Significance of Deformation Microstructures of Mineral Grains in the Study of Diffusivity and Permeability in Intact Granitoids

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Abstract

Microscopic observation of intact granitoids reveals that different kinds of deformation microstructures within mineral grains result from various processes; deformation microstructures due to microcracking, microfaulting, microfolding, recovery and recrystallization. Some samples of intact granitoids exhibit only the undulose extinctions of quartz, plagioclase and biotite, while the others show abundant deformation microstructures, indicating that they contain many submicron-sized apertures in them. These deformation microstructures may be important as a possible cause of diffusivity and permeability of intact granitoids.

Water pathways within intact granitoids are detected in an experiment based on the capillarity of a KMnO_4 solution. The EPMA images show that MnO_2 is present on the polished surfaces of orthoclase, plagioclase and biotite grains after the experiment. MnO_2 occurs in three ways: on grain-boundaries and/or intragranular cracks, in clustered submicron-sized pores, and dispersed on plagioclase and biotite grains. These modes of occurrence suggest that water pathways in intact granitoids are not only grain-boundaries and/or intragranular microcracks, but may also be mineral grains themselves that are permeated with submicron-sized apertures possibly having formed in deformation microstructures.

It follows that deformation microstructures should be most apparent at sites where abundant submicron-sized apertures are present. There are differences of deformation grade even in intact granitoids. This means that some intact granitoids include relatively few deformation microstructures, whereas others include many deformation microstructures. Since deformation microstructures are possible pathways for water, it is very likely that the diffusivity and permeability of a granitoid sample correlates with the nature and abundance of its included deformation microstructures. These microscopic observations and experiment suggest that deformation microstructures, as well as microcracks, should be studied much more thoroughly with regard to the diffusivity and permeability of intact granitoids.

Key words: deformation texture, diffusivity, permeability, granitoid

1. Introduction

Microcracks in the mineral grains of intact granitoids have been intensively studied from the viewpoint of material transport properties such as diffusivity and permeability. This interest arose because increases in diffusivity or permeability of intact granitoids are mainly attributed to microcracks that originate from tectonic, thermal, and other stresses. In addition to the microcracks seen under a microscope, various

kinds of submicron-sized apertures, including grain boundaries and pores as well as submicron-sized microcracks, are also important as water pathways in intact granitoids^{1)~3)}. The deformation microstructures of mineral grains exhibit various kinds of submicron-sized apertures, which may be important as possible causes of diffusivity and permeability, especially for intact granitoids with very few microcracks or with low permeabilities around 10^{-6} to $10^{-12} \text{ m/s}^{4)}$. This paper describes a series of deformation microstructures of the mineral grains in intact granitoids, and also presents the result of experiment on the permeability of intact granitoids. These microscopic observations and experiment suggest that deformation microstructures, as well

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Table 1 Deformation textures in intact granitoids

Deformation textures in five kinds of mineral grains (left-side column) are arranged according to their types (uppermost row)

	Microcrack	Microfault	Microfold	Undulose extinction	Subgrain
Quartz	Microcrack • irregular • subparallel • <i>en echelon</i>			Undulose extinction • simple • irregular • banded	Subgrain • isolated • clustered • twig-like
Plagioclase	Microcrack • irregular • subparallel	Microfault Slipped cleavage Slipped twin	Bent twins Kink band	Undulose extinction • simple • irregular • banded	Subgrain • isolated
Micas	Microcrack • irregular Pseudostylolite Cloven cleavage	Microfault Slipped cleavage	Bent cleavages Kink band Cusped cleavages <i>En echelon</i> wrinkles	Undulose extinction • simple	
Orthoclase	Microcrack • irregular	Microfault		Undulose extinction • simple • irregular	
Amphiboles	Microcrack • irregular			Undulose extinction	

as microcracks, should be studied much more thoroughly with regard to the diffusivity and permeability of intact granitoids.

2. Deformation textures of mineral grains

Even for intact granitoids, some constituent mineral grains exhibit deformation microstructures to a greater or lesser degree. Microscopic observation reveals that different kinds of deformation textures result from various processes, as follows (Table 1).

2.1 Deformation textures due to various processes

Textures due to microcracking: Microcracks generally form in quartz, plagioclase, micas, orthoclase and amphiboles and they may have irregular, subparallel, or *en echelon* patterns (see the review by KRANZ⁵⁾). Irregular microcracks generally form in all of these five kinds of mineral grains, although subparallel microcracks preferentially form in quartz and plagioclase⁶⁾. *En echelon* microcracks with lengths less than about 10⁻⁴m mainly form in quartz grains^{6),7)}. Pseudostylolites and cloven cleavages form in biotite grains⁸⁾. Pseudostylolites are a deformation texture resembling stylolites in limestones (Photo 1-a), and cloven cleavages refer to cloven and open cleavages that are generally filled with minerals such as chlorite or quartz (Photo 1-b).

Textures due to microfaulting: Microfaults generally form in plagioclase, biotite and orthoclase

(Photo 1-c), but rarely in quartz and amphiboles of intact granitoids⁸⁾. Slipped cleavages form in plagioclase and biotite^{8),9)}. Slipped twins form in plagioclase⁸⁾ (Photo 1-d).

Textures due to microfolding: Bent twins generally form in plagioclase and bent cleavages generally form in biotite^{8),10),11)} (Photo 1-e). Kink bands also generally form in plagioclase and biotite, as described in many literatures^{9),12),13)}. Cusped cleavages and *en echelon* wrinkles form in biotite grains⁸⁾ (Photo 1-f, -g).

Textures due to undulose extinction: Undulose extinction (i.e., undulatory or wavy extinction) occurs generally as simple, irregular or banded patterns^{8),14)}. Quartz and plagioclase grains exhibit these three patterns of undulose extinction, while micas show a simple pattern of undulose extinction or bent cleavages. Orthoclase generally exhibits simple or irregular undulose extinctions, but amphiboles scarcely show undulose extinctions in intact granitoids.

Textures due to recovery and recrystallization: Subgrains generally form in quartz as isolated, clustered or twig-like patterns (Photo 1-h). Subgrains occasionally form in plagioclase, but generally do not form in biotite, orthoclase or amphiboles in intact granitoids.

2.2 Abundances of deformation textures

Figure 1 shows the relative abundances of deformation textures in two samples of intact granitoids from central Japan; one from the

Photo 1 Photomicrographs of deformation textures in intact granitoids

- (a) Pseudostylolite in biotite. (b) Cloven cleavages in biotite. (c) Microfaults in plagioclase.
 (d) Slipped twin in plagioclase. (e) Bent twins in plagioclase. (f) Cusped cleavages in biotite.
 (g) *En echelon* wrinkles in biotite. (h) Subgrain twig in quartz.

Figure 1 Relative abundances of deformation textures based on the deformation of quartz

(a) The result of microscopic observation of more than 150 thin sections. (b) The result of microscopic observation of about 30 thin sections. Almost all : Almost all grains show the corresponding deformation texture. Abundant : About three quarters of grains show the corresponding deformation texture. Common : About one half of grains show the corresponding deformation texture. A few : A few grains show the corresponding deformation texture. Rare : The corresponding texture is formed in only few grains. None : No grains show the corresponding deformation texture.

Miocene Tokuwa granodiorite (Fig. 1-a) and the other from the Miocene Kaikoma granite¹⁵⁾ (Fig. 1-b). In this figure, samples are classified as I, II or III, based on the deformation textures seen in quartz. I, II and III are the respective classes of samples in which [undulose extinction], [undulose extinction + isolated subgrains], and [undulose extinction + isolated subgrains + clustered subgrains] occur. Figure 1 shows that class I samples exhibit only the undulose extinctions of quartz, plagioclase and biotite. Class III samples show abundant deformation textures, indicating that they contain many deformation microstructures, even though all samples are intact and appear as non-deformed granitoids to the naked eye.

3. Water pathways within intact granitoids

Water pathways within intact granitoids may be detected in an experiment based on the capillarity of a KMnO_4 solution³⁾. The samples were shaped into cylindrical form of 25 mm in diameter and 12 mm height. The top and bottom faces of cylinders were polished with $1\ \mu\text{m}$ -diamond paste, and the surrounding sides of cylinders were coated with epoxy resin. The lower

halves of cylinders was sunk into KMnO_4 solution of 0.2 mol/l for two weeks inside a vacant box. After the capillarity experiment, the samples were dried for a few days at 110°C . MnO_4^- deoxidizes into MnO_2 , which sticks to the walls of apertures and is reddish purple in color. The pre-polished surfaces of intact granitoids are stained by the reddish purple MnO_2 , which is then detected with an electron probe microanalyzer (EPMA). **Figure 2** shows the result of experiment with Tokuwa granodiorite. The EPMA images show that MnO_2 is present on the polished surfaces of orthoclase, plagioclase and biotite grains. MnO_2 occurs in three ways : on grain-boundaries and/or intragranular cracks, in clustered submicron-sized pores, and dispersed on plagioclase and biotite grains. These modes of occurrence suggest that water pathways in intact granitoids are not only grain-boundaries and/or intragranular microcracks, but may also be mineral grains themselves that are permeated with submicron-sized apertures.

4. Discussion

Deformation microstructures include various kinds of submicron-sized apertures. It is well known that microcracking and microfaulting produce a variety of apertures in quartz, feldspars and micas¹⁶⁾. It is now known that similar apertures are caused by microfolding. SEIFERT and VERPLOGE¹⁷⁾ reported a continuous series of small connected microcracks less than 10^{-6}m wide and less than 10^{-5}m long occurring along kink band boundaries in albite. Similar features have been reported elsewhere¹⁶⁾. Undulose extinction, especially banded undulose extinction, is also indicative of submicron-sized apertures. TULLIS and YUND¹⁸⁾ noted that the optical undulose extinctions of quartz and feldspars may be manifestations of microcrack arrays or submicroscopic gouge zones 10^{-6}m wide and 10^{-5}m long.

Various kinds and sizes of apertures, including submicron-sized cracks, pores, and grain boundaries, have recently been studied by employing blue resins¹⁹⁾, fluorescent materials^{20), 21)}, replica films²²⁾, and other laboratory experiments^{1)~3), 23)}. These studies have statistically delineated features, such as the distribution of apertures by their lengths and widths, which may not be apparent under a microscope. The spatial distribution patterns of apertures, as well as their connectivity, are also important features when studying permeability²⁴⁾. The sizes of such aper-

Figure 2 EPMA images of a polished surface of the Tokuwa granodiorite.

Upper figures are images of Si level, indicating different mineral grains. Lower figures are the same areas with the corresponding upper ones, indicating the level of stuck Mn. In Fig. 2 (a) (lower), MnO_2 occurs in clustered submicron sized pores in plagioclase (two clusters in upper right) and disperses on biotite (lower right). In Fig. 2 (b) (lower), MnO_2 disperses on plagioclase.

tures range from microscopic to submicroscopic, or 10^{-6} to 10^{-8}m ^{3),25)}.

It follows that deformation microstructures should be most apparent at sites where abundant submicron-sized apertures are present. There are differences of deformation grade even in intact granitoids^{8),14)}. This means that some intact granitoids include relatively few deformation microstructures, whereas others include so many deformation microstructures that their diffusivity or permeability is increased. Since deformation microstructures are possible pathways for water, it is very likely that the diffusivity and permeability of a granitoid sample correlates with the nature and abundance of its included deformation microstructures. It is also noteworthy that many deformation textures in Photo 1 are connected with grain boundaries.

5. Summary

Various kinds of deformation microstructures tend to form in constituent mineral grains even within intact granitoids. Although their abundances differ from sample to sample, submicron-sized apertures can form within such microstructures and are the possible cause of the diffusivity and permeability of intact granitoids. The deformation microstructures of intact granitoids need to be more intensively studied with regard to material transport properties. This is especially true for intact granitoids that have few microcracks or low permeability.

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Appendix

*: in Japanese with English abstract, **: in Japanese.

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インタクトな花崗岩類の拡散性・透水性研究における 鉱物粒内変形微小構造の意義

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要 旨

インタクトな花崗岩類の場合でも, 構成鉱物粒内には多かれ少なかれ変形微小構造が形成されている. それらの微小変形構造は, 微小割れ目形成, 微小断層, 微小褶曲, 回復, 再結晶という過程を通じて形成される. これらの微小変形構造の中のサブミクロンサイズの割れ目やガウジはインタクトな花崗岩類の拡散や透水の通路になっている. 実際に, 過マンガン酸カリウム水溶液を用いた毛管実験によって, いわゆるマイクロクラックやグレインバウンダリー以外の鉱物粒内にも水溶液の通った痕跡が EPMA により確認される. 変形微小構造内にサブミクロンサイズの割れ目やガウジが多く作られていることから判断して, インタクトでマイクロクラックの少ない花崗岩類の拡散や透水を評価する上で, 偏光顕微鏡による変形微小構造の種類や量の評価は重要な視点となろう.

キーワード: 変形組織, 拡散, 透水, 花崗岩