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論 文 内 容 要 旨

In recent years, fracture generation processes and the nature of fluid flow in large granitoid intrusions have been widely investigated, with regard to their potential technological utilization. Structural characteristics have been addressed, to assess the use of granite bodies as a high-level radioactive waste repository, and for development of (artificial) geothermal energy extraction systems. To evaluate fracture network systems in granite, such as in the Japanese tectonic (active arc) setting, it is important to estimate changes in the nature of fracturing, from early solidification to emplacement, subsequent uplift and during exposure of the intrusion. This thesis clarifies the development of fractures and associated fluid flow processes in granitoid intrusions, during their uplift and emplacement in the shallow crust, by focusing attention on the Takidani Granodiorite (central Honshu, Japan). Field studies are coupled with petrological studies and integrated laboratory experiments, concerned with the nature of microcrack development (particularly in quartz), to address the goals of this project.

This thesis is comprised of seven chapters. The background and major objectives of this study, and literature review are described in Chapter 1. In Chapter 2, synthetic fluid inclusion experiments are described, which were undertaken to assess the healing behavior of fractures in quartz, and potential use of synthetic fluid inclusions for simultaneous temperature, pressure logging in high temperature geothermal boreholes. In Chapter 3, a new approach is described to study crack development resulting from thermal contraction. Investigations focus on the initiation of thermal cracks in granite during cooling by the thermally healed granite, which is analogous to crack-free granitic magma. Chapter 4 and 5 detail field studies related to the Takidani Granodiorite (Japan Alps). Fluid inclusion characteristics in quartz (Chapter 4) were investigated to clarify the fracture development and associated fluid migration in the Takidani Granodiorite. In Chapter 5, crystallographic defects, including impurities as a consequence of crystallization, dissolution, recrystallization and fracturing are investigated, by application of scanning electron microscope-cathodoluminescence (SEM-CL), electron probe microanalysis (EPMA), secondary ion mass spectrometry (SIMS), and transmission electron microscope (TEM). In Chapter 6, the nature of fracture network formation within active geothermal systems is discussed in detail, expanding on field and laboratory observations described in Chapters 2, 3, 4, and 5. A summary, highlighting the major findings and conclusions of this study are presented in Chapter 7.

Chapter 2: Fundamental Experiments for the Application of Synthetic Fluid Inclusions for Simultaneous Temperature, Pressure logging in Geothermal System at Sub to Supercritical Conditions

If a rock is fractured in the presence of a fluid, then that fluid is likely to enter the fracture and will start to dissolve and/or recrystallize the host rock. If the process is allowed to continue quartz healing of the fracture may result, and fluid may be trapped in the fractures as small inclusions. Crack healing is closely related to rock mass permeability, and fluid migration in the fracture is inseparably linked to the healing character of the microcrack. Chapter 2 describes the findings of synthetic fluid inclusion experiments, conducted using a batch-type autoclave, which were undertaken to investigate the healing mechanism and character of the fluid inclusions. The experiments tested the possibility of utilizing synthetic fluid inclusions for simultaneous temperature and pressure logging in geothermal systems, at sub- to supercritical hydrothermal conditions.

Fluid inclusions were synthesized in thermally pre-fractured quartz for at least 5 days at 375°C/388bars, in the presence of pure or saline (silica-saturated) solutions. Healing was more noticeable, and irregular shaped large inclusions were more likely to form in high saline fluids, than in pure water. Orientation of healed cracks may be controlled by crystallographic orientation. Microcrack generation is a dynamic process, and further investigations concerning crack healing behavior are needed to better understand fluid flow in large granitoid intrusions.

Synthetic fluid inclusion logging has the potential to offer a precise borehole temperature measurement technique, within an estimated 12°C error (without any pressure correction). However, pressure estimates are less precise, due to steep isochore slope. To improve the accuracy of the logging method, this study found that solutions confined with quartz should best be a saline fluid, rather than pure water.

Chapter 3: Thermal Crack Initiation in Granite during Heating and Cooling Processes

In this chapter, hydrothermally healed granite was synthesized in a batch-type autoclave, to simulate magma solidification from magma of granitic-composition, with corresponding measurement of acoustic emissions. This experiment aimed to establish the timing of crack initiation and propagation during cooling, due to thermal contraction.

Acoustic emissions during cooling were detected at ~360°C for the hydrothermally healed granite. A likely explanation for the observed result is that crack healing occurred as a consequence of the hydrothermal condition, and that crack generation occurred in response to thermal contraction during cooling.

The petrographic character of induced cracks in the hydrothermally healed granite samples differs from those observed in intact granite. The observations indicate that experimental conditions did not match the stress field, water-rock ratio, and cooling path that are most advantageous for inducing fracture formation in granite. Further experimental work using pseudo intact granite will be undertaken in the future, to facilitate a more accurate estimation of fracturing initiation and behavior.

Chapter 4: Fluid Migration in Granite, Deduced from Fluid Inclusion Characteristics

Fluid inclusions give direct information about past fluid compositions and temperature conditions in the Earth's crust. Moreover, fluid inclusions are sometimes trapped in fractures, and may provide invaluable information about the structural development and fabric of the rock. At deep levels in the crust, ductile deformation reduces porosity and permeability, which constrains fluid transportation, so the maximum depth of fluid migration is limited by the occurrence of the brittle-ductile transition zone. Thus, fluid inclusions may record the inelastic behavior of a rock mass in the ductile regime.

Fluid inclusion microthermometry and gas analysis, using Laser Raman microprobe spectroscopy, were conducted for natural granite samples, and these results are described in Chapter 4. The chapter also outlines a case study for use of granite systems as a repository of high-level radioactive waste, and the potential of granitoid intrusions to provide the reservoir (host) rock for development of deep-seated geothermal energy extraction systems.

Fluid inclusions in the fossil Takidani magmatic hydrothermal system provide evidence of a past convective hydrothermal system at epithermal conditions (~154 to 393°C, 0.4 to 73.9 wt% NaCl eq. reservoir, at about 3 km depth). In addition, during early crystallization of the Takidani Granodiorite, hypersaline >500°C, magmatic-derived fluid was trapped, at a time when the host rock was apparently still in a deformable, or non-brittle state.

Uplift of the pluton resulted in phase separation of the magmatic fluid into a hypersaline liquid phase, of 4 to 14 wt.% NaCl composition (at 600°C, 0.8 kb and depth of 3 km, assuming 2.66 g/cm^3 crustal density at lithostatic pressure), and CO_2 and N_2 rich gas phases. Subsequent fracture development allowed fluid migration into the pluton at ~400°C, 0.2 kb temperature-pressure conditions. Phase separation of meteoric water (i.e. due to boiling), resulted in fluids with a wide range of salinities. The brittle-ductile transition zone is inferred to exist at a depth of around 3 km, which restricted meteoric water migration into deeper parts of the pluton.

Microcrack orientation measurements, determined using the universal stage, reveal that the microcracks have three preferred orientations coincident with joint orientation in the host rock, with fluid inclusions along the respective microcrack sets having unique physical and temporal characteristics. Open cracks are oriented parallel to rift joints. The development of microcracking is one of the main factors causing joint progression, and corresponds to the timing of unique magmatic-hydrothermal events in the fossil Takidani geothermal system.

Chapter 5: Structural History of Igneous Quartz, Clarified by Microanalysis of Trace Elements and Defects

Microcracking is one of the most common deformation characteristics (in rock behaving in a brittle manner), and are recorded in quartz as healed or open cracks. Healed cracks in quartz are easily recognized using optical microscopy, by identification of bubble planes of fluid inclusions. The entrapment of fluid in crystal defects, at some time in the geological past, has resulted in the formation of fluid inclusions that give insights into the development of fractures and fluid migration in the Takidani Granodiorite.

Crack healing is not only a means to trap fluid inclusions. Quartz is chemically and structurally very stable, but quartz microcracking provides a potential site for a variety of hydrothermal reaction to occur, with chemical (material) exchange from the rock (mineral) to the fluid, and from the fluid to the rock.

The main focus of this chapter is to present a structural history of igneous quartz, clarified by the microanalysis of trace element abundances and other defects (but not otherwise observed using optical microscopy), using the Takidani Granodiorite as a case study. To achieve this goal, scanning electron microscope-cathodoluminescence (SEM-CL), electron probe microanalysis, secondary ion mass spectroscopy (SIMS), and transmission electron microscope (TEM) were used.

SEM-CL imaging is useful for unraveling complex crystal growth histories in the Takidani Granodiorite, and subsequent deformation, such as fracturing, healing and grain boundary dissolution. Primary crystal growth textures may reflect multiple quartz generation and unstable melt condition. Other SEM-CL features include the occurrence of alteration halos, of up to 20 to 30 μm lateral extent, around healed cracks in some Takidani Granodiorite samples. Alteration halos are enriched in sodium, potassium, and magnesium. Trace elements analysis indicates that some healed cracks are sealed by aluminum-rich quartz.

TEM observation shows that deformation bands due to dislocations and amorphous phases are associated with the healed cracks, which locally related to the plastic deformation in response to shear stress. The CL intensity of the growth zones was consistent with aluminum content.

Chapter 6: Development of Models to Explain Fracture Formation and Fluid Migration in Granite during Uplift and Emplacement

Initially, nucleus crystal growth occurs in granitic melts in the form of β-quartz. At this time, the temperature and pressure condition in the Takidani Granodiorite was likely to be less than 700°C and 2 kb (at 7.5 km depth, in lithostatic pressure) based on constraints imposed by Al-in-hornblende geobarometry. The nucleation of quartz is episodic, with simultaneous crystal growth of other mineral phases. Granitic melts are enriched in aluminum, which is incorporated into the SiO_4 tetrahedra as a replacement of Si^{4+} during early stages of crystal growth. Rapid uplift and cooling of the Takidani Granodiorite resulted in volatile contents in the remnant granitic melts having a composition in the range of 2-8 wt.% H_2O and 0.2 wt.% Cl^-. Unstable physico-chemical conditions in the melt may cause resorption, and growth impediment due to compositional gradients, induced by volatiles sticking onto the surface of crystals. At around 600°C, 0.8 kb (3 km depth, in lithostatic pressure), magmatic fluid of 4-14 wt.% NaCl aq are exsolved from the crystallizing magma, which is separated into CO_2- and N_2-rich vapor phases, and a hypersaline fluid of 30 to 40 wt% NaCl eq. Although the rock is in a ductile regime, stress gradually accumulates due to thermal contraction and mismatch of physical property in the granite, as consequence of uplift and cooling (α-β quartz transition has a strong influence on initiation of fracture above 573°C, at 0.1 MPa).

The brittle-ductile transition zone for granite occurs at around 400°C, and thermal contraction initiates microcracking at about the same temperature (400°C). A convective hydrothermal system may have developed as a consequence of fracturing in the granite, with fluid derived from meteoric water entering the fractures, and simultaneously starting to dissolve and recrystallize the host rock. Healed cracks are likely to have formed due to fluid-rock interactions, with corresponding entrapment of fluid inclusions. A large-scale convective geothermal system is likely to develop in granitoid intrusions only up to a temperature of about 400°C, since fractures conducive for fluid migration will be poorly developed in granite behaving on ductile manner. However, the rock mass may be refractured, which could account for an alteration halo texture around some healed cracks, as indicated by SEM-CL imaging. Further uplift and cooling was accompanied by fracturing and crack healing. The primary origin of microcracks in the Takidani Granodiorite is thermal contraction due to the cooling, however, microcrack orientation is at least partly controlled by the external stress field.

論文審査結果の要旨

花崗岩中に発達するき裂は，地下における物質移動の主要な経路であり，地殻内部における流体移動や熱移動を評価ためには，き裂の形成条件，発達メカニズムを解析して，地下岩体利用のための最適な地質要件を明らかにすることが必要である．著者は，花崗岩中に発達するき裂群の特徴，形成条件を野外地質学的手法および実験的手法を用いて解明し，岩体の上昇・固結過程とき裂の発達過程の因果関係を求めている．本論文はこれらの研究成果をまとめたもので，全編 7 章よりなる．

第 1 章は緒論であり，本研究の背景と目的を述べている．

第 2 章は，異なる流体組成の人工流体含有物を合成し，組成および環境制御された流体が岩石中に取り込まれることを実験的に証明し，この結果を利用して，従来法では困難であった高温地熱井の温度・圧力の同時検層法，および坑井内部において地殻流体を捕獲する新方法について述べている．これは，超臨界高温高圧坑井の新たな検層法に応用できる重要な知見である．

第 3 章は，花崗岩中に発生する熱き裂の形成温度を求める新たな方法を考案し，岩体の冷却過程におけるき裂発生温度を推定している．従来法では，花崗岩の加熱過程において熱き裂の形成温度を計測していたが，本方法は，水熱環境下で花崗岩を加熱保持することにより，既存き裂をヒールさせ，その後の降温過程でき裂発生挙動と形成温度を求めている．これは，従来法とは大きく異なる視点からの実験であり，学術上きわめて重要な成果である．

第 4 章は，飛騨山脈，滝谷花崗閃緑岩体をモデルフィールドとして，岩体の上昇史，冷却史を明らかにし，この過程でのき裂発達プロセスを解析している．特に岩石中の流体含有物の温度－圧力－流体組成経路の検討から，花崗岩体の脆性-延性遷移領域は，およそ 400～500℃に存在することを明らかにしている．このことは，岩体内の熱き裂はおよそ 400℃付近から発達したことを示しており，また，400℃以上の高温域では，地殻中にはき裂は乏しく，充分な流体流動が生じていなかったことを推定している．き裂の発達温度領域を流体含有物とき裂系の特徴から解明したきわめて有用な知見である．

第 5 章は，石英中の微小き裂と露頭規模で観察される節理との因果関係を求めている．この結果，ヒールしたき裂は不純物および転移構造の集合体であること．また，微小き裂は露頭規模の巨視的き裂と組織的・構造的に密接に関係し，巨視き裂へ発達するであろう弱面を形成していることを明らかにしている．これは重要な成果である．

第 6 章は，花崗岩体の固結・上昇・定置過程において，岩体内を移動した流体の温度－圧力－組成変化とき裂形成プロセスとの関係を総合的に考察し，プレート境界で急激な上昇・冷却過程を被った花崗岩体に発達するき裂系とこれに関与する流体の役割を明確にしている．この成果はきわめて重要である．

第 7 章は結論である．

以上要するに本論文は，花崗岩中にあるき裂の発達プロセスを，岩体内部に流動した流体の特徴解析から解明する方法を提案し，これを用いて，き裂の発達プロセス，地殻内部の流体移動に関する知見を整備したもので，地殻科学および地球工学の発展に寄与するところが少なくない．

よって，本論文は博士(工学)の学位論文として合格と認める。