Japan Geoscience Union Meeting 2013
(May 19-24 2013 at Makuhari, Chiba, Japan)

SSS01-P01 会場:コンベンションホール 時間:5 月 19 日 18:15-19:30

日本海溝近傍のプレート境界断層浅部の透水性構造
Fluid transport property of sediments near the plate boundary fault at Japan Trench

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2011 年の東北沖地震（Mw 9.0）では、プレート境界沿い浅部において数十 m にもわたる大きな地震断層すべりが引き起こされた。これまでの地震断層研究では日本海溝沿いや沈み込み帯浅部では、巨大地震は発生しないと考えられていたため、その発生過程に注目が集まった。プレート境界断層の物性評価は、その発生過程を解明するための重要な手がかりとなる。断層帯の物性の中でも流体移動特性は、断層帯内部の流体圧と流体の流れを支配する重要なパラメータである。断層帯とその周囲の岩石の透水係数は、（１）地震断層すべりに伴い Thermal pressurization が有効に働いたのか、（２）堆積物の沈み込みに伴う粘土鉱物などの脱水反応により高間隙水圧場が発達していたのか、を評価するための重要な物性値である。また、浅部で大変位すべりが誘発された原因を検討するうえで上記二つの評価は重要な事項となる。そこで本研究では、IODP 第 343 次研究航海（JFAST）において採取された浅部断層帯近傍のコア試料を用いて水理特性の測定を行った。実験ではプレート境界浅部の断層上盤側の泥岩（岩石層序区分 Unit4、714mbsf, 785mbsf）を用いた。透水係数と間隙率は封圧 0〜30MPa、間隙圧 0.2〜0.8MPa、室温環境下で測定を行った。透水係数は定差圧流量法により評価し、間隙水は塩化ナトリウム溶液（35 ‰）と蒸留水を用いた。

713mbsf 試料は初期圧（1MPa）には透水係数と間隙率はそれぞれ $3*10^{-17}$ m^2 と 43%を示したのに対し、有効圧の増加とともに両物性とも減少し、有効圧 10MPa では $2*10^{-18}$ m^2 と 30%まで減少した。また貯留係数は $5*10^{-8}$ から $1*10^{-8}$ Pa^{-1} の範囲を示した。一方、785mbsf 試料は初期圧で $7*10^{-17}$ m^2 と 40%を示し、有効圧 10MPa では $5*10^{-18}$ m^2 と 31%を示した。また、いずれの試料も透水係数は間隙率の減少に対し指数関数的に減少する傾向が認められた。コア試料の深度に相当する透水係数は 10^{-17} m^2 から 10^{-18} m^2 の比較的低い値を示すことから、プレート境界浅部で（１）と（２）のプロセスが起こる可能性を示唆する。ただし、より詳細な検討を行うためには、プレート境界断層の摩擦係数や広域的な温度構造の情報とせん断変形に伴う水理特性の変化を評価する必要がある。

キーワード: 透水係数, JFAST, 東北沖地震, IODP Expedition 343
Keywords: permeability, JFAST, Tohoku Earthquake, IODP Expedition 343

Japan Geoscience Union Meeting 2013
(May 19-24 2013 at Makuhari, Chiba, Japan)

SSS01-P02 会場:コンベンションホール 時間:5 月 19 日 18:15-19:30

海陸自然地震観測による 2011 東北地震震源域周辺の構造不均質
Structural heterogeneities around the shallow megathrust zone of the 2011 Tohoku earthquake

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The coseismic rupture area of the 2011 Tohoku Earthquake has estimated over the wide region from the coastline to near the Japan Trench. Several kinds of studies, such as tsunami source inversion [e.g., Fujii et al., 2011], coseismic slip inversion [e.g., Ide et al., 2011], submarine topography change [Fujiwara et al., 2011] and seafloor displacement observation [Sato et al., 2011; Ito et al., 2011; Kido et al., 2011], share the common feature that the largest coseismic slip occurred at the shallow plate boundary in close vicinity to the Japan Trench. However, the structural image just beneath the largest coseismic slip area was unclear since the observation areas of previous ocean bottom seismographs (OBSs) in this region were limited and there were few OBSs near the Japan Trench [e.g., Yamamoto et al., 2011]. To understand the relationship between coseismic rupture behavior and structural heterogeneities, it is necessary to know the seismic velocity structure of the subducted slab crust and mantle near the trench axis.

After the occurrence of 2011 earthquake, some National Universities (Hokkaido, Tohoku, Chiba, Tokyo, Kyushu, and Kagoshima), JAMSTEC, and Meteorological Research Institute together have conducted the aftershock observations along the landward slope of Japan Trench to obtain detail hypocenter distribution [Shinohara et al., 2012]. Tohoku University has performed the other OBS observation off Miyagi prefecture from 2010 to 2011. During this observation, a sequence of foreshocks, the mainshock, and aftershocks of the 2011 Tohoku earthquake were recorded [Suzuki et al., 2012]. In addition, JAMSTEC has conducted the aftershock observation at outer slope of Japan Trench, around the epicenter of a Mw 7.6 earthquake that occurred about 40 minutes after the 2011 mainshock, from May to June [Obana et al., 2012].

In this study, we performed the three-dimensional seismic tomography by combining these OBS dataset and land seismic data to obtain the fine hypocenter distribution and velocity structure around the largest coseismic slip zone of 2011 Tohoku earthquake. From the relocation results, we found that some deep intraslab earthquakes occur near the trench and their focal mechanism are normal fault type. Since these earthquakes occurred before the 2011 mainshock showed thrust type [e.g., Gamage et al., 2009], our results suggest the change of stress regime in this region. In the outer-rise area, the hypocenter distribution of the relocated shallow earthquakes has a linear trend along the horst-graben structure. Subducted oceanic crust has some heterogeneous structure around the hypocenter of the 2011 mainshock as follows: (1) relatively low Vs and high Vp/Vs zone at landward side of the mainshock location, (2) high Vs and low-Vp/Vs in the south of mainshock. These structural heterogeneities might represent the heterogeneous distribution of fluid in the oceanic crust and/or existence of subducted seamount. In addition, the velocity of uppermost slab mantle from 143 degree E to the trench axis showed low Vp, Vp/Vs (~1.70) and high Vs (> 5.0 km/s). This feature might reflect the existence of strongly anisotropy in the slab mantle or indicate the locally orthopyroxene enrichment.

This work is supported in part by the Special Coordination Funds for the Promotion of Science and Technology (MEXT, Japan) titled "the integrated research for the 2011 off the Pacific coast of Tohoku earthquake". A part of this study also supported by "Research concerning Interaction between Tokai, Tonankai and Nankai Earthquakes" funded by MEXT, Japan, and the JAMSTEC's rapid response research project for the 2011 Tohoku-oki earthquake.

キーワード: 東北地方太平洋沖地震, 地震波トモグラフィー, 海底地震観測, 海洋性地殻
Keywords: Tohoku megathrust earthquake, seismic tomography, ocean bottom seismic observation, oceanic crust

Japan Geoscience Union Meeting 2013
(May 19-24 2013 at Makuhari, Chiba, Japan)

SSS01-P03 会場:コンベンションホール 時間:5 月 19 日 18:15-19:30

Rock-magnetic properties of the plate-boundary thrust material drilled during IODP Expedition 343 (JFAST)

Rock-magnetic properties of the plate-boundary thrust material drilled during IODP Expedition 343 (JFAST)

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During IODP Expedition 343, Japan Trench Fast Drilling Project (JFAST), boreholes were drilled through the prism and across the fault that is thought to have slipped during the 11 March 2011 Tohoku-Oki Earthquake. 74 subsamples of the core recovered from hole C0019E were subjected to rock magnetic analyses to identify magnetic minerals, determine the magnetic-grain size distribution and investigate rock magnetic changes related to fault zone processes.

Magnetic hysteresis curves and backfield DC demagnetization curves of isothermal remanent magnetization were measured using a MicroMag 2900 alternating gradient field magnetometer. Hysteresis parameters (Ms, Mr, Hc, Hcr) were calculated and coercivity spectra were obtained as the derivative of DC demagnetization curves. Thermal demagnetization of low-temperature IRM acquired at 10 K and 5 T after zero-field cooling was performed with an MPMS-XL. Thermomagnetic analyses in 0.4 T and ambient pressure were carried out with a Natsuhara NMB-89 thermobalance.

Samples from the sheared scaly clay zone (Lithologic Unit 4: 820-824 m CSF, inferred to be the plate boundary decollement) clearly have low Hc and Hcr (10-13 and 22-24 mT) compared with the lower part of the frontal prism sediment (Lithologic Unit 3: 688-820 m CSF; Hc = 15-52 mT; Hcr = 45-85 mT) and the brown underthrust sediment (Lithologic Unit 5: 824-832 m CSF; Hc = 13-26 mT; Hcr = 45-85 mT), suggesting a difference in magnetic mineralogy and/or grain size. However, there is no obvious variation in magnetic properties within between the decollement zone.

As for the thermal demagnetization curves of low-temperature IRM, the samples from llithologic Unit 3 show loss of magnetization at ˜120 K, reflecting the Verwey transition of stoichiometric magnetite. In contrast, the samples from the lithologic Units 4-5 do not show significant loss of magnetization at the Verwey transition temperature. For the thermomagnetic curves, the heating branches of some samples from lithologic Unit 3 have humps above ˜400 deg C possibly caused by thermal decomposition of some iron-bearing minerals and formation of magnetic minerals during heating, while the samples from lithologic Units 4-5 do not show any humps on the heating branches. These results imply a difference in magnetic mineralogy between lithologic Units 3 and 4-5 (ie. a difference between hangingwall and fault zone / footwall).

Within Lithologic Unit 4, the lower four samples (822.07-822.48 m CSF) show large magnetization increases in the cooling branches below ˜100 deg C which might reflect the formation of magnetic minerals with low Curie temperatures during heating, compared with the upper four samples (821.54-821.78 m CSF). These samples may correspond to material that generated a peak in the on-board magnetic susceptibility log.

In summary, we found minor magnetic signals at the lower part of the sheared clay zone core sample of fault zone processes resulting from localized variation of magnetic mineralogy within the sheared clay zone samples recovered from the hole C0019E, but the origin and process of the minor magnetic variation should be further examined.

SSS01-P04 会場:コンベンションホール 時間:5 月 19 日 18:15-19:30

Sediment fabric record in the trench axis formed during the 2011 Tohoku-oki earthquake
Sediment fabric record in the trench axis formed during the 2011 Tohoku-oki earthquake

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The rupture of the 2011 Tohoku-oki earthquake propagated to the trench. Kodaira et al., (2012) revealed that the several ten meters scale displacement of the lower landward slope of Japan Trench occurred during the earthquake. Meantime an uplifted seafloor appeared in the trench axis, and the seismic reflection image beneath the trench floor reveals a thrust up structure. These observations are important keys to understand the slip of the 2011 Tohoku-oki earthquake. In order to detail the dynamics of the slip, surface sediments around the trench deposited before and after the earthquake were studied. Surface sediment cores were collected in the upheaval and un-upheaval areas from the trench axis, and the foot of the lower landward slope using piston and gravity cores. Cores from the trench axis consist mainly of coherent hemiplegic layers. On the other side, the sediment cores in the foot of the lower landward slope is characterized by mass-transport deposits and inclined layers of hemipelagite interbeded with silt/sand layers. Anisotropy of magnetic susceptibility (AMS), which is sensitive to soft sediment deformation, was studied to detect the sediment deformation. AMS from the trench axis shows fairly foliated magnetic fabric parallel to bedding planes, and parameters of AMS suggest that no lateral compression is recorded in the surface sediment. Instead, their sediment magnetic fabric in the trench sediment involve information of paleo-current of turbidites. On the other hand, AMS from the foot of lower landward slope is characterized by randomly orientated magnetic fabric indicating chaotic depositions, and inclined magnetic fabric indicating layer tilting downslope. Those fabric patterns in the slope suggest that the surface sequence were slid toward the trench. Preliminary interpretation on those data is that AMS reveal no compressional environment in the seafloor surface but sediment transporting information. If the upheaval structure in the trench axis formed during the earthquake, it should controlled the sedimentation pattern in the trench axis. It is expected that analysis of the sedimentary fabric in the area document such pattern. It will provide an unique information to understand the deformation during the slip in the trench axis. In this presentation, we will present detail properties of sedimentation on the basis of magnetic fabric.
Keywords: the 2011 Tohoku-oki earthquake, Japan Trench, turbidite, mass-transport deposits, Magnetic fabric

Japan Geoscience Union Meeting 2013
(May 19-24 2013 at Makuhari, Chiba, Japan)

SSS01-P05 会場:コンベンションホール 時間:5 月 19 日 18:15-19:30

宮城沖日本海溝軸近傍における地下構造調査
Seismic imaging in the Japan Trench axis area off Miyagi, northeastern Japan

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On March 11, 2011, the M9 great Tohoku megathrust earthquake ruptured the plate boundary at the Japan Trench off eastern Honshu, Japan. Several seismological, geodetic and tsunami wave inversion studies indicate a large magnitude of slip (30-60m) occurred on the shallow portions of the plate boundary. Differential bathymetric and seafloor geodetic studies also document large coseismic displacement near the trench. Thus, it is important to understand the detailed structure of the shallow portion of the subduction zone and the trench axis area of the Japan Trench to evaluate mechanisms of deformation and the geometry of the structures that accommodated shallow slip.

We conducted a high resolution reflection seismic survey in the vicinity of the Japan Trench axis off Tohoku in October-November, 2011. The high-resolution seismic profiles we obtained successfully image the detailed structure around the Japan Trench axis, and were used for site selection of the rapid response drilling program for IODP Expedition 343 (JFAST). We identify four seismic units in the study area: an acoustically transparent frontal wedge (Unit I), a sequence of parallel continuous reflections interpreted as sediments on the incoming plate (Unit II), a sequence of relatively strong reflections correlated to chert recovered in DSDP Site 436 (Unit III), and acoustic basement of the Pacific plate (Unit IV). The incoming Pacific plate sediments, including the basal chert layer (Units II and III), have been offset by normal faulting during plate bending seaward of the trench. Mapping of the relief on the igneous oceanic basement (Unit IV) shows that the trench axis in the survey area is located in a graben. The relief observed on the basement landward of the trench is related to the subduction of horsts and graben formed seaward of the trench. The hemipelagic/pelagic sediments (Unit II) overlying the basal chert layer (Unit III) are imbricated at the trench axis. The detachment surface is located slightly above the top of the chert-rich layer (Unit III) in the trench axis graben. We observe a seaward-dipping reflection branching off the top of the chert-rich layer (Unit III) at the edge of a horst block at the base of the landward trench slope. This reflection short-cuts the horst-graben normal fault, and soles into a horizon slightly above the top of chert-rich layer (Unit III) in the trench graben. This reflection is interpreted as a part of the decollement in the lowermost Japan Trench inner slope, and was likely generated by an increase of the loading and failure of the underthrust hemipelagic/pelagic sediments. The imbricate structure of the graben-fill sediments could have been developed by a combination of aseismic deformation as well as repeated megathrust earthquakes which caused failure and slip along the seaward dipping decollement. These data clearly image structures resulting from deformation and sediment subduction at the Japan Trench in the region that ruptured during the March 11, 2011 great Tohoku earthquake.

In January 2013, we carried out another seismic survey around the JFAST drill site using larger volume of sounding sources, longer streamer cable, and ocean bottom seismographs. Preliminary processed data provide seismic profiles with enhanced quality in the deeper portion. We will also present the velocity model deduced from the analysis of these seismic data.

Keywords: seismic image, Japan Trench, Tohoku earthquake

Japan Geoscience Union Meeting 2013
(May 19-24 2013 at Makuhari, Chiba, Japan)

SSS01-P06 会場:コンベンションホール 時間:5 月 19 日 18:15-19:30

海底 GPS 手法による海底地殻変動観測高度化に向けた新たな取り組み
New approaches to advanced GPS/A geodetic observation on the seafloor

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(1) 短時間観測で測位精度を確保する取り組み
2011 年東北地方太平洋沖地震は海溝軸付近で例外的に大きなすべりを示したが、陸上 GPS 観測ではそこにおけるプレート境界の固着状態を知ることは難しい。そこで我々は文部科学省の委託を受けて共用型の観測点を日本海溝沿いに 20ヶ所設けた。海上保安庁海洋情報部も地震後南海トラフ沿いに 9 点増設している。陸上の高密度の観測網と比べればまだ大きな差はあるが、海底 GPS 観測点が広がったことは画期的なことである。しかし一方で観測点が増えれば観測に要する多くのシップタイムが必要となる。この問題を解決しなければ、南海トラフ軸近くなどにある観測の空白沖を埋めることも難しい。これまでの海底 GPS 観測では 1 観測点における観測に半日から 1 日要していたので、まずはこの観測時間の短縮に取り組む必要がある。
我々はこれまでの観測結果から、海中表層の音速構造の水平勾配の観測がこの問題を解決するブレークスルーであると推定しており、それに対処する観測手法を提案する。名大のグループはこの目的のために 2 〜 3 台の係留ブイを用いた観測を提案している。我々はこのような観測における重要な点は、適切な距離を保持した 2 台の海上観測装置から 4 台の海底音響装置にほぼ同時に音響測距信号を送ることであることを見出した。そうすれば表層の 2 点を結ぶ方向の水平音速勾配の近似値を測定できる。海上観測装置の位置を変えることにより、任意の方向の音速勾配が求まる。試験観測を繰り返してこの観測に必要なノウハウを獲得できれば、半日以上の測位結果を平均する必要性はなくなるので観測時間を短縮できる。表層の 3 ヶ所で同時に観測すれば、理論的には、音響測位毎に精密な測位結果を得ることができる。東北沖は世界でも有数の漁場であり、10 km 以上の長さの流し網等が多く用いられている。漁業者とも相談して場所と時間を選び、この手法の有効性を確認する観測を行ってみたい。

(2) セミリアルタイム連続観測に向けた取り組み
実時間連続観測は海底測地観測の究極の目標であるが、当面の課題は日あるいは週座標値の観測であろう。海底 GPS 観測でこれを実現するには二つの壁を越えなければならない。その一つは海上の GPS 観測用の装置であり、係留ブイか自航式のブイが必要である。海の波の力を利用して最大 1.5 ノットで進むことができ、台風の荒海にも耐える Wave Glider という自航式ブイがある。我々は Wave Glider というブイ 2 台か、あるいは係留ブイとそれ 1 台でこの課題をこなすことができると考えている。
第二の壁は精密 GPS 測位である。我々が用いてきたキネマティック GPS 測位という手法は、海上の GPS 測位データを陸上に送る必要がある。これには最低でも 4800 bps の衛星通信が必要であり、その方法を JAXA のグループと検討している。我々は簡易的な代替案を最近見出した。山本ほか（当大会）は、昨年 10 月に StarFire システムによる補正を用いた陸上観測点のキネマティック測位を行い、その解の安定性を調べた。その結果、水平位置の標準偏差は約 1.5 cm であり、我々がキネマティック GPS 解析で用いている手法で解析した日座標値との差も 2 cm 以内であった。
我々が 2012 年に新たに設置した海底音響装置の電池では、長期観測の場合、1 日に約 20 回の観測ができる。この場合でも 3 台の海上装置による観測により数センチ程度の測位精度は確保できるであろう。StarFire と Iridium の 1 日当たりの経費は傭船費に比べればはるかに低額であるが、1 年以上の観測であれば週 1 回の観測が限界であろう。長期にわたる日座標値の観測にはもっと低額の衛星通信が必要である。

キーワード: 海底地殻変動観測, 海底 GPS, 東北地方太平洋沖地震, 固着状態, 音速構造の水平勾配, 日座標値
Keywords: seafloor geodetic observation, GPS/A, Tohoku-oki earthquake, seismic coupling, horizontal gradient of sound speed, daily position

Japan Geoscience Union Meeting 2013
(May 19-24 2013 at Makuhari, Chiba, Japan)

SSS01-P07 会場:コンベンションホール 時間:5 月 19 日 18:15-19:30

2011 年東北沖地震（Mw9.0）の大滑り域周辺の先行地震活動
Precursory Seismic Activity Surrounding the High-Slip Patches of the 2011 Mw9.0 Tohoku-Oki Earthquake

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The 2011 Tohoku-Oki earthquake (Mw9.0) was preceded by foreshock activity that occurred north of the main-shock epicenter two days earlier. The epicentral area of the foreshock activity is almost the same as that of the prominent seismic activity in 1981 [Ando and Imanishi, 2011; Shao et al., 2011a]. The question arises, why did the 1981 event not trigger an event like the 2011 Tohoku-Oki earthquake? The time difference of 30 years is negligible in comparison with the long time required for the slip deficit of more than 40 m. In order to address this problem, we investigated the long-term seismicity pattern with reference to the slip distribution of the Tohoku-Oki earthquake. We used the earthquake catalogue compiled by the Japan Meteorological Agency (JMA) for the past 90 years since 1923. We assume that the variation of frictional strength on the megathrust, as suggested by the slip distribution of the Tohoku-Oki earthquake, would manifest itself in the spatio-temporal distribution of seismic activity.

The slip distribution of the Tohoku-Oki earthquake we obtained from the coseismic displacements of the GEONET and sea-bottom stations is characterized by a low-slip zone sandwiched between the two patches of high slip (20m) along the Japan Trench. The epicenters of the foreshock activity are distributed over the boundary between the low-slip zone and the two high-slip patches (LHSB seismic zone), where other prominent activity had been accommodated during the past 90 years. The main-shock initiated near the junction of the northern edge of the southern high-slip patch and the mid-asperity seismic zone that divides the southern high-slip patch into two parts. The main-shock was able to rupture the western half of the southern high-slip patch, which is located down-dip of the main-shock epicenter, because the stress increased by the foreshock activity surpassed its strength. However, we infer that it is not only because the foreshock activity was the largest to have ever occurred in the LHSB seismic zone, but also because the western half of the southern high-slip patch had been sufficiently weakened by surrounding events since 2003. A substantial reduction of its strength might have been caused by the 2003 M6.8 event in the mid-asperity seismic zone and the 2005 events in the area of characteristic events such as the 1936 and 1978 Off-Miyagi earthquakes. The afterslip of the 2008 and 2010 events off the coast of Fukushima prefecture might also have contributed to weakening the western half of the southern high-slip patch. The last significant stress change was caused by the foreshocks that occurred along the northern edge of the southern high-slip patch one day before the main-shock.

The following rupture of the eastern half of the southern high-slip patch, which is located up-dip of the main-shock epicenter and includes an area of slip greater than 60 m, was probably made possible because that portion had also been sufficiently weakened by the surrounding events since 2003. The contribution of the 2003 activity extending along the southern edge of the center of the southern high-slip patch may be important because no prominent activity had occurred there before. A couple of moderate-sized events on the eastern edge of the southern high-slip patch might also have made important contributions. We infer that the foreshocks occurring along the northern edge of the southern high-slip patch also played an important role for weakening of the center of the southern high-slip patch. Lastly, the main-shock was able to expand to its large size by rupturing the center of the southern high-slip patch. The magnitude of the slip caused the subsequent ruptures of adjacent areas including the northern high-slip patch. The doughnut-shaped seismicity pattern that formed around the center of the southern high-slip patch is considered to be due to the presence of an extremely strong area on the megathrust.

Keywords: Off the Pacific coast of Tohoku Earthquake, Tohoku-Oki earthquake, Pacific plate, subduction zone, precursory seismic activity, foreshock activity

Japan Geoscience Union Meeting 2013
(May 19-24 2013 at Makuhari, Chiba, Japan)

SSS01-P08 会場:コンベンションホール 時間:5 月 19 日 18:15-19:30

Aftershock seismicities of three great earthquakes and their implications for lithospheric deformation
Aftershock seismicities of three great earthquakes and their implications for lithospheric deformation

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Assessment of influence of great earthquakes on reginal seismicity is high priority for seismic hazard mitigation. However, the properties of aftershock seismicity have not been fully understood. Since 2004, there were three great earthquakes with magnitudes greater than 8.8, which are the 26 December 2004 M9.1 Sumatra-Andaman earthquake, the 27 February 2010 M8.8 Maule earthquake, and the 11 March 2011 M9.0 Tohoku-Oki earthquake. In this study, we investigate the seismicities and focal mechanism solutions of earthquakes in the three regions that belong to active convergent plate boundaries. The seismicities and focal mechanism solutions of the earthquakes before and after the great earthquakes during 2000-2012 are investigated by time period, focal depth, and faulting type. It is observed that the numbers of events increase abruptly right after the great earthquakes, and decrease gradually with time. Thrustal earthquakes occur dominantly in the regions. It is observed that a large number of strike-slip events occur in the Sumatra-Andaman region after the great earthquake. On the other hand, thrustal earthquakes are still most dominant in the Maule region after the great earthquake. Also, we find large numbers of shallow-focus normal-faulting events in the Tohoku-Oki region after the great earthquake. It is intriguing to note that all three regions present shallow-focus normal-faulting earthquakes that are clustered around the slab boundaries with large slips. Thrustal earthquakes are found to be clustered around the slip edges. The observation suggests that the ambient stress field changes by the slip amount. The occurrence of normal-faulting earthquakes in large slip regions can be explained as a result of lithospheric elastic rebounds of plates after the great earthquakes.

キーワード: aftershock, seismicity, focal mechanism, b value, lithospheric deformation
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