Fluid flow, detachment kinematics, and core complex formation in the extensional Basin and Range Province

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Metamorphic core complexes (MCCs) are crustal-scale structural features in the North American Cordillera that result from exhumation of middle crust through large extensional detachment systems. They contribute to thermal and mechanical re-equilibrium of the orogenic crust after and during the Cenozoic extensional collapse of the Cordilleran orogen and thus, record the kinematic boundary conditions during the late stage(s) of orogenic evolution of western North America. The interplay among various parameters such as strain localization, fluid-rock interaction, and surface processes dominates the evolution of these detachment systems. In particular, localized synextensional interaction of fault zone rocks with surface-derived fluids appears to be a common feature that directly impacts the conditions of crustal flow, mineral recrystallization, elemental and isotopic exchange, and temperature gradients of actively extending crust.

To resolve the temporal and kinematical relationship between core complex formation and fluid flow from the Earth`s surface to the actively extending middle crust, we used a multi-disciplinary approach, including (1) observation of microstructures, (2) $^{40}Ar/^{39}Ar$ thermochronology, and (3) oxygen isotope thermometry (D $\delta^{18}O$), and (4) hydrogen isotope analyses (δ D) of syntectonic hydrous minerals. The hydrogen isotopic composition of recrystallized hydrous minerals allows us to track the infiltration of meteoric water into brittle fault zones (e.g. clay gouges) and strongly localized fluid flow down to the brittle-ductile transition (e.g. mica-bearing mylonites) at mid-crustal levels.

One key example to resolve the structural evolution and multiphase synkinematic fluid-rock interaction of a detachment system is the Raft River MCC (Utah, USA). Combined microstructural, $^{40}Ar/^{39}Ar$ geochronological, and stable isotopic evidence from exhumed mylonitic footwall rocks of the Raft River MCC suggest that very low- δ D surface-derived fluids penetrated through brittle faults in the upper crust down to the brittle-ductile transition as early as the mid-Eocene during a first phase of exhumation. Thus, Eocene extension within the Cordilleran hinterland not only occurred at more northerly latitudes, but most likely also characterized regions of the northeastern Basin and Range Province. In the eastern part of the core complex, prominent top-to-the-east ductile shearing, mid-Miocene $^{40}Ar/^{39}Ar$ ages, and higher δ D values of recrystallized white mica, indicate Miocene structural and isotopic overprinting of Eocene fabrics. Miocene shearing in the western Raft River MCC seems to be a reactivation and/or continuation of an Eocene top-to-the-east shear zone with accompanied localized rather than pervasive fluid flow. Moreover, a significant component of cooling of the core complex might be due to fluid-induced refrigeration rather than exclusively to rock uplift and circulating fluids appear to have actively influenced the kinematic of the detachment and as a consequence the exhumation history of the core complex.

Collectively, combined geochronological and stable isotope geochemical studies in MCCs along strike of the North American Cordillera document that meteoric fluid flow was an integral component of crustal extension and surface-derived water was able to penetrate extending upper crust down to the

brittle-ductile transition. We therefore argue that meteoric fluid flow in extensional fault and detachment systems may be more common than previously assumed which permits to export this approach to extensional settings in other orogens.

Keywords: meteoric fluid infiltration, hydrogen isotopes, metamorphic core complex formation

A new method to estimate fault activity based on the fraction of saturation of quartz luminescence and ESR signals in fault rocks

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The activity of faults is usually estimated from the fault-displaced Quaternary sediments, containing both measurable displacement markers as well as dateable materials (Research Group for Active Faults of Japan, 1991). However, geologically- or geomorphologically-recognized faults especially in erosion area are not always cutting, or covered by, dateable Quaternary units. For such faults, there is currently no available method to evaluate their activity. The same problem also arises for the detection and dating of seismic slip events from borehole cores. In this presentation, we introduce a new concept to evaluate fault activity using the fraction of saturation of trapped charge in quartz –specifically, of the optically stimulated luminescence (OSL), thermoluminescence (TL) and electron spin resonance (ESR) signals. These signals, alone or in combination, have the potential to quantify the activity of faults with presently unknown slip rates, in Japan and elsewhere.
Active faults in Japan are categorised according to their slip rates into three classes (A, B, and C-classes) (Matsuda, 1975). An A-class fault experiences more frequent and larger-energy earthquakes than B- and C-class faults, contributing to a greater removal of trapped charge in quartz by frictional heating. Therefore, our working hypothesis is that the fraction of trapped charge saturation of A-class faults should be significantly lower than that of B-class faults, which themselves are lower than those of C-class; i.e. the fraction of trapped charge saturation is a function of the fault activity. By inverting the fractions of saturation using their corresponding trap kinetic parameters, one can estimate one of the following: the frequency, the temperature, or the duration of the resetting events (earthquakes), if the other two parameters are independently constrained.
In this presentation, we share our preliminary results from the Atotsugawa Fault, central Japan (including experimental data, modelling and inversion), and discuss the method’ s potential contribution to understanding fault mechanics (flash heating, in particular) and to estimate fault activity.

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Geochronology and thermochronology of fault zones: an overview

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Thermal signatures as well as timing of fault motions can be constrained by thermochronological analyses of fault-zone rocks (e.g., Tagami, 2012). Fault-zone materials suitable for such analyses are produced by tectocic and geochemical processes, such as (1) mechanical fragmentation of host rocks, grain-size reduction of fragments and recrystallization of grains to form mica and clay minerals, (2) secondary heating/melting of host rocks by frictional fault motions, and (3) mineral vein formation as a consequence of fluid advection associated with fault motions. The geothermal structure of fault zones are primarily controlled by the following three factors: (a) regional geothermal structure around the fault zone that reflect background thermo-tectonic history of studied province, (b) frictional heating of wall rocks by fault motions and resultant heat transfer into surrounding rocks, and (c) thermal influences by hot fluid advection in and around the fault zone. Thermochronological methods widely applied in fault zones are K-Ar (^{40}Ar/^{39}Ar), fission-track (FT), and U-Th methods. In addition, OSL, TL, ESR and (U-Th)/He methods are applied in some fault zones, in order to extract temporal imformation related to low temperature and/or very recent fault activities. Here I briefly review the thermal sensitivity of individual thermochronological systems, which basically controls the response of each method against faulting processes. Then, the thermal sensitivity of FTs is highlighted, with a particular focus on the thermal processes characteristic to fault zones, i.e., flash and hydrothermal heating. On these basis, representative examples as well as key issues, including sampling strategy, are presented to make thermochronologic analysis of fault-zone materials, such as fault gouges, pseudotachylytes and mylonites, along with geological, geomorphological and seismological implications. Finally, the thermochronologic analyses of the Nojima fault are overviewed, as an example of multidisciplinary investigations of an active seismogenic fault system.

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キーワード：熱年代学、断層帯、年代測定、摩擦発熱、熱水
Keywords: thermochronology, dating, fault zone, shear heating, hot fluid

高速摩擦実験に基づく，石英ガウジのOSL/TLタイムゼロイング検証
An investigation of coseismic OSL / TL time zeroing of quartz gouge based on high-velocity friction experiments

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OSL法/TL法は，石英や長石が微弱な自然放射線や宇宙線を浴びて捕獲電子を蓄積していくことを利用した年代測定法であり，主に堆積物に用いられてきた．近年, 鴈澤ほか（2013）では, 活断層の年代測定法としての有用性を見出している．OSL法/TL法で古地震イベントを決定するための背後となる考え方は, 蓄積された自然放射線による損傷が摩擦発熱または破砕によってゼロになる（タイムゼロイング）ことである。しかし，断層運動とルミネッセンス信号の消滅（タイムゼロイング）の関係性は十分に解明されていない．この関係性を解明できれば，活断層年代測定にOSL法やTL法の測定年代範囲が加わり，活断層評価に大いに貢献できる．そこで本研究では，OSL法TL法を用いた断層年代測定法確立のため，低速～高速摩擦実験に基づいたタイムゼロイングの実証を行い，そのための物理条件（速度，垂直応力，変位量，含水率など）の解明にあたった．

試料は，兵庫県淡路島北部浅野断層近傍の都志川花崗岩より採取・分離した石英粒子（粒径150 μm以下）を用いた．高速摩擦実験では，粒径150 μm以下の石英1.0 gに対して速度依存性と変位量依存性を調べた．なお，破砕の影響を考慮するために，実験後の試料を75 μm以下及び75～150 μmに粒径調整した．

我々は２つの一連の実験を行った．（1）OSL/TL信号のリセットに対する速度依存性を見るための様々なすべり速度での実験、（2）OSL/TL信号のリセットに対する変位量依存性を見るための様々な変位量での実験である．

我々は, 粉砕の効果を考慮するために、回収された試料を<75μmおよび75-150μmの2つの粒子サイズに分離した．

OSL測定の結果では，（1）せん断によって細粒化したガウジ（＜75μm）が、プレスリップのみ行った試料よりもfast成分比が高いこと，（2）すべり速度の200 μm/s から0.13 m/sまでの増加に伴い粒径75 μm以下の粒子のfast成分比が増加すること，（3）0.65 m/sで剪断された実験では, OSL信号がゼロになることが分かった. 比較的低いすべり速度の実験で見られるfast成分比の増加は、電離した電子（粉砕中に新たに形成された破断表面から電子捕獲中心の電子が放出される）の添加によって引き起こされた可能性がある. 高速摩擦実験で観測されたタイムゼロイングは, 温度測定によって600℃まで急激に上昇した摩擦発熱に起因する. 0.65m/sの摩擦実験に加えた摩擦エネルギーの計算に基づいて、天然の地震条件（変位1.6m）の深度を117mに推定した．

キーワード：浅野断層、ルミネッセンス、高速摩擦実験、タイムゼロイング
Keywords: Asano fault, luminescence, high-velocity friction experiment, time-zeroing

ESR法による断層活動性評価ー浅野断層トレンチ掘削試料を用いた摩擦実験によるアプローチ

ESR technique for the assessment of fault activity; an approach from frictional tests using the Asano fault gouge collected by a trenching survey

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断層岩の年代から断層活動性評価を行う手法の一つとして，ESR（電子スピン共鳴）年代測定法がある（福地，2004）。ESR法では，断層岩中に含まれるESR信号が断層摩擦熱によりリセットされることを仮定して最新活動年代を求めるが，ESR信号が不完全にリセットされている場合には実際の活動年代よりも古い年代値が得られてしまう。ESR信号の不完全リセットの問題は，摩擦熱温度が上昇しやすい地下深部から断層岩試料を採取することで解決できると考えられるが，ボーリングの掘削深度が大きい程コストが掛かるので，ESR信号が完全にリセットされる深度を明らかにすることが重要である。そこで今回，浅野断層のトレンチ掘削調査で採取された断層ガウジを用いて摩擦試験を実施し，試験後のガウジ試料のESR解析を実施し，ESR信号が完全にリセットされる条件について検討を行った。また，試験後のガウジ試料から得られるESRスペクトルと浅野断層トレンチ及びボーリング掘削で採取された断層ガウジから検出されるESRスペクトルを比較し，天然における断層摩擦熱によるリセット現象の考察を行った。

摩擦試験に用いた断層ガウジ試料は，浅野断層トレンチ北壁の断層中軸部において花崗岩と大阪層群が接する部分に発達する幅～10 mmの灰白色ガウジである。自然乾燥後粉砕した灰白色ガウジは，直径24.98 mmに整形した一対の円柱状斑レイ岩試料の間に挟み，一方の円柱を回転させて剪断摩擦を与えた（堤・他，2016）。摩擦試験は，dry及び蒸留水で浸したwet条件下において，垂直応力2 MPa，すべり速度1.3 m/sで実施した（堤・他，2016）。 総変位量30mの時のガウジ内の最高到達温度は，dry条件下で380℃程度，wet条件下で340℃程度に達していたと推定される。摩擦試験後は，dry及びwet条件とも剪断面の中心を基準（=0mm）として，ガウジ試料を 0～9mm（中心部），9～16㎜（中間部），16～25mm（円周部）に三分割し，各々の部分についてESR測定を行った。その結果，dry条件下では，三分割した部分全てから摩擦熱により生成するFMR（フェリ磁性共鳴）信号が検出され（Fukuchi，2012），中心部から円周部に向かって信号強度が著しく増大しているのが確認された。また，中間部および円周部では，ESR年代測定に使用できる石英E’中心やモンモリロナイト（Mo）四重信号がリセットされているのが確認された。これに対して，wet条件下では，円周部において弱いFMR信号が検出されたが，E’中心やMo四重信号はほとんどリセットされていなかった。従って，浅野断層ガウジのESR信号がリセットされる時にはFMR信号の著しい増大が起こっている可能性が高いことが判明した。一方，浅野断層300m掘削コア試料の深度200m付近に位置するfa-5断層破砕帯のガウジ試料からは，wet条件下の円周部と同様のFMR信号が検出され，浅野断層ではwet条件下で断層摩擦熱が上昇した可能性が示唆される。

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Keywords: ESR dating, Electron spin resonance, Asano fault, Fault gouge, Assessment of fault activity, Frictional test

地震時に断層破砕帯における粉粉になった断層破砕物の貫入と天水・海水を含む流体の流動

Repeated coseismic injection of pulverized fault rocks and infiltration of fluids including meteoric and sea-waters within fault damage zones

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In the past decades, increasing geological evidence has emerged that faults and shear zones within the middle to upper crust play a crucial role in controlling the architecture of crustal fluid migration and seismic faulting process. It is also well known that fluid can be released by dehydration reaction caused by seismic frictional heating during large earthquakes within both intracontinental faults and subduction zones that contain abundant hydrous minerals (Lin et al., 2003, 2013). Such rapid dehydration reaction would induce a sudden increase in fluid pressure that would simultaneously act to reduce the effective normal stress and markedly weaken the dynamic strength of seismogenic faults during seismic faulting, thereby facilitating seismic slip during large earthquakes. For an integrated multidisciplinary study on the assessment of activity of active faults involving active tectonics, rock-fluid interactions, geochemistry and geochronology of active fault and seismogenic fault zones, recently, a new project of “Drilling into Fault Damage Zone” has being conducted by Kyoto University on the Nojima Fault again after 20 years of the 1995 Kobe earthquake.
In this presentation, I will review the previous studies and report the recent progresses on the fluid infiltration concerning with coseismic faulting and recent activity on two seismogenic faults that recently triggered the large earthquakes, one from the active faults of the Longmen Shan Thrust Belt that triggered the 2008 M_w 7.9 Wenchaun earthquake in the Sichuan basin, China, the other is the Nojima Fault that triggered the 1995 M_w7.2 Kobe earthquake. Circulating fluids deposit fine-grained sediments including clay and carbonate material and pulverized rock materials into cracks within the fault zones. Such crack-fill fine-grained materials, calcite veins, and oxidized/weathered open cracks have well been observed in the drill cores, from both the Nojima Fault and the active faults of the Longme Shan Thrust Best. 3D micro-X-ray scanning data and powder X-ray diffraction analyses show that the fault core zone contains a numerous of veinlets which are composed of fine-grained materials, carbonate material and clay minerals. Isotopic analyses of carbonate material within the fine-grained materials and calcite veins reveal that the calcite veins are sourced from typical meteoric and seawater. ^{14}C dating ages of 10 calcite vein samples range from 35.0 to 58.4 kyr B.P. Geological, petrological, stable isotopic, and ^{14}C data suggest that these crack-fill fine-grained materials and calcite veins and brown open cracks were developed by the repeated infiltration of O_2- and CO_2-bearing meteoric and seawater downward into the deep fault zone during the last 35–60 kyr. We propose a seismic fault suction-pumping model to interpret the infiltration of subsurface waters being carried down into the deep fault zone by rapid potential change during episodes of seismic faulting.

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Keywords: coseismic injection of pulverized fault rocks, coseismic infiltration of fluid, seismic fault suction-pumping model

