様式 W-2

共同利用実施報告書（研究実績報告書）
（研究集会）

１．課題番号　　　２０１４－W－０６

２．研究集会名（集会名の英訳もご記入ください）

和文：　スロー地震の発生メカニズムを探る：観測・実験・理論・モデリングからの情報の統合化と巨大地震との関連性の解明を目指して

英文：　Study on occurrence mechanism of slow earthquakes: Toward resolving the relationship between slow earthquakes and megathrust earthquakes based on unification of results from observation, experiments, theoretical studies, and modeling

３．研究代表者所属・氏名　神戸大学・廣瀬　仁

（地震研究所担当教員名）小原　一成

４．研究集会参加者の詳細（研究代表者を含む。必要に応じ行を追加すること）

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５．研究集会の概要（200-400 字）

本研究集会は、平成 24, 25 年度に引き続き、スロー地震の発生メカニズムの理解や、巨大地震との関連性の解明を目的とし、2014 年 9 月 8 日～10 日の 3 日間にわたって京都大学宇治キャンパスきはだホールにて開催された。地震・測地観測に基づくスロー地震の検出手法開発・活動特性解析，野外調査や実験による震源域の特性、スロー地震発生場の構造、活動様式に関する数値シミュレーションなど，非常に幅広い分野にわたる総計 44 件の講演がなされ，活発な議論を行なうことができた。また前回に引き続き、海外から 7 名の講演者を招聘して国内・国際研究集会として実施し、世界各地におけるスロー地震活動の比較に基づいた議論を深めることができた．なお、京都大学特定研究集会「西日本大震災の減災に向けたスロー地震研究の今後の可能性」、J-DESC フィジビリティ研究「ニュージーランド・ヒクランギ沈み込み帯のスロースリップ域掘削計画に向けたスロー地震のモニタリング研究」、科研費特別推進研究「深海調査で迫るプレート境界浅部すべりの謎～その過去・現在」、科研費基盤 A 海外「沈み込み帯浅部のスロースリップはトラフ軸まで到達するか？」と合同で実施された。

６．延べ参加人数、研究集会の概要（100 字程度）についてご記入ください（共同利用・共同研究拠点実施報告書に掲載します）

延べ参加人数　　　　78 名

スロー地震の発生メカニズムの理解を目的とし、2014 年 9 月 8 日～10 日に京都大学宇治キャンパスきはだホールにて国内・国際研究集会として実施し、広範な分野にわたる 44 件の講演と活発な議論が行われた。

Joint Workshop on Slow earthquakes, 2014:

“The prospects for studies of slow earthquakes toward Nankai Megaquake predictions and disaster preventions”

Scope:

We focus on understanding of slow earthquake itself, and relationships between slow earthquakes and megathrust event, such as a future Nankai-Tonankai earthquake. We also focus on seismic and geodetic monitoring of slow earthquake at sea-bottom as well as landward.

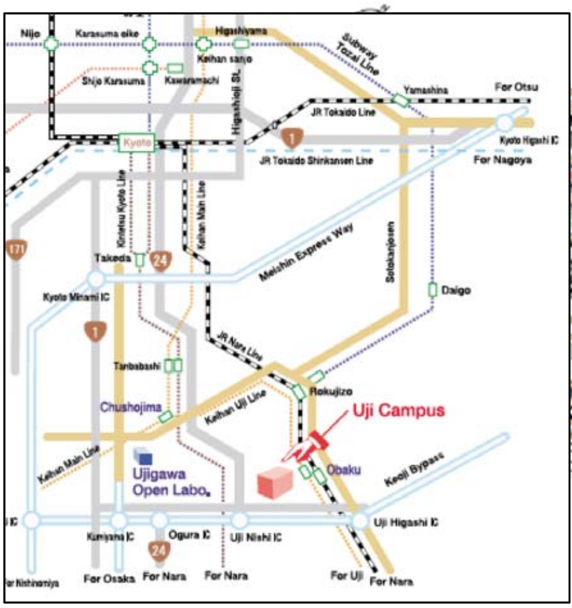
Venue: Kihada hall, Uji campus, Kyoto University

http://www.uji.kyoto-u.ac.jp/english/access_e.html

Date: September 8–10, 2014

Conveners: Yoshihiro Ito, Hitoshi Hirose, Kazushige Obara

This workshop is supported by Joint Usage/Research Center Programs of DPRI Kyoto University and ERI The University of Tokyo, J-DESC feasibility study, JSPS KAKENHI Specially Promoted Research and Scientific Research (A).



Agenda

Sep. 8th, Official language: JAPANESE [Slides written in English are recommended]

(Chair: Yoshihiro Ito)

13:00-13:25 (J01), Akio Fujita/藤田明男, Temporal variation of coupling distribution around slow slip zone in southwest Japan/西南日本のスロースリップ発生域における固着分布の時間的変化

13:25-13:50 (J02) Kazuki Miyaoka/宮岡一樹, Slow slip monitoring by stacking method of strain data/ひずみ計データのスタッキングによるゆっくりすべり監視

13:50-14:15 (J03) Akio Kobayashi/小林昭夫, 四国中部・東部で発生した小規模な長期的スロースリップ

14:15-14:40 (J04) Kazuhiro Kimura/木村一洋, The change except the Short term Slow Slip Events at the Tokai region that JMA's strainmeters may detect/気象庁のひずみ計に見られる東海地域の短期的スロースリップ以外の変化

14:40-15:05 (J05) Aitaro Kato, Detection of a hidden Boso slow slip event immediately after the 2011 Mw 9.0 Tohoku-Oki earthquake, Japan

Coffee Break (15 min.)

(Chair: Hitoshi Hirose)

15:20-15:45 (J06) Satoshi Itaba/板場智史, Generation conditions of triggered slow slip events /短期的 SSE が誘発される条件

15:45-16:10 (J07) Yusuke Yamashita, Migration episode of shallow low-frequency tremor at the Nankai Trough subduction zone

16:10-16:35 (J08) Kensuke Suzuki, Synchronous changes in the seismic activity and ocean-bottom hydrostatic pressure off the Kii Peninsula

16:35-17:00 (J09) Michiyo Sawai, Depth limits of slow slip events at the Japan Trench: Insights from high temperature and pressure friction experiments

Sep. 9th, Official language: English

(Chair: Hitoshi Hirose)

8:45-9:10 (I01) Kazushige Obara, Ambient Tremor Triggered by Long-term Slow Slip Event in Bungo Channel, Southwest Japan

9:10-9:35 (I02) Yoko Tu, The connections and variations between recurrent slow slip events and very low frequency earthquakes near the southwestern Ryukyu subduction zone

9:35-10:00 (I03) Akiko Takeo, Estimation of moment release in the very low frequency band during episodic tremor and slip

10:00-10:30 (I04) Ken Creager, (Keynote) Review of Cascadia Slow Slip and Tremor

Coffee Break (15 min.)

(Chair: Kazushige Obara)

10:45-11:10 (I05) Heidi Houston, Response of tremor and slow slip to tidal stress: Constraints on fault friction and weakening

11:10-11:35 (I06) Suguru Yabe, The spatial variation of tidal sensitivity of tectonic tremors

11:35-12:00 (I07) Kosuke Heki, Post-3.11 acceleration of the Pacific Plate: First direct evidence

Lunch (1 hour)

(Chair: Ryota Hino)

13:00-13:25 (I08) Tomoaki Nishikawa, Tectonic controls on earthquake size distribution and seismicity rate

13:25-13:50 (I09) Roy Hyndman, ETS Tremor and Slip at Cascadia, SW Japan, and Mexico: Subducting Plate Fluids Channelled Updip to the Forearc Mantle Corner and Silica Deposition

13:50-14:15 (I10) Nobuaki Suenaga, Relations among temperature, dehydration of the PHS plate, and the three seismic events in the Tokai district

14:15-14:45 (I11) Vladimir Kostoglodov, (Keynote) Diversity of Slow Slip Events and Nonvolcanic Tremor in Guerrero, Mexico

14:45-15:10 (I12) Takuya Nishimura, Interplate coupling and its spatial relation with slow slip events along the Nankai Trough

Coffee Break (15 min.)

(Chair: Yoshihiro Ito)

15:25-15:55 (I13) Takeshi Iinuma, Interplate coupling beneath NE Japan before the 2011 Tohoku Earthquake

15:55-16:20 (I14) Ryota Hino, Postseismic motion of the high-slip shallow fault during the 2011 Tohoku-oki Earthquake

16:20-16:50 (I15) Stephen Bannister, (Keynote) Diverse SSE and seismicity behaviour on the Hikurangi subduction zone, New Zealand

16:50-17:20 (I16) Anne Sheehan, (Keynote) Alpine Fault Tectonic tremor recorded by MOANA project ocean bottom seismometers, South Island, New Zealand

17:20-17:45 (I17) Erin Todd, Coulomb stress variations associated with slow slip, tectonic tremor, and seismicity along the northern Hikurangi Margin, New Zealand

18:00-20:00 Reception (Café Restaurant Kihada, Uji Campus, Kyoto University)

Sep. 10th, Official language: English

(Chair: Hitoshi Hirose)

8:45-9:10 (I18) Yoshihiro Ito, Transient crustal deformation due to slow slip observed on ocean bottom pressure recorders in the Hikurangi margin

9:10-9:35 (I19) Takeshi Tsuji, Pore pressure distribution of a mega-splay fault and seaward plate boundary decollement in the Nankai Trough subduction zone: Up-dip extent of the seismogenic zone?

9:35-10:00 (I20) Yoshitaka Hashimoto, Geological signature of slow slip in on-land accretionary complex using vitrinite reflectance

10:00-10:25 (I21) Yasuhiro Yamada, Drilling to fault zone: what we can get from there?

Coffee Break (15 min.)

(Chair: Takuya Nishimura)

10:40-11:10 (I22) Kelin Wang, (Keynote) On the geology of slow slip events

11:10-11:40 (I23) Martin Vallée, (Keynote) Intense seismic activity associated with slow slip in the Central Ecuador subduction zone

11:40-12:05 (I24) Aitaro Kato, Multiple slow-slip events during a foreshock sequence of the 2014 Iquique, Chile Mw 8.1 earthquake

Lunch (1 hour)

(Chair: Kazuaki Ohta)

13:00-13:30 (I25) Yoshihiro Kaneko, (Keynote) Insights into the mechanism of fault creep from geodetic observations and earthquake-cycle simulations

13:30-13:55 (I26) Yingdi Luo, Slow to Fast Earthquake Transition Introduced by Fault Heterogeneity

13:55-14:20 (I27) Teruo Yamashita, Why do slow earthquakes occur favorably in hot subduction zones?

14:20-14:45 (I28) Benchun Duan, 3D dynamic rupture simulations of a megathrust fault with a subducted seamount

14:45-15:10 (I29) Takanori Matsuzawa, Numerical simulation of long- and short-term slow slip events in the Nankai subduction zone

15:10-15:35 (I30) Ryosuke Ando, Theoretical relationship between tremor migration patterns and rheology on heterogeneous faults

Coffee Break (15 min.)

(Chair: Yoshihiro Ito)

15:55-16:20 (I31) Kazuaki Ohta, Slip inversion for deep tremor

16:20-16:45 (I32) Satoshi Annoura, Seismic wave radiation energy of deep low-frequency tremor in the Nankai subdution zone

16:45-17:10 (I33) Masaki Kanao, Ice sheet dynamics and glacial earthquake activities in Greenland

17:10-17:35 (I34) Fekadu Aduna Duguma, Assessing volcanic hazards from future eruptions of Chabbi volcano, Central Main Ethiopian Rift, Ethiopia

17:35-18:00 (I35) Naofumi Aso, Modeling and Observations of Deep Volcanic Long-Period Earthquake

西南日本のスロースリップ発生域における固着分布の時間的変化.

＃藤田明男，加藤照之，小原一成（東大地震研），生田領野（静大理）

Temporal variation of coupling distribution around slow slip zone in southwest Japan.

#Akio Fujita, Teruyuki Kato, Kazunari Obara (ERI, UT), Ryoya Ikuta (Shizuoka Univ.).

１．はじめに

西南日本のプレート境界面では，固着域（深さ 10~30km）ではプレート境界型の地震が 100~150 年の周期で繰り返し発生しており，固着域の深部から遷移領域（深さ 30~40km）では SSE イベントや微動が発生していることが知られている．これらのプレート境界型地震やスロースリップイベントは同じプレート境界面上で発生している現象であり，プレート境界面の固着の時空間的な変化をモニタリングすることは，プレート境界型地震の応力蓄積過程の解明において重要である．我々は，これまで GNSS 記録を用いてプレート境界面の固着分布の推定を行ってきた．本発表では，特に SSE 発生領域における固着の時間変化と固着率について，また深部低周波微動と SSE の関係についても考察を行う．

２．データと方法

我々は国土地理院による GNSS 連続観測網（GEONET）の三次元座標値，西南日本における２００１年から２０１０年の１０年間のプレート境界面の固着分布の連続的な推定を以下の手順で行った.

Ⅰ．GNSS 時系列データからアンテナ保守作業，地震によるオフセットを除去.

Ⅱ．全ての観測点の時系列に対して主成分分析を行い，共通誤差を除去.

Ⅲ．７日間のギャップを挟んだ，その前後１０日間の平均位置の差を取る.

Ⅳ．上記のデータに対して，Yabuki and Matsuura.(1992)の断層インバージョンを行う.

このとき以下の制約条件でインバージョンを行った.

・断層面上で十分な分解能がないところはすべり量が小さくなる.

・すべり方向はフィリピン海プレートの沈み込み方向とその逆方向に拘束.

・バックスリップは沈み込み速度を超えない.

・すべり量の推定の下限を深さ 70km にする.

これを一日ずつずらし行うことで時間的に連続した固着分布を推定し，推定した短期的な固着分布を積算しプレート境界面の固着分布の時間的変化を求めた.

３．結果

SSE 発生域では，固着とすべりを繰り返しており，そのすべり（SSE）が微動のイベントに同期している．規模の大きい微動イベントほど SSE の検出率が高く，微動活動の大きさと地殻変動の大きさに正の相関があることが示唆される. SSE はプレートの沈み込みに伴う歪を全て解放しておらず, 特に微動・SSE がほとんど検出されない紀伊水道で他の領域よりも高い固着率を示した．このことは遷移領域で歪が蓄積されていることを示唆している.

ひずみ計データのスタッキングによるゆっくりすべり監視
Slow slip monitoring by stacking method of strain data

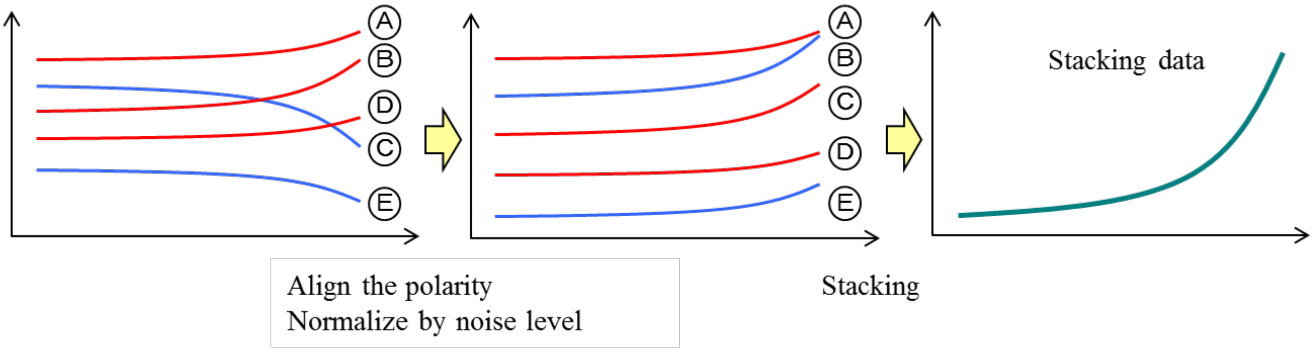
気象研究所　宮岡 一樹
Kazuki Miyaoka (MRI)

気象庁では東海地震の前兆すべりを早期に検知することを目的に、静岡県、愛知県などにひずみ計による観測網を展開している。プレート境界すべりによる微小なひずみ変化を検出するため、気象庁では昨年度からスタッキング法（宮岡・横田，2012）を用いた監視を行っている。今回、このスタッキング法の概要とそれによる解析事例を紹介する。

スタッキング法はひずみ計の時系列データ（以下、波形）を重ね合わせて SN 比の向上を図る手法である。プレート境界すべりによる各観測点での波形は、断層の位置や大きさが大きく変わらなければ概ね相似形を示す。ただし、変化の方向（伸び／縮み）は様々である。そのため、それらが同一方向の変化（伸び）を示すよう必要な観測点のデータについてはその極性を反転させた上で重ね合わせるという操作を行う。このことによりノイズ成分はキャンセルされる一方で、シグナル成分は加算され、SN 比の良い合成波形を得ることができる。なお、その際、ノイズ成分のキャンセルの効果を高めるため、観測点毎のノイズレベルで各波形を規格化しておくことが必要となる。また、観測点毎にシグナルレベルは大きく異なっており、ノイズレベルに比してシグナルレベルが小さい観測点の波形を重ね合わせに用いた場合、合成波形の SN 比の向上が損なわれることになる。このため、ノイズレベルで規格化した後のシグナルレベルの大きい観測点の波形から順に重ね合わせ、合成波形の SN 比が最も大きくなる組み合わせを選択する。

実際の監視にあたっては、対象とするプレート境界面上に小断層をグリッド状に配置し、グリッド毎に合成波形を作成することになる。あるグリッドにおける小断層でのすべりによる各観測点でのひずみ変化は理論的に求まるので、ノイズレベルや極性、重ね合わせに用いる観測点の組み合わせなどのパラメータを予め計算しておけば、これらを基に監視すべき合成波形をリアルタイムで作成することができる。多数の合成波形を監視し、変化が見られた合成波形があればそのグリッドでプレート境界すべりがあったことが推測される。また仮定通りの断層すべりであれば、その合成波形の変化量から直接、すべり量（モーメント）を読み取ることができる。

現在、気象庁および産業技術研究所などのひずみ計にこの手法を適用した面的監視を行っている。それによれば、想定震源域の陸域および短期的 SSE 発生域では 48 時間に Mw5.0 相当のすべりがあれば検知可能となっている。また従来、ひずみ計での検知が困難と考えられていた長期的 SSE についても監視対象にできると考えている。



四国中部・東部で発生した小規模な長期的スロースリップ

2014.9　スロー地震研究集会
気象研究所　小林昭夫

南海トラフ沿いの沈み込み帯において、複数の領域で長期的スロースリップ（SSE）が観測されている。これら長期的 SSE は地域ごとに発生間隔、発生規模が異なっている。ここでは、GNSS の解析から明らかになった四国中部・東部で発生した 3 つの小規模な長期的 SSE について報告する。

データは、国土地理院 GEONET の日座標値（F3 解）を用いた。非定常な地殻変動を見るため、注目する期間ごとに適切な期間のデータから直線トレンド係数を求め、全期間からその係数を用いて定常成分を差し引いた。GEONET 観測点のアンテナ交換などに伴う人為的要因によるオフセットは、国土地理院 Web ページで公開されているデータセット［corrf3o.dat］を用いて補正した。

観測された非定常変位がプレート境界上の長期的 SSE によるものとして、そのすべり分布を求めた。このとき弘瀬・他（2007）のプレート境界深さ分布を参考に各点震源のパラメータを与えた。

(1) 2003 年（四国東部）

1997 年 10 月から 3 年間のデータを用い直線トレンド係数を求め、全期間からその係数を用いて定常成分を差し引いた。年周補正はしていない。四国東部の観測点には東から南東向きの数 mm の水平変位が見られ、四国東部にすべりが推定された。すべりの規模は Mw6.3 相当である。

(2) 2005～2009 年（四国中部）

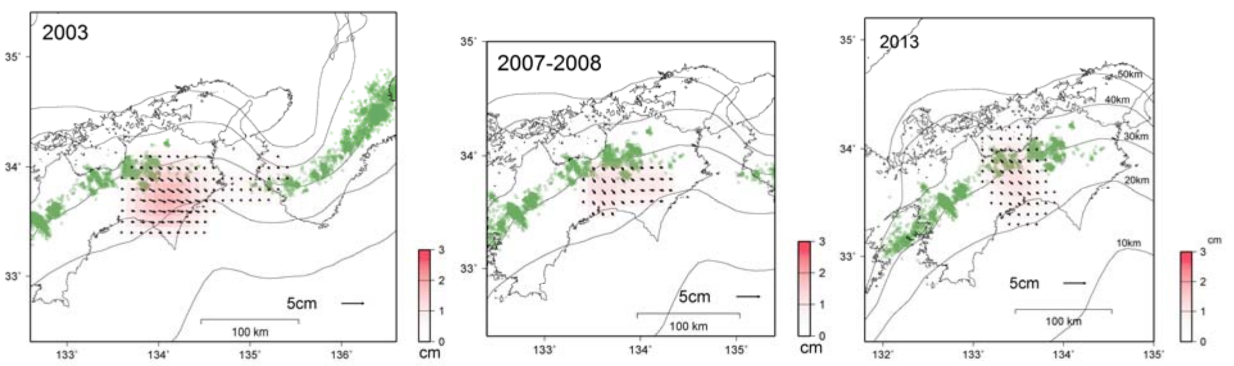
2009 年 1 月から 1 年間のデータを用い直線トレンド係数を求め、全期間からその係数を用いて定常成分を差し引いた。年周補正はしていない。四国中部の観測点には東から南東向きの数 mm の水平変位が見られ、四国中部にすべりが推定された。すべりの規模は Mw6.0 相当（2007 年から 2008 年の 2 年間分）である。

(3) 2013 年（四国中部）

2011 年 10 月から 1 年間のデータを用い直線トレンド係数を求め、全期間からその係数を用いて定常成分を差し引いた。年周補正はしていない。四国中部の観測点には南から南東向きの数 mm の水平変位が見られ、四国中部にすべりが推定された。すべりの規模は Mw6.1 相当である。

いずれも南海トラフ沿いで今までに報告されている他の長期的 SSE の規模より小さい。非定常変位が小さいため、すべり分布の信頼度は豊後水道など他の長期的 SSE のものより劣ると考えられる。長期的 SSE は紀伊半島以外の領域で発生しているが、東海・豊後水道以外はその規模が小さい。

本調査には国土地理院 GEONET の座標値を使用させていただきました。



The change except the Short term Slow Slip Events at the Tokai region that JMA's strainmeters may detect

気象庁のひずみ計に見られる東海地域の短期的スロースリップ以外の変化

Kazuhiro Kimura（Meteorological Research Institute）
気象庁気象研究所　木村一洋

気象庁のひずみ計は東海地域で発生した短期的スロースリップを2005年に初めて検知し、その後も着実に検知している実績を有する。その一方でGNSSや傾斜計で検知できているにも関わらず、気象庁のひずみ計では検知できていない地殻変動現象も存在している。近年、降水の影響を受けやすかった体積ひずみ計に降水補正（木村・他(投稿中)）を行うことによって、長期・短期ともに検知力が向上することが認められた。この降水補正を行った体積ひずみ計のデータで、これまで検知できていなかった地殻変動現象の確認を行った。

・銚子沖スロースリップ（中川・他(2000)、廣瀬・他(2001)、縣・他(2009)）については、いずれの期間でもGNSSと同期する明瞭な伸びの変化が銚子明神の体積ひずみ計で確認できた。但し、すべりのソースが沖合遠方にあると仮定した場合、理論的には縮みの変化になるはずであり逆のセンスである。

・房総半島東方沖のスロースリップについては，ノイズの小さい幾つかの体積ひずみ計で、ごく微小なひずみ変化が確認できた。但し、周辺のGNSSによる面積ひずみとは逆のセンスになる観測点（大多喜宇筒原）もあるほか、確認できた体積ひずみの変化の大きさもかなり小さい。気象庁が房総半島に設置したひずみ計は周辺媒質が柔らかい可能性があることが指摘されており（福留(1984)）、そのような影響があるのかも知れない。

・東海地域の長期的スロースリップについては，田原福江の体積ひずみ計で周辺のGNSSによる面積ひずみと極めて類似した時系列グラフが得られた.
2001年頃から2004年にかけてGNSSに見られる縮み変化が東海地域の長期的スロースリップによるものだとすると、田原福江の体積ひずみ計で見られる縮み変化も東海地域の長期的スロースリップによる可能性がある。その他の観測点では同様な傾向は見られなかった。地震等によって強い振動を受けると地下水面が揺らぐことによって体積ひずみ計の長期的なデータの安定性に支障が出るが、田原福江は標高が6mと非常に低く地下水面の擾乱の影響を受けにくいため、長期的なデータの安定性が優れているのかも知れない。

・その他、1989年12月に東京湾で発生した可能性があると指摘されている東京湾サイレント・アースクェイク（広瀬ほか，2000）については、やはり検知できなかった。

Detection of a hidden Boso slow slip event immediately after the 2011 Mw 9.0 Tohoku-Oki earthquake, Japan

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Abstract

Near the Boso Peninsula in Japan, a series of slow slip events (SSEs) occurring along the top surface of the subducting PHS plate have been well documented by geodetic measurements and have a recurrence interval of 5–7 years. Utilizing a cross-correlation detector technique, we discovered an increase in swarm-like seismicity within the source area of the Boso SSE immediately after the 2011 Tohoku-Oki earthquake. The epicentral distribution of the detected seismicity was similar to that of previously recognized Boso SSEs. In addition, small repeating earthquakes were identified within this seismic swarm sequence. These seismic observations indicate that a hidden SSE occurred along the top surface of the subducting Philippine Sea plate immediately after the Tohoku-Oki earthquake. We propose that external stress transfer by the coseismic slip of the Tohoku-Oki earthquake and the following afterslip could have led to the occurrence of the newly detected Boso SSE. In contrast to previous work, we demonstrate that the recurrence interval of the Boso SSEs has not shortened over time, but has shown a more complex evolution as a result of external stress perturbations imposed by the Tohoku-Oki earthquake.

Reference: Kato, A., T. Igarashi and K. Obara (2014), Detection of a hidden Boso slow slip event immediately after the 2011 Mw 9.0 Tohoku-Oki earthquake, Japan, *Geophys. Res. Lett.*, 41, doi:10.1002/2014GL061053.

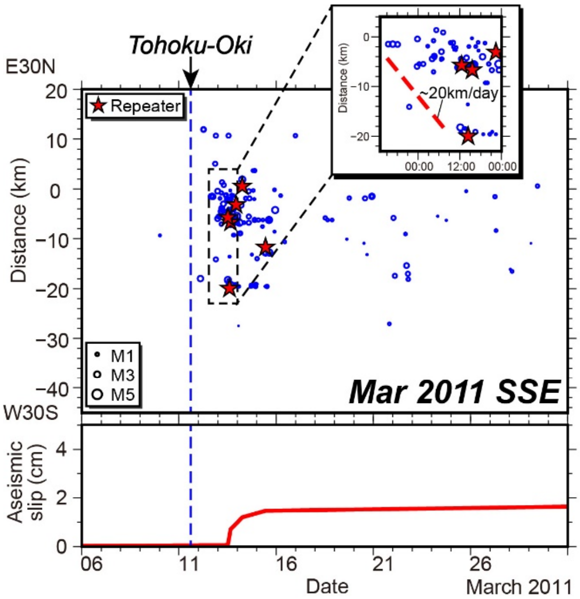

Fig. 1. Space-time diagram of all detected events before and after the Tohoku-Oki earthquake as shown by the blue circles scaled to magnitude. The red stars denote the repeating earthquakes. The diagram shows the earthquake origin times and locations projected onto a strike of E30°N–W30°S.

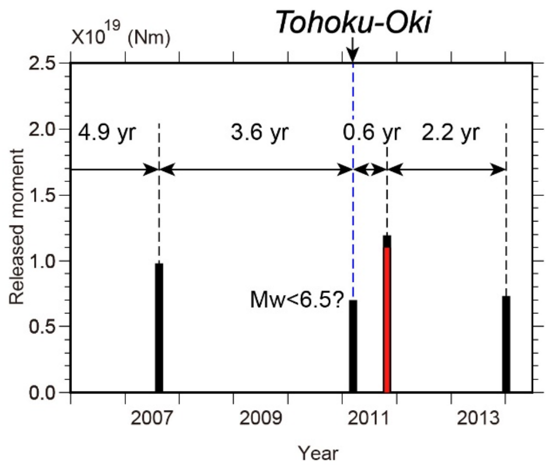

Fig. 2. Revised history of the Boso SSEs, showing the newly detected hidden SSE that occurred immediately after the Tohoku-Oki earthquake. The black and red bars denote the moment magnitude of SSEs determined by Ozawa [2014] and Hirose et al. [2014], respectively.

短期的SSEが誘発される条件

Generation conditions of triggered slow slip events

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スロー地震には，様々な誘発現象が存在する．深部低周波微動の誘発現象については，たとえば，遠地における巨大地震の表面波によって誘発する現象が多数報告されている[例えばMiyazawa and Broadsky, 2008]．また，潮汐変化に対応して微動が活発・静穏化する現象も報告されている[例えばNakata *et al.*, 2008]．これらの現象は，表面波や潮汐による応力擾乱が発生している間の一時的な現象である．

一方，継続時間の長い現象であるSSEについても誘発現象が報告されている．例えば，台風による大きな気圧低下によって，SSEが誘発された現象[Liu *et al.*, 2009]や，遠地地震の表面波によって短期的SSEが誘発された現象[Itaba and Ando, 2011]である．後者の例について，誘発されたSSEの応力降下量，その領域における短期的SSEの繰り返し発生間隔，表面波による応力変化量を調査したところ，プレート沈み込みによって臨界状態であったところに，表面波による応力擾乱が最後の一押しとして作用したことによって，短期的SSEが発生したことが明らかになった．

産総研では，東海〜紀伊半島〜四国において，歪・傾斜・地下水データの統合解析[板場ほか, 2012]によって，短期的SSEのカタログ化を進めている．本研究では，2011年以降のカタログと，遠地巨大地震，近地におけるM5.0程度以上の地震，台風などによる大きな気圧低下と，短期的SSE発生との関係を調査した．その結果，地震によって誘発したと考えられる例が，上述の例以外にも9例，気圧低下によって誘発したと考えられる例が9例見つかった．これらの例について，短期的SSEの発生間隔および誘発された時点での経過率を調べたところ，気圧低下による1例を除いて，短期的SSEが誘発されるのは経過率がほぼ100%に近い場合に限られることが分かった．遠地の巨大地震や台風による気圧低下では，誘発されなかった領域においても誘発された領域と同程度の応力擾乱が起こっている事を考えると，これらの事例についても，応力擾乱が最後の一押しとして作用して短期的SSEが発生したものと考えられる．

一方，経過率が100%に近い状態で大きな応力擾乱があったにも関わらず，短期的SSEが誘発されなかった事例についても調査を行った．例えば，2014年3月14日に発生した伊予灘の地震(Mw6.3)では，震源に近い四国西部では経過率が100%に近かったにもかかわらず，短期的SSEが発生しなかった．伊予灘の地震による静的なクーロン破壊応力変化(ΔCFS)を計算したところ，四国西部の短期的SSE発生領域では，-0.5〜-1.5kPaであり，短期的SSEを発生させにくく作用していたことが分かった．短期的SSEが誘発された事例に加えて，誘発されなかった事例について事例を積み重ねることによって，短期的SSEが発生する条件を，応力などによって定量的に評価することができると期待される．

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Migration episode of shallow low-frequency tremor at the Nankai Trough subduction zone

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Abstract

Shallow transition zone on the plate interface between megathrust seismogenic zone and trench axis may play very important role for development of huge earthquake rupture and generation of tsunami. For understanding the transition zone, detection of slow earthquakes is required. However, slow earthquakes occurring at the shallow transition zone have been only detected in limited ranges with space and time. In this presentation, we report about shallow low-frequency tremor associated with distinct migration episode and shallow VLFE activity in the shallow transition zone for the first time. We carried out the temporal observation of offshore seismicity near the Nankai trough (Hyuga-nada) using 11 short-period ocean bottom seismometers in 2013. During 3 months observation, we have succeeded in detecting the shallow tremor activity as a completed episode lasting 1 month. The shallow tremor episode exhibits two migration modes similar to the deep tremor: one is diffusive and slower migration at a speed of 10-60 km/day and another is reverse propagation with several times faster speed. These similar migration properties of shallow and deep tremor and common association of VLFE indicate the occurrence of episodic SSE at the shallow transition zone as is the case with the coupling phenomena composed of tremor, VLFE, and episodic SSE occurring at the deep transition zone. In addition, the shallow tremor is distributed within a relatively-narrow range and migration path is detouring. These migration properties may suggest that these slow earthquakes are governed by a specified condition of pressure and temperature along the same depth of the plate interface deformed by subducting ridge or seamount.

Acknowledgements: We thank the crews of *T/S Nagasaki-maru* (Faculty of Fishers, Nagasaki University) for their skillful work.

Synchronous changes in the seismic activity and ocean-bottom hydrostatic pressure off the Kii Peninsula

Kensuke Suzuki (JAMSTEC)

The Philippine Sea plate is subducting to northwest below the Eurasian plate along the Nankai trough in southwestern Japan at a convergence rate of about 65 mm/year. In this region mega-thrust earthquakes have repeatedly occurred along the Nankai trough and caused serious and widespread damages in central and western Japan. The Japan Agency for Marine-Earth Science and Technology (JAMSTEC) installed permanent ocean-bottom observation stations named as Dense Oceanfloor Network System for Earthquakes and Tsunamis (DONET) off the Kii Peninsula to monitor earthquakes and tsunamis and to decrease damage due to those. Because several kinds of continuous data have sent to JAMSTEC in real time, we can discuss continuous seismicity and other seismic/geodetic information. It is important for considering occurrence of large earthquakes to judge seismicity of small earthquake and to monitor crustal deformation.

We detected changes in the hydrostatic pressure at the DONET ocean-bottom stations, off the Kii Peninsula, synchronized with the decrease in the background seismicity. Since we have removed the effects due to ocean mass variations and sensor drift from the pressure records, the observed changes may indicate that uplift or subsidence occurred at the stations. The stations that were observed the hydrostatic pressure changes are located above the region where the seismicity change occurred. We consider that the vertical deformation is caused by a slow slip event (SSE) occurred below the stations, which alters the stress state to reduce the seismic activity. Since the pressure changes were observed only at two adjacent stations, we suppose the SSE has occurred on a splay fault in the sedimentary wedge, not the plate boundary. The synchronous observation of SSE and background seismicity might be an indication of a preparatory process for the next mega-thrust earthquake along the Nankai trough. Therefore we must carefully continue to monitor the seismic and crustal activity in this region by DONET.

Depth limits of slow slip events at the Japan Trench: Insights from high temperature and pressure friction experiments

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Episodic tremor and slip occurred just before the 2011 Tohoku-oki earthquake on a shallow portion (less than 20 km depth) in the Tohoku subduction zone (Ito et al., 2013). The area where slow slip occurred overlapped with the seismogenic zone. To understand such diverse slip behaviour around the Japan Trench, not only the major earthquakes but also the slow slip events, it is essential to reveal the frictional properties of rocks distributed at the Tohoku subduction zone. We thus conducted friction experiments using a rotary shear apparatus on powders of blueschist (probably distributed at hypocenters at major Tohoku earthquakes) and smectite-rich pelagic sediments (distributed along the shallow portion of the Tohoku plate boundary (Chester., et al 2013)). Simulated gouges were sheared at temperatures of 20-400ºC, and effective normal stresses of 25-200 MPa and pore fluid pressures of 25-200 MPa. We conducted velocity-stepping sequences (0.1 to 100 μm/s) to determine the rate and state parameter *(a-b)* and investigated the effects of temperature, effective pressure and slip rate on slip stability.

Blueschist gouges show a friction coefficient of about 0.75 and positive *(a-b)* values which decrease to become negative with increasing temperature. At 200ºC, the behavior is velocity weakening and shows negative *(a-b)* values with a background friction of ~0.75. At 300ºC, friction is ~0.65 and the gouges show neutral to positive values of *(a-b)*, showing larger *(a-b)* values than at 200 ºC. *(a-b)* values slightly decrease at 400ºC with a background friction of ~0.7. There is also effective normal stress dependence: even at temperature conditions where *(a-b)* tends to be positive, *(a-b)* values are negative at low effective pressure and increase to positive with increasing effective normal stress. This suggests that increasing pore pressure is a possible factor causing unstable slip, leading to slow slip events.

Smectite-rich pelagic sediments show that at low temperatures of 20 and 50ºC, the simulated gouges exhibit negative values of *(a-b)* with a background friction coefficient of 0.38, except at the highest slip rate of 0.1 mm/s. However, the gouges show neutral to positive values of *(a-b)* at temperatures of >100ºC with the same background friction coefficient as at lower temperatures. In addition, the value of parameter *(a-b)* depends significantly on slip rates: at temperatures of 20 and 50ºC it increases from negative to neutral (or slightly positive at 20ºC) with increasing slip rates to 0.1 mm/s, whereas it tends to decrease with increasing slip rate at temperatures higher than 100ºC. The downdip temperature limit of the slow slip events at Japan Trench (Ito et al., 2013) seems to be in the range between 100 to 150ºC. The transition in *(a-b)* value from neutral to positive, particularly at lower slip rates, occurs at the same temperature range. Hence, this could correspond to the observed downdip limit of the slow slip events.

Ambient Tremor Triggered by Long-term Slow Slip Event in Bungo Channel, Southwest Japan

Kazushige Obara (ERI, UTokyo), Hitoshi Hirose (Kobe U), Youichi Asano, Takanori Matsuzawa, Sachiko Tanaka (NIED), and Takuto Maeda (ERI, UTokyo)

Episodic tremor and slip (ETS) is a stick-slip in the transition zone between locked and stable sliding zones on the plate interface in Southwest Japan and Cascadia. ETS episode with duration of several days usually recurs at interval of several months at each segment. On the other hand, in the Bungo channel region where is the western edge of the ETS zone in SW Japan, tremor activity continued for several months during the long-term slow slip event (SSE) in 2003 and 2010. In this presentation, the relationship between long-term SSE and surrounded triggered tremor is discussed.

Tremor triggered by the long-term SSE is spatially localized in the narrow width of about 10 km at the shallowest part of the tremor zone, and at the neighboring area just downdip from the source fault of the SSE. The frequency distribution of tremor along the dip direction during the SSE period is consistent with the spatial distribution of total slip estimated for 2010 SSE. Therefore, the slip of the long-term SSE penetrated in the ETS zone may generate tremor. The daily number of the activated tremor is 12-14 during the SSE; however, it is 40-50 for regular ETS episode during the inter-SSE period. On the other hand, slip rates of the long-term SSE and ETS are typically 1 mm/d and 3 mm/d, respectively. Therefore, tremor rate may be controlled by slip rate.

After SSEs in 2003 and 2010, tremor activity seems to slightly increase in the east region within 50 km from the triggered tremor area. Such 7-year period variation in tremor activity is observed in only the shallower side of the tremor zone. Moreover, pattern of the long-term variation seems to slightly migrate to east during a few years. We interpret that a tiny transient slip after the long-term SSE slowly propagates between transition and locked zones.

Tremor activity at the shallowest part of the tremor zone in the Bungo channel continued longer than that of regular ETS in the late 2006 during the inter-SSE period. Associated tiny GPS change may suggest a minor long-term SSE. Similar tremor activity with duration longer than a few months has been observed from May 2014. However, no GPS change so far may suggest the occurrence of a very tiny SSE near the tremor zone.

The connections and variations between recurrent slow slip events and very low frequency earthquakes near the southwestern Ryukyu subduction zone

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Slow slip events (SSEs) and very low frequency earthquakes (VLFEs) are two types of slow earthquakes (Beroza and Ide, 2011), which normally occur on intensely coupled plate boundaries and are considered to have mechanical relations to large subduction thrust earthquakes. Although SSEs (Heki and Kataoka, 2008) and VLFEs (Ando et. al, 2012) were detected along the western Ryukyu trench individually, the mutual relations and the time variations of these events are still unknown. To understand these phenomena, the GEONET GPS data of 16 yrs (1997 to 2014) and F-net broad band seismic data of 3 yrs (2007 to 2009) are analyzed. 32 SSEs are identified beneath Hateruma Island, western Ryukyu, at depths of 20 to 40 km and 959 VLFEs are detected in nearly the same area at depths of 10 to 30 km. The average recurrence interval of SSEs is calculated to be 6.3 months and the average magnitude is M_w 6.6. However, the recurrence interval of SSEs is not invariable. During 2004 to 2007, the recurrence interval suddenly decreases from 6.2 to 4.5 months, and then turns back to the previous level. Coincidentally, the number of VLFEs of 2007 is only about 60% of those of 2008 and 2009. Although the sampling time period of VLFEs is insufficient, the phenomenon still shows a slight negative correlation between SSEs and VLFEs. Furthermore, the amount of SSEs slip in this area is 8.6 cm/yr on average, but the value varies with time. The slip values of SSEs increase remarkably from 2002 to 2003 and from 2013 to 2014. At each period, an earthquake swarm activity occurs in the Okinawa trough, approximately 50 km north of the SSE fault patch. These observations imply that the Okinawa trough rifting may accelerate the activity of SSEs. By contrast, the slip amount tends to decrease from 2008 to 2012. Taking into account the results of recurrence interval of SSEs and the amount of VLFEs, we conclude that SSEs and VLFEs activities have a negative correlation in southwestern Ryukyu trench.

Estimation of moment release in the very low frequency band during episodic tremor and slip

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Very low frequency earthquake (VLFE) is a kind of slow earthquakes with a moment magnitude of 3-4 observed at a period range of 10-200 s, the intermediate time scale between tremor (< 1s) and slow slip events (> day). It was first discovered in the southwest Japan both at the up-dip (Obara and Ito 2005 EPSL) and down-dip (Ito et al. 2007 Science) parts of seismogenic zone on the subducting plate interface especially during episodic tremor and slip (ETS) events. In the Cascadia subduction zone, Ghosh et al. (2014, IRIS abs.) recently reported the presence of five VLFE events that migrates with the tremor during an ETS event in 2011. In this study, we analyzed VLFEs in and around the Olympic Peninsula to confirm their presence in the Cascadia subduction zone and to estimate their moment release in a period range of 20-100 s.

We first detected VLFE events by using broadband seismograms with a band-pass filter of 20-50 s. The preliminary result shows that there are at least 16 VLFE events with moment magnitudes of 3.2-3.7 during the M6.8 2010 ETS. The focal mechanisms are consistent with the thrust earthquakes at the subducting plate interface. The epicenters of VLFEs and tremor are within the errors of VLFE locations (~5-15 km). The total seismic moment of 16 VLFEs is corresponding to a M4.3 earthquake, which is about 0.02% of the moment release by the slow slip during the M6.8 2010 ETS.

We further estimated moment release below noise by stacking long-period waveforms at the peak timings of tremor amplitudes for tremors within a 10-15 km radius by using tremor catalogs in 2006-2010, and estimated the focal mechanisms for each tremor source region as done in southwest Japan (Takeo et al. 2010 GRL; Ide and Yabe 2014 GRL). As a result, VLFEs could be detected for almost the entire tremor source region at a period range of 20-50 s with average moment magnitudes in each 5-min tremor window of 2.4-2.8. Although the region is limited, we could also detect VLFEs at a period range of 50-100 s with average moment magnitudes of 3.0-3.2. The moment release at 50-100 s is 4-8 times larger than that at 20-50 s, roughly consistent with an omega-squared spectral model. The ratio is close to the ratio previously obtained in southwest Japan (Takeo et al. 2010). If M~3 earthquake exists at each of ~24,000 time windows with tremor, the total seismic moment at a period range of 50-100 s corresponds to a M~6 earthquake, which is about 1% of the moment release by slow slip events in 2006-2010. The ratio is roughly consistent with the value of 1-2% obtained by Takeo et al. (2010) in southwest Japan.

Further study including slow slip events and characteristic activities, such as rapid tremor reversal and tremor streaks, will reveal the source spectrum of slow earthquakes in a broader time scale from 0.1 s to days.

Review of Cascadia Slow Slip and Tremor

Tremor in Cascadia occurs spatially continuously for over 1200km from California to Vancouver Island and clusters in space and time into over 1000 tremor swarms. All of the large swarms correspond closely in space and time with geodetically observed slow slip at time scales of 4 hours up to 47 days. For the largest events the duration of tremor is linearly related to geodetically observed seismic moment. Assuming this relation holds for the smaller tremor swarms, the inferred slow-slip events follow a standard Gutenberg-Richter relationship with a b-value of 1. In contrast, low-frequency earthquakes (LFEs), that appear to make up tremor, follow an exponential relationship: the number of LFEs with moment exceeding M_0 is proportional to $e^{-Mo/Mc}$ where Mc is the characteristic seismic moment for the distribution. We find that Mc increases systematically by a factor of 10 from down-dip to up-dip suggesting that either the patch size or the amount of slip varies with down-dip position. The focal mechanisms from tremor particle motions, and LFEs are consistent with thrust on the plate boundary in the direction of relative plate motion. Receiver function studies suggest the existence of a thin (~3-km) low-velocity zone associated with the upper half of the subducted oceanic crust. Observed Vp/Vs=2.4 suggests high pore pressures, consistent with sensitivity of tremor to small tidal stress. Frequent, small tremor and LFE swarms down dip as well as fewer, but larger ones up dip suggest a weaker fault down dip that is driven continuously by steady plate-interface slip. The large episodic tremor and slip events generally initiate down dip. The tremor area expands linearly for 5-8 days as tremors propagate up dip to fill the width of the slow-slip region. During this time tremor amplitudes increase approximately linearly with time and are not sensitive to tidal forcing. Then tremor propagates along strike at 7-12 km/day with huge variability in amplitudes as tremor becomes extremely sensitive to tides. This is followed by Rapid Tremor Reversals propagating 20-40 times faster but in the opposite direction of the rupture front and by linear streaks propagating even faster but parallel to plate motion direction.

Response of tremor and slow slip to tidal stress: Constraints on fault friction and weakening

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Solid Earth and ocean loading tides generate stresses that modulate slow slip and tremor on deep plate boundaries. I show that this influence increases over several days as slow slip occurs at a spot, implying weakening of the fault. Tidal stress perturbations are computed every 10 minutes in time on a spatial grid with 12 km spacing for six large ETS that ruptured the same portion of northern Cascadia. The migration front of each ETS is determined from the space-time distribution of tremor and used to classify tremor into early, intermediate, and late activity at each location. Analysis of tidal stresses at the times and locations of 33,000 tremors reveals that tremor rates are exponential functions of stress, with the dependence increasing over several days following passage of the front as slip accumulates at a spot. This progressively increasing tidal sensitivity contrasts with insensitivity of tremor early during the rupture. These results constrain the pace and degree of fault weakening during ETS.

The relative importance of shear and normal stress on the inferred fault interface is evaluated using the friction coefficient. The inclusion of volumetric stress in the formulation of pore pressure allows inference of intrinsic, rather than merely effective, friction. Correlation of tremor and tidal stress is maximized for very low values of intrinsic friction of 0 to 0.1 (i.e., far below laboratory values).

A model of threshold failure strength, in which tremor occurs when fault stress exceeds the strength, can explain the evolving, increasing, exponential sensitivity to tides.

Abstract for the workshop on Slow Earthquakes in Kyoto

The spatial variation of tidal sensitivity of tectonic tremors

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Various quantities charactering tectonic tremors, which have been detected in many regions and tectonic environments, are spatially variable among regions and even within an individual region. As one such quantity, we investigated the spatial variation of seismic energy rate or amplitude of tectonic tremors in some subduction zones (Yabe and Ide, in revise). We observed spatial variation of seismic energy rate of tremors, and interpreted that it represents the spatial variation of plate-interface strength. Tidal sensitivity of tectonic tremors is also known to vary spatially. If our interpretation was correct, some relation between them may be expected. Hence, in this study, we investigate such a relation by calculating tidal stress quantitatively in Nankai and Cascadia subduction zones, and present preliminary results in this presentation.

We calculate tidal stress tensor including both body tide loading and ocean tide loading. Green functions for spherical Earth are calculated based on the method by Okubo and Tsuji (2001). The SPOTL program (Agnew, 2012) with appropriate ocean tide model is used to calculate the time history of sea surface level. The plate-interface geometry is from the fault planes of VLFs estimated by Ide and Yabe (2014) or the plate geometry model by (Hayes et al., 2012).

Tidal sensitivity is significant after the slip pulse of SSE passes in ETS events. High sensitivity can be seen especially around regions where high-energy-rate or large-amplitude tremors already occurred during the slip pulse. Large slip in that region might weaken the fault, resulting in the appearance of tidal sensitivity. Tidal sensitivity is less significant in inter-ETS tremors and initiating tremors in ETS events, though some clusters show clear tidal sensitivity. Tremor rate dependency to tidal stress is roughly approximated by an exponential function, as pointed out by some previous studies (Houston, 2013, AGU; Ide and Tanaka, 2014).

Workshop on Slow Earthquakes in Kyoto, Sep. 8-10 2014

Post-3.11 acceleration of the Pacific Plate: First direct evidence

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Oceanic plates may accelerate after large inter-plate earthquakes (Anderson, 1975). This was indirectly substantiated by Heki and Mitsui (2013), who analyzed crustal deformation in an island arc after the 2003 Tokachi-oki megathrust earthquakes. Here we show direct evidence of postseismic acceleration of the Pacific Plate from the data of a Global Navigation Satellite System (GNSS) station on the Minami-torishima (Marcus) Island ~2000 km off the Pacific coast of Japan.

Heki and Mitsui (2013) found the enhancement of the inter-plate coupling in NE Japan on segments adjacent to those ruptured in the 2003 Tokachi-Oki (Mw8.0) and the 2011 Tohoku-Oki (Mw9.0) earthquakes. They inferred that the subduction of the Pacific Plate slab significantly accelerated after these earthquakes. During interseismic periods, the balance between the down-dip (slab pull and ridge push) and up-dip (viscous traction and interplate coupling) forces realizes convergence rate constant over geological timescales. A megathrust event reduces interplate coupling, and the down-dip forces temporarily exceed the other. The accelerated subduction occurs under the new balance and continues until the interplate coupling recovers.

In the Marcus Island, the closest island on the Pacific Plate to the Japan Trench, continuous GNSS observations started in 2002, and showed linear movement toward WNW of ~7.7 cm/year (in the nnr-NUVEL1 frame) (Fig.1). This station showed coseismic jump of ~1 cm toward the epicenter of the 2011 Tohoku-oki earthquake. This vector is consistent with the coseismic displacement field calculated using the program by Sun et al. (2009) and a realistic earth model (PREM).

In addition to the coseismic step, the Marcus GNSS station showed ~10 percent increase of its speed with little change in azimuth, resulting in post-2011 speed of ~8.5 cm/year (Fig.2). This is difficult to explain with simple postseismic relaxation in viscous asthenosphere, partly because we need to assume unduly low asthenospheric viscosity to realize the observed rate, and partly because the observed velocity change is toward WNW (viscous relaxation would move the station toward NW).

The surface velocity field would have been disturbed over an extensive area by the 2011 earthquake, which might cause changes in rates of translation, rotation and scale change of the whole network. We examined the velocities of Kita-Daito and Okino-Torishima stations, located in the stable interior of the Philippine Sea Plate (and at similar distances from the Tohoku-oki earthquake epicenter), and confirmed that they did not show velocity changes synchronized with the 2011 earthquake exceeding 1-2 mm/yr. Hence it is unlikely that the velocity change of the Marcus Island is due to the distortion of the reference frame. We also confirmed that such an acceleration does not exceed 1 mm/yr in Hawaii (http://sideshow.jpl.nasa.gov/post/series.html), ~6000 km away from the fault, suggesting that the accelerated region has not covered the entire Pacific Plate, but is limited to the Western Pacific region.

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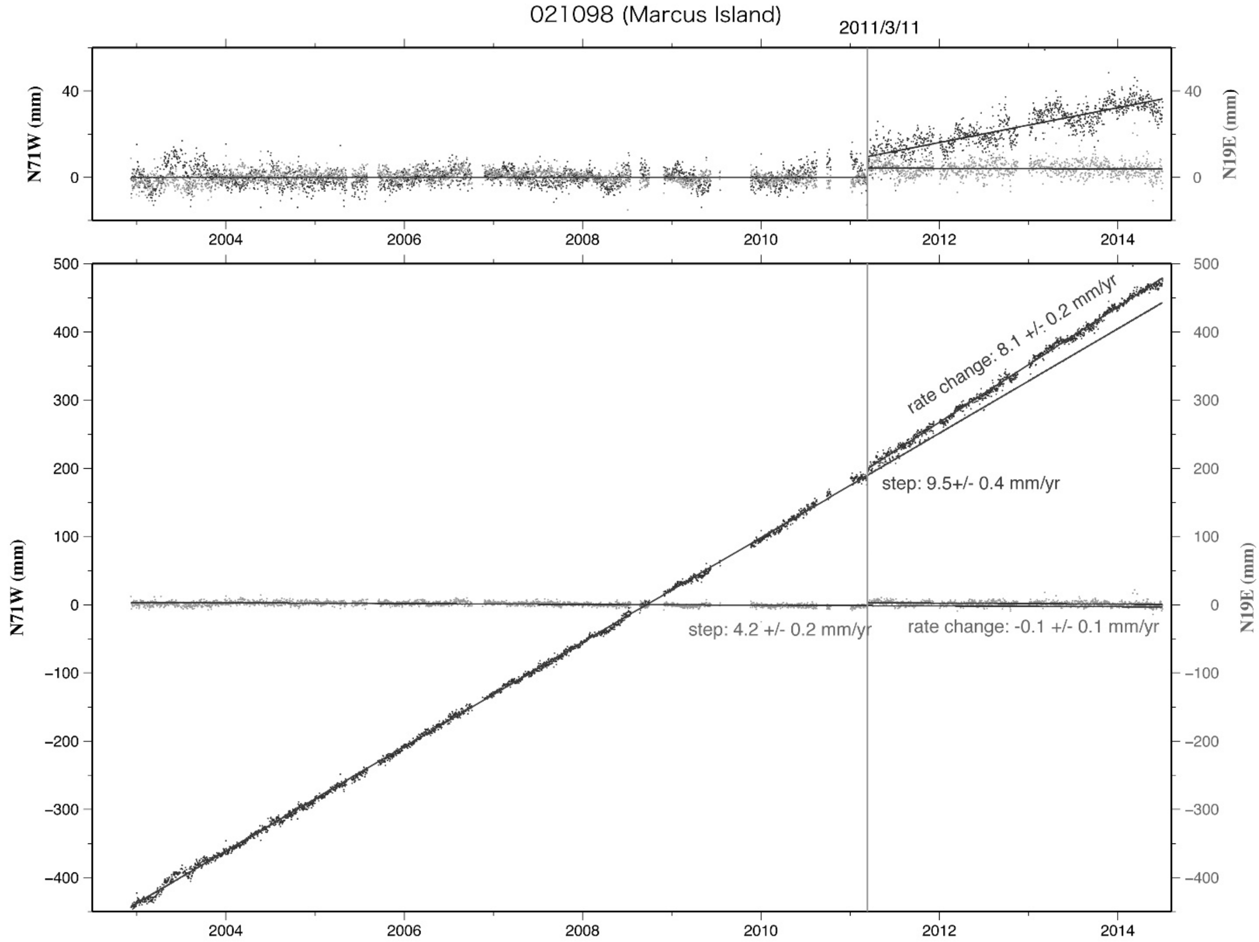

Fig.1 Absolute motion (ITRF frame) of the Minami-Torishima (Marcus) Island station (021098) of GEONET. The bottom figure shows the raw data (average values are subtracted) and the top figure shows the residual from the best-fit line calculated by fitting the pre-2011.3.11 portions of the time series. The components parallel (N71W) and perpendicular (N19E) to the secular plate motion are shown in black and gray, respectively. We can recognize ~10 percent post-3.11 acceleration only in the direction of the plate motion.

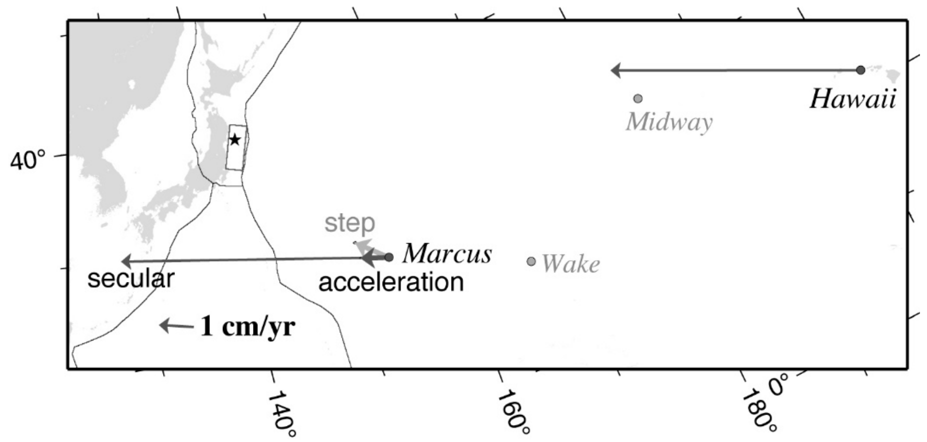

Fig.2 Map drawn by the Mercator's projection with the projection pole at the Euler pole of the Pacific Plate. Here, the rigid motion of the Pacific Plate is expressed as the leftward movement. The movement of the Marcus (Minami-Torishima) island GNSS station has experienced ~10 percent acceleration (thick black arrow) in the direction of the secular plate movement (thin black arrow). Coseismic step is northwestward and is shown with a gray arrow.

Tectonic controls on earthquake size distribution and seismicity rate

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There are clear variations in maximum earthquake magnitude among Earth's subduction zones. These variations have been studied extensively and attributed to differences in tectonic properties in subduction zones, such as relative plate velocity and subducting plate age [*Ruff and Kanamori*, 1980]. In addition to maximum earthquake magnitude, the seismicity of medium to large earthquakes also differs among subduction zones, such as the *b*-value (i.e., the slope of the earthquake size distribution) and the frequency of seismic events. However, the casual relationship between the seismicity of medium to large earthquakes and subduction zone tectonics has been unclear. Here we divide Earth's subduction zones into over 100 study regions following *Ide* [2013] and estimate *b*-values and the background seismicity rate—the frequency of seismic events excluding aftershocks—for subduction zones worldwide using the maximum likelihood method [*Utsu*, 1965; *Aki*, 1965] and the epidemic type aftershock sequence (ETAS) model [*Ogata*, 1988]. We demonstrate that the *b*-value varies as a function of subducting plate age and trench depth, and that the background seismicity rate is related to the degree of slab bending at the trench. Large earthquakes tend to occur relatively frequently (lower *b*-values) in shallower subduction zones with

younger slabs, and more earthquakes occur in subduction zones with deeper trench and steeper dip angle. These results suggest that slab buoyancy, which depends on subducting plate age, controls the earthquake size distribution, and that intra-slab faults due to slab bending, which increase with the steepness of the slab dip angle, have influence on the frequency of seismic events, because they produce heterogeneity in plate coupling and efficiently inject fluid to elevate pore fluid pressure on the plate interface. This study reveals tectonic controls on earthquake size distribution and seismicity rate, and these relationships between seismicity and tectonic properties may be useful for seismic risk assessment.

ETS Tremor and Slip at Cascadia, SW Japan, and Mexico: Subducting Plate Fluids Channelled Updip to the Forearc Mantle Corner and Silica Deposition

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Abstract

In this study we first show that on the Cascadia, SW Japan, Mexico and other hot subduction zones, there is a ~50 km gap downdip between the seismogenic zone and the Episodic Tremor and Slip (ETS). There is not a continuous transition from unstable to conditionally stable sliding. Seismic rupture occurs mainly offshore, ETS lies mainly onshore. Secondly, we describe what does control the downdip position of ETS. We argue that rising fluids responsible for ETS are focussed above the forearc mantle corner. There is a remarkable correspondence between the position of ETS and this corner along the whole margin for all three subduction zones. Hydrated minerals in the subducting oceanic crust are dehydrated with down-dip increasing temperature, and seismic tomography data indicate that these fluids have strongly serpentinized the forearc mantle. Recent laboratory data show that such forearc mantle serpentinite has low permeability and updip flow should be restricted to the underlying permeable oceanic crust. At the forearc mantle corner these fluids are released upward into the more permeable overlying forearc crust. Finally, we show that there is indication of this fluid flux in seismic tomography data from Northern Cascadia. There is a region of very low Poisson's Ratios above the forearc mantle corner that may be explained by a concentration of silica which has exceptionally low Poisson's Ratio. The rising fluids should be silica saturated and precipitate silica with decreasing temperature as they rise above the corner. The separation of the seismogenic zone from the ETS slow slip zone might suggest that the slow slip may not directly trigger great earthquakes in the seismogenic zone. However, the evidence that the ETS slow slip results from fluids that propagate updip in the subducting oceanic crust indicates that there may be fluid connection between the ETS zone and the seismogenic zone further updip so there may be a strain connection, although with some as yet unknown delay.

Relationships Among Temperature, Dehydration of the PHS plate, and the three seismic events in the Tokai district

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In this study, we performed numerical simulations of temperature distribution at the plate boundary and estimated the dehydration process of hydrous mid ocean ridge basalt (MORB) in the oceanic crust in the Tokai district, central Japan. We discuss the relationships among temperature, dehydration, and a future megathrust earthquake, deep low-frequency earthquakes (LFEs), and a slow slip event (SSE). Our results identified a strongly coupled region for an expected megathrust Tokai earthquake based on temperature conditions at the plate boundary. The depth range of the plate boundary where the megathrust earthquake may occur is 9~21 km, narrowing toward the east. An SSE is estimated to have occurred in the transition zone between unstable and stable sliding. Hypocentral depths of LFEs deviating from the isodepth contours of the Philippine Sea plate toward the east may be explained by differences in the dehydration process associated with phae transformations in hydrous MORB.

Diversity of Slow Slip Events and Nonvolcanic Tremor in Guerrero, Mexico

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The Guerrero segment of the Central Mexico subduction zone is a sanctuary of Slow Slip Events (SSE) and Non-Volcanic Tremor (NVT) because of the frequency and variety of these phenomena in a relatively limited area. Subduction along the subhorizontal interface extends up to almost 200 km inland in Guerrero. The apparently mature Guerrero seismic gap (GSG, no earthquakes with M>6.5 in more than 100 years), with a potential for Mw~7.8-8.0 earthquake, may be triggered by one of the SSEs periodically occurring downdip from the shallow seismogenic zone.

The GPS network in Guerrero has detected five large SSEs of the equivalent magnitude Mw>7.0, which occurred in 1998, 2001-2002, 2006, 2009-2010, and 2014. There is also evidence of smaller and more frequent short-period SSEs. Tide gauges recorded one mega-SSE in 1972, which produced the uplift of about 10 cm in Acapulco. Comprehensive analysis and modeling of GPS data revealed a notable strain release by recent SSEs in the deepest portion of the GSG. This suggests that the interplate coupling and elastic strain accumulation of the seismogenic zone of the Guerrero gap is much lower than in the neighboring segments of the subduction zone where large subduction thrust earthquakes were occurring more frequently. When the large 2009 SSE had almost proceeded through it's cycle it was promptly followed by a second significant SSE pulse in 2010, whose initiation coincided with, and was probably triggered by the Maule Mw8.8 earthquake in Chile.

The last 2014 SSE started in January and should cease in October of this year if the SSE in Guerrero obeys the slip predictable model. The onset stage of the 2014 SSE was somewhat faster when compared with all previous events, and a series of subduction thrust earthquakes (Mw 7.2, 6.4, 6.1) in April-May in the NW part of Guerrero trench could be triggered by this slow slip.

SSEs significantly perturb the records of all GPS stations in Guerrero, nevertheless several of GPS stations have more than 10 years of continuous data that makes it possible to estimate a log-term trend of the displacement at each such GPS site. The secular GPS velocity vectors are oblique to the trench and the along-trench (lateral) velocity components abruptly diminish to the north by 4-5 mm/year across the Chacalapa fault zone (CFZ). This velocity drop can be interpreted as a partitioning of the oblique convergence between the Cocos and North America plates with a sinistral motion of a forearc sliver.

While the subduction thrust slow slip events (t-SSE) are clearly observed roughly every ~4 years in Guerrero they could be accompanied by the strike-slip SSE on the Chacalapa Fault, akin to the SSE on the San Andreas Fault. An analysis of the long GPS displacement records in Guerrero shows that during the inter-t-SSE periods the Chacalapa Fault is mainly locked, and the shear rate across it is only about of 2.0 mm/year but during the t-SSE episodes in 2002 and 2006 there was a noticeable increase of lateral displacement on several GPS stations located on the coast, south from the fault, which may be understood as the SSEs on the CFZ. The subduction zone in Guerrero may be a rare region where two different types of SSE are occurring together.

Since 2005, when continuous seismic data became available, NVTs were discovered in Guerrero. We observe an inherent relation between the tremor activity and the SSE. Detailed analysis of the NVT duration and epicenters' distribution, a modeling of the SSEs in Mexico show that the NVT high activity with duration of a few days occur periodically every 3-4 months without clear GPS indication of large concurrent long-term SSE. These NVT episodes in many cases correlate with small (~5 mm), short-period (15-30 days) swells in the GPS time series at only inland stations, far from the trench. We interpret these episodes as short-term SSEs occurring at plate interface between ~180 km and ~220 km from the trench.

Large long-term SSE dislocations develop just downdip the shallow seismogenic segment of the subduction zone, and do not overlap with the main area of the NVT. Nevertheless they modulate notably the intensity and frequency of the NVT bursts. There are two energetically distinct tremor groups of relatively low (LE) and high energy (HE). The HE NVTs are typical for the repeating downdip episodes. Low energy NVT is occurring persistently at a distance of ~215 km ("Sweet Spot") from the trench. During large SSEs, the duration and frequency of the NVT bursts increase and LE bursts are also observed as close as ~150 km to the trench. The latest studies reveal that various periods of the NVT in Guerrero are associated with a similar activity and distribution of the Low-Frequency Earthquakes (LFE).

We also observed strong triggering of the NVT activity by surface waves from Maule, Chile 2010 and other teleseismic earthquakes. It is interesting that some teleseismic events and regional deep intraplate earthquakes produce notable postseismic NVT activity in Guerrero.

Interplate coupling and its spatial relation with slow slip events along the Nankai Trough

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We developed a method to detect a short-term SSE (slow slip event) solely using continuous GNSS data and systematically searched short-term SSEs along the Nankai trough and the Ryukyu trench (Nishimura et al., 2013; Nishimura, 2014). We found 369 probable and possible SSEs with Mw ≥ 5.6 for 17 years. Along the Nankai trough, the short-term SSEs occurred only at a depth of 30-40 km and formed a narrow ETS (Episodic tremor and Slip) zone at a down-dip of source regions for great megathrust earthquakes. Annual slip rate of short-term SSEs in the ETS zone is ~30 mm/yr in western and central Shikoku and 10-20 mm/yr in the other areas. However, many shallow SSEs are distributed at a depth of 10-40 km along the Ryukyu trench. Slip rate is generally less than 10 mm/yr except for several patches of frequent SSEs.

In 2013, the Cabinet Office of the Japanese government published a new source model for the maximum-class Nankai megathrust earthquake. In the new model, the source area is supposed to expand toward updip and downdip of those of the 1944 Tonankai and the 1946 Nankai earthquakes. The expanded source area includes the ETS zone. In order to investigate how fast strain is accumulated in the anticipated source region along the Nankai trough, we estimate the distribution of interplate coupling using GNSS velocity data.

We used daily coordinates of 510 GEONET stations to estimate horizontal and vertical velocities from April 2005 to December 2009. We divided the overriding plate into nine crustal blocks. The block boundaries include the Median Tectonic Line, the Beppu-Shimabara Tectonic Line, and Niigata Kobe Tectonic zone. The geometry of the plate interface between the subducting Philippine Sea and the overriding plates is referred. DEFNODE (McCaffrey) is used for the block-fault modeling. The estimated interplate coupling is represented by average slip-defict rate for 4.8 years.

Along the ETS zone, slip-deficit rate ranges between 5 and 35 mm/yr, which means a transient zone between full locking and stable sliding. It suggests that significant strain is accumulating even in the ETS zone and that the accumulated strain might be released by future earthquakes. It is interesting that the ratio of the SSE slip rate and the slip-deficit rate to the long-term slip rate is considerably varied along the ETS zone. The sum of the slip-deficit rate and the SSE rate is almost equal to the long-term plate rate in western Shikoku, which suggests that no stable creeping occurred in western Shikoku. On the other hand, the sum of the slip-deficit rate and the SSE rate is ~ 60 % in an east part of Kii Peninsula. It suggests significant creeping is ongoing in the ETS zone.

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Interplate coupling beneath NE Japan before the 2011 Tohoku Earthquake

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Postseismic slip on the plate interface can be regarded as a slow earthquake that releases strain energy accumulated due to the interplate coupling in the interseismic period. It is important to grasp the spatial distribution of the both postseismic slip and interplate coupling in order to understand the earthquake generation cycle and to assess the risk due to seismic and tsunamic hazards.

Many studies have already investigated interplate coupling beneath Tohoku district, northeastern Japan, where large earthquakes have repeatedly occurred on the plate interface of the Pacific plate that is subducting beneath the overriding continental plate (Okhotsk or North American plate), based only on terrestrial geodetic data [e.g., *El-Fiky and Kato*, 1999; *Nishimura et al.*, 2004; *Suwa et al.*, 2006; *Loveless and Meade*, 2010]. However, large coseismic slip along the trench axis during the 2011 off the Pacific coast of Tohoku Earthquake (M9.0, hereafter Tohoku Earthquake) highlighted the necessity of the re-examination of these estimations of interplate coupling. In the re-examitation, interplate coupling along the shallowest portion of the megathrust before the Tohoku Earthquake must be the most important issue, because spatial resolution of the inversion analysis based only on terrestrial geodetic data is generally not high enough to constrain the coupling state in the far offshore area.

Seafloor geodetic observation has been developed and applied off the Pacific coast of Tohoku district [e.g., *Fujita et al.*, 2006; *Sato et al.*, 2011; *Kido et al.*, 2011], and *Sato et al.* [2013] reported the secular displacement rate before the 2011 Tohoku Earthquake. Tohoku University has also derived displacement rate at their seafloor stations [*Mizukami et al.*, 2006]. These seafloor geodetic observation data are invaluable to estimate the interplate coupling beneath the northeastern Japan, but have not been used in any inversion analyses estimating the distribution of the degree of interplate coupling. Thus, we have estimated the backslip distribution based on terrestrial and seafloor geodetic data with taking the correlations between the observed displacement rates at terrestrial GPS stations into account in the inversion analyisis. We assumed that the covariance between the displacement rates at two different GPS sites depends on the distance, and configured the covariance between the different components, such as EW, NS and UD, by applying the result of raw GPS data processing.

The results show that interplate coupling had been persistently large before the 2011 Tohoku earthquake at the very shallow portion on the plate interface near the trench corresponding with the area of very large coseismic slip (> 50 m). A comparison of the distributions of the backslip and the postseismic slip associated with the Tohoku earthquake implys that the postseismic slip has been occurring at the trantision zones of the interplate coupling.

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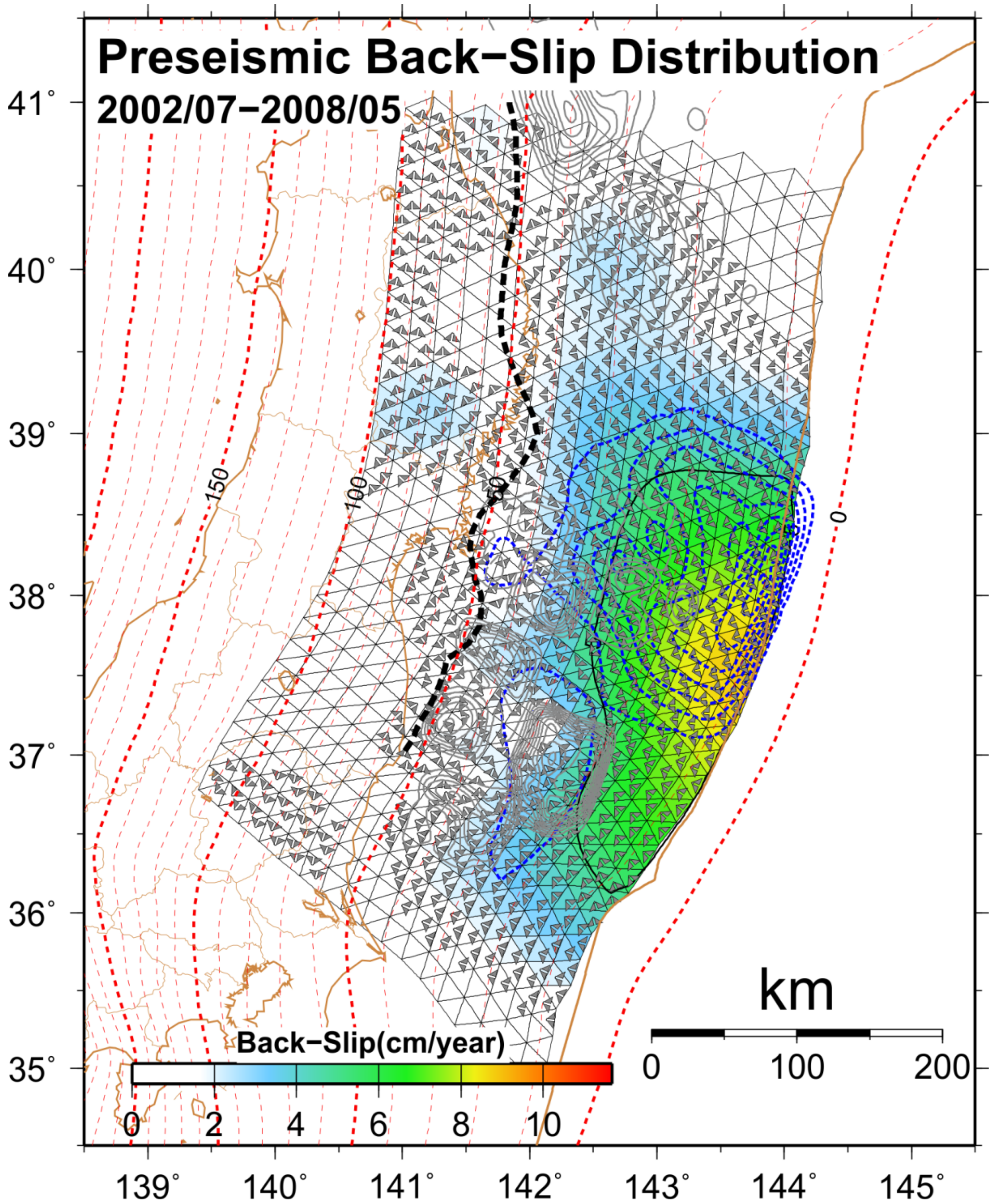

Figure 1. Distributions of estimated back-slip in the period from July 2002 to May 2005. The result when the covariance matrix is not diagonal is exhibited.

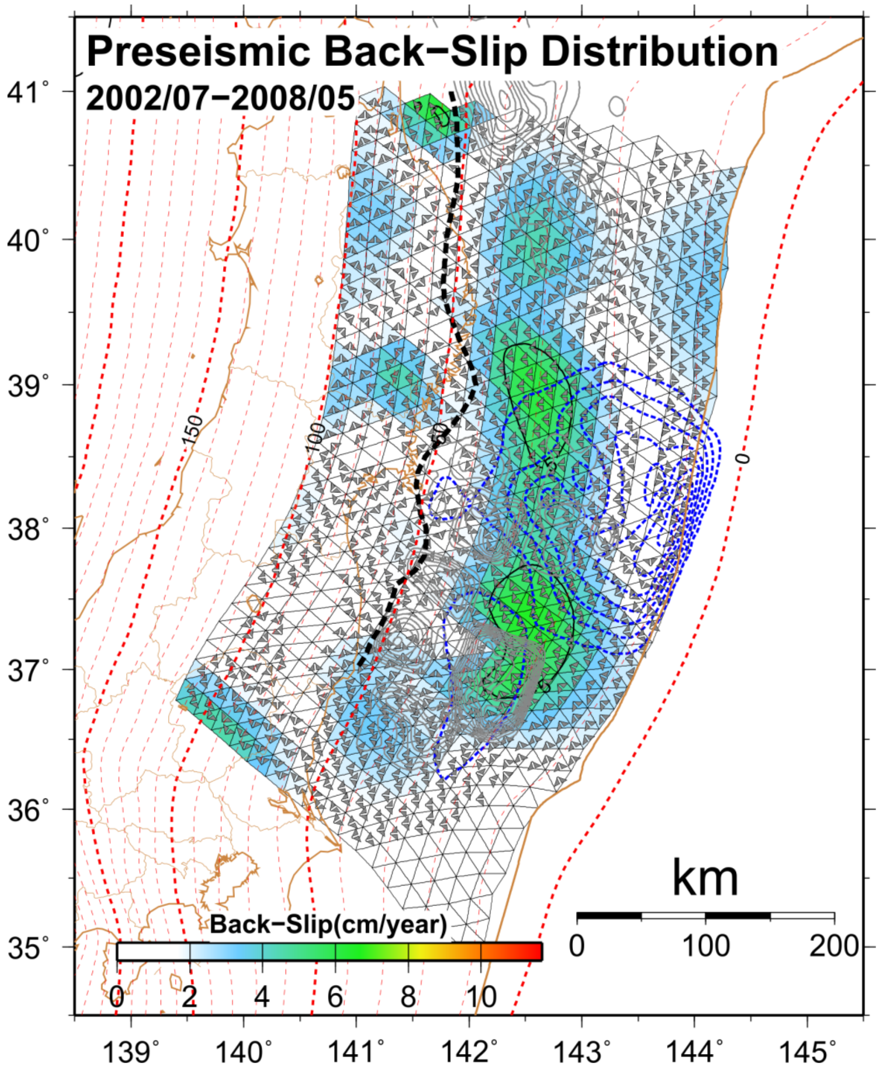

Figure 2. Distributions of estimated back-slip in the period from July 2002 to May 2005. The result when the covariance matrix is diagonal is exhibited.

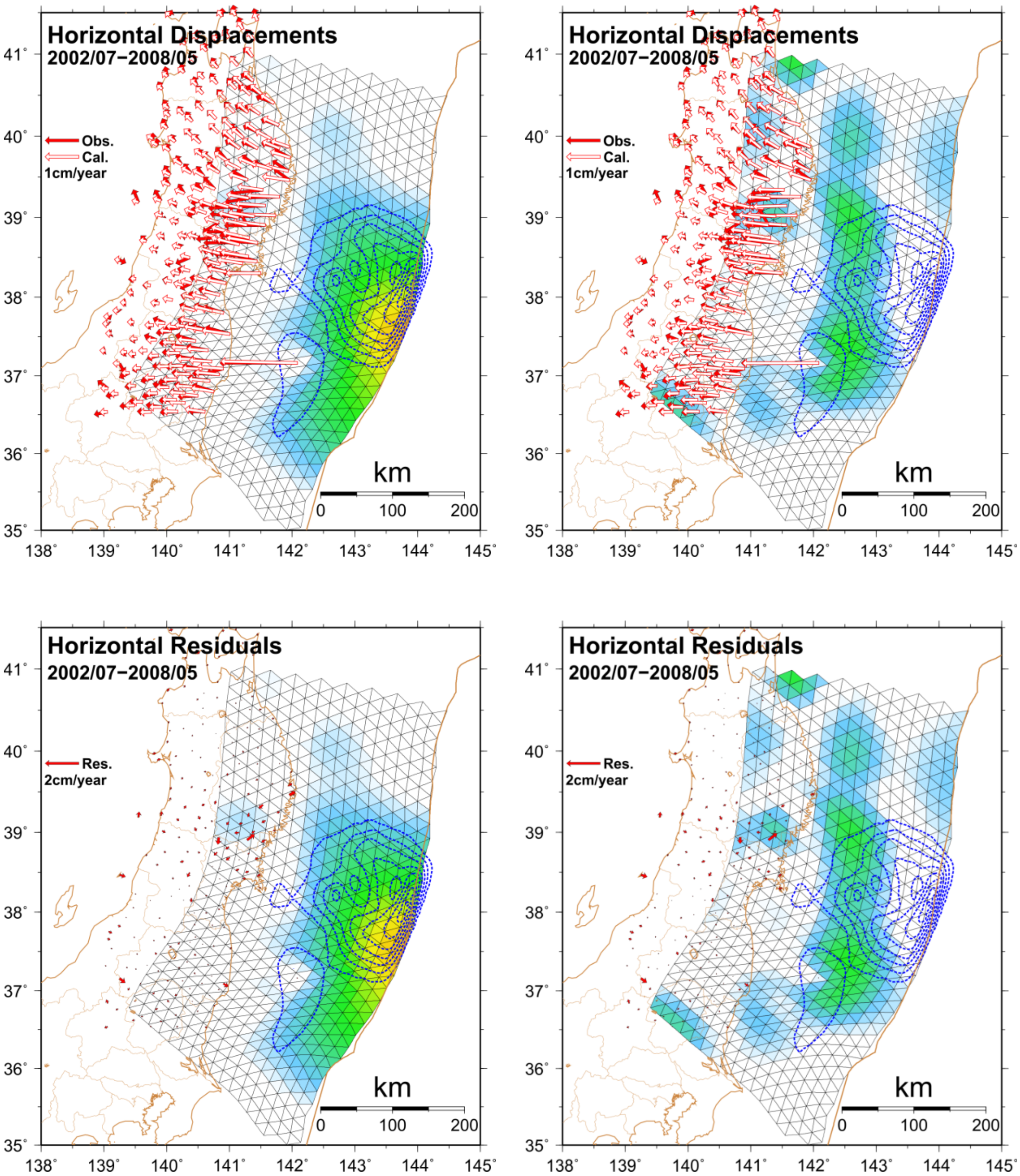

Figure 3. Distributions of estimated back-slip and displacement rates. Left and right panels correspond the result when the covariance matrix is not diagonal and that when the covariance matrix is diagonal. Top and bottom panels represent comparisons of observed and calculated displacement rates and their residuals (observation - calculation), respectively.

Postseismic motion of the high-slip shallow fault during the 2011 Tohoku-oki Earthquake

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International Research Institute of Disaster Science, Tohoku University

The Tohoku earthquake was followed by a large postseismic deformation across a broad region of eastern Japan. In early studies characterizing the afterslip, it was usually assumed that the observed postseismic deformation had been caused by slip along the plate boundary fault. The postseismic deformation patterns reported by Japan Coast Guard and Tohoku University (2013) were significantly different from the one estimated from the onshore observations. The most striking features in the offshore GPS observations were landward motions recorded in the Miyagi-oki region with the largest coseismic slip during the mainshock and subsidence across a broad region. It is unlikely that these features can be explained by afterslip alone and an alternative mechanism must also have been involved in the post-Tohoku earthquake deformation. The most plausible mechanism controlling postseismic deformation other than afterslip on the fault is viscoelastic relaxation of the earthquake-induced stress. The offshore postseismic displacements, completely opposite to those in the onshore region, indicated the importance of viscoelastic relaxation in interpreting the crustal deformation after the large stress perturbation induced by the Tohoku earthquake. Iinuma *et al.* (2014) computed the postseismic deformation observed at onshore and offshore sites as a combination of effects of afterslip and viscoelastic deformation. The following three features were robustly obtained: 1) significant slip occurred on the deep extension of the mainshock rupture zone, 2) the amount of afterslip was minimal in the large coseismic slip area located in the Miyagi-oki region, and 3) occurrence of afterslip near the trench in the southern area.

Diverse SSE and seismicity behaviour on the Hikurangi subduction zone, New Zealand

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SSEs have been documented since 2002 on the Hikurangi subduction margin , North Island, New Zealand, as detailed by Wallace et al (2012), Wallace and Beavan (2010), Wallace and Eberhart-Phillips (2013), and Bartlow et al (2012). These SSEs have been recorded by the CGPS sites of the New Zealand GeoNet network, which, along the East Coast of the North Island, are only 12-20 km above the subduction megathrust. The observed SSEs in this area have diverse characteristics - in their duration, extent of slip and in their frequency of occurrence. The shallow depth of the plate interface beneath the coastal CGPS make this subduction margin an ideal place to investigate controls on SSE behaviour, as recognized by the various research programmes associated with the IODP offshore drilling proposed for offshore.

In addition to the CGPS measurements the national New Zealand GeoNet network has a dense seismometer network along the East Coast, albeit using surface seismometers rather than borehole seismometers. In the last few years we have been complementing the national seismograph network with additional broadband seismometers at temporary sites, and recording M_L1-M_L4 seismicity associated with SSEs occurring in the Raukumara peninsula (northern Hikurangi margin). We observe a diversity of seismic behaviour, with close synchronicity between bursts of seismicity, and the initiation of documented SSEs. Offshore seismic activity prior to 2002 along the margin can be inferred to also be associated with earlier SSE episodes, especially where the spatial and depth extent of earlier seismic bursts matches present-day SSE-related seismic activity.

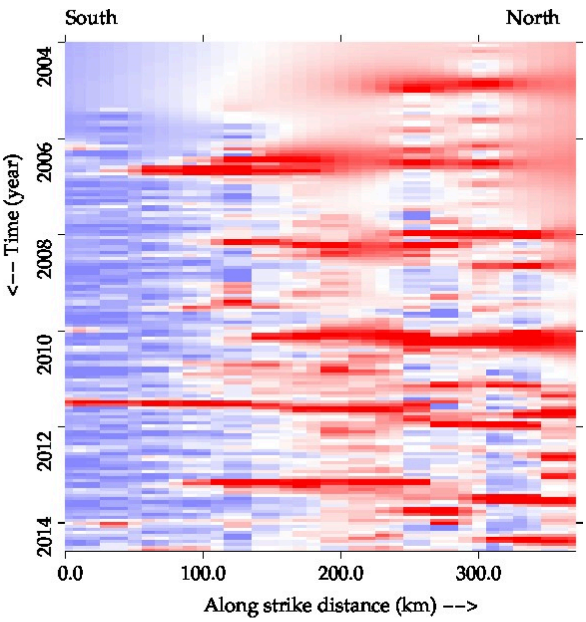

Figure. Derivative of the continuous GPS detrended time series, interpolated between CGPS sites along the east coast of North Island, New Zealand. Full red colour highlights the periods of SSE, illustrating that the SSE sometimes involve spatial migration of up to 200 km (e.g. in 2011 in the central Hikurangi margin)

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Alpine Fault Tectonic Tremor Recorded by MOANA Project Ocean Bottom Seismometers, South Island, New Zealand

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Widespread observations of tremor and slow slip in different tectonic reveal that these processes play fundamental roles in accommodating and marking fault motion. Understanding the relationship between fault dynamics, stable (slow) slip, and more rapid earthquake rupture, however, requires a reliable method of identifying and characterizing slow-slip phenomena. These tasks are particularly challenging in offshore environments where the investigation of plate boundary processes, especially within subduction-zone megathrusts, typically relies, at least in part, on ocean bottom seismometers (OBS). OBS deployments are increasingly common and have improved our ability to detect offshore earthquake swarms, but their utility for detecting or locating seismic tremor associated with slow slip has not been investigated in detail. Here we demonstrate that seismic tremor associated with the deep extension of the Alpine fault has been recorded on an OBS network lying off the west coast of New Zealand's South Island. We focus on time windows known to contain tremor based on land observations (Wech et al., 2012) and identify coherent tremor signals on OBS stations at distances of as much as 150 km. Applying routine tremor processing techniques (Wech and Creager, 2008), the envelopes of the OBS signals were correlated against each other and with land stations to constrain tremor epicenters. This correlation highlights the performance of OBS stations in the tremor frequency band (~1–10 Hz), underscoring the potential effectiveness of OBS networks in constraining slow-slip processes offshore. With the increased emphasis on OBS data collection in ongoing and future experiments, these results show that tremor can, at least in some cases, be both identified and utilized on OBS networks with existing tremor methodologies (Wech et al., 2013).

The Marine Observations of Anisotropy Near Aotearoa (MOANA) experiment involved the deployment of 30 broadband OBS offshore from both the east and west coasts of the South Island of New Zealand (Stachnik et al., 2012; Yang et al., 2012).The OBS, provided by the Scripps Institution of Oceanography (SIO) Institutional Instrument Center (IIC) of the U.S. Ocean Bottom Seismic Instrument Pool (OBSIP), were deployed in water depths between 550 m and 4700 m and recorded continuously at 50 sps between January 2009 and February 2010. Each OBS was equipped with Nanometrics Trillium 240 broadband seismometer, and a Differential Pressure Gauge (DPG). In this paper we focus on seismograms from the four MOANA OBS stations that were closest to the Alpine Fault tremor and the Southern Alps Microearthquake

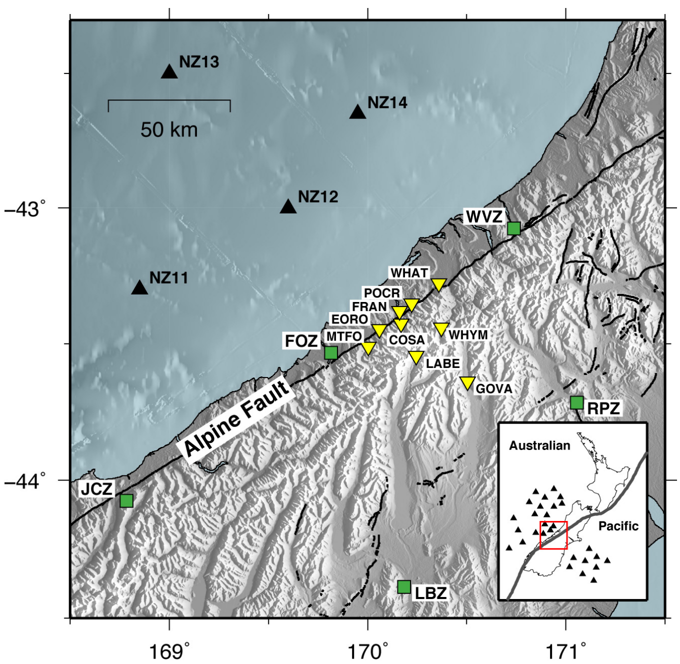

Figure 1.Seismic networks surrounding the Alpine Fault used in this study. Black triangles, MOANA ocean bottom seismometers; yellow triangles, SAMBA borehole seismometers; green squares, GeoNet broadband seismometers. The inset map shows New Zealand, the Australian and Pacific plates, the total extent of the MOANA OBS network, and the location of the main map.

Borehole Array (SAMBA) (Boese et al., 2012) array deployed off the west coast of the South Island at depths of 600–1200 m. The SAMBA and MOANA deployments overlapped during 2009, and we use the Alpine Fault tremor catalog of Wech et al. (2012) to focus our search for tremor signals on OBS stations.

Even at reasonably large distances (80–150 km) from the tremor source, the OBS stations were able to record the tremor; and their envelopes were well correlated with stations within 25 km of the tremor source. In our case, we benefited from having observed tremor on a land array residing above the source. This land array did not increase detectability on OBS, however. It simply allowed us to confirm that the observed signals were, in fact, tremor. By itself, the OBS network was too far away to reliably characterize the source, but even land-based seismometers would face such limitations at similar distances. Ultimately, as with any instrument, proximity and appropriate data processing will determine detectability, but we find that OBS are fully capable of providing useful, informative tremor observations (Wech et al., 2013).

Using land data, Wech et al. (2012) found that the tremor hypocenters concentrate at 25-45 km depth in the lower crust at the downdip projection of the Alpine Fault. The tremor coincides with a zone of high P-wave attenuation (low Qp) and bright seismic reflections, suggesting a fluid-rich zone. Recent work by Chamberlain et al. (2014) demonstrates that the tremor occurring near the Alpine Fault is composed of several families of low frequency earthquake (LFE) swarms, and conclude that the LFEs and tremor in the Southern Alps are the manifestation of slow shear slip on the plate interface.

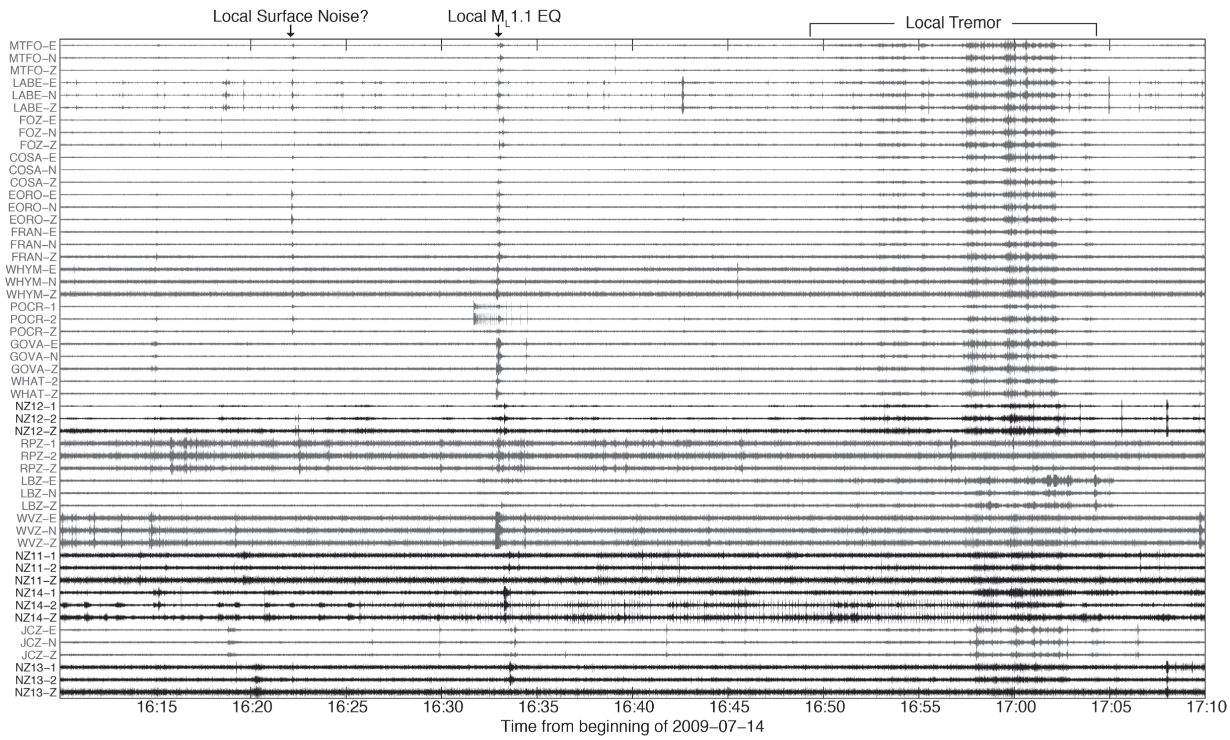

Figure 2. One hour of 4–10 Hz filtered waveforms from SAMBA, GeoNet, and MOANA ordered by distance from the tremor source region. The MOANA OBS stations are highlighted in black.

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Coulomb stress variations associated with slow slip, tectonic tremor, and seismicity along the northern Hikurangi Margin, New Zealand

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We investigate the spatiotemporal relationships between slow slip, tectonic tremor, and earthquakes along the northern Hikurangi Margin, New Zealand. The northern Hikurangi Margin plays host to some of the shallowest (<15km depth) slow slip events (SSEs) in the world, thus providing a unique window into the shallow subduction zone environment. There have been numerous observations of SSEs showing a diverse range in behavior that varies along strike. Working within the framework of existing observations, we use the recently quantified geometry of the Hikurangi subduction interface and PyLith, a sophisticated finite-element crustal deformation modeling tool, to simulate early 2010 northern Hikurangi SSEs. We then analyze the spatial extent of slip from each SSE and compute the changes in Coulomb failure stress imparted on the megathrust with respect to tremor and seismicity.

January/February 2010 saw the near-simultaneous rupture of two SSEs, one beneath the Mahia Peninsula and another 100 km north near Tolaga Bay. Following these events, the middle gap near Gisborne subsequently slipped for two weeks in March/April. The cGPS slip inversions from each SSE were interpolated onto the Hikurangi geometry mesh and used as an input for the SSE PyLith simulations, with all slip being applied at a single time step. Our simulation incorporated the existing New Zealand 3D velocity model to compute the spatial extent of slip along the megathrust. PyLith-computed traction changes in both the along convergence and fault normal directions were then used to compute the Coulomb failure stress for each node in the subduction interface mesh, resulting in a calculation of the change in Coulomb failure stress resulting from the simulated slow slip events.

Located in regions of high amplitude seismic reflectivity often interpreted as fluid entrained subducted sediments, the Tolaga Bay and Mahia Peninsula SSEs have similar patterns of a stress decrease in the slip patch and stress increase in the surrounding area of

the subduction interface. The Tolaga Bay SSE even shows that the stress decrease may extend all the way to the trench. The larger magnitude SSE in the Gisborne region (March/April 2010) is located in a region of distinctive seismic reflectivity, called the lens reflectivity zone, where there may be a complex 3D geometry to the subduction interface. While this SSE shows a decrease in stress within a portion of the slip patch, the region of stress increase is higher magnitude and encompasses a larger region. To account for the observed differences in the potential fluid content of the slow slip source regions, we spatially vary the pore fluid ratio using published values along the margin. This in turn allows us to use a spatially varying modified friction coefficient when calculating the Coulomb failure stress.

To investigate the effects of slow slip induced Coulomb stress changes on local seismicity, earthquakes from the GeoNet catalog were relocated using NonLinLoc, a probabilistic, non-linear, 3D earthquake location tool. Relocated events within 5 km depth of the subduction interface were then plotted against the changes in Coulomb failure stress to look at the spatial relationship between slow slip and earthquakes. We also looked at the spatial relationship between slow slip and tremor using a modified version of the popular envelope cross-correlation method to detect tremor during the early 2010 SSEs. Tremor locations were visually examined with respect to slow slip imparted stress changes. Both seismicity and tremor are concentrated at the down-dip extent of the slow slip rupture patches in regions of Coulomb stress increase.

Transient crustal deformation due to slow slip observed on ocean bottom pressure recorders in the Hikurangi margin

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We describe two slow slip events observed using seafloor instruments at the northern Hikurangi margin, New Zealand. These transient deformation events were observed using ocean bottom pressure recorders (OBPR) as well as an onshore GPS network in 2013. The four OBPRs were deployed for over one year, from March 2013 to May 2014. Data from only two OBPRs are available as the other two instruments had trouble with their data loggers. One of the available OBPRs was installed on the incoming Pacific Plate near the trench. The other was installed approximately 40 km away from the trench on the Australian Plate, landward of the Hikurangi Trough, approximately 6 km above the plate interface. To remove tidal and oceanographic noise from the raw ocean bottom pressure data, we use the incoming plate site as a reference site to remove the oceanographic noise, which is largely common mode over such a small region. The first slow slip event was observed in July 2013, and produced up to 2 cm eastward displacement at onshore GPS sites over a period of 2-3 weeks. Crustal deformation observed by the OBPRs involved 16 mm of uplift during the slow slip event observed by the cGPS sites, followed by a subsequent subsidence over the following weeks. This suggests that the slow slip event initiated beneath the coastline and the rupture propagated seaward over ~3 weeks. We expect that large slip probably occurred near the trench in the later stages of the slow slip event. A second slow slip event was observed at onshore cGPS and the landward seafloor bottom pressure recorder in October 2013. The October SSE produced 36 mm total uplift at the OBPR. This suggests that in the offshore region, most of the slow slip in the October 2013 event was focused beneath the OBPR, and did not migrate trenchward significantly. Our results demonstrate the value of seafloor pressure observations to investigate slow slip events at offshore subduction margins.

Pore pressure distribution of a mega-splay fault and seaward plate boundary decollement in the Nankai Trough subduction zone: Up-dip extent of the seismogenic zone?

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We use the pore pressure distribution predicted from a waveform tomography (WT) velocity model to interpret the evolution of the mega-splay fault system in the Nankai Trough (Tsuji et al., 2014a). To map pore pressure around the mega-splay fault and trenchward décollement, we integrate the high-resolution WT velocities with laboratory data and borehole well log data using rock physics theory. The predicted pore pressure distribution shows that high pore pressures along the footwall of the mega-splay fault extend seaward to the trough region, and the normalized pore pressure ratio is nearly constant over that extent. This continuity of the overpressured zone indicates that a coseismic rupture can potentially propagate nearly to the trough axis. The pore pressure is highest in the transition zone (~30 km from the trough axis) and slightly decreases landward. The region of the highest pore pressure ratio almost coincides with the hypocenters of the very low frequency earthquakes (Ito and Obara, 2006; Sugioka et al., 2012).

We interpret a high-pressure belt within an accretionary wedge on the landward side of the present mega-splay fault as evidence of the ancient mega-splay fault. Because the ancient mega-splay fault soles into the active mega-splay fault, the active mega-splay fault may function as a basal detachment fault and is directly connected to the seaward plate boundary décollement. Furthermore, our recent study (Tsuji et al., 2014b) demonstrates that a large part of the trench-parallel component of oblique plate subduction is released by strike-slip motion along a fault located just landward of, and merging down dip with, the mega-splay fault. The strike-slip fault located at the boundary between inner and outer wedges is one of key structures controlling the stress state (including pore pressure) within the accretionary prism.

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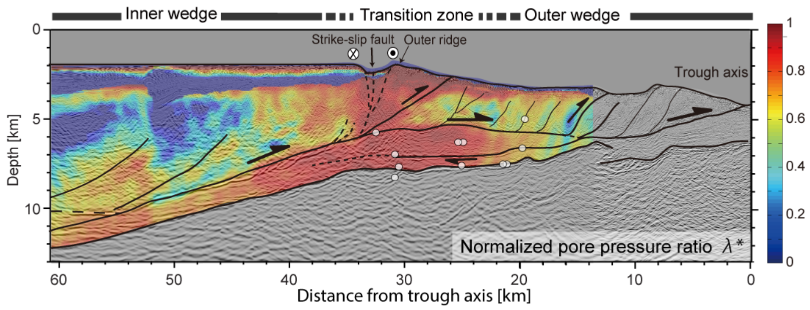

Figure 1. Normalized pore pressure ratio with geological interpretation (Tsuji et al., 2014a). White dots indicate the hypocenters of very low frequency earthquakes (Sugioka et al., 2012).

Geological signature of slow slip in on-land accretionary complex using vitrinite reflectance

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Generation of friction heat associated with fault slip is controlled by friction, slip distance and fault thickness. Nature of fault slip can be estimated from the record of frictional heating along a fault (e.g., Fulton et al., 2012). Purpose of this study is to detect the record of frictional heating along a microfault observed in on-land accretionary complex, Shimanto Belt, SW Japan using vitrinite reflectance (Ro) and to examine the characteristics of fault slip in deeper subduction zone.

The study area is located in Nonokawa formation, the Cretaceous Shimanto Belt, in Kochi Prefecture, Southwest Japan. We found a carbonaceous material concentrated layer (CMCL) in the formation. The thickness of CMCL is about 3-4m.Some micro-faults cut the layer. Ro of host rock is about 0.98-1.1% and of fault rock is over 1.2%. Distribution of Ro is mapped in thin sections to make the Ro-distance pattern perpendicular to the fault plane. Within the fracture zone, abnormally high Ro (about 2.0% or above) was observed. Ro was 1.25% at the wall of fracture zone and decreases to 1.1% at about 5cm from the wall. We interpreted that the Ro-distance pattern was resulted from the thermal diffusion.

Using this diffusion pattern, the characteristic fault parameters, Q (= friction times slip rate) and rise time (Tr), was examined. We have simulated frictional heating and Ro maturation on the basis of the method by Sweeny and Burnham (1990). Grid search was conducted to find the best fitted combination of Q and Tr at the smallest residual between simulated Ro and observed Ro. In the result, we estimated about 1500 (Pa m/s) of Q and about 130000(s) of Tr.

Because the base temperature is about 185˚C based on the 1.1% of Ro, the depth of fault activity can be corresponded to about 6 km. The effective pressure is estimated about 94MPa. If we put friction coefficient as 0.4-0.6, the friction is about 37.6-56.5MPa. Therefore, slip rate is calculated to be about 27-40μm/s. The very slow slip rate is consistent with that for very low frequency earthquake (VLFe) reported by Sugioka et al. (2012).

Intense seismic activity associated with slow slip in the Central Ecuador subduction zone

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Slow slip events (SSE) are more often associated with non-volcanic tremors than with classical earthquakes. We document here deformation episodes where abundant seismicity has been triggered by SSEs. We mainly focus on a one week long slow-slip event (SSE), with an equivalent moment magnitude of 6.0-6.3, which occurred in August 2010 below La Plata Island (Ecuador), south of the rupture area of the Mw=8.8 1906 megathrust earthquake. GPS data reveal that the SSE occurred at a depth of about 10km, within the downdip part of a shallow (<15km), isolated, locked patch along the subduction interface. The availability of both broad-band seismometer and continuous geodetic station located at the La Plata Island, 10km above the SSE, enables a careful analysis of the relationships between slow and rapid processes of stress release along the subduction interface. During the slow slip sequence, the seismic data shows a sharp increase of the local seismicity, with more than 650 earthquakes detected, among which 50 have a moment magnitude between 1.8 and 4.1. However, the cumulative moment released through earthquakes accounts at most for 0.2% of the total moment release estimated from GPS displacements. Most of the largest earthquakes are located along or very close to the subduction interface with focal mechanism consistent with the relative plate motion. These largest events appear to occur randomly during the slow slip sequence, which further evidence that the seismicity is driven by the stress fluctuations related to aseismic slip. A large part of the seismic events observed during the SSE is organized into families of repeating earthquakes, which may indicate a progressive rupture within small locked patches.

During this episode, no other type of seismic signals (for example tremor-like) has been detected. If these other mechanisms exist, they have a small amplitude compared to the triggered seismicity. Another episode of slow and rapid deformation in January 2013 confirms that SSE and seismicity are intimately related in this area. These findings offer an *a posteriori* interpretation of the seismogenesis in the Central-Ecuador subduction zone, where intense seismic swarms have been regularly observed (1977, 1998, 2002, 2005). These swarms have likely been triggered by large magnitude slow-slip events. Spatially, the extent of the North Andean subduction zone affected by this mixed behavior is under study. First clues coming from an SSE in Northern Ecuador in late 2013 indicate that the seismic triggering potential of SSEs is not limited to the La Plata Island area.

Multiple slow-slip events during a foreshock sequence of the 2014 Iquique, Chile Mw 8.1 earthquake

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Abstract

The 1 April 2014 Iquique, Chile Mw 8.1 earthquake occurred at 23:46(UTC) along a mega-thrust fault off northernmost Chile, where the Nazca plate is subducting beneath the South America plate at a convergence rate of ~8 cm/year. Northernmost Chile has been quiescent for 136 years since the 1877 M 8.6 earthquake, resulting in a current “North Chile seismic gap” stretching for ~450 km length along the strike of the plate boundary. According to the US Geological Survey (USGS) catalog, the mainshock was preceded by intensive foreshock sequence lasting around 15 days. To obtain a precise record of the foreshock sequence before the 2014 Iquique, Chile Mw 8.1 earthquake, we applied a matched-filter technique to continuous seismograms recorded near the source region. We newly detected about 10 times the number of seismic events listed in the routinely constructed earthquake catalog, and identified multiple sequences of earthquake migrations at speeds of 2–10 km/day, both along-strike and down-dip on the fault plane, up-dip of the mainshock area. In addition, we found out repeating earthquakes from the newly detected events, likely indicating aseismic slip along the plate boundary fault during the foreshock sequence. These observations suggest the occurrence of multiple slow-slip events up-dip of the mainshock area. The final slow-slip event, which had the fastest migration speed, migrated toward the mainshock nucleation point. We interpret that several parts of the plate boundary fault perhaps experienced slow slip, causing stress loading on the prospective largest slip patch of the mainshock rupture.

Reference: Kato, A., and S. Nakagawa (2014), Multiple slow-slip events during a foreshock sequence of the 2014 Iquique, Chile Mw 8.1 earthquake, *Geophys. Res. Lett.*, 41, doi:10.1002/2014GL061138.

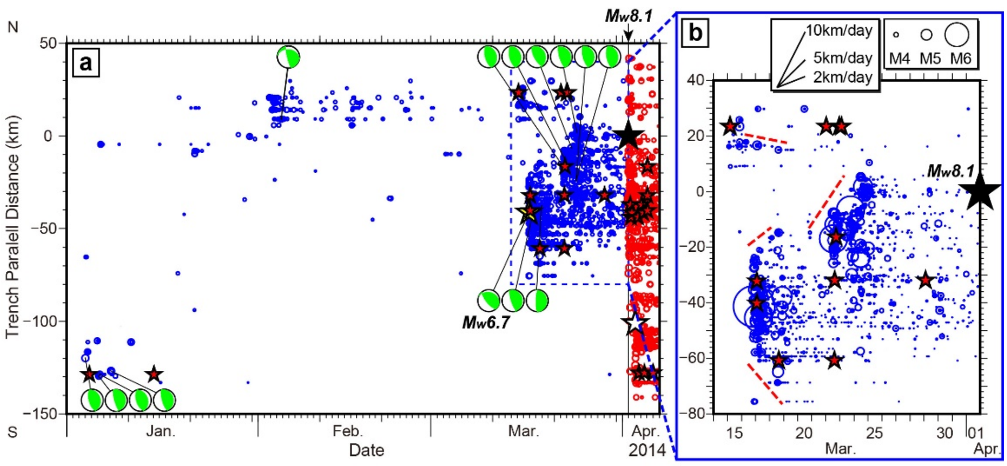

Fig. 1. (a) Space-time diagram of all the detected events before and after the 2014 Iquique, Chile Mw 8.1 earthquake. The blue and red circles denote the foreshocks and aftershocks, respectively. The red stars indicate the repeating earthquakes. The diagram shows the earthquake origin times and locations projected onto the strike of the fault plane. The black, yellow, and white stars denote the hypocenters of the Mw 8.1 main shock, the largest Mw 6.7 foreshock, and the largest aftershock Mw 7.7, respectively. Focal mechanisms (from the USGS) are plotted as green beach balls. hile all available focal mechanisms are used from January to February, only focal mechanisms withMw>5.0 are selected from1-March until the main shock origin. (b) Enlargement of Figure 4a showing the intensive foreshocks between 14 March and 1 April 2014 (blue circles scaled to magnitude). The red dashed lines represent the approximate locations of the fronts of earthquake migrations.

Title:
Insights into the mechanism of fault creep from geodetic observations and earthquake-cycle simulations

Author:
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Abstract:
Studies of interseismic strain accumulation on major active faults are critical for our understanding of fault mechanics. Based on rate-and-state friction formulations, opposing views of friction properties at shallow depths (< 2– 3 km) have emerged. Friction properties at shallow depths are commonly considered to be velocity strengthening, based on laboratory experiments, the occurrence of afterslip following large earthquakes, and the deficit of seismicity at shallow depths. On the other hand, a majority of active faults appear to be locked near the Earth surface, implying that friction properties are mostly velocity weakening. In this work, we investigate interseismic deformation and shallow fault creep using high-resolution geodetic observations and earthquake-cycle simulations. We show that dynamic models that incorporate rate-and-state friction combined with geodetic observations of interseismic deformation can be used to infer in situ rate-state parameters of uppermost crust. Our results suggest that the friction properties of creeping fault segments are mostly velocity strengthening, whereas locked fault segments are characterized by mostly velocity-weakening conditions at shallow depths, although portions of a given fault can slip both seismically and aseismically. On the creeping segment of well-studied faults (e.g., the Superstition Hills fault), observed episodic creep events are thought to arise from smaller-scale heterogeneities of friction properties at shallow depths. Numerical models suggest that the amount of slip on the fault and the duration of a creep event depend on the thickness, stress and friction properties of the shallow, smaller-scale velocity-weakening layer. Such frictional heterogeneity may also be the mechanism responsible for slow slip events in subduction zones.

Slow to Fast Earthquake Transition Introduced by Fault Heterogeneity

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Geological studies of exhumed faults and seismological observations reveal interesting aspects of fault heterogeneity. We thus carried numerical studies to explore the implications of fault heterogeneity on the organization of seismicity and transient aseismic slip. Our quasi-dynamic, continuum models are based on laboratory derived rate-and-state friction with heterogeneity introduced by spatial distributions of characteristic slip distance (Dc), and mixed rheology of velocity-weakening (VW) and velocity-strengthening (VS) materials with various frictional properties. In the first model of pure VW material, our systematic study shows that by varying the distribution of Dc value, we are able to reproduce a wide variety of macroscopic fault behaviors ranging from characteristic seismic events to steady-slip. For different combinations of minimum and maximum Dc values on a fault we simulated multiple earthquake cycles with a total duration long enough to characterize the general behavior of the fault: characteristic (regularly repeating events that break the whole fault), non-characteristic (events with a range of magnitudes, in some cases with a complex but repeating pattern), aseismic transients and steady slip. We found that non-characteristic seismicity behavior occurs only over a relatively narrow range of Dc distributions. We extended our study in this regime and observed complex sequences of seismic events ranging over two orders of magnitude of seismic moments. We generated a synthetic catalog containing over 10,000 events and studied their source scaling relations. The catalog shows a transition in the moment magnitude (M0) - rupture area (A) scaling, from M0~A3/2 at low magnitudes to M0~A at large magnitudes, controlled by the effect of the finite seismogenic depth. Our modeling provides promising insight on the connections between the microscopic properties of the heterogeneous fault and the macroscopic behavior of the fault. The transition from seismic to aseismic events and steady-slip in these models may shed light on the transient behaviors of faults.
In the second model of mixed VW and VS materials, we find that the (b-a)*sigma value (effectively the frictional properties and pore pressure) of the VW fault portions determine the criticalness of the whole fault (i.e. its ability to produce spontaneous transient events). A combined analytical and numerical study of fault criticalness as a function of density of VW material and contrast of (b-a)*sigma values reveals subcritical-to-supercritical transitions both with increasing criticalness of the individual VW patches and, less trivially, by increasing the (b-a)*sigma value of the VW patches. Higher effective normal stress of the VW portions can bring the whole fault to a supercritical state even if the VW patches are individually subcritical. We are able to reproduce a rich family of fast and slow events using that mixed rheology model, from Slow Slip events and complicated tremor migration patterns in Cascadia, to the interesting earthquake swarms and patterns in the recent Pisagua earthquake in Chile.

Why do slow earthquakes occur favorably in hot subduction zones?

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It is puzzling why slow earthquakes occur in hot subduction zones only, between 30 and 50 km depth. We study numerically how antigorite dehydration coupled with slip-induced dilatancy and thermal pressurization affects rupture behavior to solve the above puzzle. Recent observational and laboratory studies actually suggest importance of antigorite dehydration. In fact, between 30 and 50 km depth, tomographic images indicate the existence of high fluid pressures, while shear wave splitting studies are compatible with the presence of serpentine minerals in the subduction channel. In hot subduction zones, antigorite (main serpentine mineral constituent) dehydration will occur between 30 and 50km depth. This coincidence in location suggests that antigorite dehydration reaction plays an important role in the generation of slow earthquakes.

We assume shear rupture in a 2D thermoporoelastic medium. The mineral reaction is assumed using a first order Arrhenius law. Nondimensional parameters important in the modeling are Su, Su’ and χ’ according to our former study; Su’ and Su are proportional to permeability and increase rate of slip-induced porosity, respectively. The parameter χ’ denotes volume change induced by the reaction; χ' is negative if void space created by the reaction is larger than the space occupied by the fluid released by the reaction. In hot subduction zone environment, antigorite dehydration involves a complex two stage reaction process. The second stage, on which we focus, is characterized by a range $-0.1<\chi'<0$ according to the slope of Clapeyron curve and geothermal gradient. On the other hand, cold subduction zones will be characterized by slightly negative values of χ’.

Our calculation shows that moment release rate and fault tip growth rate are smaller for larger values of Su, smaller values of χ’ or smaller values of Su’. These two rates are found to be negligibly small compared with the solutions for the dynamic elasticity analysis when $Su>1$ and $\chi'<0$ are satisfied. The parameter space in which slow sustained slip is simulated is found to be broader for smaller values of χ’. This suggests that $Su>1$ and $\chi'<0$ are satisfied at locations where slow earthquakes occur in hot subduction zones; the condition $\chi'<0$ is consistent with the slope of Clapeyron slope.

Our calculation also shows that rupture growth rate accelerates to the shear wave speed soon after its nucleation for any values of χ’ when $Su\sim0$ is assumed. The moment release rates for negative values of χ’ and for $Su\sim0$ are found to be a few orders smaller than expected by the dynamic elasticity analysis. This occurs because the slip velocity evolution is highly pulse-like. In such way, antigorite dehydration could also be the source of a non-negligible fraction of intermediate depth seismicity. Our study suggests that the condition Su~0 will be satisfied at cold subduction zones because slip-dilatancy is more prohibited at larger depth.

Abstract for Workshop on "Slow Earthquakes" at Kyoto University, Sept 8-10, 2014

3D Dynamic Rupture Simulations of a Megathrust fault with a Subducted Seamount

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Subducted seamounts increase the normal stress across the subduction interface. The increased normal stress results in high frictional strength patches associated with subduction seamounts on megathrust faults, which may act as barriers to coseismic ruptures and thus may limit extents of frequently occurring large earthquakes of magnitude 7~8. However, large shear stress also likely accumulates on these high frictional strength patches due to both a long period of tectonic loading and terminations of previous magnitude 7~8 earthquake ruptures at seamounts. When the shear stress accumulation on a subducted seamount (or a subducted seamount chain) finally approaches the frictional strength across the seamount, a giant megathrust earthquake with ~Mw 9 that breaks the seamount and surrounding large areas can occur. This may what had happened along the portion of the Japan Trench that accommodates the 2011 Mw 9.0 Tohoku earthquake rupture.

We use a finite element method code (EQdyna) to perform spontaneous dynamic rupture modeling of a megathrust fault with a subducted seamount in a 3D half-space to examine the above hypothesis of controls on the 2011 Tohoku earthquake. The 3D subducted seamount geometry is built in the finite element mesh. The code has been verified in a community-wide effort, the SCEC/USGS dynamic code validation exercise (http://scecdata.usc.edu/cvws/), on many benchmark problems, including a recent benchmark problem of a vertical strike-slip fault with two bumps. The code has also been under parallelization using a hybrid MPI/OpenMP approach, so that we can simulate large earthquake ruptures at reasonably fine spatial and temporal resolutions to gain physical insights into recent large earthquakes. We will present our preliminary results on this work.

A shallow subducted seamount near a trench in a relatively low rigidity material may locally increase the interface coupling, resulting in slow rupture propagation and relatively large slip associated with the subducted seamount. The slow rupture and large shallow slip are efficient in generating tsunami. This may what had happened at the southeast end of the 1992 Nicaragua Mw 7.7 slow earthquake. We also plan to explore this topic using 3D dynamic rupture modeling.

Numerical simulation of long- and short-term slow slip events in the Nankai subduction zone

Takanori Matsuzawa (*National Research Institute for Earth Science and Disaster Prevention*), Bunichiro Shibazaki (*Building Research Institute*), Kazushige Obara (*Earthquake Research Institute, University of Tokyo*), and Hitoshi Hirose (*Research Center for Urban Safety and Security, Kobe University)*

We numerically simulate slow slip events (SSEs) in the Nankai subduction zone, considering the distribution of tremor and the configuration of subducting plate. As short-term SSEs are accompanied by tremor, short-term SSEs and tremor are sometimes called as episodic tremor and slip (ETS). Occurrence of ETS is more episodic at the shallower part of the ETS region (e.g., Wech and Creager, 2011; Obara et al. 2011). Long-term SSEs occur on the plate interface between the ETS region and the interseismic locked region of megathrust earthquakes, and are found in the Bungo channel and the Tokai region. Recently, Kobayashi (2012) has reported that a long-term SSE also occurred in the Kochi region. The recurrence of long-term SSE in the Kochi region is still not clear, while long-term SSEs in the Bungo channel recur at the intervals of 6-7 years. In this study, these two types of long-term SSEs and short-term SSEs in the Shikoku region are reproduced within a single numerical model.

In our simulation, a rate- and state-dependent friction law (RS-law) with cut-off velocities is adopted. We assume low effective normal stress and negative (a-b) value in the RS-law at the short-term SSE region which is based on the actual distribution of tremor. We also assume that |a-b| value in the short-term SSE region decreases with depth. In the long-term SSE region of the Bungo channel, effective stress is assumed to be lower than those in the surrounding region. We model the configuration of plate interface by triangular elements based on Baba et al. (2006), and Shiomi et al. (2008).

Our numerical model reproduces recurrences of short-term SSEs and the segments. Slip of short-term SSEs is more episodic in the shallower part of the short-term SSE region, as found in the actual ETS. Long-term SSEs in the Shikoku region recur at the interval of several years. Moreover, long-term SSEs in the Kochi region are also reproduced and recur in a seismic cycle. The recurrence intervals of the SSEs in Kochi are long and widely fluctuated intervals, in contrast to the long-term SSEs in the Bungo channel. This suggests that the long-term SSEs in the Bungo channel may be characterized by the low effective normal stress (otherwise, small |a-b| value). Our numerical model comprehensively explains the characteristics of short- and long-term SSEs including the newly found long-term SSEs in the Kochi region.

Theoretical relationship between tremor migration patterns and rheology on heterogeneous faults

Ryosuke Ando

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Episodic tremor and slip (ETS) events repeating at roughly annual intervals propagate over 100 km at low velocities, about 10 km d^{-1} on average, along the brittle–ductile transition zones of plate interfaces. These events also entail various fine-scale tremor phenomena, including different emergent activities and diffusional or somewhat parabolic migration, but the underlying physics is poorly understood. Here we show that these phenomena and other characteristics provide major clues to the basic physics of slow earthquakes and are, like ordinary earthquakes, inevitable consequences of a rupture process controlled by persistent structures of heterogeneous brittle and ductile fault properties. By physically modelling the migration patterns of slow earthquakes, we found that the migration is controlled by so called stress diffusion emerging from the ductility of fault zones. Further, the migration patterns inherently relate to the types of rheology such as the Newtonian, the power laws or logarithmic dependence on the slip rates (Ando *et al.*, 2012).

Fig. 1 shows how the shear stress diffuses in time and space on a 2-D fault obeying ductile rheology or velocity strengthening constitutive laws. For a simplicity purpose, a point source of stress concentration is assumed at the location *X*=0 and time *T*=0. The fault rheology is assumed in the forms of $\tau \propto v^m$ common in plastic flows, and $\tau \propto \log v$ known for friction, where τ and *v* denotes the strength of the fault and the slip velocity. Fig. 1a-c shows the power law viscosity cases with *m*=0.5, 1 and 2. The diffusion fronts exhibit the unique power law curves depending on the values of *m*. Fig. 2 shows the compilation result of the exponent of these curves *k* plotted as a function of *m*, confirming the systematic changes following this dependency.

This theoretical result implies the possibility of distinguishing the fault rheology types by analysing the migration patterns of small scale events such as tremors during slow slip events as well as aftershocks associated with after-slip events. It will be worth comparing the results obtained by other technique using the tidal responses of the occurrence numbers of tremor and low frequency earthquakes (Beeler *et al.*, 2013).

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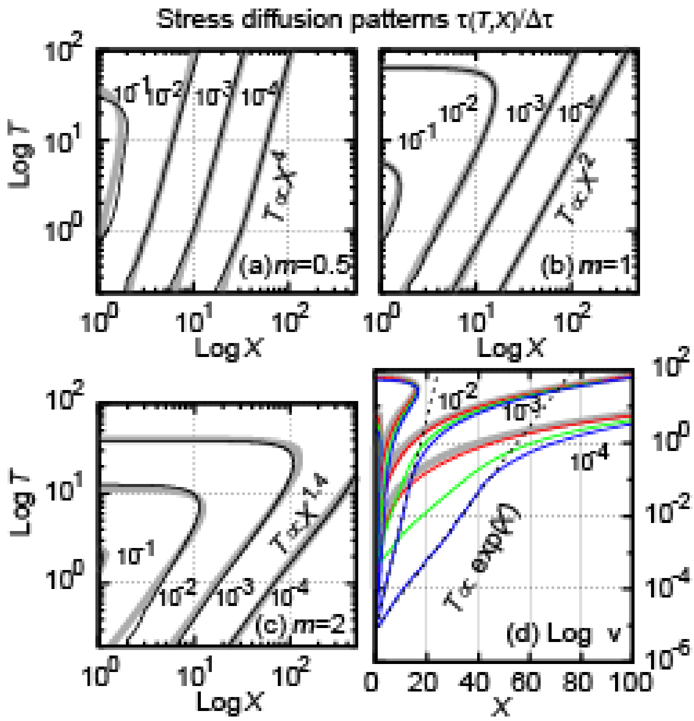

Figure 1. Space-time plot of shear stress. (a)-(c) the cases of the power low velocity strengthening $\tau \propto v^m$. (d) the case of the logarithmic velocity strengthening $\tau \propto \log v$. The power law and exponential functions of time *T* and distance *X* fitted to diffusion fronts are indicated in each panel. Modified after Ando *et al.* (2012).

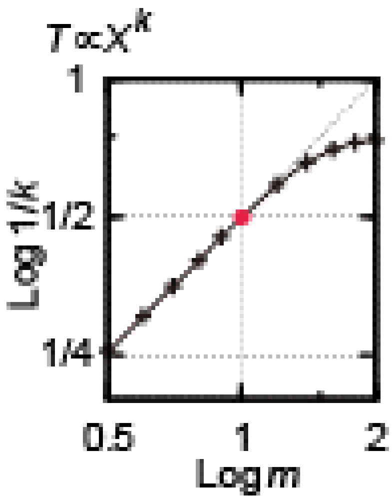

Figure 2. Relationship between power law exponents of velocity strengthening rheology *m* and diffusion fronts *k* Modified after Ando *et al.* (2012).

Slip inversion for deep tremor

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Recent studies have shown that deep tectonic tremor in many subduction zones consist of numerous low-frequency earthquakes (LFEs) that occur as shear slips on the plate interface. The hypocenter locations of LFEs are determined relatively accurately, and in western Japan, they are concentrated in a narrow zone around the anticipated plate interface [Ohta and Ide, 2011]. Therefore, the location of LFEs may constrain the instantaneous location of tremor sources and illustrate its migration behavior, as demonstrated by a matched filter analysis with template LFEs [Shelly et al., 2007]. Such migration of tremor sources indicates close association between tremor and larger scale slip on the plate interface.

The information of detailed rupture process of slip associated with tremor is useful for understanding the physics of tremor and other slow earthquakes, yet an ordinary slip inversion analysis using full waveform is not available due to inadequate knowledge of Green's functions. Here we study the detailed spatio-temporal behavior of tremor in western Japan, by developing and applying a new slip inversion method. In the method, we introduce the "synthetic template waveforms" as typical waveforms of tremor sources on the plate interface by stacking the seismograms of the LFEs at arranged points on the interface. Using the synthetic template waveforms as substitutes of Green's functions, we invert continuous tremor waveforms by iterative deconvolution method with a Bayesian constraint.

The method is applied to a tremor burst episode for 12 days in the western Shikoku and for 1 day in the central Shikoku region which contains known VLF events. The resultant slip distribution shows a patchy structure and relatively rapid moment releases with durations less than 100 s occur on some patchy regions on the fault. These spatially and temporally heterogeneous slip patterns may be associated with the heterogeneities of material properties on the plate interface. The source size of VLFs in the central Shikoku approximated by slip distribution of tremor, ~5 km in radius, is much larger than the size of patchy slip region of tremor in the western Shikoku. Such difference in source size might possibly control the occurrence of (observable) VLF events.

Seismic wave radiation energy of deep low-frequency tremor in the Nankai subduction zone

S. Annoura, K. Obara and T. Maeda (ERI, the University of Tokyo)

We propose a method for estimating seismic wave energy radiated from deep low-frequency tremor in the Nankai subduction zone, southwestern Japan. Tremor is commonly detected associated with slow slip event on the subducting plate interface at the downdip part of the megathrust seismogenic zone. Spatio-temporal distribution of tremor has been well investigated to get a general feature of tremor activity. However, more detailed characteristics may be revealed by estimating tremor energy through densely observed seismic traces, which considerably contribute for understandings of megathrust earthquakes.

To estimate total tremor energy as accurate as possible, we first measured time duration segment of tremor by systematic multi-station analysis. The tremor element was located every one minute by using the envelope correlation method and the duration segment was searched around each origin time of the tremor element. The duration with amplitude simultaneously higher than the noise level at some stations was extracted. If the duration continued longer than two hours, it was separated. Then one or two source location was determined by applying clustering process to each duration segment using hypocenters of tremor elements. Finally, we estimated tremor energy for each duration segment.

By analyzing continuous seismograms at western Shikoku area in southwestern Japan for 1 year in 2012, we obtained characteristic spatial distribution of tremor energy. Larger energy was concentrated with a length of about 20km at the updip part of tremor zone. It has been already known that there are two peaks of the number of tremor along the dip direction. The spatial distribution of energy of tremor is different with that of the number of tremor. Concentrated energy at the updip part suggests that the updip part is relatively more brittle in the brittle-ductile transition zone.

Ice sheet dynamics and glacial earthquake activities in Greenland

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The Greenland ice sheet and its response to climate change have potentially a great impact upon mankind, both through sea-level rise and modulation of fresh water input to the oceans. Monitoring a dynamic response of the Greenland ice sheet to climate change is a fundamental component of long-term observations in global science. “Glacial earthquakes” have been observed along the edges of Greenland with strong seasonality and increasing frequency in this 21st century by the data from Global Seismographic Network (GSN). During the period of 1993-2006, more than 200 glacial earthquakes were detected, but more than 95% have occurred on Greenland, with the remaining events in Antarctica. Greenland glacial earthquakes are considered to be closely associated with major outlet glaciers at the margins of the continental ice sheet. Temporal patterns of these earthquakes indicate a clear seasonal change and a significant increase in frequency after 2002. These patterns are positively correlated with seasonal hydrologic variations, significantly increased flow speeds, calving-front retreat, and thinning at many outlet glaciers. These long-period surface waves generated by glacial earthquakes are incompatible with standard earthquake models for tectonic stress release, but the amplitude and phase of the radiated waves can be explained by a landslide source model. The seismicity around Greenland including tectonic/volcanic events was investigated by applying a statistical model to the globally accumulated data. Calculated b values, the Magnitude-frequency-dependence parameter, indicated a slight increase from 0.7 to 0.8 in 1968-2007, implying that the seismicity including glacial events around Greenland become slightly higher during the last four decades. The detection, enumeration, and characterization of smaller glacial earthquakes were limited by the propagation distance to globally distributed stations of the GSN. Glacial earthquakes have been observed at stations within Greenland, but the coverage has been very sparse. In order to define the fine structure and detailed mechanisms of glacial earthquakes, a broadband, real-time network needs to be established throughout the ice sheet and perimeter. The International Polar Year (IPY 2007-2008) was a good opportunity to initiate the program with international collaboration. Then, the “Greenland Ice Sheet Monitoring Network (GLISN)” was initiated for the purpose of identifying the dynamic response of the Greenland ice sheet to climate change.

Assessing volcanic hazards from future eruptions of Chabbi volcano, Central Main Ethiopian Rift, Ethiopia.

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Abstract

Chabbi Quaternary volcano is located on the Wonji Fault Belt or magmatic segment of the Main Ethiopian Rift (MER) where active extensional tectonics and volcanism is taking place. Particularly, it is found in the southern part of the MER between Lake Shalla to the north and Lake Hawassa within Corbetti caldera to the south. From field observation, previous work, satellite image and GIS and Remote sensing incorporation, the volcanic evolution and current activity of Chabbi has been interpreted. It has been established that Chabbi is a composite rhyolite volcano built during the Holocene. The eruption sequence of this volcano consists of rhyolitic lavas and domes, at the base followed by explosive eruptive products in the intermediate and degassed obsidian flows in the final phase. The volcano has emitted very young products in recent geological times and is currently at fumarolic stage.

Since Chabbi volcano currently shows vigorous fumarolic activity, its potential future eruptions may poses a significant volcanic hazard to a large population, important infrastructures and booming economic activity.

An assessment of the potential volcanic hazard from its future eruptions has been attempted based on the volcano’s past eruptive behavior and probable future scenarios. Tentative volcanic hazard maps and zones have been attempted in GIS environment considering eruption scenarios from six identified vents affecting an area over a moderate distance of 15km radius.

Modeling and Observations of Deep Volcanic Long-Period Earthquakes

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Deep long-period events (DLP events) or deep low-frequency earthquakes (deep LFEs) are deep small earthquakes that radiate low-frequency seismic waves. While deep tectonic LFEs on plate boundaries are thought to be slip events, the physical mechanism of volcanic DLP events around the Moho beneath volcanoes is not well understood. For initial brittle failure to be produced at these temperature-pressure conditions, high strain rates should exist there. Since an ascending magma diapir tends to stagnate near the Moho, where there is a density discontinuity, we suspect its thermal contraction acts as a driving force of volcanic DLP events.

We calculated thermal evolution after an initial perturbation of 400K uniformly within planar and cylindrical magma intrusions. Then, we estimated thermal strain rates within the region of $\delta T < 200K$, where the medium can be treated as a Poissonian elastic body. As a result, strain rates larger than the effect of tectonic loading ($>5\times10^{-14}$/s) is observed for tabular magmas of width of <200m and cylindrical magmas of radius of <160m. Assuming that magma shape and strain rate correspond to source distribution and source mechanism of DLP events, respectively, we expect a correlation between source distribution and source mechanism for volcanic DLP events. Both event relocations and mechanism analyses are needed to verify this model.

Waveform inversions of focal mechanisms are not straightforward for volcanic DLP events because they have generally oscillating waveforms and it is difficult to select common phases among stations, components, and phases (P- and S-waves). In the present study, we first obtain the source function by stacking waveforms of all stations, components, and phases. Then, we fit the waveforms of all components and phases at each station by the source function to maximize their cross-correlations. In this process, we utilize the orthogonality of P- and S-waves, which is not considered previously but would stabilize the results. In this talk, we show some preliminary results of this technique to select common phases toward future mechanism analyses.