Nano-scale viscous flow, slip zone thickness and dynamic weakening during earthquakes: an experimental investigation

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Viscous flow at high strain rates is a well-known deformation mechanism occurring in metals, but has only recently been associated with the behaviour of natural fault materials during earthquakes in mobile belts. In particular, microstructures attributed to grain boundary sliding have been recognised in high velocity shear experiments where the recrystallized materials commonly have a nanometric grainsize.

We designed and performed a set of friction experiments using a rotary shear apparatus with pure calcite microgouge (60 μm < D < 90 μm) and nanogouge (D ~ 200nm). Experiments were run at different velocities, from sub-seismic (<10 cm/s) to seismic (up to 1.4m/s), and were arrested at different finite slip values in order to document the evolution of microstructures and link these to the mechanical data.

Experiments show a characteristic four stage evolution of the friction coefficient when the material is sheared at seismic velocities (v>10 cm/s): I) an increase from initial Byerlee's values, f = 0.6-0.7, up to peak values, f = 0.8-0.9; II) a sudden decrease to low values, f < 0.4; III) the attainment of low steady-state values, f = 0.15-0.3; and IV) a sudden increase to final value, f < 0.6, upon machine deceleration. The latter stage is not recognised in nanogouge experiments.

Microstructural analysis of samples recovered after each stage studied backscattered SEM images of polished cross-sections through the principal slip zones (PSZ). During Stage I, initially widespread brittle deformation (Riedel shear bands) localises into a planar Y shear producing intense cataclastic comminution (<200 nm). By Stage II, the Y shear band develops sharp boundaries showing patches of sintered material in the regions immediately adjacent to, and outside of the PSZ. On reaching Stage III, the Y-shear band becomes a well-developed nanograin recrystallized (viscous) PSZ, sharply bounded by continuous planar 'mirror' fault surfaces. It is characterised by an equigranular texture with triple junctions, low porosity and oblique shape preferred orientations. A sintering gradient is also developed centred on the PSZ and appears to propagate outwards into the surrounding deactivated layers. At Stage IV) fracturing and reworking of the material occurs and is limited to the PSZ, possibly due to thermal cracking upon cooling.

Mirror surfaces are interpreted here to be dynamic equilibrium boundary discontinuities between the PSZ where viscous grain boundary sliding occurs, and the outer deactivated layers that are dominated by sintering and quasi-static grain growth. The thickness of the PSZ is a function of the grain size, temperature, velocity and available flow stress. The evidence of rheological decoupling is best preserved in Stage III microstructures of nanogouge experiments where mirror surfaces are marked by an abrupt grain size change.

Our findings illustrate the critical role that extreme comminution and localisation play in the onset of seismic weakening in carbonate gouges. Under steady state conditions (Stage III), the thickness of the viscous PSZ is an important physical parameter that controls dynamic weakening behaviour.

Keywords: Earthquakes, Weakening, Viscous Flow, Mirror Faults, Nanoscale, Grain Boundary Sliding

Injection-driven failure and fault mechanics in high fluid flux faulting regimes

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Fault zones formed in overpressured, high fluid flux regimes typically are characterized by a predominance of dilational damage over wear damage, and contain abundant fault-fill veins, dilational breccias and lateral damage zones that are dominated by extension vein arrays. Development of vein-rich fault zones is associated typically with extensive hydrothermal alteration and disturbance of isotopic, major and trace element systems due to flux of large volumes of externally-derived, overpressured fluids through rupture zones developed in intrinsically low permeability host rocks. Vein arrays in high fluid flux faults provide insights about the dynamics of fluid pressure variations and stress states during repeated rupture cycles in these settings. Rupture events are driven predominantly by fluid pressurization at low differential stress.

Contemporary injection-driven swarm seismicity provides novel insights about the dynamics of formation, timescales of activity, and flow rates in high fluid flux fault zones. Results from fluid injection experiments and natural, fluid-driven seismic sequences demonstrate that swarm seismicity is the characteristic response to injection of large volumes of overpressured fluids into low permeability rock. Injection-driven swarm seismicity and related permeability enhancement typically involves repeated sequences of thousands of ruptures with moment magnitude M_w mostly in the range $-2 < M_w < 2$. Individual ruptures within each swarm sequence usually have diameters much less than 100m and slips less than a few millimetres. Cumulative rupture areas during a single swarm seldom exceed several km^2. Diffusion-like migration of a seismicity front away from the injection source at rates up to approximately 100m/day is a key characteristic of injection-driven seismicity and correlates with migration of a fluid pressure pulse along activated faults. Fluid injection rates in excess of tens of $L.s^{-1}$, and total injected volumes of 10^4 - 10^5 m^3 produce swarms with cumulative moment magnitudes in the range 4 - 5. Recurrence intervals of natural injection-driven swarms indicate that net slips of approximately 100m can accumulate on timescales as little as 10^4 to 10^5 years.

Keywords: fault mechanics, high fluid flux regimes

石英の流動則から推定した三波川変成帯の応力：水のフュガシティの効果
Stress in the Sanbagawa metamorphic belt estimated from flow laws of quartz: influence of water fugacity

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Strength of the continental lithosphere has been extensively studied, but little is known about stress states in subduction zones. At deep parts of subduction zones, shear deformation on the plate interface would be localized within the oceanic crust layer, especially within the siliceous sedimentary layer, which is undergoing high pressure metamorphism. Thus plastic deformation of quartz is a key to understand stress states on the subducting plate interface. Herein we extrapolate laboratory-based dislocation creep flow laws of quartz to high pressure and temperature (PT) conditions of the Sanbagawa metamorphic belt and constrain stress fields in the Cretaceous subduction zone in southwest Japan.

Flow law parameters of quartz determined in laboratories varies with water content, confining pressures, and the initial grain size. The influence of confining pressures on dislocation creep of quartz has been understood in terms of water fugacity; high water fugacity leads to large concentrations of water defects, which are the cause of water weakening effects. However, whether or not the equilibrium concentration of water defects was attained during high PT metamorphism remains unsolved. Previous infrared (IR) spectroscopic studies of water in quartz schists taken from the Asemi-gawa root in the Sanbagawa metamorphic belt demonstrated that the amounts of non-structured water decrease with increasing metamorphic grades (Nakashima et al., 1995). They suggested that fine-grained siliceous sedimentary rocks, such as chert, gradually released water during prograde metamorphism. We also made IR analysis of water in quartz schists taken from the same area but with more detailed mapping analysis. The amounts of water in mica-poor parts of quartz aggregates in the chlorite and garnet zones were far smaller than previously reported values, and showed no systematic changes with metamorphic grades. To evaluate flow stress at the time of peak metamorphism, we postulated that equilibrium concentrations of water defects were attained even in the lowest metamorphic grade zone, and applied dislocation creep flow laws of wet quartz (Luan and Paterson, 1992) with water fugacity correction.

Paleostress in the Sanbagawa belt was also estimated using grain size piezometers of quartz. The grain size of quartz was measured by the electron back-scattered diffraction (EBSD) mapping method (Ueda & Shimizu, 2017, *JpGU*). The differential stresses derived from theoretically calibrated grain size piezometers (Shimizu, 2012; Shimizu and Ueda, in prep.) were within reasonable agreement with the dislocation creep model, whereas direct application of the experimental piezometers gives considerably smaller estimates.

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978-953-51-0122-2, pp. 371–386.

キーワード：流動応力、石英、転位クリープ流動則、H2Oフュガシティー、再結晶粒径差応力計、三波川変成帯
Keywords: flow stress, quartz, dislocation creep flow laws, water fugacity, recrystallized grain size piezometer, Sanbagawa metamorphic belt

Coupled effect of grain-size evolution and phase mixing: A two phase model for the ductile deformation of rocks.

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Rocks are complex materials and particularly their rheological behavior under geological stresses remains a long-standing question in geodynamics. Numerical modeling is the main tool to test large scale lithosphere dynamics but encounter substantial difficulties to account for this complexity. One major unknown is the origin and development of strain localization. This localization is observed within a large range of scales and is commonly characterized by sharp grain size reduction. These considerations argues for a control of the microscopic scale over the largest ones through one predominant variable: the mean grain-size. However, the presence of second phase and broad grain-size distribution may also have an important impact on this phenomenon.
To address this question, we built a model for ductile rocks deformation based on the two-phase damage theory of Bercovici & Ricard 2012. We aim to investigate the role of grain-size reduction but also phase mixing on strain localization. Instead of considering a Zener-pining effect on damage evolution, we propose to take into account the effect of the grain-boundary sliding (GBS)-induced nucleation mechanism which is better supported by experimental or natural observations (Precigout et al 2016). This continuum theory allows to represent a two mineral phases aggregate with explicit log-normal grain-size distribution as a reasonable approximation for polymineralic rocks. Quantifying microscopic variables using a statistical approach may allow for calibration at small (experimental) scale. We use the interface density as a measure of mixture quality, and propose that its evolution is controlled by the dominant deformation mechanism. Based on the microscopic set of equations derived from these hypothesis, we compute grain-size dependent viscosity fields for a 2D creep flow model using anorthite/pyroxene gabbroic composition. The influence of initial parameters such as grain-size variability, phase proportions and strain-rate field on the occurrence and importance of strain-localization is then discussed.

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Keywords: Ductile deformation, Numerical model, Earth crust, Phases mixing

三重県中央構造線断層帯の発展： 断層コアの軟化における意味
Development of fault zones along the Median Tectonic Line, Mie Prefecture, south-west Japan: implication for weakening in the fault core

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The Median Tectonic Line (hereafter referred to as the MTL), which is the largest-scale tectonic line in Japan, extends from eastern Kyushu to the Kanto mountains, north-west of Tokyo, over 800 km throughout south-western Japan. Although the structural development of the MTL is complex, the proto-MTL was originally formed as a granitic mylonite belt in the Ryoke belt of the inner belt of south-west Japan in the latest Cretaceous (Kashio phase). This was later developed into the boundary normal fault between the Sambagawa high P/T-type metamorphic rocks of the outer belt, and Ryoke low P/T-type metamorphic rocks and granitoids, when the former were exhumed and juxtaposed against the latter at 63-58 Ma (Ichinokawa phase, e.g. Kubota and Takeshita, 2008).
We have investigated the MTL in this area to elucidate structural development and weakening processes in a large-scale fault zone, and found the following facts. (1) The upper plate of the MTL consists of c. 70 m thick cataclasite (i.e. fault core) originated from granitic mylonite and protomylonite, overlain by weakly fractured mylonite and protomylonite (fault damage zone). It should be noted however that thin anastomosing cataclasite zones are also developed in the weakly fractured mylonite and protomylonite. (2) Cataclasite was developed into foliated cataclasite with increasing degree of fracturing, and the foliated cataclasite developed along the MTL contains clasts of ultramylonite (Jefferies et al., 2006). (3) Both Y-maximum and type-I cross-girdles with rhomb-maxima (i.e. rhomb plane parallel to the foliation) quartz c-axis fabrics are developed in deformed and recrystallized quartz constituting the mylonite and protomylonite in the fault damage zone (cf. Sakakibara, 1995; Shimada et al., 1998). On the other hand, the quartz c-axis fabrics in mylonite to ultramylonite from the fault core are very heterogeneous, and vary between Y-maximum, type-I cross-girdle with rhomb-maxima, Z-maximum, and random patterns even in a thin section (Czertowicz et al., this session, cf. Okudaira and Shigematsu, 2012). (4) Some areas of mylonite and protomylonite in the fault damage zone suffered overprinting deformation at higher stresses indicated by bulging recrystallization with an average recrystallized quartz grain size of 10 mm in contrast to that of 70 mm associated with the development of the Y-maximum quartz fabric pattern (Bui et al., this session).
As the mylonite and protomylonite formed along the proto-MTL were elevated and cooled, the ductile deformation could have become localized into the fault core, where the differential stresses were built up to form ultramylonite, which is shown by the clast of ultramylonite contained in the cataclasite zone. This strain localization of ductile deformation is evidenced by the development of type-I crossed girdles with rhomb-maxima in the ultramylonite, whereas a Y-maximum c-axis fabric is dominant in quartz from the protomylonite, which are inferred to have been formed at low (300 to 400 °C) and intermediate (400 to 500 °C) temperature conditions, respectively (e.g. Takeshita and Wenk, 1988). Note that this strain

localization occurred very heterogeneously, shown by the very heterogeneous development of quartz c-axis fabrics in the fault core. However, once cataclasite was formed by faulting, fluids migrated into the MTL fault core zone, resulting in the formation of mica and clay minerals, which weakened the MTL by not only lowering the coefficient of internal friction in rocks, but also enhancing the operation of pressure solution creep shown by the development of foliated cataclasite. When the fault core consisting of cataclasite was weakened, the stress buildup no longer occurred there, which could have resulted in stress concentration in the surrounding rocks, leading to the low-temperature deformation overprint in the protomylonite shown by bulging recrystallization in quartz.

キーワード：中央構造線、マイロナイト、カタクレーサイト、石英ｃ軸ファブリック、圧力溶解
Keywords: Median Tectonic Line, Mylonite, Cataclasite, Quartz c-axis fabric, Pressure solution

Heterogenous quartz LPO development and strain partitioning in Median Tectonic Line mylonites

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During ductile deformation within fault zones, the process of dislocation creep can result in the formation of a lattice preferred orientation (LPO) in deforming minerals. The strength and rheology of the continental crust are thought to be primarily controlled by the strength of quartz, and therefore quartz LPO development has been acknowledged as a fundamental control on plate boundary processes within the crust. Overprinting of previously developed LPOs may occur during accumulation of strain or due to changes in deformation conditions (kinematics, temperature, stress, strain rate). Deformation temperature and kinematics are often inferred to have changed during the history of many large fault zones, evidenced by overprinting of quartz LPOs. However, these fabrics are typically found to be consistent on the outcrop scale.

This study focusses on the Median Tectonic Line (MTL) in SW Japan, which is the largest onshore fault in Japan, having a deformation history dating back to the Cretaceous, with segments of the fault still active today. Previous studies, focussed on the broad zone of mylonitisation that occurs to the north of the MTL, identified type-1 cross girdles, Y-maximum, rhomb-max (rhomb plane oriented parallel to the foliation), and Z-maximum quartz c-axis fabrics (Sakakibara, 1996; Shimada et al., 1998). They inferred that the variation in dominant LPO reflects changes in deformation temperature during evolution of the fault zone, with mid-temperature fabrics (e.g. Y-maximum) observed in the north and low-temperature fabrics (e.g. type-1 cross girdle) found in the south, closer to the MTL. Okudaira & Shigematsu (2012) came to a similar conclusion from analysis of mylonitic borehole samples from the hanging wall of the MTL. In addition, they described random quartz c-axis fabrics within ultramylonites adjacent to the fault.

In our investigation, we aim to characterise the distribution of quartz LPO fabrics within a narrow zone (less than 1 km) to the north of the MTL where significant brittle overprinting has taken place (Takeshita et al., this session). In the study area in Mie Prefecture, we have found distinct quartz LPOs preserved on a small scale, including Y-maximum, Z-maximum, rhomb-maximum, type-1 cross girdles, and single girdles, as well as random fabrics within the fine-grained quartz in ultramylonite samples. Within one thin section of weakly fractured mylonite, we observe type-1 cross girdles, single girdles, Y-maximum and Z-maximum quartz c-axis patterns within different patches of recrystallised quartz. This previously undescribed small-scale quartz LPO variation implies heterogeneous overprinting and/or strain partitioning during deformation. Mechanisms which were likely responsible for this process will be discussed and the results placed within the framework of crustal deformation in SW Japan.

Keywords: Fault rheology, LPO, Deformation

Structural development of cataclasite zones associated with large-scale faulting: an example of the Median Tectonic Line

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The Median Tectonic Line (MTL) is the largest fault, which defines the boundary between the Cretaceous Sambagawa high P/T-type metamorphic rocks and the Ryoke low P/T-type metamorphic rocks and granitoids. The MTL in eastern Kii Peninsula is known as a non-active fault, and preserves the structural development at the brittle-ductile transition conditions formed at deep levels of the crust. There are some detailed researches focused on the MTL distributed in Tsukide-area, Iitaka-town, Matsusaka-city, Mie-prefecture (e.g. Jefferies *et al.,* 2006, Webberley and Shimamoto*,* 2003). However, in this area there are few researches which cover a broad area including the MTL for understanding of the development process of the fault zone. In this study, we constructed a geological map around the MTL and analyzed the microstructures in deformed rocks, and conducted analyses of microchemistry with EDS and XRD aided by RockJock (Eberl. D. D. 2003) in order to identify fractures and newly-grown mineral phases. Then, in comparison with the existing fault zone development model (Fusseis *et al.,* 2006, Schrank *et al.,* 2008), we discussed the structural development process of fault zones along the MTL with brittle deformation. In this study, we first measured the crack density (number/cm) in cataclasite and fractured protomylonite. As a result of the measurements, we classified deformed granitic rocks into four groups: very weakly, weakly, moderately, strongly fractured rocks. It has been found that the crack density decreases in the rocks with increase in distance from the MTL from strongly through moderately to weakly fractured rocks, and finally to very weakly fractured protomylonite. As a result of the mineral composition mode measurement with XRD, we showed that the proportion of plagioclase in cataclasite decreases, on the other hand, the proportion of the clay minerals (e.g. muscovite and chlorite) increases with decrease in distance from the MTL. The cataclasite which deformed in direct proximity to the MTL exhibits Fe-rich pressure solution seams, and contains the clasts of strongly deformed mylonite (ultramylonite). Based on the results described above, we showed the three stages exist in the structural development of the cataclasite and fractured protomylonite: increase of the crack density, increase of the matrix with reduction in grain size, and foliation formation. In the stage of increase of the matrix with reduction in grain size, it seems that the cracks which are initially created in intact rocks gradually grow and widen, and the softening of minerals by chemical reaction like muscovitization of feldspars promotes the production of the matrix. In the stage of foliation formation, the increase of modal ratio of clay minerals and development of their preferred orientations resulting from pressure solution and precipitation are responsible for the formation. We particularly showed the degree of fracture development in fault rocks in the cataclasite zone is very heterogeneous. The fact could be partly attributed to the fact that the architecture of the protolith mylonite zone had a heterogeneous structure: not consisting of homogeneous mylonite, but varying from ultramylonite through mylonite to protomylonite away from the MTL. Finally, we concluded that the cataclasite started to form in the ultramylonite in direct proximity to the MTL, and propagated toward the protomylonite away from the MTL, as the site of stress concentration moved away from the MTL, due to the softening of strongly fractured rocks.

キーワード：中央構造線、カタクレーサイト、断層帯、圧力溶解、粘土鉱物

Keywords: Median Tectonic Line, cataclasite, fault zone, pressure solution, clay minerals

山陰ひずみ集中帯に発達する断層岩と応力場：2000年鳥取県西部地震余震域の例

Fault rocks and paleostress fields in the San-in shear zone

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山陰地方は，沈み込み帯からの距離が比較的遠いこともあり，ひずみ速度が日本列島の中では小さいと考えられてきたが，現在では観測データの蓄積と詳細な解析により，実はひずみ速度が大きく，地震帯と重なる帯状の領域が存在することが示唆されている（例えば，西村,2014）．それは「山陰ひずみ集中帯」と呼ばれ，規模の大きな内陸地震（1943年鳥取地震，2000年鳥取県西部地震，2016年鳥取県中部地震）を頻繁に発生させている．ひずみ集中帯内部の詳細な地殻変動解明にアプローチするために，「地殻ダイナミクス」プロジェクトがGNSS観測網を充実させているが，一方で地質調査より，ひずみ集中帯に分布する断層系の性状やひずみ集中帯の過去の応力場を把握し，対比させることも重要な課題の一つである．

昨年の連合大会において，向吉ほか（2016）は2000年鳥取県西部地震余震域内に発達する断層の分布が余震分布と調和的であることを明らかにし，地質時代に形成された断層が2000年鳥取県西部地震の起震断層の幾何学形態と何らかの関わりがあると述べた．また，内田ほか（2016）は，2000年鳥取県西部地震余震域内の断層が互いに切断関係にあることに注目し，断層のセグメント化が地質時代において繰り返した結果，複雑な断層系をしていることを明らかにした．

本研究では，Hough変換に基づく応力逆解析法（Yamaji et al.,2006; Sato and Yamaji, 2006）を用いて，余震域内の花崗岩に観察される地質時代の断層を形成させた応力場を推定した．まず断層の性状に基づく分類として，断層ガウジ及びカタクレーサイトを挟む断層についてそれぞれ応力場を推定した．その結果，断層ガウジを挟む断層からは2つの横ずれ断層型の応力場が検出された． E-W方向のσ_1軸，N-S方向のσ_3軸を持つ応力場と，N-S方向のσ_1軸，E-W方向のσ_3軸を持つ応力場である．このうち前者は測地学的手法に基づく現在の西南日本の広域応力場と概ね一致する．一方，カタクレーサイトを挟む断層からはN-S方向のσ_1軸を持つ逆断層型応力場，E-W方向のσ_1軸を持つ逆断層型応力場，E-W方向のσ_3軸を持つ正断層型応力場の3つが検出された．

これら全く異なる応力場に関して，余震域内の断層系は過去の地震発生帯では正断層～逆断層型応力場を経験しており，封圧が小さい断層ガウジ形成条件下では2つの横ずれ断層型応力場であった可能性がある．

本研究により検出された応力場は正確な時間変化の把握が困難であるのが課題である．それを補うため，花崗岩体を覆う中新統相当の堆積層から断層スリップデータを採取し，本発表で花崗岩体中の応力場との比較検討を行いたい．

キーワード：断層岩、2000年鳥取県西部地震、古応力解析
Keywords: fault rocks, The 2000 Western Tottori earthquake, Paleostress analysis

岩石ー水反応に伴う反応誘起応力・歪の支配要因とそのモデル化: $CaSO_4$–H_2O系における実験的研究

Controlling factors and modelling of reaction-induced stress and strain during water–rock reactions: Experimental investigation in $CaSO_4$–H_2O system

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沈み込み帯の水循環は脱水・吸水反応によりコントロールされ，そこから放出・吸収される水は沈み込み帯のダイナミクスに大きな影響を与える．特に吸水反応は固相の大きな体積変化を伴うため，反応のギブス自由エネルギー変化に伴い大きな応力を発生しうる．その圧力変化は熱力学的に見積もることができ，例えば蛇紋岩化反応では最大~1 GPaにもなる．このように反応誘起応力は岩石の破壊強度を超えうるため，その挙動は反応に伴う流体流路形成や，反応の空間的広がり，変形の理解に重要である．しかしながら，吸水反応による体積増加が破壊を引き起こして流体流れを増加させ，さらなる吸水反応を促進するのか，あるいは，空隙を埋めて流体流れを減少させ，吸水反応を抑制するのか，実際の岩石の力学的応答は制約されていない．本研究では，反応による体積に変化に対する多結晶体の力学的応答様式を明らかにするために，蛇紋岩化反応と同じく水との反応で大きな体積変化(~+46%)のある$CaSO_4$–H_2O系で，吸水反応による反応誘起応力・反応誘起歪を測定した．

これまでの$CaSO_4$–H_2O系での反応誘起応力・歪の直接測定から，吸水反応に対する系の力学応答は反応速度と変形速度の競合により支配されていることが示唆されている．さらなるプロセスの制約のために本実験では，反応速度・空隙率・変形速度の時系列変化を測定した．その結果，静水圧条件下では，変形(膨張)速度は常に反応速度に比例すること，反応速度は反応表面積に律速され，ある臨界空隙率から急激に減少することが明らかになった．また，反応表面積の減少後，膨張速度は時間とともに振動しており，反応誘起割れによる透水率・有効反応表面積の変動が示唆される．一方，差応力下での変形は，静水圧下での膨張と，溶解沈殿クリープで予測される収縮の和で説明されることが明らかになった．

本実験系で観測された反応誘起歪み[ε]は，以下のパラメーターでモデル化することができる：表面反応速度定数[k_s], 反応による固相のモル体積変化[ΔV_s], 粒径分布[f(d)], 初期空隙率[Φ_0], 臨界空隙率[Φ_c], 初期反応表面積[A_0], 反応表面積減少係数[a].

本発表では，観測された反応誘起歪を定量的に説明するモデルを提示すると共に，その律速過程・流体分布への影響について議論する．

キーワード：反応誘起応力、反応誘起歪み、吸水反応、流体、蛇紋岩化作用、石膏
Keywords: Reaction induced stress, Reaction induced strain, Hydration reaction, Fluid, Serpentinization, Gypsum

Percolation of open grain boundaries and electrical conductivity in fluid-bearing rocks

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Numerical experiments were conducted on the percolation of open grain boundaries to study the percolation threshold and evolution of connectivity. Open grain boundaries are a major component of pores in crustal materials. Electrical conductivity and permeability are highly sensitive to the connectivity of open brain boundaries. The length and size of the largest cluster was surveyed in a 3D array of cubic grains for various fractions of open grain boundary. For sufficiently large size of array, the percolation threshold was found to be 0.20. If more than 20% of grain boundaries are open, an interconnected network of open grain boundaries is formed. If the aggregate is saturated with brine, the electrical conduction can occur through open grain boundaries. The connectivity of open grain boundaries steeply increases to 1.0 around the threshold. The electrical conductivity is also expected to increase steeply. The crack density parameter for the percolation threshold is estimated to be 0.1. The large change in electrical conductivity for a small change in crack density parameter is thus expected around crack density parameter of 0.1. Simultaneous measurements on elastic wave velocity and electrical conductivity in a brine saturated granitic rock (Watanabe and Higuchi, 2015) showed a steep change in electrical conductivity around the crack density parameter of 0.1. XCT images show that open grain boundaries are the dominant pores in the sample. The steep change in conductivity must thus be related to the percolation of open grain boundaries.

キーワード：パーコレーション、粒界、電気伝導度
Keywords: percolation, grain boundary, electrical conductivity

Northward lateral cooling of the Himalayan metamorphic nappe in central and eastern Nepal, and uplifting rate of the Everest Massif

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We undertook the Himalayan nappe project, in order to clarify the thermal and tectonic history of the Higher Himalayan Crystalline (HHC) nappe, and the underlying middle Proterozoic Lesser Himalayan sediments (LHS) and overlying the Tethys sediments (TTS) by means of fission track dating of zircons. We obtained 40 zircon fission track (ZFT) ages from the samples collected along a transect of 80 km in length, crossing the Kathmandu nappe in NNE-SSW directions in central Nepal. In addition, 22 ZFT ages were also obtained from the HHC nappe and the LHS between Mt. Everest and the Main Boundary Thrust (MBT) in eastern Nepal.
As the consequence, it was revealed that ZFT ages of both HHC and LHS as a whole become young toward the north from 12-10 Ma at the frontal zone, 8-6 Ma at the middle zone, and to 3-2 Ma at the root zone along both transects. We estimated retreating rate of isotherm line of the lowest annealing temperature of ZFT as 7-8 km/myr, on the basis of FT age distribution on the transect lines. In accordance with the rate, present position of 0 Ma was inferred to be located at around 95 km to the north of the MBT, just below the summit of Himalayan giants. Those results suggest that heat source that has kept the HHC nappe under hot condition for more than 10 myr is ascribed to partially melted middle crust of Tibet, which southern front is located at about 100 km to the north of Himalayan giants.
On the other hand, the Tethys sediments (TTS) cooled earlier than cooling of the underlying HHC and LHS. The FT ages of the uppermost unit indicate 18.2 Ma, and the lower part yielded 9.7 Ma. The former suggests that the TTS cooled earlier than exposing of the HHC, and the latter implies that the basal part of the TTS cooled down below at the same time when the nappe front started to cool.

Keywords: Himalaya, metamorphic nappe, Kathmandu nappe, Everest, zircon, fission-track dating

プレート沈み込み帯のテクトニック応力場：基本的考え方
Tectonic stress fields in subduction zones: Basic concept

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In subduction zones, one (oceanic) plate moves under another (oceanic or continental) plate against some frictional resistance and descends into the earth's mantle. Long-term deformation of the overriding plates varies from mountain building to back-arc spreading, whereas the descending oceanic plates are only bent convex upward. The patterns of long-term deformation are generally considered to be the reflection of background tectonic stress fields. In the case of subduction zones, not only frictional resistance at plate interfaces but also steady subduction of oceanic plates itself cause the tectonic stress fields. The frictional resistance fluctuates with the occurrence of large interplate earthquakes, but it can be regarded as constant on a geological timescale. So, the stress field due to frictional resistance is constant in time, and its pattern is basically compressional in the direction of plate convergence. On the other hand, the steady plate subduction brings about convex upward bending of both the overriding and descending plates at a constant rate by the effect of gravity (Fukahata and Matsu'ura, GJI, 2016). So, the rates of stress increase due to steady plate subduction is constant in time, and its pattern is basically tensile (compressional) in the upper (lower) half of plates in the direction of plate convergence. To evaluate the first type of stress field, we need to know the present distribution of frictional strength along plate interfaces, which will strongly depend on fault-confined fluid pressure. To evaluate the second type of stress field, we need to know the past history of plate subduction and the rheological property of the earth's lithosphere, which will control the rate of inelastic deformation (brittle fracture and/or plastic flow) to release the tectonic stress caused by mechanical interaction at plate interfaces. However, all of these problems are very difficult to directly solve except one specific case; the stress fields of oceanic plates produced by steady plate subduction. In this case, the oceanic plate passes through the plate-to-plate interaction zone within a limited time (1-2 Myr), and so we need not to consider the whole past history of plate subduction. Furthermore, the rheological property of oceanic plates is much simpler than the overriding plates. Using the evaluated stress field of an oceanic plate as a reference, we can determine the frictional strength distribution along a plate interface so as to reproduce the spatial pattern of stress tensor orientation at and below the plate interface, estimated from observed focal mechanism data of seismic events (Terakawa & Matsu'ura, Tectonics, 2010). In this way, we finally got a starting point to reveal the tectonic stress field and inelastic deformation of the overriding plate.

キーワード：テクトニック応力場、プレートの定常沈み込み、プレート境界での定摩擦抵抗、沈み込む海洋プレート
Keywords: Tectonic stress fields, Steady plate subduction, Steady frictional resistance at plate interfaces, Descending oceanic plates

海洋プレートの応力蓄積シミュレーションに基づく東北沖プレート境界の摩擦強度の推定

Frictional strength of the plate interface off northeast Japan inferred from the simulation of oceanic plate stress

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Steady plate subduction along a curved interface brings about stress changes at constant rates in the surrounding lithosphere (Fukahata and Matsu'ura, 2016). So, in subduction zones, not only frictional resistance at plate interfaces but also steady plate subduction causes tectonic stress fields. The stress field caused by frictional resistance is basically compressive, but that caused by steady plate subduction is basically tensile in a seismogenic depth-range. In northeast Japan, the Pacific plate is descending beneath the North American plate. Before the 2011 Tohoku-oki earthquake, the focal mechanisms of seismic events at and around the plate interface were thrust-fault type (e.g., Asano et al., 2011), indicating that the compressive stress field due to frictional resistance was dominant there. The remarkable increase of normal-fault type events after the Tohoku-oki earthquake could be interpreted as the change in stress regime from compression to tension. In this study, we estimate the lower limit of frictional strength at the plate interface through the 2-D numerical simulations of stress fields for descending oceanic plates. We model the lithosphere-asthenosphere system by an elastic surface layer overlying a viscoelastic substratum, and introduce a curved interface that divides the elastic surface layer into two parts; the oceanic and continental lithosphere. The geometry of the plate interface is taken to be the vertical section of the CAMP standard model (Hashimoto et al., 2004) crossing the main rupture zone of the Tohoku-oki earthquake in the direction of plate convergence. First, we computed the rates of stress increase produced in the oceanic lithosphere by steady plate subduction at 83 mm/yr. Then, we simply integrated them along the paths of mass transfer in Lagrangian description. The tensile stress obtained in this way takes the maximum at the uppermost part of the oceanic lithosphere, and gradually increases as moving downward along dip up to 1 GPa, which clearly exceeds the yield strength of the oceanic lithosphere. So, to overcome this inconsistency, we introduced a standard yield strength envelope for the oceanic lithosphere. When differential stress exceeds the yield strength, inelastic deformation (brittle fracture and/or plastic flow) would occur to release the excess stress. Based on such an idea, we cut out the excess stress at each step of the path integration of stress increments. The results of numerical simulations show that the tensile stress in the upper part of the oceanic lithosphere, which is almost controlled by the brittle strength, reaches 200 MPa at the depth-range of 10-20km. In order to reproduce the pre-seismic compressive stress field at and around the plate interface, the steady frictional resistance of the plate interface must be greater than 200 MPa at the depth-range of 10-20km.

キーワード：沈み込み帯、テクトニック応力場、プレートの定常沈み込み、プレート境界の摩擦強度
Keywords: Subduction zone, Tectonic stress field, Steady plate subduction, Frictional strength of plate interfaces

Correlations Between Stress Orientation and Seismic Coupling in Subduction Zones

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Subduction zone megathrust faults range from being completely locked to continuously creeping. The locked regions pose the greatest seismic hazard because they accumulate stress that is often released in large earthquakes. We find that the creeping versus locked behavior of subduction zone megathrust faults correlates with the apparent frictional strength of these faults as inferred from their orientation in the regional stress field inverted from moment tensors. Our global investigation of stress orientations in subduction zones finds that the average angle between the maximum compressive stress axis and the subduction interface is significantly correlated with the average seismic coupling. The most coupled subduction zones exhibit a maximum compressive stress axis at angles of 20°-45° to the megathrust, well oriented for failure with a typical laboratory friction coefficient. The least coupled zones have angles in the range of 40°-65°, less well oriented, and implying reduced frictional strength. Comparisons between existing maps of stress orientations and geodetically-derived coupling models for the Japan Trench show a similar correlation: the locked patches on the megathrust fault are on average at lower angle to the maximum compressive stress axis than the creeping patches. Our new finer-scale model of stress orientations in the Japan Trench reveals additional complexity. Much of the plate interface exhibits angles near 30°, consistent with the overall coupling of the Japan Trench in the global subduction zone context. Exceptions are shallow zones of geodetically-inferred creep and deep locked zones, which are at angles closer to 45°, suggesting they are weaker. Our observations, excluding the deep locked zones of the Japan Trench, suggest that creeping megathrust faults have on average lower frictional strength than locked megathrust faults.

Keywords: subduction zone, stress, fault coupling

Probing the rheology of continental crust in the new era of big data geodesy

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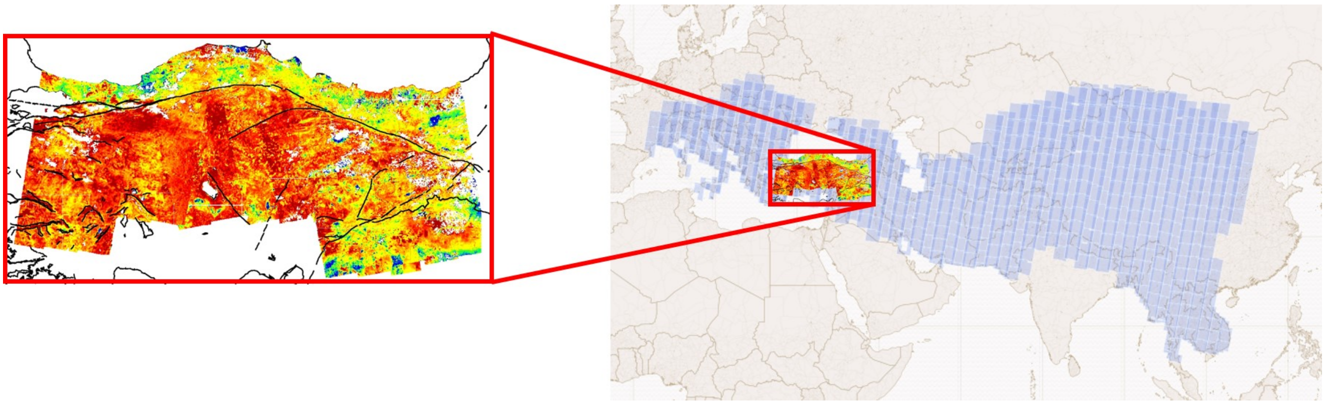
The dramatic increase in the availability of continuous GNSS stations and the launch of new radar satellite constellations like Sentinel-1 mean that we are entering a new "big data" era, where we will have long, accurate time series of surface motions for the entire planet. In this presentation, I will review what these new data are already telling us about the rheology of continental crust, and what we might learn in the future. I will use examples from the Alpine-Himalayan belt, focusing on observations and models of strain accumulation along the North Anatolian Fault, observations of postseismic deformation from continental earthquakes, and on data from the India-Asia collision zone.

Keywords: Earth, Rheology, Geodesy, Continental Tectonics, Earthquake cycle, Deformation



The role of the lower crust in crustal deformation of the Japan island arc

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In the Japanese island arc, interplate locking along the subduction interface of the Pacific plate and the Philippine Sea plate has been considered as the main source of the crustal deformation. On the other hand, detailed analysis of crustal deformation before and after the 2011 Tohoku-oki earthquake has revealed existence of persistent deformation associated with the Niigata-Kobe Tectonic Zone, a major inland deformation zone (Meneses-Gutierrez and Sagiya, 2016), which is independent of the mechanical interaction at the subduction interface. This observation suggests that activity of inland deformation zones is driven by regional tectonic stress that has been built up over a geological time scale. In addition, a special structure that promotes localized deformation must exist in the lower crust associated with active deformation in the upper crust. Such an idea is supported by a numerical simulation study, in which shear localization occurs in the lower crust beneath an inland active fault even with a slow fault slip rate such as 1 mm/year. The nonlinear rheology is considered to be the most important cause of the shear localization (Zhang and Sagiya, submitted). Thus it is expected that localized deformation in the lower crust is pertinent to each active fault. Once such a structure is created in the lower crust, it in turn controls the deformation of the upper crust. Such an idea is supported by the fact that crustal deformation pattern around active faults is well explained by an elastic dislocation model with a locking depth of ~15km. Around the Atera fault and the Gofukuji fault, major left-lateral strike slip faults, observations with dense GNSS network show that the lower crustal shear localization beneath the active fault traces continue even during significant perturbation due to the 2011 Tohoku-oki earthquake (e.g. Kumagai et al., 2017). The idea also provides a physical basis for the block modeling of inland areas.

キーワード：地殻変動、下部地殻、非弾性変形
Keywords: crustal deformation, lower crust, inelastic deformation

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Fast Scalable Finite Element Analysis Method for Crustal Deformation using a 3D Island-scale High-fidelity Model

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Recently, three-dimensional high-fidelity crustal structure data in island-scale domains are becoming available due to the accumulation of high-resolution observation data. However, it has been difficult to use such data to perform crustal deformation analysis in an island-scale domain with quality assurance of the numerical simulation because of its huge analysis cost.
We propose a high-fidelity crustal structure finite element (FE) model construction method using high-fidelity crustal structure data, and a fast FE analysis method to reduce its huge analysis cost. These methods used an automatic FE model generation method for parallel computation, MPI and OpenMP hybrid parallel computation on a distributed memory super-computer, a geometric multigrid, variable preconditioning, and multiple-precision arithmetic. Using the proposed methods, we constructed 10 billion DOF high-fidelity crustal structure FE models including the whole Japanese Islands, and conducted elastic/viscoelastic crustal deformation analysis using this model with quality assurance of numerical simulation.
The proposed method can be applied for larger crust deformation problems and extended to nonlinear/dynamic problems. As illustrative examples, we present a crust deformation analysis with 2.05 trillion DOF and an implicit nonlinear wave analysis with 1.08 trillion DOF on 0.270 trillion unstructured finite elements.

キーワード：crust deformation、finite element method、fast scalable parallel computation
Keywords: crust deformation, finite element method, fast scalable parallel computation

Modeling deformation processes of the island arc crust and mantle during the postseismic periods of the Tohoku-oki earthquake considering the heterogeneous rheological structure

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This paper investigates postseismic viscoelastic deformation in the island arc crust and mantle and postseismic slip of the Tohoku-oki earthquake considering the heterogeneous rheological structure. We first calculated the effective viscosity distribution of the Japanese island arc crust and upper mantle. Then, we calculate the viscoelastic deformation of the Japan island arc during the postseismic period of the Tohoku-oki earthquake considering the coseismic slip distribution obtained by our inversion analysis using a finite element method. After removing the viscoelastic deformation from the observed displacement data, we performed inversion analysis to obtain postseismic slip distribution.

For calculation of the effective viscosity distribution of the Japanese island arc crust and upper mantle, we first considered the thermal structure obtained by dense geothermal observations from Hi-net boreholes (Matsumoto, 2007) and by Tanaka et al. (2004). The model could not reproduce well a postseismic strain anomaly (decreases in areal strain) along the volcanic front after the 2011 Tohoku-oki earthquake, which was found by Miura et al. (2014). Therefore, we considered local low viscosity region beneath volcanoes. In this case, a postseismic strain anomaly (decreases in areal strain) along the volcanic front can be reproduced. We also obtained postseismic slip by the inversion analysis. The results indicate large postseismic slip occurred below the deeper part of the coseismic slip region. We test several viscoelastic structures and report a model which explains well the postseismic deformation in the inland region of northeastern Japan.

キーワード：東北沖地震、余効変動、不均質レオロジー構造、島弧地殻・マントル
Keywords: the Tohoku-oki earthquake, postseismic deformation, heterogeneous rheological structure , the island arc crust and mantle

Viscoelastic lower crust and mantle relaxation following the 14-16 April 2016 Kumamoto, Japan, earthquake sequence

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The M_w 7.0 16 April 2016 Kumamoto, Japan, earthquake is the largest-intensity earthquake to strike Japan since the 2011 Tohoku earthquake, and it was preceded by a M_w 6.0 foreshock on 14 April. The 16 April event ruptured earth’ s surface and involved predominantly right-lateral strike slip ranging from decimeters to several meters along a ENE-WNW trending fault of length ~80 km and width ~20 km. Crustal motions have been constrained during the pre-seismic, co-seismic, and post-seismic phases by Global Positioning System (GPS) data from GEONET and Interferometric Synthetic Aperture Radar (InSAR) data from ALOS. Relative to background (pre-seismic) motions, horizontal postseismic crustal motions during the first six months following the sequence exhibit a quadrant pattern centered on the fault that acts to restore right-lateral horizontal shear strain in the epicentral region. These motions are asymmetric about the fault, reaching ~5 cm/yr 50 km north of the fault and only 1-2 cm/yr 50 km south of the fault. This pattern is inconsistent with afterslip and is rather suggestive of viscoelastic lower crust and mantle relaxation driven by the coseismic stress changes, with relatively low viscosity northwest of the rupture zone. We explore 2.5D and 3D models of viscoelastic lower crust and mantle relaxation and afterslip to explain the postseismic motions. A preliminary 2.5D Burgers body model involves transient lower-crust/mantle viscosities of 3 x10^{17} Pa s and 1.5x10^{18} Pa s northwest and southeast of the rupture, respectively. This model replicates the first-order pattern of observed postseismic deformation. It is consistent with relatively high heat flow north of the local trace of the Median Tectonic Line, as well as low seismic-wave attenuation in the mantle beneath the volcanic gap of central Kyushu.

Keywords: transient motions, crustal deformation, rheology

Imaging the distribution of transient viscosity following the 2016 Mw 7.1 Kumamoto earthquake

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Postseismic studies of geodetic data following large earthquakes indicate a wide range of mechanisms contribute to the observed deformation and stress relaxation. Both on-fault afterslip and off-fault viscoelastic relaxation can contribute to the postseismic transient phase of the earthquake cycle. One problem with these (quasi-) dynamic models is that there is a wide range of parameter space to be investigated, with each parameter pair possessing their own tradeoffs. This becomes especially problematic when trying to model both on-fault and off-fault deformation simultaneously. Here, we draw insight from postseismic geodetic observations following the 2016 Mw 7.0 Kumamoto earthquake by utilizing a novel inversion technique.

We present a novel approach to invert for on-fault and off-fault deformation simultaneously using analytical Green's functions for distributed deformation at depth [Barbot, Moore and Lambert., 2016] and on-fault deformation [Okada 1992, Nikkhoo and Walter 2015]. Using these Green's functions, we jointly invert InSAR images and GEONET GPS time series following the Kumamoto earthquakes for afterslip and lower-crustal viscoelastic flow.

The calculated strain-rates in the lower crust are directly converted to effective viscosities and we investigate the implications of the effective viscosity structure within an outlier-senstitive Bayesian statistical framework to estimate in-situ parameters, such as temperature. Using our new method, we are able to interrogate the transient deformation in the first few months of the postseismic deformation to obtain these parameters.

The postseismic deformation at Kumamoto brings new insights into the distribution of brittle and ductile crustal processes beneath Japan and can be used to infer lower crustal properties.

Keywords: Rheology, Kumamoto, Geodesy

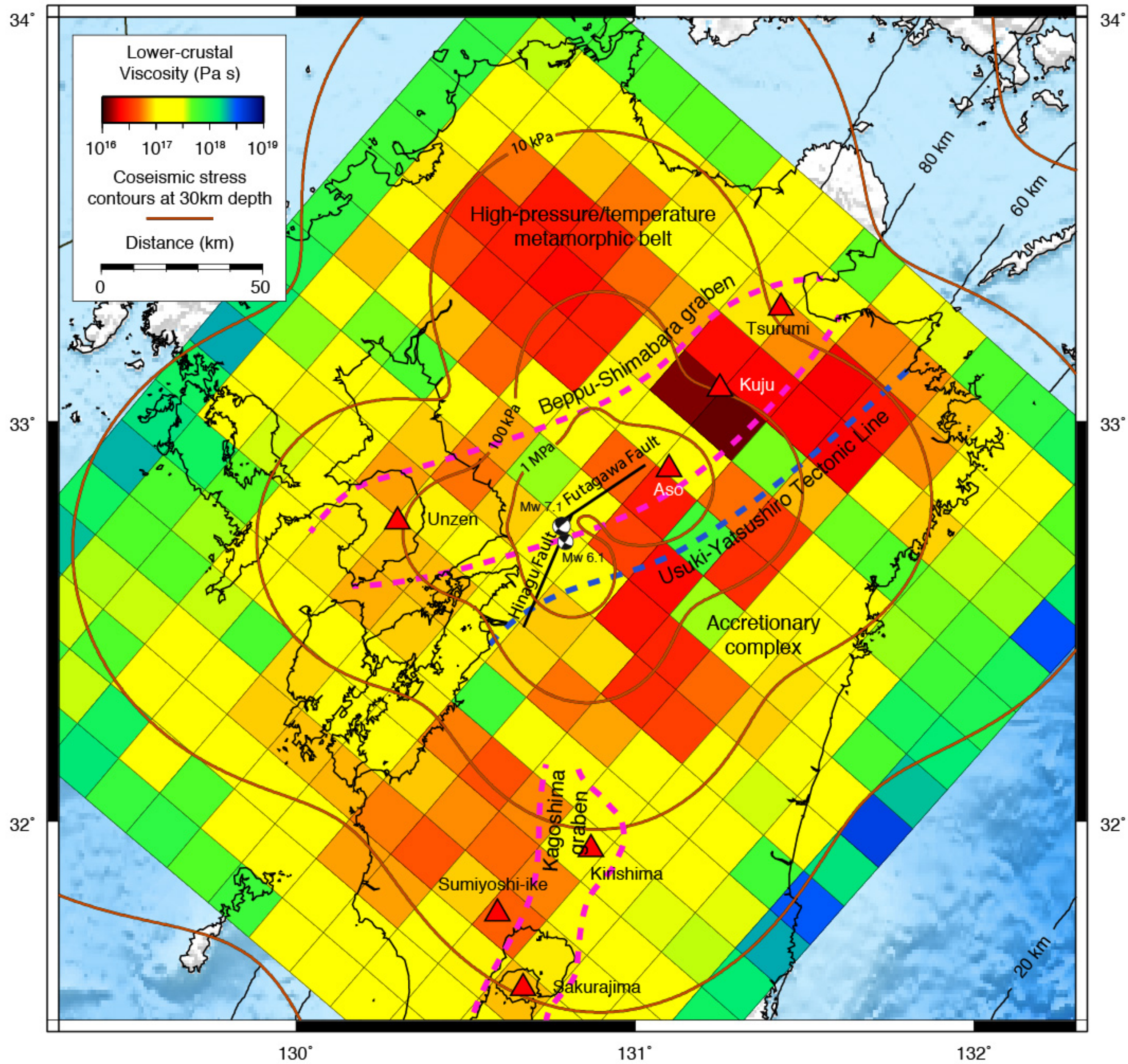

Figure 1 – Transient viscosity structure of the lower crust beneath Kyushu
Transient viscosity of the lower crust with volcanoes marked in red triangles, the Hinagu and Futagawa faults in black, and coseismic stress contours in orange. The regions of low viscosity follow the pattern of coseismic stress change modulated by the distribution of arc volcanism and plutonic bodies in Kyushu, with noticeable low viscosity anomalies beneath Mt Aso and Mt Kuju.

Change in stress field around fault zones of the 2016 Kumamoto earthquake (Mj7.3) inferred from moment tensor data of micro-earthquakes

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*Satoshi Matsumoto[1], Yusuke Yamashita[2], Manami Nakamoto[3], Masahiro Miyazaki[2], Shin'ichi Sakai[4], Yoshihisa Iio[2], Group for urgent joint seismic observation of the 2016 Kumamoto earthquake

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The 2016 Kumamoto earthquake (Mj7.3, Mj: magnitude scale by Japan Metrological Agency) occurred on 16 April 2016 in Kumamoto prefecture, middle part of Kyushu Island, Japan. Several earthquakes over Mj 6 also occurred before and after the mainshock. The earthquake killed resident people and heavily damaged the cities around the hypocentral area. The seismic activity in and around the area was highest in the Kyushu Island before the earthquake occurrence. Dense seismic observation carried out in the area enable us to estimate high precision focal mechanism solutions. Here we analyzed the focal mechanisms before and after the occurrence of the sequence as seismic moment tensors and estimated stress field in the hypocentral area. As general tendency, dominated minimum principal stress (sigma 3) in the N-S direction obtained and the maximum principal stress takes value close to the moderate one. The stress field reveals spatial heterogeneous feature, which varies from southern to northern part of the area. We found that the stress field around the fault zone is consistent with co-seismic fault behavior of the earthquake sequence and decreasing maximum horizontal stress.

キーワード：２０１６年熊本地震、応力場、モーメントテンソル
Keywords: 2016 Kumamoto earthquake, stress field, moment tensor

鳥取県西部・島根県東部の応力場–満点地震観測による-
Stress field in the Western Tottori and Eastern Shimane regions deduced by the Manten seismic observation

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鳥取県西部・島根県東部地域における応力場を推定した。Kawanishi et al. (2009)は、中国地方全体においてσ$_1$の方位はほぼ東西であるのに対して、地震帯直下では西北西-東南東に回転していることを見出し、それを、直下の下部地殻内のゆっくりすべりで説明した。今回、稠密地震観測データに加えて2000年鳥取県西部合同地震観測データも用いて、鳥取県西部、島根県東部、およびその間の地域にわたる広域の応力場を推定した。島根県東部では、以前示されたように、σ$_1$の方位は、大局的には南部で東西、その北側で西北西-東南東から北西-南東に回転、地震発生域の北端付近で再び東西方向に戻る傾向が見られる。鳥取県西部および両者の間の地域でも、大局的には南部で東西、その北側で西北西-東南東から北西-南東に時計回りに回転する傾向が見られる。ただし、この２つの領域では、北端では、σ$_1$の方位は、さらに反時計回りに回転して、南北方向に近づいているように見える。このことは、P軸の方位分布から指摘されていたが、応力逆解析により確認された。

キーワード：応力場、下部地殻、地震帯、満点計画、鳥取県西部地震
Keywords: stress field, lower crust, seimic belt, Manten project, Western Tottori earthquake

Episodic tectonic behaviour from crystal-plasticity to seismicity

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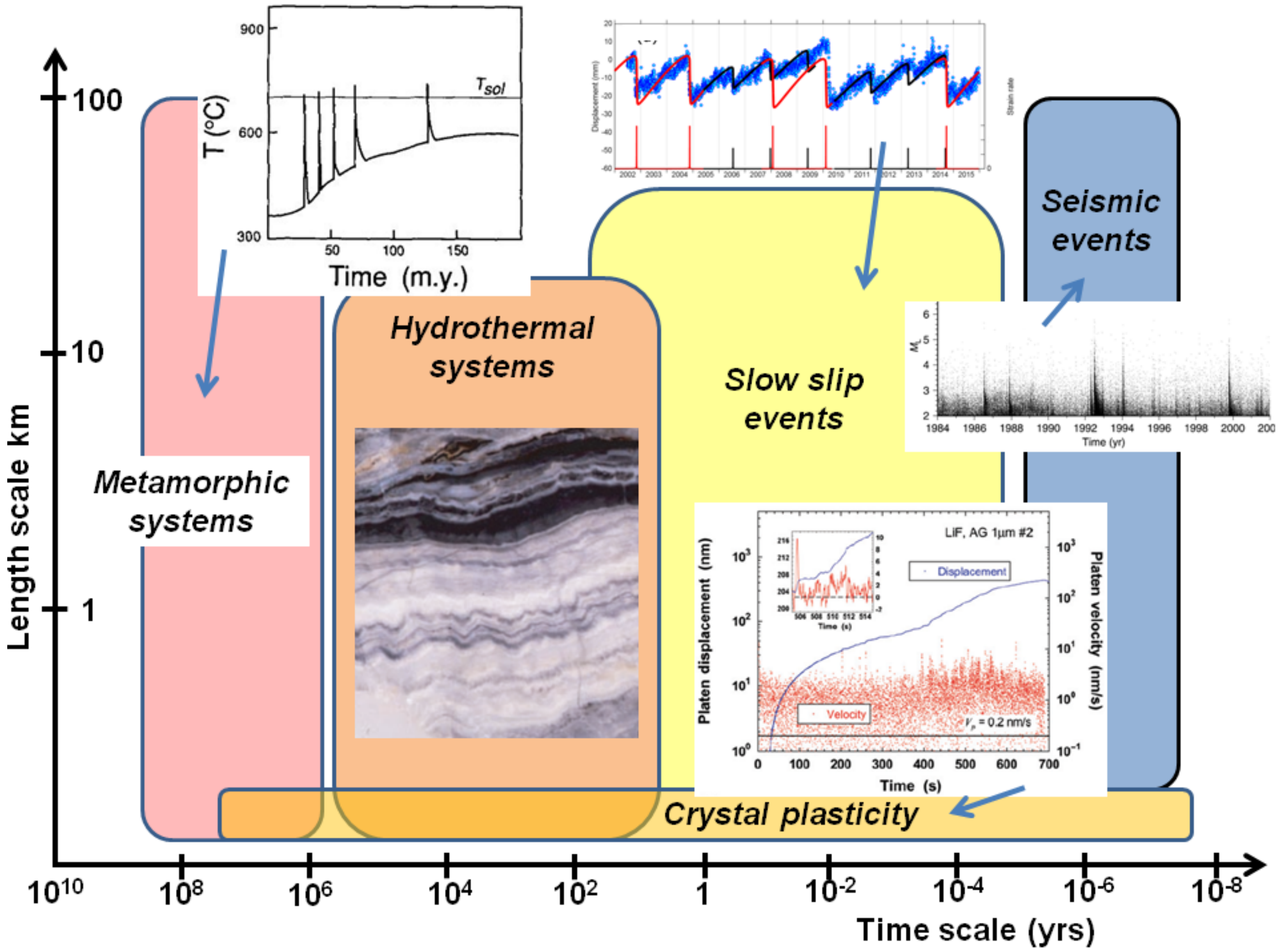
The purpose of this paper is to emphasise that deforming, chemically reacting systems in the Earth operate as nonlinear dynamical systems held far from equilibrium by the influx of energy and mass. The nonlinear behaviour leaves its mark as apparently stochastic distributions of mineral assemblages, mineralisation, structures and seismic activity. However these irregular (apparently random) distributions are deterministic and, in principle, contain all the information required to understand the dynamics of the underlying mechanisms.

Tectonic systems in common with most large nonlinear systems such as weather and ocean circulation systems are characterised by being forced to evolve by energy supplied at a large spatial scale; in order to do so mechanisms of evolution are adopted that involve dissipation of energy at finer and finer spatial scales. The coupling of deformation and mineral reactions in tectonic systems is one mode of cooling for the planet Earth. Thus, plate tectonic motions driven by cooling of the Earth at a global scale drive the development of through-going lithospheric faults and associated damage zones that focus mantle derived fluids. Energy is dissipated by these deformation processes and by the flow of fluids through the deformed regions. Energy continues to be dissipated by exothermic chemical and deformation processes such as hydrothermal alteration, fracturing and sliding on faults. These processes occur at increasingly finer scales until ultimately any energy in the system is either stored by endothermic reactions such as melting, the deposition of sulphides (such as pyrite), non-hydrous silicates (such as K-feldspar) and metals (such as gold) or is dissipated by heat conduction and advection to the surface of the Earth. Processes of dissipation at finer and finer scales resemble energy cascades which are multifractal in their energy distribution. Thus tectonic systems are multiscale dynamical systems and need to be studied using the insights and tools developed to study such systems over the past 50 years or so. This involves knowledge gained from statistical mechanics and the thermodynamics of chaotic systems.

Episodic behaviour in the deformation of the Earth has been described at length scales from asthenospheric shear flow to nano-scales in crystal plasticity and at time scales ranging from 100’s of millions of years in metamorphic complexes to milliseconds in seismic events. We discuss such episodic behaviour in the context of energy cascades and their associated scaling laws as the systems approach criticality. The processes that dissipate energy in the global energy cascades almost always involve coupling between exothermic processes, such as fracturing, brecciation, sliding on faults and hydrothermal alteration of fault zones, and endothermic processes, such as melting and deposition of anhydrous silicates and of carbonates in hydrothermal systems or fault zones.

By considering the energy and mass balances for these systems one can show that coupling between processes that compete for energy and/or mass results in the episodic behaviour of temperature and/or chemical composition and the response can be periodic or chaotic depending on a range of parameters we will discuss. We explore the phase space for these interactions and illustrate the transitions between different modes of operation with different attractors in phase space. The chaotic behaviour of these systems means that the outputs are multifractal both in time and space. We discuss fast efficient ways of analysing the multifractal nature using wavelet transforms. Finally, the complexity of these systems can be fully quantified both in space and time using various versions of recurrence plots. These plots (given sufficient data) enable the attractor to be derived for a given system along with estimates of the predictability of system behaviour. We illustrate these analytical procedures with data from deformed rocks, hydrothermal systems and from seismic events.



Detailed application of the microboudin palaeopiezometer: estimation of principal deviatoric stresses imposed on a metachert from the Warrawoona greenstone belt in East Pilbara Terrane, Western Australia

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The microboudinage structure of columnar mineral grain is used a passive marker for the palaeostress analysis of rock. In this presentation, we report a detailed application of the microboudin palaeopiezometer through the palaeostress analysis of an individual metachert specimen from the Warrawoona greenstone belt in East Pilbara Terrane, Western Australia. The metachert includes the microboudinaged tourmaline grains. We separately applied the microboudin palaeopiezometer to 3621 tourmaline grains divided into every 10° of their long axes on the foliation surface. The palaeostress analysis revealed that the far-field differential stress σ_0 is obtained the group of mineral lineation ±15° and perpendicular to the mineral lineation ±15° as 10.2 MPa and 5.3 MPa, respectively. Also, the values of σ_0 varied corresponding to the orientation of the tourmaline grains; relatively large value of σ_0 obtained from tourmaline grains oriented around the mean orientation defined as the mineral lineation, whereas relatively small value of σ_0 obtained from tourmaline grains oriented around perpendicular to the mineral lineation. Given that $\sigma_1 - \sigma_3$ and $\sigma_1 - \sigma_2$ are as 10.2 MPa and 5.3 MPa, respectively, magnitude of principal deviatoric stresses (σ'_1, σ'_2 and σ'_3) are obtained as σ'_1 = 5.3 MPa, σ'_2 = -0.1 MPa and σ'_3 = -5.1 MPa. In this stress state, the stress ratio $\phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$ is 0.48 that indicates typical triaxial compression. As the microboudinage is considered to have occurred immediately before the rock encountered the brittle-plastic transition during the plastic deformation, these values correspond to conditions at approximately 10–15 km depth and 300°C within an Archaean greenstone belt.

キーワード：古応力解析、マイクロブーディン応力計、メタチャート、電気石、マイクロブーディン構造
Keywords: palaeostress analysis, microboudin palaeopiezometer, metachert, tourmaline, microboudinage structure

*P*波初動データを用いた応力空間パターン推定手法の開発：実データへの適用例

Development of a method to estimate spatial stress pattern from *P*-wave first motion data: an application to a real dataset

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A method of estimating spatial stress pattern from *P*-wave first motions has been developed in Iwata [2016, JpGU meeting; AGU meeting]. In this method, it is assumed that the strike and dip angles of a fault plane are randomly distributed with the uniform distribution and that the direction of slip of the fault is parallel to the direction where the shear stress is maximized. Under these two assumptions, spatial stress pattern that fits the dataset of P-wave first motions is estimated with the smoothness constraint on a spatial variation of the stress pattern. In this method, it is unnecessary to determine the focal mechanisms of each events.

To demonstrate the performance of the method, a numerical experiment was done. 3,000 events were randomly and uniformly distributed and five seismic stations were deployed in a study area. The strike and dip angels of each of the events were taken from the uniform distribution. The rake angle (or focal mechanism) of the event that maximizes the shear stress was computed from an assumed stress field at the hypocenter of the event. Then, the polarities of the *P*-wave first motion that are expected to be observed at the five stations were determined; in total, 15,000 *P*-wave first motions were generated. They were reversed with a probability of 0.05 to consider the possibility of error recording. As a result of the application of the method to this synthetic dataset, the assumed stress field and the probability of error recording were successfully reproduced.

In the next step, this method was applied to the real dataset that was taken from the aftershocks of the 2000 Western Tottori Earthquake, which was complied and analyzed in Kawanishi et al. [2009, JGR]. From this dataset, 47,570 *P*-wave first motions from 3592 events were chosen on the basis of O-C time for the *P*-wave arrival (and *S*-wave arrival if it was picked). The estimated spatial stress pattern reveals that the sigma_1 (maximum principal stress) axis has the direction of WNW-ESE in the northern part of the aftershock area while is is almost parallel to the direction of EW in the southern edge of the area. This is consistent with the result of Kawanishi et al. [2009], suggesting the validity of this developed method.

キーワード：応力場、空間統計、P波初動、ベイズ推定、平滑化
Keywords: stress field, spatial statistics, P-wave first motion, Bayesian estimation, smoothness constraint

2011年東北沖地震後の流体圧変化で誘発されたと推定される山形-福島県境群発地震活動の震源移動の詳細
Details of hypocenter migration in the Yamagata-Fukushima swarm probably caused by fluid pressure change after the 2011 Tohoku-Oki earthquake

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地下への注水により、地震活動が誘発されることが知られている (e.g., Shapiro, 2008)。注水により上昇した間隙流体圧で断層の摩擦強度が低下し、摩擦すべりの条件が満たされた結果、誘発されると考えられる。同様に、自然地震の場合も、深部から上昇してきた流体による断層強度の低下がその発生要因になり得る。その顕著な例の一つに、2011年東北沖地震後、山形-福島県境で誘発された群発地震活動がある (吉田・他，2012; Terakawa et al., 2013; Okada et al., 2015; Yoshida et al., 2016)。

この群発地震活動は、2011年東北沖地震時にせん断応力が減少したにも拘わらず、その7日後に急激に活発化した。震源が migrationする特徴を持つことや、発生場所が大峠カルデラの直下であることから、流体に起因した強度低下により活動が活発化したと推定されてきた。さらに、この群発地震活動では、応力降下量、b値 (吉田・他，2016, SSJ)、摩擦強度 (Yoshida et al., 2016)が、顕著に時間変化することが知られている。本研究では、この群発活動において、震源移動や地震発生数、b値、応力降下量、摩擦強度の時間変化を生じさせている背後のメカニズムについて知見を得る目的で、震源の時空間発展をより詳細に調べることにした。

最初に、気象庁一元化カタログに記載されている最初の地震より前の期間に発生した地震のdetectionを行った。近傍の観測点の連続波形記録にSTA/LTA法 (Ross & Ben-Zion, 2014)を適用することにより、2011/3/18にS-P時間が 3秒以内の地震を748個検知することに成功した。そのうち4点以上の観測点でP, S波の到達時刻を読み取ることが可能であった地震20個を、一元化カタログのデータセットに加えて、計28,010個の地震を震源再決定の対象とした。

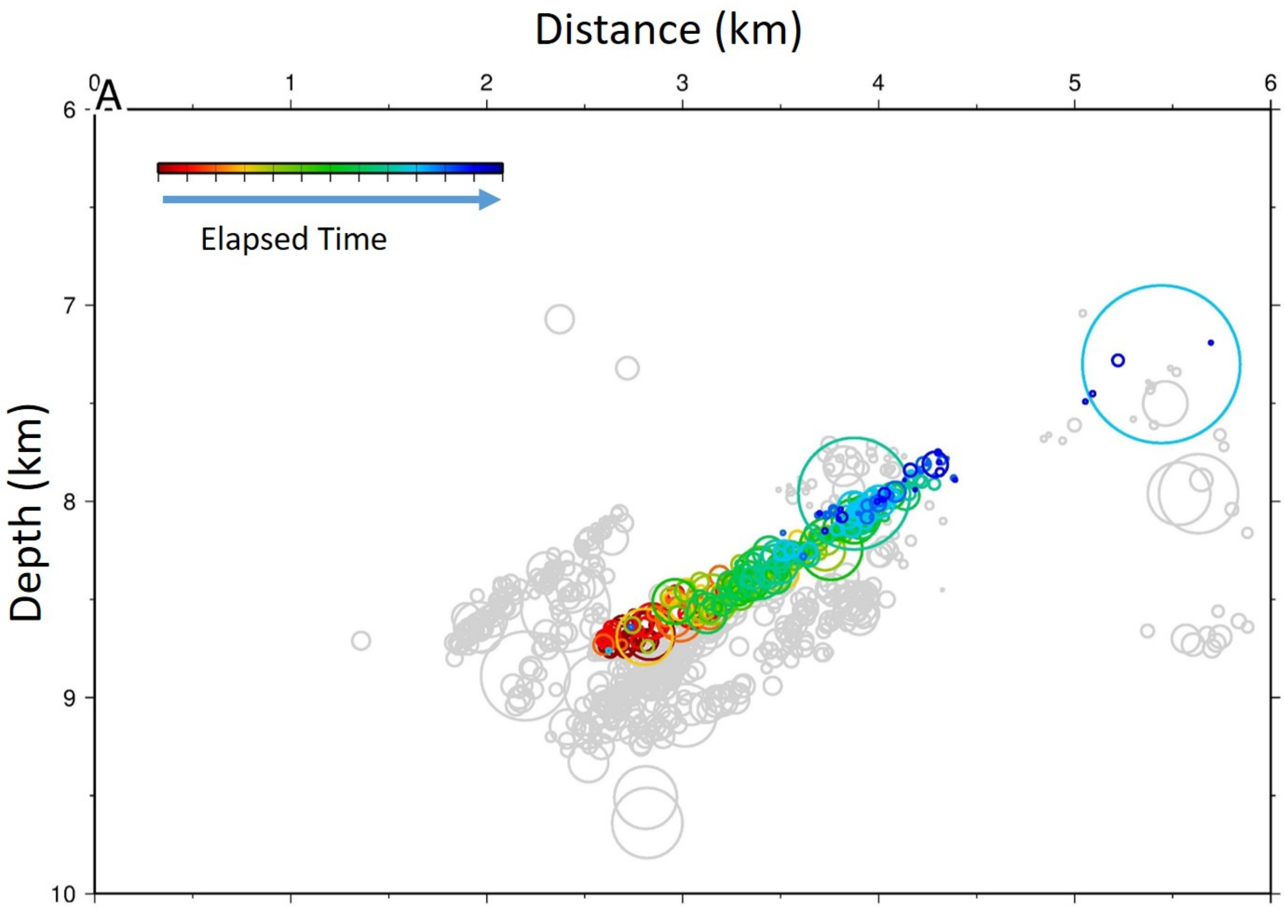
次に、震央間距離 1 km以内の地震同士で相互相関関数を計算し、その最大値と対応する時間差を求めた。得られた波形相関による時間差データを、一元化震源記載のP, S波到達時刻データに加えて、DD法 (Waldhauser & Ellsworth, 2002)を適用することにより、震源の再決定を行った。波形相関により得られた走時差の残差は 160msecから20 msecまで減少した。

その結果、震源は、cloud状にばらついた分布から、複数枚の面状構造へと著しく変化した。地震波形の相似性を利用して相似地震群の分類をすると、分類された異なる相似地震群は、それぞれ異なるクラスター・面に集中するようになった。面の方向は、それを構成する地震のメカニズム解の一つの節面と一致しており、地震がこれらの面に沿う断層運動で生じていることを示す。震源の migrationも面に沿って進行しており、ほとんどは深部から浅部に向かって移動している。移動速度は概ね流体拡散により説明できそうであるが、M2-3程度の比較的大きな地震が発生した際には、急激な移動が生じる。

本研究でdetectした最初期の地震は、気象庁一元化カタログに記載されている地震活動の空白域に分布しており、カルデラ壁の北西部に沿っているように見える。その後、震源域が東西に広がり、 50日ほどの間、震源域最深部の水平に近い層の中で非常に活発な活動が起こっている。この時期の非常に活発な地震活動は、間隙水圧が極端に高い状態にあったことに起因する可能性がある。この期間は、応力降下量と摩擦強度が顕著に小さく、b値が大きい時期に対応する。また、震源再決定によりsharpに求まったそれぞれの面に沿う地震活動に注目すると、面上の同じ箇所が数度に渡って地震を生じさせているようにみえる。背後にaseismic slip が存

在する可能性を示唆する。

キーワード：摩擦強度、間隙水圧、震源移動、群発地震、2011年東北沖地震
Keywords: frictional strength, pore pressure, hypocenter migration, swarm, 2011 Tohoku-Oki earthquake



Localized deformation in Mid-Niigata as observed by dense GPS network before and after the 2011 Tohoku-oki earthquake

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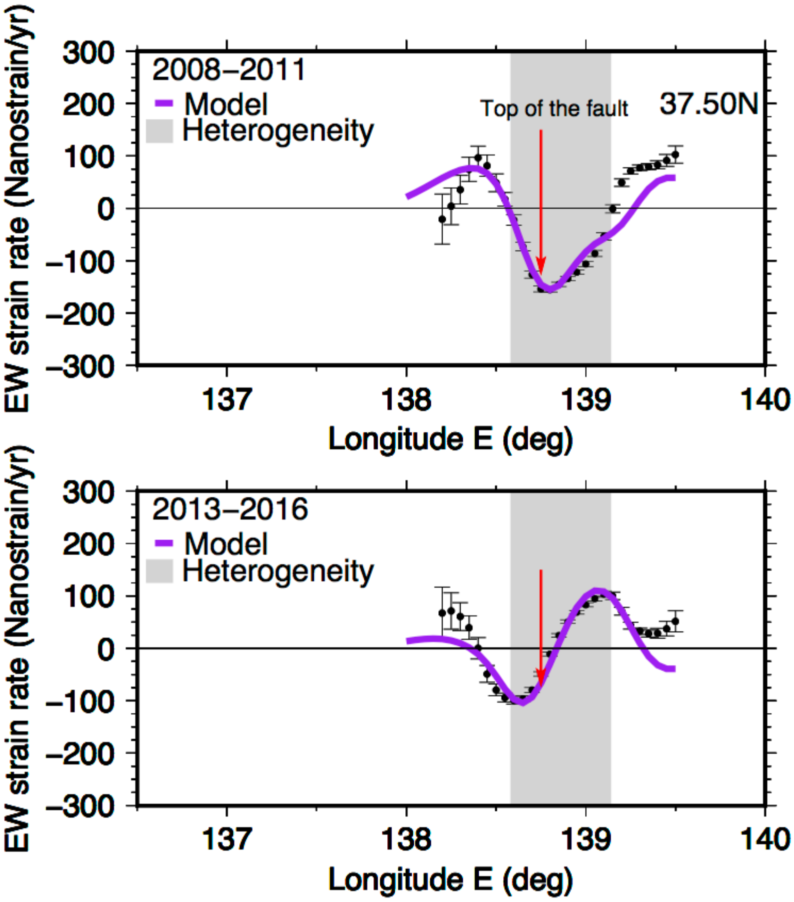
The Niigata-Kobe Tectonic Zone (NKTZ) is a deformation zone along the east coast of Japan Sea, with localized geodetic contraction (10^{-7}/yr, Sagiya et al. 2000), one order of magnitude larger than the long-term deformation rates in the area (10^{-8}/yr, Wesnousky et al., 1982). Meneses-Gutierrez and Sagiya (2016) studied strain rate distributions based on GPS sites from the GEONET array in central Japan before and after the Tohoku-oki earthquake and found a persistent localized contraction (4~10x$10^{-8/}$yr), in northern NKTZ, showing that the concentrated contraction is mainly inelastic in the form of aseismic fault slip. However, a complete scale characterization of the deformation source was not possible due to limited spatial resolution of the GPS data.
In December 2010, the Association for the Development of Earthquake Prediction (ADEP), in collaboration with Nagoya University, constructed 20 continuous GPS sites in Mid-Niigata, for the purpose of monitoring crustal activity around the Western Nagaoka Basin fault, one of major active faults in this area. Analysis of this network with GEONET allows a better characterization of the deformation source in the area.
We evaluate the response of Mid-Niigata during the preseismic (2008/3-2011/2) and postseismic period (20013/3-2016/2) of the Tohoku-oki earthquake. We calculate horizontal strain rate distributions from the displacement rate data using the method developed by Shen et al. (1996), with a distance decay constant of 15 km. Then, we decomposed the E-W strain rate with respect to its wavelength following Meneses-Gutierrez and Sagiya (2016). We found a persistent localized contraction in the short wavelength component within 40 km before and after the Tohoku-oki earthquake. However, differences in the amplitude and horizontal location of the localized deformation suggested that elastic heterogeneities of the crust, acting in different sense before and after the earthquake, might affect the deformation in Mid-Niigata. Localized deformation in the preseismic and postseismic period was modeled across a longitudinal profilie considering an aseismic east dipping fault and an elastic heterogeneity as the source of deformation. We found that the data is better explained by faults cutting the lower crust and part of the upper crust with a dipping angle of 30-40º with a slip rate larger than 10 mm/yr and an elastic heterogeneity with a horizontal width of 50km located above the fault. Although our model is simple, it is effective in showing that the contribution from both, elastic heterogeneities within the upper crust and aseismic fault slip on the lower crust and part of the upper crust, are necessary to explain the deformation in the Niigata region. Such discussion was not possible before due to the lack of spatial resolution in the area.

Keywords: Crustal deformation, GPS, Niigata-Kobe Tectonic Zone


2008–2011
Model
Heterogeneity
Top of the fault
37.50N
300
200
100
0
–100
–200
–300
EW strain rate (Nanostrain/yr)
137
138
139
140
Longitude E (deg)
2013–2016
Model
Heterogeneity
300
200
100
0
–100
–200
–300
EW strain rate (Nanostrain/yr)
137
138
139
140
Longitude E (deg)

