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Fractal analysis of geomagnetic data to decipher pre-earthquake processes in the Andaman–Nicobar region, India

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Supplementary materials

Synthetic test of monofractal and multifractal method:

For the numerical simulation or synthetic test of fractal and multifractal analysis, we preferred to simulate three different types of monofractal signals with known Hurst exponent h1(0.2), h2(0.4), h3(0.6), and a multifractal signal h4 (addition of h1, h2, and h3 in series). The smaller Hurst exponent indicates the less correlated signal or noisier than signal of large Hurst exponent which indicates high correlated or smoother (Figure S1). From the theoretical approach, the fractal dimension of noisier or less correlated signal should be larger than smoother or correlated signal. The fractal dimension of h1, h2, and h3 calculated from Higuchi method is 1.7, 1.6, and 1.4, while for h4 is 1.6 (Figure S2). For multifractal signal h4, the fractal dimension is lower than the h3 even it is more heterogeneous than h3. From the concept of multifractal, the noisier or heterogeneous signal encompasses through higher degree of multifractal nature and large spectrum width than the spectrum width of less disturb or smooth signal i.e. spectrum width of h4>h1>h2>h3. The spectrum width computed with the same procedure as discussed above is shown in Figure S3, which clearly deciphers that the spectrum width of h4>h1>h2>h3. Thus, the multifractal analysis shows the true and generalised nature of heterogeneity of multifractal signal from width of spectrum. Thus, fractal and multifractal approach tested over known synthetic signal indicates the efficacy of method to reveal the degree of complexity or heterogeneity or disturbances in signals.

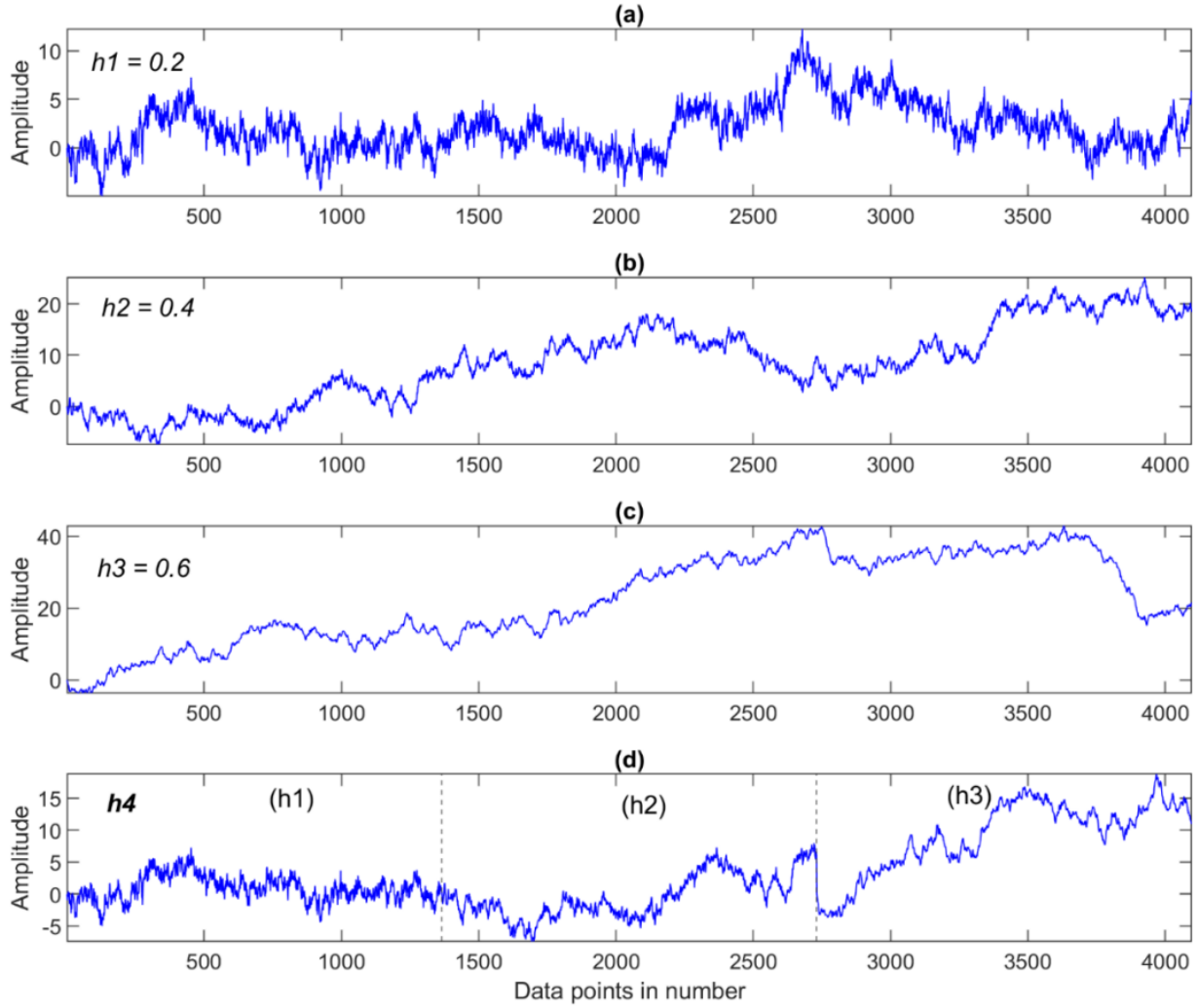

Figure S1. The synthetic signal generated at hurst exponent (a) 0.2, (b) 0.4, (c) 0.5, and (d) combination of all three in series.

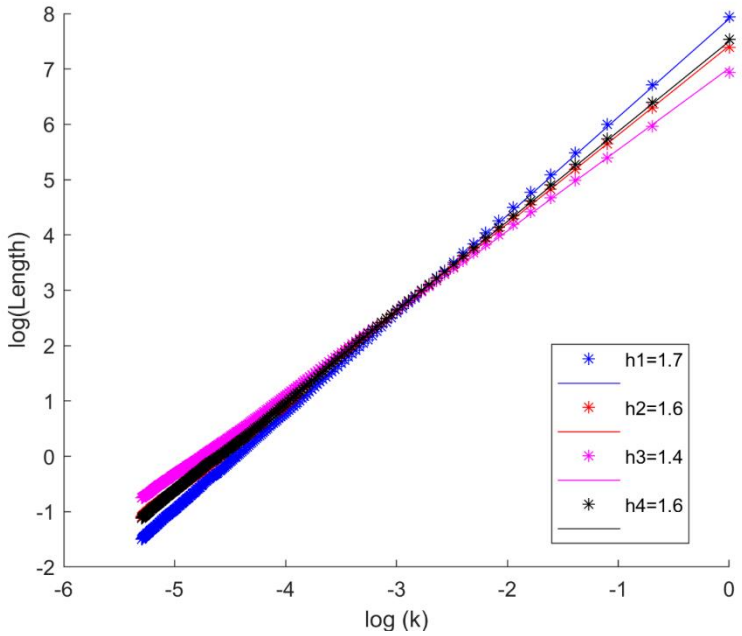

Figure S2. Fractal dimension of synthetic signal h1, h2, h3, and h4 from Higuchi method.

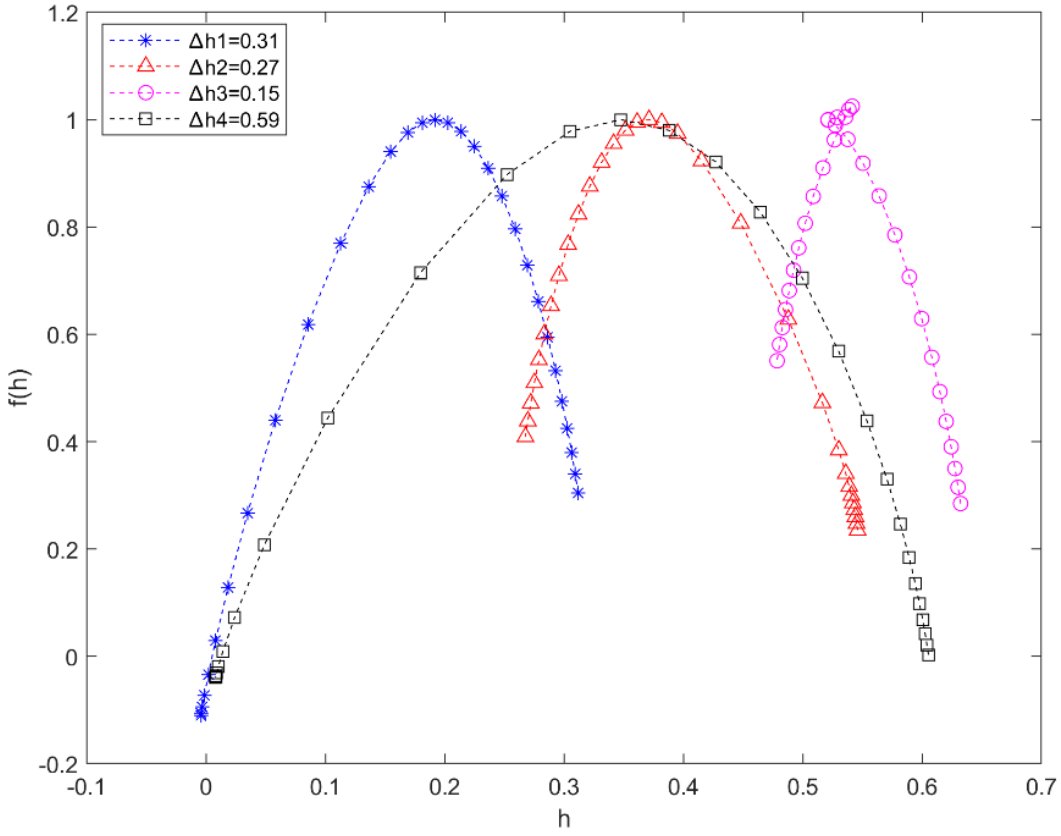

Figure S3. The multifractal spctrum of signal h1, h2, h3, and h4 showing the degree of multifractality**.**

Figures of fractal and multifractal component's variation of each month:

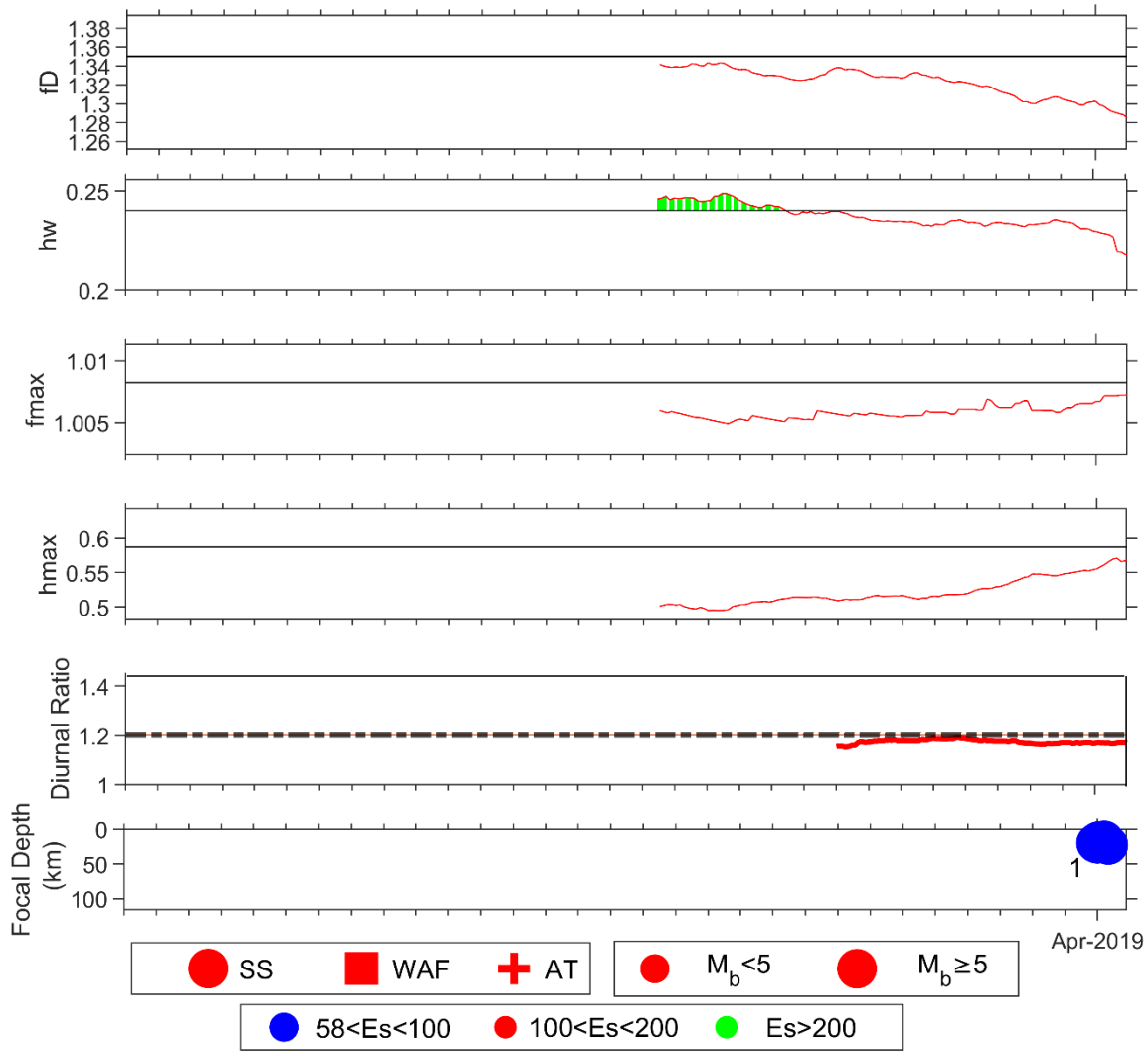

Figure S4. The temporal variation for March-2019 of components monofractal analysis (a) Higuchi fractal dimension, and multifractal analysis (b) spectrum width component, (c) fmax component, (d) hmax components. Panel (e) and (f) showing the diurnal ratio component and occurrences of earthquakes in same time duration with magnitude and focal depth respectively. The significant enhancements from each component are shaded by green color.

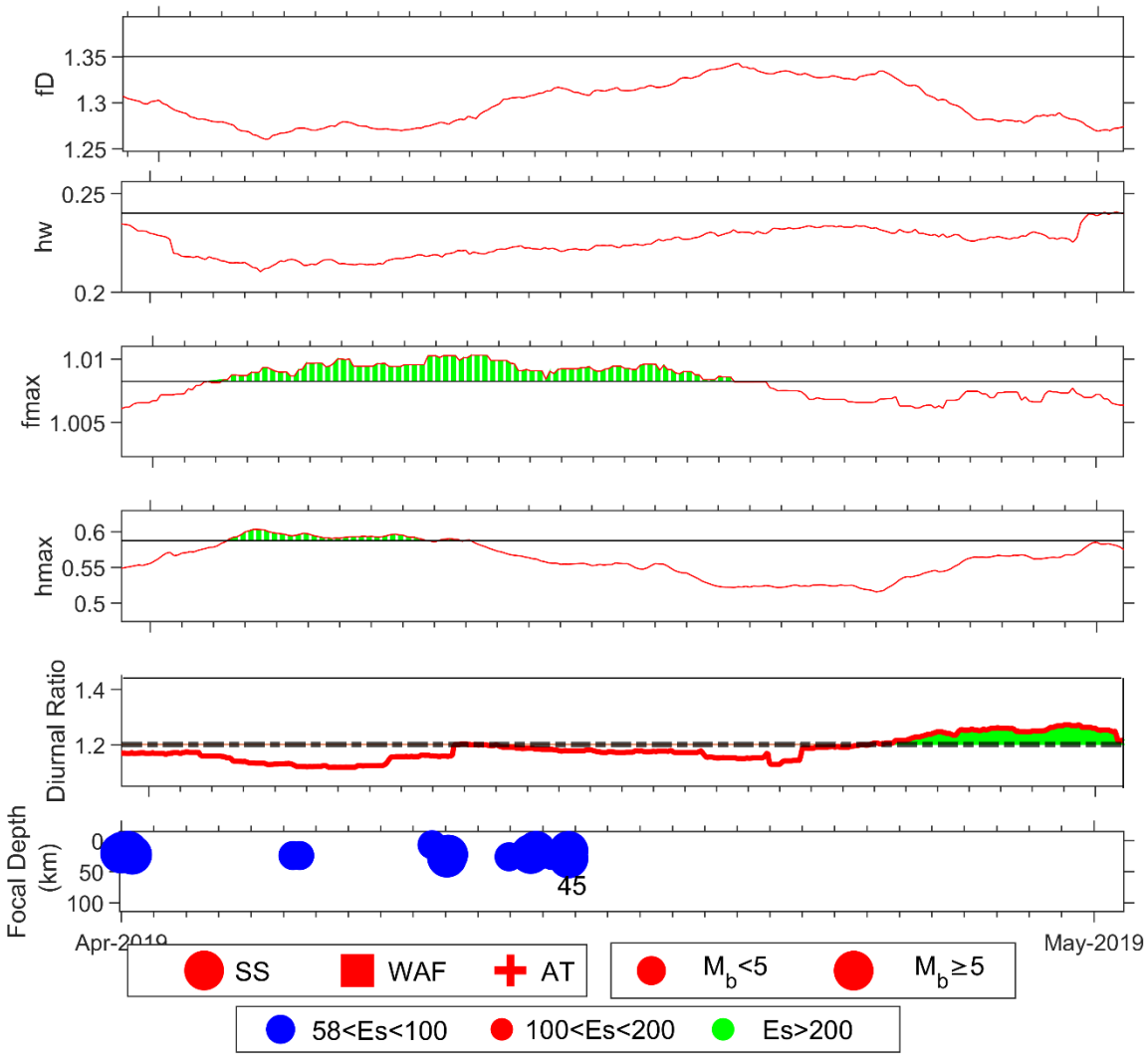

Figure S5. The temporal variation for April-2019 of components monofractal analysis (a) Higuchi fractal dimension, and multifractal analysis (b) spectrum width component, (c) fmax component, (d) hmax components. Panel (e) and (f) showing the diurnal ratio component and occurrences of earthquakes in same time duration with magnitude and focal depth respectively. The significant enhancements from each component are shaded by green color.

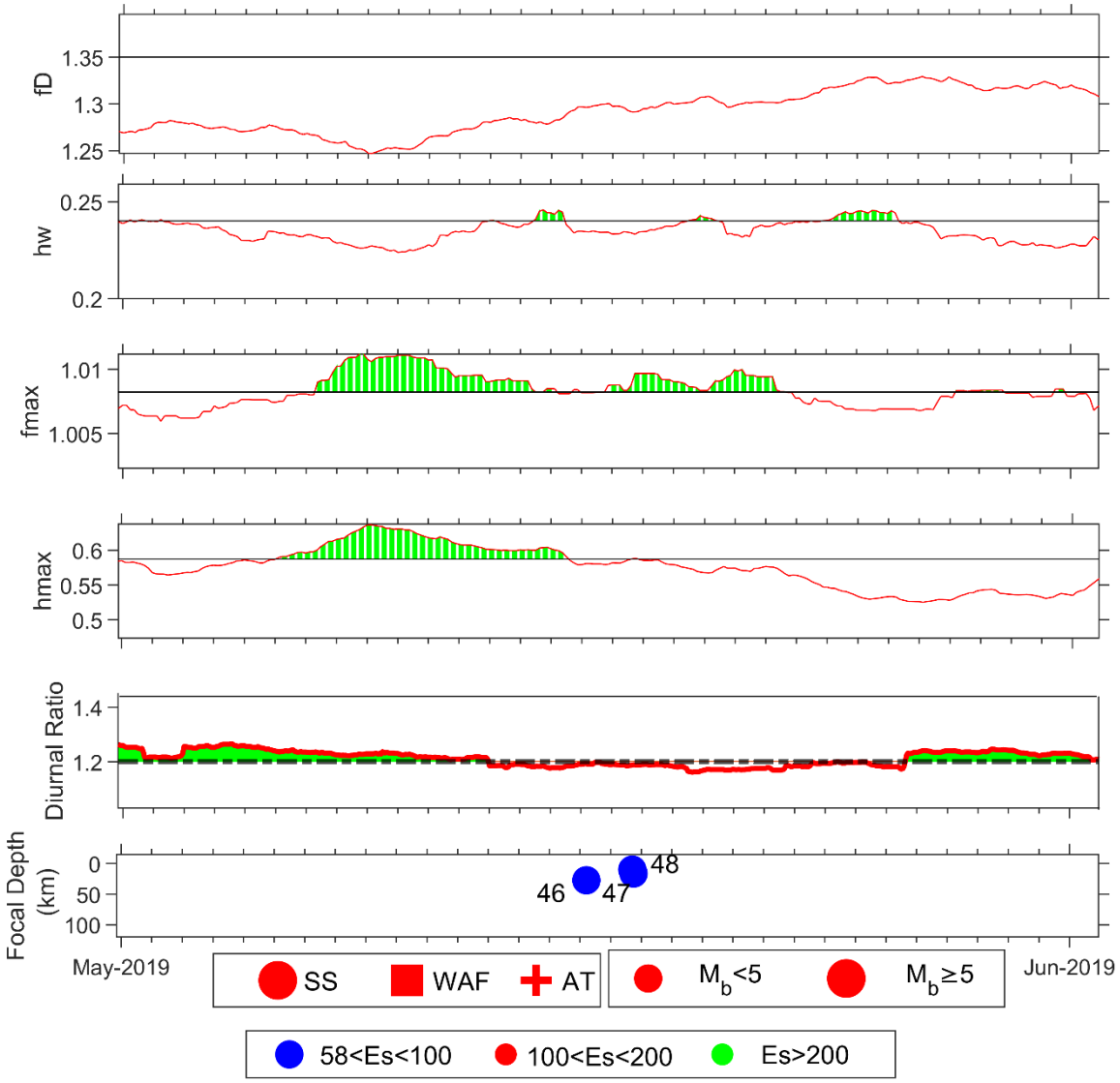

Figure S6. The temporal variation for May-2019 of components monofractal analysis (a) Higuchi fractal dimension, and multifractal analysis (b) spectrum width component, (c) fmax component, (d) hmax components. Panel (e) and (f) showing the diurnal ratio component and occurrences of earthquakes in same time duration with magnitude and focal depth respectively. The significant enhancements from each component are shaded by green color.

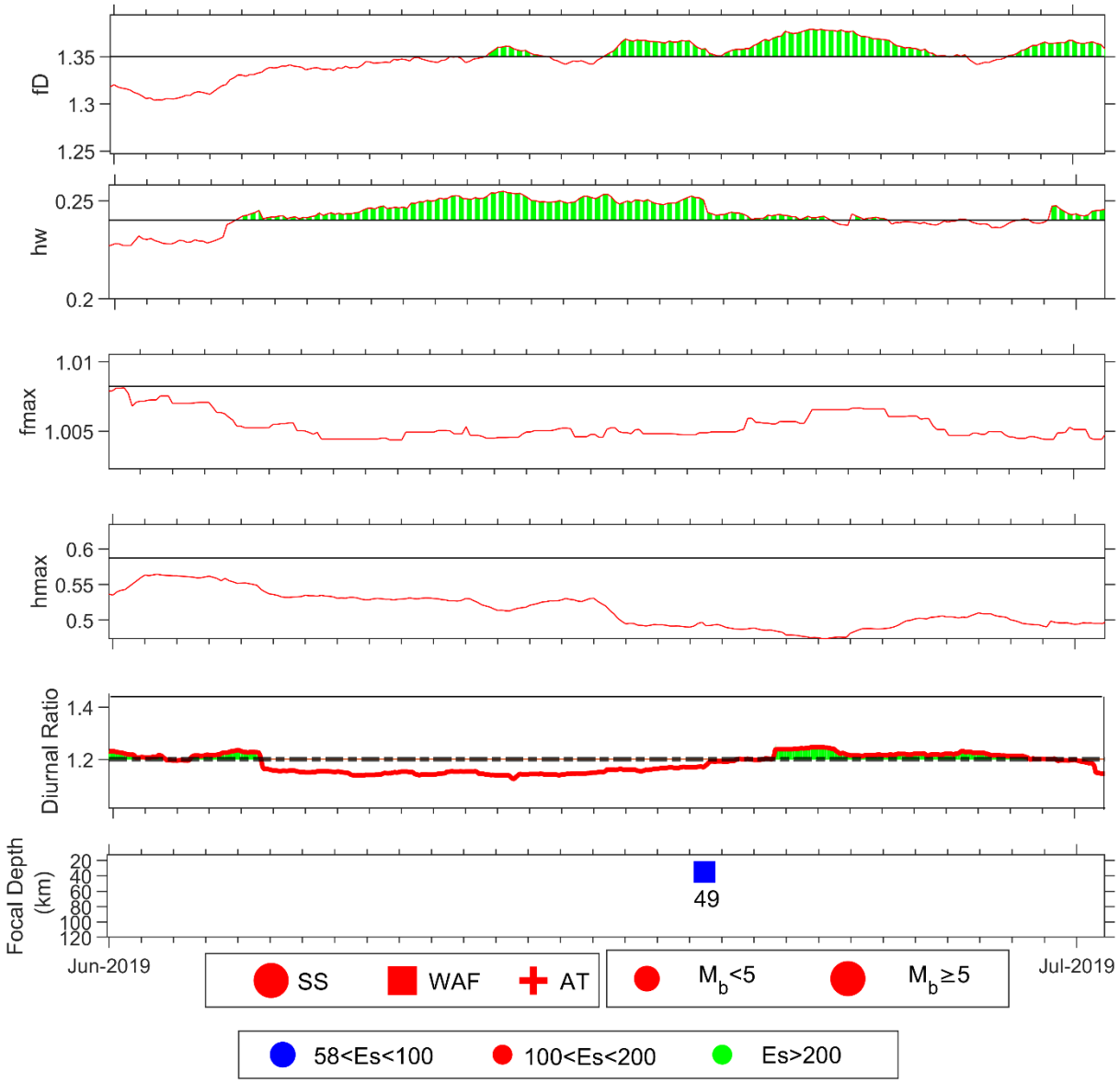

Figure S7. The temporal variation for Jun-2019 of components monofractal analysis (a) Higuchi fractal dimension, and multifractal analysis (b) spectrum width component, (c) fmax component, (d) hmax components. Panel (e) and (f) showing the diurnal ratio component and occurrences of earthquakes in same time duration with magnitude and focal depth respectively. The significant enhancements from each component are shaded by green color.

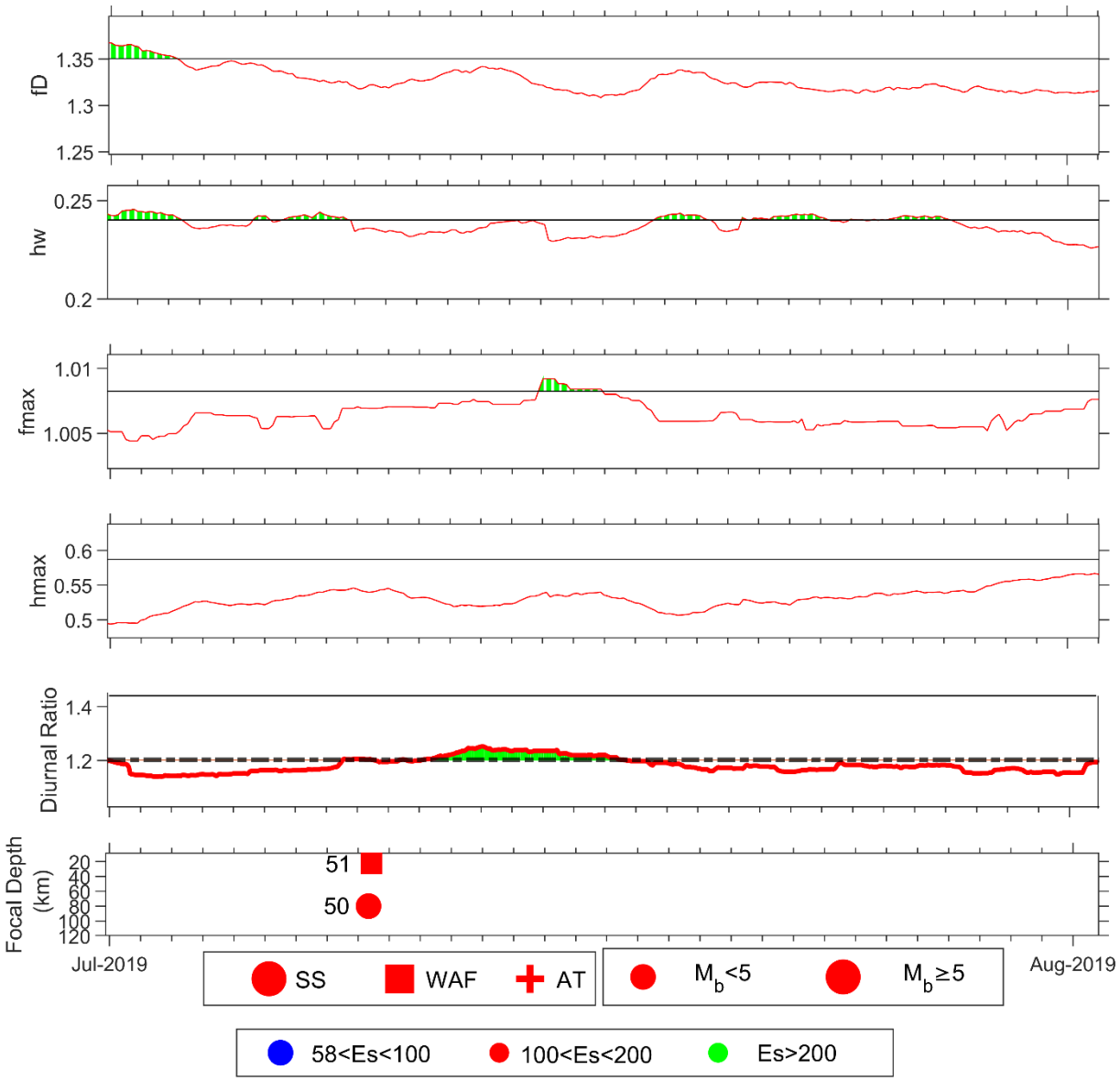

Figure S8. The temporal variation for Jul-2019 of components monofractal analysis (a) Higuchi fractal dimension, and multifractal analysis (b) spectrum width component, (c) fmax component, (d) hmax components. Panel (e) and (f) showing the diurnal ratio component and occurrences of earthquakes in same time duration with magnitude and focal depth respectively. The significant enhancements from each component are shaded by green color.

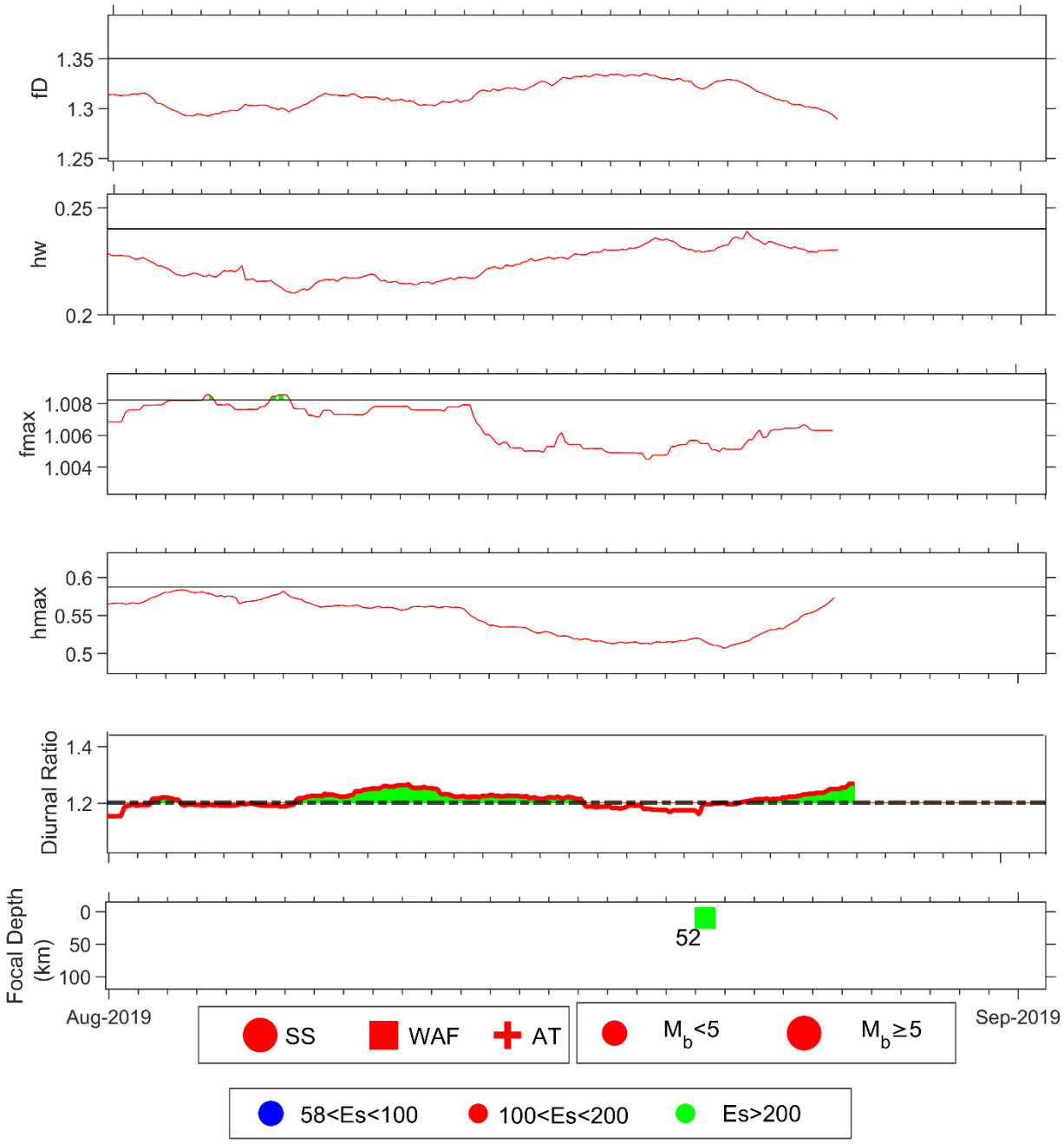

Figure S9. The temporal variation for Aug-2019 of components monofractal analysis (a) Higuchi fractal dimension, and multifractal analysis (b) spectrum width component, (c) fmax component, (d) hmax components. Panel (e) and (f) showing the diurnal ratio component and occurrences of earthquakes in same time duration with magnitude and focal depth respectively. The significant enhancements from each component are shaded by green color.

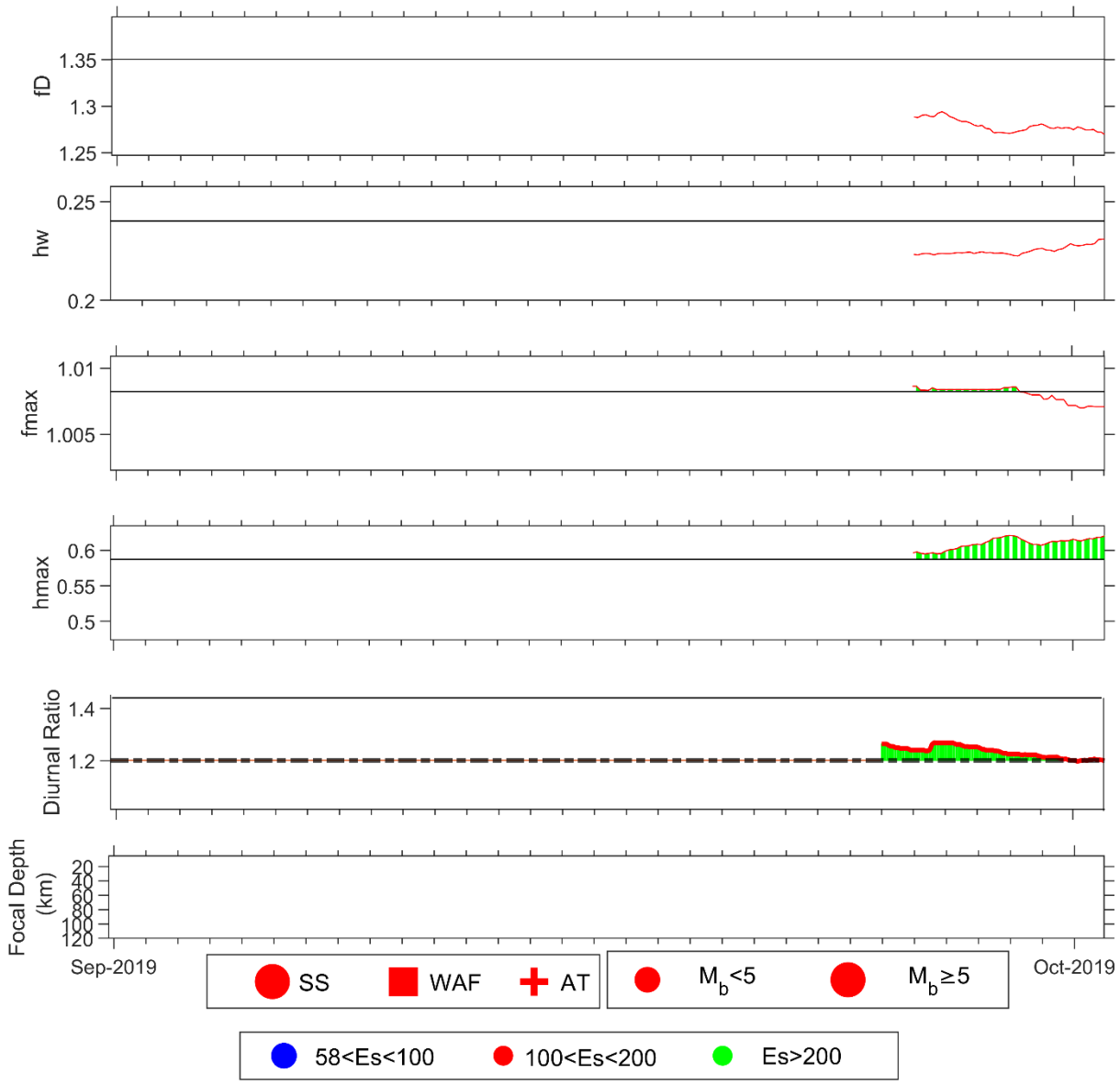

Figure S10. The temporal variation for Sep-2019 of components monofractal analysis (a) Higuchi fractal dimension, and multifractal analysis (b) spectrum width component, (c) fmax component, (d) hmax components. Panel (e) and (f) showing the diurnal ratio component and occurrences of earthquakes in same time duration with magnitude and focal depth respectively. The significant enhancements from each component are shaded by green color.

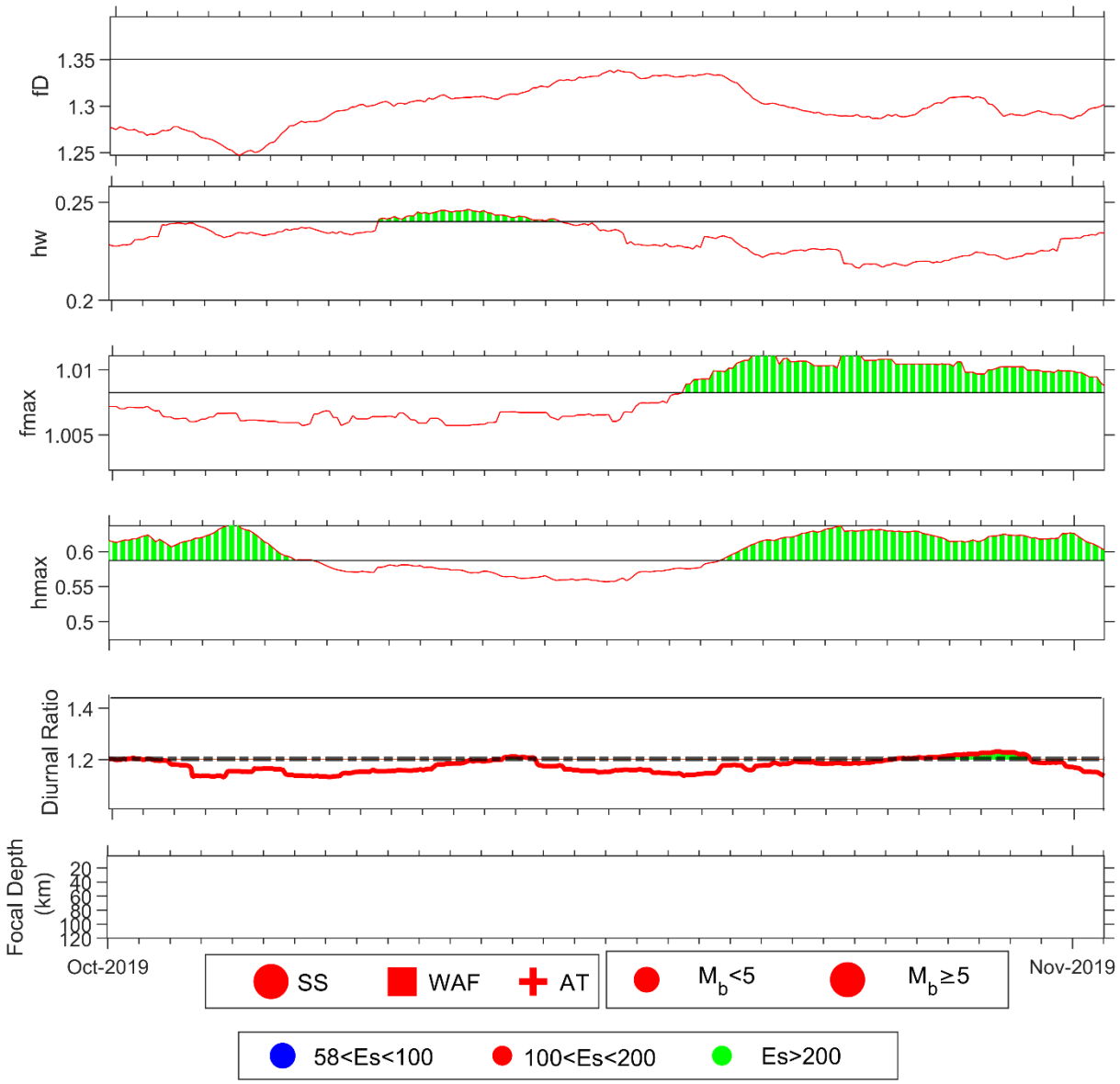

Figure S11. The temporal variation for Oct-2019 of components monofractal analysis (a) Higuchi fractal dimension, and multifractal analysis (b) spectrum width component, (c) fmax component, (d) hmax components. Panel (e) and (f) showing the diurnal ratio component and occurrences of earthquakes in same time duration with magnitude and focal depth respectively. The significant enhancements from each component are shaded by green color.

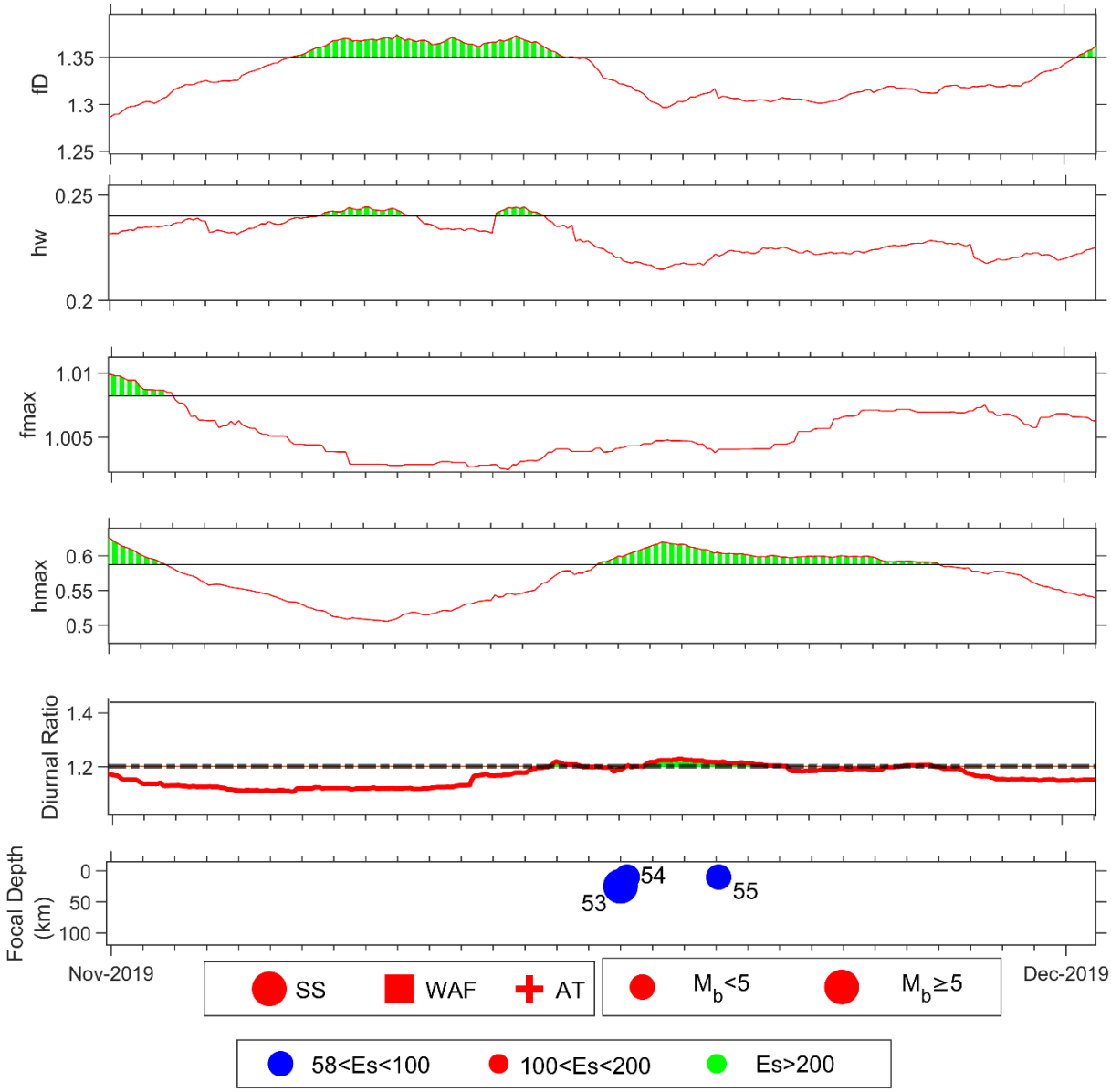

Figure S12. The temporal variation for Nov-2019 of components monofractal analysis (a) Higuchi fractal dimension, and multifractal analysis (b) spectrum width component, (c) fmax component, (d) hmax components. Panel (e) and (f) showing the diurnal ratio component and occurrences of earthquakes in same time duration with magnitude and focal depth respectively. The significant enhancements from each component are shaded by green color.

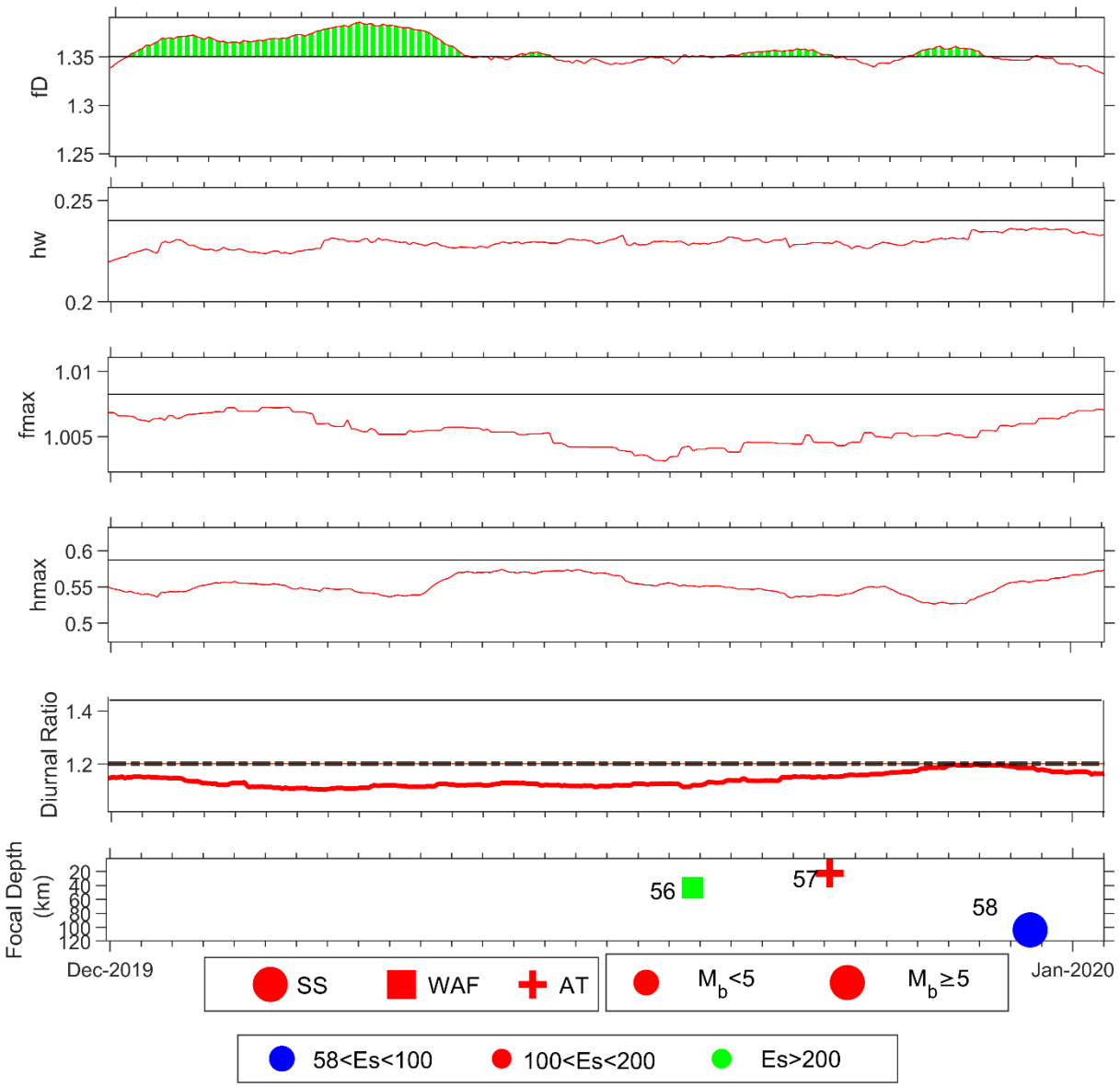

Figure S13. The temporal variation for Dec-2019 of components monofractal analysis (a) Higuchi fractal dimension, and multifractal analysis (b) spectrum width component, (c) fmax component, (d) hmax components. Panel (e) and (f) showing the diurnal ratio component and occurrences of earthquakes in same time duration with magnitude and focal depth respectively. The significant enhancements from each component are shaded by green color.

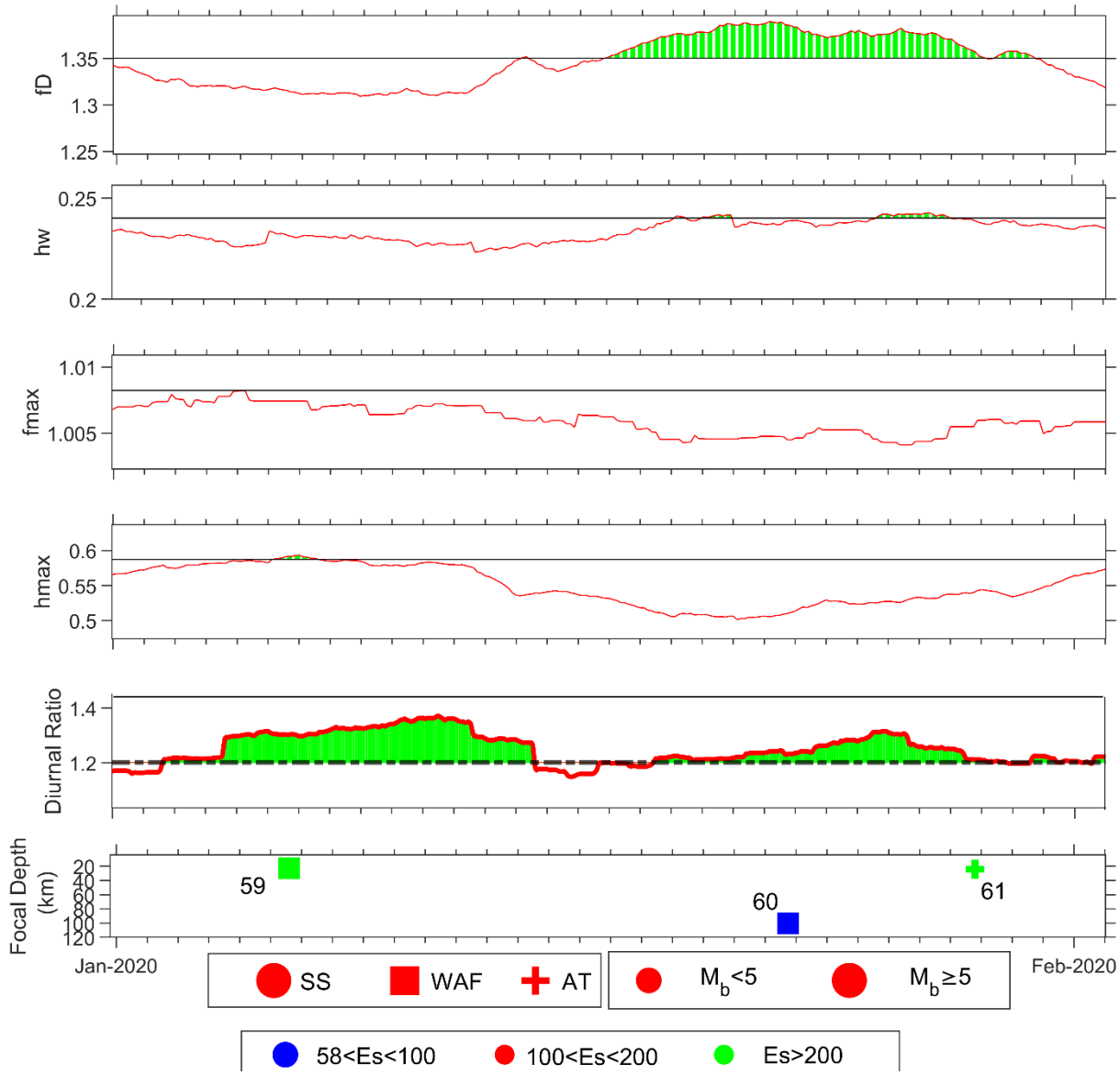

Figure S14. The temporal variation for Jan-2020 of components monofractal analysis (a) Higuchi fractal dimension, and multifractal analysis (b) spectrum width component, (c) fmax component, (d) hmax components. Panel (e) and (f) showing the diurnal ratio component and occurrences of earthquakes in same time duration with magnitude and focal depth respectively. The significant enhancements from each component are shaded by green color.

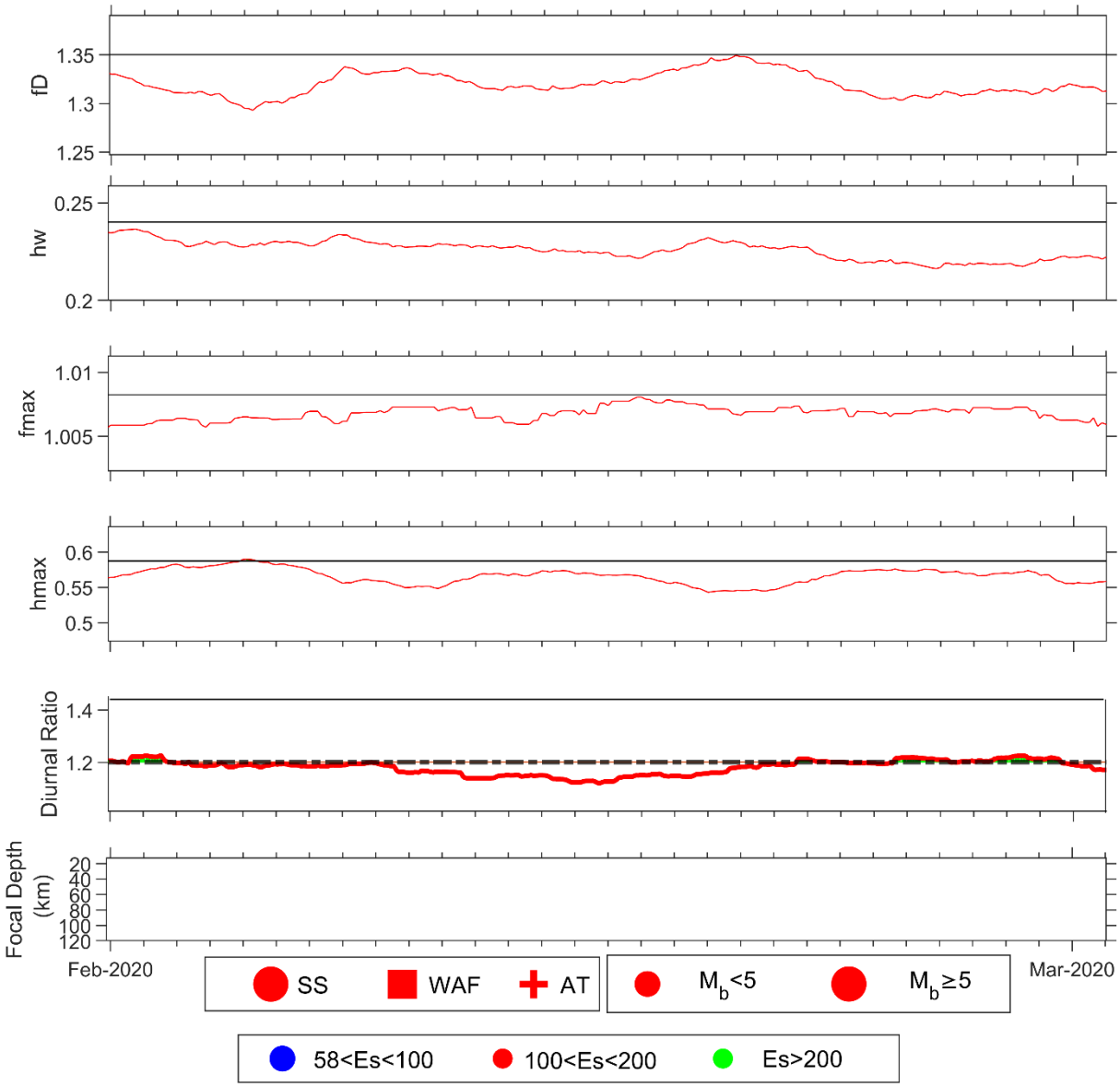

Figure S15. The temporal variation for Feb-2020 of components monofractal analysis (a) Higuchi fractal dimension, and multifractal analysis (b) spectrum width component, (c) fmax component, (d) hmax components. Panel (e) and (f) showing the diurnal ratio component and occurrences of earthquakes in same time duration with magnitude and focal depth respectively. The significant enhancements from each component are shaded by green color.

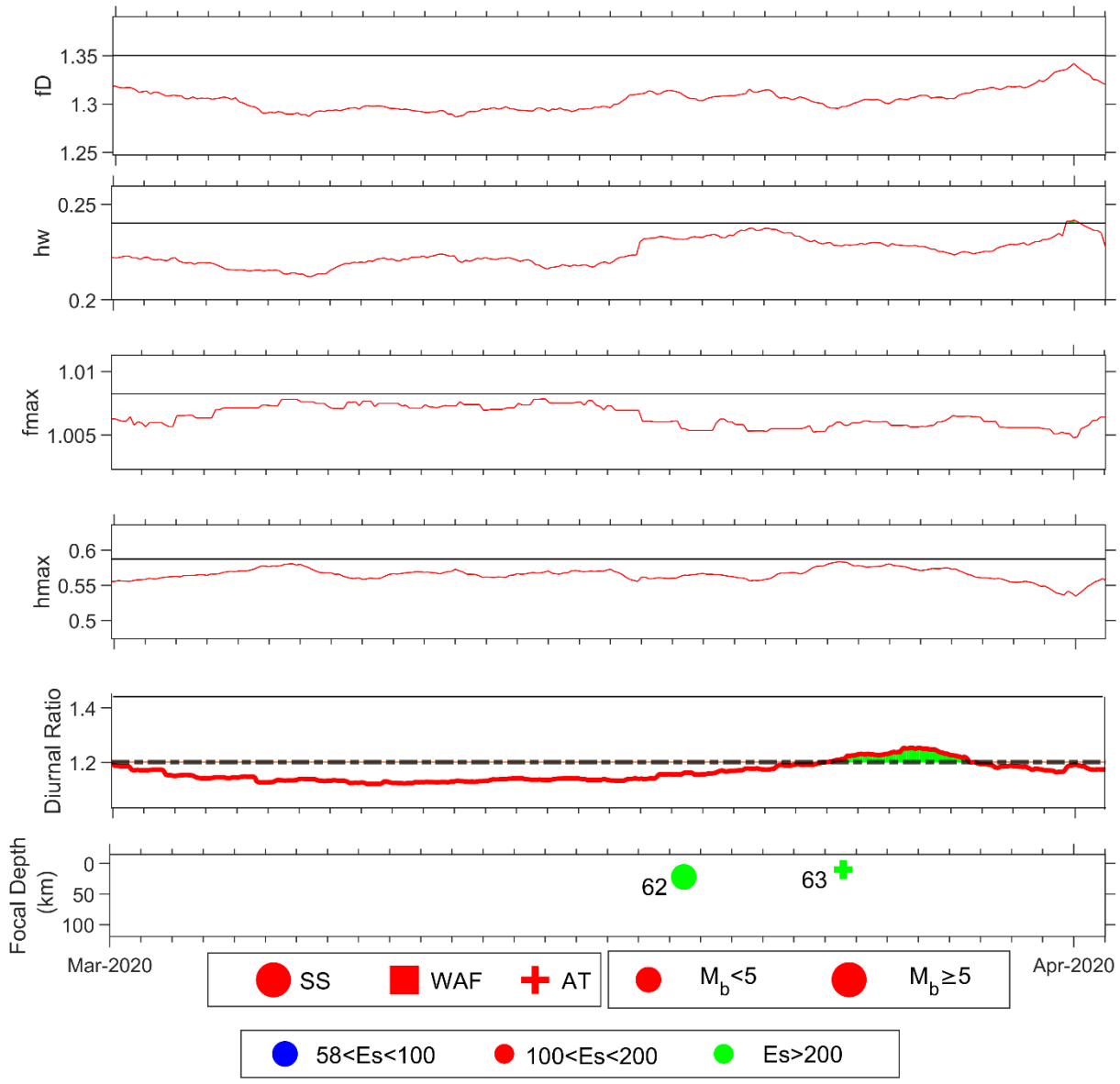

Figure S16. The temporal variation for Mar-2020 of components monofractal analysis (a) Higuchi fractal dimension, and multifractal analysis (b) spectrum width component, (c) fmax component, (d) hmax components. Panel (e) and (f) showing the diurnal ratio component and occurrences of earthquakes in same time duration with magnitude and focal depth respectively. The significant enhancements from each component are shaded by green color.

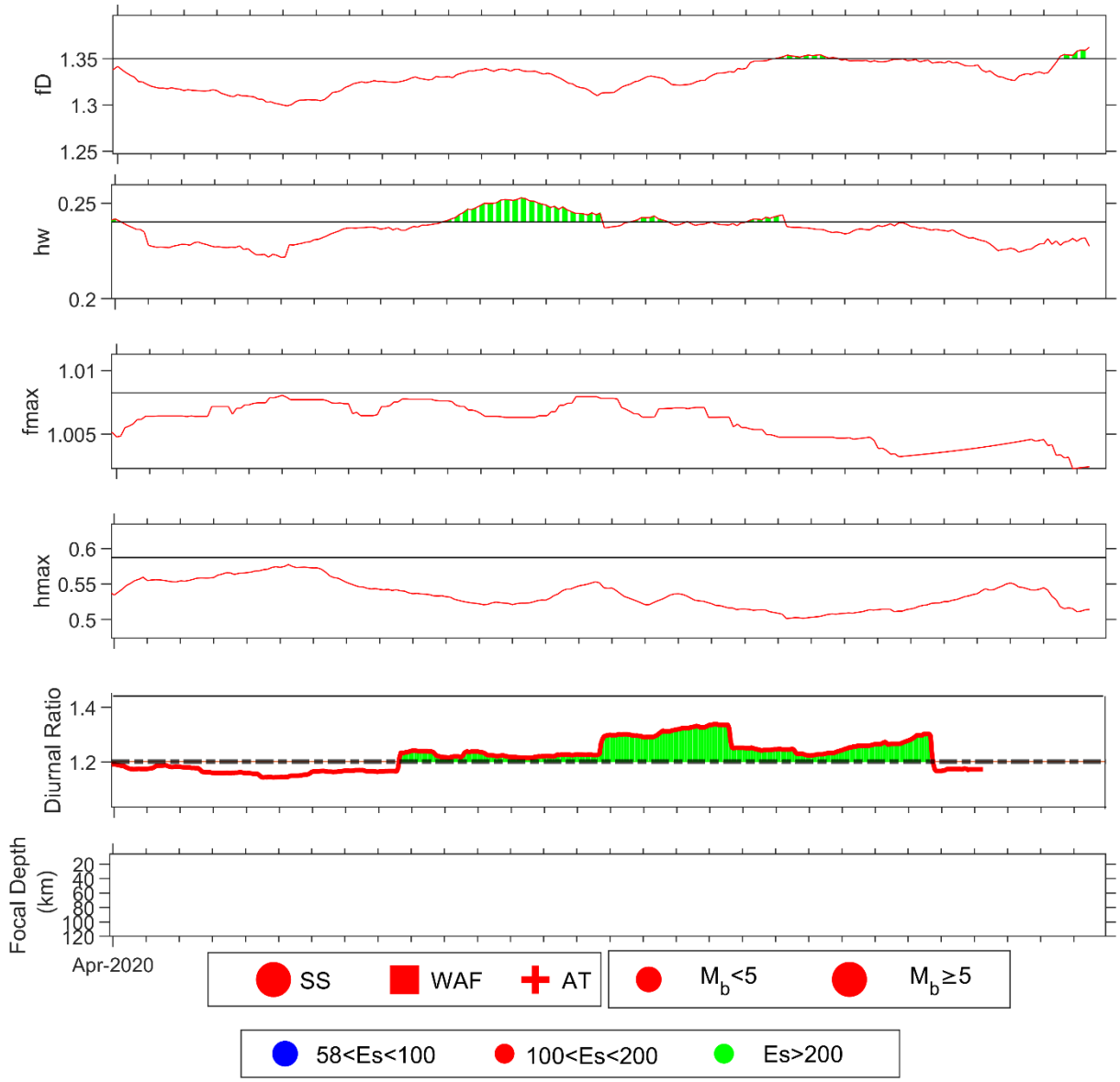

Figure S17. The temporal variation for Apr-2020 of components monofractal analysis (a) Higuchi fractal dimension, and multifractal analysis (b) spectrum width component, (c) fmax component, (d) hmax components. Panel (e) and (f) showing the diurnal ratio component and occurrences of earthquakes in same time duration with magnitude and focal depth respectively. The significant enhancements from each component are shaded by green color.

Comparison of raw data with and without enhancement of fractal parameters on quiet days.

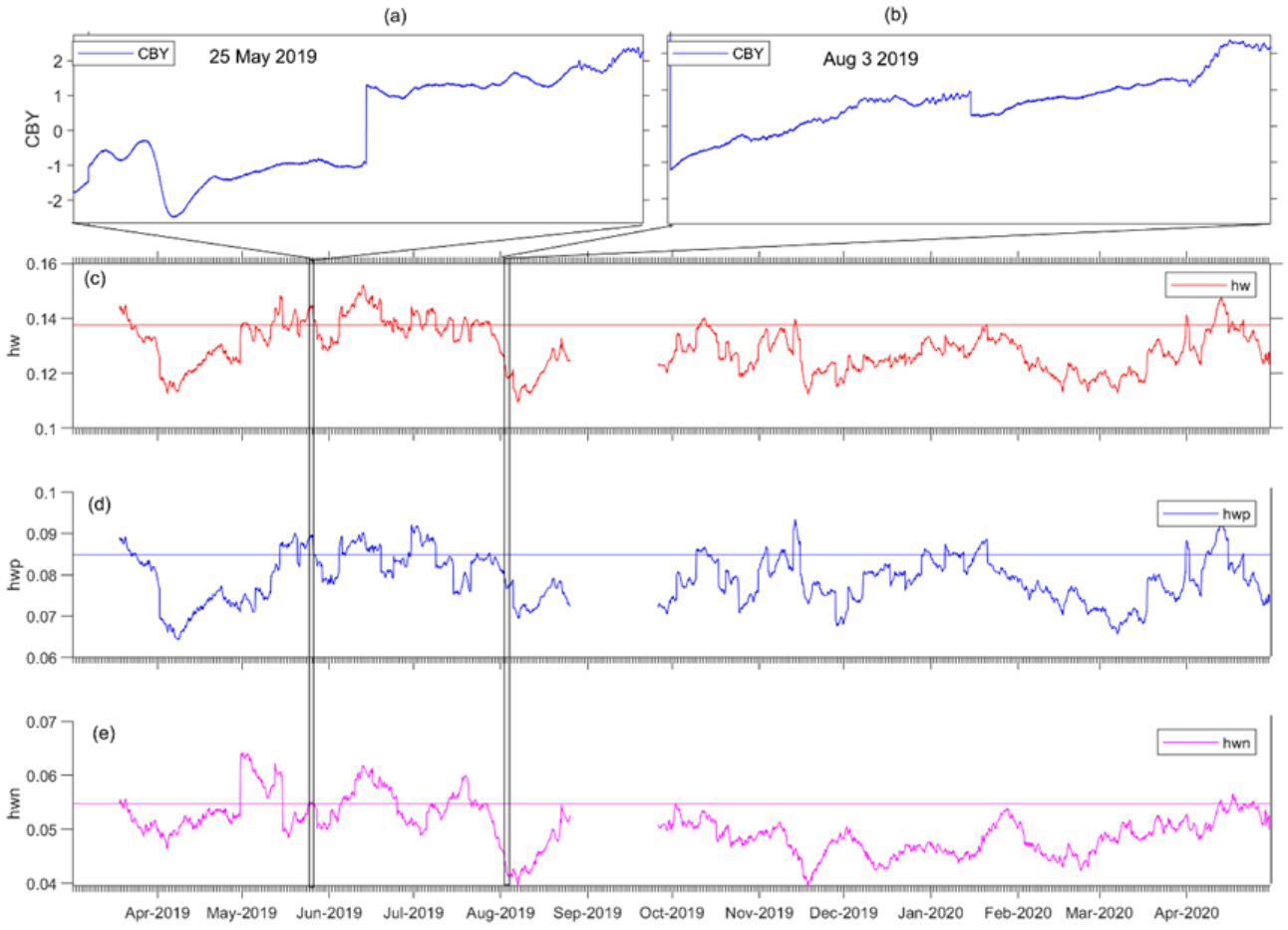

Figure S18. The night time data of vertical component of geomagnetic field on (a) 25th May, 2019 and (b) 3rd Aug, 2019. The multifractal component of (a) hw, (b) hwp, and (c) hwn from Mar, 2019 to April, 2020.

Table S1. List of earthquakes with time of occurrence, location, focal depth, and magnitude.

S.I.	DATE	TIME	Epicentre	Focal-Depth (km)	Magnitude (Mb)
1	31-03-2019	23:42:32	7.6996,94.2492	20	4.7
2	31-03-2019	23:44:43	7.5909,94.1253	13	4.9
3	31-03-2019	23:46:42	7.6686,94.1727	20	5.1
4	31-03-2019	23:48:58	7.5608,94.1282	20	4.6
5	31-03-2019	23:56:45	7.541,94.3568	24	4.8
6	31-03-2019	23:59:48	7.7878,94.4918	24	4.7
7	01-04-2019	00:03:44	7.6917,94.2339	20.9	5
8	01-04-2019	00:23:39	7.6193,94.259	24	4.7
9	01-04-2019	00:25:45	7.5951,94.2425	23.7	4.9
10	01-04-2019	00:34:10	7.5698,94.3452	24	4.6
11	01-04-2019	00:37:29	7.4526,94.2756	24	4.8
12	01-04-2019	00:44:27	7.5388,94.3337	24	4.7
13	01-04-2019	00:49:39	7.5407,94.1947	20	4.9
14	01-04-2019	00:58:20	7.4883,94.219	20	4.8
15	01-04-2019	01:08:08	7.5659,94.2647	24	4.7
16	01-04-2019	01:11:44	7.5249,94.3343	16.9	4.9
17	01-04-2019	01:21:32	7.6171,94.1999	20	4.7
18	01-04-2019	01:22:49	7.3636,94.2171	20	4.6
19	01-04-2019	01:23:59	7.5703,94.1277	17.3	5.1
20	01-04-2019	01:34:21	7.614,94.3289	24	4.5
21	01-04-2019	02:28:05	7.728,94.2903	10	4.6
22	01-04-2019	02:46:50	7.533,94.2648	24	4.5
23	01-04-2019	02:49:43	7.402,94.164	20	4.5
24	01-04-2019	03:21:41	7.4521,94.2288	20	4.5
25	01-04-2019	03:38:09	7.4656,94.2122	20	4.8
26	01-04-2019	04:09:16	7.4718,94.2433	20	4.8
27	01-04-2019	05:09:18	7.5492,94.2107	20	4.8
28	01-04-2019	05:52:39	7.463,94.2283	16.3	5
29	01-04-2019	06:56:42	7.6223,94.2961	24	4.5

30	01-04-2019	07:37:52	7.4665,94.2506	28.1	4.8
31	01-04-2019	08:11:34	7.5566,94.1453	22.6	5.3
32	01-04-2019	10:14:06	7.4182,94.2619	24	4.5
33	06-04-2019	08:12:47	7.3892,94.3412	24	4.5
34	06-04-2019	13:23:07	7.3815,94.4192	24	4.5
35	10-04-2019	15:09:33	7.5339,94.1907	6.6	4.5
36	11-04-2019	02:39:32	7.6655,94.2167	27.4	5
37	11-04-2019	03:50:40	7.5952,94.1612	22.4	5.1
38	11-04-2019	03:55:15	7.5914,94.1947	18.8	4.8
39	12-04-2019	23:14:03	7.2498,94.3414	26	4.6
40	13-04-2019	16:12:57	7.3145,94.3829	21.6	5.3
41	13-04-2019	16:20:18	7.2623,94.3904	24	4.7
42	13-04-2019	20:43:31	7.262,94.3367	16.4	5
43	14-04-2019	08:12:09	7.3932,94.3761	24	4.6
44	18-04-2019	21:52:11	7.5409,94.2677	16.5	5
45	18-04-2019	21:57:58	7.5612,94.2611	28.7	5
46	16-05-2019	06:52:02	7.3961,94.2224	27.4	4.8
47	17-05-2019	18:29:24	7.5362,94.2358	10	4.5
48	17-05-2019	19:05:20	7.586,94.2535	16.3	4.8
49	19-06-2019	12:05:01	6.6871,93.4415	35	4.6
50	09-07-2019	09:26:13	8.6569,94.0188	80	4.5
51	09-07-2019	11:40:26	8.3982,93.7661	22	4.5
52	21-08-2019	09:19:11	8.9309,93.4665	10	4.8
53	17-11-2019	01:28:57	7.1332,94.4124	24.8	5.1
54	17-11-2019	06:47:06	7.1291,94.6991	10	4.5
55	20-11-2019	03:37:08	7.2687,94.5378	10	4.7
56	19-12-2019	19:01:52	5.1651,94.3996	43	4.5
57	24-12-2019	05:52:58	6.9983,92.3125	23	5
58	30-12-2019	16:59:04	6.6953,94.4063	103.8	5
59	06-01-2020	15:08:01	8.8571,93.5786	23	4.5
60	22-01-2020	19:23:26	7.6921,93.9163	100	4.6
61	28-01-2020	20:29:38	7.2879,92.0567	24	4.9

62	19-03-2020	12:58:57	8.8682,93.8319	22	4.5
63	24-03-2020	15:00:31	7.8407,92.2031	10	4.5

Table S2. The relationships between the observed significant fractal dimensions (fD) and earthquake (Eq) occurrence are as below:

Earthquake characteristics								Anomaly characteristics	
EQ No.	Time of Eq.	Magnitude	fD	Epicentral Distance	Type of Fault		Eq details	Anomaly details	Lead/lag
49	19-06-2019	4.6	35	60	WAF		Mod mag, mod fd, mod epidist	One small + one sig enhancement 12-13 Jun 2019 16-18 Jun 2019	7 3
50	09-07-2019	4.5	80	185	SS	2 diff loc	Mod mag, Large fd, large epidist+ mod fd, large epidist	Two sig enhancements 20-25 Jun 2019 29 Jun-2 Jul 2019	19 10
51	09-07-2019	4.5	22	156	WAF				
52	21-08-2019	4.8	10	219	WAF		Mod mag, v. shallow fd, v large epidist	No enhancements	
53	17-11-2019	5.1	24.8	60	SS	Similar loc	Mod mag, shallow/v shallow fd, mod epidist	One persistent enhancement 6-15 Nov 2019	11
54	17-11-2019	4.5	10	91	SS				
55	20-11-2019	4.7	10	78	SS				14
56	19-12-2019	4.5	43	212	WAF		Mod mag, mod fd, v large epidist	One persistent enhancement	18

								1-14 Dec 2019	
57	24-12-2019	5	23	173	AT		Mod mag, mod fd, v large epidist	Minor enhancement 18-23 Dec 2019	6
58	30-12-2019	5	103.8	67	SS		Mod mag, v large fd, mod epidist	Minor enhancement 27-31 Dec 2019	3 and co
59	06-01-2020	4.5	23	209	WAF		Mod mag, mod fd, v large epidist	No enhancements	
60	22-01-2020	4.6	100	77	WAF	2 diff loc	Mod mag, v deep/mod fd, mod/v large epidist	One persistent enhancement 16-28 Jan 2020	6 and co 12 and co
61	28-01-2020	4.9	24	204	AT				
62	19-03-2020	4.5	22	207	SS	2 diff loc	Mod mag, shallow fd, v large epidist	No enhancements	
63	24-03-2020	4.5	10	208	AT				

Table S3. The relationships between the observed significant multifractal width parameter and earthquake occurrence are as below:

Earthquake characteristics								Anomaly characteristics			
Eq. No.	Time of Eq.	Mag.	fD.	Epicentral distance	Fault			Hw	Hwp	Hwn	Lead/Lag time (in Days)
1-45	31-03-2019 18-04-2019				SS			One small enhancement 17-22 Mar, 2019	One small enhancement 17-20 Mar, 2019	One small enhancement 17-20 Mar	14
46	16-05-2019	4.5	27.4	58	SS		Mod mag, mod fd, mod epidist	One small enhancement 14 May, 2019	Two small enhancements 14-15, 17-20, May, 2019	One persistence, two small enhancements 29 Mar-5 May, 2019 12,14 May, 2019	2 Co and post 16 2
47	17-05-2019	4.8	10	71	SS						
48	17-05-2019	4.8	16	71	SS						
49	19-06-2019	4.6	65	60	WAF		Mod mag, mod fd, mod epidist	One minor, One sig. persistence enhancement 23-25 May, 2019	Two Persistence, One small, 22-25 May, 2019 4Jun, 7-18 Jun, 2019	One persistence 8-22 Jun, 2019	26 15 to co 12 10

								4-22 Jun, 2019			
50	9-07-2019	4.5	80	185	SS	Diff location	Mod mag, Large fd, large epidist+ mod fd, large epidist	30Jun-2Jul, 2019 5-8 Jul, 2019	31Jun-9Jul, 2019	No enhancement	9 4
51	9-07-2019	4.5	22	156	WAF						8 and co
52	21-08-2019	4.8	10	219	WAF		Mod mag, v. shallow fd, v large epidist	18 Jul, 2019	No enhancement	17-19 Jul, 2019	32
53	17-11-2019	5.1	24.8	60	SS	Similar location	Mod mag, shallow/v shallow fd, mod epidist	9-15 Oct, 2019 7-9 Nov, 11-12 Nov, 2019	9-14 Oct, 2019 2-3 Nov, 7-10 Nov, 12-14 Nov, 2019	No enhancement	36 10
54	17-11-2019	5.1	10	91	SS						6 7
55	20-11-2019	4.7	10	78	SS						15 10 5
56	19-12-2019	4.5	43	212	WAF		Mod mag, mod fd, v large epidist	No enhancement			
57	24-12-2019	5	23	173	AT		Mod mag, mod fd, v large epidist				
58	30-12-2019	5	103	67	SS		Mod mag, v large fd, mod epidist				
59	06-01-2020	4.5	23	209	WF		Mod mag, mod fd, v large epidist				
60	22-01-2020	4.6	100	77	WAF		Mod mag, v deep/mod fd, mod/v large epidist	18-20 Jan, 24-26 Jan, 2020	16-20 Jan, 2020	No enhancement	4
61	28-01-2020	4.9	24	204	AT						4 6

62	19-03-2020	4.5	22	207	SS, AT	different location	Mod mag, shallow fd, v large epidist	No enhancement	No enhancement	No enhancement	
63	24-03-2020	4.5	10	207	AT						
	NO events							10-14 Apr, 2020	10-14 Apr, 2020	11-12 Apr, 2019	NA

Table S4. The relationships between the observed significant holder exponent parameter and earthquake occurrence are as below:

Earthquake characteristics							Anomaly characteristics				
Eq. No.	Time of Earthquake	Magnitude.	fD.	Epicentral Distance. (km)			fmax	H (0)	Hmax	Hmin	Lead\ Lag time
1-45	31-03-2019 18-04-2019						One persistence enhancement 2-18 Apr 2019	One small enhancement 2-10 Apr 2019	One small enhancement 2-10 Apr	One small enhancement 2-10 Apr	Co
46	16-05-2019	4.5	27.4	58		Mod mag, mod fd, mod epidist	One significant and two small enhancements 7-14 May 2019 17-19 May 2019	One significant enhancement 6-14 May 2019	One significant enhancement 5-14 May 2019	One significant enhancement 7-11 May 2019	9 Co and post 10 11 9
47	17-05-2019	4.8	10	71							
48	17-05-2019	4.8	16	71							
49	19-06-2019	4.6	65	60		Mod mag, mod fd, mod epidist	One small enhancement				29

							20-21 May 2019				
50	09-07-2019	4.5	80	185	2 Diff location	Mod mag, Large fd, large	No enhancements				
51	09-07-2019	4.5	22	156							
52	21-08-2019	4.8	10	219		Mod mag, v. shallow fd, v large epidist	Two small enhancements 15-16 Jul 2019 6-Aug 2019			Two small enhancements 6 Aug 2019	35 15
53	17-11-2019	5.1	24.8	60	Similar location	Mod mag, shallow /v shallow fd, mod epidist	1 small enhancement and one persistence 26-28 Sep 2019 19 Oct-2 Nov 2019	1 small enhancement and one persistence 26 Sep-5 Oct 20 Oct-1 Nov 16-24 Nov 2019	1 small enhancement and one persistence 26 Sep-6 Oct 22 Oct-3 Nov 16-26 Nov 2019	1 small enhancement and one persistence 26 sep-6 Oct 20 Oct-2 Nov 16-24 Nov 2019	50 28 17 1 & co 25 1 & co
54	17-11-2019	5.1	10	91							
55	20-11-2019	4.7	10	78							
56	19-12-2019	4.5	43	212		Mod mag, mod fd, v large epidist					No enhancement
57	24-12-2019	5	23	173		Mod mag, mod fd, v large epidist					
58	30-12-2019	5	103	67		Mod mag, v large					

						fd, mod epidist					
59	06-01-2020	4.5	23	209		Mod mag, mod fd, v large epidist			One small enhancement 3-8 Jan		3 & Co 19
60	22-01-2020	4.6	100	77	Different location	Mod mag, v deep/mod fd, mod/v large epidist					 25
61	28-01-2020	4.9	24	204							
62	19-03-2020	4.5	22	207	Different location	Mod mag, shallow fd, v large epidist			One small enhancement 4 Feb		44 47
63	24-03-2020	4.5	10	207							