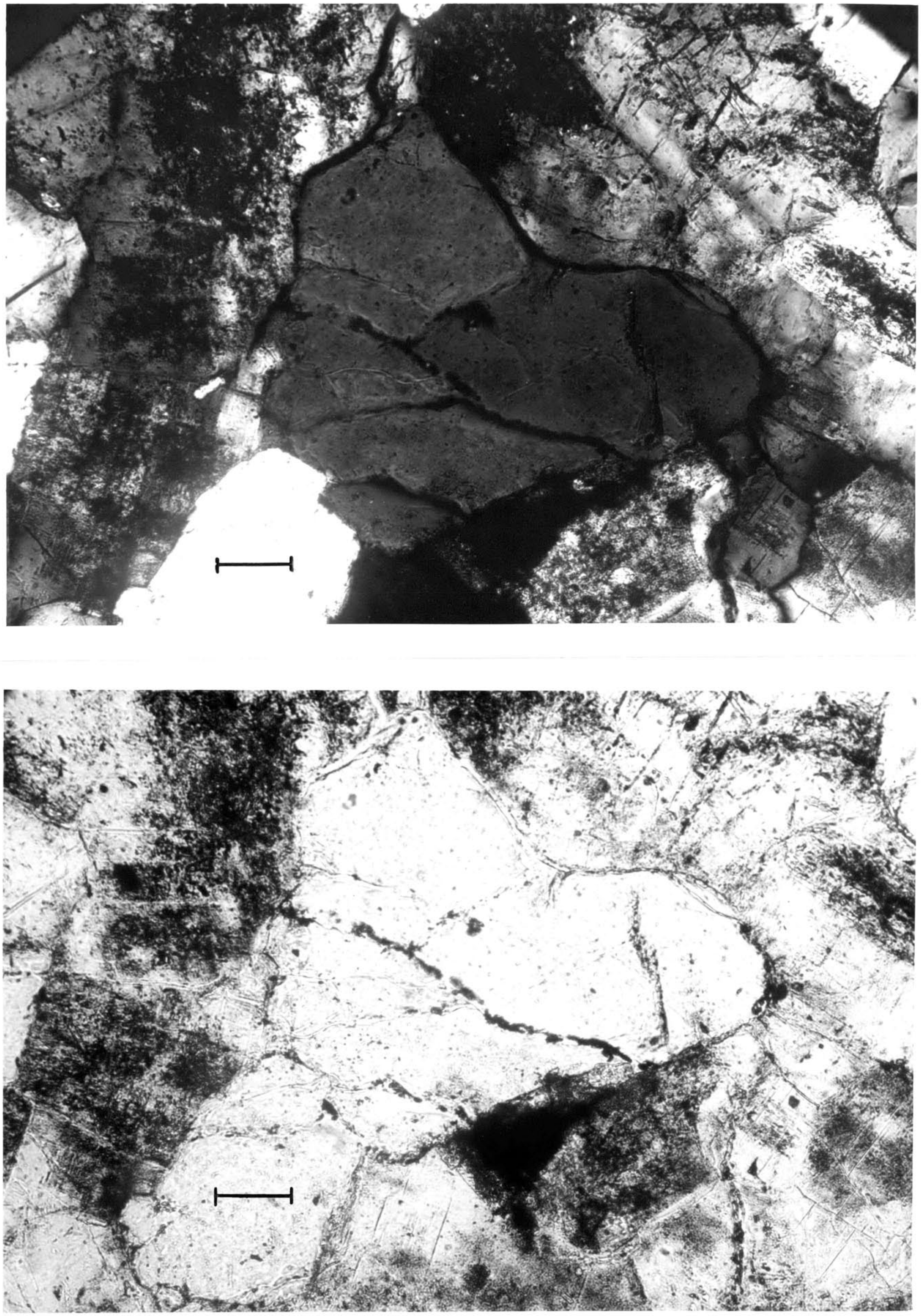


FIGURE 8

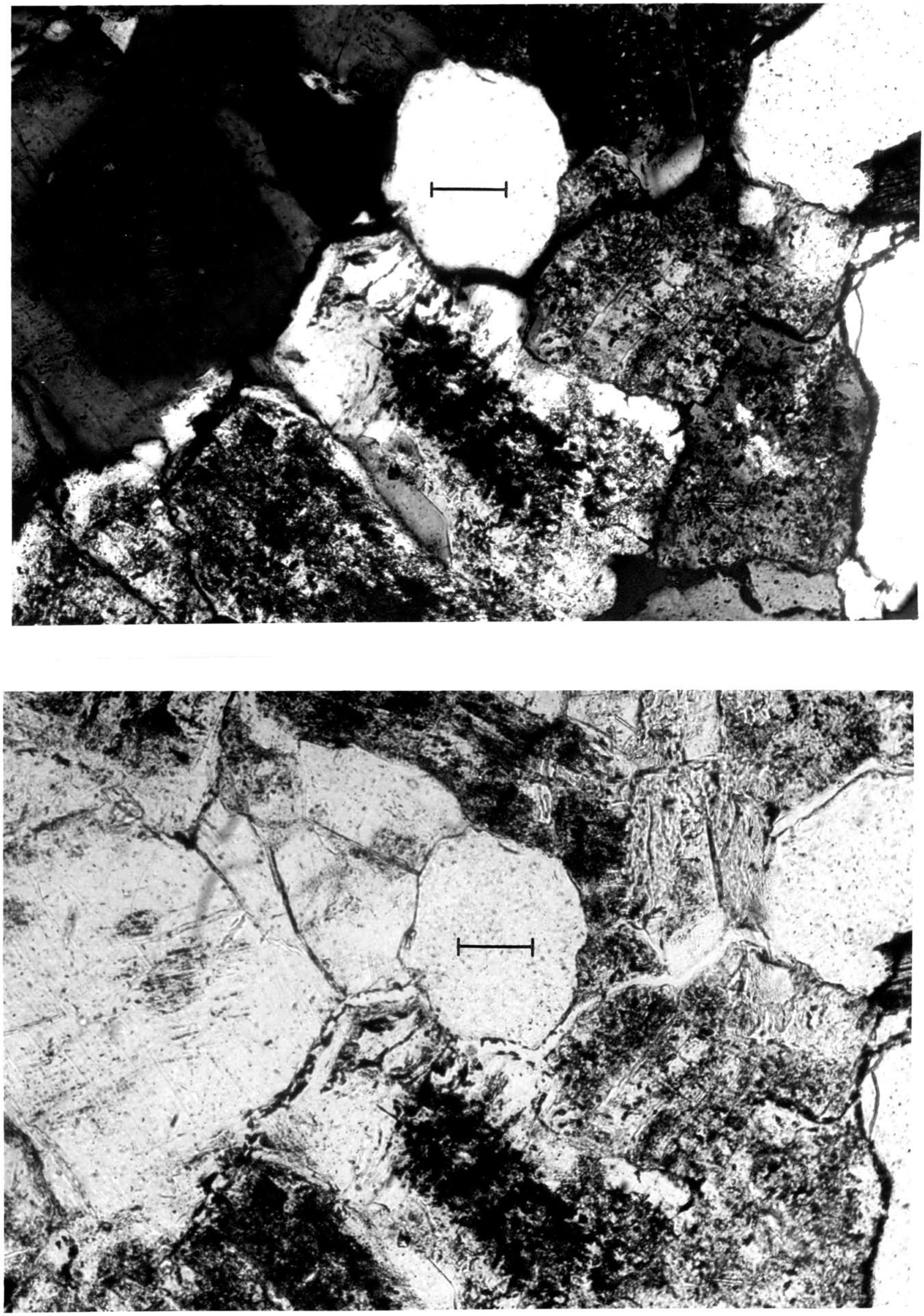


FIGURE 9

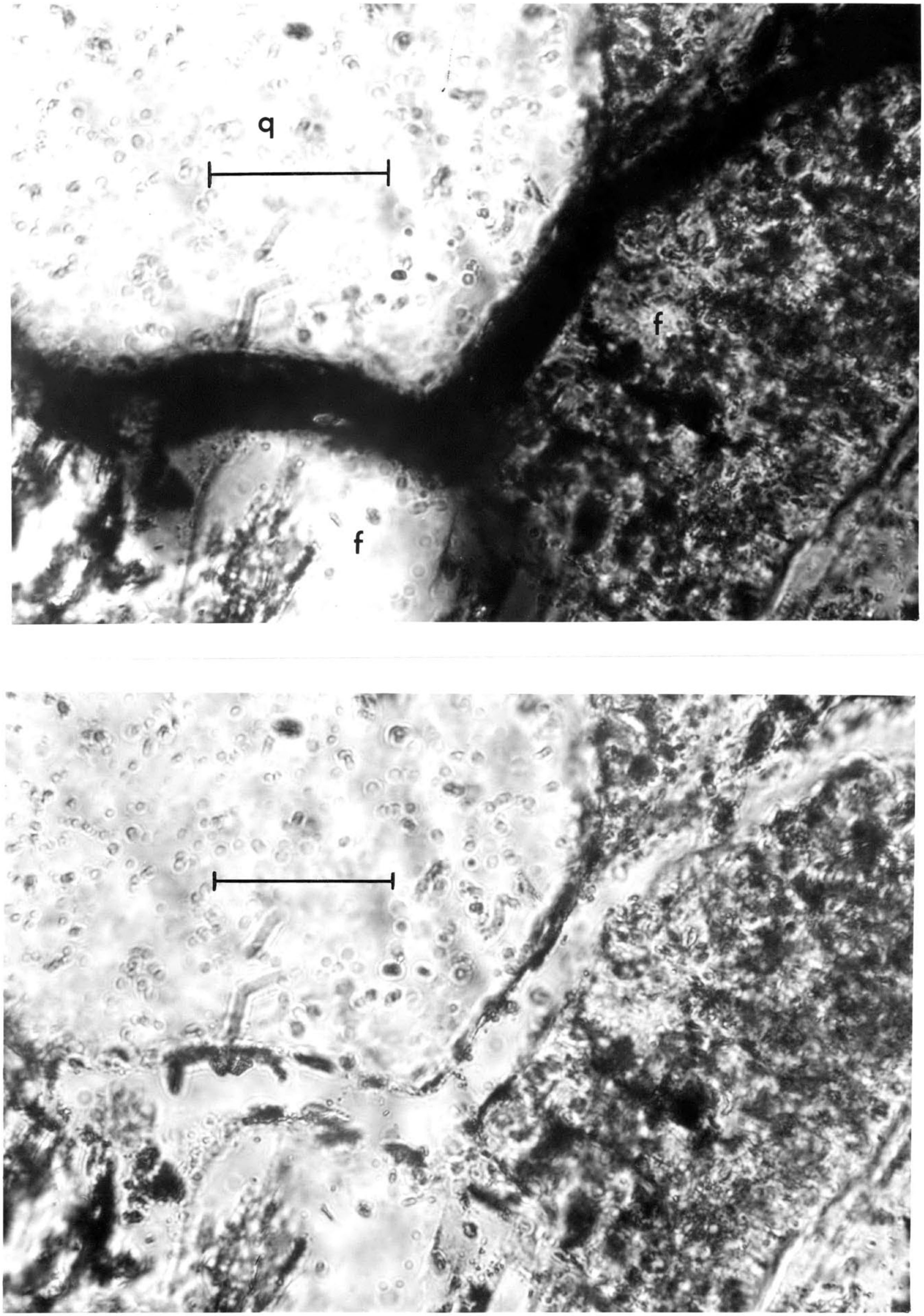


FIGURE 10

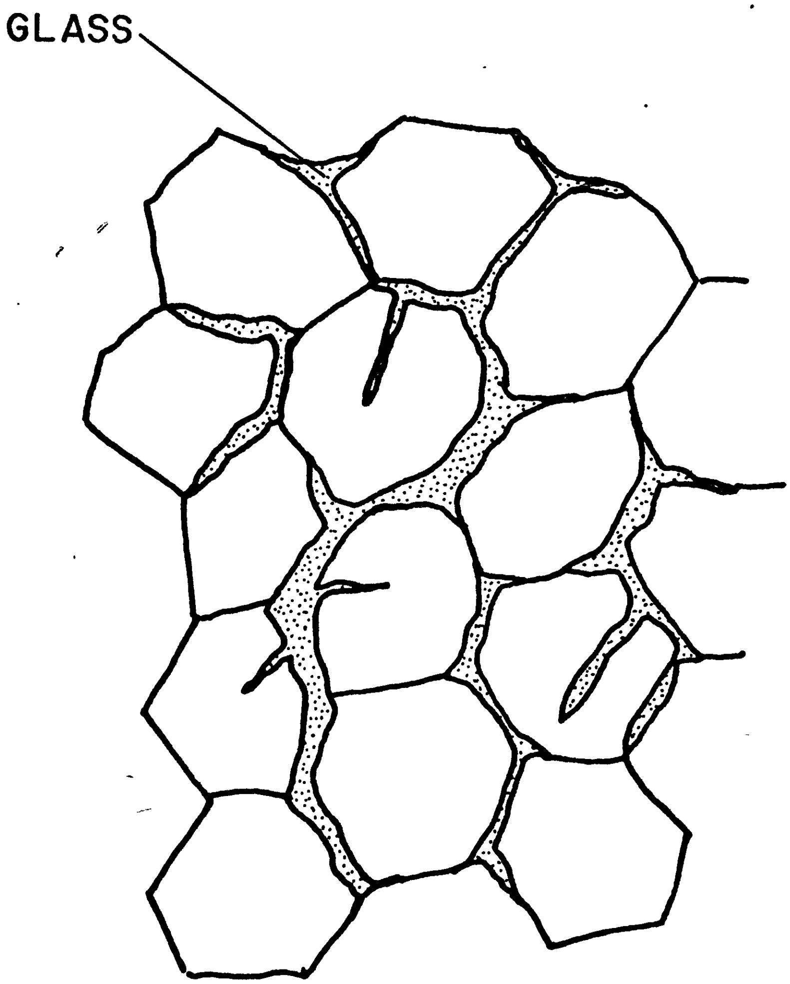


FIGURE 11

FIGURE 12

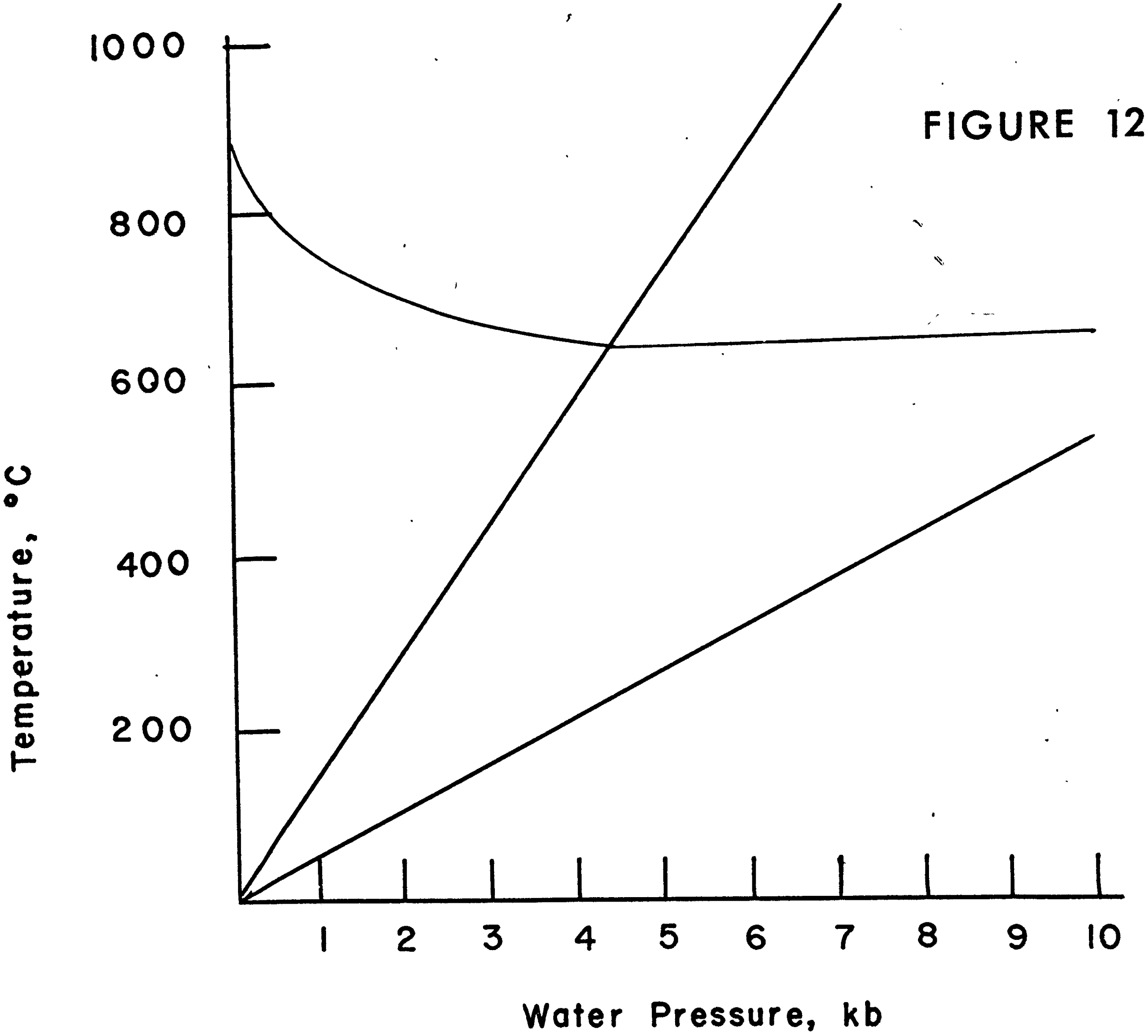

1000
800
600
400
200
Temperature, °C
1
2
3
4
5
6
7
8
9
10
Water Pressure, kb

FIGURE CAPTIONS

Figure 1. Solidus of granite as a function of water pressure and temperature. (after Tuttle and Bowen and Luth, et al.)

Figure 2. Schematic representation of a rock which has no effective stress acting on it. P_{H2O} is the water pressure inside the jacket and P_T is the total external pressure. Here P_{H_2O} equals P_T.

Figure 3. Schematic representation of a rock which has an effective stress acting on it. Here P_{H_2O} is less than P_T.

Figure 4. Arrangement of the rock specimen and end plug water reservoir in the copper jacket.

Figure 5. Specific volume of water versus pressure plot. The upper curve is for a temperature of 750 °C; the lower curve for 725 °C. (after Holser and Kennedy).

Figure 6. Virgin Westerly granite with crossed nicols. Notice the sharpness of the grain boundaries and the absence of any cracks in the mineral grains. Length of bar is 0.1 mm. q=quartz; f=orthoclase and plagioclase; m=mica.

Figure 7. Partially melted granite with plane polarized light. Notice the glass at the quartz-quartz, quartz-feldspar, and feldspar-feldspar grain boundaries and the absence of glass around the grains of biotite. Length of bar is 0.1 mm.

Figure 8. Pair of photographs showing glass almost completely surrounding a quartz grain in the center of the photograph. Notice the hematite contaminating the glass along the crack

in the large quartz grain. Upper photograph is with crossed nicols, the lower with plane polarized light. Length of bars is 0.1 mm.

Figure 9. Pair of photographs showing a sheet of glass which formed along numerous grain boundaries and which completely separates a number of grains. Upper photograph is with crossed nicols, the lower one with plane polarized light. Length of bars is 0.1 mm.

Figure 10. Pair of photographs which are magnified views of the glass around the quartz grain in the center of photographs in Figure 9. Upper photograph is with crossed nicols, the lower one with plane polarized light. Length of bars is 0.05 mm.

Figure 11. Plot of the solidus of granite (upper curve) and the extremes of the measured geothermal gradients (straight lines) as a function of temperature and water pressure; with the assumption that the water pressure equals the total lithostatic pressure. (after Tuttle and Bowen).

Figure 12. Schematic model of partially melted granite.

Rock	Grain Size mm	Modal Analysis
Granite, Westerly, Rhode Island	0.75	27.2 qu, 66.4 feld, 6.3 mica
Aplite, Mt. Katahdin Maine	0.20	31.2 qu, 65.2 feld, 3.7 mica

Abbreviations: qu quartz
feld orthoclase, plagioclase, and microcline
mica biotite

TABLE 1

Rock	vol. water cm^3	pore vol. cm^3	specific vol. water cm^3	temp. °C	P_{water} bars	P_T bars	P_E bars	time hrs.
Granite	0.14296	0.9647	6.748	745	610	1350	740	18.5
Granite	0.20560	0.9647	4.692	745	840	1570	730	16.5
Granite	0.24020	0.9647	4.016	750	1000	1650	650	22.0
Aplite	0.16746	0.7402	4.4201	745	905	1875	975	20.0
Aplite	0.01826	variable	-	735	1000	1000	0	46.0
Aplite	0.01876	variable	-	735	1000	1000	0	20.0

TABLE 2

Rock	Grain Size mm	Modal Analysis
Granite, Westerly, Rhode Island	0.75	24.7 qu, 60.5 feld, 5.7 mica, 9.1 glass
Aplite, Mt. Katahdin Maine	0.20	28.8 qu, 60.8 feld, 3.4 mica, 7.5 glass

Abbreviations:	qu	quartz
	feld	orthoclas, plagioclase, microcline
	mica	biotite

TABLE 3

TABLE 4

Rock	Q-Q	Q-F	F-F
Granite	16.7	11.6	3.9
Granite	19.6	11.1	3.1
Granite	18.4	11.8	3.1
Aplite	13.5	10.4	2.9
Aplite*	10.8	11.8	3.0

Abbreviations:

Q-Q grain boundary formed by two quartz grains

Q-F grain boundary formed by a quartz and a feldspar grain

F-F grain boundary formed by two feldspar grains

*average of two specimens melted without an effective stress

TABLE CAPTIONS

Table 1. Grain sizes and modal analses of the two rocks used in the experiments.

Table 2. The experimental conditions for some of the specimens used in the experiments. P_E is effective stress.

Table 3. Mode analyses of the two rocks used in the experiments after being partially melted.

Table 4. Percent of the available grain boundaries which contained glass.

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