

## 蛇紋岩の浸透率異方性と沈み込み帯での流体経路 Permeability anisotropy of serpentinite and fluid pathway in subduction zone

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日本列島のような沈み込み帯で発生する火山や地震活動は、沈み込むプレートにより地球内部へ運び込まれる水と密接に関わっている。沈み込み帯での水循環は、これまで含水鉱物の相関係に支配されると考えられてきたが、本研究では水循環が岩石の浸透率に支配されるとの新しいモデルを提案する。含水鉱物の脱水分解によりマントルへ吐き出された水は、一般に浮力のため直上に移動すると考えられているが、蛇紋岩のように片理が発達した岩石では浸透率に異方性が生じ、流体移動が面構造に制約される可能性がある。本研究では蛇紋岩の浸透率異方性を検証する透水実験を行い、沈み込み帯での水循環と火山・地震活動の関連性を議論する。

実験試料は長崎県野母半島に産する片理の発達したアンチグライツ蛇紋岩を用い、容器内変形透水試験機（広島大学設置）により、蛇紋岩の浸透率を片理に平行方向と垂直方向でそれぞれ測定した。その結果、蛇紋岩の片理に垂直な浸透率は片理に平行なものに比べ系統的に低い値を示し、高封圧下では2桁程度の差が見られた。この結果は、蛇紋岩など面構造が強く発達した岩石では透水性に著しい異方性の効果が存在し、水の移動は浮力のみならず岩石の剪断面（応力場）に制約される可能性を示唆している。蛇紋岩化がみられるプレート境界では、沈み込みによる剪断変形のためプレート境界に平行な面構造が発達していることが期待される。その場合、脱水反応によりマントルへ放出された流体は蛇紋岩の面構造に沿ってプレート境界方向に選択的に移動することが予想される。

プレート境界での流体移動速度を、蛇紋岩の浸透率をもとに計算した結果、プレート境界方向では7cm/yearと見積もられる。西南日本では、この流体速度がフィリピン海プレートの沈み込み速度（~4cm/year）より速いため、マントルウェッジ内を流体は上方に移動すると期待される。一方、東北日本では、太平洋プレートの沈み込み速度（~10cm/year）が流体上昇速度より速いため、マントルウェッジへ吐き出された水は、上方へ移動するのではなく、コナフローによりさらに深部へ運び込まれる可能性が高い。日本列島での火成活動は均質ではなく、西南日本では東北日本に比べその活動度は著しく低い。西南日本では水循環が浅部で完了し、マグマの生成に至らないのに対し、東北日本ではより深部へ運び込まれた水が活発な火成活動を引き起こしていると考えられる。また、深部低周波微動の分布にも地域性があり、西南日本でその頻度が高いのはプレート境界上を上昇する水と関連があるのかもしれない。このように、水の循環様式が岩石中の流体移動速度に支配されることが、沈み込み帯での火山や地震活動の不均質性を生じている要因なのかもしれない。

キーワード: 浸透率, 蛇紋岩, 流体移動, 沈み込み帯

Keywords: permeability, serpentinite, fluid migration, subduction zone

## 沈み込み帯の地震：地震発生に果たす地殻流体の重要な役割 Earthquakes in subduction zones: An important role of aqueous fluids in earthquake generation

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沈み込み帯では、主として3つのタイプの地震、すなわち プレート境界地震、 スラブ内地震、 内陸地殻内地震が発生する。近年の研究により、これら3つのタイプの地震のいずれも、その発生に、沈み込んだスラブから供給された水が決定的に重要な役割を果たしているらしいことがみえてきた。

スラブ内稍深発地震の詳細な空間分布や解像度を上げたスラブ内の地震波速度構造の研究は、スラブ内稍深発地震の発生原因として脱水脆性化説を支持する観測的証拠を提供しつつある。水による間隙流体圧が有効法線応力を低下させ脆性破壊を可能とさせると推定される。プレート境界近傍の詳細な地震波速度構造の研究からは、プレート間カプリングが、プレート境界の間隙流体圧や直上のマントルウェッジの蛇紋岩化に支配されていることを示唆する観測的証拠が得られている。スラブ沈み込みに伴う2次対流の上昇流部分に対応すると推定される、スラブにほぼ平行な傾斜した地震波低速度域が東北地方直下のマントルウェッジ内に見出されていた。遠地地震の走時データをも用いた最近の地震波トモグラフィの研究は、東北地方だけでなく、この傾斜した低速度域が日本列島の他地域でも広域に認められることが明らかになった。スラブから吐き出された水は、その一部がプレート境界面を通り越し、やがてはこの上昇流に取り込まれ、最終的に島弧地殻にまで運ばれると推定される。運ばれた水は特定の場所に集中し、その下部地殻の強度を下げ、その結果、直上の上部地殻に応力集中が生じる。どうやら内陸地震は、そのような場所で選択的に発生しているようである。

キーワード: 沈み込み帯, 地殻流体, プレート境界地震, スラブ内地震, 内陸地震

Keywords: Subduction zone, aqueous fluids, interplate earthquake, intraslab earthquake, shallow inland earthquake

## プレート境界断層の高間隙水圧による海溝域までの破壊の暴走－2011東北沖地震による津波発生メカニズム

### Runaway slip to the trench due to rupture of highly pressurized megathrust, Tsunamigenesis of the 2011 Tohoku earthquake

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The gigantic 2011, March 11 Mw 9 Tohoku earthquake is examined from the viewpoint of the pre-seismic forearc structure, the seismic reflection properties of megathrust around the usual up-dip limit of the seismogenic zone, the thermal state of a shallow subduction zone, and the dehydration of underthrust sediments. At the Japan Trench the Pacific Plate is subducting westward beneath the northeast Japan at a dip angle of 4.6. The middle and lower slopes dip eastward at angles of ~2.5 and ~8.0, respectively. The forearc prism beneath the middle and lower slopes is inferred to be in extensionally and compressively critical states, respectively, based on the presence of clear internal deformation features and on the occurrence of aftershock earthquakes. The rapid uplift of the forearc that caused the 2011 Tohoku tsunami may have been associated with this internal deformation of the prism. The critical state of the prism indicates that the effective basal friction of the plate boundary megathrust is <0.03 for the middle prism and >0.08 for the lower prism. The megathrust, especially under the middle slope, is characterized by a prominent reflector with negative polarity; i.e., a landward-increasing wave amplitude. This observation suggests that the megathrust hosts highly pressurized fluids. Underthrust sediments in this part of the Japan Trench are dominated by pelagic and siliceous vitric diatomaceous silt with clay. The dehydration kinetics of opal-A to quartz, the clay transformation of smectite to illite, and the thermal structure of the Japan Trench suggest that maximum dehydration of the sediments would take place at 50-60 km horizontally from the deformation front, where the temperature along the megathrust is 100-120. The zone of maximum dehydration coincides with the prominent seismic reflector that has negative polarity. We hypothesize a possible free slip along this portion of the megathrust during the 2011 Tohoku earthquake, caused by anomalously high fluid pressure resulting from fluid accumulation over centuries.

## 沈み込み帯地震発生領域における海洋地殻の脱水挙動

## Diagenesis and dehydration of subducting oceanic crust within seismogenic subduction zones

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Seismogenic plate-boundary faults at accretionary margins may lie within or close to the subducting oceanic crust, composed of basaltic rocks, in contact with the overriding plate of a lithified accretionary prism (Kimura and Ludden, 1995; Park et al., 2001; Matsumura et al., 2003). Therefore, diagenesis and dehydration of the oceanic crust within the seismogenic zone (normally defined as a temperature condition from ~100-150 to 350-450°C; Hyndman et al., 1993) is supposed to have a great influence on the interplate mechanical behaviors where great earthquakes occur. Our previous work showed that basaltic basement at the top of the oceanic crust is remarkably hydrated prior to reaching the trench axis, and pointed out a possibility to be a significant source of fluid in the seismogenic zone (Kameda et al., 2011). The aim of this work is to provide complementary dataset on the state and pathways of diagenesis in the subducting oceanic crust to verify the argument presented in the previous paper. In particular our focus is on a more validate quantification of the dehydration processes within the seismogenic zone. In this work, we analyzed 5 pillow basalt samples exposed in the Cretaceous to Tertiary accretionary complex, the Shimanto Belt, southwest Japan. Based on the vitrinite reflectance measurement of terrigenous sediments accompanied by these rocks, they are estimated to have been subjected to burial diagenesis at 150-300 °C. X-ray diffraction (XRD) analyses of the bulk samples revealed that they contain ~25wt% of hydrous clay minerals. Moreover, clay-fraction XRD exhibited a successive conversion of smectite (saponite) into chlorite as a function of diagenesis grade. In this talk, we will present an improved model of the dehydration behavior of subducting basaltic crust inferred from these data, and address its potential influence on the evolution and physical states of the seismogenic-plate boundary faults.

Keywords: seismogenic zone, dehydration, oceanic crust, saponite

## 南海トラフ付加体先端部デコルマ付近の10年間連続孔内間隙圧記録 10 years of ACORK: Continuous pressure from the decollement zone at Nankai Trough off Muroto

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プレート境界断層面上の固着域では、間震期には断層面が固着しており、下盤のプレート運動がほぼそのまま上盤（陸側の付加体）に伝達していると考えられている。固着域よりも海側のプレート境界（デコルマ等）は、固着の性質は持っていないものの、運動学的には固着域とは区別できない、つまりまるで固着しているような挙動を示すと考えられる。実際のデコルマの状態は、堆積後の経過時間が短いことなどから有効差応力が大変小さく、破壊を生じやすい状態だろうと予想される。もしそうだとすると、大地震時に破壊が深部から伝搬してくると、動的破壊条件によっては一気に破壊が海底まで達する。東北地方太平洋沖地震（2011.3.11）ではまさにこれが起こったと考えているが、同様のことが、室戸沖の南海地震の震源域でも発生するかどうか、検討が必要である。

室戸沖デコルマにおける有効応力を規定する最大の要素である間隙圧・水理状態（排水・非排水）を現場で実測するために、孔内間隙圧長期計測装置（ACORK）が2001年に設置された。ACORKからのデータは2001年以来、先端部のデコルマ（808I孔）およびトラフ底（1173B孔）で取得されているが、808I孔では最深部のデコルマ（約950m）が水理的にシールされていなかったため、間隙圧の絶対値は取得できていなかった。平成20年（2008年）に孔口にパッカーを設置し、デコルマがシールされたと期待される。

KR11-12航海では、「かいこう」による3潜航が予定通りに遂行された。シリアル通信速度の向上のおかげで、両サイトにおいて、3-4年間分のデータをそれぞれ1時間程度で取得することに成功した。これにより、我々は11年半におよび間隙圧連続データを得ることができた。両サイトとも、ここ4年間は圧力が一定であり、潮汐応答も記録されていた。また3月11日の東北地震時に、ほぼすべての圧力データが一斉に変動するなど、いくつか興味深い変動が記録されていた。一方、808I孔で、孔口のバルブを閉じることにより、シール状態が確認できる状態とすることができ、今後ようやくデコルマでの間隙圧値が取得できる見込みとなった。

2009年の潜航で、孔口のバルブから揺らぎを伴った流体が湧出していることが確認されていた。今回はその流体を保圧状態で採水し、また面積式（フロート式）流速計による流速測定を実施した。

観測は今後も継続するが、特に間隙圧の潮汐・地震応答データからデコルマや付加体の浸透率を推定するために、新型データロガーを用意し、1秒サンプリングを行って低周波地震の波形も検出できるようにする予定である。また流体が海底に湧出している証拠は、生物群集の存在が最も顕著であるが、熱流量異常や硫酸イオン濃度異常も良好な proxy となる。熱流量異常はこれまでトラフ底で観測されているが、数値解析からは断層に沿って海底に湧出する単純なモデルでは説明できないことが分かってきた。デコルマの水理状態把握のためには、海底への流体湧出量の正確な把握が不可欠であるので、熱流量計測・間隙水分析を継続して行う。

Keywords: ACORK, Nankai Trough, pore pressure, decollement



## 地震性滑りに伴う断層での高温流体発生の実験的再現

### Experimental demonstration of high-temperature fluid generation during coseismic fault slip

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地震時の断層滑り挙動における流体の役割は重要である。例えば断層滑りに伴う摩擦発熱によって岩石中の間隙水が温められ、間隙水圧が上昇することで、断層の弱화가生じる (thermal pressurization, 以下 TP)。また、温められた間隙水 (高温流体) が発生すると、断層にて岩石と流体が反応し様々な元素組成・同位体値異常が発生する可能性がある。例えば、台湾チェルンブ断層や房総付加体での断層では、fluid-mobile element として知られている Li, Rb, Cs, Sr などの濃度異常と Sr 同位体比の異常が報告されている。南海トラフの泥質堆積物を使った水熱実験での岩石 - 流体間の分配係数に基づき、先の組成変化を評価した結果、350 度以上の高温状態が明らかとなった。また、これらの断層の水理特性や微細組織も考慮に入れると、地震時に断層にて TP が機能したと言える。それゆえ、断層の微量元素・同位体の検出は地震時における断層の滑り挙動を特定する可能性があると言える。しかし、このような異常が断層滑り時に発生しうるかどうかの実験的な検証も必要である。そこで本研究では、高速摩擦試験機を使用、地震性滑り時の高温流体の発生を実験的に再現し、かつ実験前後の試料の微量元素・同位体分析を実施することによって、上記の問題についての検討を行った。

高速摩擦試験機は高知コア研究所に所有されている透水制御型回転式剪断摩擦試験機を使用した。岩石試料は台湾チェルンブ断層の母岩である泥岩を用い、粉末状にした岩石試料を 2 枚のステンレス製剪断プレート間に挟み、含水環境下にて試料に剪断応力を作用させた。実験時の試料温度は試料部に取り付けられた熱電対によって測定され、水圧は試料部外部の水圧ラインの途中に取り付けられた水圧計によって測定された。実験は開放系と閉鎖系の場合の 2 種類を行った。開放系は水圧を常に一定になるように維持し、閉鎖系は剪断による摩擦発熱で水圧が変動するようにした。両方の条件とも変位速度 0.2-0.4 m/s、垂直荷重 14-15 MPa、水圧 2-5 MPa のもと実験を行った。また実験前後の試料に関する微量元素組成は ICP-MS によって測定した。

実験の結果、変位量増加に伴う剪断強度の弱화가認められ、一部の run では試料温度が最高 300 度以上にまで達したデータが得られた。また閉鎖系の場合、温度上昇とともに、水圧の上昇、模擬断層における有効垂直応力の低下が認められた。これら変化は TP の機能を再現したことを意味する。さらに、実験前後試料の微量元素分析の結果、実験後試料には Li の濃度の有意な低下が認められた。Li は fluid-mobile element であり、300 度以上の高温環境における流体と岩石との反応によって岩石から流体側に移動する。以上の結果、地震性滑り時の高温流体の発生を示す直接的な証拠として、微量元素・同位体異常が有効であることを実験的に検証できたと言える。

## 日本海溝に沈み込む直前の海洋プレート構造の不均質性と含水量

### Along-trench variation of the water contents within the incoming plate offshore north-eastern Japan

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沈み込む海洋プレートの脱水やそこから放出される水は、沈み込み帯における地震・火山活動とその空間不均質性に強い影響を与えていると考えられている。したがって、沈み込み帯における諸活動を理解するには、海洋プレートが沈み込み帯に持ち込む水の量を把握することが不可欠である。

日本海溝沈み込み帯では、2011年東北地方太平洋沖地震(Mw9.0)に代表されるようなプレート境界型大地震が繰り返し発生している。プレート境界型大地震の破壊域分布は海溝軸に沿う方向に不均質であり、海溝海側における海底地形の複雑さと興味深い相関があることが指摘されている。一方、近年の中南米における海溝域の構造研究では、プレート折れ曲りに起因する正断層の発達度合や、海山の存在など、海溝海側斜面における海底地形の複雑さが海洋プレートの含水量と相関がよいことも指摘されている。したがって、日本海溝域におけるプレート境界型大地震の不均質な分布は、沈み込む海洋プレートが持ち込む水の量の空間不均質性がと相関がある可能性が考えられる。

そこで、海洋プレートによって沈み込み帯に持ち込まれる水量の空間不均質性を把握することを目的として、我々は日本海溝北部の海溝海側において海底地震計(OBS)とエアガンを用いた大規模な構造探査観測を実施した。走時解析や重合前深度マイグレーションにより構築したP波速度構造、S波速度構造、 $V_p/V_s$ 構造や反射断面は、いずれも海溝軸に沿う方向に顕著な不均質が存在することを示している。予期されたように、海底地形がもっとも起伏に富む北緯38°39'度付近では海洋地殻、海洋マントルとも低速度で、且つ、 $V_p/V_s$ が高い。これは海底地形が複雑な場所では、海洋マントルまで多くの水が入り込んでいることを示唆している。すなわち、日本海溝に沈み込む直前の太平洋プレートは、場所により大きく含水量が異なっている可能性があるだろう。

キーワード: アウターライズ, 地震波速度構造, 水, 水和, 構造探査, 海底地震計

Keywords: outer rise, seismic velocity, water contents, hydration, wide-angle seismic survey, OBS

## PS変換波から推定した東北地方における海洋性地殻の速度構造

### Estimation of velocity structure in the oceanic crust of the Pacific slab beneath northeast Japan from PS converted wave

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地震波速度トモグラフィー (e.g., Nakajima et al., 2009) やレシーバー関数解析 (Kawakatsu and Watada, 2007) により、東北日本弧下の太平洋スラブ表面付近には地震波速度の遅い海洋性地殻が存在することが明らかになってきた。しかしながら、これらの方法では海洋性地殻の詳細な速度分布を推定することは難しく、その空間分布の特徴はまだよくわかっていない。

スラブ内で発生する地震には、スラブの上部境界面での変換波が観測されることが知られており、Matsuzawa et al. (1986) では、スラブ表面直下に低速度域を仮定することにより、スラブ境界面でのPS変換波の走時や振幅が説明できることを示した。そこで、本研究では非常に密に展開されている基盤地震観測網で観測されたPS変換波を用いて、東北地方下に沈み込む太平洋プレートの海洋性地殻の速度構造の詳細な空間分布の推定を試みた。

本研究では、太平洋スラブ内で発生した地震の波形について、理論走時や振動軌跡を参考にスラブ境界面でのPS変換波を同定し、その到達走時の読み取りを行った。そして、プレート形状や速度構造を仮定した上で、読み取ったPS変換波の走時から海洋性地殻のP波速度を推定した。結果として、火山フロント付近を境に、前弧側では6.5-7.0 km/s程度、背弧側では7.5-8.5 km/s程度の速度が得られた。この速度変化は、海洋性地殻内部での相転移によって生じていると推測され、スラブ内地震の発生と深く関わっていると考えられる。今後は、海洋性地殻の密度や含水率の推定に加え、速度分布と地震活動との関係の詳細な検討などを行う予定である。

キーワード: PS変換波, 海洋性地殻, 太平洋スラブ

Keywords: PS converted wave, oceanic crust, Pacific slab



## 沈み込み帯の脱水作用と非火山性群発地震の発生 Fluids dehydrated from the subducting oceanic crust and non-volcanic seismic swarms

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A non-volcanic seismic swarm is often assumed to be tied to fluid movements, based on earthquake migrations obeying a diffusion equation. However, seismological observations that relate to the presence and driving force of fluids are not well documented. One of the most intensive non-volcanic seismic swarms in Japan is located in the Wakayama district, SW Japan, and quite distant from the present volcanic front.

It is important to fully describe the crustal heterogeneity originating in crustal fluids. We have deployed a very dense seismic array with a length of about 100 km at the western edge of the Kii Peninsula. The dense seismic observations were conducted from December in 2010 to June in 2011. The linear array consists of 86 seismometers with 1 Hz natural frequency, those continuously recorded three-component signals. Both P- and S-wave arrival times from local earthquakes including some low-frequency earthquakes (LFEs) were manually picked from waveforms observed by both dense temporary stations and permanent stations. The dense and well-covered ray-paths from local and teleseismic events afford us precious opportunities to investigate the fine-scale seismic structures.

The most striking feature of the fine seismic image is low-velocities with low Poisson ratios beneath the seismic swarm region. This low-velocity feature is also supported by the receiver functions. In addition, the corner of mantle wedge is characterized as low velocity, leading to an inverted inland Moho at depth of about 30 km. This low velocity mantle seems to extend to deeper depths.

At depths shallower than 40 km, a depth-section of receiver functions shows that the oceanic crust, of which the top and bottom (plate interface and oceanic Moho) are outlined by strong negative and positive amplitudes, respectively, is subducting at a dip angle of approximately 15-degree. In contrast, the polarity of the plate interface changes from negative to positive at depths greater than 50 km. The dip-angle of the oceanic crust increases with depth. We interpret the transitions of the polarity as indicating the onset of eclogitization of the oceanic crust. The subducting oceanic crust beneath LFEs is characterized by low-velocities and high Poisson ratios, which are commonly observed at Tokai or Shikoku regions.

We propose that fluids dehydrated from the subducting oceanic crust could infiltrate into the mantle wedge and crust, leading up to the intensive non-volcanic seismic swarms in Wakayama and high-helium isotopes widely observed in the Kii Peninsula.

Keywords: seismic swarm, crustal fluid, non-volcanic, velocity structure, receiver function, dehydration

## 地殻断層帯の流体組成 台湾リーシャン断層中の流体包有物分析 Fluid chemistry of the fault propagation zone ?fluid inclusion analysis from the Lishan fault, Taiwan-

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Liberation of CO<sub>2</sub>-rich gas from fluid preserved in the fault propagation zone would be important phenomena in the earthquake and aftershock process. We have detected that injected fluid in link thrust would cause fault propagation and fault lubrication due to vapor-separation [1]. Recently, one of the authors, Yu-Chang Chan found unusual quartz vein on the great link-thrust, Lishan fault, in Taiwan orogenic belt [1]. The quartz vein is spherical shape and is composed of large crystals and surrounding milky fine-grained crystals. The transparent quartz grains contain large primary fluid inclusions over 100 microns in diameters. The fluid inclusion is classified as two phase, vapor phase and three phase inclusion. Homogenization temperature is 260 oC and NaCl wt% estimated from freezing T, is 7.41. In order to measure fluid chemistry, PIXE analysis was done at Tsukuba University. Analytical procedure is shown in [2]. The result is summarized as follows. Br/Cr ratio is lower than that in seawater. Ti, Cr, and Ni contents are high, suggesting that fluid is related to magma activity beneath the fault. Vapor-phase inclusion contains considerable amount of metal elements (Ti, Zn, Ge, Mn, Ca, Fe, Pb, Rb, and Cu) as well as K, and Br. Fractionation differences between the vapor and the fluid would be useful tool to detect vapor separation due to fault propagation.

### References

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[2] Kurosawa M. et al., Island Arc, 19, 17-29 (2010)

キーワード: 台湾リーシャン断層, 付加スラスト, 石英脈, 流体包有物, PIXE 分析, 断層破壊進展によるガス分離

Keywords: Lishan Fault, Taiwan, Accretionary thrust, Quartz vein, fluid inclusion, PIXE analysis, gas separation due to fault rupture

## 東北日本におけるマントル起源ヘリウムと深部起源炭素の空間分布 Spatial distributions of mantle helium and deep-seated carbon in northeastern Japan

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On the basis of a progressed seismograph network in recent years, geophysical studies indicate detailed structure and transportation paths of fluids in subduction zone, northeastern Japan (Hasegawa et al., 2005). The presence of fluid is presumed by the seismic velocity anomalies, however, it is difficult to detect directly what kind of fluid is upwelling from geophysical studies. We focus on showing an outline of the geographical distribution of mantle helium and deep-seated carbon obtained from hot spring water/gases in northeastern Japan.

We have collected water/gases samples from hot springs throughout the northeastern Japan and analysed the helium isotope ratio ( $^3\text{He}/^4\text{He}$ ) and the deep-seated carbon concentration (Cds) both of which are good indicators to distinguish the origin of fluid. Helium-3 is originated from mantle and Cds is considered to be derived from the slab.

Spatial variation clearly showed the high  $^3\text{He}/^4\text{He}$  ratio and Cds in volcanic front and back-arc region in northeastern Japan. However, the distribution has regional variation. The geographical distributions of  $^3\text{He}/^4\text{He}$  ratio and Cds observed at the surface are found to be similar to that of seismic low-velocity zone of wedge mantle. The distribution of seismic low-velocity zone is thought to be resulted in the existence of fluids, partial melts or mantle diapirs. Therefore, the similarity of the distributions may represent that there are some fluid path for the upwelling the helium and carbon species to the surface from the underlying seismic low-velocity zone.

Keywords: helium isotope ratio, deep-seated carbon, northeastern Japan, fluid

## 東北日本弧の地殻深部の不均質 Lower crustal heterogeneity beneath the northeast Japan

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東北地方太平洋沖地震以降、余効変動の影響で、東北日本地殻内部を震源とする比較的規模の大きい内陸地震が多数発生している。しかし、内陸地震の分布には偏りがあり、いわき市周辺地域では比較的多くの内陸地震が発生している。東北地方太平洋沖地震以降の余効変動やそれに伴う内陸地震発生不均質な分布を考える際には、東北本州弧の地殻や最上部マントルの粘性や強度の不均質を考慮する必要がある。

東北日本の下部地殻の不均質については Nishimoto et al. (2008, Journal of Geophysical Research) により報告されている。この研究では一の目潟捕獲岩の P 波 ( $V_p$ )・S 波 ( $V_s$ ) 速度測定を行ない、北緯 39~40 度の範囲の地震波速度トモグラフィーを用いて下部地殻構成岩石の解釈を行った。その結果、下部地殻において、背弧側では、日本海沿岸部は角閃石輝石はんれい岩、東北本州弧西側は角閃石はんれい岩が分布すると推定された。背弧側の鳥海山周辺と奥羽脊梁山脈地域の火山体周辺では、角閃石はんれい岩が部分熔融状態にある可能性が高い。北上山地は東北本州弧の中では特異な地震波速度値を示し、相対的に石英に富む岩石が分布すると推定された。この下部地殻の不均質性は東北本州弧の地質発達史と対応する。すなわち、「北上山地の古い地殻」、「背弧海盆拡大期における日本海西縁及び沿岸部の大和海盆・飛鳥海盆の新しい地殻」、「鳥弧火山活動期における奥羽脊梁山脈での火山体の発達に対応する現在の地殻」、という長い地質発達史のなかでそれぞれに特徴的な下部地殻が形成されたと考えられる。上記の下部地殻モデルでは議論されていないが、東北日本の地質発達史の時間軸の中で、前述の「北上山地の古い地殻」と「背弧海盆拡大期」の間に位置する重要なイベントが存在する。それは東北日本の白亜紀左横ずれ運動である。

東北地方太平洋沖地震以降、余効変動と関連していると思われる内陸地震がいわき市周辺地域において比較的多く発生しており、最大級の内陸地震の一つとして、2011年4月11日にM7.0の地震(震源深さ6km)が発生した。この内陸地震に伴って、塩ノ平断層に沿って地表地震断層(正断層)が出現している。塩ノ平断層の分布する基盤地質は阿武隈変成帯の東半分を占める御斎所変成岩類(緑色片岩や角閃岩を主要構成岩石として、変成チャートや泥質片岩を含む)であり、地表地質としては比較的硬い結晶質な岩石が分布している地域である。御斎所変成岩類は玄武岩類を主とするジュラ紀付加体が変成したものであり、角閃岩相から緑色片岩相の変成作用を被りつつ、白亜紀左横ずれ運動を全体として被っている。左横ずれ運動に伴い御斎所変成岩類には北北西の方向の褶曲が著しく発達しており、片理面の傾斜は非常に高角になっている。高角な片理面は東西圧縮場の東北日本においては主応力軸に対してほぼ直行するので弱面としては機能しにくいと考えられるが、今回の東北地方太平洋沖地震以降の引張場においては弱面として機能しやすいと考えられる。白亜紀左横ずれ運動は地殻浅部では棚倉剪断帯のように局在化するが、地殻深部では御斎所変成岩類のように地殻深部全体が左横ずれ剪断帯として振る舞ったと考えられ、下位のマントルも左横ずれ剪断帯として振る舞った可能性は高い。もしそうであれば、マントルから地殻全体には白亜紀左横ずれ運動に伴い垂直な面構造が発達しており、強度や流体移動を考える上で非常に重要な役割を果たしていると思われる。

キーワード: 地殻, 島弧, 東北, 地震波速度, 弾性波速度

Keywords: crust, island arc, Tohoku, seismic velocity, elastic wave velocity

## 沈み込み帯におけるアンダースラスト堆積物からの脱水とプレート境界断層上のすべりの加速

### Runaway slip to the trench due to rupture of highly pressurized megathrust beneath the middle trench slope

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In plate subduction zone, enormous earthquakes occur repeatedly on the plate boundary, which is facing surface between subducting sediments and basal rocks. The subducting rocks have been presumed to supply water to the plate boundary during subducting, which has much effect on deformation processes and earthquakes in the subduction zone. To clarify the relation between dehydration, deformation and earthquakes along subduction zone, we discussed diagenesis and deformation processes of ribbon cherts embedded in a Jurassic accretionary complex, central Japan, and evaluated the dehydration region in the Japan Trench through numerical simulation.

The diagenesis and deformation processes of ribbon cherts were investigated in detail to gain a better understanding of the mechanical behavior of the plate boundary at depth in cold subduction zones. The analyzed cherts record two stages of deformation: (1) map- to outcrop-scale ductile folding, and (2) subsequent brittle faulting. The ductile deformation was facilitated by silica dehydration?precipitation, and is represented by multiple stages of vein networks. The folds are cut by brittle faults, indicating lithification and the concurrent mechanical transition from ductile to brittle behavior. Slip zones along the faults are typically filled with brecciated chert in a chlorite matrix. Geothermometry analysis of the matrix chlorite suggests that faulting occurred following the completion of opal-CT to quartz transition reaction. This is also confirmed by the kinetic simulation of silica conversion reactions. The results suggest that ductile deformation of thick pelagic deposits with abundant fluids results in an aseismic plate boundary, whereas chemical diagenesis of the deposits, producing crystalline cherts, results in strong interplate coupling in cold subduction zones such as the Japan Trench.

Based on the upper results and discussion, the gigantic 2011, March 11 Mw 9 Tohoku earthquake is examined from the viewpoint of the pre-seismic forearc structure, the seismic reflection properties of a megathrust around the usual up-dip limit of the seismogenic zone, the thermal state of a shallow subduction zone, and the dehydration of underthrust sediments. At the Japan Trench the Pacific Plate is subducting westward beneath the northeast Japan at a dip angle of 4.6 deg. The middle and lower slopes dip eastward at angles of ~2.5 and ~8.0 deg, respectively. The forearc prism beneath the middle and lower slopes is inferred to be in extensionally and compressively critical states, respectively, based on the presence of clear internal deformation features and on the occurrence of aftershock earthquakes. The rapid uplift of the forearc that caused the 2011 Tohoku tsunami may have been associated with this internal deformation of the prism. The critical state of the prism indicates that the effective basal friction ( $\mu_b'$ ) of the plate boundary megathrust is  $<0.03$  for the middle prism and  $>0.08$  for the lower prism. The megathrust, especially under the middle slope, is characterized by a prominent reflector with negative polarity; i.e., a landward-increasing wave amplitude. This observation suggests that the megathrust hosts highly pressurized fluids. Underthrust sediments in this part of the Japan Trench are dominated by pelagic and siliceous vitric diatomaceous silt with clay. The dehydration kinetics of opal-A to quartz, the clay transformation of smectite?illite, and the thermal structure of the Japan Trench suggest that maximum dehydration of the sediments would take place at 50?60 km horizontally from the deformation front, where the temperature along the megathrust is 100?120C. The zone of maximum dehydration coincides with the prominent seismic reflector that has negative polarity. We hypothesize a possible free slip along this portion of the megathrust during the 2011 Tohoku earthquake, caused by anomalously high fluid pressure resulting from fluid accumulation over centuries.

キーワード: アンダースラスト, 堆積物, 脱水, 異常間隙水圧

Keywords: underthrust, sediment, dehydration, excess pore pressure



## 古い沈み込み帯での遠洋性珪質堆積物からの水の供給と挙動

### Source, sink and pathway of fluid dehydration from pelagic siliceous sediments in cold subduction zone

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The fluid existing at plate boundaries in subduction zone makes a strong effect on seismicity and fault slip along the plate boundary megathrusts. Seismogenesis controlled mainly by temperature which ranges from ~150 degrees C to 350-450 degrees C (Hyndman and Wang, 1993; Hyndman et al., 1995, 1997; Oleskevich et al., 1999). Additionally, the dehydration at shallow zones cooler than ~150 degrees C along plate boundaries is also important to understand the propagation of fault slip occurring at further deep seismogenic zones. In this study, we firstly evaluated the amount of dehydration from siliceous sediment on subducting plates. Siliceous sediments might be thick and abundant because of long-period exposure to the ocean far from the continents in the case of old oceanic plates, for example, the Japan Trench. The diagenesis and dehydration of siliceous sediments are calculated quantitatively introducing reaction kinetics and temperature profile models of the Japan Trench, a cold subduction zone, where the siliceous sediments dominantly subduct. As a result, structured water within silica minerals is released through the diagenesis much as ~160 g/m<sup>2</sup>/year along shallow plate boundary (~5-10 km depth), where the temperature is ~100 degrees C. Second, we performed parameter sensitivity analyses of silica diagenesis to explain the depth variation of dehydration zone in above calculation and to evaluate the possible range of it. The analyses revealed that the dehydration from silica can proceed at various temperature ranges (80-120 degrees C) depending on subducting parameters. The most effective parameter is temperature gradient, gamma, and result dispersion in above estimation can be explained by the variation of it. To discover evidence of dynamic dehydration from silica diagenesis and to connect dehydrated water and rock deformation, we thirdly performed geological research in the Inuyama area, Mino-Tamba Belt, Jurassic accretionary complex in Central Japan as an on-land analog of the sediments on the old oceanic plates. As well as white chert recording focused fluid flow and silica precipitation, we investigated the pressure solution seam (PSS) evolved inside of a red chert and conducted element analyses using Electron Probe Micro Analyses (EPMA). Isocon method was introduced to the results and revealed that ~530 vol% of silica had escaped from pressure solution seam. This result supports our calculation results and suggests the existence of abundant water in subducting sediments on the old oceanic crusts, although this estimation is too large to give a sufficient explanation from silica diagenesis. There are some ways to explain this problem, and we finally discussed the possible deformation mechanism depending on the diagenesis and dehydration of siliceous sediments with depth and temperature.

キーワード: 珪質堆積物, 沈み込み帯, チャート, 脱水, 変形

Keywords: siliceous sediment, subduction zone, chert, dehydration, deformation

## 野島断層への注水実験による影響域のイメージング : 2003年淡路島注水実験の再解析 Imaging of the fluid injection zone at the Nojima-fault: Reanalysis of 2003 Awaji Island water injection experiment

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Monitoring the physical states of seismogenic zone is one of the most demanded subjects in seismology. The attempt to monitor the underground fluid behavior by seismic ACROSS (Accurately Controlled Routinely Operated Signal System) has been continued by the research group of Nagoya University and other institutions. The air injection experiment in 100m depth in Awaji Island in 2011 showed clear image of injection zone by the time-reversal method (Kasahara et al., 2012). In order to compare the 2011 results and the previous water injection experiment in 2003, we reanalyzed the data obtained by the seismic ACROSS at Awaji Island in 2003 (Misu et al., 2003), to detect the influence of the water-injection experiments at the Nojima Fault.

The continuous observation was made for about five months in February to June, 2003, using two seismic ACROSS vibrators and two seismic arrays at about 300 m away from the source to NW and SWW, respectively. In the water injection from March 13 and March 23, 225 tons water in total with 4.5MPa was injected at 540 m depth of the 1,800 m borehole at 150 m distance of NNW of the source. Two ACROSS vibrators shared the frequency band and generated vibration in 10-22 Hz in total. Each seismic array comprised 10 seismometers shaping a cross with 10 m spacing.

By the previous analysis by Misu et al. (2003), no significant signal accompanied with the water injection was found in the temporal variation of travel times of S- and surface waves, which showed the obvious response to the rainfall. By the water flow simulation, we found the similarity of flow speed caused by rain falls and the observed S-wave travel-time changes (Kasahara et al., 2011).

In this study, we performed the time-reversal imaging using the differential waveforms between before and after the water injection, in order to examine the ability of detecting the area of influence by the water injection. As a result, the NS-oscillation of the time-reversal using the two arrays focuses around the borehole of the water injection. The array distribution seems not to be appropriate to this imaging and might be the reason for the other components not focusing around the injection point.

For the fluid migration into the subduction, we obtained the clear image of fluid layer by simulation (Tsuruga et al., 2010) and the current imaging method using seismic ACROSS can be useful for the real-time monitoring physical state change along the future focal zones on subduction zone.

キーワード: 野島断層, 注水実験, アクロス, 断層解剖計画, タイムラプス, 4 D

Keywords: Nojima Fault, Water injection experiment, ACROSS, Nojima Fault-zone Probe, Time lapse, 4D

## 南海掘削孔の温度検層データから検出した熊野海盆のガス層における流体上昇 Upward fluid migration in free gas zone in the Kumano basin detected from the temperature logging at IODP Site C0009

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統合国際深海掘削計画による南海トラフ地震発生帯掘削計画ステージ2の第319次航海で掘削されたサイトC0009において、ワイヤライン検層によって孔井内の深さ方向の温度プロファイルが複数取得された。これらの温度プロファイルは別々の検層によって得られたもので、孔井内の泥水循環を伴う掘削作業の終了からの経過時間が異なる。我々は、ふたつの温度検層データに Honer plot 法を適用して、掘削前の地層の温度プロファイルを推定した。この地層の温度プロファイルは、検層・コア/カッティングス解析に基づく地層区分に対応して異なった温度勾配をしめし、地層区分 IIIA では 31 K/km、地層区分 IIIB では 17 K/km、地層区分 IV では 28 K/km であった。地層区分 IIIB の温度勾配が小さいことは、地層区分の熱伝導率が他の地層に比べて大きいことでは説明しにくい。なぜなら、サイト C0009 と類似の層序をもつと考えられるサイト C0002 の孔井で得られたコアで測定された熱伝導率は、地層区分 III と IV で差がなかったからである。地層区分 IIIB の小さな温度勾配は、熊野海盆の堆積物から生じた流体の上方への移動によるものと考えたと説明できる。温度プロファイルの解析から推定された地層区分 IIIB での流体の移動速度は  $9.2 \times 10^{-9}$  m/s である。これは、水理試験から得られた透水係数から得られるものと同程度の速度である。温度勾配やそれから得られる見かけの熱伝導率、そしてコアから得られる熱伝導率を総合的に解析することは、地下の流体移動を検出する有力な手段となりうる。流体移動は、熱伝導だけを仮定して得られる温度勾配と実際の温度勾配とのずれから推定可能である。この方法は、流量の直接測定などでは検出不能な速度の遅い流体移動にも適用できる可能性がある。

キーワード: 熱構造, 地殻内流体移動, 前弧海盆, 深海掘削, 孔井検層, 南海トラフ地震発生帯掘削計画

Keywords: Thermal structure, crustal fluid flow, forearc basin, deep drilling, well logging, NanTroSEIZE

## 瀬戸内海下を伝播するP・S波とフィリピン海プレートの形状 P and S Waves Traversing Beneath the Seto Inland Sea and the Shape of the Subducting Philippine Sea Plate

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By examining later phases of P and S waves from slab earthquakes at depths of ~40-50 km around Shikoku, we obtain constraints on the shape of the subducting Philippine Sea plate and the structure around the mantle wedge. Although the mantle wedge structure as well as the location of contact between the island arc and oceanic crusts can control shallow mantle flow, affecting thermal structure around the plate boundary, it is not easy to infer them because the target often lies beneath the ocean with sparse seismic stations. For slab earthquakes at depths of 45-49 km in northwestern Shikoku, we observe two arrivals of P wave at the Hi-net stations in the azimuth range from the north to the east, which are located on the downdip side. The apparent velocities of the initial and later phases are about 8 and 6.7 km/s, approximating P velocities in the mantle and crust, respectively. Dominant S waves propagate by apparent velocity of about 3.8 km/s, which corresponds to a crustal speed. Because the slow phases at the crustal speeds are not observed or observable only at small distances in the northwestern direction, it is unlikely that the earthquakes occurred within the island arc crust. The observations imply that the oceanic crust where the earthquakes occurred is connected with the island arc crust in the northeastern direction, whereas it is not in the northwestern direction. Synthetic waveforms computed by the 3-D Gaussian beam method do not predict slow phases crossing mantle wedge of high velocity. The observations of the slow phases thus suggest that high-velocity mantle does not intrude the region beneath the Takanawa, Ehime, Peninsula. For an earthquake at a depth of 39km in central Shikoku, we also observe later phases in the downdip direction. For earthquakes at depths of 40-45 km in northeastern Shikoku, on the other hand, we do not observe later phases to the downdip direction.

## 日高地域下の3次元地震波減衰構造: 島弧 島弧衝突過程のイメージング Seismic attenuation structure beneath the Hokkaido corner: Imaging the arc-arc collision process

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### 1. Introduction

In the Hokkaido corner, the Kuril forearc sliver collides with the northeastern Japan arc. Using data from the nationwide Kiban seismic network and temporary seismic network, we determined high resolution three-dimensional seismic velocity structure beneath this area to understand the collision process between the Kuril and NE Japan forearcs [Kita et al., 2010, EPSL; 2011, AGU Fall Meeting], which revealed that an anomalously low- $V$  zone (crust material) descends into the mantle wedge area and reaches a depth of  $\sim 80$  km immediately above the subducting Pacific slab. Many earthquakes also occur in this low- $V$  zone down to  $\sim 80$  km depths. In order for deeper understanding of the collision process, we estimated three-dimensional seismic attenuation structure beneath the Hokkaido corner and compared the obtained seismic attenuation images with the seismic velocity images of Kita et al. [2011].

### 2. Data and method

We applied the methods of Eberhart-Phillips and Chadwick (2002) and Hada et al. (2010, 2010 JPGU meeting) to seismic waveform data from the Kiban network. We simultaneously determined a value of  $t^*$ , corner frequency, and amplitude level for the calculated spectra. Then, seismic attenuation structure ( $Q$  value structure) is imaged using  $t^*$  values. The study region is 41-45N, 140.5-145E, and a depth range of 0-200 km. We obtained 5721 P-wave and 3579 S-wave spectra from 723 events ( $M > 2.5$ ) that occurred in the period from October 2006 to April 2011. Horizontal and vertical grid nodes were set with a spacing of 0.10 degree and 10-30 km, respectively.

### 3. Result

Obtained images show that low- $Q$  zone are located at depths of 0-60 km beneath the western area of the Hidaka mountain range, whereas the eastern area of it (Kuril forearc) has very high- $Q$  values. The low- $Q$  zone almost corresponds to the low- $V$  zone by Kita et al. [2011]. Western portion of the low- $Q$  zone has relatively lower  $Q$  values, where inland-type deep seismicity is active. The fault plane of the 1982 M6.7 Urakawa-Oki earthquake is also located on the edge of the lowest  $Q$  portion. These results imply that the occurrence of anomalously deep depth earthquakes in this region is related with spatial distribution of hydrous minerals or fluids.

キーワード: 減衰構造, 島弧-島弧衝突帯, 地殻流体, 1982年 M6.7 浦河沖地震

Keywords: Seismic attenuation structure, Arc-arc collision zone, Geofluids, 1982 M6.7 Urakawa-oki earthquake



## 南海トラフの浅部超低周波地震と付加体内構造

### Very-low-frequency earthquakes and imbricate thrusts within the accretionary prism in the Nankai subduction zone

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We describe the possible source faults of very-low-frequency (VLF) earthquakes within the accretionary prism in the Nankai subduction zone, Japan. A high-resolution 3D seismic image of a megasplay fault system in the Nankai subduction zone in the region off Kumano was obtained (Moore et al., 2007). Many centroid-moment tensor solutions for VLF earthquakes were calculated from seismic data observed by on-shore broadband seismic networks (Ito and Obara, 2006). In order to understand the generation mechanism of VLF earthquakes, which are considered to reflect slow slip events, it is important to determine the parameters such as fluid pressure and frictional properties of the source faults the corresponding slow slip events. We compare the locations and fault geometry of moment tensors of VLF events to 3D seismic image, and investigate the possible source faults of VLF earthquakes from the imbricate thrusts that are imaged by performing a 3D seismic survey. Many events located within the accretionary prism near or above the decollement and nodal planes of VLF events were consistent with fault geometry of the megasplay or decollement. The decollement above the plate boundary corresponded to regions with high amplitudes and negative polarities in the 3D seismic image, suggesting that VLF events may occur on faults with high fluid pressure. Sakaguchi et al. (2011) had determined the high localized temperatures to be higher than 380°C by vitrinite reflectance geothermometry in the case of the decollement and megasplay faults. They had suggested that frictional heating accompanied by velocity weakening at a high slip velocity occurred along the decollement and megasplay faults during megathrust events. Our observations suggest that frictional heating at the decollement and/or megasplay fault occurs accompanied by velocity weakening even at medium slip velocities.

キーワード: 超低周波地震, 3次元反射法探査, 巨大分岐断層, デコルマ

Keywords: Very-low-frequency earthquake, 3D seismic reflection survey, Megasplay fault, Decollement

## ニュージーランド北島におけるテクトニックな微動活動と温度構造 Tectonic tremors and its thermal condition in the Hikurangi Subduction Zone, North Island, New Zealand

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Tectonic tremors are widely detected in the subduction zone around the Pacific since its discovery. The oceanic plates, which are subducting beneath such subduction zone, are usually young (~30Myr). The subduction zone with younger oceanic plate is supposed to have a proper condition for tremor generation, such as a shallower slip transition and a active dehydration reaction from oceanic slab, both of which is considered to be important for tremor generation. However, in North Island, New Zealand, where much older oceanic plate (~80Myr) is subducting, tectonic tremor activities were reported by Kim et al., 2011, Fry et al., 2011 and Ide 2012. In North Island, slow slip events (SSEs) are also well known. Tremor activity and SSEs in such cooler subduction seems to be strange. Therefore, in this study, we aim to understand the physical conditions, especially temperature of tremor source areas in North Island. To find out the physical conditions of tremor source areas in cooler subduction zone would be an important clue for clarifying tremor mechanism.

To detect and locate tremors, we use the envelope correlation method of Ide 2010, 2012. The Data is continuous horizontal velocity seismographs from January 2004 to March 2010 downloaded from GeoNet. The 100 Hz sampling original data is 2~8 Hz band-passed and take envelope, then down sampling to 2 Hz in 300 s time windows. In each time window, if more than 40 pairs of cross correlations of envelope between different stations exceed threshold value, we detect seismic signals and try to locate. We also apply same method to 10~20 Hz band-passed data. We rejected detected signals if more than 10 pairs of correlation exceed threshold in 10~20 Hz data as applied in Kim et al., 2011. We also use duration thresholds and simple clustering method to get clearer image of tremor activity. Our analysis detects and locates short belt-like distributed tremor activities. It is just at the transition zone from deeper SSEs to shallower SSEs and at down dip area of deeper SSEs. We also estimated the absolute depth of tremors using S-P time of tremors obtained from cross correlation between vertical and horizontal components of the same station. The estimated depth of tremors suggests its occurrence on the plate interface though the estimation error is not so small due to low signal-to-noise ratio.

McCaffrey et al., 2008 and Fagereng and Ellis, 2009 already estimate the thermal state of Hikurangi Subduction, North Island. However, the estimation error is not clear in these studies. We are interested in the thermal profile along plate interface, especially possible thermal range around the tremor source areas. Therefore, to assess estimation error is important for us. To estimate the temperature profile on the plate interface, we use the subduction thermal model based on Yoshioka and Sanshadokoro, 2002 using finite difference method. In this model, we consider the viscous dissipation, frictional heating and advection. To assess the estimation error of temperature along plate interface, we try some parameter sets, and then the possible temperature range of tremors source areas in North Island is evaluated.

キーワード: 深部低周波微動, 沈み込み帯, ニュージーランド, 温度構造

Keywords: tectonic tremor, subduction, New Zealand, thermal structure

## 地殻流体が関与した可能性がある秋田県森吉山周辺の地震活動 Possible geofluid driven seismic activity near the Moriyoshi-zan volcano in Akita prefecture, northeastern Japan

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### 1. Introduction

The great 2011 Off the Pacific coast of Tohoku (Tohoku-oki) Earthquake caused triggered seismicity in many areas apart from the source area. In the inland part of Tohoku district, the induced seismicity is quite high in Akita prefecture. Among the three activated clusters in the prefecture, the one to the north of Moriyoshi-zan volcano is quite interesting, because the earthquakes form an unusual vertical column with a height of about 5 km. Considering a possible existence of geofluid beneath the source area inferred from previous studies, the examination of activity of this cluster is important to clarify the relation of induced earthquakes to geofluid.

### 2. Seismic Activity

The Moriyoshi-zan volcano is a Quaternary volcano located to the west of the Hachimantai volcano along the volcanic front of northeastern Japan. The column-like earthquake cluster was formed from May 2011, about two months after the Tohoku-oki earthquake. The process of column formation is unique. The activity started at the bottom, then elongated vertically forming a central column, and extended horizontally with less seismicity in the central column. This process suggests the migration of geofluid from the bottom followed by horizontal permeation.

### 3. Reflected Phase

A prominent feature of the seismograms observed at stations around the volcano is a reflected phase that appears on tangential component. This SxS phase is commonly observed for earthquakes in the cluster. Similar phase has previously observed from an earthquake swarm in 1982 [1]. A plane of reflection was estimated using the travel time data of SxS phase from the 1982 swarm [1]. The existence of reflector strongly suggests the concentration of geofluid in its location.

### 4. Discussion

Moriyoshi-zan area is one of the source areas of deep low-frequency microearthquakes occurring mainly beneath active volcanoes in the northeastern Japan [2]. The low-frequency earthquakes that occur well below the elastic plastic boundary are interpreted as the events generated by magmatic activity of mantle diapirs in the uppermost mantle [2]. In the cross-sectional view of seismicity, the westward bottom of reflector is close to the upper limit of low-frequency earthquakes and the eastward top seems to reach the bottom of column-like cluster. From this we can image a pathway of geofluid from the upper mantle to the source of column-like cluster. However, we should note that the horizontal location of reflector and column-like cluster is separated about 5 km. Thus, to conclude if the earthquakes that formed the column-like cluster were driven by geofluid, we need to estimate the present location of reflector using arrival times and waveform characteristics of SxS phase observed in 2011.

### Acknowledgments

We used hypocentral parameters of the JMA catalog that was prepared by the JMA and the Ministry of Education, Culture, Sports, Science and Technology in Japan. We thank JMA, NIED, Tohoku University, and Aomori Prefecture for providing waveform data used for our phase picking of hypocenter location.

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キーワード: 地殻流体, 森吉山, 誘発地震, 反射面, 低周波地震

Keywords: geofluid, Moriyoshi-zan volcano, induced earthquakes, reflector, low-frequency earthquakes

## 秋田県森吉山周辺の深部低周波地震と浅部誘発地震の活動

## Seismicity of deep low-frequency and shallow induced earthquakes near the Moriyoshi-zan volcano in the Akita prefecture

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Deep low-frequency earthquakes occur mainly around active volcanoes in northeastern Japan. These events are thought to be generated by geofluid such as magma or supercritical aqueous fluid, however, there is no direct evidence so far to support the idea. The great 2011 Off the Pacific coast of Tohoku (Tohoku-oki) Earthquake caused triggered seismicity in many areas apart from the source area. The investigation of relation between the induced shallow crustal earthquakes and deep low-frequency earthquakes may be helpful to examine the effect of geofluid. To do this, we plot spatiotemporal distribution of both the shallow ordinary events and deep low-frequency earthquakes for the source areas of low-frequency earthquakes. We found that the activity of low-frequency events in some areas changed after the Tohoku-oki earthquake. For example, the activity has decreased in a shallower source area beneath Iwate volcano. Anomalous induced seismicity was found in an area to the north of Moriyoshi-zan volcano in the Akita prefecture. The earthquakes form an unusual vertical column with a height of about 5 km. In addition, a reflected phase is commonly observed for the events in the column-like cluster. This area is also one of the source areas of deep low-frequency earthquakes. Before the Tohoku earthquake, the low-frequency earthquakes have been occurring intermittently at a depth range of 25-40 km. After the Tohoku-oki earthquake, the range became shallower to 25-30 km, which suggests the migration of geofluid and resultant increase in seismicity started two months after the Tohoku-oki earthquake.

キーワード: 深部低周波地震, 地殻流体, 森吉山

Keywords: deep low-frequency earthquake, geofluid, Moriyoshi-zan volcano

## 付加体スラスト物質の摩擦速度依存性と超低周波地震

### Frictional rate dependence of thrust materials in accretionary prisms and its implication for VLFES

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Recent seismological studies identified that very low frequency earthquakes (VLFES) occurred on thrusts within accretionary prisms or at plate interfaces. On the other hand, clay-rich accreted sediments commonly show velocity-strengthening behavior, which may be unfavorable for occurrence of slow slip events. Here we examined the characteristics and the frictional rate dependence of the thrusts in the Eocene Shimanto accretionary complex of Okinawa Island (Kayo Formation).

The Kayo Formation consists of coherent trench-fill turbidites and it was deformed by folds and thrusts during off-scraping accretion under the subduction of young oceanic crust, possibly representing an on-land analog of the Nankai and Ryukyu subduction zones where VLFES occur on thrusts within accretionary prisms. Two representative thrusts in the Kayo Formation develop in quartz-rich sandy materials, and the fault zones are composed of cataclastic slip zone, amalgamated slip zone, foliated zone, fibrous quartz veins, and sandstone cemented by quartz, suggesting the fluid saturated conditions during faulting.

To determine the friction rate dependence on the thrust materials, the frictional experiments were conducted on the samples taken from the cataclastic slip zone showing random fabric, the foliated zone, and the host rock (quartz-rich sandstone) at slip rates of 0.0026 - 0.026 - 0.26 - 2.6 mm/s and normal stress of 1.0 MPa under wet conditions using a rotary-shear friction testing apparatus in Kyoto University. At slip rates of 0.0026 - 0.026 - 0.26 mm/s, the cataclastic zone and the host rock show velocity-weakening behavior with frictional rate dependence parameter (a-b) ranging -0.0038~-0.0013 and -0.0032~-0.0016, respectively, whereas the foliated zone exhibits velocity-strengthening behavior (a-b=0.0003~0.0012). At slip rate of 0.26 - 2.6 mm/s, all samples show velocity-strengthening behavior. Microstructural and XRD analyses reveal that velocity-weakening samples show the localized cataclasis along the boundary between gouge and specimen with its quartz and clay minerals contents being 58.9 - 75.8 wt.% and 4.9 - 7.7 wt.%, respectively, while velocity-strengthening sample indicates the clay foliation outside the localized slip zone with lower quartz content (51.5 wt.%) and higher clay content (23.9 wt.%). These features are consistent with occurrence of the fault rocks along the thrusts in the Kayo Formation.

In summary, our field and experimental data suggest that frictional instability tends to generate along quartz-rich material (e.g., quartz-rich sandy materials and quartz veins) but frictional stability increases at higher slip rates of 0.26 - 2.6 mm/s regardless of mineral composition, which will be favorable for VLFES occurrence in accretionary prisms.

キーワード: 超低周波地震, 嘉陽層, 速度弱化, 石英に富む砂質物質

Keywords: very low frequency earthquakes, Kayo Formation, velocity-weakening, quartz-rich sandy materials



## 南海掘削浅部試料を用いた断層帯の流体移動特性と断層運動への影響 Permeability of shallow nankai subduction zone and its role for mechanical property

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南海トラフ沖地震発生域では巨大分岐断層と前縁衝上断層が発達しており、いずれの断層帯も地震すべりを誘発しかつ巨大津波を発生させることが予想される。断層帯の力学特性、応力状態、幾何学特性が分岐断層の破壊伝播方向や破壊過程を支配することが予想される。そこで本研究では国際海洋掘削計画 (IODP) Expedition316 (NantroSEIZE) で掘削された地震発生域浅部において採取されたコア試料 (site C0004 と siteC0007) を用いて流体移動特性と摩擦特性の測定を行い、巨大分岐断層と前縁衝上断層の力学特性の比較を行った。

摩擦特性は高知コアセンターに設置してある回転式せん断試験装置を用いて行った。コア試料は砕いてふるいにかけて 0.2mm 以下の粉末状 (ガウジ) にした。粉末状にした 1 グラムの試料を二つの円柱形のインド砂岩 (透水係数 =  $10^{-15}$  ~  $10^{-16}$  m<sup>2</sup>) の間に挟み込み、片方のインド砂岩を回転させることによりガウジをせん断変形させた。せん断変形前後のインド砂岩とガウジの試料の透水係数を測定することにより、せん断変形に伴う断層ガウジの透水係数の変化を評価した。せん断変形は垂直荷重 2MPa、すべり速度 7.9 m の条件で行った。また、すべり速度と含水条件を変化させて、力学特性に対するそれぞれの影響を考察した。

キーワード: 透水係数, 沈み込み帯地震, 摩擦係数, NantroSEIZE

Keywords: permeability, Subduction earthquake, friction coefficient, NantroSEIZE

## 流体制御型摩擦試験装置を用いた高間隙水圧条件下における摩擦実験 Frictional property of gouge materials under high velocity and moderate water pressure condition

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Fluid can act as important roles in faulting and earthquake cycle processes. Geochemical analysis, recently, provided the chemical anomaly in the Chelungpu fault, and this anomaly is explained by the fluid-rock interaction in the fault zone induced by thermal pressurization during co-seismic friction (Ishikawa et al., 2008). However the role of fluid in a fault for a mechanical process and a chemical reaction is still a matter of debate. In addition, we had never achieved high velocity friction experiments to reproduce the water-rock interaction. Here, we designed the rotary shear apparatus that can perform shear deformation of powdered gouge materials with water as pore fluid under high pore pressure condition. We used core samples from the Taiwan Chelungpu fault Drilling Project (TCDP) of Hole B near the fault zones. We used sample holder with 30/60 mm internal/external diameter. We rotated gouge specimen until displacement reaches to 15 - 30 m, and 0.1 to 0.4 of the equivalent slip velocity were applied. We applied normal stress from 5 to 15 MPa and pore pressure from 2 to 5 MPa. We conducted two types of friction test: one is drained condition test that pore pressure is kept at a constant value, and the other is undrained condition test that normal stress is kept constant and that allows pore pressure change during sliding.

In the most of the drained test, shear stress gradually decreased with slip displacement and finally it reached to the stable value after 5 to 15 m displacement. Temperature at slip surface increased with sliding, and it peaked at several m of displacement. Then it kept at a nearly constant temperature till the end of slip. Steady state shear stress is proportional to effective pressure, and friction coefficient showed about 0.2. In the undrained tests, shear stress decreased with slip displacement as well. In addition pore pressure is gradually increased with sliding until the end of sliding. For example, pore pressure is increased from 2 to 9 MPa at 12 MPa of normal stress and 0.2 m/s of slip velocity. Temperature at slip surface increased dramatically as well. The maximum elevated temperature is about 310 degrees celsius for the drained test, and 320 degrees for the undrained test.

Our results indicate that pore pressure increase during sliding that associates with shear stress reduction in undrained condition is due to frictional heating that expanded the volume of water. However, shear stress reduction could be caused by the other mechanical process as well, such as slip localization or fluidization of gouge material.

キーワード: 間隙水圧, 高速摩擦, thermal pressurization, 断層ガウジ

Keywords: pore pressure, high velocity friction, thermal pressurization, fault gouge

## 含水岩石の弾性波速度および電気伝導度に対する間隙流体圧の影響 Influence of Pore-Fluid Pressure on Elastic Wave Velocity and Electrical Conductivity of Water-Saturated Rock

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Pore-fluid pressure in seismogenic zones can play a key role in the occurrence of an earthquake (e.g., Sibson, 2009). Its evaluation via geophysical observation can lead to a good understanding of seismic activities. It is critical to understand how pore-fluid pressure affects seismic velocity and electrical conductivity. We have studied the influence of pore-fluid pressure on elastic wave velocity and electrical conductivity of water-saturated rocks.

Measurements have been made using a 200 MPa hydrostatic pressure vessel, in which confining and pore-fluid pressures can be separately controlled. Pore-fluid (0.1 mol/l KCl aqueous solution) is electrically insulated from the metal work by using a specially designed pore-fluid pressure controlling system. Elastic wave velocity was measured with the pulse transmission technique (PZT transducers,  $f=2$  MHz), and electrical conductivity the four-electrode method (Ag-AgCl electrodes,  $f=100$  mHz - 100 kHz) to minimize the influence of polarization on electrodes.

Berea sandstone (OH, USA) was used for its high porosity (19.1%) and permeability ( $\sim 10$ - $13$  mD). It is mainly composed of subangular quartz grains. Microstructural examinations show clay minerals (e.g., kaolinite) and carbonates (e.g., calcite) fill many gaps between quartz grains. A small amount of feldspar grains are also present. The grain size is 100-200 micrometers. Cylindrical samples have dimension of 25 mm in diameter and 30 mm in length. Their axes are perpendicular to sedimentation bed. Elastic wave velocity is slightly higher in the direction perpendicular to the axis than in that parallel to the axis.

Confining and pore-fluid pressures work in opposite ways. Increasing confining pressure closes pores, while increasing pore-fluid pressure opens. For a given pore-fluid pressure, both compressional and shear velocities increase with increasing confining pressure, while electrical conductivity decreases. When confining pressure is fixed, velocity decreases with increasing pore-fluid pressure while conductivity increases. The closure and opening of pores can explain observed changes of velocity and conductivity.

Effective confining pressure is defined by the difference between confining and pore-fluid pressures. Velocity increases with increasing effective confining pressure, while conductivity decreases. However, neither velocity nor conductivity is unique function of the effective confining pressure. For a given effective confining pressure, conductivity significantly increases with increasing confining pressure. Velocity also increases with increasing confining pressure, though it is not so significant. Increasing pore-fluid pressure can compress clay minerals to increase pore space. This might explain observed conductivity change.

キーワード: 弾性波速度, 電気伝導度, 含水岩石, 有効圧力, 空隙

Keywords: elastic wave velocity, electrical conductivity, water-saturated rock, effective confining pressure, pore