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The Attenuation Structure of the South Korea: A review

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ABSTRACT Fukuoka earthquake on March 20, 2005 showed the potential hazard of large events out of S. Korea. From the viewpoint of seismic hazard, seismic amplitude decrease Q^{-1} is very important. Related to the crustal cracks induced by the earthquakes, the value of Q^{-1}- high Q^{-1} regions are more attenuating than low Q^{-1} regions - shows a correlation with seismic activity; relatively higher values of Q^{-1} have been observed in seismically active areas than in stable areas. For the southeastern and central S. Korea, we first simultaneously estimated Q_P^{-1} and Q_S^{-1} by applying the extended coda-normalization method to KIGAM and KNUE network data. Estimated Q_P^{-1} and Q_S^{-1} values are 0.009 $f^{-1.05}$ and 0.004 $f^{-0.70}$ for southeastern S. Korea and 0.003 $f^{-0.54}$ and 0.003 $f^{-0.42}$ for central S. Korea, respectively. These values agree with those of seismically inactive regions such as shield. The low Q_{Lg}^{-1} value, 0.0018$f^{-0.54}$ was also obtained by the coda normalization method. In addition, we studied Q_{Lg}^{-1} by applying the source pair/receiver pair (SPRP) method to both domestic and far-regional events. The obtained Q_{Lg}^{-1} for all *Fc* is less than 0.002, which is reasonable value for a seismically inactive region.

Key words S.korea, Q^{-1}, Q_P^{-1}, Q_S^{-1}, coda-normalization method, Q_{Lg}^{-1}, source pair/receiver pair method

1. Introduction

On March 20, 2005, South Korea experienced heavy shaking caused by M 7.0 earthquake occurred at the coast of Fukuoka, northern city of Kyushu Island in Japan. Although there is no direct damage to South Korea (hereafter, S. Korea), the ground shake was estimated up to M 4 class in the southeastern Korea, and was felt far to Seoul more than 500 km hypocentral distances. This earthquake showed the potential hazard of large events out of S. Korea, and accelerated Korean government to reinforce the criterion of earthquake-resistant design of construction.

From the viewpoint of seismic hazard, amplitude decrease of seismic wave with distances is very important. Besides geometrical spreading effects and reflection and transmission coefficients at discontinuities, seismic amplitude decrease is caused by internal friction, commonly described as the inverse of the quality factor Q^{-1}. Related to the crustal cracks induced by the earthquakes, the value of Q^{-1} — high Q^{-1} regions are more attenuating than low Q^{-1} regions — shows a correlation with seismic activity; relatively higher values of Q^{-1} have been observed in seismically active areas than in stable areas (Sato and Fehler, 1998).

In S. Korea, the preliminary Q^{-1} studies initiated in the southeastern Korea where the digital seismic network started to deploy from 1994 (e.g. Jun *et al.*, 1995; Kim *et al.*, 2000). Recently, our group conducted reliable Q^{-1} research based on extensive data (e.g. Chung and Sato, 2001; Chung *et al.*, 2005). This review will provide the Q^{-1} studies for *P*, *S* and *Lg* waves in S. Korea.

2. Q_P^{-1} and Q_S^{-1} studies

2.1 The southeastern S. Korea

In S. Korea, the Yangsan fault (Fig. 1) has been receiving increasing attention in its seismic activity, because the fault lies in the industrial region where nuclear power plants are located. In Korean history, the fault is believed to be responsible for the most damaging earthquake (star in Fig. 1) that caused more than hundred deaths in A.D. 779 (Lee, 1998).

In the Yangsan fault, the first regional seismic network in Korea has been in operation by Korea Institute of Geology, Mining and Materials (KIGAM) from December

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1994 (solid squares in Fig. 1). Based on the network data, Kim *et al.* (1999) first obtained very low Q^{-1} for P-waves (hereafter, Q_P^{-1}); however, the value was derived from only ten earthquake data. There have been no reports on Q^{-1} for S-waves (hereafter, Q_S^{-1}) in Korea.

From more than 120 local earthquakes, Chung and Sato (2001) measured Q_P^{-1} and Q_S^{-1} simultaneously by using the extended coda-normalization method (Yoshimoto *et al.*, 1993). The obtained values were $0.009f^{-1.05}$ for Q_P^{-1} and $0.004f^{-0.70}$ for Q_S^{-1}, which indicate that Q_P^{-1} and Q_S^{-1} in the southeastern Korea are one of the lowermost in the world (Fig. 2; Table 1; 2). The low Q_P^{-1} and Q_S^{-1} values correspond to those of the seismically stable regions such as shields.

2.2 The central S. Korea

Choongchung provinces in central S. Korea are densely populated regions, and recently received increasing attention because a new administrative capital will be constructed. In 1978, two damaging earthquakes took place in these provinces with magnitude (M) over 5.0; earthquakes over M 5 (star in Fig. 3) have occurred 3 times in S. Korea since 1905 when the instrumental recording of the earthquakes began. Historically Choongchung provinces have suffered three earthquakes with the Modified Mercalli intensity (MMI) scale estimated to be more than nine (Lee, 1998).

Beginning in December 1997, we installed the seismic network of Korea National University of Education (KNUE), and have monitored seismicity in the Choongchung provinces (Kyung *et al.*, 2000). Based on events recorded by 4 stations of the KNUE network (Fig. 3), we have analyzed Q_P^{-1} and Q_S^{-1} using the extended coda normalization method (Yoshimoto *et al.*, 1993). In addition, we (Kim *et al.*, 2004) studied the data of 2 stations of the network of

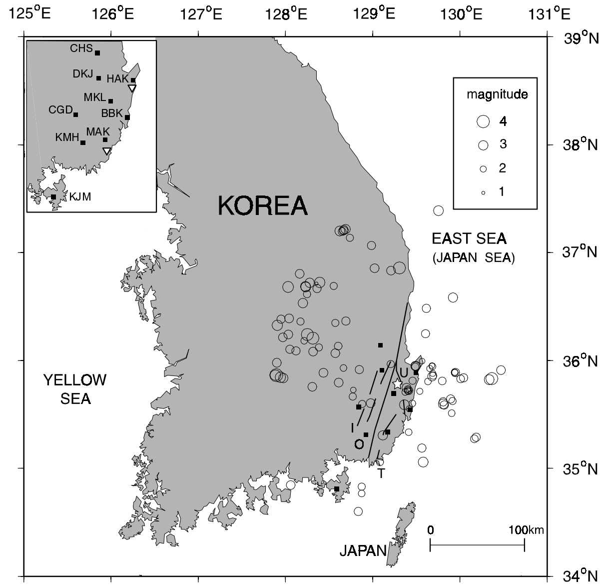

Fig. 1 Map of S. Korea showing seismic stations (solid squares), epicenters (open circles) of 121 earthquakes used in the study by Chung and Sato (2001), and the Yangsan fault systems. Solid line represents the main fault while dashed lines are subfaults: symbols I, O, U, and T show the Miryang fault, the Moryang fault, the Ulsan fault, and the Tongre fault, respectively. An asterisk represents the epicenter of the earthquake of June 26, 1997 (M 4.3). The inset in the upper left shows atomic power plants (reverse triangles) and the seismic stations of KIGAM with the abbreviation names.

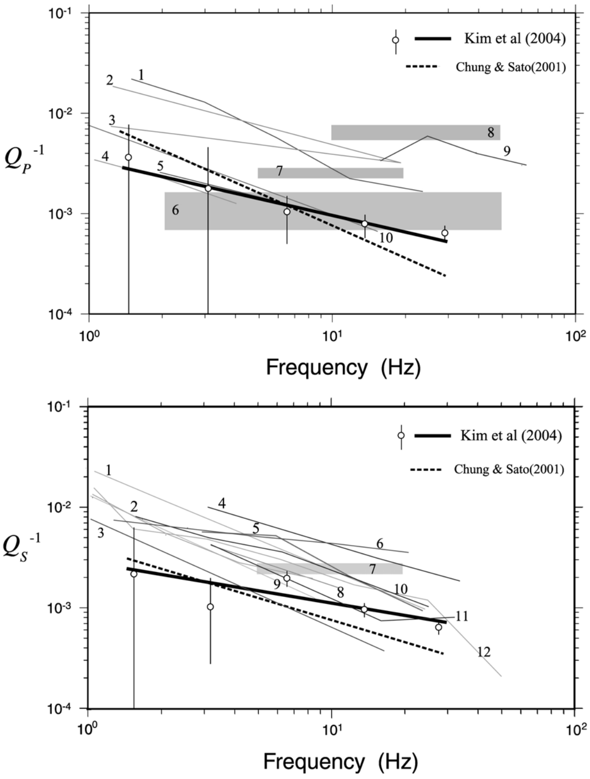

Fig. 2 Comparison of Q_P^{-1} (upper) and Q_S^{-1} (lower) values measured in our studies with the values of other regions in the world. The error bars indicate the standard deviation; bold lines refer to the best-fit regression lines by least squares. Broken lines represent the values in the southeastern S. Korea (Chung and Sato, 2001). The numbers in gray areas and lines refer to those listed in Table 1 and 2 (modified from Sato and Fehler, 1998).

Table 1 The Q_P^{-1} values shown in Fig. 2.

No.	Regions	Hypocentral Distance (km)	Values
1	Kanto, Japan (Yoshimoto *et al.*, 1993)	60 - 160	$0.031\ f^{-0.95}$ $(1.5 < f < 24$ Hz$)$
2	Depth 55-85km, Kurils (Fedotov & Boldyrev, 1969)	90 - 250	$0.0217\ f^{-0.64}$ $(1.25 < f < 20$ Hz$)$
3	Depth < 55km, Kurils (Fedotov & Boldyrev, 1969)	90 - 250	$0.0086\ f^{-0.29}$ $(1.25 < f < 20$ Hz$)$
4	Baltic shield (Kvamme & Havskov, 1989)	15 - 300	$0.008\ f^{-0.89}$ $(1.25 < f < 15$ Hz$)$
5	U.S. shield (Taylor *et al.*, 1986)	< 50°	0.001-0.007 $(0.05 < f < 5$ Hz$)$
6	France (Campillo & Plantet, 1991)	200 - 1000	$0.0042\ f^{-0.6}$ $(1.5 < f < 10$ Hz$)$
7	Arette, France (Modiano & Hatzfeld, 1982)	< 40	0.006 - 0.008 $(10 < f < 50$ Hz$)$
8	Nagano, Japan* (Yoshimoto *et al.*, 1998)	< 0.2	$0.052\ f^{-0.66}$ $(25 < f < 102$ Hz$)$
9	Northern Caribbean (Frankel, 1982)	40 - 200	0.0027-0.0033 $(5 < f < 20$ Hz$)$
10	Southern California* (Abercrombie, 1995)	5 - 120	0.0007-0.0017 $(2 < f < 50$ Hz$)$
---	Southeastern Korea (Chung & Sato, 2001)	40 - 160	$0.009 \pm 0.003\ f^{-1.05 \pm 0.14}$ $(1.5 < f < 24$ Hz$)$

* borehole record data

Table 2 The Q_S^{-1} values shown in Fig. 2.

No.	Regions	Hypocentral Distance (km)	Values
1	Southern Itali, Montenegro (Rovelli, 1983; 1984)	< 150	$0.025\ f^{-1}$ $(0.1 < f < 25$ Hz$)$
2	Hindu-Kushi (Roecker *et al.*, 1982)	100 - 250	0.0002 - 0.07 $(0.4 < f < 48$ Hz$)$
3	Pacific coast of Kanto (Takemura *et al.*, 1991)	43 - 243	0.0014-0.017 $(1 < f < 10$ Hz$)$
4	Baltic shield (Kvamme & Havskov, 1989)	15 - 300	$0.008\ f^{-1.08}$ $(1.25 < f < 15$ Hz$)$
5	Southern California (Frankel *et al.*, 1990)	15 - 90	0.002- 0.009 $(3 < f < 30$ Hz$)$
6	Eastern Kanto (Sato & Matsumura, 1980)	20 -120	$0.012\ f^{-0.65}$ $(3 < f < 23$ Hz$)$
7	Northern Itali (Console & Rovelli, 1981)	9 - 195	$0.0125\ f^{-1.1}$ $(0.1 < f < 10$ Hz$)$
8	Depth < 25km, Kurils (Fedotov & Boldyrev, 1969)	90 - 250	$0.0082\ f^{-0.26}$ $(1.25 < f < 20$ Hz$)$
9	Northern Caribbean (Frankel, 1982)	40 - 200	0.0026-0.0031 $(5 < f < 20$ Hz$)$
10	Utah (Brockman & Bollinger, 1992)	10 - 250	$0.010\ f^{-0.80}$ $(3 < f < 10$ Hz$)$
11	Kanto (Yoshimoto *et al.*, 1993)	60 - 160	$0.012\ f^{-0.73}$ $(1.5 < f < 24$ Hz$)$
12	New York State (Frankel *et al.*, 1990)	15 - 90	0.0043-0.0008 $(3 < f < 30$ Hz$)$
---	Southeastern Korea (Chung & Sato, 2001)	40 - 120	$0.004 \pm 0.001\ f^{-0.70 \pm 0.14}$ $(1.5 < f < 24$ Hz$)$

KIGAM, which have been operated since 1999.

Estimated Q_P^{-1} and Q_S^{-1} show frequency dependence that decrease from $(3.6 \pm 4.2) \times 10^{-3}$ and $(2.2 \pm 4.4) \times 10^{-3}$ at 1.5 Hz to $(6.3 \pm 0.1) \times 10^{-4}$ and $(6.5 \pm 0.1) \times 10^{-4}$ at 24 Hz, respectively. The best fit of Q_P^{-1} and Q_S^{-1} are $(3.0 \pm 0.1) \times 10^{-3}\ f^{-0.54 \pm 0.01}$ and $(3.0 \pm 0.1) \times 10^{-3}\ f^{-0.42 \pm 0.02}$, respectively. These values and those of southeastern Korea (Chung & Sato, 2001) generally correspond to those of seismically stable regions, but are slightly less dependent on frequency than those of southeastern Korea, due to large Q^{-1} values at high frequencies (Fig. 2).

3. Q_{Lg}^{-1} studies

The seismic *Lg* wave is prominent at regional distances in the continental crust. The Q_{Lg}^{-1} has been studied extensively because its regional variations reflect geological structure and tectonic activity (e.g., Sato and Fehler, 1998). Q_{Lg}^{-1} around 1 Hz, in particular, shows close correlation with tectonic seismicity; active regions have higher values than inactive regions (Aki, 1980; Jin and Aki, 1988).

Although *Lg* phases were observed for propagation paths across the Korean Peninsula (e.g. Furumura and Kennett, 2001), the Q_{Lg}^{-1} in Korea was not obtained until quite recently because of the lack of high quality seismic stations. Since 1999, digital network stations have been deployed nationwide in S. Korea, and have recorded more than one hundred earthquakes with clear *Lg* phases.

Based on this Korean event data, efforts were made to estimate Q_{Lg}^{-1} (Chung and Lee, 2002; Chung, 2002) by means of the reversed two-station method (RTSM) requiring colinear alignment of event and receiver pairs (Chun *et al.*, 1987). The results showed values higher than 0.01 at 1 Hz, which is inconclusive because of insufficient data to meet the colinear restriction. Above all, it was difficult to obtain sufficient long station spacing (*SP*) from events in S. Korea and Q_{Lg}^{-1} measurements are better determined for longer *SP*.

Recently, Chung and Lee (2003) found reliable value of Q_{Lg}^{-1} by using the coda-normalization method (CNM) and Chung *et al.* (2005) reported similar results by the source pair/receiver pair (SPRP) method (Shih *et al.*, 1994).

3.1 Q_{Lg}^{-1} by the CNM

We (Chung and Lee, 2003) first measured Q_{Lg}^{-1} of South Korea by applying CNM to long time recorded seismograms at 4 KIGAM's stations (Fig. 4): Seoul National University (SNU), Taejon (TJN), Kimcheon (KMC), Yongwang-beksu (YGB). We analyzed 345 seismograms of 50 earthquakes that occurred from January 1999 to May 2002. The hypocentral distances range between 155 and 400 km. The regression of the plots of Q_{Lg}^{-1} shows frequency dependence, which decrease from $(1.4\pm1.0)\times10^{-3}$ at 1.5 Hz to $(0.3\pm0.1)\times10^{-3}$ at 24 Hz. If we fit a power law depending on frequency, the best fit line for Q_{Lg}^{-1} is $0.0018f^{-0.54}$. This value generally agrees with those of seismically inactive region (Fig. 5).

3.2 Q_{Lg}^{-1} by the SPRP

Although reasonable value was derived by Chung and Lee (2003), their CNM method was based on the combined

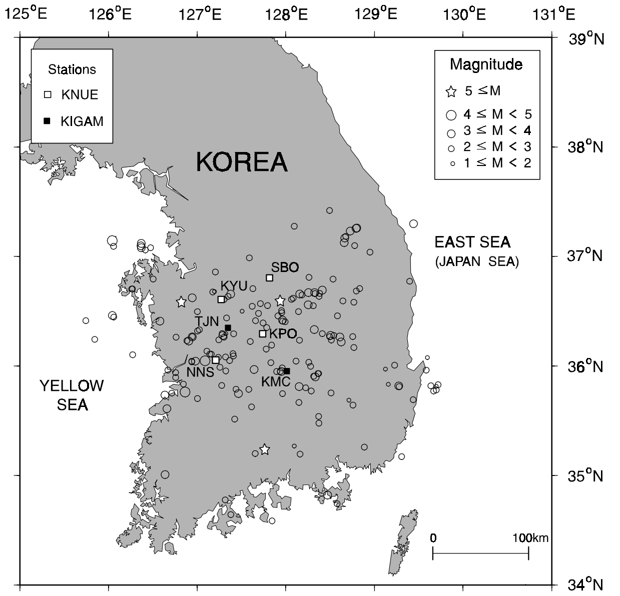

Fig. 3 Map of seismic stations and epicenters of earthquakes used in the study by Kim *et al.* (2004). Open squares and solid squares represent the network of KNUE and KIGAM, respectively. Star marks represent earthquake of M over 5.0 that occurred in S. Korea after 1905.

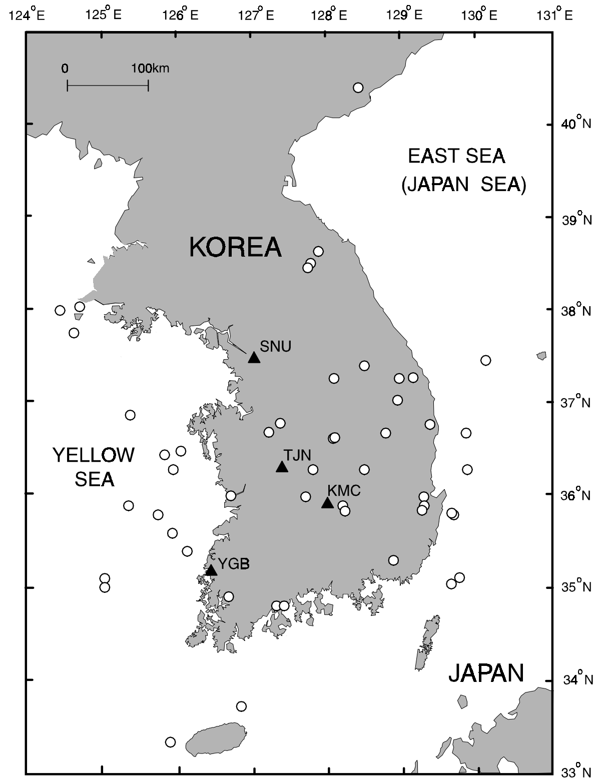

Fig. 4 Map of seismic stations SNU, TJN, KMC, and YGB (solid triangles), and epicenters of 50 earthquakes (open circles) used in the study by Chung and Lee (2003).

station data to compensate for insufficient data from individual stations. The CNM is originally single station method and is possible to extend to multiple stations showing the similar coda decay (Frankel *et al.*, 1990). Since the ambiguity could not be avoid completely in judging the coda decay similarities between the multiple stations, the previous CNM study also has a problem of insufficient data.

We (Chung *et al.*, 2005) analyzed Q_{Lg}^{-1} in S. Korea with the source pair/receiver pair (SPRP) method (Shih *et al.*, 1994), which is a generalized version of the RTSM relaxing the colinear restriction on the sources and receivers. By this modification, we can greatly increase the amount of available data for source-receiver pairs (Fig. 6). In addition, we supplement with data of far-regional events, and obtain nearly 1500 source-receiver pairs.

The obtained Q_{Lg}^{-1} values with small errors are 0.0014, 0.0011, and 0.0014 at 1.5, 3, and 6 Hz, sequentially (Fig. 5). These values are reasonable for S. Korea, as a seismically inactive region. In previous work, however, RTSM suggested anomalously high values based on the hypocentral distances within 380 km and *SP* less than 100 km (Chung and Lee, 2002, Chung, 2002). In this study, the epicentral distances and *SP* are extended to 2729 km and 505 km by applying the SPRP method to not only Korean but also far-regional events. The SPRP method also increases the available data and reduced the anomalously high values.

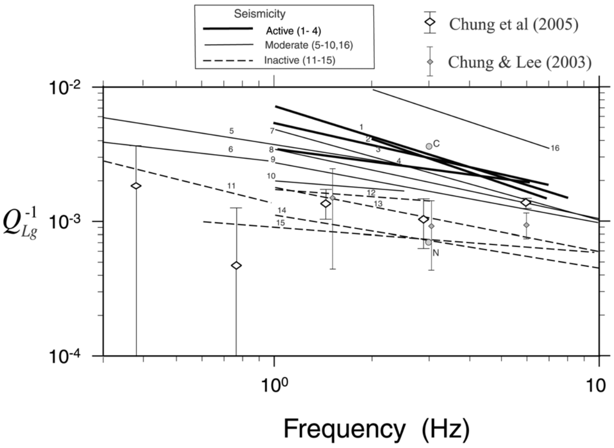

Fig. 5 The Q_{Lg}^{-1} of our results and other studies, the numbers of which correspond to those listed in Table 5. Certain regions are classified as active and inactive regions of seismicity; the thick solid lines (1- 4) denote active regions, the broken lines (11-15) denote inactive regions.

4. Discussions

4.1 Q_P^{-1} and Q_S^{-1} studies

Generally we would expect that Q^{-1} values decrease with increasing depth in the crust. Since rays penetrate to greater depth when propagating longer distance, we may expect a dependence of attenuation in epicentral distance. The measurements with hypocentral distances less than 40 km show high Q_P^{-1} in Arette, France (Modiano & Hatzfeld, 1982), and Nagano, Japan (Yoshimoto *et al.*, 1998). Very low Q_P^{-1} was obtained from events at epicentral distances between 200 and 1000 km in France (Campillo & Plantet, 1991), and over 50° in Basin and Range in North America (Taylor *et al.*, 1986). The down hole measurement at a depth of 2.5 km also shows low Q_P^{-1} values in southern California (Abercrombie, 1995). The southern Kurils, however, shows higher Q_P^{-1} from events with focal depths of 5-55 km than from events with focal depths of 55-85 km, which seems to be related to molten magma (Fedotov & Boldyrev, 1969). If we compare the events within the hypocentral range of 300 km, seismically active regions such as Kanto, Japan (Yoshimoto *et al.*, 1993) and southern Kurils have high Q_P^{-1} values, while seismically stable regions such as the Baltic Shield

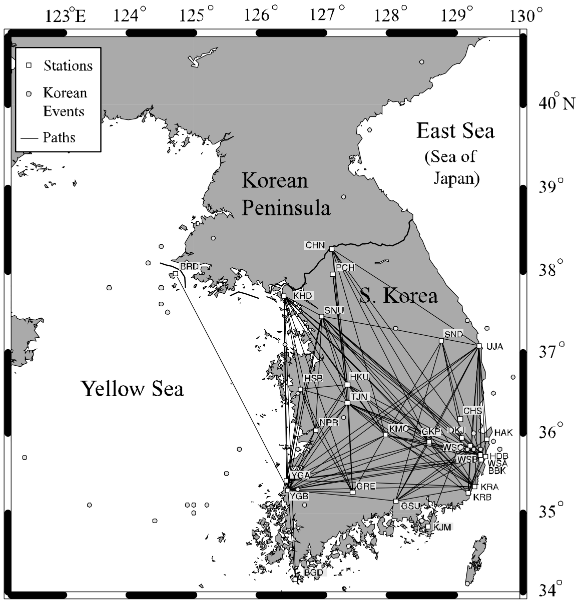

Fig. 6 Map of paths connecting 15 seismic stations (open triangles) and epicenters of 16 earthquakes (solid circles) used in the study by Chung *et al* (2005).

(Kvamme & Havskov, 1989) show low Q_P^{-1} values. Our results and those of southeastern Korea (Chung & Sato, 2001) generally correspond to the value in Baltic shield, which lies in the lowest portion of surface measurements (Fig. 2, Table 1).

Also Q_S^{-1} has lower values in seismically stable regions than in active regions. Since there were numerous studies of Q_S^{-1} compared to Q_P^{-1}, we have compiled measurements on the ground surface for the similar depth range with the longest hypocentral distances between 90 and 300 km (Fig. 2, Table 2). Similar variations in Q_P^{-1} are observed in the same region: Baltic shield, Kanto in Japan, southern Kurils, and southeastern Korea. Frankel *et al.* (1990) also reported the difference of Q_S^{-1} between New York State and southern California, which are seismically inactive and active regions, respectively. The other regions, expressed by light lines, also correlate well with seismical activity. Our Q_S^{-1} values for high frequency agree well with those of New York State.

Although our results also contain very low values, the fitted values of Q_P^{-1} and Q_S^{-1} are slightly less dependent on frequency than those of southeastern Korea, due to high Q^{-1} values at high frequencies. The high values may reflect relatively active seismicity of central S. Korea compared to southeastern S. Korea, as reflected by the large events.

4.2 Q_{Lg}^{-1} studies

Fig. 5 compares our results and measurements of Q_{Lg}^{-1} for 16 regions (Table 3), some of which are classified by worldwide seismicity level as active or inactive. All the active regions of seismicity show high Q_{Lg}^{-1}, including the Sierra Nevada, California (Paul *et al.*, 1996), southern California (Frankel *et al.*, 1990; Benz *et al.*, 1997), the subduction zone in Mexico (Domínguez *et al.*, 1997), and northern Baja California (Domínguez and Rebollar, 1997). Low Q_{Lg}^{-1} portions are occupied by inactive regions of seismicity, including Norway (Sereno *et al.*, 1988), central Appalachian (Shi *et al.*, 1996), the Adirondack mountains in the United States (Shi *et al.*, 1996), eastern Canada (Chun *et al.*, 1987), and New York State (Frankel *et al.*, 1990). We also express the values for relatively less active regions, which are distributed between the active and inactive regions of Q_{Lg}^{-1}. These regions include the Basin and Range province (Xie and Mitchell, 1990), central France (Campillo *et al.*, 1985), the Great Basin (Chávez and Priestley, 1986), the Tibetian Plateau (McNamara *et al.*, 1996), and eastern Kazakhstan (Sereno, 1990).

Table 3 The Q_{Lg}^{-1} values for regions shown in Fig. 5.

No.	Regions	Hypocentral Distance (km)	Q_0^{-1} ($\times 10^{-3}$)	Exponent	Frequency Range (Hz)
1	Southern Sierra Nevada, California (Paul *et al.*, 1996)	150- 400	7.2	-0.76	1 - 8
2	Subduction zone, Mexico (Domínguez *et al.*, 1997)	285- 640	7.5	-0.83	2 - 7
3	Southern California (Benz *et al.*, 1997)	150-1000	5.3	-0.55	1 - 7
4	Northern Baja California (Domínguez and Rebollar, 1997)	135-420	3.5	-0.32	1 - 6
5	Basin and Range province (Xie & Mitchell, 1990)	300-2910	3.7	-0.37	0.2 - 2.5
6	Eastern China (Shih *et al.*, 1994)	> 6000	2.7	-0.29	0.167 - 1.0
7	Central France (Campillo *et al.*, 1985)	289-576	3.4	-0.52	0.5 - 10
8	Great Basin (Chávez & Priestley, 1986)	200-500	4.9	-0.68	0.3 - 10
9	Tibetian Plateau (McNamara *et al.*, 1996)	150-700	2.8	-0.45	5 - 16
10	Eastern Kazakhstan (Sereno, 1990)	200-1300	2.0	-0.19	0.5 - 2.5
11	Northern China (Shih *et al.*, 1994)	> 6000	1.4	-0.61	0.167 - 1.0
12	Norway (Sereno *et al.*, 1988)	200-1400	1.7	-0.26	1 - 7
13	Central Appalachian (Shi *et al.*, 1996)	< 1394	1.8	-0.47	1 - 15
14	Eastern Canada (Chun *et al.*, 1987)	90 - 867	0.9	-0.19	0.6 - 10
15	Adirondack mountains in the U.S.A. (Shi *et al.*, 1996);	< 1394	1.4	-0.46	1 - 15
16	Granada basin, southern Spain (De Miguel *et al.*, 1992)	80 - 250	9.5	-0.93	1 - 18

The Granada basin in southern Spain (De Miguel *et al.*, 1992), however, shows an anomalously high value as a relatively less active region. The value was derived using RSTM with the *SP* less than 60 km. For the southeastern Korea, Kim *et al.* (1999) also reported that the RSTM produced anomalously high value as $Q_P^{-1}(f) = 0.033f^{-1.48}$ from the *SP* less than 53 km. Q_{Lg}^{-1} studies in S. Korea for the *SP* less than 100 km (Chung and Lee, 2002, Chung, 2002) suggested almost ten times higher values than that of the CNM. These high values seem to be related to high Q^{-1} of shallow crust due to the close *SP*. Originally, Chun *et al.* (1987) obtained reasonably low Q^{-1} value for eastern Canada by weighting for the longer *SP*, the longest *SP* is 210 km (Fig. 5).

By using the SPRP method and far-regional events, the long *SP* extending to 505 km produces the Q_{Lg}^{-1} value generally correlate well with seismically inactive regions (Fig. 5). In addition, the errors at higher than 1.5 Hz are smaller than those of the previous study (Chung and Lee, 2003), which generally agree with the Q_{Lg}^{-1} found here. Nearly 1500 source-receiver pairs in our study provided the combined difference of epicentral distance, *D* ranging from 16 to 657 km. The large errors at low frequencies, however, are most likely caused by the short *D*, because the SPRP method was initially applied for the very long *D* up to 6000 km. Nonetheless, we find the SPRP method done with the short *D* provides reliable results at 1.5 and 3 Hz, at which clearly correlate with tectonic seismicity.

5. Conclusions

Fukuoka earthquake on March 20, 2005 showed the potential hazard of large events out of S. Korea. From the viewpoint of seismic hazard, seismic amplitude decrease Q^{-1} is very important. Related to the crustal cracks induced by the earthquakes, the value of Q^{-1} − high Q^{-1} regions are more attenuating than low Q^{-1} regions − shows a correlation with seismic activity; relatively higher values of Q^{-1} have been observed in seismically active areas than in stable areas.

For the southeastern and central S. Korea, we first simultaneously estimated Q_P^{-1} and Q_S^{-1} by applying the extended coda-normalization method to KIGAM and KNUE network data. Estimated Q_P^{-1} and Q_S^{-1} values are $0.009f^{-1.05}$ and $0.004f^{-0.70}$ for southeastern S. Korea and $0.003f^{-0.54}$ and $0.003f^{-0.42}$ for central S. Korea, respectively. These values agree with those of seismically inactive regions such as shield. The low Q_{Lg}^{-1} value, $0.0018f^{-0.54}$ was also obtained by the coda normalization method. In addition, we studied Q_{Lg}^{-1} by applying the SPRP method to both domestic and far-regional events. The obtained Q_{Lg}^{-1} for all *Fc* is less than 0.002, which is reasonable value for a seismically inactive region.

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