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Did the Little Ice Age release earthquakes

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Abstract: The Little Ice Age possibly released many shallow earthquakes in Korea and other places of the Earth. Decrease of temperature penetrates into hundreds meters deep into the Earth's crust when its surface temperature is kept low for centuries. The resultant reduction of hydrostatic pressure in the crust can trigger earthquakes. According to historical records in Korea, comparatively much more earthquakes occurred in 1500s, 1600s, and 1700s. Near surface earthquakes among those could have been triggered by low temperature of the same periods.

Keywords: Earthquake, Little Ice Age, Thermal Stress

1. Introduction

1.1. Little Ice Age

Although its cause and features on the whole globe have been controversial, the Little Ice Age is generally accepted to have existed between 15th and 18th centuries. Matthes early interpreted the mountain glacier retreat and advance records for the Holocene climate history, and made the notion of 'the Little Ice Age' [1]. The most persuasive presumption for the origin of the Little Ice Age could be the volcanic dust eruption and/or the solar irradiance reduction in the prior and contemporary periods [1-3 and references therein]. Diverse proxy data, such as, tree rings, ice cores, sediments, *etc*. are continually acquired and analyzed for better understanding of the past environment of the Earth [2-3].

1.2. Historical Korean Earthquakes

Table 1. *Excerpts of Lee and Yang's historical Korean earthquake catalog. Each row is consisted of event number, date, location, and approximate magnitude estimate.*

Num	Year	Mon & Day	Lat(N)	Long(E)	Mag
277	1413	Feb 19	35.6	127.5	5.2
278	1413	May 20	35.8	129.3	3.5
279	1414	Jan 21	40.2	124.5	3.5
280	1414	Mar 25	37.6	127.0	3.5
(more earthquakes)					
736	1524	Dec 31	40.0	124.5	4.7
737	1525	Feb 6	35.8	129.3	3.5
740	1525	Feb 28	36.7	127.4	4.7
741	1525	Mar 13	37.6	127.0	3.5
742	1525	Apr 14	35.0	126.9	3.5
743	1525	Apr 17	35.1	128.0	4.1
744	1525	Apr 22	35.0	128.3	4.7
745	1525	Apr 25	35.0	126.9	3.5
746	1525	May 7	35.2	128.5	5.8
751	1525	May 31	38.9	124.8	4.7
753	1525	Jun 5	36.7	126.5	5.2
755	1525	Sep 3	36.1	128.3	4.7
(more earthquakes)					
1760	1675	Oct 25	38.5	125.7	4.7
1762	1675	Dec 15	39.8	125.8	3.5
1763	1676	May 07	36.5	127.1	4.7
1764	1676	May 22	38.9	125.3	3.5
1765	1676	Jun 29	36.6	127.2	3.5
1766	1676	Jul 17	35.0	127.0	4.1
1767	1677	Aug 14	40.0	124.6	4.1
1768	1677	Sep 09	36.1	127.5	4.1
(more earthquakes)					

source:
http://sillok.history.go.kr/main/main.jsp, in Korean with English guide, last accessed in November 22, 2014.
http://osmstar.com.ne.kr/goreosajelo/kframe1.htm, in Korean with Chinese records, last accessed in November 22, 2014.

Being located in an intra-plate region several hundred kilometers away from the Japan trench, Korea is seismically much more silent than Japan. Only about a thousand medium size earthquakes occurred in Korea during the last millennium. 'Joseon Wangjo Sillok' (Annals of Choson Dynasty, A.D. 1392 - 1904) and 'Goryeosa' (History of Goryeo, A.D. 1012 - 1392) contain records of earthquake occurrences composed of plain but clear descriptions of epoch, location, and damages. Table 1 shows a few selected contents of the historical Korean earthquake list made from the two sources and others [4].

The total number of earthquakes in Lee and Yang's catalog is 2185. However, some records of the same or close dates are believed to be reduplicative on same events. We counted such redundant ones as single events. Following is an example;

746. 1525 May 07, 35.2N, 128.5E (M=5.8)
747. 1525 May 07, 36.5N, 129.4E (M=4.7)
748. 1525 May 07, 35.0N, 126.9E (M=4.1)
749. 1525 May 07, 36.5N, 126.9E (M=5.2)

There are further refinements made on the catalog as we did before [5]. After A.D. 1000, about fourteen hundred earthquakes were recorded. In Figure 1, these historical Korean earthquake occurrences are illustrated.

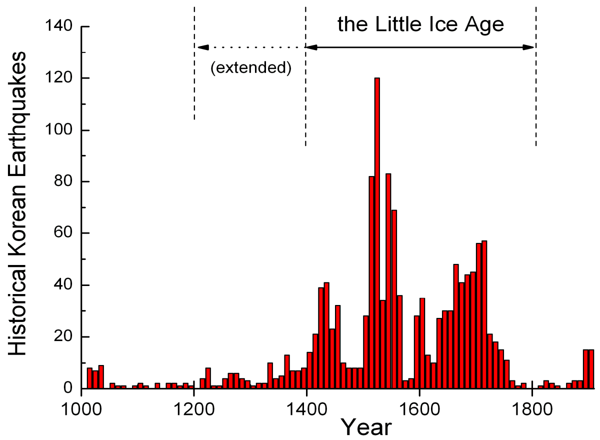

Figure 1. *Earthquake occurrence in Korea between A.D. 1000 and 1910 based on the historical records (Number of earthquakes of each decades are shown). Compared with small number of earthquakes in the 12th, 13th and 19th centuries, large number of earthquake occurrences were recorded during the 16th, 17th and 18th centuries. The Little Ice Age period and its possible extension are shown by arrows.*

As illustrated in Figure 1, earthquake occurrence in Korea was relatively more frequent during periods of A.D. 1630 - 1760, 1500 - 1570, and 1400 - 1470. These time spans overlap with the Little Ice Age period.

2. Earth's Uppermost Crust under Surface Cooling

2.1. Thermal Evolution due to Surface Cooling

When the Earth's surface temperature suddenly changes by a certain amount and be maintained afterward, the inside temperature slowly changes as time passes. This is one of thermal diffusion problem, and the solution $T(z,t)$, which is the temperature change from initial equilibrium configuration, can be written as follows.

$$T(z,t) = T_0 \, [\, 1 - erf(\frac{z}{2\sqrt{\kappa t}}) \,]$$

where T_0 is the surface temperature change, z is depth, κ is the thermal diffusivity of the crust, t is the time, and $erf(x)$ is the error function; $erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt$ [6-7].

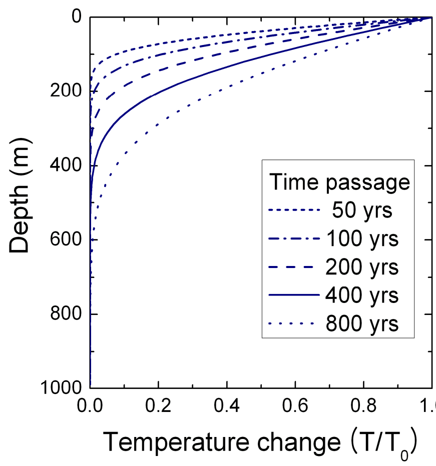

Figure 2. *Temperature change of the Earth's uppermost crust in hundreds years time, while its surface temperature is instantaneously changed by T_0 and held constant afterward.*

In Figure 2, $T(z,t)$ of the Earth's uppermost crust from its free surface to one thousand meter depth is drawn for time passages of 50, 100, 200, 400, and 800 years. The thermal diffusivity was taken here as $\kappa = 1.0 \times 10^{-6} m^2 s^{-1}$, which is most widely accepted value for the Earth's upper crust.

2.2. Associated Pressure Change in the Crust

Solid substances undergo expansion or contraction due to their pressure and temperature changes, and the rate of the volume change can be expressed as follows.

$$\frac{dV}{V} = \alpha_V dT - \frac{1}{B} dP$$

where α_V is the coefficient of thermal expansion, and B is the isothermal Bulk modulus. When the volume change in the Earth's crust is suppressed, a temperature change in the crust results in associated change of its hydrostatic pressure as follows.

$$dP = \alpha_V B \, dT$$

Turcotte and Schubert [7] termed this pressure change ΔP induced by temperature change as 'thermal stress', and estimated that $\Delta P \simeq 3$ MPa would be induced by a unit temperature change $\Delta T = 1$ K. Using the incompressibility value of the upper crust of the PREM model ($B = 52$ GPa) and an experimentally determined value of the thermal expansion coefficient of granite and limestone as

$\alpha_V = 3\alpha_L \simeq 2.4\times10^{-5}$ [8], we attained a smaller value for the thermal stress in the crust as $\Delta P \simeq 1.25$ MPa for a unit temperature change. Assuming thermal stress along horizontal directions only, these estimates should be adjusted to $\Delta P_{11} = \Delta P_{22} \simeq 0.8$ MPa [7].

2.3. Effect of Hydrostatic Pressure Change in Fracturing

Suppose a certain amount of deviatoric shear stress (close to critical amount for fracture development) is accumulated unto a region, which has been under hydrostatic equilibrium pressure. If the hydrostatic pressure decreases without change of the shear stress in this region, the circumstance becomes more unstable and possibly will yield fracture.

Experimental studies reported that increase of confining pressure significantly enhances rock strength [9-10]. Janach [9] gave an empirical formula between the yielding stress σ_1 and the confining pressure σ_3 as follows.

$$\sigma_1 = \sqrt{1.05\times10^4(\sigma_3+5)} \quad \text{[unit: MPa]}$$

According to this formula, reduction of confining pressure weakens the rock strength. By differentiation of Janach's formula, one can also deduce the ratio $\Delta\sigma_1/\Delta\sigma_3$, *i.e.*, the relation between an incremental confining pressure change and the resultant incremental change in the rock strength. Using Janach's formula, the rock strength and the corresponding ratio were calculated for an ideal granite crust at a few selected depths and are shown in Table 2. It is noted that $\Delta\sigma_3$ here is identical to ΔP in the former subsection.

Table 2. *Approximate hydrostatic pressure and rock strength as well as the ratio $\Delta\sigma_1/\Delta\sigma_3$ at selected depths of uppermost granitic crust. Each units used are [m], [MPa], [MPa], and [none].*

Depth	Pressure σ_3	Strength σ_1	Ratio $\Delta\sigma_1/\Delta\sigma_3$
0	0	229	22.9
100	3	290	18.1
200	6	340	15.4
330	10	397	13.2
500	15	458	11.5
1000	30	606	8.7

3. Possibility of the Little Ice Age to Release Earthquakes

If the Earth's surface temperature drops by 1 K and be maintained for two hundred years, then the temperature decrease at 200 m depth would be about 0.076 K (Fig. 2). Since the hydrostatic pressure at 200 m depth is about 6.0 MPa, the maximum strength of granite at 200 m depth would be 340 MPa, and the ratio $\Delta\sigma_1/\Delta\sigma_3$ would be 15.4 (Table 2). This 0.076 K temperature decrease at 200 m depth would result in (i) reduction of the hydrostatic pressure $\Delta\sigma_3$ by 0.076 × (3 ~ 1.25) ≃ 0.23 ~ 0.095 MPa, and (ii) reduction of the rock strength by 15.4 × $\Delta\sigma_3 \simeq$ 3.5 ~ 1.5 MPa. Twice longer time span, *i.e.*, four hundred year cooling by the same surface temperature drop [11] would cause a temperature decrease by 0.21 K at the same depth (Fig. 2). Corresponding reductions in both the hydrostatic pressure and rock strength are 0.63 ~ 0.26 MPa and 9.6 ~ 4.0 MPa respectively.

Thus the Earth's surface temperature drop by 1 K for two to four hundred years will lead to (i) reduction of the hydrostatic pressure by 3.8 ~ 11 percent and (ii) reduction of the rock strength by 1.0 ~ 2.8 percent (both maxima at 200 m depth). While these calculations were based on the fixed volume assumption, the more realistic value of horizontal thermal stress $\Delta P_{11} = \Delta P_{22}$ (with zero vertical component; $\Delta P_{33} = 0$) should be about one quarter to half of the each estimates above. Unlike at near surface, a few hundred year period is not long enough to give comparable effect to other regions at 500 m depth or deeper (Fig. 2). Nevertheless, a few percent reductions in the hydrostatic pressure and rock strength could be crucial to the Earth's crust which is close to failure. Therefore, we speculate the near surface earthquakes within one kilometer focal depth in Korea during 15th to 18th centuries were possibly triggered by the Little Ice Age cooling.

4. Conclusion

Historical Korean earthquake records show high seismic activities during the 16th and 17th (also early 18th) centuries. Two to four hundred year cooling at the Earth's surface is found to result in a few percent reductions in the hydrostatic pressure and strength of the near surface crust down to hundreds meters deep. Therefore, the Little Ice Age cooling must have contributed to release near surface earthquakes in Korea as well as other places on the globe. However, the whole historical Korean earthquakes recorded in that time span cannot be fully explained by this thermal stress reduction effect only, because the penetration depth of cooling is limited.

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[11] Effective cooling can be regarded to have started around at the end of the Medieval Warm Period (A.D. 1200)