

Supplementary Information

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Hot springs reflect the flooding of slab-derived water as a trigger of earthquakes

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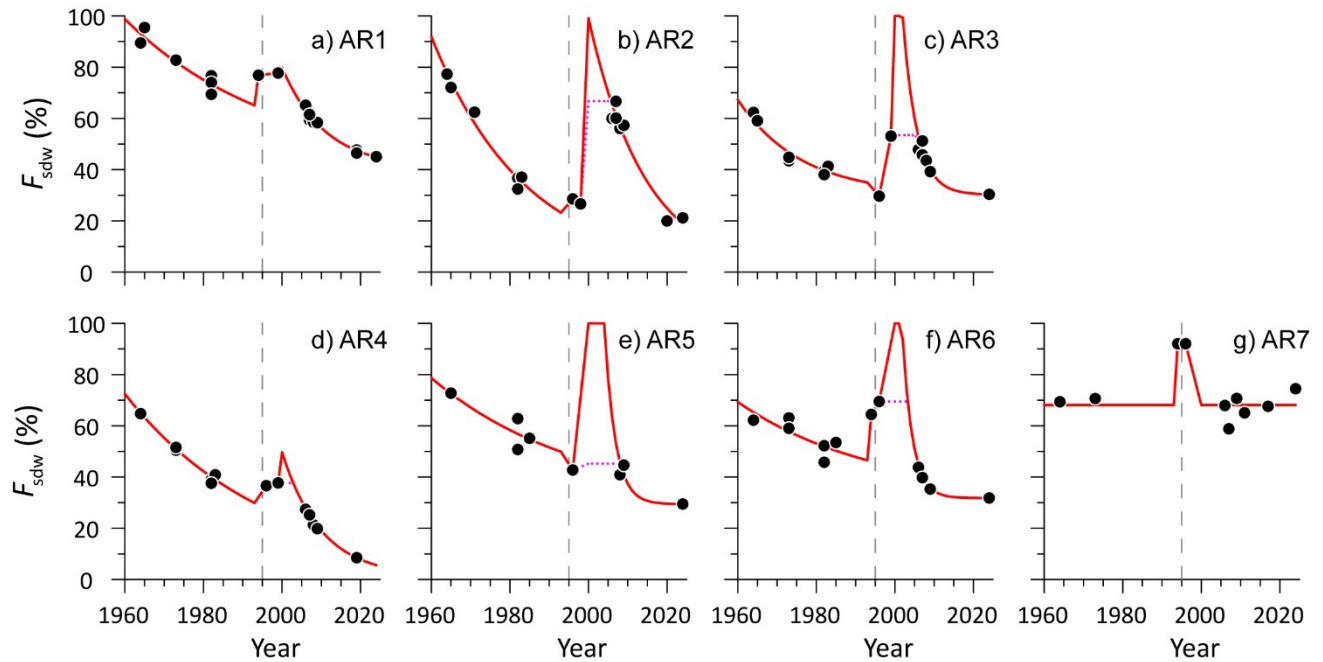
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Supplementary Figure 1: Secular variation in the fraction of slab-derived water (F_{sdw}) at the seven hot springs (AR1-AR7).



Black solid circles denote estimations of F_{sdw} based on isotope or Cl data. Red lines represent those approximated by asymptotic exponential regression for periods I (1960-1993) and III (2000-2024), or obtained by linear interpolation for period II (1994-1999). Dashed vertical lines show the year of the Kobe earthquake occurrence. Magenta dotted lines represent the case where the maximum estimated F_{sdw} after the earthquake is taken as the lower limits of the approximated values.

Supplementary Table 1 Location of sampling sites.

ID	Type	Latitude (°N)	Longitude (°E)	Elevation (m asl)	Borehole depth (m bgl)	Catchment area (km ²)	Catchment mean elevation (m)
AR1	Hot spring	34.797149	135.248641	389.4	206	N/A	N/A
AR2	Hot spring	34.795568	135.248662	399.3	223	N/A	N/A
AR3	Hot spring	34.796233	135.249172	387.9	185	N/A	N/A
AR4	Hot spring	34.796418	135.247900	382.8	182	N/A	N/A
AR5	Hot spring	34.797361	135.249660	391.8	277	N/A	N/A
AR6	Hot spring	34.797198	135.249408	391.6	270	N/A	N/A
AR7	Hot spring	34.794154	135.248882	443.4	300	N/A	N/A
CS1	Cold spring	34.795004	135.250320	410.9	16	N/A	N/A
CS2	Cold spring	34.796867	135.247858	375.4	67	N/A	N/A
RV1	River	34.788792	135.246372	433.1	N/A	1.385	617
RV2	River	34.796991	135.251849	398.5	N/A	2.685	694

Supplementary Table 2 Measured isotope data in the present study.

ID	Year/Month	$\delta^{18}\text{O}$ (‰)	$\delta^2\text{H}$ (‰)	d-excess (‰)
AR1	2019/8	-0.26	-41.30	-39.22
AR4	2019/8	-7.31	-49.30	9.18
AR1	2024/1	-0.38	-41.79	-38.75
AR2	2024/1	-4.67	-47.01	-9.67
AR3	2024/1	-2.96	-45.09	-21.38
AR5	2024/1	-2.97	-45.49	-21.71
AR6	2024/1	-2.61	-44.88	-23.98
AR7	2024/1	4.75	-35.14	-73.13
CS1	2019/8	-8.26	-53.50	12.58
CS2	2019/8	-7.75	-51.00	11.00
RV1	2024/1	-7.75	-48.12	13.86
RV2	2024/1	-7.82	-48.12	14.42

Supplementary Table 3 Isotope and Cl data in previous studies.

ID	Year/Month	$\delta^{18}\text{O}$ (‰)	$\delta^2\text{H}$ (‰)	d-excess (‰)	Cl (mg/kg)	Temp. (°C)	Ref.
AR1	1965/10	6.5	-27.8	-79.8	38,700	98	1
AR2	1965/10	4.2	-35.5	-69.1	31,800	98	1
AR3	1965/10	1.9	-38.4	-53.6	26,400	98	1
AR5	1965/10	4.5	-35.6	-71.6	34,800	98	1
AR1	1973/5	5.7	-32.6	-78.2	37,670	98	1
AR3	1973/5	-0.9	-41.2	-34.0	19,200	98	1
AR4	1973/5	0.6	-40.1	-44.9	22,500	98	1
AR6	1973/5	2.4	-39.1	-58.3	28,500	98	1
AR7	1973/5	4.3	-36.3	-70.7	32,900	48	1
AR1	1982/11	4.39	-37	-72.1	34,100	98.2	2
AR2	1982/11	-2.54	-44.7	-24.4	14,800	78.5	2
AR3	1982/11	-1.29	-43.8	-33.5	17,700	86.5	2
AR4	1982/11	-1.08	-44.3	-35.7	17,700	86.8	2
AR5	1982/11	3.58	-37.6	-66.2	32,100	96.2	2
AR6	1982/11	0.02	-42	-42.2	22,000	97	2
AR1	2007/12	2.22	-37.71	-55.5	25,828	88.3	3
AR2	2007/12	2.07	-38.15	-54.7	25,088	95.3	3
AR3	2007/12	0.77	-40.5	-46.7	20,786	88.3	3
AR4	2007/12	-4.09	-45.92	-13.2	8,742	80.3	3

Supplementary Table 4 Cl, temperature, and discharge data in previous studies.

ID	Year	Cl (mg/kg)	Temp. (°C)	Discharge (m ³ /d)	Ref.
AR1	1964	40,980	97.5	N/A	4
AR1	1973	37,612	N/A	N/A	8
AR1	1982	34,900	94.7	25.6	8
AR1	1982	33,650	98.6	65.3	8
AR1	1994	35,000	94.7	N/A	6
AR1	1999	35,400	98.2	40.3	8
AR1	2006	29,420	95.1	N/A	8
AR1	2007	26,680	90.3	35.0	8
AR1	2008	26,300	97.3	79.2	8
AR1	2009	26,200	97.0	115.2	8
AR1	2019	21130	99.4	76.3	*
AR2	1964	35,200	97.0	N/A	4
AR2	1971	28,153	88.0	29.0	8
AR2	1982	15,930	83.4	10.8	8
AR2	1983	16,100	84.2	6.8	8
AR2	1996	12,600	94.7	N/A	7
AR2	1998	11,700	72.9	8.5	8
AR2	2006	26,990	99.7	N/A	8
AR2	2007	30,150	98.5	34.3	8
AR2	2008	25,110	97.6	96.3	8
AR2	2009	25,710	98.6	73.4	8
AR2	2020	7980	96.1	N/A	*
AR3	1964	28,091	96.0	N/A	4
AR3	1973	19,143	N/A	N/A	8
AR3	1982	17,210	88.6	80.9	8
AR3	1983	18,100	86.6	53.1	8
AR3	1996	13,100	88.6	N/A	7
AR3	1999	23,700	93.8	40.3	8
AR3	2006	21,220	97.6	73.0	8
AR3	2007	20,240	95.7	52.8	8
AR3	2008	19,180	97.2	49.4	8
AR3	2009	17,130	97.3	99.4	8
AR3	2019	21980	100.5	172.8	*
AR4	1964	29,247	90.7	N/A	4
AR4	1973	22,475	N/A	N/A	8

Supplementary Table 4 (continued)

ID	Year	Cl (mg/kg)	Temp. (°C)	Discharge (m ³ /d)	Ref.
AR4	1982	17,010	87.8	N/A	8
AR4	1983	17,900	86.5	36.4	8
AR4	1996	15,900	87.8	N/A	7
AR4	1999	16,400	83.5	34.6	8
AR4	2006	11,510	82.7	43.2	8
AR4	2008	8,625	80.7	35.4	8
AR4	2009	7,927	79.3	25.9	8
AR5	1982	22,600	86.6	N/A	5
AR5	1985	24,670	90.1	69.8	8
AR5	1996	18,800	81.0	67.1	8
AR5	2006	1,753	45.1	21.5	8
AR5	2008	17,920	92.5	42.3	8
AR5	2009	19,700	94.1	25.9	8
AR5&6	2012	15100	83.1	72.0	*
AR5&6	2019	15470	81.0	66.2	*
AR6	1964	28,033	96.0	N/A	4
AR6	1973	28,466	N/A	N/A	8
AR6	1982	23,300	96.0	N/A	5
AR6	1985	23,900	96.8	90.7	8
AR6	1994	29,100	96.0	N/A	6
AR6	1996	31,500	94.8	29.8	8
AR6	2006	19,300	92.2	31.4	8
AR6	2007	17,390	79.3	32.1	8
AR6	2009	15,260	78.1	28.8	8
AR7	1964	31,443	50.0	N/A	4
AR7	1994	42,200	90.5	49.0	8
AR7	1996	42,200	90.5	N/A	7
AR7	2006	30,750	99.4	71.6	8
AR7	2007	26,430	90.3	8.9	8
AR7	2009	32,070	99.7	67.7	8
AR7	2011	29,400	98.5	N/A	*
AR7	2017	30,600	96.6	83.5	*

* Measured by authorized inspection agencies commissioned by hot spring owners (Supplementary Table 6)

Supplementary Table 5 Asymptotic exponential regression and water budget analysis.

	AR1	AR2	AR3	AR4	AR5	AR6	AR7	Total	Mean	SD
<u>Period I (1960 - 1993)</u>										
a^*	-0.026	-0.042	-0.062	-0.028	-0.027	-0.028				
b^*	58.4	92.0	37.1	71.2	49.3	37.5				
c^*	40.4	0.0	30.2	1.2	29.4	31.8				
r^2	0.87	0.96	0.89	0.96	0.66	0.54				
τ (yr)	38.4	23.9	16.1	36.3	37.6	35.3			31.3	8.3
F_0 (%) [#]	98.8	92.0	67.3	72.4	78.7	69.3				
O (m ³ /d)	62.4	37.0	77.7	35.1	45.3	42.6	56.1			
I_{sdw} (m ³ /d)	25.2	0.0	23.5	0.4	13.3	13.5	38.2			
V (m ³)	8.7E+05	3.2E+05	4.6E+05	4.6E+05	6.2E+05	5.5E+05		3.3E+06		
<u>Period III (2000 - 2024)</u>										
a^*	-0.091	-0.069	-0.280	-0.100	-0.364	-0.390				
b^*	39.4	99.1	121.0	48.4	302.8	134.9				
c^*	40.4	0.0	30.2	1.2	29.4	31.8				
r^2	0.98	0.96	0.99	1.00	0.99	1.00				
τ (yr)	11.0	14.5	3.6	10.0	2.7	2.6			7.4	4.7
F_0 (%) [#]	79.8	99.1	151.2	49.6	332.2	166.7				
O (m ³ /d)	62.4	37.0	77.7	35.1	45.3	42.6	56.1			
I_{sdw} (m ³ /d)	25.2	0.0	23.5	0.4	13.3	13.5	38.2			
V (m ³)	2.5E+05	2.0E+05	1.0E+05	1.3E+05	4.5E+04	4.0E+04		7.6E+05		

* Empirical parameters in an exponential asymptotic function, $F_{sdw} = c + b \exp(at)$.

[#] Value of F_{sdw} in 1960 for Period I and in 2000 for Period III.

Supplementary Table 6 Chemical compositions of some hot spring waters.

	Unit	AR1	AR2	AR3	AR5&6	AR5&6	AR7	AR7
Year		2019	2020	2019	2012	2019	2011	2017
Date		24-Sep	27-Jan	24-Sep	6-Sep	5-Feb	4-Feb	28-Feb
Temperature	°C	99.4	96.1	100.5	83.1	81.0	98.5	96.6
Discharge	m ³ /d	76.3	N/A	172.8	72.0	66.2	N/A	83.5
pH		6.6	6.94	6.7	6.26	6.06	6.14	6.14
EC	S/m	5.10	N/A	5.11	N/A	4.01	N/A	6.39
Rn	Bq/kg	<2.0	<1.08	<2.0	4.68	<7.4	N/A	44.1
Li ⁺	mg/kg	N/A	N/A	N/A	25.7	24.6	65.0	46.5
Na ⁺	mg/kg	10,470	4,506	10,840	7,120	7,072	13,500	13,800
K ⁺	mg/kg	2,003	843	2,045	1,760	1,625	2,790	3,220
NH ⁴⁺	mg/kg	3.7	2.0	4.0	N/A	N/A	N/A	N/A
Mg ²⁺	mg/kg	12.8	5.0	13.8	15.7	13.7	27.0	23.6
Ca ²⁺	mg/kg	1,725	443	1,825	1,270	1,330	2,760	2,900
Sr ²⁺	mg/kg	N/A	N/A	N/A	20.4	21.2	56.9	50.4
Ba ²⁺	mg/kg	N/A	N/A	N/A	15.5	15.8	42.7	40.2
Al ³⁺	mg/kg	<0.1	0.2	<0.1	0.50	N/A	N/A	<0.01
Mn ⁺	mg/kg	13.7	2.5	17.1	9.59	8.84	N/A	32.2
Fe ²⁺	mg/kg	40.4	11.4	67.0	56.7	45.6	63.9	48.5
Zn ²⁺	mg/kg	0.3	1.4	0.05	0.42	0.87	2.94	1.6
F ⁻	mg/kg	1.6	1.7	0.3	2.17	2.42	3.35	2.8
Cl ⁻	mg/kg	21,130	7,980	21,980	15,100	15,470	29,400	30,600
Br ⁻	mg/kg	38.5	14.6	38.7	26.0	29.5	53.1	57.4
I ⁻	mg/kg	4.9	1.9	5.1	<0.1	N/A	0.23	0.4
HS ⁻	mg/kg	<0.1	0.5	0.1	0.02	N/A	N/A	N/A
S ₂ O ₃ ²⁻	mg/kg	<0.1	0.1	<0.1	N/A	N/A	N/A	N/A
SO ₄ ²⁻	mg/kg	20.8	17.0	29.6	21.0	23.2	0.67	0.2
HCO ₃ ⁻	mg/kg	243.5	630.3	298.4	96.3	156	60.8	465
CO ₃ ²⁻	mg/kg	<0.5	0.3	<0.1	<0.01	0.06	N/A	N/A
H ₂ SiO ₃	mg/kg	121.4	99.9	160.4	112	94.6	273	297
HBO ₂	mg/kg	257.1	129.6	271.5	206	184	406	388
CO ₂	mg/kg	183.2	104.3	136.4	88.8	60.9	N/A	565
H ₂ S	mg/kg	<0.1	0.4	0.2	0.10	N/A	N/A	N/A

Supplementary Note 1 Uncertainty in sampling dates

Date (at least year and month) of sample collection for Cl measurements are given in most of the cited references, but not given in Refs. 6 and 7. Unfortunately, the authors of these papers have already retired, and exact information about sampling dates cannot be known. So, we guessed the sampling years as following.

The submission of Ref. 6 has received Feb. 14, 1995. It is undoubted that the samples in Ref. 6 were collected before this date. Similarly, it is certain that the samples in Ref. 7 has collected before the reception date, Jan. 16, 1997. Ref. 6 serves as a preliminary report for Ref. 7, and presents data only for AR1 and AR6. Although the data for AR1, AR2, AR3, AR4, AR6, and AR7 are presented in Ref. 7, those for AR1 and AR6 are completely the same as in Ref. 6. Therefore, data for AR1 and AR6 in Ref. 7 are repetition of data in Ref. 6.

Apart from these, a sample at AR7 was collected on Jan. 25, 1994, and major ion concentrations were measured by Public Health Institute of Hyogo Prefecture under commission from the hot spring owner. The major ion concentrations data in Refs. 6 and 7 were also measured by the same institute. Major ion concentrations data at AR7 in 1994 and in Ref. 7 are partially similar but are not completely the same. Additionally, the AR7 is not included in Ref. 6, implying that these two measurements were independent and the samples in Refs. 6 and 7 were supposed to be collected after Jan. 25, 1994.

Thus, it is highly certain that samples of AR1 and AR6 were collected in 1994. Since the AR7 data in Ref. 7 are not just repetition of data in 1994, samples of AR2, AR3, AR4, and AR7 are supposed to be collected in 1995 or 1996. Because these hot springs and spa facilities have received damage by the 1995 Kobe earthquake occurred on Jan. 17 of 1995, we adopted 1996. We cannot reject completely a possibility that some samples in Ref.7 have been collected 1994 together with AR1 and AR6. However, even so, the estimated results of episodic replenishment of slab-derived water do not change much.

Although there is uncertainty in the sampling dates in Refs. 6 and 7, the most important point is that Cl concentrations at AR1 and AR6 as well as at AR7 have certainly increased before the earthquake. Therefore, we did not exclude these data.

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