

Damage process of intact granite under uniaxial compression: microscopic observations and contact stress analysis of grains

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ABSTRACT: Understanding the damage mechanism in materials is one of the very important subjects in the science and engineering field. The microstructural change, microcracking, which causes material strength deterioration, is usually termed as damage. We observed micro-damage localization and propagation in a coarse-grained granite specimen under uniaxial compressive stress to better understand the fundamental problems of the true damage process at a micro to macro scale. With the use of an experimental system, the continuous observation of the damage process also enabled us to clarify micro-damage in great detail. The results indicate that the mechanisms of micro-damage initiation in a granite specimen under uniaxial compressive stress may be separated into two cases; the first in which two grains, such as quartz and feldspar, contact each other in the same direction as the axial stress, and the second in which a biotite grain inclined to the axial stress direction is contained within a feldspar grain. The damage is strongly localized for both cases and some shear zones are found in the specimens.

Key words: granite, uniaxial compressive stress, micro-damage localization, damage mechanism

1. INTRODUCTION

Studies of microcracks in rock specimens may shed some light on the rock damage mechanics. Microcracks may be used to infer local stress domains. Additionally, they may be used for comparisons between natural and laboratory conditions, and because of apparent morphological and mechanical similarities between microcracks and joints/faults, knowledge about microcrack propagation is a necessary input for the modeling and study of micromechanics and fault formation.

Rocks and rock masses are composed of discrete microstructural elements such as grains and microcracks. Accordingly, instead of a simplified continuum approach, we must account for these discrete structural elements and the mechanical properties of various grains. Damage mechan-

ics and fracture mechanics have recently been developed as effective methods for estimating damage process of these materials (Zhu and Tang, 2004).

Damage denotes the process of gradual material deterioration brought on by the creation, growth and coalescence of a multitude of microcracks. The damage is generally induced by the initiation of microcracks and microcavities, starting from pre-existing microdefects, with their growth and coalescence giving rise to the initiation of macroscopic cracks in the material. The ultimate stage of the damage process corresponds to macrocrack initiation or the failure of the material (Fig. 1).

Rock is a natural material with some pre-existing microdefects and its mechanical properties are strongly dependent on microcracks and microcavities which occur during loading. Being able to accurately describe the inelastic behavior of rock is essential for solving numerous boundary-value problems in mining or civil engineering (e.g., the opening of underground spaces and in radioactive waste disposal). It is evident that classical elastic-plastic analysis does not provide realistic information on the stress distribution within elements of the material or toward the assessment of the safety factor against failure. On the other hand, the limit analysis approach, based on a perfect plasticity model with unlimited ductility, may overestimate the real load carrying capacity and does not provide any information on magnitudes of strain or displacement occurring before failure.

In the case where damage propagates from pre-existing mesoscale or macroscale cracks, certain methods of analysis (e.g., macro damage mechanics and fracture mechanics) are very effective at providing important information. However, considerable work (e.g., Peng et al., 1972; Lockner et al., 1992) has shown that the coalescence and increased density of microcracks cause mesoscale or macroscale cracks, and that the elastic and plastic properties of rocks are significantly affected by changes in these microcracks.

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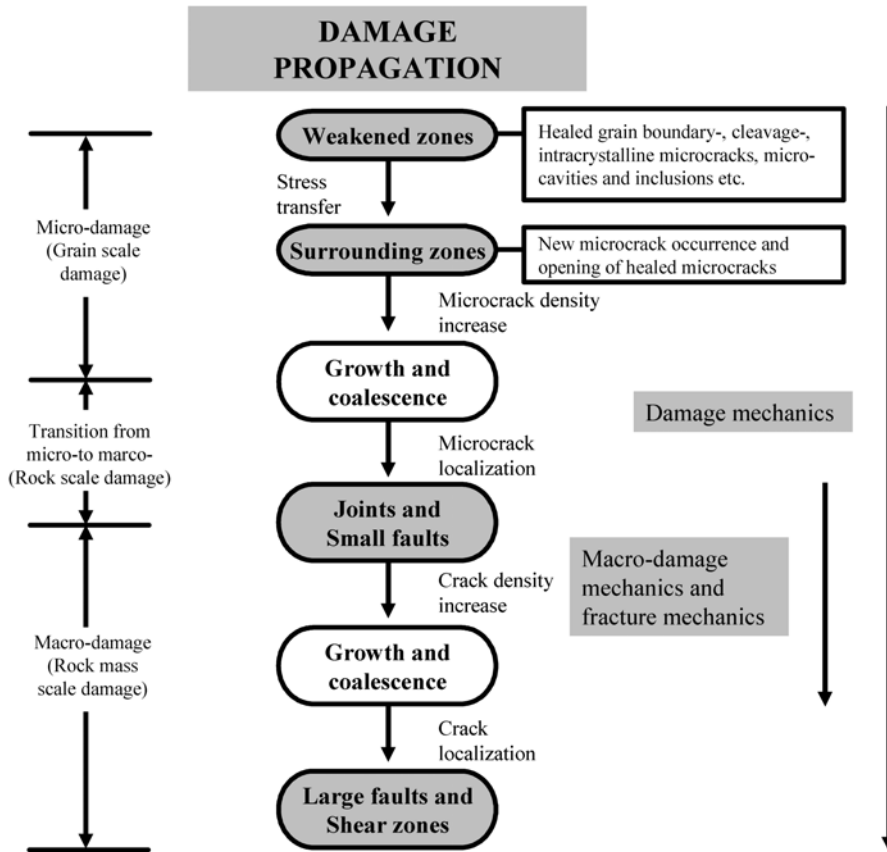


Fig. 1. Schematic diagram of the relationship between damage mechanics and fracture mechanics.

On these points, the precise understanding of the true damage process in rocks on the micro to macro scale is very important and critical for investigating mechanism of damage propagation.

Microcracking during complex loading can result from stress concentration around flaws such as grain boundary microcracks, intracrystalline microcracks and microcavities. Therefore, a detailed knowledge about microcracks may also substantially improve the interpretation of the damage process, microcrack-induced dilatancy and failure in intact rocks.

For these reasons, and to clarify the true micro to macro scale damage process in granite specimens under uniaxial compressive stress, detailed observations of the process were carried out using the experimental system described by Seo et al. (2002). An estimation for the relationship of stress-induced microcrack length between two grains was carried out using Hertzian fracture mechanics.

2. SPECIMENS AND EXPERIMENTAL METHOD

Specimens were made from a block of coarse grained granite (Figs. 2 and 3). The specimens consisted mainly of 36.5% quartz, 56.3% feldspar and 7.2% biotite. The mean size of grains, determined by the linear intercept method, is 3.5 mm. The bulk density and apparent porosity of the



Fig. 2. Photograph of the granite specimen with adhered strain gauge.

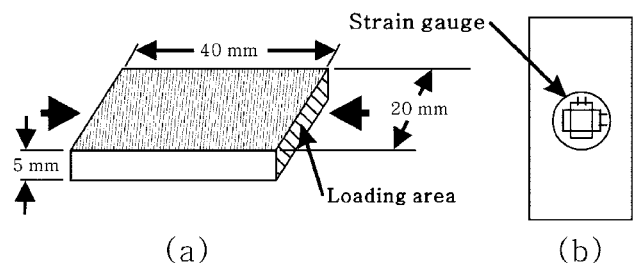


Fig. 3. Schematic diagram of specimen; (a) dimensions of specimen, and (b) location of strain gauge.

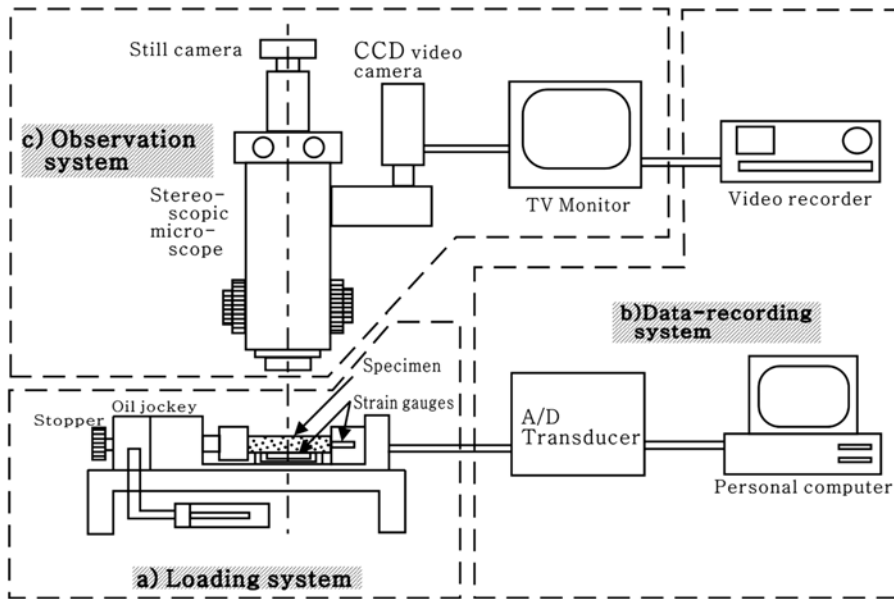


Fig. 4. Schematic diagram of experimental system; (a) loading system, (b) data-recording system, and (c) observation system.

granite are 2.58 g/cm^3 and 0.83% , respectively.

In order to directly observe the initiation and growth pattern of microcracks which are developed in feldspar and at pre-existing grain boundaries, a stereoscopic microscope (Nikon, SMZ-U) with a magnifying power of 110 times was used. A video monitoring system was used for continuous recording and a still camera for intermittent recording (Seo et al., 2002; Fig. 4).

Specimens were loaded at an average stress velocity of 0.02 MPa/sec under unconfined conditions. Axial stress versus axial and lateral strain records were similar for all tests. A representative record of stress, shown in Figure 5, is characterized by four stages: the closing of pre-existing

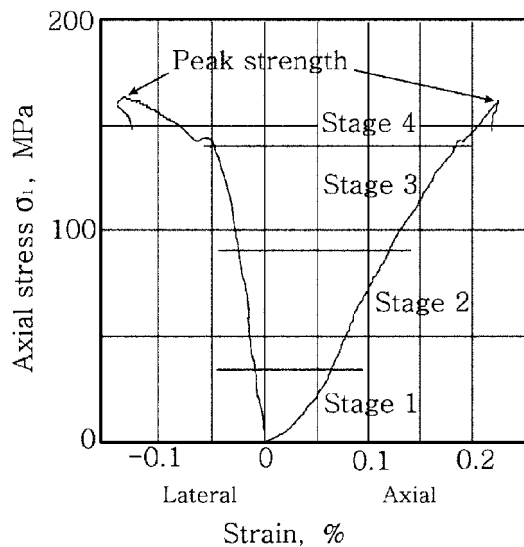


Fig. 5. Typical axial and lateral strains versus axial stress.

microcracks (Stage 1), the linear elastic phase (Stage 2), the dilatancy initiation phase (Stage 3) and the shear fracture development phase (Stage 4) up through the peak strength.

3. MECHANISMS OF MICRO-DAMAGE LOCALIZATION

Microcracks caused by non-hydrostatic stress (termed mechanical microcracks) are chiefly related to the principal directions of the deviatoric stress and seem to be largely independent of relative crystallographic orientations of the various minerals once the microcrack begins to grow. As succinctly stated by Simmons and Richter (1976), stress-induced microcracks in rock are produced when the local stress exceeds the local strength.

Many intracrystalline microcracks which emanate from the pre-existing microcracks are also visible. The mineral cleavage orientations exert a strong influence on intracrystalline microcracking. Under the experimental conditions, mechanical stresses can generate microcracks through at least two mechanisms; elastic mismatch and stress concentrations at grain boundaries.

3.1. Elastic Mismatch

Mismatch of the volumetric properties between a host grain and a totally enclosed grain can produce microcracks (Fig. 6). If the total volumetric strain of the enclosed grain is less than the volumetric strain of the host, then concentric microcracks occur either within the host or along the grain boundary. If the microcrack is a grain boundary microcrack, then it is a coincident grain boundary microcrack and may extend along the entire boundary. On the other hand, if the

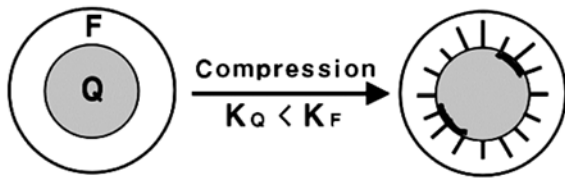


Fig. 6. Microcracking in quartz(Q)-feldspar(F) induced by external stress.

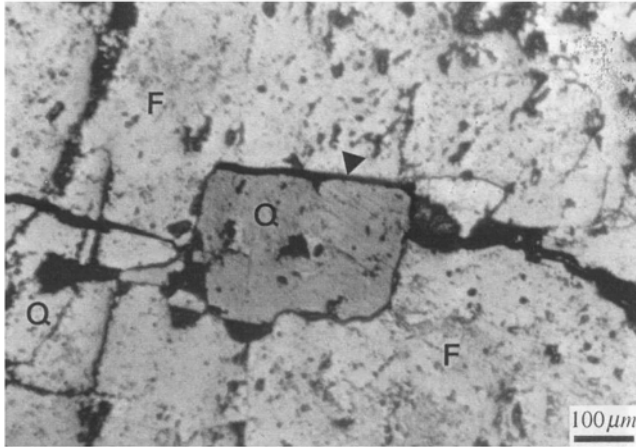


Fig. 7. Quartz(Q) grain enclosed in feldspar(F). Differential elastic mismatch of the two grains caused the microcracks.

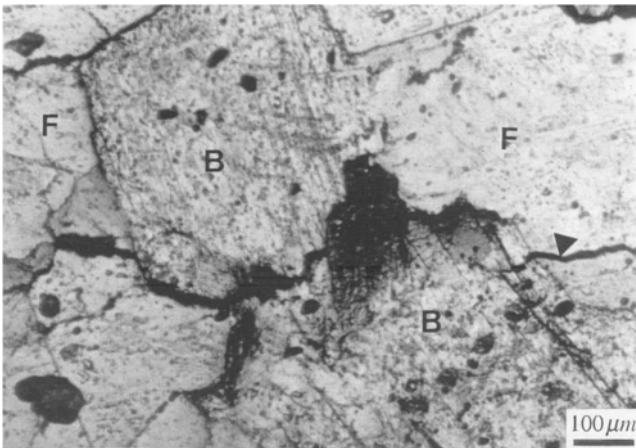


Fig. 8. Biotite(B) grain enclosed in feldspar(F). Differential elastic mismatch of the two grains caused the microcracks.

volumetric strain of the enclosed grain exceeds that of the host by an amount sufficient to overcome the strength of the host, then radiating, non-coincident grain boundary microcracks occur. It is suggested that these microcracks form in response to the differential volumetric strains of two grains due to change of stress (Figs. 7 and 8).

When two different minerals in effectively welded contact are subjected to the same externally applied stress, the stiffer or least compressible mineral will also be subjected

to additional boundary tractions (Dey and Wang, 1981). These can exceed the local tensile strength of bonds at the boundary, leading to extensional microcracks in the stiffer mineral.

3.2. Stress Concentrations at Grain Boundaries

Point and line contacts between portions of grain boundaries are sites of highly concentrated stresses. Tensile stresses exceeding local tensile strength are easily attained and microcracks are almost always extensional, that is, Mode I microcracks in fracture mechanics are initiated in these regions (Figs. 7 and 8). Gallagher et al. (1974) showed the examples of microcracking initiated at grain boundaries in sandstones and for cemented and uncemented aggregates. Hallbauer et al. (1973) found that point loading of quartz grains by other grains was a frequent source of microcrack initiation in quartzite. Batzle et al. (1980) observed new microcracks formed at points of microcrack wall contacts. The analyses of indentation fracture given by Swain and Lawn (1976) and microcrack wedging by Dey and Wang (1981) are also applicable on the grain scale damage.

4. DISCUSSION

Because rocks and rock masses are composed of discrete micro-structural elements, we must be careful to consider these discrete structural elements and mechanical properties of the various grains. To efficiently estimate the damage process, damage mechanics and fracture mechanics have recently been developed as effective tools for estimation. Where the damage propagates from a pre-existing mesoscale or macroscale crack, these methods are very effective. However, a number of studies (Peng et al., 1972; Lockner et al., 1992) have shown that a coalescence and increased density of microcracks cause mesoscale or macroscale cracks, and elastic and plastic properties of rocks are significantly affected by changes in these microstructures. From this standpoint, a precise understanding of the damage process on the micro to macro scale in rocks is very important.

In the past, many attempts (Peng et al., 1972; Hadley, 1975; Tapponier et al., 1976; Kranz, 1979a; Lockner et al., 1992) to observe damage initiation and propagation leading to shear fracture were carried out with thin or cut section or by a SEM observation method after unloading. These studies demonstrated microcrack damage of rock specimens only under no loading or unloading conditions.

Through indirect methods such as AE observations, Lockner et al. (1992) demonstrated the ability to retard unstable fracture propagation so that quasistatic fault growth can be studied on a timescale of minutes to hours. This ability is based on the technique of controlling stress to maintain a constant AE rate. The brittle fracture process was experi-

mentally found to involve three stages; (1) distributed damage during loading of the specimen to peak stress, (2) fault nucleation after peak stress, and (3) fault propagation. Though the results can explain the macro-damage growth successfully, the first stage in the detailed description of micro- to macro-damage is not demonstrated completely.

To clarify the true damage process on the micro to macro scale in granite specimens under uniaxial compressive stress, we have observed the process in much detail. Microscopic observations have revealed that incipient micro-damage is generated from the two grain contact portions by elastic mismatch and by the local stresses exceeding the critical stress intensity factor of the two grains. The direction of micro-damage is parallel or subparallel to the axial stress direction.

Since most grains are in contact with each other, our interpretation is based on the microcrack initiation and growth at the contact portion of grains on the special nature of the inhomogeneous stress field of Hertzian loading (Frank et al., 1967; Wilshaw, 1971). The radius a , as shown in Figure 9, of the circle of contact between spherical two grains is derived from the Hertzian analysis:

$$a^3 = \frac{3}{4}Pr \left[\frac{(1-\nu^2)}{E} + \frac{(1-\nu'^2)}{E''} \right] \quad (1)$$

Where P is the normal load applied on the grain, E'' and E

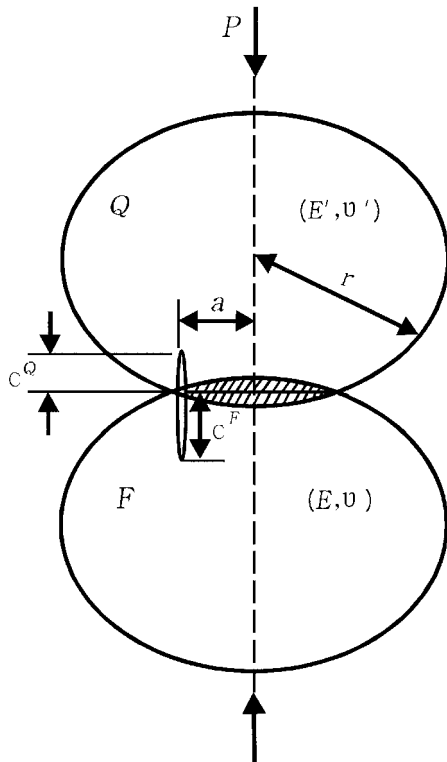


Fig. 9. Hertzian loading arrangement showing a schematic array of grain contact.

are the Young's moduli in the loading direction of quartz and feldspar grains, respectively, and ν' and ν are the corresponding values of the Poisson ratio.

The primary stress-induced intracrystalline microcrack is initiated from the contact portion of the two grains. While the crack is small and normal to the contact surface, the maximum tensile stresses σ_m^Q and σ_m^F in the quartz and feldspar grains are uniformly distributed along the microcrack. Moreover, the microcracking criterion is assumed to be equivalent to that for a single edge microcrack in tension (Wilshaw, 1971). The stress intensity factors K_I^Q and K_I^F , which are function of the stress and microcrack length c^Q and c^F , are given by

$$K_I^Q = 1.12\sigma_m^Q(\pi c^Q)^{1/2} \quad (2)$$

$$K_I^F = 1.12\sigma_m^F(\pi c^F)^{1/2} \quad (3)$$

where

$$\sigma_m^Q = \frac{(1-2\nu')P^Q}{2\pi a^2} \quad (4)$$

$$\sigma_m^F = \frac{(1-2\nu)P^F}{2\pi a^2} \quad (5)$$

By substituting equation (4) and (5) into equation (2) and (3), we obtain the critical forces for the propagation or growth of microcracks in quartz and feldspar grain as

$$P_{critical}^Q = \frac{2\pi a^2 K_{IC}^Q}{1.12(\pi c^Q)^{1/2}(1-2\nu')} \quad (6)$$

$$P_{critical}^F = \frac{2\pi a^2 K_{IC}^F}{1.12(\pi c^F)^{1/2}(1-2\nu)} \quad (7)$$

In the above analysis, we should assume that the local stress field in the vicinity of the microcrack is solely due to the elastic contact between two grains (Zhang et al., 1990). This is a reasonable assumption in our microcrack initiation analysis, since the contact stress concentration is highly localized (Johnson, 1985) and the microcrack at the initiation of Hertzian fracture is very short (Zhang et al., 1990).

We may now evaluate the characteristics for microcrack growth. Since $P_{critical}^Q$ must be equal to $P_{critical}^F$ at a contact portion of two grains, we obtain the following relation;

$$\frac{K_{IC}^F}{K_{IC}^Q} = \frac{(1-2\nu)}{(1-2\nu')} \cdot \left(\frac{c^F}{c^Q}\right)^{1/2} \quad (8)$$

where the critical stress intensity factors of quartz, biotite and feldspar have been measured using the method of Atkinson et al. (1980) for several orientations. And we take their average critical stress intensity factors $0.383 \text{ MPa}\sqrt{m}$ for

Table 1. Physical properties of quartz, feldspar and biotite (from Birch, 1961).

Substance	β	ν	E (GPa)
Quartz	26.8	0.109	87.54
Feldspar	21.0	0.299	54.86
Biotite	23.5	0.200	76.60

β : Compressibility

ν : Poisson's ratio

E : Young's modulus

K_{IC}^Q , $0.375 \text{ MPa}\sqrt{m}$ for K_{IC}^B and $0.364 \text{ MPa}\sqrt{m}$ for K_{IC}^F . The Poisson ratios are obtained as $\nu' = 0.109$, and $\nu = 0.299$ by the equation of Birch (1961) (Table 1). Using these values, we obtain the microcrack growth condition as:

$$c^F = 3.42c^Q \quad (9)$$

$$c^F = 2.17c^B \quad (10)$$

However, if open pre-existing intracrystalline microcracks are developed in quartz and feldspar grains, the Hertzian theory presented here is not appropriate.

5. SUMMARY AND CONCLUSIONS

In order to better understand the fundamental problems of micro-damage localization and propagation and to clarify the true damage process on the microscale to the macroscale in granite specimens under uniaxial compressive stress, we have observed the micro-damage procedure in great detail using a developed experimental system which allows continuous observation of the procedure.

Microcracking at the contact of constituent minerals plays an important role in the nonlinear deformation process and leads to shear fracture of brittle material such as granite.

The response of microcracks to compressive stress is more complex and varied than that to tensile stress. However, the mechanism of microcrack initiation in our granite specimen under uniaxial compressive stress, may be separated into two general cases; one is the case in which feldspar contains a quartz grain. Quartz grains contain many pre-existing intracrystalline microcracks, and these microcrack planes are generally weak with low bond density or strength and low surface energy. Due to applied stresses, surface energy stored in the grain will tend to be relieved on the plane firstly, and then pre-existing intracrystalline microcracks perpendicular to axial stress direction are closed. On the other hand, those microcracks parallel or subparallel to the axial stress direction are opened. The primary stress-induced intracrystalline microcrack in the feldspar grain is initiated from the portion contacting the opened microcrack within the quartz. These stresses induced by microcracks are predominantly tensile in nature, and the directions are

parallel or subparallel to the axial stress direction. The other case is when a feldspar contains a biotite grain oriented in the axial stress direction. Cleavage microcracks are common in biotite. Additionally, localized shear strain of the specimens and ductile shear zones are frequently associated with the presence of biotite.

Inelastic strains in biotite with pre-existing cleavages, quartz grains with pre-existing intracrystalline microcracks and deformation of favorably oriented biotite grain appear to have led to local stress concentration in neighboring phases, resulting in initiation of tensile microcracks. Finally, the important conclusion from in this study is that the analysis technique and processing strategies developed and explored in this study will provide some idea of how microcracking can be triggered from a pre-existing microcrack.

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