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Discussion and Discovery

Limit of crustal drilling depth

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ABSTRACT

Deep drilling is becoming the direct and the most efficient means in exploiting deep mineral resources, facilitating to understanding the earthquake mechanism and performing other scientific researches on the Earth's crust. In order to understand the limit of drilling depth in the Earth's crust, we first conducted tests on granite samples with respect to the borehole deformation and stability under high temperature and high pressure using the triaxial servo-controlled rock testing system. Then the critical temperature-pressure coupling conditions that result in borehole instability are derived. Finally, based on the testing results obtained and the requirements for the threshold values of borehole deformations during deep drilling, the limit of drilling depth in the Earth's crust is formulated with ground temperature.

1. Introduction

In the efforts to utilize hot dry rock geothermal energy in exploiting deep oil and gas resources, deep drilling (depth $H = 4500–6000$ m), ultra-deep drilling ($H = 6000–9000$ m) and super-deep drilling ($H > 9000$ m) have become the direct and most efficient means to understand the earthquake mechanism associated with engineering geology. Recently, a huge investment on continental scientific deep drilling has been made in many countries, such as Russia, USA, Germany, and China (Matsunaga, 1995; Muraoka et al., 1998; Smithson et al., 2000; Cornet et al., 2007; Elders et al., 2014). For example, the depth of Kola Peninsula borehole Kola-3 in Russia reached 12,262 m, and the borehole KTB-HB in Germany reached a depth of 9101 m (Haimson and Chang, 2002). As is known, deep drilling basically involves underground rocks with high temperature and high pressure. Subsequently, a series of risks such as necking, creeping, instability, and collapsing of borehole has been reported (Heuze, 1983; David et al., 1999) due to significant decrease in rock strength and increase in borehole deformation during drilling process under such conditions. This can greatly increase the cost of borehole drilling and its maintenance, which in some extreme cases can stop the projects being carried out. In this text, we aims to find out the relationship of borehole wall deformation and borehole instability under high temperature and high pressure conditions, and then a limit of drilling depth is expected.

2. Materials and methods

The details of the testing system are described by Zhao et al. (2012). The granite specimens used in the test are sampled from Pingyi, Shandong Province, China. The granite specimens are hard and intact, containing no joints and fractures. Cylinder specimens were prepared in the size of ϕ200 mm × 400 mm. For each specimen, a hole with diameter of 40 mm was drilled along the cylinder axis. The deformation of the borehole in the tests was measured using optical methods. Three specimens have been tested under the hydrostatic pressures below 150 MPa and temperatures below 600 °C in order to understand the borehole deformation pattern in terms of critical conditions.

During the tests, the hydrostatic pressure (equal axial and confining pressures) was applied to the specimen, and no pressure is imposed on the borehole. Each specimen was heated to the target temperatures gradually. At each step, the levels of temperature and pressure were kept constant for a certain period, during which the deformation of borehole was measured. The tests for each specimen lasted for more than 400 h.

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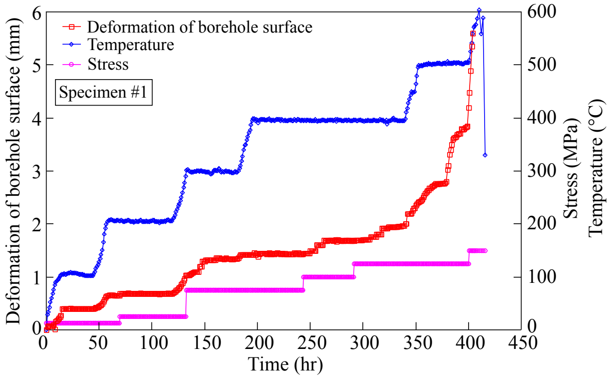
3. Results

Fig. 1 shows the borehole deformation of the specimens #1, #2 and #3 measured at each level. It indicates that the borehole aperture experiences a steady creep when the temperature is below 400 °C and the hydrostatic pressure is less than 100 MPa. When the temperature increases to 500 °C and the hydrostatic pressure increases to 125 MPa, the borehole experiences an accelerated creep within the following 60 h, and eventually it fails. It is also shown that the steady creep (elastic deformation and creep) of borehole changes exponentially with respect to the temperature and hydrostatic pressure. According to the experimental results of the three specimens, the relationship between the deformation and hydrostatic pressure and temperature can be fit using the least square method as follows:

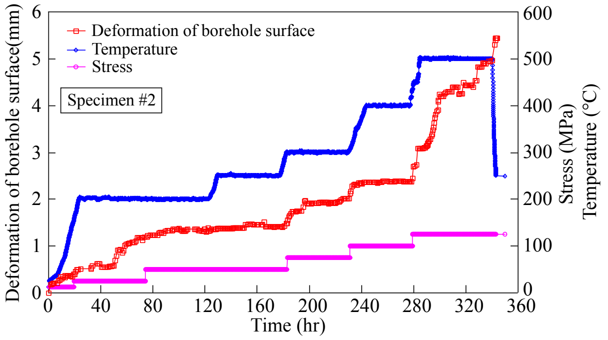
$$U_{\rm rc} = 0.22767\exp(0.004454\sigma + 0.00483T) \quad (1)$$

where $U_{\rm rc}$ is the borehole radial displacement (mm), σ is the hydrostatic pressure on the rock specimen (MPa), and T is the temperature (°C).

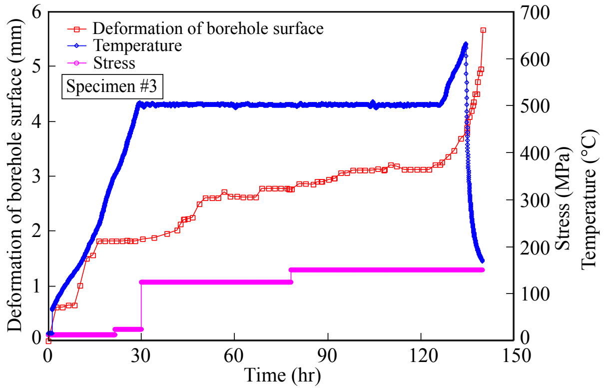
Eq. (1) indicates that the borehole displacement increases exponentially with the temperature and the hydrostatic pressure on the specimen. It implies that the temperature has almost the same impact on the borehole deformation as the hydrostatic pressure does, i.e. the borehole deformation increases significantly as either the temperature or the hydrostatic pressure increases.



(a) Specimen #1.



(b) Specimen #2.



(c) Specimen #3.

Fig. 1. Deformations of boreholes in rock specimens #1, #2 and #3 under different temperatures and stresses.

4. Discussion

The above-described testing results also reveal that the borehole in the granite fails when the temperature and the hydrostatic pressure are above 500 °C and 125 MPa, respectively. At this stage, the borehole gradually collapses. Figs. 2 and 3 show the change of borehole diameter along the specimen axis measured after the tests and the inside view of the collapsed borehole walls for specimen #2, respectively. The results indicate that:

(1) The borehole deformation in the granite experiences different stages due to the increasing temperature and pressure. When the temperature and the hydrostatic pressure are below 400 °C and 100 MPa, respectively, viscoelastic deformation is dominant in the borehole. In this stage, the borehole diameter tends to decrease. The borehole remains stable and the granite specimen does not fail. Viscoelastoplastic deformation appears when the temperature increases from 400 °C to 500 °C and the hydrostatic pressure from 125 MPa to 150 MPa. In this stage, the borehole diameter increases due to the creep of granite. Small pieces fall off the borehole wall and the borehole starts to collapse. In the

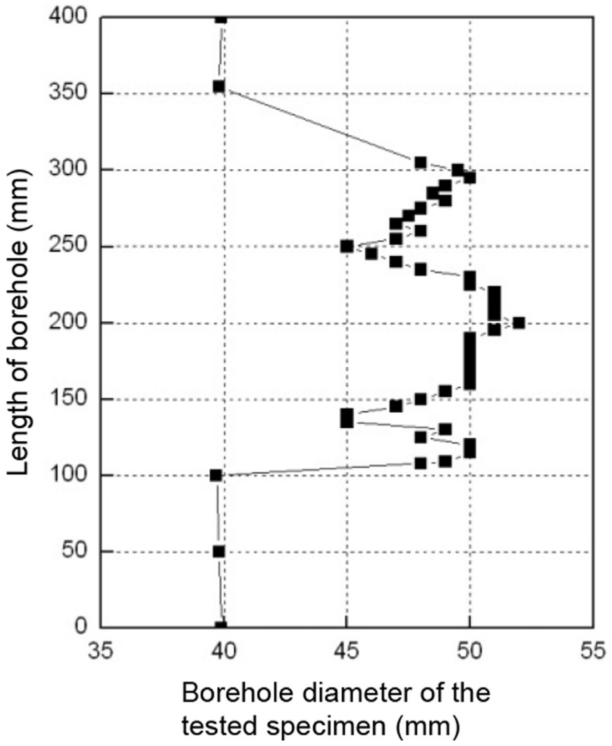


Fig. 2. Variation of borehole diameter along axis of the tested specimen #2.