Aftershock Sequences of Intermediate-depth Earthquakes Beneath Japan

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Introduction

At subduction zones, earthquakes occur from the surface to nearly 700 km depth in the subducting slab. Greater than 60 km depth, earthquakes occur where temperature and pressure conditions should prevent brittle fracture, suggesting a different mechanism is responsible for the deep earthquakes than for the shallow earthquakes. At all depths, earthquakes appear to have predominantly double-couple radiation patterns and similar rupture velocities, source-time histories, and magnitude-frequency distributions [Frohlich, 2006].

One suggested difference between deep and shallow earthquakes is the aftershock productivity: deep earthquakes have fewer observed aftershocks than shallow earthquakes. Previous observations of deep aftershock sequences suggest that:

(1) The magnitude differential ΔM between the mainshock and the largest aftershock is ~2 [Wiens et al., 1997]. For shallow earthquakes, ΔM is ~1.

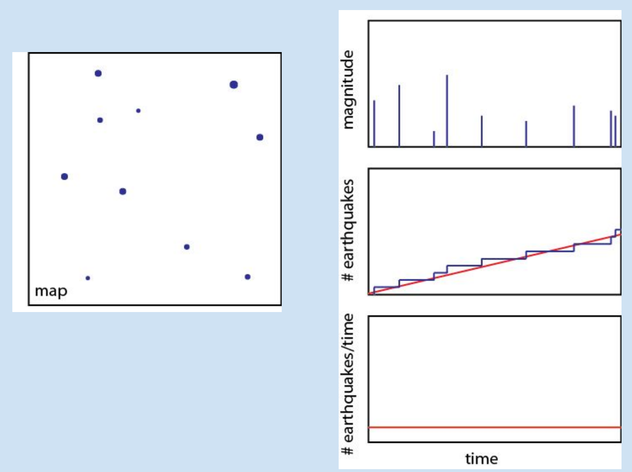
(2) Earthquakes in cold slabs have more aftershocks than earthquakes in warm slabs [Wiens & Gilbert, 1996].

Since deep earthquake aftershock sequences have been more readily observed in cold subduction zones and in regions with an earthquake catalog with a low magnitude of completeness M_C, we study intermediate-depth aftershock sequences beneath Japan. In characterizing these earthquakes, we address these questions:

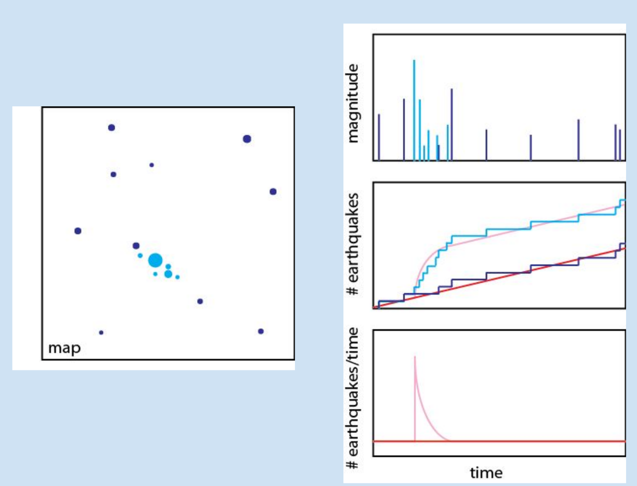
- Do all intermediate-depth earthquakes have aftershocks?
- What is the magnitude differential between the mainshock and the largest aftershock?
- When does a region return to the background seismicity level?

What is an Aftershock?

Earthquakes occur relatively randomly in space and time. As a result, the cumulative number of earthquakes increases linearly with time and the rate of earthquakes is constant.

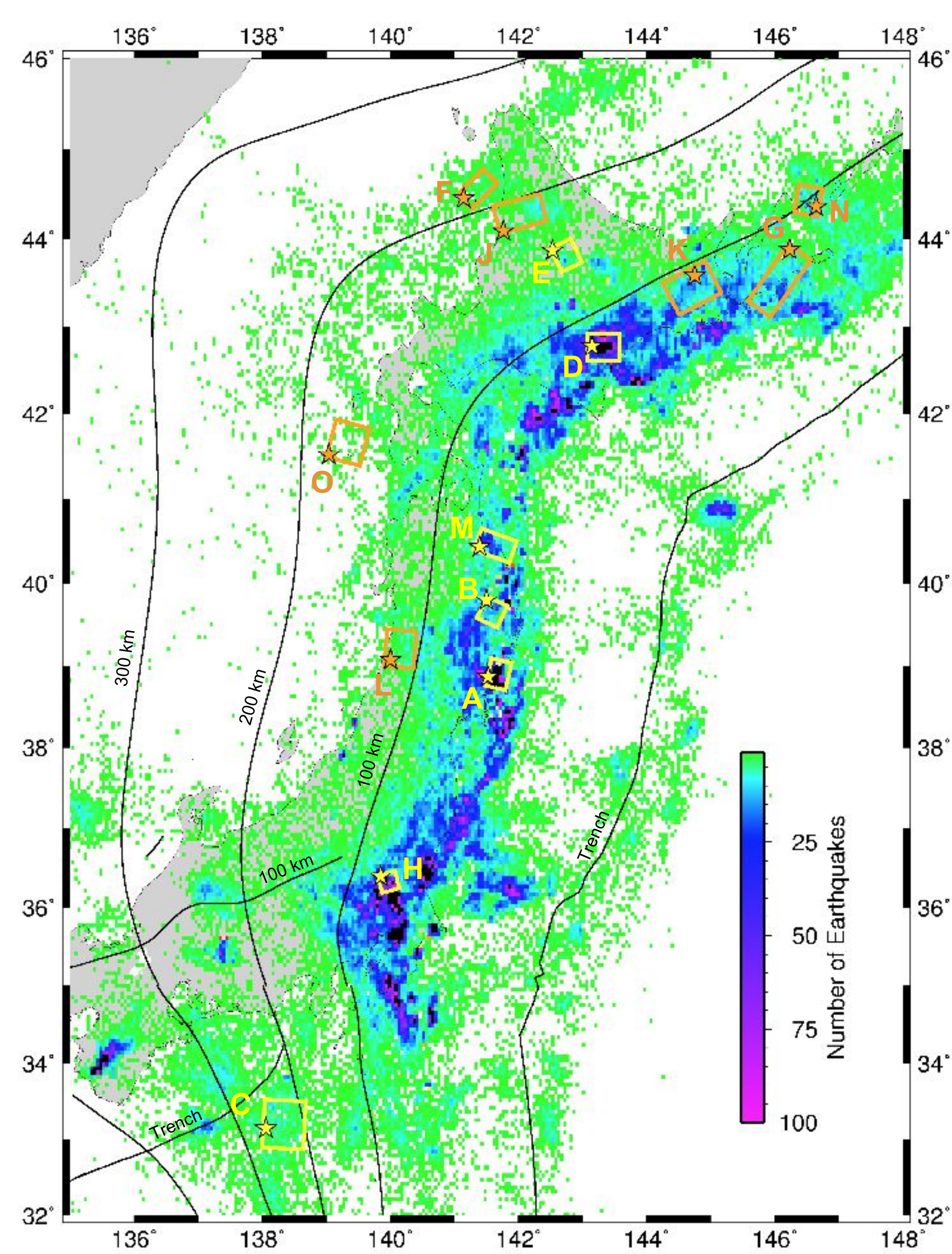
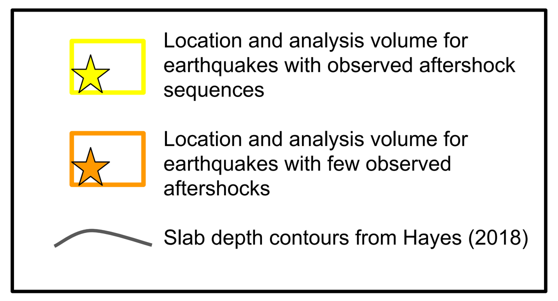


Aftershocks, as shown by the light blue symbols, are spatially and temporally close to a large earthquake but have smaller magnitudes than the mainshock. The maximum magnitude of aftershocks decreases with time. The number of aftershocks increases immediately after the mainshock and decreases exponentially with time, eventually returning to the background rate.



Study Area and Data Set

The Japan subduction zone is relatively cold: the Pacific Plate is 115-130 Ma [Müller et al., 2008] and subducting at 8-9 cm/yr [Argus et al., 2006]. Earthquakes in this region are detected by Japan's dense seismic networks and catalogued. The Japan Meteorological Agency (JMA) unified earthquake catalog, which we acquired from the International Seismological Centre (ISC), has a magnitude of completeness M_C of ~1 beneath the land areas. For our analysis, we use the JMA catalog from May 2002 through February 2016 and select the 14 earthquakes with local magnitude $M_J \geqq 5.7$ that occurred at depths of 70-305 km for further analysis.

Observed Aftershock Sequences

Event ID	Date	Depth (km)	M_J	Max M_{after}	ΔM	M_C
A	26 May 2003	71.2	7.1	4.7	2.4	0.6
B	3 July 2008	113.1	6.8	4.8	2.0	0.9
C	9 August 2009	302.2	6.8	4.8	2.0	2.9
D	2 February 2013	105.0	6.5	3.5	3.0	1.0
E	21 October 2011	189.0	6.3	2.7	3.6	2.1
F	11 January 2016	245.0	6.2	2.5	3.7	2.5
G	21 September 2005	102.2	6.0	2.9	3.1	1.7
H	16 April 2011	78.1	5.9	5.0	0.9	2.2
J	19 February 2003	218.9	5.9	2.9	3.0	2.0
K	1 July 2007	131.7	5.8	3.7	2.1	1.4
L	16 April 2008	167.7	5.8	2.1	3.7	1.6
M	9 July 2015	81.0	5.7	3.0	2.7	1.3
N	21 May 2002	148.1	5.7	2.6	3.1	2.6
O	4 June 2008	210.1	5.7	2.7	3.0	2.4

We observe productive aftershock sequences for 7 earthquakes ☆ and few aftershocks for 7 earthquakes ☆. To show both types of events, we present Event A, the 2003 Miyagi earthquake which has a productive aftershock sequence, and Event K, the 2007 Hokkaido earthquake which has few observed aftershocks. Earthquakes with observed aftershocks tend to have large magnitudes and low M_C whereas earthquakes with few observed aftershocks tend to have smaller differences between the mainshock magnitude and the M_C.

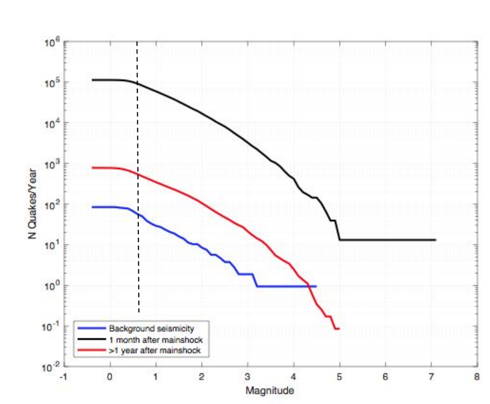
Magnitude of Completeness. To ensure a complete earthquake catalog, we compute M_C for three time periods (prior to the mainshock, one month following the mainshock, and starting one year after the mainshock), pick the largest M_C as the M_C for the earthquake, and only analyze earthquakes with $M_J \geqq M_C$.

Aftershock Volume. To identify the aftershock region, we plot the distribution of earthquakes for different time periods (before the mainshock, 0-2 days after the mainshock, and 2-30 days after the mainshock) in map and cross-section views. We manually extract a volume that contains the mainshock and aftershocks.

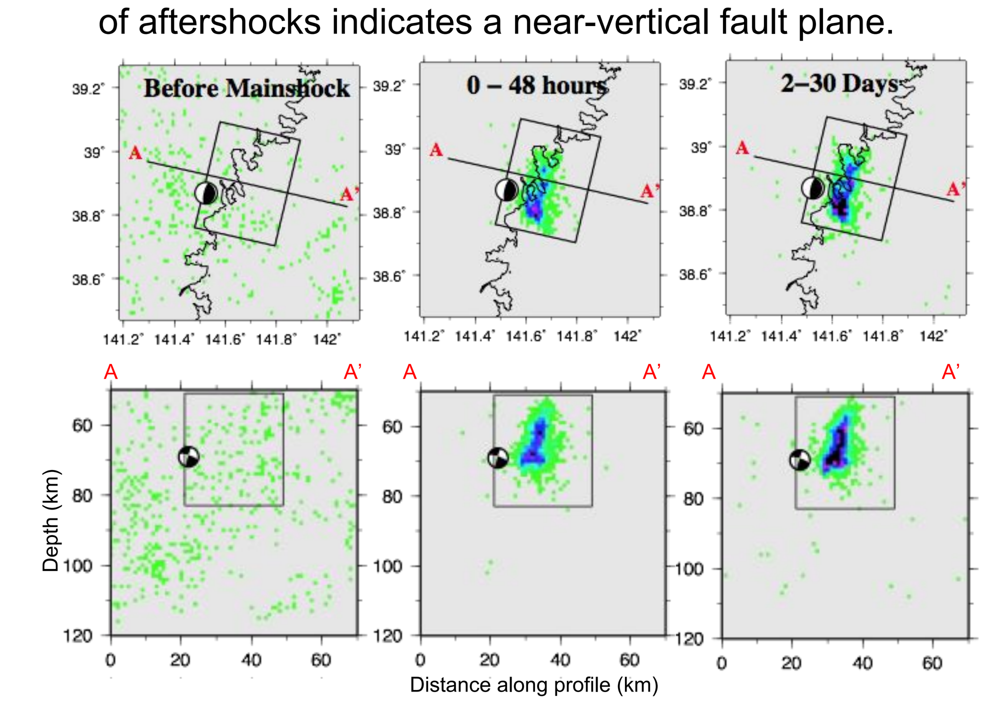
Time Progression. For the aftershock volume, we plot the cumulative number of earthquakes, earthquake rate, and magnitudes of all earthquakes for the entire time period.

Event A: The 2003 Miyagi Earthquake

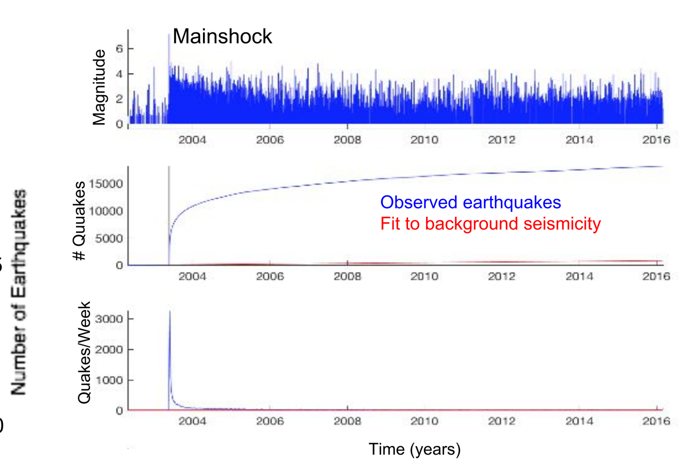
The earthquake catalog is complete for $M_J \geqq 0.6$.



After the mainshock, the number of earthquakes in the aftershock box increases. In cross section, the distribution of aftershocks indicates a near-vertical fault plane.

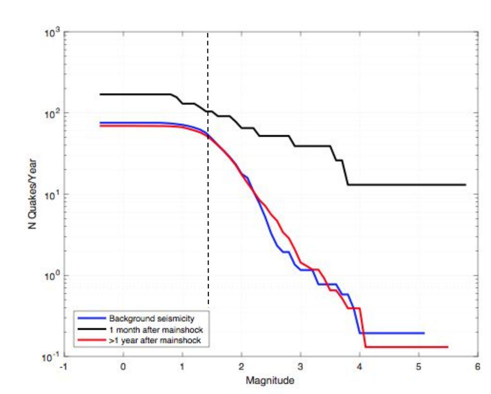


Prior to the mainshock, there is a constant rate of earthquakes. After the mainshock, the rate of earthquakes increases sharply and then exponentially decays with time.

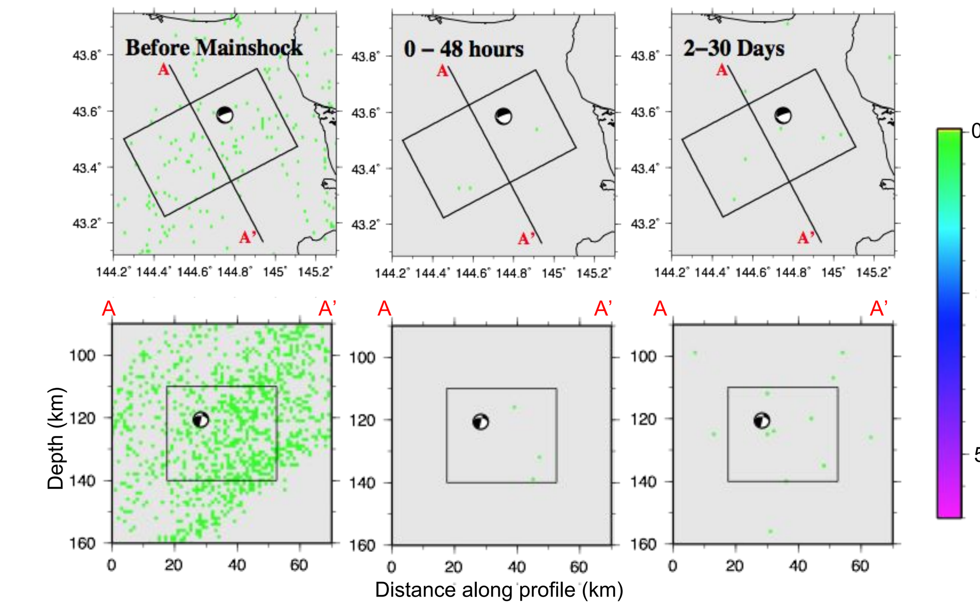


Event K: The 2007 Hokkaido Earthquake

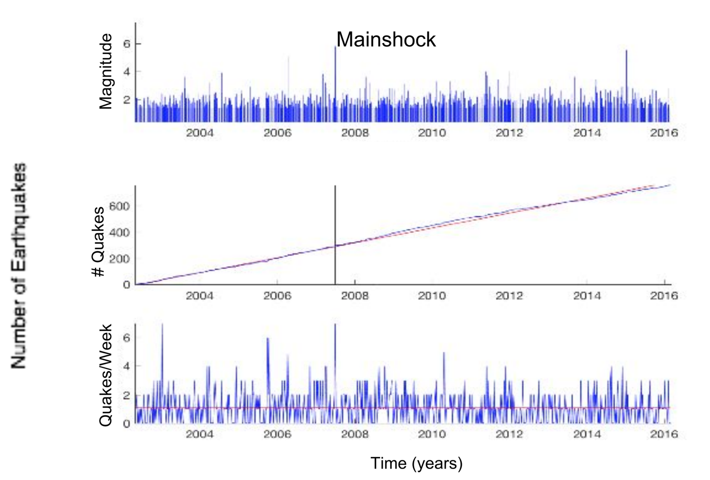
The earthquake catalog is complete for $M_J \geqq 1.4$.



The number of earthquakes does not increase in the aftershock box in contrast to the 2003 Miyagi earthquake.



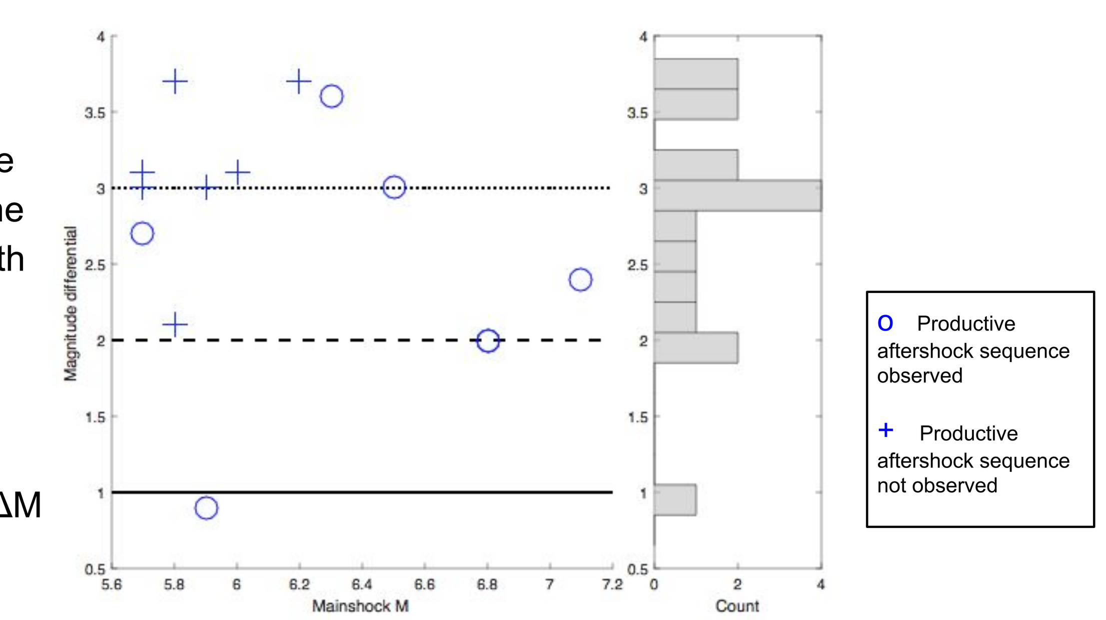
The rate of earthquakes stays constant with the background seismicity after the mainshock. There are few observed aftershocks.



Properties of Aftershock Sequences

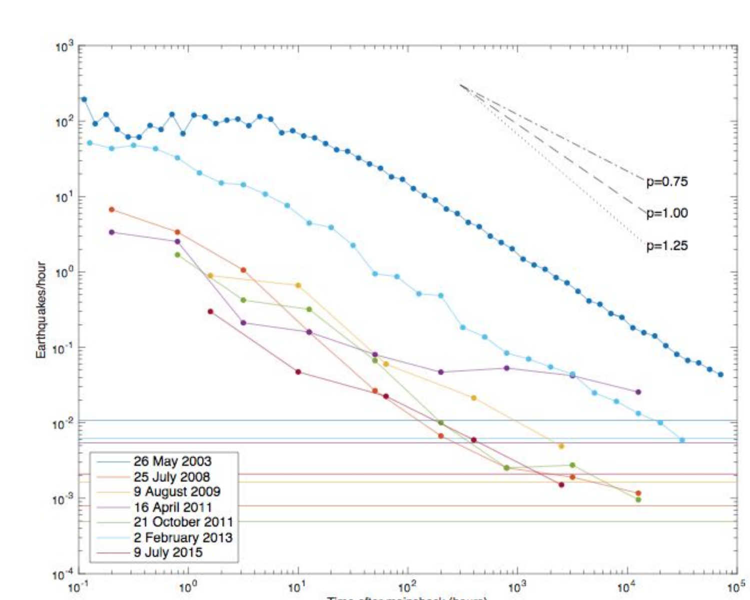
Magnitude Differential

For earthquakes with observable aftershocks, the magnitude differential ΔM between the mainshock and the largest aftershock ranges from 0.9-3.7. However, only one earthquake has ΔM <2.0 and that earthquake, with a depth of 78 km, was one of the shallowest ones analyzed. Previous observations have suggested that deep earthquakes have a ΔM of ~2 and our observations show that typical values may be even higher. Thus, intermediate-depth earthquakes appear to have a larger ΔM than shallow earthquakes, which have a value of ~1.



Aftershock decay

The rate of aftershocks is often described by the modified Omori's Law, $dN/dt = k/(t+c)^p$, where N is the number of earthquakes, t is time, k is a constant, c is the duration of the incomplete catalog, and p is the decay rate. As shown below, the analyzed aftershock sequences have a linear decrease in the number of earthquakes with time on a log-log plot and are well fit by the modified Omori's Law. For most earthquakes with observed aftershocks, the decay rate has a p value of ~1, similar to the value for aftershock sequences of shallow earthquakes.



The horizontal lines indicate the background seismicity rate for each earthquake.

Conclusions

- The low magnitude of completeness of the JMA catalog allows us to observe productive aftershock sequences for 7 intermediate-depth earthquakes.
- The magnitude differential between the main shock and the largest aftershock ranges from 0.9-3.7. For most earthquakes the magnitude differential is >2, which is larger than for shallow earthquakes.
- The decay in the rate of earthquakes with time can be fit with a modified Omori's Law p-value of ~1, similar to the decay rate for shallow earthquakes.

References

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Acknowledgements

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