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SHORT NOTES

The correlation between stress direction and extinction pattern of radial crystal fibres in synthetic quartz aggregates

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Abstract—Experimentally deformed synthetic quartz aggregates composed of spherulites show a strong relationship between the direction of applied stress (shortening direction) and the extinction pattern of deformed radial fibres as seen in a polarizing optical microscope. This pattern can be used to indicate that deformation has taken place and to determine the orientation of the principal stress responsible for the deformation.

INTRODUCTION

IN AN attempt to study the long-outstanding problems of water-weakening phenomena in quartz, we have recently carried out experiments on synthetic quartz aggregates (Luan *et al.* 1986). These are often composed of spherulitic quartz when the grain sizes of matrix are larger than 30 μm. This Short Note reports observations on the microstructure of the spherulitic quartz fibres. It was found that the change in extinction pattern of this peculiar structure, as seen in a polarizing optical microscope, is well related to the loading direction and, therefore, can be used to determine the orientation of the maximum principal stress.

EXPERIMENTAL DETAILS

The starting material is silica gel with a particle size of less than 1 μm. The as-received gel contains about 1% impurities (mainly Na and Ca) and 12% water as determined by weight loss on ignition at 1300 K. The gel, as-received or pre-dried to reduce the water content, was first cold pressed in a steel die into a pellet 10 mm in diameter and 5–10 mm long. Two or three pellets were then placed in a metal tube (Fe or Cu). Such compacts were hot-pressed in a Paterson gas-medium apparatus (Paterson 1970) at 300 MPa and temperatures in the range 900–1300 K for times between 1 and 5 h to grow different grain sizes in the samples. In the deformation experiments the load was applied immediately after hot-pressing.

MICROSTRUCTURE OBSERVATIONS

Thin sections of hot-pressed and deformed specimens, both perpendicular and parallel to the sample longitudinal direction (loading direction in the case of deformed specimens), were examined by optical microscopy. Spherulitic aggregates of quartz fibres, seen as radiating patterns in thin section, are common in all of the specimens with grain sizes larger than 30 μm.

In undeformed samples (i.e. hot-pressed only), the radial patterns of the crystal fibres in sections prepared both parallel and perpendicular to the longitudinal directions show right angle extinction cross patterns. Within each individual radiating aggregate, extinction patterns seen with crossed polarizers make a regular cross with two arms at right angles, each arm parallel to the analysing or polarizing light transmission direction. These right angle extinction crosses remain unchanged relative to analyzer direction when the thin section is rotated (Fig. 1).

In a thin section perpendicular to the loading direction of a deformed sample, an unchanging right angle extinction cross pattern is also seen as the thin section is rotated. However, in a thin section parallel to the loading direction the extinction cross pattern shifts regularly in relation to the loading direction, when the thin section is rotated. When the loading direction is parallel or perpendicular to the polarization direction, the extinction pattern is a right angle cross. When the thin section is rotated from this position, that is, the loading direction is oblique to the microscope polarization axes, the right angle extinction cross pattern is distorted. The angle

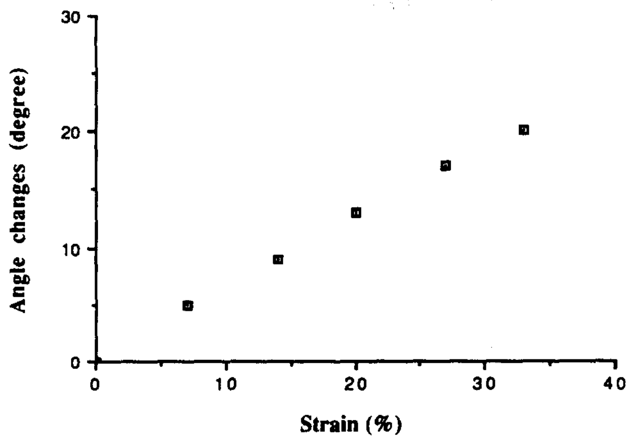

Fig. 3. Plot showing the relationship between angle changes of the extinction cross pattern and axial strains.

between the arms of the cross is no longer a right angle, and the loading direction always bisects the obtuse angle of the extinction cross pattern (Fig. 2). As the extinction cross pattern changes during rotation, the intersection of the two arms of the cross becomes two triple junctions. The link between the two triple junctions is perpendicular to the loading direction. Furthermore, the magnitude of the maximum angle change is proportional to the relative amount of strain the specimen has undergone. The relationship between the angle changes of the extinction cross pattern and axial strains can be described as $\Delta\theta = 0.6\,\varepsilon$ (Fig. 3). The angle changes were measured by drawing lines through the centre of each arm after a thin section was rotated 45° from the position where loading direction is parallel to the analyzer direction of microscope (Fig. 2).

DISCUSSION

It has been noted that quartz crystal fibres grown in a high temperature and high pH environment are normally elongated in the direction of the *c*-axis (Folk & Pittman 1971, Oehler 1976, Frondel 1978). In the present case, the Na and Ca impurities might act as nucleation centres for fibres. Under hydrostatic pressure and high temperature, the opportunity for crystallization of quartz from silica gel is equal in all directions. After nucleation, the crystals grow as fibres parallel to the *c*-axis equally in all directions, forming a spherically symmetrical structure (the *c*-axis elongation can be easily determined by the insertion of a first-order red plate into the microscope light path in the cross polarization mode). Therefore, no matter in which orientation a thin section is cut from an undeformed specimen, a symmetrical radial fibre arrangement is present and, when the thin section is rotated, other fibres are rotated to the extinction directions (Fig. 4a), showing a stationary right angle extinction cross pattern.

However, if intracrystalline slip processes operate during deformation, the symmetrical radiating pattern in sections parallel to the direction of the maximum

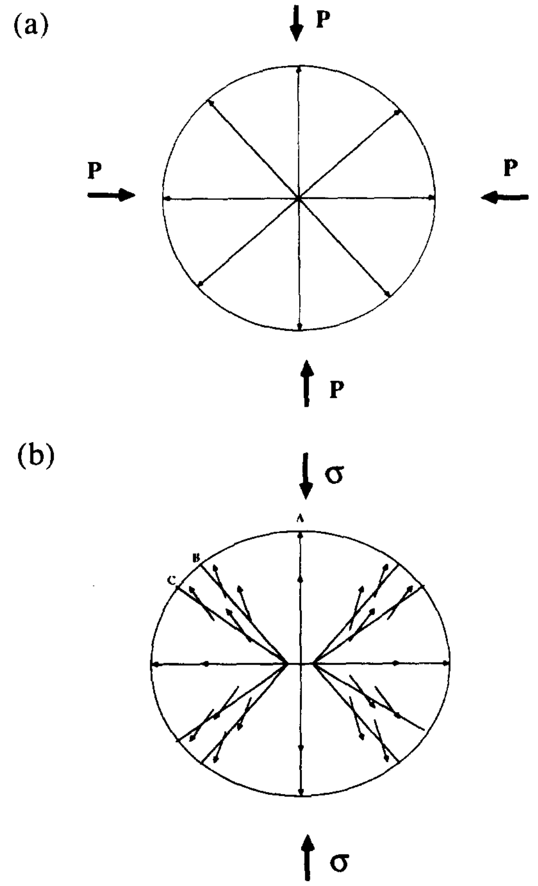

Fig. 4. (a) Schematic drawing showing quartz crystal fibre growth under a hydrostatic condition. (b) Schematic drawing showing quartz crystal *c*-axis rotations in a deformed sample, see text for explanation.

principal stress will be distorted. It is well known that among the slip systems in quartz, basal slip is the easiest (Nicolas & Poirier 1976). In the fibre crystals at 45° to the principal stress direction, basal planes of crystal fibres are subjected to the largest shear stress (highest Schmid factor). Under this shear stress, basal planes rotate away from the maximum principal stress direction and the slip directions simultaneously approach the minimum principal stress direction (Nicolas 1987, p. 100). As a result, the *c*-axes of fibre crystals rotate towards the maximum principal stress direction (Fig. 4b). In Fig. 4(b), when fibre B rotates to the position of fibre A, fibre C will be in extinction instead of fibre B, resulting in the observed distorted extinction cross patterns. Such *c*-axis rotation towards the maximum principal stress direction has been also noticed by Green *et al.* (1970) and by Mainprice (1981) in experimentally deformed fine-grained quartz aggregates. The basal slip planes in crystal fibres parallel and perpendicular to the principal stress directions are subjected to no shear stress, and therefore their crystal orientations remain unchanged while deformation is achieved by a climb mechanism (Ball & White 1978) or by other diffusion processes which cause the quartz originally at the spherulitic centre to move away from the central region, creating a line at the centre of the shifted extinction cross patterns. This discussion suggests that the 'rock' is deformed by intracrystalline

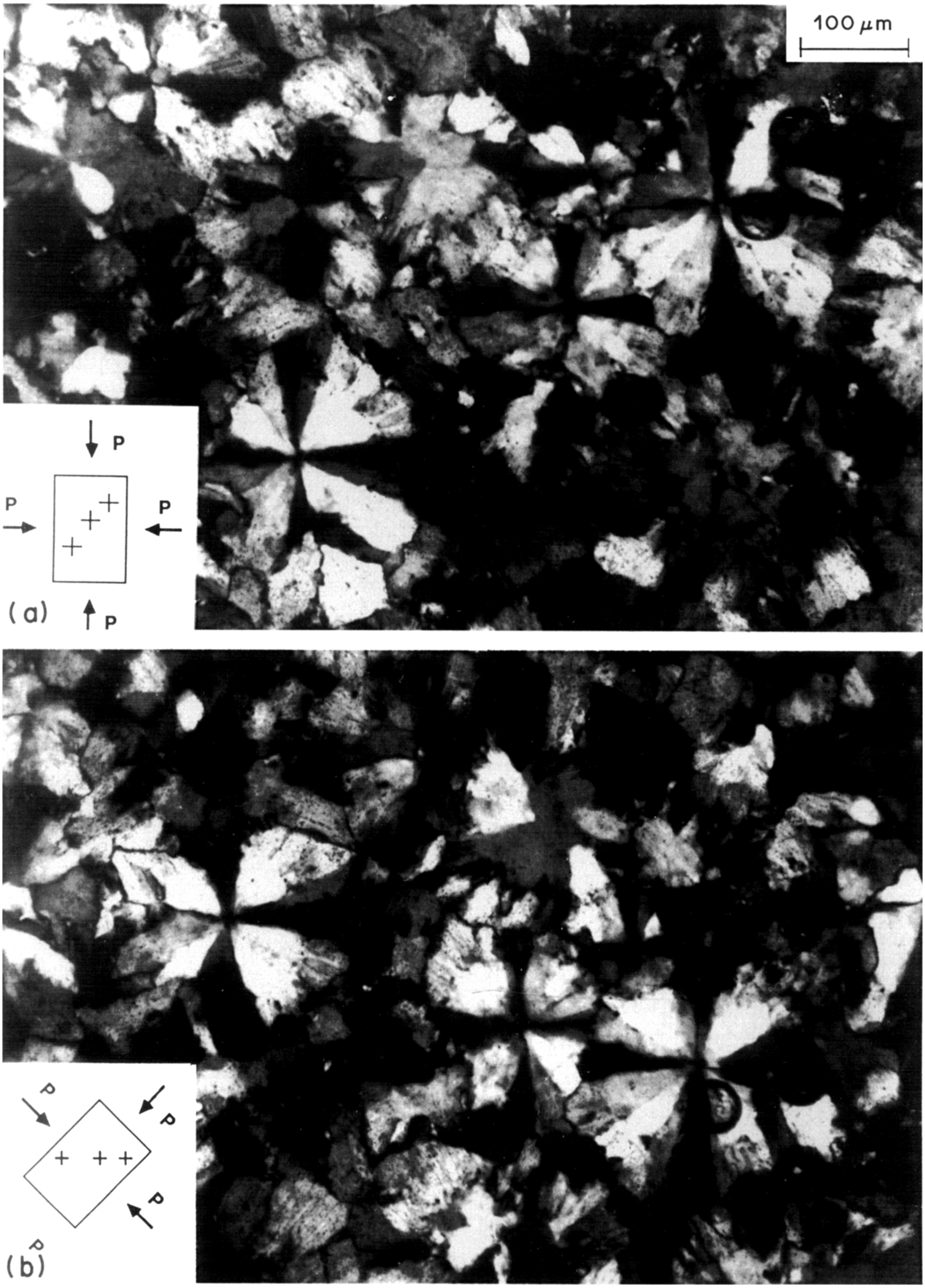

Fig. 1. Photomicrographs of an undeformed sample. (a) The long dimension of sample parallel or perpendicular to polarization directions. (b) Thin section is rotated 45° from (a).

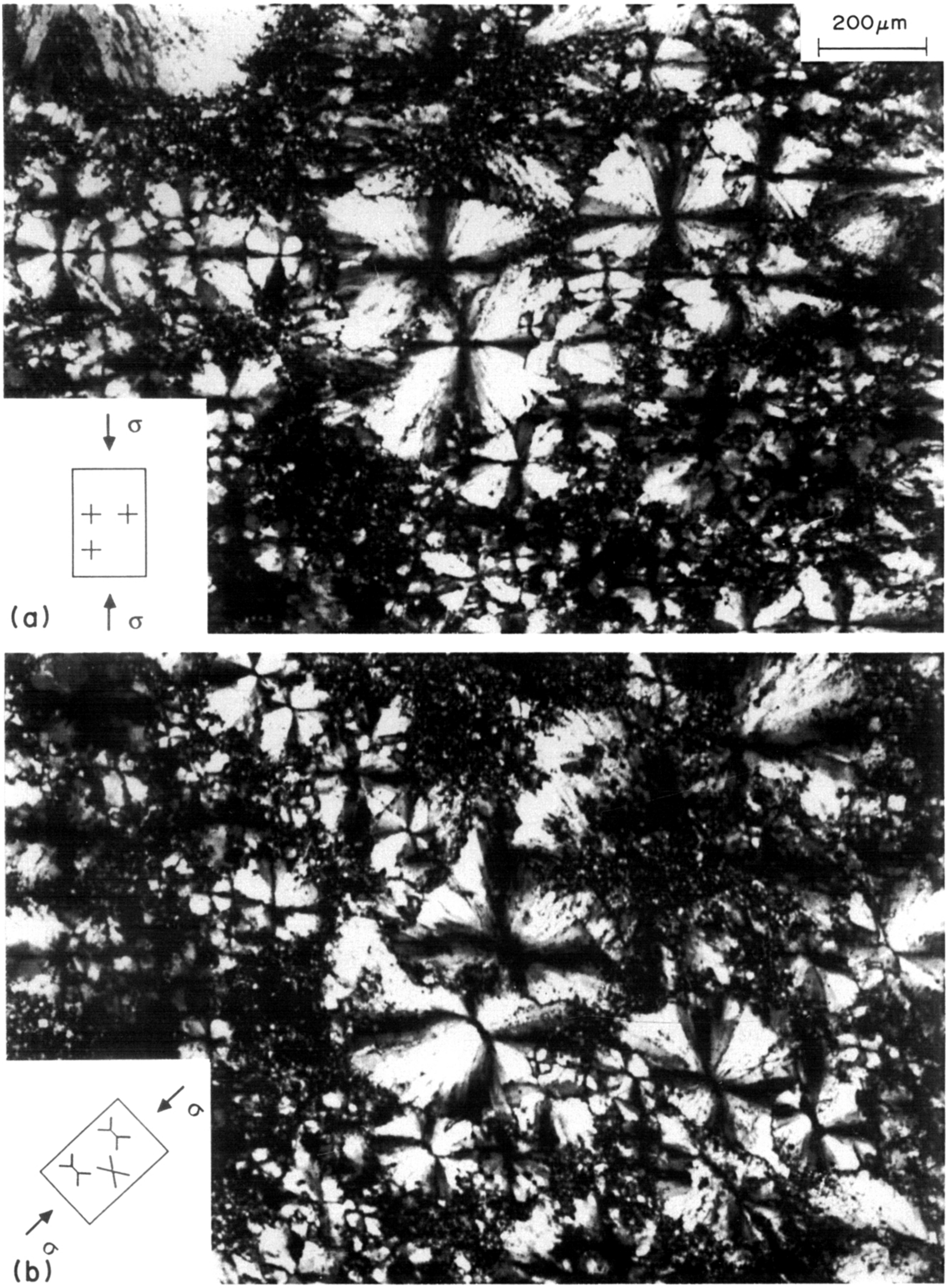

Fig. 2. Photomicrographs of a sample deformed at 1300 K and $5 \times 10^{-5} s^{-1}$ to 15% strain. (a) The long dimension (loading direction) of sample parallel or perpendicular to polarization directions. (b) Thin section is rotated 45° from (a).

slip mechanisms in grains with soft orientations and by some diffusion processes in grains with hard orientations (for explanation of the terms, see Karato 1988). The observed stress exponent values of around 2.5 may lend further support for this interpretation.

Although the above discussion is for the case of length-slow (*c*-axis elongation) spherulitic quartz fibres, the same result would occur for length-fast (*a*-axis elongation) spherulitic quartz fibres in which prism slip systems will be operative. As long as the spherulitic fibres are generated in an isotropic environment, the change in their extinction cross patterns will be related to the principal compressive stress direction in a coaxial deformation mode. It seems apparent that in a simple shear deformation the changes in the extinction cross pattern will be related to the principal strain field.

GEOLOGICAL IMPLICATIONS

The geological importance of chalcedonic spherulites has been discussed previously by other authors in terms of inference of ancient environments and crystallization processes. Radial arrangement of fibres with their *c*-axis and long axis parallel is an identifying characteristic of silicified evaporites in a sulphate-rich environment (Folk & Pittman 1971). Quartz crystallized from a viscous colloid normally assumes a spheroidal habit (Oehler 1976). Although the spherulitic structure of mineral aggregates is uncommon in nature, they are often found in fine-grained quartz aggregates such as chalcedony (Folk & Pittman 1971, Miehe *et al.* 1984) and topaz (Spry 1969). The results presented here show that the change in the extinction cross pattern of spherulitic aggregates of crystal fibres can be used, in a simple way, to determine if tectonic activity has occurred since the formation of such rocks and to determine the principal orientations of the stress (or perhaps strain) field. It can also be used to determine the relative magnitude of the strain involved. This phenomenon also shows that under the same tectonic environment different deformation mechanisms can coexist, depending on crystal orientations relative to the principal stress (or strain) field.

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