ARTICLE IN PRESS

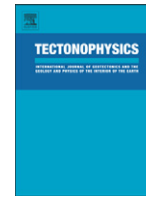
TECTO-125322; No of Pages 11

Tectonophysics xxx (2012) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto



Seismic evidence for reverse activation of a paleo-rifting system in the East Sea (Sea of Japan)

Hoseon Choi [a,b], Tae-Kyung Hong [c,*], Xiaobo He [c,1], Chang-Eob Baag [a]

[a] Seoul National University, School of Earth and Environmental Sciences, 1 Gwanak-ro, Gwanak-gu, Seoul 151-742, South Korea
[b] Korea Institute of Nuclear Safety, 62 Gwahak-ro, Yuseong-gu, Daejeon 305-338, South Korea
[c] Yonsei University, Department of Earth System Sciences, 50 Yonsei-ro, Seodaemun-gu, Seoul 120-749, South Korea

ARTICLE INFO

Article history:
Received 30 April 2011
Received in revised form 13 December 2011
Accepted 15 December 2011
Available online xxxx

Keywords:
Continental margin
Paleo-rifting
Reverse activation
East Sea (Sea of Japan)

ABSTRACT

渐新世

中新世的

The Japanese Islands were separated from the Eurasian plate due to continental rifting during the Oligocene to mid-Miocene, which caused the opening of the East Sea (Sea of Japan). Such tectonic evolution in the East Sea is important for understanding the evolution of back-arc regions with active convergent margins. To understand the evolution of the paleo-rifted back-arc region, we investigate seismicity, crustal seismic anisotropy, focal mechanism solutions and ambient stress field around the Korean Peninsula. The Korean Peninsula displays diffused seismicity with small and moderate earthquakes. Shallow earthquakes rarely occur in the central East Sea. The crustal fast shear-wave polarization directions in the Korean Peninsula are observed to vary in azimuth between 40° and 90°. The focal mechanism solutions are calculated by long period waveform inversions. The ambient stress field is calculated from the focal mechanism solutions. The compressional stress field in the Korean Peninsula is observed to be in ENE-WSW, which is consistent with the fast shear-wave polarization directions. The compressional stress directions in the East Sea progressively change from ENE to SE with increasing longitude. The rapid change of compressional directions in the central East Sea prohibits accumulation of stress, causing rare shallow seismicity. High seismicity of reverse faulting events is observed at the fringes of the East Sea, in particular, around the east coast of the Korean Peninsula and the west coast of Japanese Islands, which correspond to paleo-rifted margins where compressional stresses are accumulated. The compressional stress field and active thrustal events suggest reverse activation of paleo-normal faults that were developed during the opening of the East Sea.

1. Introduction

The Korean Peninsula, Japanese Islands and East Sea (Sea of Japan) comprise the eastern margin of the Eurasian plate. The regions are surrounded by the Okhotsk, Pacific, and Philippine Sea plates. There are long lasting debates on the formation of the Korean Peninsula, Japanese Islands and East Sea. Their tectonic relationship to the adjacent regions remains unclear (Chough et al., 2000; Jolivet et al., 1994; Oh, 2006; Otofuji et al., 1985).

It is agreed that the East Sea was opened due to continental rifting during the Oligocene to mid-Miocene (Jolivet et al., 1994; Kano et al., 2002). Two prominent models were proposed for the explanation of the opening of the East Sea. The models include a pull-apart basin model and a double-door fan-shaped opening model. The pull-apart model explains that the East Sea was developed as a result of regional extension by activation of northeast-directional strike-slip faults (Jolivet and Huchon, 1989). On the other hand, the double-door fan-shaped opening model suggests that the East Sea was opened by rotational separation of marginal blocks of the Eurasian plate.

In the pull-apart basin model, the Hupo and Yangsan faults in the eastern margin of the Korean Peninsula are regarded as the western segments of a pull-apart basin system (e.g., Yoon and Chough, 1995). In the double-door fan-shaped opening model, the southern Japanese Islands are explained to have been rotated clockwise and separated from the eastern Korean Peninsula. Similarly, the northern Japanese Islands were separated from the Sikhote Alin mountain region (eastern Russian region) by an anticlockwise rotation.

It is known that the double-door fan-shaped opening model agrees well with the observations of geological differences between the northern and southern Japanese Islands and geological similarity between the southern Japanese Islands and Korean Peninsula (e.g., Oh, 2006; Otofuji and Matsuda, 1983). Also, palaeomagnetic observations in the Japanese Islands support the opposite directional rotations between the northern and southern Japanese Islands (Otofuji et al., 1985).

Despite the proposition of East Sea opening models, it is still unclear how the East Sea opening is associated with current seismicity and tectonic evolutions in the East Sea. Also, it is rarely understood how the paleo-rifting structures respond to the current tectonic forces,

* Corresponding author. Tel.: +82 2 2123 2667.
E-mail address: tkhong@yonsei.ac.kr (T.-K. Hong).
[1] Now at Yale University, Department of Geology and Geophysics, New Haven, CT 06520, USA.

0040-1951/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.tecto.2011.12.023

which are different from those in the period of East Sea opening. The evolution of paleo-rifting regions like the East Sea region is particulary important not only for comprehension of the plate tectonics in back-arc regions, but also for mitigation of seismic hazards in back-arc regions.

Tectonic evolutions typically accompany lithospheric deformation that can be identified from seismicity, geological structures, mineral alignment, cracks, faults, folds and medium heterogeneities (e.g., Christensen, 2004; Savage and Silver, 1993). In particular, seismic signatures such as seismicity, focal mechanism solutions and seismic anisotropy are useful to illuminate tectonic structures in inaccessible regions.

The spatial distribution of earthquakes enables us to infer active seismogenic structures. Focal mechanism solutions provide us information on fault plane directions, faulting types and ambient stress fields (e.g., Zoback and Zoback, 2002). It is known that crustal seismic anisotropy is associated with cracks that are aligned to the ambient stress field (Crampin, 1994). In this study, we investigate the seismic features around the East Sea from spatial distribution of earthquakes, focal mechanism solutions, ambient stress field and crustal seismic anisotropy. Also, we infer the tectonic evolutions of the paleo-rifted back-arc region in the East Sea.

2. Tectonic setting

The region around the Korean Peninsula is an intraplate zone which features shallow earthquakes with low occurrence rate. The high seismicity around the Japanese Islands is associated with plate subductions. Many earthquakes occur along descending slabs, and their focal depths increase from the fore-arc to back-arc regions. Shallow events also occur in the back-arc regions (Fig. 1).

The Pacific and Philippine Sea plates subduct beneath the Japanese Islands with speeds of ~8 and 3–5 cm/yr, respectively (e.g., Seno et al., 1996). The subducting slab of the Pacific plate reaches the upper mantle transition zone beneath the western fringe of the East Sea (Sea of Japan), and lies on the 660 km discontinuity beneath the northern Korean Peninsula (Gudmundsson and Sambridge, 1998). The fast subduction of the Pacific plate causes shallow to deep focus earthquakes. The Philippine Sea plate, on the other hand, has recently begun to subduct, and its marginal front reaches to a depth of 200 km beneath the southern Japanese Islands (e.g., Nakajima and Hasegawa, 2007).

The southern Korean Peninsula shows a typical continental crust with thickness of ~32 km (Chang and Baag, 2006; Hong et al., 2008). The Japanese Islands were separated from the Eurasian plate due to the opening of the East Sea. The Korean Peninsula, East Sea and Japanese Islands comprise the eastern margin of the Eurasian plate (Fig. 1). The opening of the East Sea developed a transitional crustal structure between continental and oceanic crusts. Also, three deep-seated basins (Japan, Yamato, and Ulleung basins) were formed during the opening.

The crustal thicknesses decrease abruptly in the East Sea across the coasts of the Korean Peninsula and the Japanese Islands. The crustal thicknesses in the East Sea are as shallow as 8.5–14 km (e.g., 1992, Hirata et al., 1989; Kim et al., 1998). The East Sea region remains in a compressional regime since late mid-Miocene (e.g., Itoh et al., 2006). Shallow earthquakes in the East Sea mainly occur around the fringe regions. In particular, large events frequently occur in the eastern margin of the East Sea (Fig. 1). On the other hand, moderate

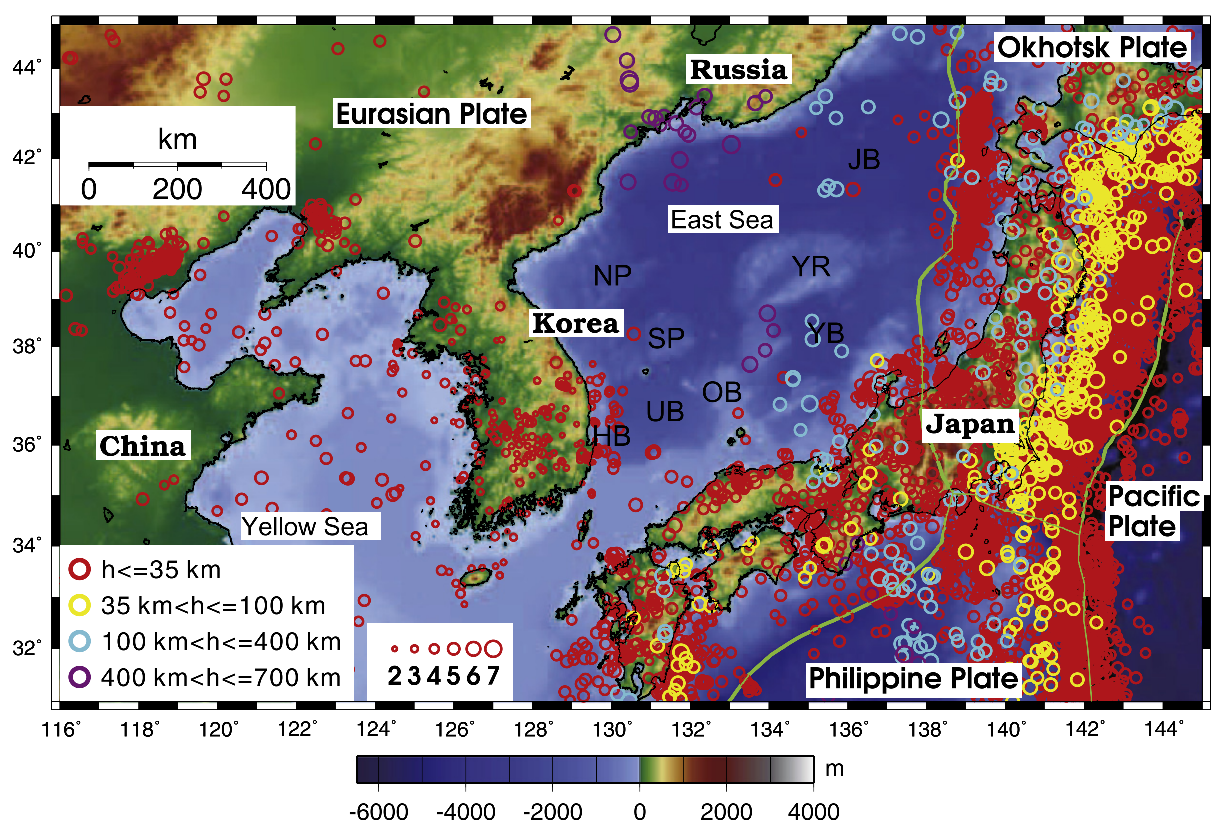


Fig. 1. Seismicity around the eastern margin of the Eurasian plate. Events with depths less than 35 km are represented by red circles, those with depths between 35 and 100 km by yellow circles, those with depths between 100 and 400 km by azure circles, and those with depths between 400 and 700 km by purple circles. Only shallow-focus earthquake occurs around the Korean Peninsula. Focal depths increase with distance from the Pacific plate boundaries to the East Sea (Sea of Japan). Shallow-focus earthquakes are clustered in several offshore regions in the East Sea. Shallow-focus earthquakes occur rarely in the central East Sea. Major tectonic structures are denoted: Hupo bank (HB), Japan Basin (JB), North-Korea plateau (NP), Oki bank (OB), South-Korea plateau (SP), Ulleung Basin (UB), Yamato Basin (YB), and Yamato rise (YR).

Please cite this article as: Choi, H., et al., Seismic evidence for reverse activation of a paleo-rifting system in the East Sea (Sea of Japan), Tectonophysics (2012), doi:10.1016/j.tecto.2011.12.023

earthquakes occur in the western margin, off the east coast of the southern Korean Peninsula (Kim et al., 2006).

The source parameters of some noticeable events around the East Sea and Korean Peninsula have been subjected to only limited investigations in the past (e.g., Jo and Baag, 2007; Jun, 1991; Kang and Baag, 2004; Kim and Kraeva, 1999; Park and Mori, 2005). The overall properties of seismicity, spatial distribution of earthquakes, faulting types and response to ambient stress field are not fully understood despite several attempts (e.g., Park et al., 2007; Rhie and Kim, 2010). In particular, previous studies are based on insufficient data sets, yielding results that appear to be incompatible with known tectonic settings (e.g., Park et al., 2007). Further, the earthquake occurrence mechanism remains unclear. Also, the ambient stress field and medium properties in this back-arc region is not known.

3. Methods

The moment tensor solutions of regional events are determined from seismic waveforms bandpass-filtered between 0.05 and 0.1 Hz using a long-period waveform inversion (Sokos and Zahradnik, 2008). The filtering range can be slightly modified depending on the signal-to-noise ratios and frequency contents. The Green's functions are computed based on a one dimensional velocity model (Chang and Baag, 2006) using a frequency-wavenumber integration method (Bouchon, 1981). The long-period waveform inversions, however, are not suitable for small-size events due to low signal-to-noise ratios at low frequencies. We apply *P*-polarity analyses to such small-size events for determination of the focal mechanism solutions (Snoke, 2002).

The directions of compressional-stress axes (P-axes) are calculated from the fault-plane solutions and slip vectors. The P-axis unit vector, $\hat{\mathbf{p}}$, is given by (Aki and Richards, 1980; Gasperinia and Vannuccib, 2003)

$$\hat{p}_i = \frac{\hat{n}_i - \hat{d}_i}{\sqrt{2}}, \tag{1}$$

where $\hat{\mathbf{n}}$ is the unit normal vector of the fault plane, and $\hat{\mathbf{d}}$ is the unit slip vector.

Shear-wave splitting is a prominent phenomenon associated with seismic anisotropy that is observed in various media including igneous and metamorphic rocks and sedimentary reservoirs (Crampin, 1994). Thus, analysis of shear-wave splitting is widely used for quantification of seismic anisotropy. Shear waves are split into fast and slow shear-wave components when they propagate through anisotropic media. The time lags between the fast and slow shear waves increase with propagation distances in anisotropic media. Micro-cracks are developed by ambient stress field, and are aligned to the stress directions. These stress-induced cracks cause development of seismic anisotropy (Savage, 1999; Zhang et al., 1999). Fast shear waves are polarized in the strike directions of the cracks.

The properties of shear-wave splitting are expressed in terms of fast-wave polarization direction, ϕ, and time delay, δt. The time delay corresponds to time lag between fast and slow shear-wave components. We determine the shear-wave splitting parameters (ϕ, δt) using a waveform cross-correlation method (Fukao, 1984). We search a set of shear-wave splitting parameters (ϕ, δt) yielding the maximum correlation coefficients between fast and slow shear waveforms (Fukao, 1984; Levin et al., 1999).

4. Data

We collect seismic waveforms and event information from local institutes (Korea Meteorological Administration (KMA), Korea Institute of Geoscience and Mineral Resources (KIGAM)) for 48 near-regional earthquakes around the Korean Peninsula and East Sea during 1995–2010. The source parameters (locations, origin times) of events are refined by aligning *P*-wave arrival times (Klein, 2007). Record sections are collected from all available stations in Korea and neighboring regions. Only the record sections displaying clear onsets of *P* arrivals are analyzed to improve the accuracy of refined source parameters (see, Table 1).

The source parameters of 41 out of 48 events are refined (Table 1). The source parameters of the remaining 7 events are not refined due to insufficient numbers of observations. The source parameters from event catalogs of local institutes are used for the 7 events. The magnitudes of events are 2.6–5.2, and focal depths are 1.4–20.8 km (Table 1). The fault-plane solutions of the near-regional events are

Table 1
Summary of event information for earthquakes analyzed for determination of focal mechanism solutions around the Korean Peninsula.

yyyy-mm-dd	hh:mm:ss	lat (°N)	lon (°E)	dep1 (km)	dep2 (km)	M_L	M_w	N
1995-07-24**	10:02:52.0	38.20	124.40	–	11	4.2	4.4	–
1995-08-11**	18:17:49.0	38.00	124.60	–	6	3.6	3.8	–
1996-12-13	04:10:16.9	37.25	128.72	8.4	6	4.5	4.7	16
1997-05-21**	22:52:37.5	36.06	127.10	–	10	3.9	3.4	–
1997-06-25*	18:50:23.4	35.80	129.25	11.8	–	4.2	4.3	20
1998-06-08**	02:45:09.0	38.50	124.30	–	5	3.7	4.3	–
1998-09-03**	07:52:47.0	36.60	125.70	–	4	3.8	3.8	–
1998-09-13**	11:42:13.0	36.10	126.90	–	10	3.6	3.8	–
1999-04-07	14:43:17.4	37.19	128.84	1.4	1.5	3.3	3.5	18
1999-04-23*	16:35:13.5	35.84	129.26	7.0	–	3.2	3.2	13
1999-06-02	09:12:22.4	35.84	129.26	9.6	5	3.4	3.7	18
1999-09-11*	20:56:51.1	35.84	129.25	6.7	–	3.4	3.4	9
2000-12-09	09:51:00.8	36.44	129.97	11.1	11	3.7	3.9	21
2001-11-21	01:49:11.2	36.70	128.29	2.8	9	3.5	3.3	19
2001-11-24	07:10:29.8	36.79	130.04	10.3	9	4.1	3.7	22
2002-03-17	00:26:38.7	37.90	124.57	5.0	11	3.9	3.6	18
2002-07-08	19:01:50.3	35.87	129.78	16.8	20	3.8	3.7	31
2002-07-23	12:48:11.7	35.73	122.75	10.	10	4.7	4.7	12
2002-09-17	09:08:15.4	36.54	124.40	9.9	12	3.6	3.3	10
2002-12-09	22:42:51.0	38.84	127.17	9.3	9	3.8	3.6	22
2003-01-09	08:33:19.8	37.49	124.42	10.4	6	3.9	3.7	16
2003-03-22	20:38:43.0	35.04	124.51	18.0	17	4.9	4.7	36
2003-03-30	11:10:55.6	37.71	123.75	17.4	10	5.0	4.5	17
2003-04-15	17:55:24.1	36.44	126.13	9.5	3	3.3	3.3	27
2003-06-09	01:14:02.1	35.96	123.96	10.0	10	4.0	3.8	17
2003-10-13	09:14:05.0	36.97	126.43	11.5	13	3.6	3.7	25
2004-04-26	04:29:25.7	35.83	128.23	10.5	12	3.9	3.5	33
2004-05-29	10:14:25.5	36.68	130.13	20.8	9	5.2	5.0	42
2004-06-01	11:22:17.1	37.09	130.28	19.5	9	3.5	3.5	19
2004-08-05	20:32:53.5	35.84	127.32	8.5	17	3.3	3.2	32
2004-12-16**	18:59:14.0	41.79	127.94	–	17	3.9	3.9	–
2005-06-14	22:07:01.9	33.06	126.16	13.4	14	3.7	3.7	13
2005-06-29	14:18:03.8	34.39	129.25	10.9	9	4.0	4.0	31
2005-10-09	23:51:09.3	37.86	124.95	13.2	15	3.4	3.5	16
2006-01-19	03:35:35.5	37.20	128.80	6.1	7	3.2	3.4	27
2006-04-03	09:14:04.1	38.82	126.04	10.4	9	3.3	3.3	18
2006-04-29	02:01:12.6	37.09	129.95	6.7	2	3.5	3.6	21
2006-05-13	10:14:30.3	34.01	129.12	1.6	7	3.5	3.6	14
2007-01-20	11:56:53.4	37.68	128.59	10.0	10	4.8	4.5	34
2008-01-16	10:58:00.5	35.59	125.27	9.3	6	3.9	3.8	27
2008-02-29	06:53:01.2	38.77	126.33	2.8	9	3.2	3.3	22
2008-05-31	12:59:31.0	33.52	125.69	11.5	19	4.2	3.9	29
2008-10-29	00:26:14.8	36.33	127.25	5.1	6	3.4	3.3	39
2009-03-02	05:20:27.6	37.06	124.68	5.6	9	3.4	3.3	24
2009-05-01	22:58:28.0	36.55	128.71	13.3	10	4.0	3.7	29
2009-05-02*	03:28:29.4	36.55	128.71	13.1	–	2.6	3.0	24
2010-02-09*	09:08:13.9	37.45	126.80	11.1	–	3.0	3.1	28
2010-02-16	09:53:31.4	35.63	130.05	18.8	17	3.2	3.4	14

dep1 depth inverted from *P* arrival times
dep2 depth inverted from long-period waveform inversion
M_L local magnitudes reported by local institutes
M_w moment magnitudes calculated by long-period waveform inversion
N number of record sections used for refinement of source parameters
* events of which fault-plane solutions are calculated by polarity analysis
** events of which source parameters are adopted from earthquake catalog

Please cite this article as: Choi, H., et al., Seismic evidence for reverse activation of a paleo-rifting system in the East Sea (Sea of Japan), Tectonophysics (2012), doi:10.1016/j.tecto.2011.12.023

determined using the long-period waveform inversions and *P* polarity analyses.

We additionally collect focal mechanism solutions of 1295 regional events with magnitudes of 4.7–8.3 during 1977–2009 around the Japanese Islands and eastern China from the Global Centroid Moment Tensor (CMT) catalog (Global Centroid Moment Tensor Project www.globalcmt.org). Also, the calculated fault-plane solutions are combined with those from the available literature (Hong and Rhie, 2009; Jun, 1991).

Crustal seismic anisotropy in the Korean Peninsula is investigated with local earthquakes. We collect 228 pairs of horizontal waveforms from 63 stations that recorded 139 earthquakes during 1999–2008 with distances less than 50 km (Fig. 2).

5. Fault plane solutions and compressional stress axis directions

We determine the fault-plane solutions of near-regional earthquakes around the Korean Peninsula and the East Sea based on the refined source parameters (Table 1). We apply a long-period waveform inversion for moderate-size or large events (magnitudes greater than 3.2) and a polarity-based analysis for small events considering the signal-to-noise ratios of long-period signals. The calculated fault-plane solutions are combined with those from available resources (Fig. 3).

We compare the focal mechanism solutions of two moderate-size events that are also available from the Global CMT catalog (Fig. 4). The two events are the 29 May 2004 M_L5.2 and the 20 January 2007 M_L4.8 earthquakes (Table 1). The Global CMT solution of the 29 May 2004 event is given by strike of 346°, dip of 53° and rake of 78°, while that of the 20 January 2007 is given by strike of 296°, dip of 85° and rake of -2°.

In this study, the fault-plane solution of the 29 May 2004 event is determined to have a strike of 354°, dip of 46° and rake of 89°, corresponding to a typical thrust fault. Also, the fault-plane solution of the 20 January 2007 event is calculated to have a strike of 203°, dip of 86° and rake of -180°, corresponding to a pure strike-slip fault. These solutions match reasonably with the Global CMT solutions that are determined from teleseismic surface waves.

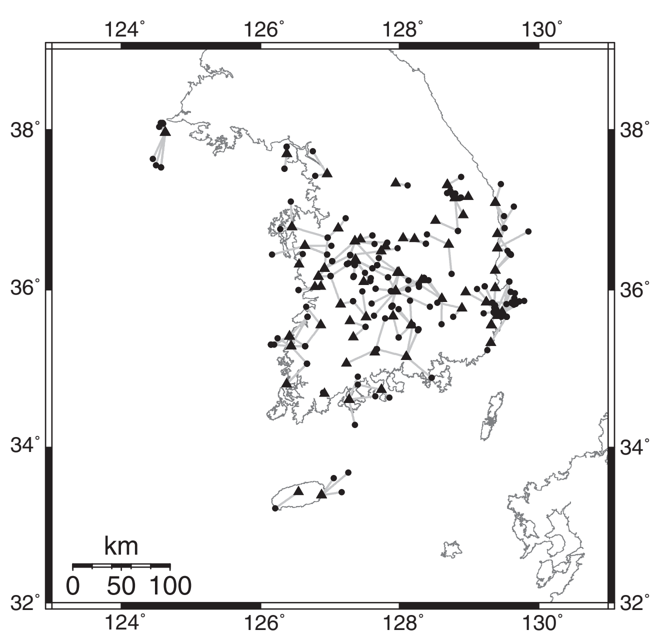


Fig. 2. Map of stations (triangles) and events (circles) that are used for crustal shear-wave splitting analysis. Pairs of stations and events with distances less than 50 km are selected to constrain only the crustal seismic anisotropy.

The dominant type of faulting around the Korean Peninsula is strike slip, accounting for about 53% of events (Fig. 5). Thrustal earthquakes are clustered in a region off the southeast coast of the Korean Peninsula. The seismicity in the region displays a N–S trending distribution along the escarpment of the Ulleung Basin (region A of Figs. 3, 6(a)). Some normal faulting earthquakes are observed around Bakryeong island in the central Yellow Sea.

The seismicity around the Japanese Islands is mixed with normal, thrustal, and strike-slip events. Thrustal earthquakes are dominant around the subduction zones. Normal faulting earthquakes are observed mostly in fore-arc regions due to activation of lithospheric extension by slab pull (Fowler, 2005). Strike-slip faulting earthquakes are mainly observed at regions off the west coast of the southern Japanese Islands. It is noteworthy that the fault plane directions of the events are similar to those of events in the southern Korean Peninsula (Fig. 3). This observation suggests that the southern Korean Peninsula and southern Japanese Islands share the same tectonic evolution, and remain in a common stress regime.

We find clustered shallow-focus earthquakes in the west and east fringes of the East Sea (regions A, B, C in Figs. 3, 6). The 29 May 2004 M_L5.2 earthquake, the second largest earthquake in the Korean Peninsula since 1978, occurred on the escarpment of the Ulleung Basin in region A. Similarly, shallow-focus thrustal earthquakes occur frequently around the Noto Peninsula, off the west coast of the central Japanese Islands (region B). It is known that there were nine events with magnitudes equal to or greater than 6.0 since 1975, e.g., the 25 March 2007 M6.9 earthquake. Shallow-focus thrustal earthquakes are found also in region C, off the west coast of the northern Japanese Islands. These events occur around the plate boundary between the Okhotsk and Eurasian plates.

The horizontal stress field around the Korean Peninsula is dominated by compressional stresses induced from active convergent margins. The compressional-stress (P-axis) directions in the crust and mantle lid are calculated from the fault-plane solutions of shallow-focus earthquakes with focal depths of 35 km or less (Fig. 7). The compressional stress directions are mainly distributed in a range of 55°–85° (Fig. 8).

We calculate the ambient compressional stress field around the Korean Peninsula, East Sea and Japanese Islands by interpolating the compression-axis directions of shallow-focus events (Fig. 9). It is observed that the constructed ambient stress field is consistent with the horizontal compression directions of deep-focus events in the East Sea and Japanese Islands, suggesting agreement with the lateral subduction directions of the Pacific and Philippine Sea plates (Figs. 7, 9).

This observation suggests that the interpolated stress field represents the actual stress field around the East Sea reasonably, and also implies that the compressional stress field in the East Sea is mainly controlled by the combined effects of active convergence of the Pacific, Philippine Sea and Indian plates with respect to the Eurasian plate. It is noteworthy that the compressional stress field in the Korean Peninsula is consistent with geodetic observations that present NNW-SSE directional extension and ENE-WSW directional compression (Jin and Park, 2007).

6. Crustal seismic anisotropy

The crustal seismic anisotropy in the Korean Peninsula is measured from local seismic records with epicentral distances less than 50 km. Anisotropy parameters for the medium beneath each station are estimated (Fig. 2). The polarization directions of fast crustal shear waves in the Korean Peninsula are found to be diverse, but are populated in an azimuthal range of 40°–90° with an average value of N82°E (Fig. 8).

Despite relatively large variability in the fast shear-wave directions, we find that the fast-wave directions generally agree with the

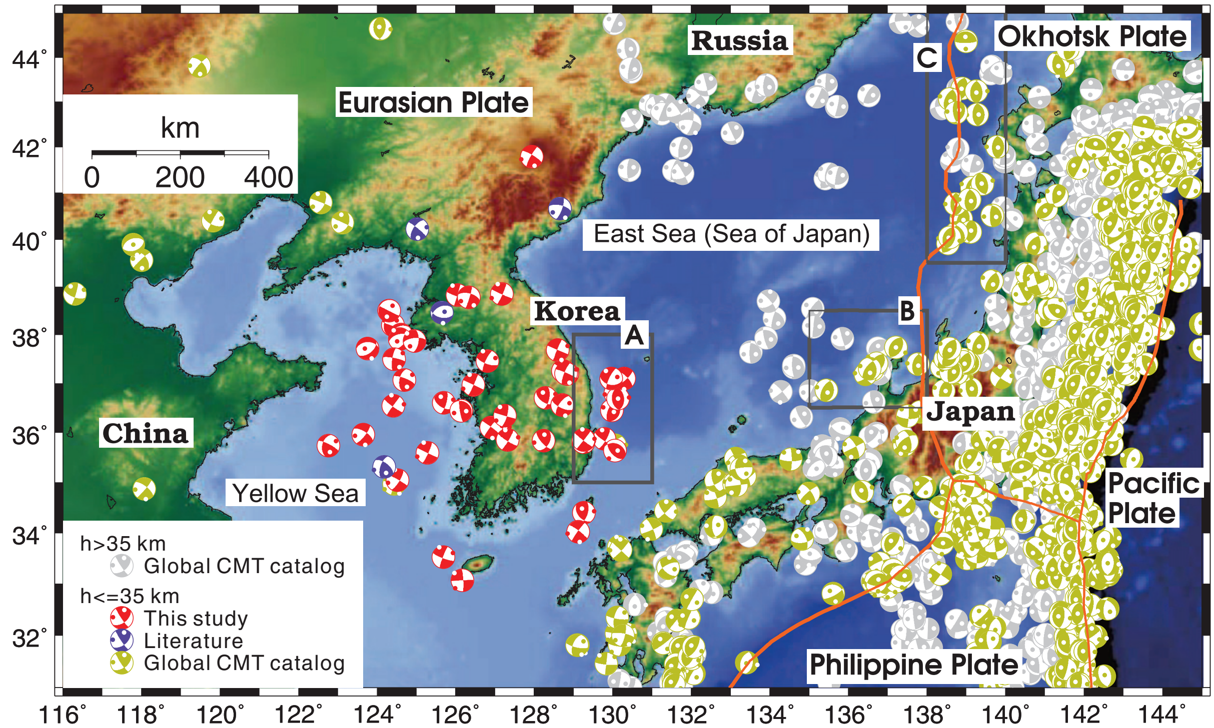


Fig. 3. Focal mechanism solutions of events around the Eurasian continental margin. Shallow earthquakes in the East Sea (Sea of Japan) region are clustered in regions A, B and C. Focal mechanism solutions in gray indicate events with depths greater than 35 km, those in the other colors indicate shallow earthquakes. Focal mechanism solutions of events in red indicate solutions from a long period waveform inversion and polarity analysis, those in violet are available solutions from literature, and those in yellow are from the Global CMT catalog.

ambient compressional stress field (Fig. 8). In addition, the polarization directions agree with the morphology of surface geological structures. It is known that crustal seismic anisotropy is developed due to alignment of micro cracks and crustal lamination as a response to the ambient stress field (Crampin, 1994). The variability in fast shear-wave directions are often found in upper crusts (e.g., Balfour et al., 2005). The variability of the crustal seismic anisotropy may be associated with local geology and previous tectonic evolutions. Also, this is partly because the analysis is based on high-frequency local seismograms that are subtle to vary with medium properties.

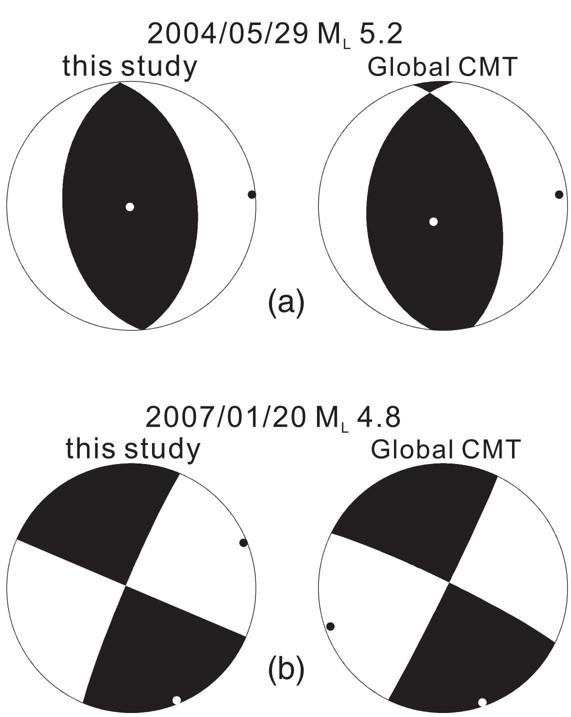


Fig. 4. Benchmark test of focal mechanism solutions. Two moderate-size earthquakes with reported focal mechanism solutions are selected. Comparisons of focal mechanism solutions between this study (left column) and the Global CMT (right column) for (a) the 29 May 2004 M_L5.2 earthquake and for (b) the 20 January 2007 M_L4.8 earthquake. The compression-axis (P) and tension-axis (T) directions are marked with black and white dots. The focal mechanism solutions of this study and Global CMT are observed to be very close.

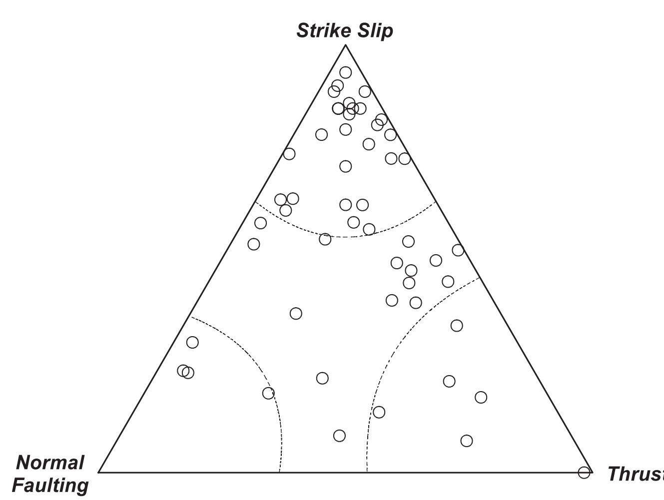


Fig. 5. Event type classification of earthquakes (53 events) around the Korean Peninsula. The dominant event type is strike-slip faulting (28 events). Some thrustal and normal faulting earthquakes (six and four events respectively) occur in localized regions.

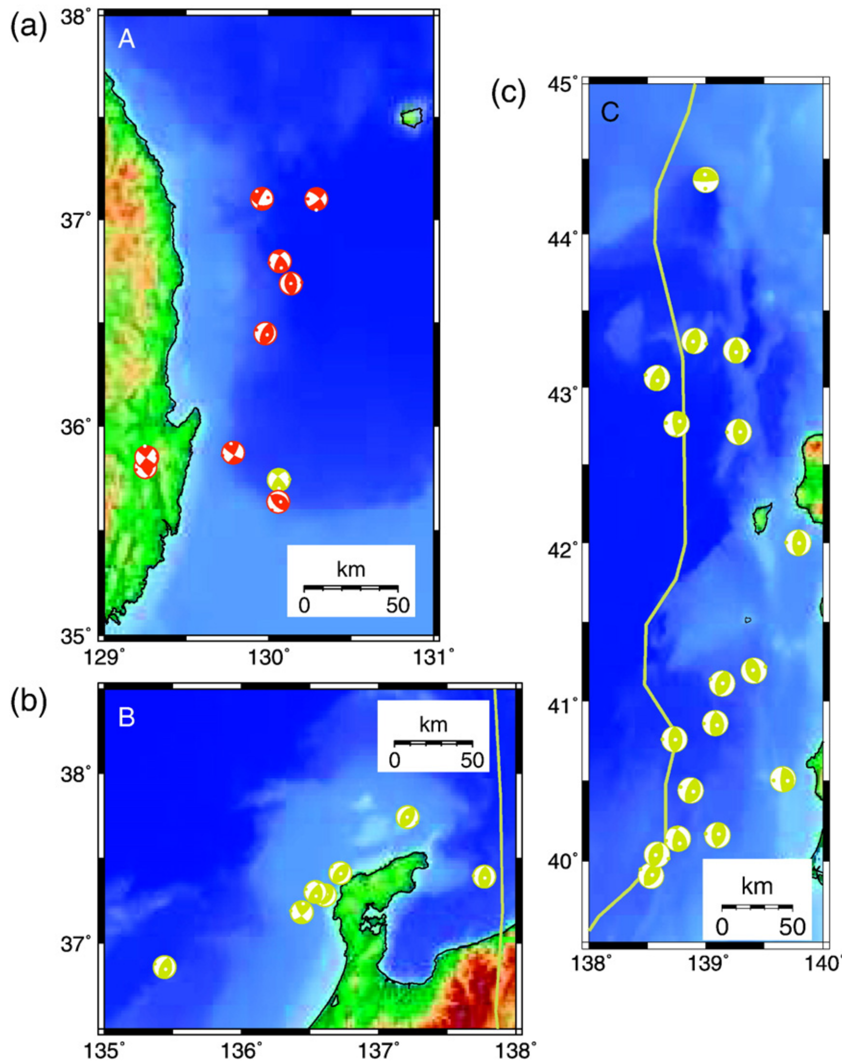


Fig. 6. Offshore shallow-focus earthquakes in selected regions around the East Sea (Sea of Japan). (a) Offshore events in region A occur along the escarpment around the Ulleung Basin. (b) Events in region B are clustered around the Noto Peninsula. (c) Events in region C occur around the plate boundary. Both strike-slip and thrustal earthquakes occur in region A. Thrustal earthquakes occur mainly in regions B and C.

7. Discussion

The crustal compression-axis directions in the Korean Peninsula, ~N70°E, are observed to be consistent with the fast shear-wave polarization directions (Fig. 8). This observation suggests the vulnerability of the crust to the ambient stress field. The ambient stress fields are observed to be similar between the Korean Peninsula and eastern China (Figs. 7, 9). We, however, find that the P-axis direction changes progressively with increasing longitude from ENE to SE in the East Sea (Sea of Japan). The events in region A show E–W directional compression (Fig. 7). The compression-axis directions in the west coast of the Japanese Islands coincide with the subduction directions of the Pacific and Philippine Sea plates. The observation shows that the crustal stress field is controlled by the relative plate motions.

The East Sea was formed by incomplete paleo-rifting during Oligocene to mid-Miocene, causing development of a translational crust. The crust in the East Sea is relatively young compared to that in neighboring regions which is composed of Precambrian massif blocks. It is known that seismic velocities are relatively high in geologically old and stable regions, while low in geologically young or active tectonic regions (e.g., Fishwick et al., 2005; Ritsema and van Heijst, 2000). The age-dependent seismic feature is clearly observed in the Moho *P*-velocity model (Hong and Kang, 2009) where the central East Sea region is imaged to have significant low-velocity anomalies (Fig. 10).

The crust in the East Sea is thinner than that in neighboring continental regions (e.g., 1992, Hirata et al., 1989; Kim et al., 1998). The crustally-guided shear waves, *Lg*, are attenuated significantly in the presence of thin crust (e.g., Kennett, 1986). On the other hand, *Lg* waves develop strongly in stable continental regions. The central East Sea region presents high *Lg* attenuation (equivalently, low *Lg* *Q*) (Fig. 11). The lateral variation of *Lg Q* suggests that the crust in the East Sea is a transitional structure between continental and oceanic crusts (Hong, 2010).

It is noteworthy that high Moho *P* (*Pn*) velocities and high *Lg Q* are observed in a N–S directional region off the east coast of the Korean Peninsula where high-density solidified magma is under-plated beneath the Moho (Cho et al., 2004). Similar features are observed in regions off the west coast of the Japanese Islands (Figs. 10 and 11). The similar appearances of high *Pn* velocities and high *Lg Q* at eastern and western margins of the East Sea presents signatures of the paleo-continental-rifting in the Oligocene to mid-Miocene. Also, the observation suggests that the paleo-rifting initiated in the region off the east coast of the Korean Peninsula, and the opening of the East

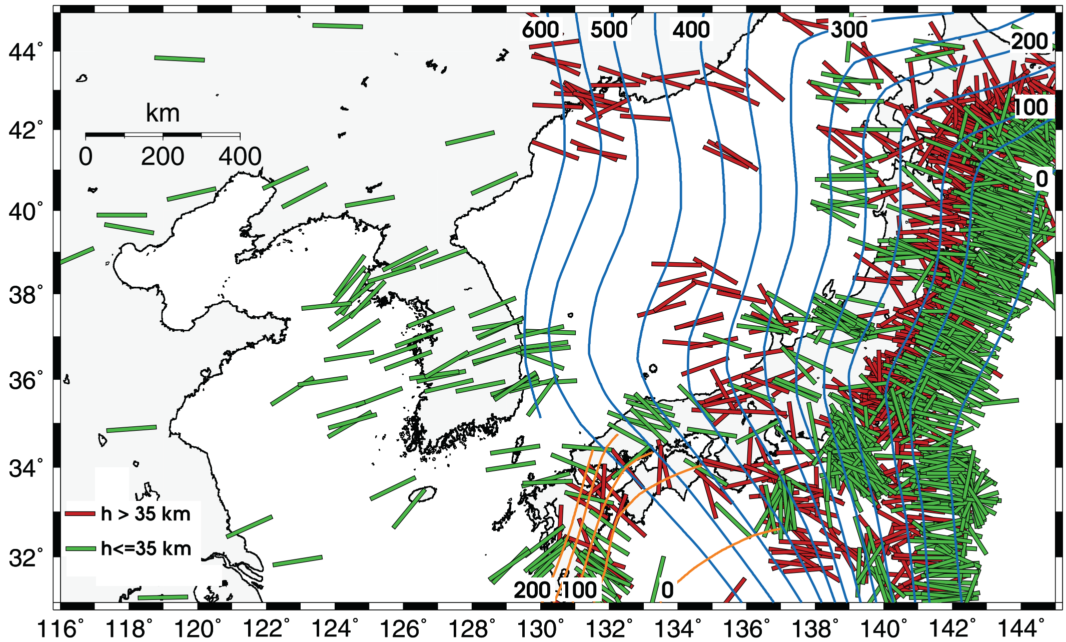


Fig. 7. Compression-axis directions around the East Sea, Korean Peninsula and Japanese Islands that are deduced from the focal mechanism solutions. The red bars indicate the compression-axis directions of events with depths greater than 35 km, while the green bars are those for events with depths less than 35 km. The subduction depths of the Pacific plate are marked with blue contours, and those of the Philippine Sea plate with orange contours.

Sea made the southern Japanese Islands separate from the Eurasian plate and move into its present position (Otofuji et al., 1985).

Shallow-focus earthquakes rarely occur in the central East Sea region (Fig. 1). This rare shallow seismicity suggests low accumulation of stress in the region. This is because the young rigid lithosphere in the East Sea responds as a whole block to the ambient stress field that is transmitted from the subduction zones. Further, rapid change of compressional-axis directions accumulates less stress in the medium than neighboring regions with laterally coherent compressional-axis directions. On the other hand, major shallow-focus earthquakes are clustered at fringes around the East Sea, off the eastern Korean Peninsula and western Japanese Islands (regions A, B, C in Fig. 3).

The earthquakes in region A are clustered mainly around the escarpment of the Ulleung Basin where seismic properties (velocity, *Lg Q*) change abruptly (Figs. 10, 11). Strike-slip and thrustal crustal earthquakes occur in region A. Similarly, thrustal crustal earthquakes occur around the Noto Peninsula (region B) where high seismic contrasts are observed. In region C, thrustal earthquakes occur along the

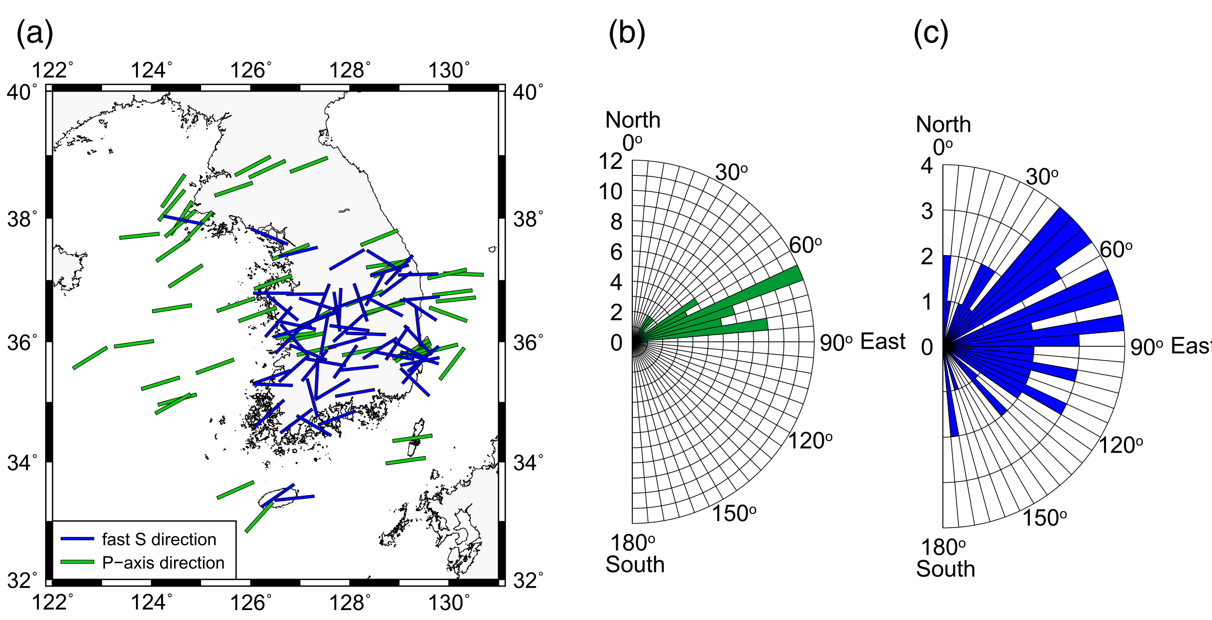


Fig. 8. (a) Comparison between compression-axis directions (green bars) and fast shear-wave directions (blue bars) around the Korean Peninsula. The compression-axis directions are calculated from focal mechanism solutions. Rose diagrams of (b) the compressional-axis directions and (c) fast shear-wave directions in the Korean Peninsula. The fast shear-wave directions are close to the compression-axis directions in the region. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Please cite this article as: Choi, H., et al., Seismic evidence for reverse activation of a paleo-rifting system in the East Sea (Sea of Japan), Tectonophysics (2012), doi:10.1016/j.tecto.2011.12.023

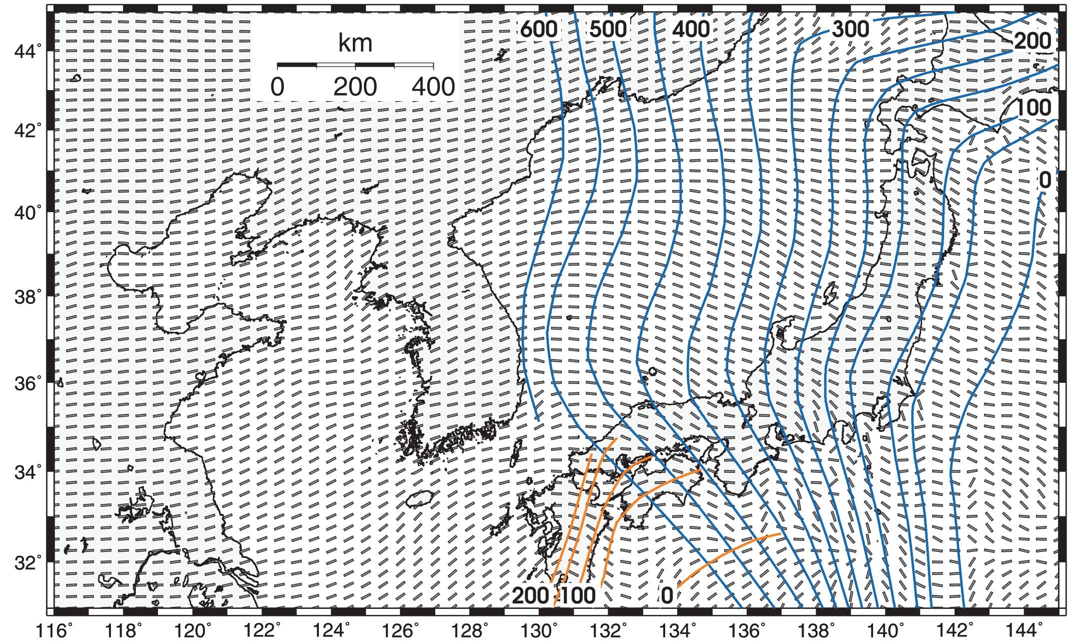


Fig. 9. Compressional stress field deduced from P-axis directions of focal mechanism solutions. Depths of subducting slabs of the Pacific and Philippine Sea plates are denoted. The compressional stress directions are observed to be correlated well with the slab penetration directions.

plate boundary between the Okhotsk and Eurasian plates. Thus, the events in the East Sea appear to occur mainly in regions with high seismic contrasts or along active plate boundaries.

It is known that normal faults typically develop in extensional regimes such as back-arc basins and continental passive margins (e.g. Sibson, 2002; Uyeda and Kanamori, 1979). Seismic reflection surveys identified various normal faulting systems around the fringes of the East Sea that were developed during the opening of the East Sea (e.g. Kim et al., 2007; Sato, 1994).

The East Sea region remains under compressional regime since the late mid-Miocene, and currently experiences shortening in the crust. The compressional stresses are accumulated in the rigid and paleo-

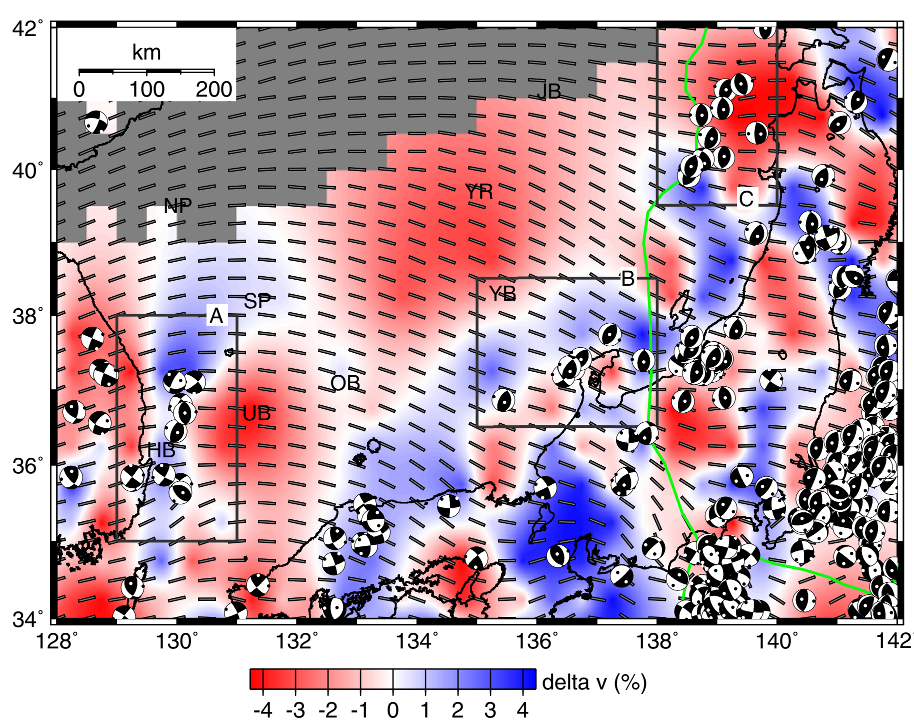


Fig. 10. Focal mechanism solutions and mantle-lid *P*-wave (*Pn*) velocities (Hong and Kang, 2009) in the East Sea (Sea of Japan). The ambient compressional stress fields are denoted with dotted lines. The reference *Pn* velocity is 7.95 km/s. The major tectonic structures are denoted: Hupo bank (HB), Japan Basin (JB), North Korea plateau (NP), Oki bank (OB), South Korea plateau (SP), Ulleung Basin (UB), Yamato Basin (YB), and Yamato rise (YR). The compressional direction changes progressively in the East Sea. The central East Sea regions display rapid changes of azimuthal directions of compressional axes, and show low *Pn* velocities. Offshore events are clustered in regions (A, B, C) either around plate boundaries or with high gradients of *Pn* velocities.

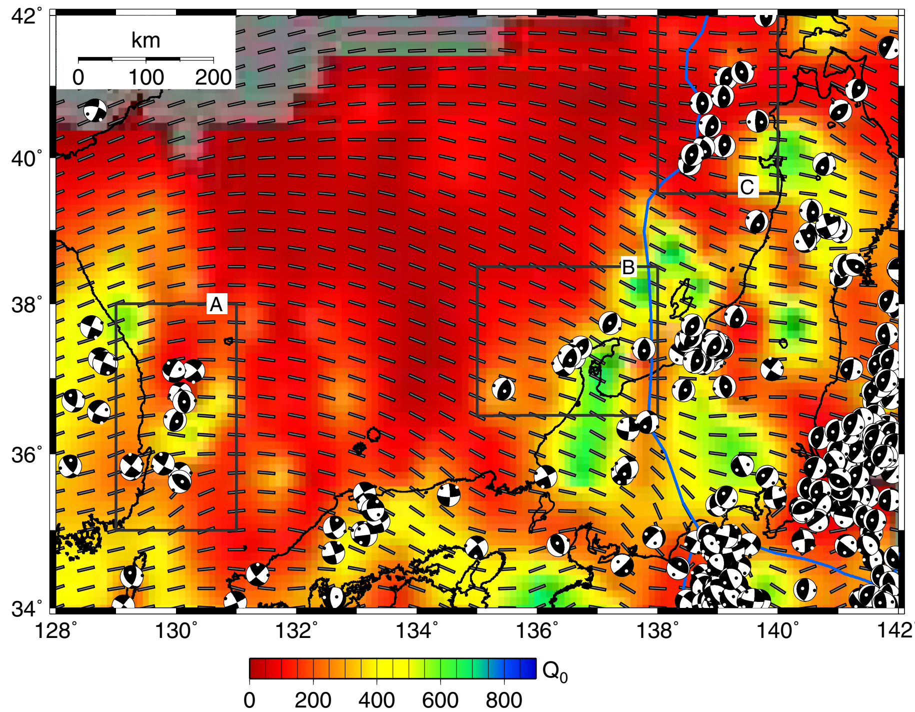


Fig. 11. Focal mechanism solutions and *Lg Q* structure (Hong, 2010) in the East Sea. The ambient compressional stress fields are presented with dotted lines. The offshore events in the East Sea (Sea of Japan) are clustered at regions with high gradients of *Lg Q*.

rifting regions in the fringes of the East Sea, causing subsequent development of vertical fractures and reverse activation of paleo normal faults (Horozal et al., 2009;Itoh et al., 2006; Fig. 12).

8. Conclusions

The properties and occurrence mechanisms of shallow-focus earthquakes in the East Sea (Sea of Japan) were investigated from lateral distribution of seismicity, fault-plane solutions, ambient stress field and tectonic structures. The seismicity in the Korean Peninsula appears to be diffuse, while shallow-focus earthquakes are observed to be clustered around the fringes of the East Sea, but are rarely in the central East Sea.

The focal mechanism solutions were calculated using waveform inversions and polarity analysis. Ambient stress fields were deduced from the focal mechanism solutions. The compressional-axis directions in the East Sea were found to change rapidly from ENE to SE with increasing longitudes. The compressional-axis directions in the eastern margin of the East Sea coincide with the subduction directions of the Pacific and Philippine Sea plates. This observation suggests that the crustal stress field in the East Sea is dominantly controlled by the relative motions of adjacent plates.

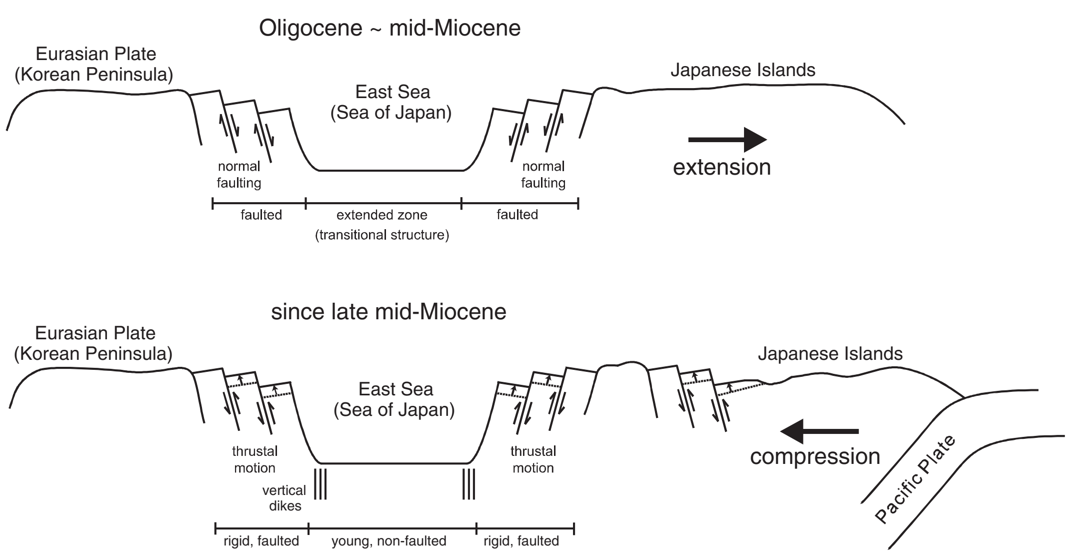


Fig. 12. A schematic 2-D model for development of normal and thrustal faults in the East Sea (Sea of Japan). (top) Seaward-dipping normal faults were developed by paleo-rifting during the Oligocene to mid-Miocene, which caused an opening of the East Sea. (bottom) Compression since the late mid-Miocene has caused contractions in the East Sea region. The compression field inverts the palaeo-normal-faulting systems on the marginal East Sea, resulting in the activation of thrust faults. Vertical fractures developed in regions between the marginal and central East Sea.

Please cite this article as: Choi, H., et al., Seismic evidence for reverse activation of a paleo-rifting system in the East Sea (Sea of Japan), Tectonophysics (2012), doi:10.1016/j.tecto.2011.12.023

The compressional stress field in the Korean Peninsula is supported by observation of crustal seismic anisotropy that was measured from short-period local shear waves. The fast shear-wave directions in the Korean Peninsula are determined to be 40°–90°, which are consistent with ambient compressional stress field. High *Lg Q* is observed in the Korean Peninsula, while low *Lg Q* in the central East Sea. The lateral variation of *Lg Q* suggests that the East Sea has a transitional structure between continental and oceanic crusts. Also, high *Pn* velocities are observed in Precambrian massif blocks in the Korean Peninsula, while low *Pn* velocities are observed in the central East Sea that was formed during the Oligocene to mid-Miocene. High *Lg Q* and high *Pn* velocities are observed in the eastern and western margins of the East Sea where magma underplating and continental margins are presents. These signatures suggest the locations of paleo-continental-rifting in the East Sea.

The rapid lateral variation of compressional-axis directions hinders the stress accumulation in the young and rigid crust of the central East Sea, causing rare shallow-focus earthquakes. However, the compressional stresses are accumulated in the eastern and western margins of the East Sea where paleo-rifting structures are present. The compressional stress field activates the paleo-normal faults to move reversely, causing thrustal earthquakes. Large and moderate-size thrustal earthquakes have occurred in the regions, and such events may keep occurring with the possible accompaniment of hazardous tsunamis to the east coast of the Korean Peninsula and the west coast of the Japanese Islands.

Acknowledgments

We are grateful to the Korea Meteorological Administration (KMA) and the Korea Institute of Geoscience and Mineral Resources (KIGAM) for making seismic data available. We thank Drs. Nick Rawlinson (guest editor), Stewart Fishwick and an anonymous reviewer for careful and constructive review comments. This work was supported by the Korea Meteorological Administration Research and Development Program under Grant CATER 2007-5111.

References

Aki, K., Richards, P.G., 1980. Quantitative Seismology, Theory and Methods, Volume 1. W. H. Freeman and Company, San Francisco.

Balfour, N.J., Savage, M.K., Townend, J., 2005. Stress and crustal anisotropy in Marlborough, New Zealand: evidence for low fault strength and structure-controlled anisotropy. Geophysical Journal International 163, 1073–1086.

Bouchon, M., 1981. A simple method to calculate Green's functions for elastic layered media. Bulletin of the Seismological Society of America 71, 959–971.

Chang, S.-J., Baag, C.-E., 2006. Crustal structure in southern Korea from joint analysis of regional broadband waveforms and travel times. Bulletin of the Seismological Society of America 96, 856–870.

Cho, H.-M., Kim, H.-J., Jou, H.-T., Hong, J.-K., Baag, C.-E., 2004. Transition from rifted continental to oceanic crust at the southeastern Korean margin in the East Sea (Japan Sea). Geophysical Research Letters 31, L07606. doi:10.1029/2003GL019107.

Chough, S.K., Kwon, S.-T., Ree, J.-H., Choi, D.-K., 2000. Tectonic and sedimentary evolution of the Korean Peninsula: a review and new view. Earth Science Reviews 52, 175–235.

Christensen, N.I., 2004. Serpentinites, peridotites, and seismology. International Geology Review 46, 795–816.

Crampin, S., 1994. The fracture criticality of crustal rocks. Geophysical Journal International 118, 428–438.

Fishwick, S., Kennett, B.L.N., Reading, A.M., 2005. Contrasts in lithospheric structure within the Australian craton.insights from surface wave tomography. Earth and Planetary Science Letters 231, 163–176.

Fowler, C.M.R., 2005. The Solid Earth: An Introduction to Global Geophysics, 2nd ed. Cambridge University Press, Cambridge, United Kingdom, p. 685.

Fukao, Y., 1984. Evidence from core-reflected shear waves for anisotropy in the Earth's mantle. Nature 309, 695–698.

Gasperinia, P., Vannuccib, G., 2003. FPSPACK: a package of FORTRAN subroutines to manage earthquake focal mechanism data. Computers & Geosciences 29, 893–901.

Gudmundsson, O., Sambridge, M., 1998. A regionalized upper mantle (RUM) seismic model. Journal of Geophysical Research 103, 7121–7136.

Hirata, N., Tokuyama, H., Chung, T.W., 1989. An anomalously thick layering of the crust of the Yamato Basin, southeastern Sea of Japan: the final stage of back-arc spreading. Tectonophysics 165, 303–314.

Hirata, N., Karp, B.Y., Yamaguchi, T., Kanazawa, T., Suyehiro, K., Kasahara, J., Shiobara, H., Shinohara, M., Kinoshita, H., 1992. Oceanic crust in the Japan Basin of the Japan Sea by the 1990 Japan-USSR expedition. Geophysical Research Letters 19, 2027–2030.

Hong, T.-K., 2010. Lg attenuation in a region with both continental and oceanic environments. Bulletin of the Seismological Society of America 100, 851–858.

Hong, T.-K., Kang, T.-S., 2009. Pn travel-time tomography of the paleo-continental-collision and Rifting Zone around Korea and Japan. Bulletin of the Seismological Society of America 99, 416–421.

Hong, T.-K., Rhie, J., 2009. Regional source scaling of the 9 October 2006 underground nuclear explosion in North Korea. Bulletin of the Seismological Society of America 99, 2523–2540.

Hong, T.-K., Baag, C.-E., Choi, H., Sheen, D.-H., 2008. Regional seismic observations of the October 9, 2006 underground nuclear explosion in North Korea and the influence of crustal structure on regional phases. Journal of Geophysical Research 113, B03305. doi:10.1029/2007JB004950.

Horozal, S., Lee, G.H., Yi, B.Y., Yoo, D.G., Park, K.P., Lee, H.Y., Kim, W., Kim, H.J., Lee, K., 2009. Seismic indicators of gas hydrate and associated gas in the Ulleung Basin, East Sea (Japan Sea) and implications of heat flows derived from depths of the bottom-simulating reflector. Marine Geology 258, 126–138.

Itoh, Y., Uno, K., Arato, H., 2006. Seismic evidence of divergent rifting and subsequent deformation in the southern Japan Sea, and a Cenozoic tectonic synthesis of the eastern Eurasian margin. Journal of Asian Earth Sciences 27, 933–942.

Jin, S., Park, P.-H., 2007. Tectonic activities and deformation in South Korea constrained by GPS observations. International Journal of Geology 2, 11–15.

Jo, N., Baag, C.-E., 2007. The 20 January, MW 4.5, Odaesan, Korea, earthquake. Geosciences Journal 11, 51–58.

Jolivet, L., Huchon, P., 1989. Crustal scale strike-slip deformation in Hokkaido, northeast Japan. Structural Geology 11, 509–522.

Jolivet, L., Tamaki, K., Fournier, M., 1994. Japan Sea, opening history and mechanism: a synthesis. Journal of Geophysical Research 99, 22237–22259.

Jun, M.-S., 1991. Body-wave analysis for shallow intraplate earthquakes in the Korean Peninsula and Yellow Sea. Tectonophysics 192, 345–357.

Kang, T.-S., Baag, C.-E., 2004. The 29 May 2004, Mw=5.1, offshore Uljin earthquake, Korea. Geosciences Journal 8, 115–123.

Kano, K., Yoshikawa, T., Yanagisawa, Y., Ogasawara, K., Danhara, T., 2002. An unconformity in the early Miocene syn-rifting succession, northern Noto Peninsula, Japan: evidence for short-term uplifting precedent to the rapid opening of the Japan Sea. Islands Arc 11, 170–184.

Kennett, B.L.N., 1986. Lg waves and structural boundaries. Bulletin of the Seismological Society of America 76, 1133–1141.

Kim, S.G., Kraeva, N., 1999. Source parameter determination of local earthquakes in Korea using moment tensor inversion of single station data. Bulletin of the Seismological Society of America 89, 1077–1082.

Kim, H.-J., Han, S.-J., Lee, G.H., Huh, S., 1998. Seismic study of the Ulleung Basin crust and its implications for the opening of the East Sea (Japan Sea). Marine Geophysical Research 20, 219–237.

Kim, W.-Y., Noh, M., Choi, H., 2006. The 29 May 2004 offshore southeast coast of Korea earthquake sequence: shallow earthquakes in the Ulleung back-arc basin, East Sea (Sea of Japan). Journal of the Korean Geophysical Society 9, 249–262 (in Korean).

Kim, H.-J., Lee, G.H., Jou, H.-T., Cho, H.-M., Yoo, H.-S., Park, G.-T., Kim, J.-S., 2007. Evolution of the eastern margin of Korea: constraints on the opening of the East Sea (Japan Sea). Tectonophysics 436, 37–55.

Klein, F.W., 2007. User's Guide to HYPOINVERSE-2000, a Fortran Program to Solve for Earthquake Locations and Magnitudes, Open File Report 02-171, U.S. Geological Survey, Revised, Version 1.1.

Levin, V., Menke, W., Park, J., 1999. Shear wave splitting in the Appalachians and the Urals: a case for multilayered anisotropy. Journal of Geophysical Research 104, 17975–17993.

Nakajima, J., Hasegawa, A., 2007. Subduction of the Philippine Sea plate beneath southwestern Japan: slab geometry and its relationship to arc magmatism. Journal of Geophysical Research 112, B08306. doi:10.1029/2006JB004770.

Oh, C.W., 2006. A new concept on tectonic correlation between Korea, China and Japan: histories from the late Proterozoic to Cretaceous. Gondwana Research 9, 47–61.

Otofuji, Y.-I., Matsuda, T., 1983. Paleomagnetic evidence for the clockwise rotation of Southwest Japan. Earth and Planetary Science Letters 62, 349–359.

Otofuji, Y.-I., Matsuda, T., Nohda, S., 1985. Opening mode of the Japan Sea inferred from the palaeomagnetism of the Japan Arc. Nature 317, 603–604.

Park, S.-C., Mori, J., 2005. Source parameters of the May 29, 2004 South Korea earthquake (M_L 5.2). Earth Planets Space 57, 471–475.

Park, J.-C., Kim, W., Chung, T.W., Baag, C.-E., Ree, J.-H., 2007. Focal mechanisms of recent earthquakes in the Southern Korean Peninsula. Geophysical Journal International 169, 1103–1114.

Rhie, J., Kim, S., 2010. Regional moment tensor determination in the southern Korean Peninsula. Geosciences Journal 14, 329–333.

Ritsema, J., van Heijst, H., 2000. New seismic model of the upper mantle beneath Africa. Geology 28, 63–66.

Sato, H., 1994. The relationship between late Cenozoic tectonic events and stress field and basin development in northeast Japan. Journal of Geophysical Research 99, 22261–22274.

Savage, M.K., 1999. Seismic anisotropy and mantle deformation: what have we learned from shear wave splitting? Reviews of Geophysics 37, 65–106.

Savage, M.K., Silver, P.G., 1993. Mantle deformation and tectonics: constraints from seismic anisotropy in the western United States. Physics of the Earth and Planetary Interiors 78, 207–227.

Please cite this article as: Choi, H., et al., Seismic evidence for reverse activation of a paleo-rifting system in the East Sea (Sea of Japan), Tectonophysics (2012), doi:10.1016/j.tecto.2011.12.023

Seno, T., Sakurai, T., Stein, S., 1996. Can the Okhostsk plate be discriminated from the North American plate? Journal of Geophysical Research 101, 11305–11315.

Sibson, R.H., 2002. Geology of the Crustal Earthquake Source. In: Lee, W.H.K., Jennings, P., Kisslinger, C., Kanamori, H. (Eds.), International handbook of earthquake & engineering seismology, Part A. Academic Press, pp. 455–473.

Snoke, J.A., 2002. FOCMEC: FOcal MEChanism determinations. In: Lee, W.H.K., Kanamori, H., Jennings, P.C., Kisslinger, C. (Eds.), International Handbook of Earthquake and Engineering Seismology, Part B. Academic Press, San Diego, pp. 1629–1630.

Sokos, E.N., Zahradnik, J., 2008. ISOLA a Fortran code and a Matlab GUI to perform multiple-point source inversion of seismic date. Computers & Geosciences 34, 967–977.

Uyeda, S., Kanamori, H., 1979. Back-arc opening and the mode of subduction. Journal of Geophysical Research 84, 1049–1061.

Yoon, S.H., Chough, S.K., 1995. Regional strike slip in the eastern continental margin of Korea and its tectonic implications for the evolution of Ulleung Basin, East Sea (Sea of Japan). Geological Society of America Bulletin 107 (1), 83–97.

Zhang, Z.J., Wang, G., Harris, J.M., 1999. Multi-component wavefield simulation in viscous extensively dilatancy anisotropic media. Physics of the Earth and Planetary Interiors 114, 25–28.

Zoback, M.D., Zoback, M.L., 2002. State of Stress in the Earth's Lithosphere. In: Lee, W.H.K., Jennings, P., Kisslinger, C., Kanamori, H. (Eds.), International handbook of earthquake & engineering seismology, Part A. Academic Press, pp. 559–568.

Please cite this article as: Choi, H., et al., Seismic evidence for reverse activation of a paleo-rifting system in the East Sea (Sea of Japan), Tectonophysics (2012), doi:10.1016/j.tecto.2011.12.023