Steady State Creep of Fine Grain Granite at Partial Melting

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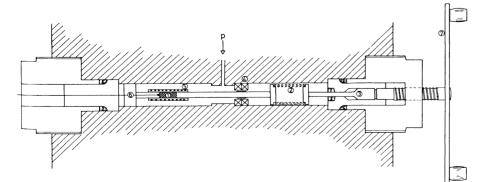
Abstract. Steady state creep under constant stress has been measured in a fine grain granite (aplite) from Schauinsland, Germany for the temperature range of partial melting 860°–1,060° C, under a hydrostatic pressure of 4.2 kbar, and at low shear stresses of 5–50 bar. The apparatus used is described briefly. Rheological measurements are complemented by microscopic investigations. With a melt fraction of up to about 20%, creep can be described by a power law with a stress exponent of 3–4 and an activation energy of 80 kcal/mole, typical for creep in solids. Above 1,010° C or 20% melt, the activation energy increases rapidly to a value of 200 kcal/mole simultaneously with a rapid increase of the melt fraction and a decrease of feldspar content. From the grain structure and from etching tests it is concluded that quartz contributes little to the plastic deformation which is governed mainly by the stress and temperature induced recrystallization of feldspar. The large temperature dependence of the creep rate above 1,010° C may be caused by the decreasing area of grain contacts and consequent rise in local stress. These results support those of Arzi (1974) and Roscoe (1952).

Key words: Steady state creep — Partial melting — High pressure research

Introduction

The creep behaviour of earth materials in the mantle governs all deep reaching tectonic processes. Almost no creep measurements have yet been performed on rocks under high hydrostatic pressure and at the low shear stresses ($\sigma < 100$ bar) typical of most parts of the upper mantle.

Controversial opinions are held and few data are available on the rheological behaviour of partially molten rocks, in particular. There is one central question: up to what melt fraction does the material creep like a solid and when does it begin to behave like a viscous liquid. Press (1959), Ringwood (1969) and Ritsema (1972) expressed the opinion that a small percentage of melt is sufficient to reduce drastically the 'strength' of the upper mantle. The experimental results of Roscoe (1952), Arzi (1974), and of this study do not support this theory. Roscoe studied suspensions of solid particles in viscous fluids and found the transition from solid to fluid behaviour in the range 20%–40% melt. Arzi found, in three successful runs, that the creep behaviour of a granite did not deviate significantly from the subsolidus behaviour for up to 10% melt. However, his samples were water saturated and showed prescribed fault lines.

In this study an air-dried, fine grain granite (aplite) from Schauinsland, Black Forest, Germany, is investigated. It is composed of approximately 50% sericitized plagioclase and orthoclase, 40% quartz and 10% coarse mica, mainly muscovite and chloritized biotite. The grain size ranges from 0.5 to 1 mm. Granite has been chosen for this study for two reasons: First, because melting begins at relatively low temperature, and second, the melt does not recrystallize so that the quenched melt can easily be identified, in the form of glass, under the microscope.

Experimental Procedure

Figure 1 shows a schematic section through the pressure vessel: the sample (1) is exposed simultaneously to a hydrostatic gas pressure p of up to 10 kbars and an axial stress of 1–200 bars. Argon gas is used as pressure medium. All experiments in this study were carried out at $p = 4.2$ kbar. Constant axial stress is produced by a helical spring (2) which is loaded from outside the vessel by a male screw (7).

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Fig. 1. Schematic cross-section of the 10 kbar pressure vessel. For description of numbered components see text

The cylindrical specimen, 20 mm long and 9 mm in diameter, is jacketed with dispersion-strengthened platinum of 0.1 mm wall thickness. Both ends are closed with platinum caps and welded pressure-tight. Axial deformation of the specimen is measured with high resolution by a differential transformer (4) mounted inside the pressure vessel. A system free of any mechanical friction is required if measurements are made under small deviatoric stress. The sample is heated in an internal Pt–Rh furnace (5). The sample temperature is measured and controlled by a thermocouple (6). The temperature in the sample varies from the center to the end by only about 5°C.

The actual measurements begin after the sample has shortened under pressure, temperature, and moderate axial stress by about 2% in plastic creep. This secures perfect adjustment of the end faces of piston and sample and reduces drastically the influence of primary creep on the measurements. The major experimental problem is that during deformation the platinum jacket frequently fails. Each sample is carefully checked after the experiment in this respect.

Results

Creep Experiments

An empirical equation of the form

$$\dot{\varepsilon} = A \; \sigma^n \; \exp(-E/RT) \qquad p = \text{const}$$

where $\dot{\varepsilon}$ = creep rate
  σ = deviatoric stress (bar)
  E = activation energy (kcal/mole)
  T = temperature (Kelvin)
  A = a parameter only weakly temperature dependent
  R = gas constant
  n = stress exponent
  p = hydrostatic pressure

is suitable to describe the steady state creep behaviour of many materials (Weertman and Weertman 1975). From this equation it follows:

$$n = \frac{\log \dot{\varepsilon}}{\log \sigma}, \qquad\qquad T = \text{const}$$

$$E = -2.3 \; R \; \frac{d \log \dot{\varepsilon}}{d\,1/T}, \qquad \sigma = \text{const}.$$

On a $\dot{\varepsilon}(\sigma)$ plot with double logarithmic scale the stress exponent n appears as the slope of the experimental curve. Similarly, the activation energy E can be derived from a semilogarithmic plot of $\dot{\varepsilon}(1/T)$, frequently called an Arrhenius plot.

Figure 2 shows the strain rate $\dot{\varepsilon}$ as a function of the stress σ at two different temperatures. After raising or lowering the stress in small steps, constant strain rate was generally reached ($\dot{\varepsilon} \approx 10^{-6}$–$10^{-7}$ s^{-1}) after 5–15 min. The duration of individual measurements was typically about one hour but varied between half a day and several minutes, depending on strain rate. Measurements were carried out up to a final strain of the sample of about 10%. The question of stationarity of creep is a very fundamental one and does not refer only to the present measurements (Paterson 1979). Stationarity requires equilibrium in the microscopic stress field and the distribution of lattice defects. It also requires chemical and structural equilibrium (with respect to grain size) corresponding to given p, T conditions. It is evident that in this broad sense a steady state is never reached under laboratory conditions. In the usual restricted sense, however, which excludes
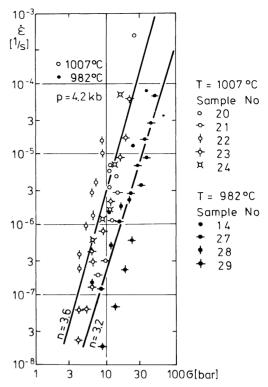
Fig. 2. Stress vs strain-rate plot for aplite. Data from the same sample are marked by identical symbols
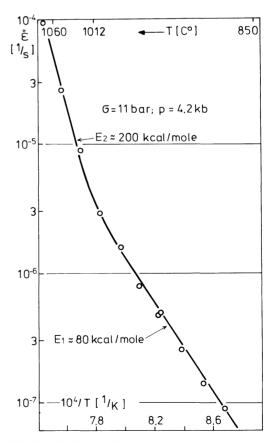
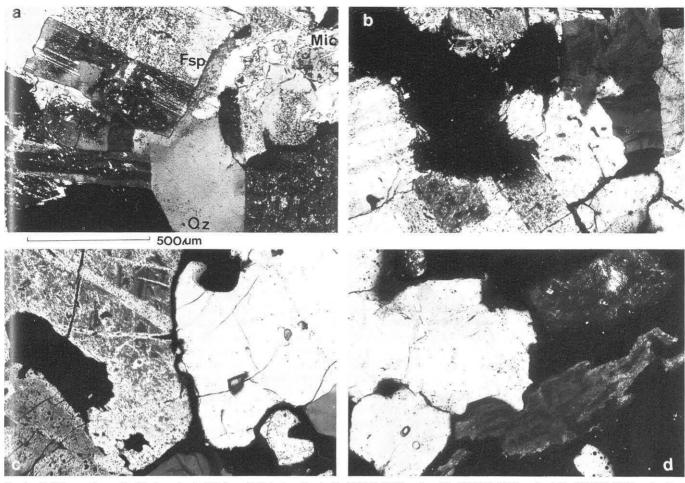**Fig. 3.** Arrhenius plot for aplite at partial melting

Fig. 4a–d. Thin sections of aplite in polarized light. **a** Original aplite; **b** $T=968°$ C, 13% melt; **c** $T=1009°$ C, 18% melt; **d** $T=1040°$ C, 37% melt. $Q_z=$ quartz, $F_{sp}=$ feldspar (plagioclase and orthoclase), Mic=muscovite and chloritized biotite, opaque areas are alteration products of mica, the melt is isotropic under crossed polarizers

long term transient phenomena, our data can be considered steady state and are compatible with each other. As an average over the stress range 5–50 bar a value of n between 3 and 4 is obtained. This value is common for creep in minerals below $\sigma \approx 1$ kbar. The rather large scatter of data is due to the fact that at $T=982°$ C four different samples, and at $T=1,007°$ C five samples were used. Although they have all been taken from the same piece of rock, at equal stress and temperature the strain rate may vary by an order of magnitude due to mineralogical and mechanical inhomogeneities. Measurements from the same sample are marked by identical symbols.

The strain rates shown in Fig. 3 were obtained at a constant stress of $\sigma = 11$ bar while the temperature varied from 860°–1,060° C. Two different activation energies can be distinguished which take over near 1,010° C. The lower branch corresponds to $E_1 \approx 80$ kcal/mole, the upper branch to $E_2 \approx 200$ kcal/mole. This means, in simple terms, that the temperature dependence of the creep rate increases strongly above 1,010° C.
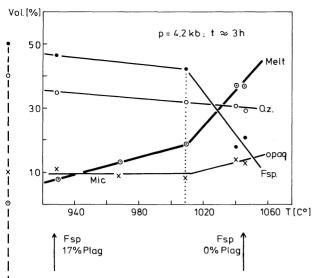
Microscopic Structure

In order to find the cause of the rapid increase of activation energy at 1,010° C, the process of partial melting has been investigated microscopically. Five samples were exposed for three hours each to a hydrostatic pressure of $p=4.2$ kbar and temperatures of

929° C, 968° C, 1,007° C, 1,040° C, and 1,046° C, respectively, at a deviatoric stress $\sigma = 0$ bar. From thin sections (Fig. 4a–d) the following qualitative statements can be made: At the lowest temperature minerals containing water (muscovite, biotite, chlorite) begin to disintegrate into a glassy melt and opaque relicts. A seam of optically isotropic melt develops which broadens with increasing temperature at the quartz/feldspar grain boundaries. The quartz/quartz boundary remains unwetted by the melt until higher temperatures are reached. At the highest temperature, it is mainly quartz which remains unmelted. Locally, more than 50% melt occurs with opaque decomposition products of mica (mainly haematite, some iron-rich opaque melt and iron-silicates) floating in the melt. The melt is chemically extremely inhomogeneous.

Figure 5 shows the result of a quantitative evaluation. The cross section of each rock sample was divided into 1,800 points and each point classified as melt, quartz, feldspar, coarse mica and its opaque disintegration products. The melt curve can be extrapolated to the beginning of partial melting at a temperature of about 870° C. The proportion of melt increases steadily to about 18% at 1,010° C, where it begins to grow more rapidly at the expense of feldspar. With further increase of temperature feldspar ultimately disappears. The quartz fraction remains essentially constant.

In an attempt to gain some information on the microscopic mechanisms of plastic deformation at partial melt three samples which were exposed to a temperature of 1,000° C and $\sigma = 0, 8, 25$ bar

Fig. 5. Mineral composition of aplite at partial melting. Q_z = quartz, Mic, opaq = mica and its opaque alteration products, F_{sp} = feldspar (plagioclase (plag) and orthoclase), t = duration of measurement

were examined microscopically after being etched with HF. Quartz crystals showed a considerable dislocation density (approximately $1-3 \cdot 10^4$ etching pits/mm^2) these had apparently been introduced beforehand by Variscan tectonics. There is no significant difference between the dislocation density in the quartz in the three samples and in that of the starting material. Apparently quartz does not contribute much to the plastic deformation but shows rather rigid or brittle behaviour. In contrast, the feldspar does not fracture. The sericitic alteration products of the feldspars decompose to yield clear recrystallized feldspar grains with occasional inclusions of opaque minerals like haematite. In the course of this process, the lamellar twinning in feldspars remains unchanged.

Discussion and Conclusions

From Figs. 2 and 5 we conclude that even in the presence of about 20% melt the creep deformation of the granite under investigation follows a power law, characteristic of creep in solids. If we assume that the intergranular melt has a comparatively low viscosity, the creep resistance at low to moderate melt fractions is apparently still controlled by the deformation within grains and at grain boundaries. This conclusion is also supported by the value of the activation energy $E_1 \approx 80$ kcal/mole which is close to that for creep of several dry, polycrystalline minerals such as quartzite or enstatolite (Carter 1976).

From microscopic inspection and etching tests, it appears that in our experiments the quartz grains remain rather brittle and contribute little to the plastic deformation. Although no relevant experimental data exist, it might be expected from general experience that recrystallization from partial melt and polygonization of original sericitized feldspar is compatible with power law creep (Carter 1976). The step in activation energy at 1,010° C coincides with the rapid increase of melt and the corresponding reduction of crystalline feldspar which is supposed to govern the creep process. An increase in the proportion of melt and the corresponding decrease of grain size in the remaining solid matrix reduces the area of the effective solid grain contacts and, consequently, raises the local stress which results in a higher creep rate. The increase of

E may, therefore, be mainly an apparent one reflecting the change of the solid matrix contact area rather than a new creep mechanism. Within the range of our experiments, our data support the result obtained by Arzi (1974) and Roscoe (1952) that somewhere in the range of 10–30% melt, the 'rheological critical melt percentage' (Arzi 1978), a drastical lowering of the effective rock viscosity occurs. Our experimental set up was not suitable for measurements in the regime in which creep is fully governed by the relatively low viscosity of the melt and in which a Newtonian type of creep has to be expected.

It should be pointed out that a much smaller fraction of melt or even subsolidus grain boundary relaxation may suffice to influence drastically the elasticity and the anelastic absorption, and to produce a low velocity, low Q zone in the mantle (Berckhemer et al. 1979).

Addenda

After completion of this paper a publication on the experimental deformation of partially melted granite by van der Molen and Paterson (1979) appeared. A major conclusion of their extensive investigations, carried out at higher shear stresses, is that the critical melt fraction separating granular-framework-controlled flow behaviour from suspension-like behaviour is deduced to be approximately 30–35 vol. %.

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