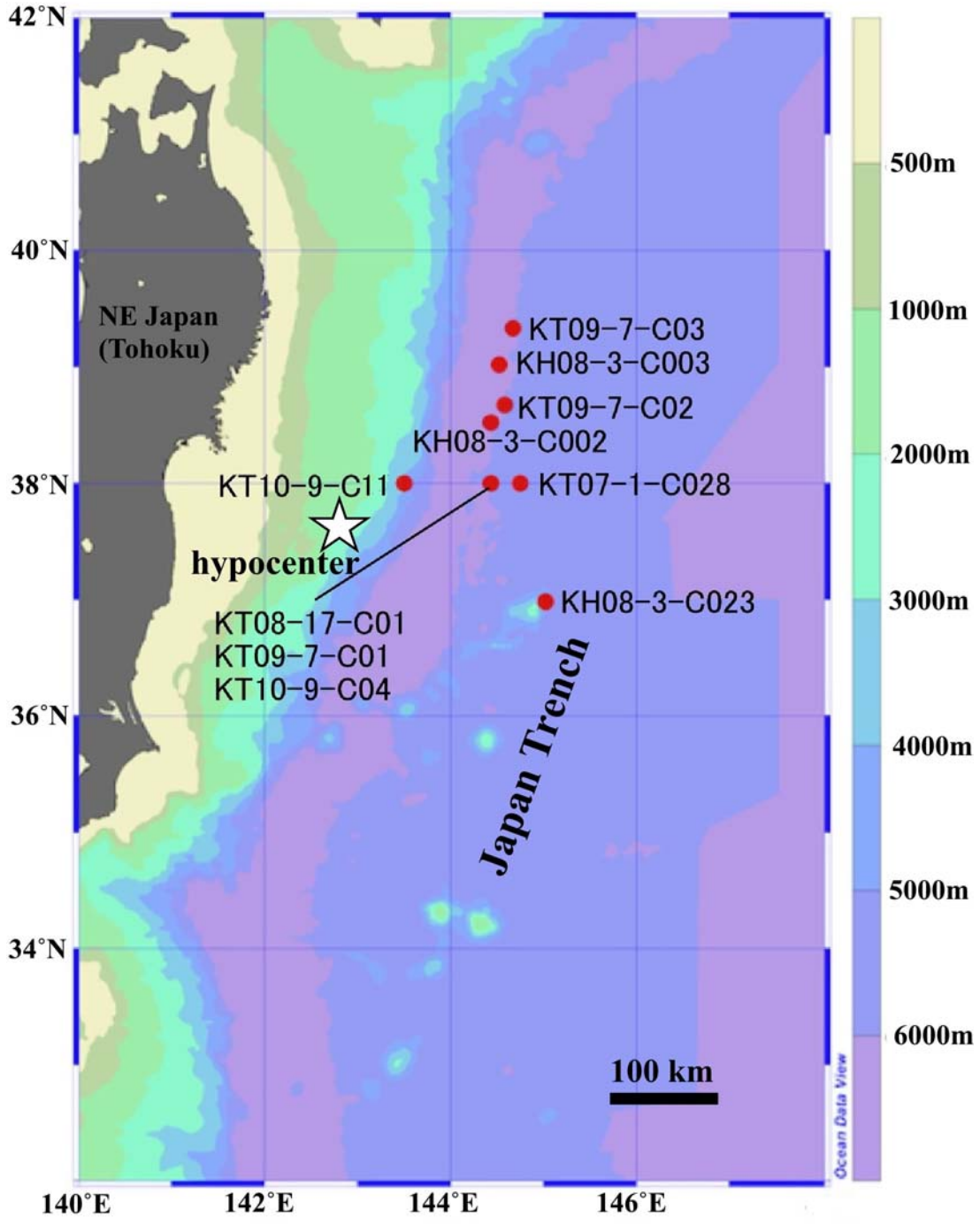
Supplementary Information

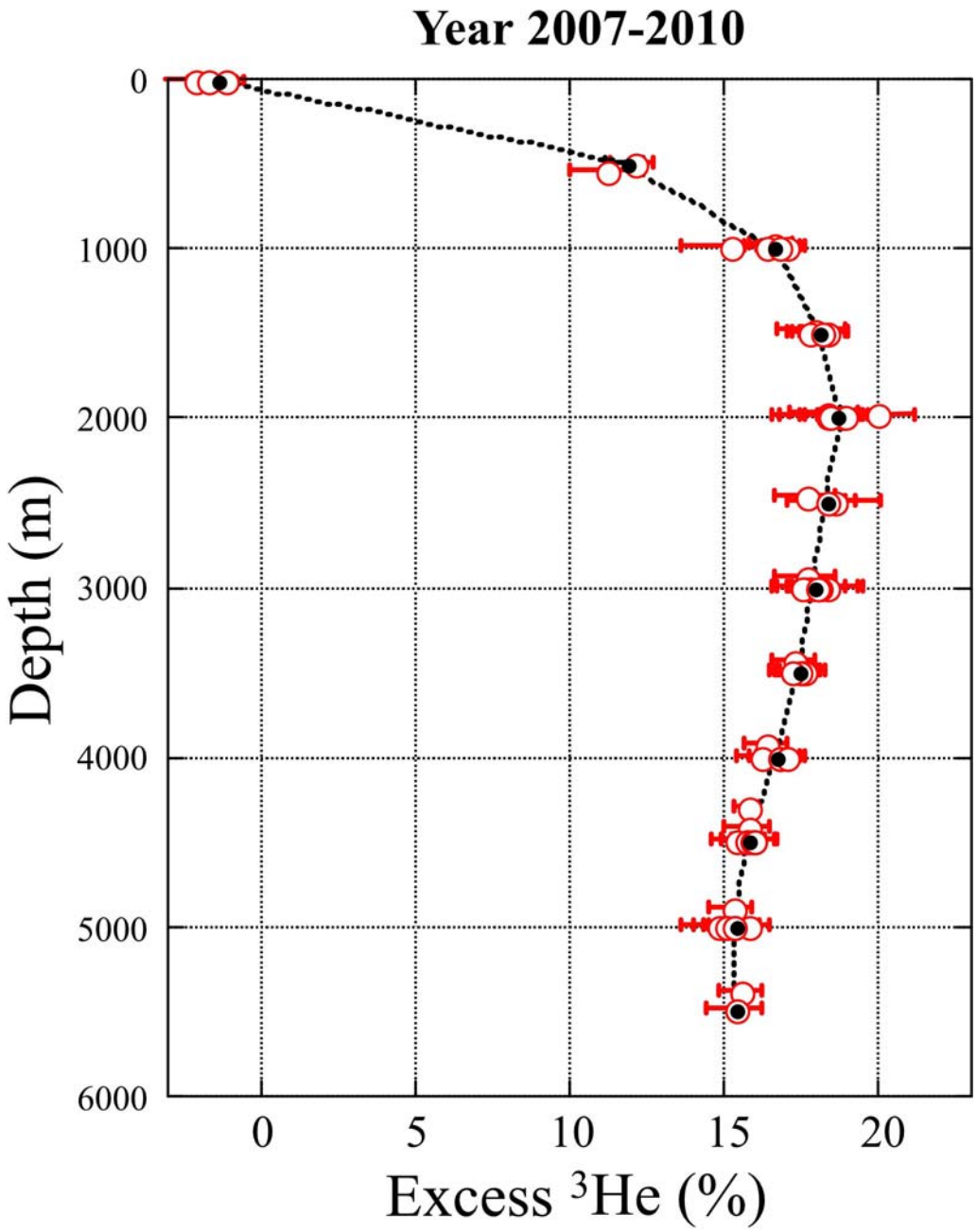
Helium anomalies suggest a fluid pathway from mantle to trench during the 2011 Tohoku earthquake

Yuji Sano, Takahiro Hara, Naoto Takahata, Shinsuke Kawagucci, Makio Honda, Yoshiro Nishio, Wataru Tanikawa, Akira Hasegawa, and Keiko Hattori

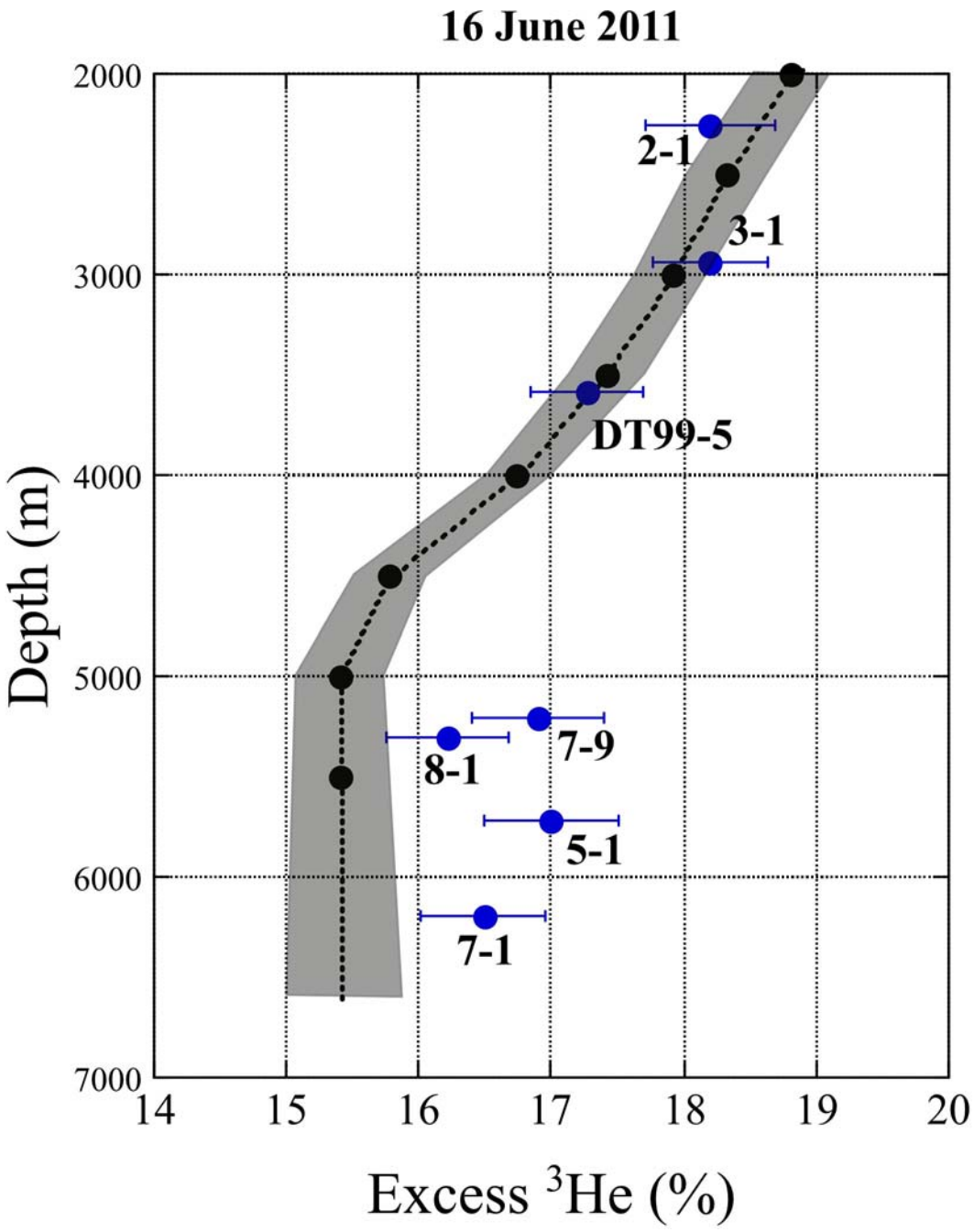
Supplementary Figures



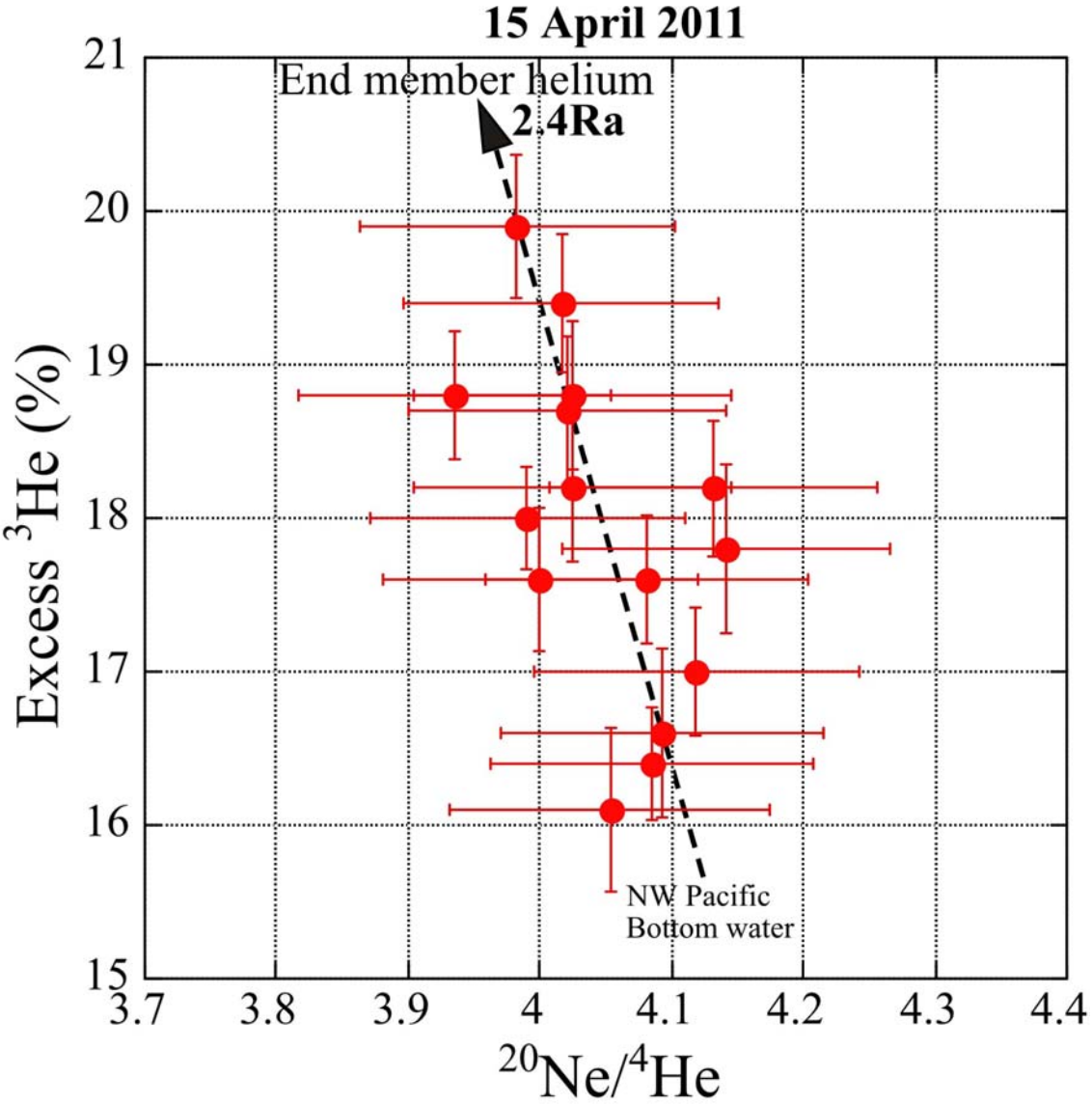
Supplementary Figure S1. Sampling sites of seawater samples at northeast of Sendai, in Northwest Pacific prior to the M9.0 earthquake. Star shows the position of hypocenter.



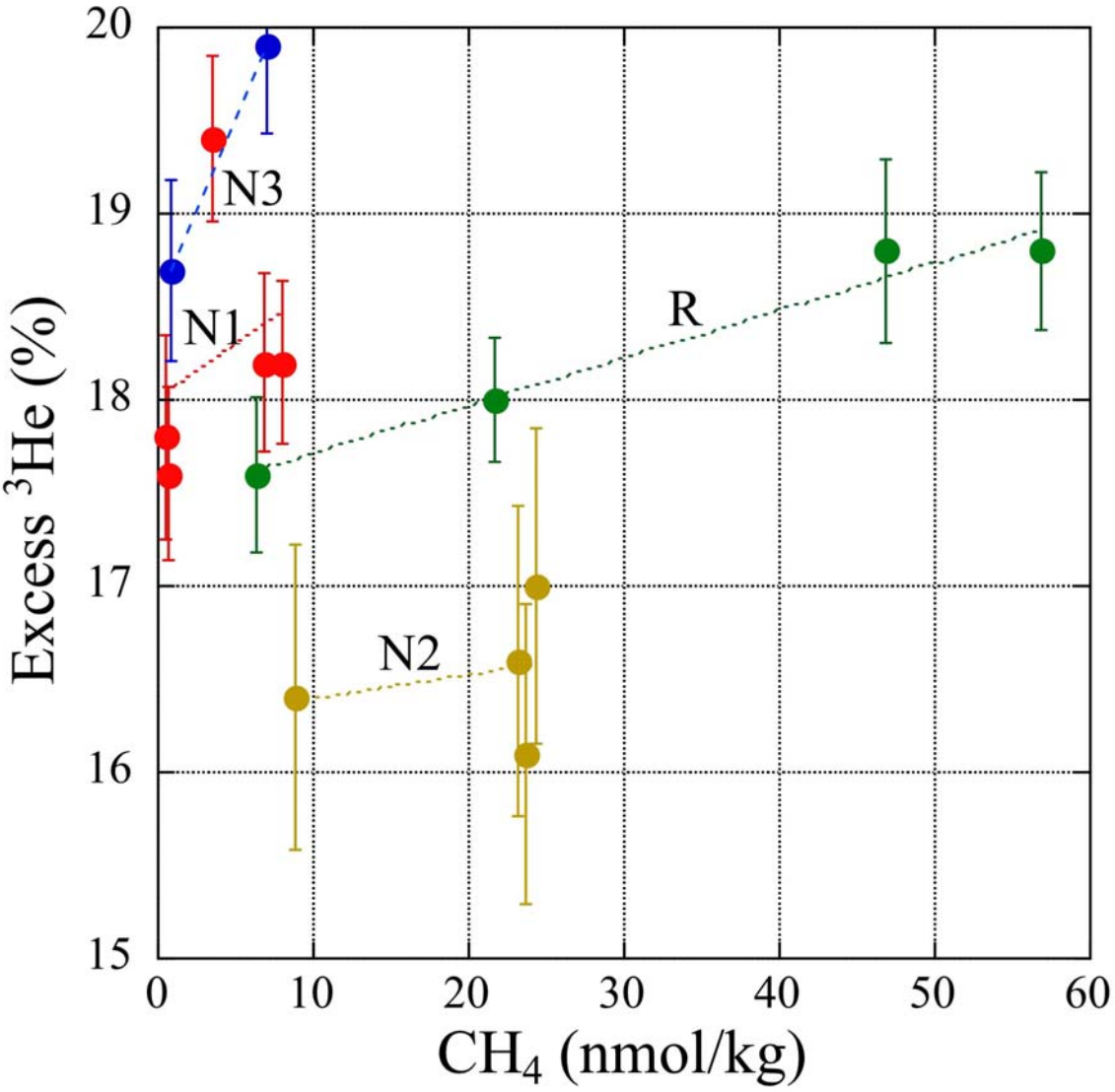
Supplementary Figure S2. Depth variation of helium isotopes in seawater samples prior to the M9.0 earthquake (open circle) together with the pre-earthquake ^{3}He profile (dotted curve). The profile was calculated by a weighted mean value of the same depth data obtained before the earthquake. Bars represent one sigma error.



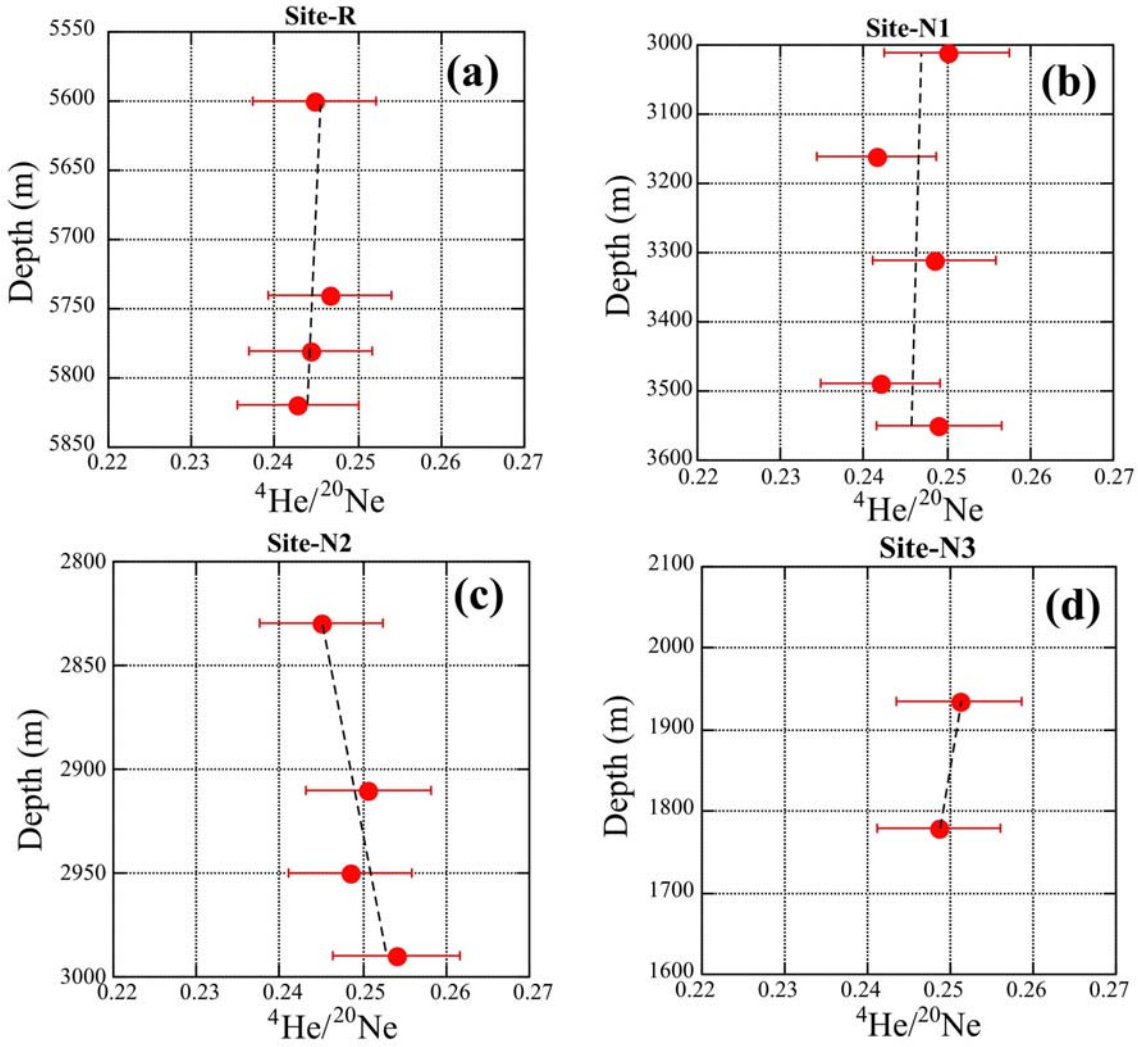
Supplementary Figure S3. Depth variation of helium isotopes of bottom seawater samples collected in June 2011. The dotted curve shows an average ^{3}He profile. Bars represent one sigma error. Shade indicates one sigma error of the pre-earthquake profile. Numerical data are given in Supplementary Table S3.



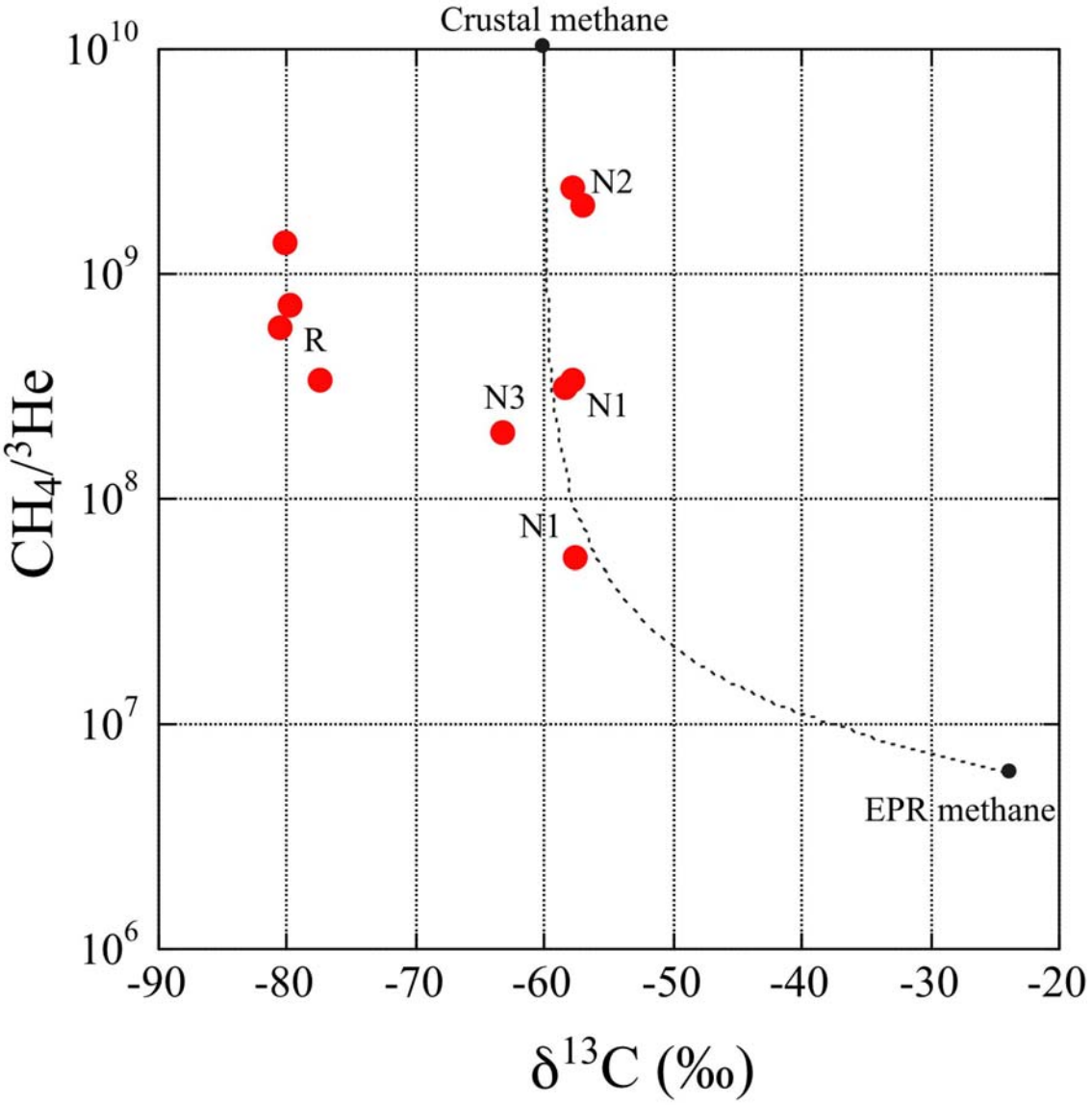
Supplementary Figure S4. A correlation diagram between the ^{20}Ne/^{4}He and ^{3}He/^{4}He ratios (excess ^{3}He) of bottom seawater samples in April 2011. A dotted line shows the best fit obtained by a least squares method. Bars represent one sigma error.



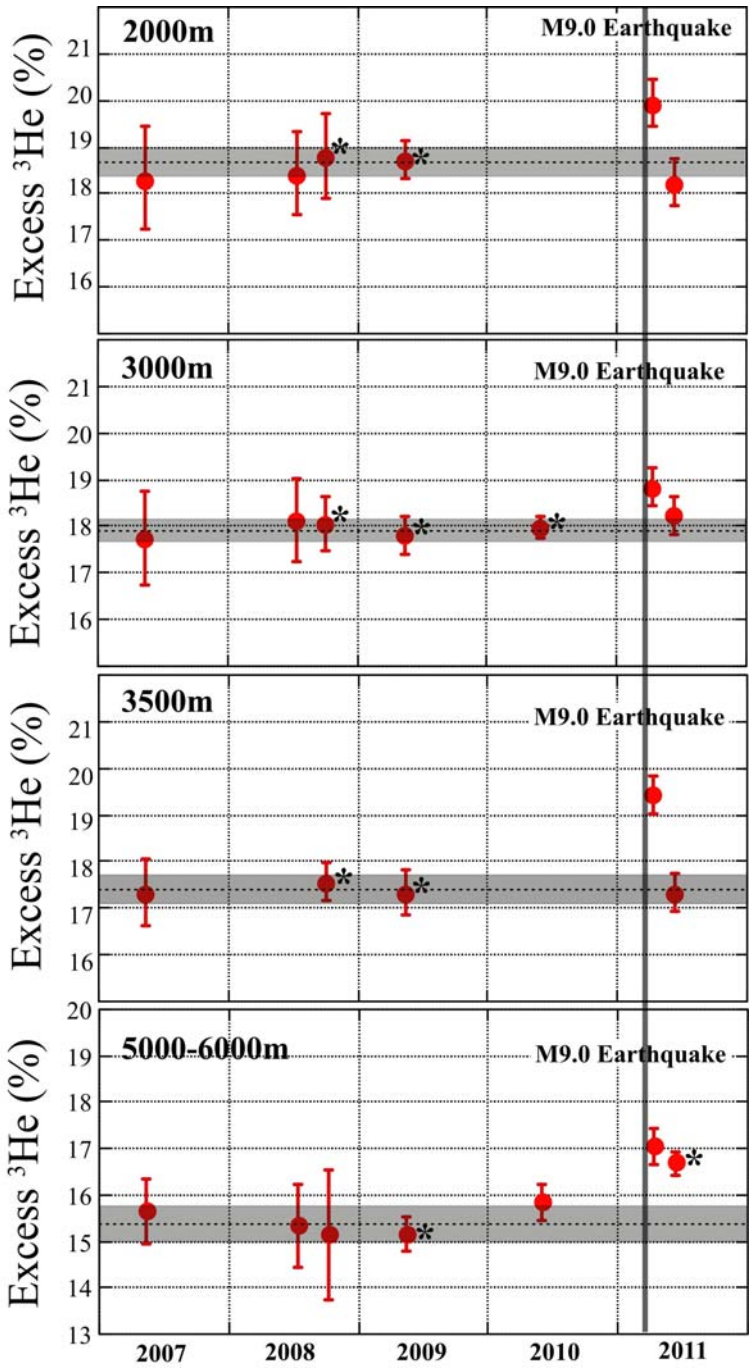
Supplementary Figure S5. A correlation diagram between CH_4 contents and excess ^{3}He of bottom seawater samples in April 2011. Bars represent one sigma error. Dotted lines show the best fit obtained by a least square method except for site N3.



Supplementary Figure S6. Depth variation of $^4He/^{20}Ne$ ratios of bottom seawater samples in April 2011. Bars represent one sigma error. Dotted lines show the best fit obtained by a least square method except for site N3.



Supplementary Figure S7. A correlation diagram between $\delta^{13}C$ values and $CH_4/^3He$ ratios of bottom seawater samples in April 2011. EPR denotes East Pacific Rise. Dotted curve shows the binary mixing between EPR-type methane with $\delta^{13}C$=-23‰ and $CH_4/^3He=6x10^6$ and crustal methane with $\delta^{13}C$=-60‰ and $CH_4/^3He=1x10^{10}$. The curve approximately replicates the distribution of N1, N2 and N3 samples.



Supplementary Figure S8. Temporal variation of $^{3}He/^{4}He$ ratios (excess ^{3}He) of seawater samples with the same depth since May 2007 to June 2011. Bars represent one sigma error. Star (*) and shade show the weighted mean average of 2-4 measurements and the one sigma region of the weighted mean average of all measurements at the depth, respectively.

Supplementary Tables

Supplementary Table S1. Observed helium isotopes, excess ^{3}He and $^{4}He/^{20}Ne$ ratios in deep seawater samples.

Sample	Location		Depth	$^{3}He/^{4}He$			Excesss ^{3}He			$^{4}He/^{20}Ne$
			(m)	(Ra)			(%)			
MR11-03 cruise of R/V Mirai (15 April 2011)										
R-1	38˚12.5'N	143˚47.2'E	5699	1.170	±	0.004	17.0	±	0.4	0.243
R-2			5661	1.166	±	0.005	16.6	±	0.5	0.244
R-3			5622	1.161	±	0.005	16.1	±	0.5	0.247
R-4			5486	1.164	±	0.004	16.4	±	0.4	0.245
N1-1	38˚10.6'N	143˚33.0'E	3493	1.194	±	0.004	19.4	±	0.4	0.249
N1-2			3435	1.182	±	0.004	18.2	±	0.4	0.242
N1-3			3260	1.182	±	0.005	18.2	±	0.5	0.249
N1-4			3113	1.178	±	0.005	17.8	±	0.5	0.242
N1-5			2966	1.176	±	0.005	17.6	±	0.5	0.250
N2-1	38˚8.7'N	143˚19.0'E	2944	1.188	±	0.004	18.8	±	0.4	0.254
N2-2			2908	1.188	±	0.005	18.8	±	0.5	0.249
N2-3			2868	1.180	±	0.003	18.0	±	0.3	0.251
N2-4			2790	1.176	±	0.004	17.6	±	0.4	0.245
N3-1	38˚6.8'N	143˚5.0'E	1936	1.199	±	0.005	19.9	±	0.5	0.251
N3-2			1779	1.187	±	0.005	18.7	±	0.5	0.249
YK11-E04 cruise of R/V Yokosuka (16 June 2011)										
2-1	38˚9.7'N	143˚26.4'E	2251	1.182	±	0.005	18.2	±	0.5	0.247
3-1	38˚8.7'N	143˚19.0'N	2943	1.182	±	0.004	18.2	±	0.4	0.251
5-1	38˚12.6'N	143˚47.1'E	5722	1.170	±	0.005	17.0	±	0.5	0.244
7-1	37˚39.4'N	143˚40.6'E	6196	1.165	±	0.005	16.5	±	0.5	0.241
7-2			5206	1.169	±	0.005	16.9	±	0.5	0.246
8-1	37˚40.7'N	143˚33.7'N	5306	1.162	±	0.005	16.2	±	0.5	0.243
DT99-5	37˚44.4'N	143˚17.0'E	3580	1.173	±	0.004	17.3	±	0.4	0.246
A 3% one sigma error is assigned to the $^{4}He/^{20}Ne$ ratios.										
Excess ^{3}He is calculated as (Ra-1)x100										

Supplementary Table S2. ^{4}He contents, $^{3}He/^{4}He$ and $^{4}He/^{20}Ne$ ratios of sediment samples.

Sample	Location		Depth (m)	^{4}He ccSTP/g	$^{3}He/^{4}He$ (Ra)	$^{4}He/^{20}Ne$	Corrected $^{3}He/^{4}He$ (Ra)*
1260-1	37˚4'N	143˚17'E	3582	$2.0x10^{-6}$	0.31±0.06	6170±580	0.31±0.06
1256-2B	39˚6'N	143˚54'E	5351	$5.4x10^{-7}$	0.69±0.49	579±72	0.69±0.49
1254-1B	39˚6'N	143˚54'E	5349	$6.6x10^{-7}$	0.79±0.34	373±18	0.79±0.34
1257-1B	37˚4'N	143˚17'E	3582	$1.0x10^{-6}$	0.11±0.15	405±20	0.11±0.15

*: Error of corrected $^{3}He/^{4}He$ ratio is the same as observed ratio because the error by the correction is negligibly small.

Supplementary Table S3. $^{3}He/^{4}He$ and $^{4}He/^{20}Ne$ ratios of pore water in sediment.

Sample	Location		Depth (m)	$^{3}He/^{4}He$ (Ra)	$^{4}He/^{20}Ne$	Corrected $^{3}He/^{4}He$ (Ra)
1260-1B	37˚4'N	143˚17'E	3582.00	0.68 ± 0.05	0.48	0.36 ± 0.03
1256-2B	39˚6'N	143˚54'E	5351.00	0.68 ± 0.04	0.47	0.35 ± 0.03
1254-1B	39˚6'N	143˚54'E	5349.00	0.71 ± 0.03	0.48	0.41 ± 0.03

A 3% one sigma error is assigned to the $^{4}He/^{20}Ne$ ratios.

Supplementary Table S4. Observed $^{3}He/^{4}He$ gradients, estimated ^{3}He flux, $CH_4/^{3}He$ and $\delta^{13}C$ values.

site	$^{3}He/^{4}He$ gradient $(x10^{-11})/m$	^{3}He gradient ccSTP/g/cm	^{3}He flux atom/cm^{2}sec	Error	$CH_4/^{3}He$ $(x10^{7})$	$\delta^{13}C$* (‰)
R	3.04	$1.2x10^{-20}$	0.34	0.37	34-140	-80
N1	3.73	$1.5x10^{-20}$	0.42	0.16	5.5-34	-59
N2	12.0	$5.0x10^{-20}$	1.36	0.56	200-240	-57
N3	10.6**	$4.4x10^{-20}$	1.18		20	-63

*: Data from ref. 35.

**: calculated from two depth

Supplementary Table S5. List of sampling date and location of seawater for average ^{3}He profile.

Sample	Date	Location	
KH07-1-C028	18 May 2007	38˚00'N	144˚45'E
KT08-17-C01	21 July 2008	38˚00'N	144˚26'E
KH08-3-C002	10 October 2008	38˚31'N	144˚26'E
KH08-3-C003	11 October 2008	39˚01'N	144˚31'E
KH08-3-C023	22 October 2008	36˚59'N	145˚01'E
KT09-7-C01	21 May 2009	38˚00'N	144˚26'E
KT09-7-C02	21 May 2009	38˚40'N	144˚35'E
KT09-7-C03	21 May 2009	39˚20'N	144˚40'E
KT10-9-C04	5 June 2010	38˚00'N	144˚26'E
KT10-9-C05	6 June 2010	38˚40'N	144˚35'E
KT10-9-C11	8 June 2010	38˚00'N	143˚30'E

Supplementary Table S6. Normal excess ^{3}He profile.

Depth (m)	Excess ^{3}He (%)
10	-1.4 ± 0.3
500	11.8 ± 0.6
1000	16.6 ± 0.3
1500	18.1 ± 0.4
2000	18.7 ± 0.3
2500	18.3 ± 0.4
3000	17.9 ± 0.2
3500	17.4 ± 0.3
4000	16.7 ± 0.2
4500	15.8 ± 0.3
5000	15.4 ± 0.3
5500	15.4 ± 0.9

Error assigned to the ratio is one sigma.