Three-dimensional deformation analysis using deformed vein sets for quantifying solution mass transfer in metasediments

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Background and Objective

Quantitative evaluation of finite deformation, with the three components of strain, rotation, and volume change, is essential for understanding rock deformation processes in orogenic belts. However, conventional methods of deformation analysis generally assume plane strain, where there is no stretching perpendicular to the observation plane, or constant volume throughout deformation. These assumptions may overlook volume changes associated with solution mass transfer processes, as well as three-dimensional deformation arising in complex tectonic settings such as zones of oblique convergence or areas around expanding magmatic intrusions, potentially leading to erroneous geological interpretations. To overcome these limitations, we introduce the Mohr-cyclide for finite deformation (Soejima & Wallis, in prep), which is a new geometric construction that can completely describe three-dimensional finite deformation. We propose an analytical method based on this construction to quantify the three-dimensional deformation history of rocks using field data of deformed vein sets. We apply this method to deformed metasediments in the Ryoke metamorphic belt, Southwest Japan, to discuss the relationship between deformation and mass transfer driven by deep crustal fluids.

Methodology: Mohr-cyclide and Automated Inverse Analysis Algorithm

The Mohr-cyclide is a fourth-degree polynomial surface that extends the two-dimensional Mohr circle into three dimensions (Coelho & Passchier, 2008), serving as a graphical tool to represent the three-dimensional deformation gradient tensor. This geometric figure can represent not only the shape and orientation of the strain ellipsoid but also the rotation and volume change components. We constructed a new algorithm to inversely analyze the geometric parameters of the Mohr-cyclide from data on the orientation and shape type (extended, shortened, etc.) of deformed vein sets, which can be measured in the field. By performing an optimization search using tens of thousands of deformation models against the observed data, this algorithm enables the estimation of complete three-dimensional deformation parameters, including the stretch in the direction of the rotation axis. This allows for the quantitative detection of deviations from plane strain (transextension or transcontraction) and three-dimensional volume changes.

Application Results: Mass Transfer and Non-plane Strain in the Ryoke Belt

We analyzed deformed quartz vein sets at 8 outcrops of metasediments distributed in the Ryoke metamorphic belt in the Hongu-san area, Aichi Prefecture. The analysis yielded the following insights. 1. Detection of significant volume increase: We identified outcrops showing a volume increase of up to approximately 50%. This suggests that regional and active syn-tectonic fluid activity occurred in the Ryoke belt, accompanied by large-scale mass transfer involving an external supply of silica. 2. Detection of non-plane strain: At outcrops near the contact with Shinshiro tonalite, we detected non-plane strain accompanied by approximately 20% stretching in the direction of the rotation axis (transextension). This suggests that the deformation of the host rock caused by pluton intrusion cannot be ignored.

Conclusion

The three-dimensional analysis method using deformed vein sets developed in this study is a powerful

tool for reconstructing rock deformation that combines analyses of strain, rotation, and volume change in a single approach. The results of applying this tool in the Ryoke belt suggest that fluid migration in the deep crust can significantly alter rock volume and that pluton intrusion has a non-negligible influence on the three-dimensional deformation of host rocks.

[Reference]
Coelho, S., & Passchier, C. (2008). Mohr-cyclides, a 3D representation of geological tensors: The examples of stress and flow. *Journal of Structural Geology*, *30*(5), 580-601.

Keywords: Finite deformation, Mohr circle, Mohr-cyclide, Deformed mineral vein, Ryoke belt, Solution mass transfer

