J. Nat. Acad. Sci. ROK, Vol. 63, No. 1 (2024) 171-182

Deep crustal earthquakes in the Korean peninsula

Kiehwa Lee*

한반도의 심부 지각에서 발생한 지진들

이 기 화*

ABSTRACT

Nearly all of the instrumental earthquakes since the 20th century in the Korean peninsula have been occurring in the upper crust less than 15km thick. However, there are quite a few historical earthquakes during the last 2,000 years which are suspected to have occurred deep in the crust. This paper demonstrates that deep crustal earthquakes actually occurred using the historic earthquake data.

Key words : Earthquakes, Deep crustal earthquakes. Historical earthquakes. Korean peninsula.

초 록

20세기 이후 한반도에서 거의 전부의 지진들은 두께 15km 이하의 상부 지각에서 발생하고 있다. 그러나 지난 2,000년간의 한반도 역사지진 자료에는 이보다 더 깊은 심부 지각에서 발생했다고 여겨지는 다수의 지진들이 있다. 이 논문은 역사지진자료를 이용하여 실제로 심부지각에서 지진들이 발생하였음을 보여준다.

주제어; 지진, 심부지각 지진, 역사지진, 한반도

---

* Member, The National Academy of Sciences, Republic of Korea

목 차

Ⅰ. Introduction

One of the important problems to be resolved in the seismicity of the Korean peninsula is the following question; how deep can earthquakes occur? Since earthquakes only provide most valuable information on the tectonic structures and processes deep in the earth, the depths of the shocks are of prime importance in understanding the vertical extent of tectonics going on in a particular region. Depths of nearly all instrumental earthquakes since the 20th century determined by KMA (Korea Meteorological Administration) are limited to less than 15km in the upper crust. However, there exist quite a few historical earthquakes during the last 2,000 years which seem to have occurred deep in the lower crust. The purpose of this paper is to estimate the depths of historical shocks from macroseismic data in the Korean historical literatures.

Ⅱ Estimation of Intensity

Regarding the sizes of historical earthquakes, only their intensities, not magnitudes, may be estimated by descriptions of earthquake damages and/or phenomena in the historical literatures. One of the serious problems in the Korean historical earthquakes is that there are many cases in which a shock was felt over a large area without specific reports on damages or earthquake effects at some locations in the felt area. Therefore, it is needed to find a way of estimating maximum or epicentral intensities of these shocks in order to better understand the seismicity of the peninsula quantitatively.

In many cases, the decrease of intensity with hypocentral distance, Δ, is expressed as follows:

$$I = I_0 + a - b\ln\Delta - c\Delta \qquad (1)$$

where I_0 and I are epicentral intensity and intensity at hypocentral distance Δ, respectively, a constant: and b and c are constants representing geometrical spreading and rate of absorption (Howell and Schultz, 1975). It should be noted that equation (1) is applicable only in the far field region where epicentral distance is large enough compared to source dimensions.

Applications of equation (1) to various parts of the world have revealed that rates of absorption for different tectonic regions differ significantly. For instance, in North America, c values for the Eastern and Southern California provinces are 0.001/km and 0.01/km, respectively (Nuttli, 1973), reflecting an order of higher absorption in the tectonically unstable California than in the stable East. This point suggests that the crustal and upper mantle velocity and absorption structure may be reflected in the absorption rate of intensity attenuation.

Lee (1984) obtained the following intensity, MMI, attenuation relation for earthquakes in the Korean peninsula, based on two MMI Ⅷ earthquakes, the 1939 Ssanggyesa and the 1978 Hongsung earthquake whose focal depths are estimated as 10km:

$$I = I_0 - 0.191 - 0.834\ln\Delta - 0.0068\Delta \qquad (2)$$

where $\Delta = \sqrt{R^2 + (10)^2}$, and R is epicentral distance.

It is interesting to note the absorption rate 0.0068/km for the Korean peninsula lies between those of 0.001/km for the stable Eastern province and 0.01/km for the unstable California province.

Based on equation. (2), Lee et al. (1985) proposed the following procedure to estimate the epicentral intensities of historical earthquakes in the Korea peninsula which provide no specific information on earthquake damage or phenomena. First, draw a smooth curve enclosing all felt places and estimate the felt area A with planimeter, Second, compute $R = \sqrt{(A/\pi}$, which is the radius of a circle of area A. Assuming MMI Ⅲ at $\Delta = \sqrt{R^2 + (10)^2}$, estimate Io from equation (2) for the value of R thus obtained.

However, since equation. (1) is based on two MMI Ⅷ earthquakes in the peninsula, a new relation is needed to estimate intensities for stronger shocks of MMI greater than Ⅷ (Ⅷ-Ⅹ). But more important than this point is that the intensity attenuation actually depends not only on distance but also on epicentral intensity. Taking this phenomenon into account, Grandori et al. (1991) proposed a method to assess the intensity attenuation which depends on distance and epicentral intensity as well. Lee and Kim (2002) adopted this method and derived the following relation using 11 MMI ≥Ⅷ earthquake data in the Sino-Korean craton during the 20^{th} century.

$$Io - I = 1/\ln\varphi * \ln[1 + (\varphi - 1)/\varphi o * (D/Do - 1)], \qquad (3)$$

where φo and φ are constants having values of 1.31 and 1.77, respectively; and values of Do are 5.2, 6.5, and 9.3km for Io of Ⅷ, Ⅸ, and Ⅹ, respectively; and D is the epicentral distance for I. Equation (3) turns out to better fit the data in the Sino-Korean craton for MMI Ⅷ - Ⅹ.

The northeastern part of China and the Korean peninsula are geologically connected, and they are collectively referred to as the Sino-Korean craton. Furthermore, temporal variation of strain release in the northeastern part of China (Mei, 1960) is similar to that in the Korean peninsula (Lee, 1998).

For earthquakes without any definite descriptions about earthquake damages and/or effects, equation (2) and (3) may be used to approximately estimate the epicentral (or maximum) intensities of the Korean historical earthquakes: equation (2) for V≤ MMI ≤ Ⅶ, and equation (3) for Ⅷ ≤ MMI ≤ X. Regarding the intensity at the boundary of felt area as MMI Ⅲ, and substituting the value of R or D obtained from the felt area in equations (2) or (3), we can approximately estimate epicentral intensities.

Alternatively, we can estimate maximum intensities if specific descriptions of earthquake damages or effects are available at some locations in the felt area. In many cases of historical earthquakes, only felt places are given However, in some cases, the maximum intensities can be estimated from damage reports as well as equations (2) or (3). Most of the values obtained by two methods are equal or differ by one unit; in such cases. larger values are adopted as maximum intensities.

Ⅲ. Estimation of Focal Depth

Among seismological source parameters, the focal depth is most difficult to determine precisely. Even in instrumental earthquakes, a dense seismic network close to and enclosing the epicenter is required for accurate determination of focal depths. For historical earthquakes, accurate determination of focal depths depending only on the insufficient and unscientific macroseismic data is even more difficult than for instrumental earthquakes.

It has been known that deep earthquakes are felt more widely than shallow ones for a given epicentral intensity. Bath (1975) gave the following relation relating focal depth to epicentral intensity and epicentral distance:

$$Io - I = 3 \log \{(r^2+h^2)/h^2\} \qquad (4)$$

where Io and I are epicentral intensity and intensity at epicentral distance r, respectively, and h is the focal depth. In this relation, a point source is assumed, and inelastic absorption of seismic energy is not considered. However, this relation may be used to approximately estimate the focal depth of Korean historical earthquake if reliable information on epicentral intensity (Io) and average radius of felt area (r) are available.

Ⅳ. Experimentations with Data

Below are given some focal depths of Korean historical earthquakes estimated by equation (4).

1. 1416 May 23

Earth quaked in Andong. Cheongdo, Seonsan, Bocheon, Uiseong, Uiheung, Gunwi, Boseong and Mungyeong, Gyeongsang province, and Chungju, Cheongpung, Goesan, Danyang, Yeonpung and Eumseong, Chungcheong province.

Shaking was severest in Andong. Tiles slid down from the roofs (Fig. 1).

For this shock, Ios estimated from earthquake damage and and equation (2) are MMI Ⅵ and Ⅶ, respectively, and r is about 100km. If we substitute these values into equation (4), we obtain h about 32km for MMI Ⅵ and 21km for MMI Ⅶ. The depth to the Moho-discontinuity in the Korean peninsula is estimated as 33km (Yoo et. al., 2007). So, this shock may be regarded as a deep crustal earthquake.

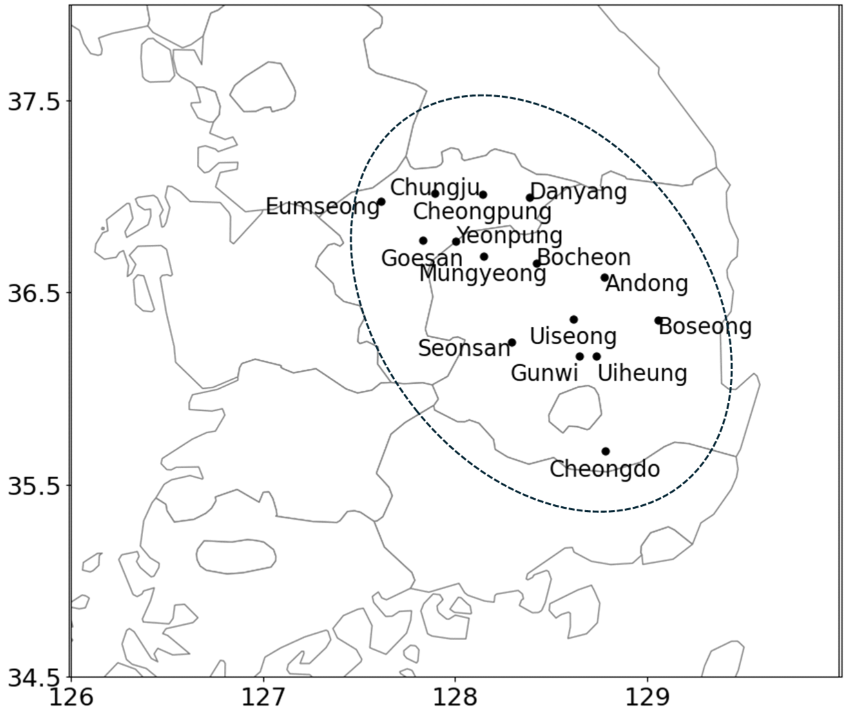

Figure 1. 1416 May 23 earthquake. Dotted curve encloses the felt area.

2. 1525 September 22

Earth quaked in Sangju, Hamchang, Punggi, Yonggung, and Mungyeong, Gyeongsang province. Houses shook in Mungyeong (Fig. 2).

For this shock, Ios estimated from earthquake damage and and equation (2) are MMI Ⅴ and Ⅵ, respectively and r is about 30km. Similarly, we obtain h about 14km. for Ios MMI Ⅴ and 9.5km for Ⅵ, respectively. From this, this shock may be regarded as a shallow crustal earthquake.

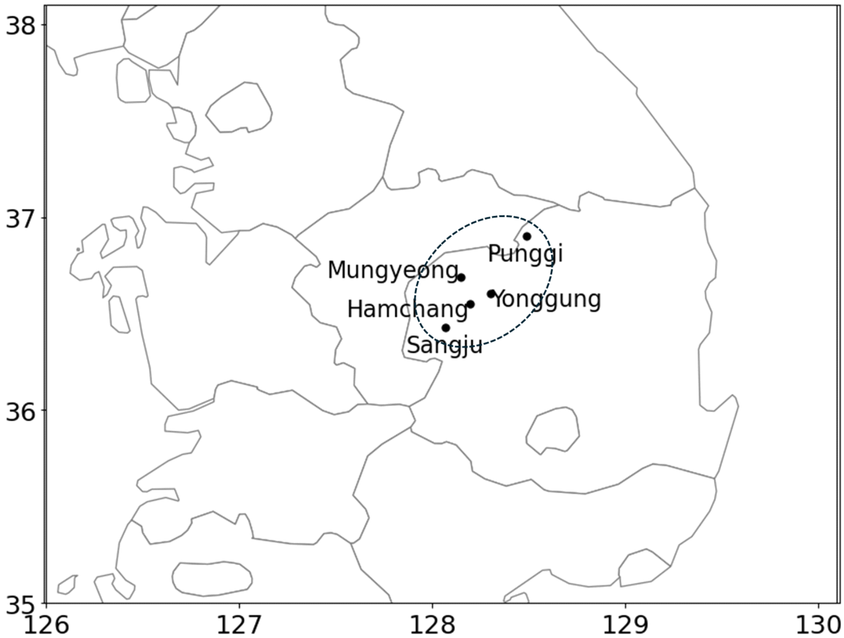

Figure 2. 1525 September 22 earthquake. Dotted curve encloses the felt area.

3. 1610 April 9

Earth quaked from north towards south with thunderous sound shaking all houses for a while in Boeun, Chungcheong province. (Fig. 3)

For this shock, Io is MMI V both from earthquake damage and equation (2), and r is about 10km. We obtain h about 4,6 km. This earthquake may be a shallow crustal shock.

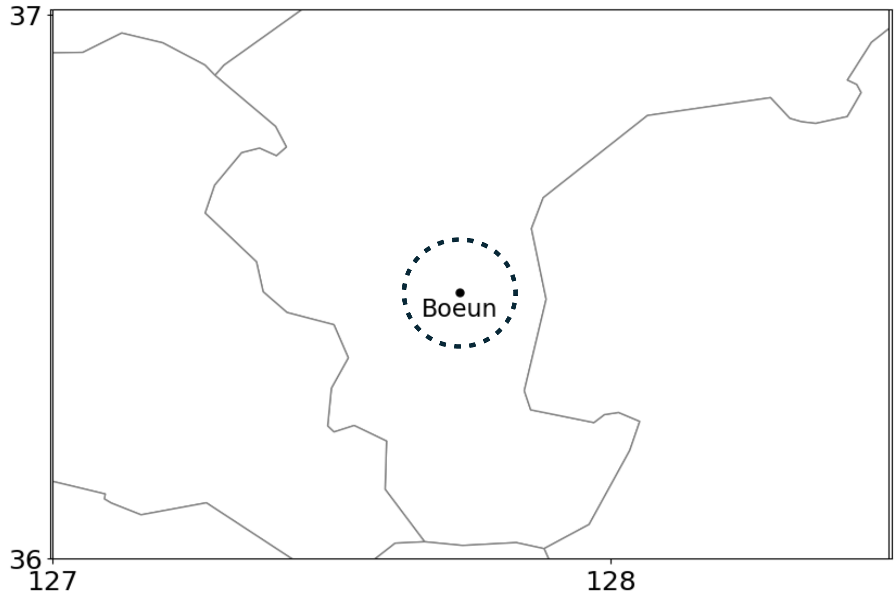

Figure 3. 1610 April 9 earthquake. Dotted curve encloses the felt area.

4. 1670 October 4

Earth quaked shaking all houses and destroying fences at about 7 p.m. in 27 towns including Daegu, Gyeongsang province.

Earth quaked in towns including Chungju, Chungcheong province.

Earth quaked in towns including Geoje, Gyeongsang province.

Earth quaked more violently than ever in 33 towns including Gwangju, Jeolla province (Fig.4)

For this shock, Ios estimated from earthquake damage and and equation (2) are MMI Ⅶ and Ⅷ, respectively, and r is about 150km.

Thus, we obtain h about 32km for MMI Ⅶ and 22km for MMI Ⅷ, respectively. This shock looks like a deep crustal earthquake.

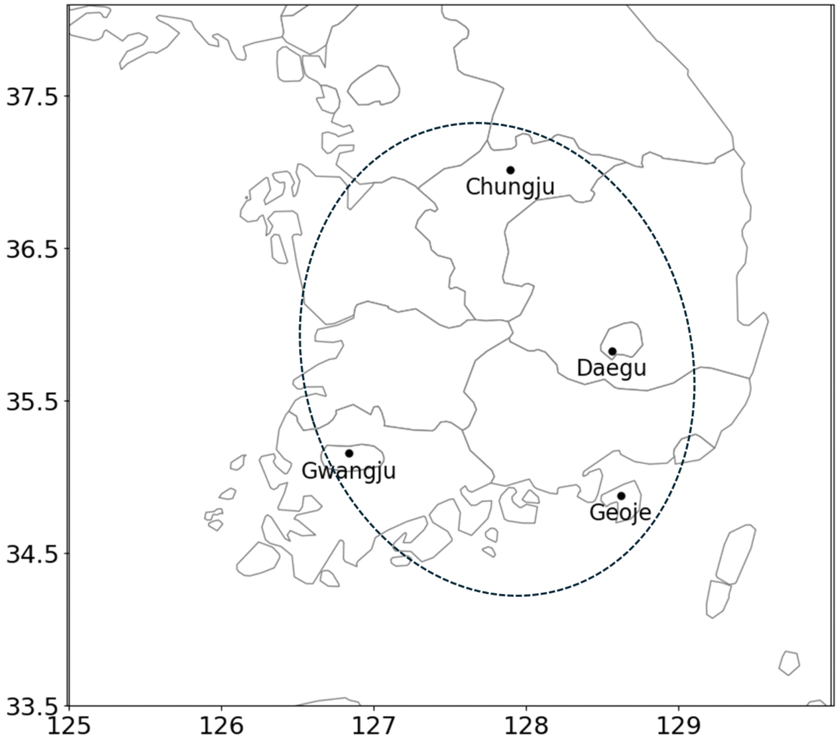

Figure 4. 1670 October 4 earthquake. Dotted curve encloses the felt area.

V. Conclusion and Discussions.

The depth of the Moho-discontinuity in the Korean peninsula is about 33km. Depths of most instrumental earthquakes since the 20th century determined by KMA are less than 15km except for the September 16, 1978, M_L 5.2 Sokrisan earthquake. The epicentral intensity of this shock is JMA 4 which corresponds to MMI Ⅵ. This shock is suspected to be deep crustal earthquake though it's depth is not determined by KMA.

Though based on the macroseimic data, this paper seems to clearly demonstrate that deep crustal earthquakes actually occurred during last 2,000 years in the Korean peninsula in addition to shallow crustal shocks.

Since the seismicity of the Korean peninsula belongs to the category of intraplate seismicity which reactivates at intervals of thousands to ten thousands years, this finding implies that earthquake generating tectonics associated with deep crustal earthquakes during last 2.000 years may be working in the peninsula at present.

The result of this study seems to present a new perspective in understanding the vertical extent of the active tectonics going on in the peninsula. However, it seems that this conclusion needs to be confirmed by instrumental earthquake data in the future.

Acknowledgment.

I thank Dr. Sang Hyun Lee for his assistance during the course of this work.

References

Bath, M. (1973). Introduction to Seismology. Birkhauser VerLag Basel and Stuttgart.

Grandori, G., A., Drei, F. Perotti, and A. Tagliani (1991). Macroseismic intensity versus epicentral distance: the case of Central Italy, Tectonophysics 193, 165-171.

Howwell, B. F,, and T. R. Schultz (1975). Attenuation of modified Mercalli intensity with distance from the epicenter. Bull. Seism. Soc. Am. 65, 651-665.

Lee, K. (1984). A study on intensity attenuation in the Korean Peninsula.. J. Geol. Soc. Korea 20, 140-146.

Lee, K. (1998). Historical earthquake data of Korea. J. Korea Geophys. Soc. 1, 3-22 (in Korean).

Lee, K., M. S. Lee, B. D. Kwon, and W. S. Yang (1985). Studies on the seismic risk of the Korean Peninsula (1). J. Geol. Soc. Korea 21, 227-240.

Lee, K., and J. K. Kim (2002). Intensity attenuation in the Sino-Korean cration. Bull. Seism. Soc. Am. 92, 783-793.

Mei S. Y. (1960). Characteristics of earthquake activity in China, Acta. Geophys. Sin 9, 1-19 (in Chinese).

Nuttli, O. W. (1973). Seismic-wave attenuation and magnitude relations for Eastern North America. J. Geophys. Res. 78, 876-885.

Yoo, H. J., R. B. Herrmann, K. H. Cho, and K. Lee (2007). Imaging the three-dimensional crust of the Korean peninsula by joint inversion of surface-wave dispersion and teleseismic reciever functions. Bull. Seism. Soc. Am. 97, 1002-1011.