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Earth and Planetary Science Letters 207 (2003) 159–164

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Snow load and seasonal variation of earthquake occurrence in Japan

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Received 24 July 2002; received in revised form 5 December 2002; accepted 16 December 2002

Abstract

Snow load along the western flank of the backbone range of the Japanese Islands causes seasonal crustal deformation. It perturbs the interseismic strain buildup, and may seasonally influence the seismicity in Japan. Intraplate earthquakes in northeastern Japan occur on reverse faults striking parallel with the snow-covered zone. In central and southwestern Japan, they occur on strike-slip faults striking either parallel with, or perpendicular to the snow cover. The snow load enhances compression at these faults, reducing the Coulomb failure stress by a few kPa. This is large enough to modulate the secular stress buildup of a few tens of kPa/yr. Past inland earthquakes with magnitudes ≥ 7.0 that occurred in regions covered with snow in winter, tend to occur more in spring and summer than in autumn and winter, while those in the snow-free regions do not show such variation. Although its statistical significance is not strong due to limited number of past earthquakes, it suggests that the spring thaw enhances seismicity beneath the snow cover.

Keywords: snow load; earthquake source mechanics; inland earthquake; crustal deformation; Japan

1. Introduction

Seasonal variation in seismicity has long been suspected in Japan (e.g. [1–3]). Ohtake and Nakahara [4] confirmed the statistical significance of the concentration of interplate thrust earthquakes in fall and winter along the Nankai, Suruga and Sagami Troughs. The atmospheric pressure increases ~1 kPa in winter, which qualitatively encourages reverse slips at the plate interface [4]. However, the stress increases are only a few tens of Pa in terms of the Coulomb failure function (CFF), and they considered it too small to significantly modulate seismicity.

Murakami and Miyazaki [5] discovered that seasonal components in site movement of nationwide continuous Global Positioning System (GPS) array are coherent in phase and spatially systematic in amplitudes. They suggested that the seasonal crustal deformation perturbs interseismic strain buildup in Japan and might cause the earthquake seasonality. However, they failed to specify the physical mechanism responsible for

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0012-821X/03/$ – see front matter
doi:10.1016/S0012-821X(02)01148-2

the seasonal crustal deformation, and were not able to pursue the issue further. Later, Heki [6] suggested that the observed annual GPS signals in northeastern Japan are mainly caused by the snow load along the western flanks of the backbone range. Identification of the seasonal crustal deformation mechanism enables the quantitative evaluation of its influence on the seismicity. In this study, I discuss the possibility that earthquakes are triggered by seasonal variation of such surface loads, and examine its consistency with the observed seasonal variation of past seismicity in Japan.

2. Secular and seasonal stress changes

In discussions of earthquake triggering we often use change of CFF (ΔCFF), which consists of shear stress change resolved on the fault plane (positive in the fault slip direction) added to the change in the fault-normal stress multiplied by friction coefficient (positive for unclamping). Here I assume that a shear stress increases secularly by tectonic loading, being perturbed by various ΔCFF, and the fault rupture starts when the total stress exceeds a critical value. Thus addition of a positive (negative) ΔCFF would allow the next earthquake to occur earlier (later). An instantaneous change in CFF occurs in response to a nearby earthquake, and snow load, solid earth tide, ocean tidal loading, etc., cause roughly cyclic ΔCFF. Significance of the periodic ΔCFF depends on its amplitude relative to the secular stress increase during the period [7]. The probability of earthquake occurrence in a unit time would vary periodically in proportion to the instantaneous increase rate of the total stress. Let the secular annual stress rate be a, and the amplitude of the annual ΔCFF change b, then the stress rate would vary between $a-2\pi b$ and $a+2\pi b$ (Fig. 1a), where 2π comes from the angular velocity (1/yr) of the annual perturbation. A high rate brings a large earthquake occurrence probability; the quantity $2\pi b/a$ equals P_m/P_0 (Fig. 1a), the amplitude of the periodic component relative to the stationary seismicity (see equation 4 of [7]).

A stress drop and recurrence interval of a typical interplate earthquake would be a few MPa and 100 yr, respectively, which suggests a to be a few tens of kPa/yr. Intraplate (inland) earthquakes generally have larger stress drops, but their longer recurrence intervals would keep a similar. As seen in Fig. 1a, b only 0.1 times as large as a could modulate the seismicity significantly ($P_m/P_0 \approx 0.6$). The seismicity peak is predicted to coincide with the dΔCFF/dt peak, a quarter year earlier than the peak of ΔCFF itself (since snow causes compression and negative ΔCFF, the highest seismicity would come with spring thaw rather than in snow-free summer), although time delay is likely because seismic nucleation phase needs finite duration. Fig. 1b shows another case, where periodic term is relatively large, i.e. $a < 2\pi b$ (tidal triggering of earthquakes usually corresponds to this case). There the total stress experiences negative stress changes, and the probability of earthquake would temporarily remain zero until the stress exceeds the previous maximum ("stress shadow" by [7]). This would also let the seismicity peak shift from the maximum dΔCFF/dt toward the maximum ΔCFF.

Ohtake and Nakahara [4] estimated the ΔCFF at the plate interface (mainly due to shear stress increase) brought by high atmospheric pressure in winter of 1 kPa to be only a few tens of Pa, too small to significantly perturb the secular stress buildup. According to Heki [6], although the snow load is equivalent to as much as 10 kPa atmospheric pressure increase, the increases of the shear stress at the offshore fault surface remains ~0.1 kPa (this is due to the distance between the snow cover and the trench), again unlikely to modulate seismicity. On the other hand, such surface loads cause significant stress disturbance directly below them, and thus may influence the occurrence of inland crustal earthquakes. Past studies focused on relatively large earthquakes (e.g., Mogi [2] considered $M \geq 8$ historic and $M \geq 7.5$ modern earthquakes, and Ohtake and Nakahara [4] examined only $M \geq 7.9$ earthquakes), and excluded most inland earthquakes because their magnitudes seldom exceed 7.5. Here I focus on the seasonality of inland seismicity, and discuss its correlation with the snow load.

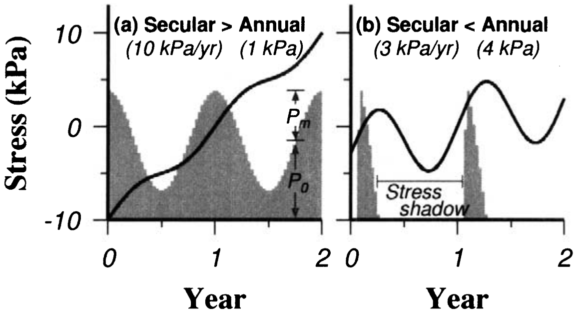

Fig. 1. Combination of secular stress increase and annual disturbance (black curves), and temporal variation of seismicity (gray histogram) composed of stationary (P_0) and annual (P_m) terms (arbitrary scale). Two cases are shown, i.e. secular increase larger than the annual amplitude (a), and an opposite case, where stress shadows occur (b).

3. Annual variation of inland seismicity in Japan

Fig. 2 shows the epicenters of past inland earthquakes ($M \geq 6.0$) compiled by Usami [8] (the oldest earthquake dates back to the 5th century, and only destructive earthquakes are listed). Their mechanisms vary between the northeastern and the central to southwestern Japan (for general description of Japanese earthquakes, see Earthquake Research Committee [9]). In northeastern Japan, they occur on high-angle thrust faults that often bound the backbone range and adjacent basins, and a typical event is the 1896 Riku-u earthquake (M7.2). These faults strike normal to the plate convergence direction and parallel with the arc (and the snow cover). Most inland earthquakes in the central to southwestern Japan occur on strike-slip faults. Because the plate converges WNW–ESE there (Fig. 2) [10], faults strike either WSW–ENE (e.g. the 1995 Kobe earthquake, M7.2) or NNW–SSE (e.g. the 1891 Nobi earthquake, M8.0), which are roughly parallel with and normal to the arc (and the snow cover), respectively.

Fig. 3a,b shows the changes in the stress normal to the reverse and strike-slip fault planes, respectively, under a simple (but realistic) arc and snow cover geometry. The arc is 200 km wide and extends 1000 km N–S. The snow cover, also running N–S, extends from the west coast to 40 km east of the backbone range axis (140 km wide), and is the deepest (2.5 m) at 30 km west of the range axis. With the snow density 0.4 g/cm^3, the maximum load is comparable to 1 m water column, or 10 kPa surface pressure. The reverse fault was assumed to dip 45° westward, and both reverse and strike-slip faults strike parallel with the arc (and with the snow cover). The elastic response of the Earth is calculated after Farrell [11] assuming crustal rigidity of 30 GPa and the Poisson's ratio of 0.25. A simple elastic half space approximation is used rather than the spherical Earth since the problem is local and most inland earthquakes are shallower than 15$\sim$20 km [9]. In Fig. 3a,b, snow load causes compression (negative stress change) larger than 5 kPa beneath the snow cover (in the strike-slip case, changing the fault strike to arc-normal reduces the compression by 1/3). In the reverse fault case, shear stress also changes ($\sim$1/3 of the compression, in the discouraging sense), and contributes to the negative ΔCFF (if the friction coefficient is 0.5, the total ΔCFF is about −5 kPa). For both the arc-normal and arc-parallel strike-slip faults, the snow load does not change shear stresses, and the normal stress change multiplied by the friction coefficient

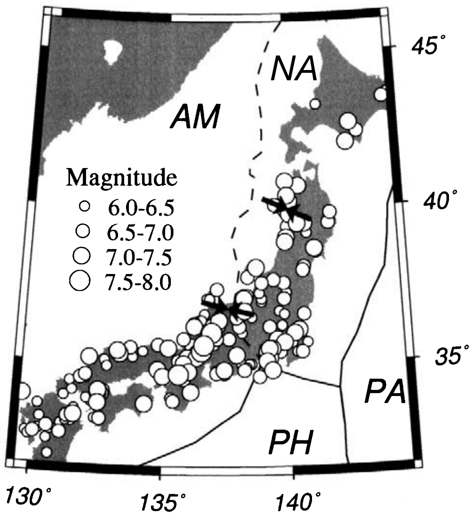

Fig. 2. Epicenters of past destructive inland earthquakes ($M \geq 6.0$) in Japan [8]. AM, NA, PA, and PH denote the Amurian, the North American, the Pacific, and the Philippine Sea plates, respectively. Black arrows in northeastern and central Japan show NA–PA and NA–AM convergence directions, respectively (arbitrary length).

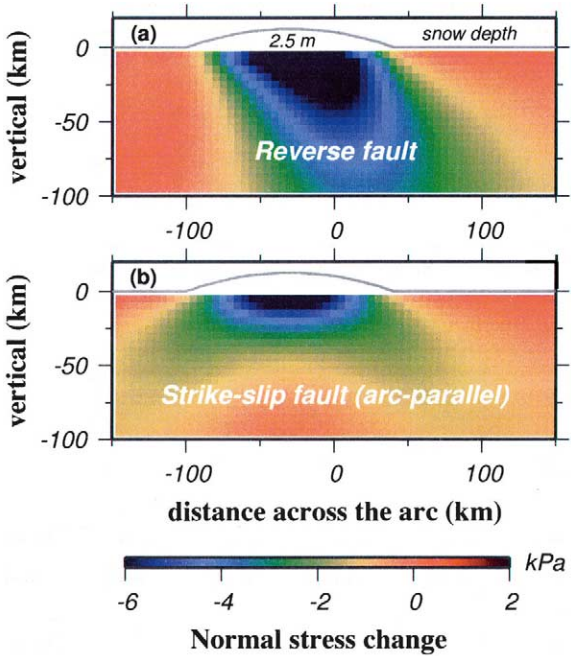

Fig. 3. Cross-section of negative changes in normal stress (compression) at a reverse (striking arc-parallel, dipping 45° westward) (a) and a strike-slip (striking arc-parallel) (b) faults beneath the island arc ($-100 \sim 100$ km) whose western part ($-100 \sim 40$ km) is covered with snow. The arc is assumed to be as long as 1000 km. Snow (density 0.4 g/cm^3) depth curve is shown above the ground (maximum depth 2.5 m at -30 km).

becomes the ΔCFF ($-2 \sim 3$ kPa with the friction coefficient of 0.5). In both cases, seasonal ΔCFF amplitudes amount to a few kPa, sufficient to significantly perturb the secular stress build-up of a few tens of kPa/yr as shown in Fig. 1a.

Okada [3] first separated inland earthquakes into those under the snow cover and the snow-free region, and investigated the monthly distribution of their occurrence, and found higher seismicity under the snow cover in spring and summer. Fig. 4 confirms this trend, based on the new earthquake catalog [8], and more precise definition of the snowy region, i.e., area where the average values of the maximum snow depths of the last five winters exceeded 20 cm (Automated Meteorological Data Acquisition System, or AMeDAS, run by Japan Meteorological Agency). Fig. 4a,b compares bimonthly distributions of earthquakes in the snowy and snow-free regions. Following past studies [2,3], I excluded aftershocks, and counted only the first one if multiple earthquakes of comparable sizes occurred nearby (<30 km for $7.0 > M \geq 6.0$ earthquakes, and <100 km for $M \geq 7.0$ earthquakes) within 1 yr. In Fig. 4c are plotted snow depths, and $M \geq 7.0$ inland earthquake epicenters within (circles) and outside (triangles) the snowy region.

Fig. 4a (red histogram) shows distribution of

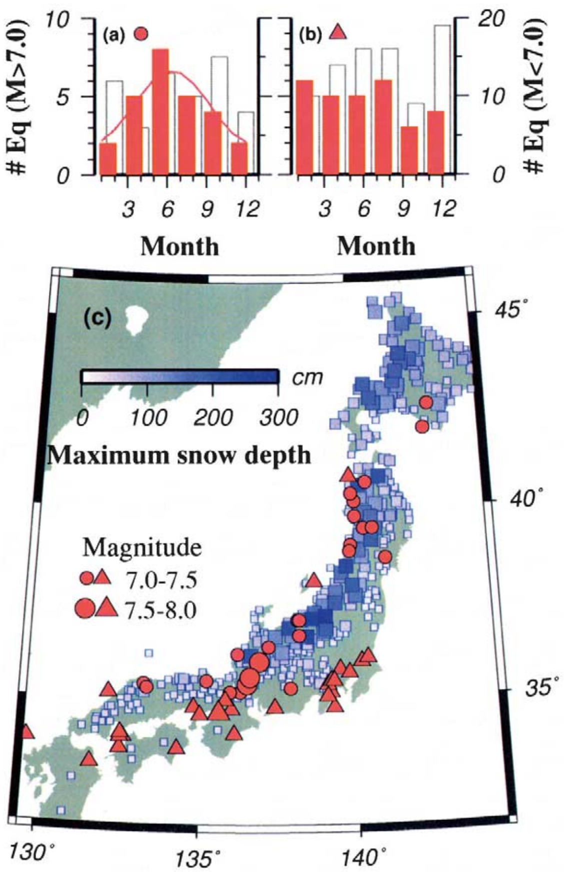

Fig. 4. Histograms showing number of earthquakes occurred in 2-month intervals, within (a) and outside (b) the snowy region. Red and white histograms show $M \geq 7.0$ (axis/label to the left) and $7.0 > M \geq 6.0$ (axis/label to the right) earthquakes, respectively. In (c) blue squares show maximum snow depths in a winter at AMeDAS stations (only points with snows deeper than 20.0 cm are shown). Epicenters of $M \geq 7.0$ earthquakes are shown in (c) as circles (snowy region) and triangles (outside). Red curve in (a) is the best-fit probability density function of the earthquake occurrence based on the two-component (stationary and annual components) model [7].

occurrence times for the 26 $M \geq 7.0$ earthquakes in the snowy region; they occur more in spring–summer than in fall–winter, a result consistent with Okada [3] (those in the snow-free region, shown in Fig. 4b, seem to occur randomly). According to the classical statistical test by Schuster [12], we cannot discard the null hypothesis that this is a result of a random process at the 95% confidence level. This is, however, due to insufficient number of earthquakes, and does not necessarily mean lack of seasonality. In fact, the observed ratio of the periodic to the stationary term of the earthquake probability density function (P_m/P_0) [7] is ~ 0.5 (red curve in Fig. 4a), a value larger than the case reported by Wilcock [13], one of the most significant cases of the tidal triggering of earthquakes. If earthquakes keep occurring with the monthly distribution similar to Fig. 4a, it will pass the Schuster's test with the 95% confidence when number of earthquakes exceeds 54. Although this will take another millennium, this number is certainly small considering hundreds and thousands of earthquakes often necessary to verify significance of tidal triggering [14]. The motivation of the present work is not the discovery of seasonal variation of earthquakes, but the identification of a mechanism (snow load) responsible for seasonal crustal deformation and its evaluation as an earthquake trigger mechanism. Hence I do not claim statistical significance of seasonal variation seen in Fig. 4a here, but just emphasize that the phase (peak in middle June) and amplitude ($P_m/P_0 \approx 0.5$ means b, the annual term amplitude, is about an order of magnitude smaller than a, the secular change in a year) there support the geophysical speculation that the removal of the snow load may increase the ΔCFF in shallow faults underneath and activate seismicity.

4. Discussion

As pointed out by Mogi [2] and Okada [3], the seasonality is not so apparent for smaller earthquakes. In Fig. 4a, bimonthly distribution of $7.0 > M \geq 6.0$ earthquakes in the snowy region (gray histogram) do not show clear seasonal variation. The enhancement of seasonal variation for larger earthquakes might be due to longer durations required for the premonitory nucleation phase of larger earthquakes. Shibazaki and Matsu'ura [15], based on the rate- and state-dependent friction law [16], hypothesized that an earthquake starts as a (1) slow quasi-static nucleation process, (2) followed by dynamic acceleration phase, (3) eventually running into the main rupture. Ellsworth and Beroza [17] analyzed the initial phases of seismic records, which correspond to the second (dynamic acceleration) phase in the above sequence, and inferred that a longer duration of nucleation precedes an earthquake with larger eventual size. Although there have been no clear geodetic observations for the duration of the first process (quasi-static nucleation), it is possible that larger earthquakes need longer duration for this process (1) as well as for the process (2). In fact, Kato and Hirasawa [18], from a numerical simulation using the friction law, suggested that a precursory fault slip (i.e. quasi-static nucleation) of a large interplate earthquake occurs over a few days. If the total nucleation process for a $M \geq 7.0$ earthquake always takes more than a few days, they would not react to shorter-term disturbances such as semidiurnal tides, but would be sensitive to longer-term disturbances such as seasonal loads. Smaller earthquakes with shorter nucleation phases, on the other hand, would be more easily triggered by shorter-term disturbances including tides and atmospheric pressure variations, and their seasonality might be blurred. Smaller earthquakes often fail to show clear correlation with tides [19], and this issue would need further investigations.

Groundwater may play a certain role in the seismicity in snowy regions. In spring, snowmelts would penetrate into cracks of crustal rocks, and might reach the fault surface. It could increase the CFF by reducing the effective normal stress with excess pore pressure as suggested by Okada [3] and Matsumura [20], although it is difficult to evaluate this effect as ΔCFF. The present study does not rule out its possibility, but we prefer the snow load mechanism since it has a quantitative model that can be tested in snow-covered areas with high seismicity in other parts of the world.

Acknowledgements

I thank Tadahiro Sato for discussion, Naoji Koizumi for sending a reprint, John Vidale, Nick Beeler and Joan Gomberg for valuable comments.*[AC]*

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