Earth and Planetary Science Letters 442 (2016) 157–161

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

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Three sets of crystallographic sub-planar structures in quartz formed by tectonic deformation

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ARTICLE INFO

Article history:
Received 19 October 2015
Received in revised form 16 February 2016
Accepted 1 March 2016
Available online xxxx
Editor: J. Brodholt

Keywords:
fine extinction bands (FEB)
planar deformation features (PDF)
shock metamorphism
low temperature tectonic deformation

ABSTRACT

In quartz, multiple sets of fine planar deformation microstructures that have specific crystallographic orientations parallel to planes with low Miller–Bravais indices are commonly considered as shock-induced *planar deformation features* (*PDFs*)[1] diagnostic of shock metamorphism. Using polarized light microscopy, we demonstrate that up to three sets of tectonically induced sub-planar *fine extinction bands* (*FEBs*), sub-parallel to the basal, γ, ω, and π crystallographic planes, are common in vein quartz in low-grade tectonometamorphic settings. We conclude that the observation of multiple (2–3) sets of fine scale, closely spaced, crystallographically controlled, sub-planar microstructures is not sufficient to unambiguously distinguish PDFs from tectonic FEBs.

1. Introduction

The occurrence of multiple sets of fine, perfectly planar, *planar deformation features* (*PDFs*) in quartz with specific crystallographic orientations parallel to low Miller–Bravais indices is an accepted criterion for the identification of shock metamorphism (e.g., Alexopoulos et al., 1988; Stöffler and Langenhorst, 1994; French and Koeberl, 2010). The identification of PDFs requires that the structures can be reliably distinguished from structures formed by crystal growth or tectonic deformation, such as healed fractures or *fine extinction bands* (*FEBs*) (Derez et al., 2015). We recently proposed the term FEB (Derez et al., 2015) to describe structures generally called *deformation lamellae* (French and Koeberl, 2010; Reimold et al., 2014), or short-wavelength undulatory extinction (Trepmann and Stöckhert, 2013). Using polarized light microscopy, shock-induced PDFs do, indeed, share a number of microstructural characteristics with low-temperature tectonic sub-planar FEBs: both PDFs and FEBs can be parallel and thin, penetrate the grain entirely or partly, never cross grain boundaries and be decorated with tiny fluid inclusions. However, PDFs are generally extremely planar, whereas FEBs are more lenticular (Reimold, 1994; Hamers and Drury, 2011; Hamers, 2013; Reimold et al., 2014). Moreover, PDFs are frequently present in three or more sets in highly-shocked rocks, whereas tectonic FEBs are thought to occur with usually one set and rarely with two sets per grain (Lyons et al., 1993; French and Koeberl, 2010). Finally, FEBs are reported to have a wide range of crystallographic orientations, whereas PDF orientations are parallel to specific planes (French and Koeberl, 2010 and the references therein).

The problem of mis-identification of PDFs has been discussed in an editorial by Reimold et al. (2014): *"What many of the cases of questionable impact structures have in common is reporting of supposed presence of PDFs, mainly in quartz, as evidence for impact. Frequently, this can be revealed to be based on obvious misperceptions of what does and what does not constitute true PDFs"*. Reimold et al. (2014) also note that *"The optical microscope may not be sufficient to identify the true nature of apparently planar microstructures; however, in all the cases of alleged impact craters mentioned here, the misidentified microstructures can be easily discriminated from bona fide shock deformation on the basis of the published photomicrographs"*. Some studies relevant to this study are those on the Warburton structures (Glikson et al., 2013, 2015) and the site of the 1908 Tunguska airburst explosion (Vannucchi et al., 2015). In the case of Tunguska, Vannucchi et al. (2015) identified an older event of shock metamorphism and claimed this was produced by an internal explosive eruption. In these papers the quartz microstructures were proposed to be PDFs rather than tectonic FEBs, partly because it is assumed that tectonic FEBs occur with a maximum of two sets per single grain and have a wide range of crystallographic orien-

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[1] Abbreviations used: planar deformation feature (PDF), fine extinction band (FEB).

http://dx.doi.org/10.1016/j.epsl.2016.03.005

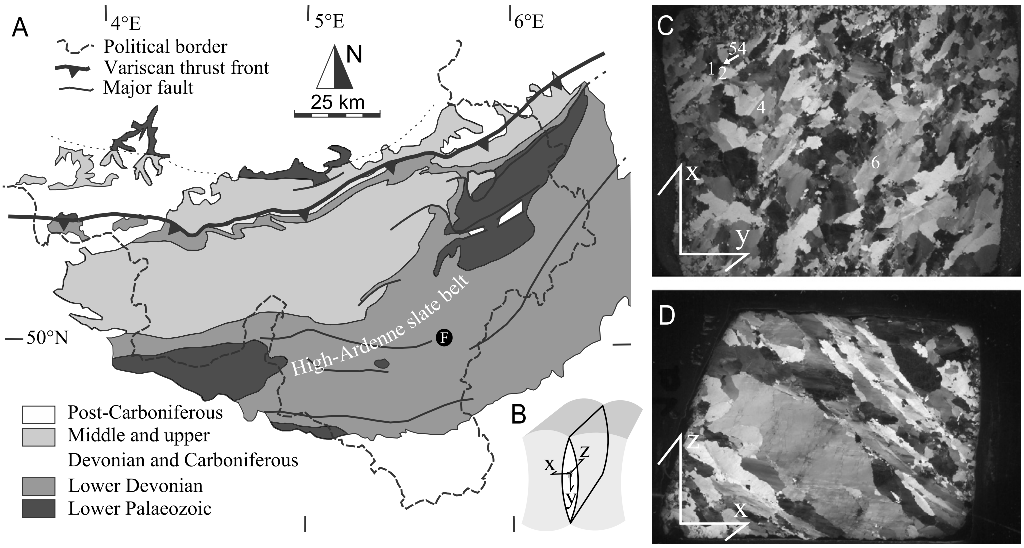

Fig. 1. (A) Geological map of Southern Belgium displaying the main tectonostratigraphical entities; location of quartz vein sample at Fosset (F) (50°01′25″N, 5°33′48″E, WGS84). (B) Line drawing of the studied intermullion vein with sample reference frame (x, y, z). (C, D) Polarized light microscopy images with crossed polarizers of the x–y and x–z sections, respectively.

tations (French and Koeberl, 2010). In the case of the Warburton structure Glikson et al. (2013) also presented some TEM data to support their interpretation of shock microstructures.

Microstructures that show more than two (multiple) sets of sub-planar crystallographically controlled lamellae, do not fit with either the FEB or the PDF criteria: the criteria for these microstructures assume a maximum of two sets for FEBs but true planarity for PDFs (Reimold, 1994; Reimold et al., 2014; Schmieder et al., 2015). This discrepancy suggests that some issues remain with the commonly used criteria that multiple sets of planar structures, with low index crystallographic orientations are an indication of shock metamorphism.

In this paper we re-examine the crystallographic characteristics and number of FEB sets formed in a clear example of tectonically deformed vein quartz. We have at our disposal a unique dataset from an extensive quartz vein study in the High-Ardenne slate belt in Belgium (e.g., Kenis et al., 2005; Van Noten et al., 2012; Jacques et al., 2014). The quartz vein is from a typical sub-greenschist metamorphic slate belt, for which no evidence whatsoever exists for any shock metamorphism. The sub-planar microstructures observed are therefore definitively tectonic FEBs. Contrary to earlier work, we recently reported that two and three cross-cutting FEB sets are very common in vein quartz in this tectonometamorphic environment (Derez et al., 2015). Here we look in detail at the orientation of three cross-cutting FEBs to determine whether there is any similarity to PDFs.

2. Sample and methods

This study focuses on quartz grains of a typical intermullion quartz vein (Kenis et al., 2005, and the references therein) within a micaceous sandstone bed, belonging to the early Devonian Anlier Formation (Pragian), sampled at Fosset (Belgium). The sampled vein is representative of the ubiquitous quartz veins in the central epizonal part of the High-Ardenne slate belt (Fig. 1A) located at the northern extremity of the Central European Variscides. The main deformation affected the High-Ardenne slate belt from the late Visean until the early Moscovian (325–310 Ma) under sub-greenschist conditions (Fielitz and Mansy, 1999). For similar aged bedding-normal veins in Bertrix (Belgium), Kenis (2004) deduced a near-lithostatic fluid pressure between 155 MPa and 255 MPa, based on microthermometry of primary fluid inclusions, in combination with an independent chlorite geothermometer indicating veining around 390 °C (Verhaert, 2001). The quartz vein was oriented at a high angle to the bedding, as a result of a regional hydraulic fracturing event during the latest burial stages (Kenis et al., 2005; Van Noten et al., 2012). Later, layer-parallel shortening caused cuspate–lobate folding (mullions) of the pelite–quartzite interfaces (Fig. 1B) during the early stages of the Variscan orogeny (Kenis et al., 2005). The quartz vein contains elongate to blocky grains that increase in size from the vein wall towards the center of the vein (Fig. 1C and D). The vein quartz shows a high degree of undulatory extinction and contains many subgrains. The edges of the grains are highly bulged. In common with other vein quartz, the grains show a weak preferred orientation, as expressed by a broad c-axis girdle orthogonal to the sample y-axis.

We studied two orthogonal thin sections to ensure that all variants of the lamellae were visible, investigating 140 grains in the x–y section and 55 grains in the x–z section. Polarized light images were taken with a Leica DMLP light microscope equipped with a DP 200 camera (KU Leuven). The orientation of the FEBs was measured with respect to the c-axes using an Ernst Leitz Wetzlar universal stage mounted on an Ernst Leitz Wetzlar light microscope (KU Leuven). The full crystal lattice orientation was determined by means of electron backscatter diffraction on a FEI Nova Nano SEM 450 equipped with an Edax Hikari xp camera (KU Leuven).

3. Results

We first describe the FEB morphology before describing the complete orientation.

3.1. Petrography

FEBs are alternating narrow bands (generally <5 μm) with a small difference in crystal lattice orientation (up to 3°) that can have an alternating high and low concentration of fluid inclusions. For a more extensive description of FEBs we refer to Derez et al. (2015). In total we observed twelve grains containing three sets of FEBs per grain, all in the x–y section. Grains containing one and two visible FEB sets occur in both sections. Of the grains studied 53% and 19% contain one visible FEB set in the x–y and x–z sections, respectively; 73% and 18% of the studied grains contain two visible FEB sets in the x–y and x–z sections, respectively. Multiple

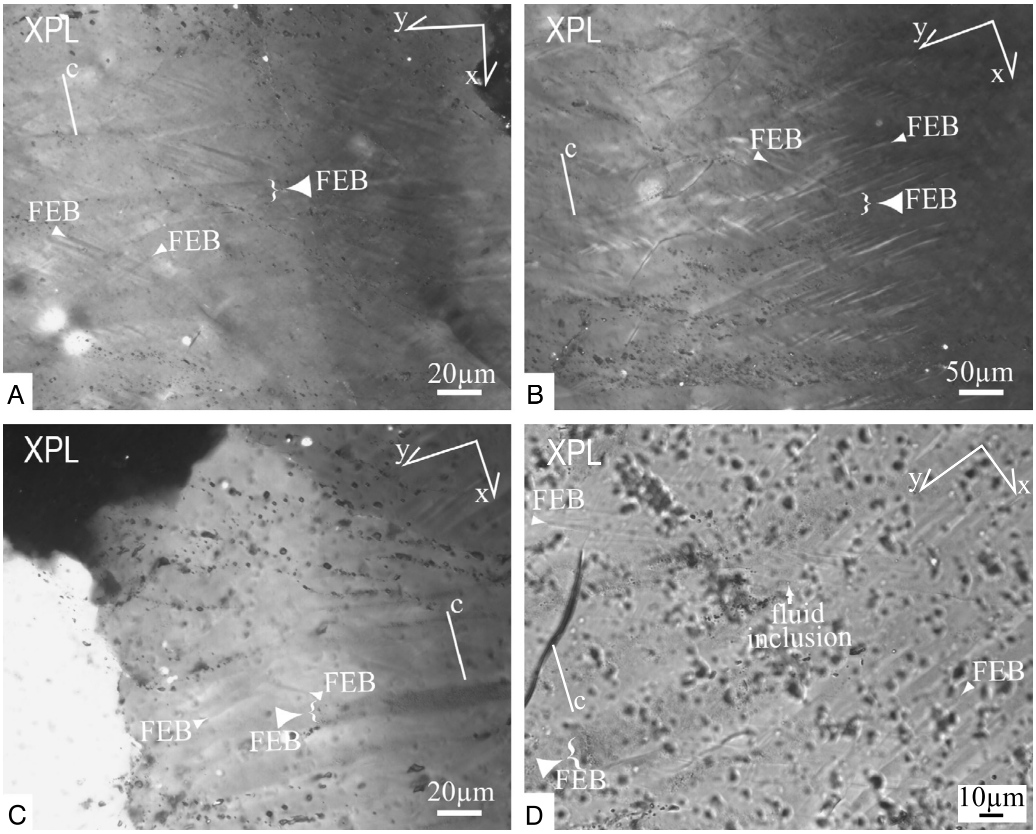

Fig. 2. Polarized light microscopy images of three FEB sets in (A) grain 1, (B) grain 4, (C) grain 54, (D) grain 4. The dark spots are fluid inclusions. c: projection of the *c*-axis in the thin section plane; FEB: fine extinction band; XPL: cross polarized light.

FEB sets visible in a single grain can have very different appearances (width, extinction angle). While one FEB set can cross the whole grain, another set can be restricted to a certain part of the grain. The FEB boundaries are generally slightly undulating and not completely parallel to one another. The three FEB sets together are only visible in a limited region within the grains.

In all the grains in which three FEB sets are observed, the traces of each of the three FEB sets consistently show the same orientation with respect to the projection of the *c*-axis to the thin section (hereafter named the projected *c*-axis) (Fig. 2). FEBs that are similarly oriented with respect to the projected *c*-axis, have similar morphologies in the polarized light microscope; the two FEB sets tracing between 60° and 75° to the projected *c*-axis are narrower (up to 5 μm wide) than the set tracing near 90° to the projected *c*-axis (up to 10 μm wide). Small inclusions are mostly observed (Fig. 2D) in alternating bands of the broader FEB set. These inclusions are mostly too small to be resolved in detail with polarized light microscopy, they are smaller than ∼300 nm, which is the optimum resolution of a polarized light microscope based on the Rayleigh criterion for a 50× objective lens and a numerical aperture of 0.75. More bands can frequently be observed at higher magnification in between the FEBs that have an observable difference in extinction angle (Fig. 2D). These bands are only visible with a high light intensity and are generally too thin (∼ 1 μm thick) to distinguish whether or not different extinction angles occur.

3.2. *FEB orientation with respect to the section and the crystal lattice*

The orientation of the FEBs was measured (using universal stage) in three grains that contain three visible FEB sets (grains 1, 4 and 6, Fig. 3A–C). These FEBs are all similarly oriented with respect to the sample reference frame and are all approximately perpendicular to the x–y section. By combining FEB orientation data with respect to the sample reference frame (universal stage) and crystal lattice orientation data of the *c*- and the *a*-axes (electron backscatter diffraction), the orientation of the FEBs with respect to the crystal lattice is assessed in the (0001)-stereographic projection. The FEBs are generally clustered around poles to the basal, γ, ω and π planes, particularly in grain 6. The FEBs in grains 4 and 1 are more scattered and only a few FEBs are parallel to the basal and γ crystal planes in grain 1. The orientation error of the FEBs in grain 1 is higher due to the lower visibility of these FEBs in the universal stage. Fig. 3D shows the basal orientation of the FEBs in a grain with one FEB set. In other grains more FEBs subparallel to crystallographic orientations with low Miller–Bravais indices were identified (see supplementary material). Of the 188 measured FEBs 97 fall within the small circles of the most important PDF poles reported for shocked quartz and are therefore said to be indexed as being parallel to these crystallographic orientations. In the literature (e.g. French and Koeberl, 2010), angle distributions of orientations that index as PDFs are typically presented in a histogram as shown for our data in Fig. 3E.

4. Discussion and conclusions

Based on our extensive study of vein quartz in the High-Ardenne slate belt (Kenis et al., 2005; Van Noten et al., 2012; Jacques et al., 2014; Derez et al., 2015), we demonstrate that multiple (two and three) FEB sets are a common deformation microstructure in this particular sub-greenschist environment. Moreover, because the High-Ardenne slate belt is typical for low-grade metamorphic slate belts worldwide, we are confident that the occurrence of multiple FEB sets in quartz is common in low-grade tectonometamorphic settings. We suggest that the scarcity of multiple FEB sets reported in the literature may primarily be because the multiple FEB sets can only be observed clearly in cases where

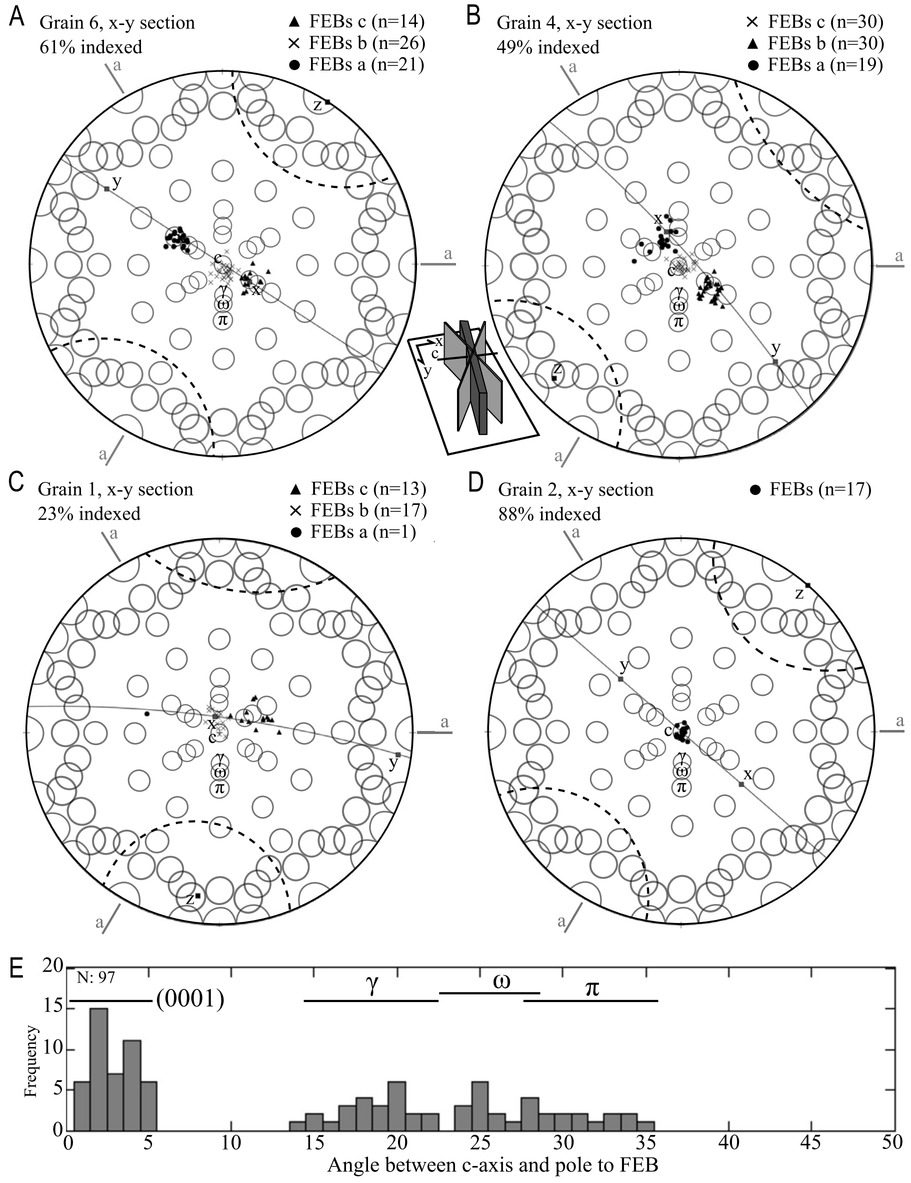

Fig. 3. The orientation of different sets of fine extinction bands (FEBs) identified in the x–y section for (A) grain 6, (B) grain 4, (C) grain 1, and (D) grain 2. Poles to FEBs are plotted in the (0001)-stereographic equal-angle, lower hemisphere projection which shows the most important PDF poles reported for shocked quartz γ {10–14}, ω {10–13}, and π {10–12} (small circles have 5° radius) (Ferrière et al., 2009). The dashed blind circle shows where FEBs could not be measured with the universal stage; the thin section is indicated with a full line, the x, y, z-axes with squares; inset illustrates the orientation of the FEBs with respect to the crystallographic c-axis and the x–y section. (E) shows the distribution of the angles between the c-axis and the poles of the 97 indexed FEBs. The horizontal lines show the 5° spread around the basal, γ, ω and π orientations, bin width 1°.

the FEBs are approximately orthogonal to the thin section. In addition, we find that three FEB sets are not easily detected in the polarized light microscope. Therefore, the scarcity of reported multiple FEB sets may also be due to an observational bias: structural geologists may not have paid particular attention to these sub-planar deformation features in quartz, contrary to researchers seeking evidence for impact.

Our detailed analysis also demonstrates that with polarized light microscopy FEBs have characteristics in common with PDFs. The occurrence of three FEB sets is common. These FEBs can be parallel to the basal, ω, and π crystallographic planes, commonly reported as diagnostic PDF orientations (e.g. Alexopoulos et al., 1988; Stöffler and Langenhorst, 1994), although with a lower indexing percentage than PDFs. For indexing we, however, also took into account the orientation of the a-axes (derived from electron backscatter diffraction), which results in a lower indexing degree than when only the c-axis is taken into account, as generally done for PDF identification (Ferrière et al., 2009). Single FEB sets parallel to the basal plane, commonly seen as diagnostic for shock metamorphism (Carter, 1965), also occur (Fig. 3D). FEBs can be very closely spaced (<5 μm), lacking a clear difference in birefringence (Fig. 2D), which is also considered characteristic of PDFs (French and Koeberl, 2010). PDFs are further reported to occur decorated with tiny fluid inclusions less than 2 μm in size (Reimold et al., 2014), which is also observed in the case of our FEBs. Although FEBs can be straight (e.g., Derez et al., 2015, Figs. 2D and F), the FEB boundary traces change slightly in orientation, so each individual FEB is not planar and the FEBs are not entirely mutually parallel. PDFs, on the other hand, are perfectly planar (e.g. Hamers, 2013; Reimold, 1994; Reimold et al., 2014). Re-deformed non-planar PDFs have been reported (e.g., Trepmann and Spray, 2004; Glikson et al., 2015), though in order to fit the PDF criteria these should still be parallel-walled and crystallographically controlled (Reimold et al., 2014).

We suggest that the presence of multiple tectonic FEBs subparallel to the basal, γ, ω, and π crystallographic planes, is common in quartz in low-grade tectonometamorphic settings. We conclude therefore that shock-induced PDFs and tectonic FEBs cannot be distinguished unambiguously solely based on their multiplicity and specific crystallographic orientations. Our findings thus support the conviction that, in light microscopy studies, PDFs can only be identified unambiguously on the basis of their perfectly planar and parallel nature (Reimold et al., 2014). PDFs are planar with respect to the crystal lattice. If the quartz grains have been plastically deformed before or after shock metamorphism, then the PDFs will follow the curved lattice (e.g. Trepmann and Spray, 2004). In cases where more than one set of PDFs or FEBs occur parallel to low index crystallographic planes, then both planarity (with respect to the crystal lattice), parallelism and the occurrence of more than three sets is needed to identify PDFs. If this is not the case, transmission electron microscopy (Cordier et al., 1994; Vernooij and Langenhorst, 2005), as well as cathodoluminescence studies with a scanning electron microscope (Hamers and Drury, 2011), should be used to provide additional evidence for the presence of shock-induced PDFs, or to support any impact hypothesis.

Acknowledgements

We would like to thank the different anonymous reviewers and prof. A. Garde, prof. H. Stunitz and Dr. L. Ferrière for careful reading of the first manuscript and the useful suggestions that have improved this paper. We are very thankful to Ir. T. Vanderdonck for performing the electron backscatter diffraction analysis. This research is financially supported by research grant OT/11/038 of the Onderzoeksfonds KU Leuven.

Appendix A. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.epsl.2016.03.005.

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