SEISMOLOGICAL AND ENGINEERING PARAMETERS OF 24 and 26 SEPTEMBER, 2019 MARMARA SEA EARTHQUAKES

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ABSTRACT

On 24th and 26th September 2019, **two earthquakes of Mw=4.5 and Mw=5.6** respectively took place in the **Marmara Sea**. They were associated with the **Central Marmara segment of the North Anatolian Fault Zone**, which is pinpointed by several investigators as the most likely segment to rupture in the near future giving way to an earthquake larger than M7.0. Both events were felt widely in the region. The Mw=5.6 event, in particular, led to a number of building damages in Istanbul, which were larger than expected in number and severity. There are several strong motion networks in operation in and around Istanbul. We have compiled a data set of recordings obtained at the stations of the Istanbul Earthquake Rapid Response and Early Warning operated by the Department of Earthquake Engineering of Bogazici University and of the National Strong Motion Network operated by AFAD. It consists of 148 three component recordings, in total. 444 records in the data set, after correction, were analyzed to estimate the source parameters of these events, such as **corner frequency, source duration, radius and rupture area, average source dislocation and stress drop**. **Duration characteristics** of two earthquakes were analyzed first by considering P-wave and S-wave onsets and then, focusing on S-wave and significant durations. **PGAs, PGVs and SAs** were calculated and compared with three commonly used **ground motion prediction models** (i.e Boore et al., 2014; Akkar et al., 2014 and Kale et al., 2015). Finally **frequency dependent Q models** were estimated using the data set and their validity was discussed by comparing with previously developed models.

CONTENT

I. OBJECTIVE

CONTENT

Source: *Modified from Taymaz, T. et al., 2007.*

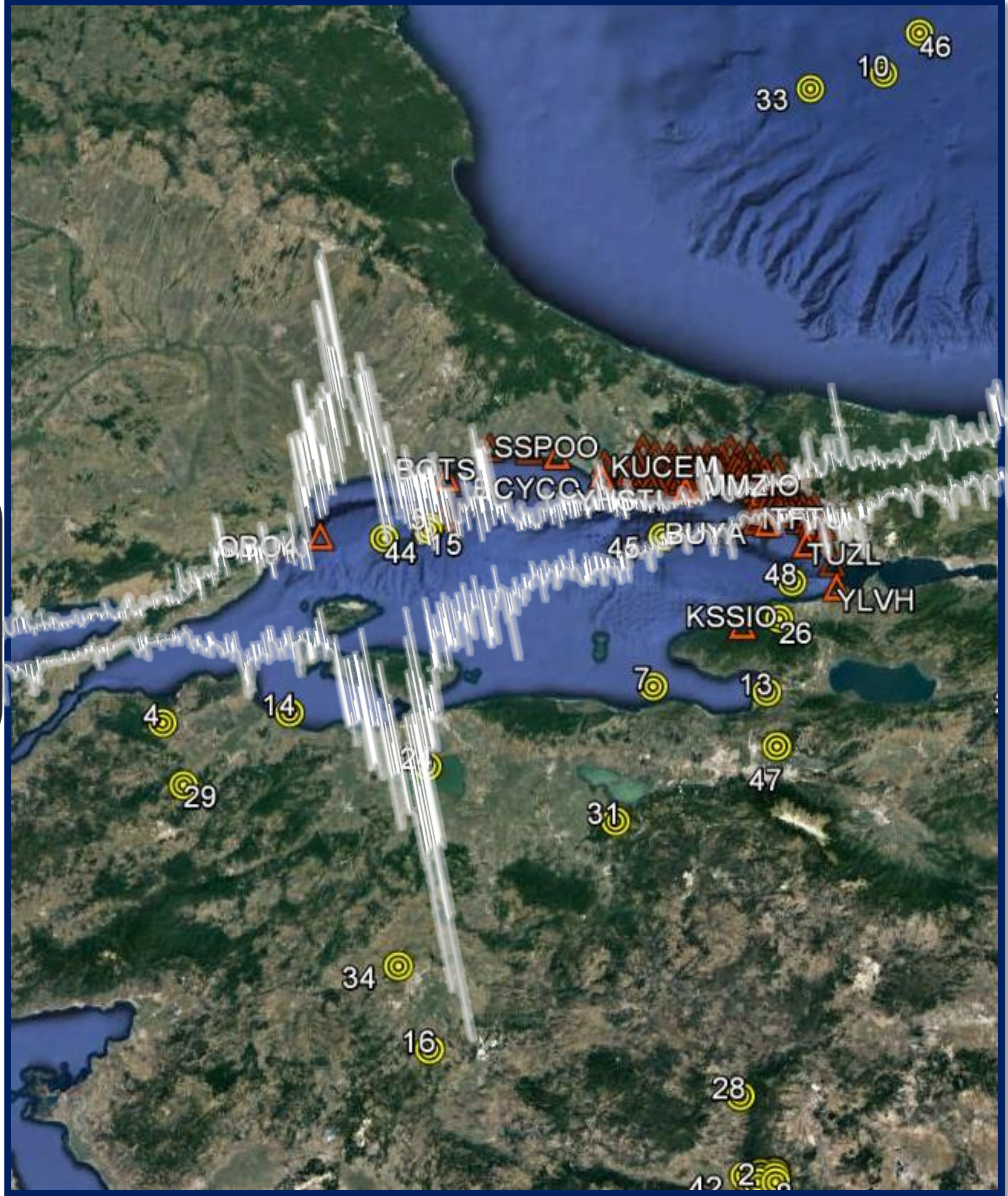
Summary sketch map of the faulting in the Turkey and direction of plate movements.

- **The most seismically active and rapidly deforming regions** within the continents,
- **Expected destructive EQ** with a larger magnitude in the region,
- One of the **largest earthquake** hitting the İstanbul province after 1999 EQs (M_w=7.4 & 7.2),
- Understanding the **potential hazard and risk** that a major earthquake may cause in this region better.

These important facts shows the necessity of the **detailed study of each earthquake** in the region.

II. CHARACTERISTICS OF THE DATABASE

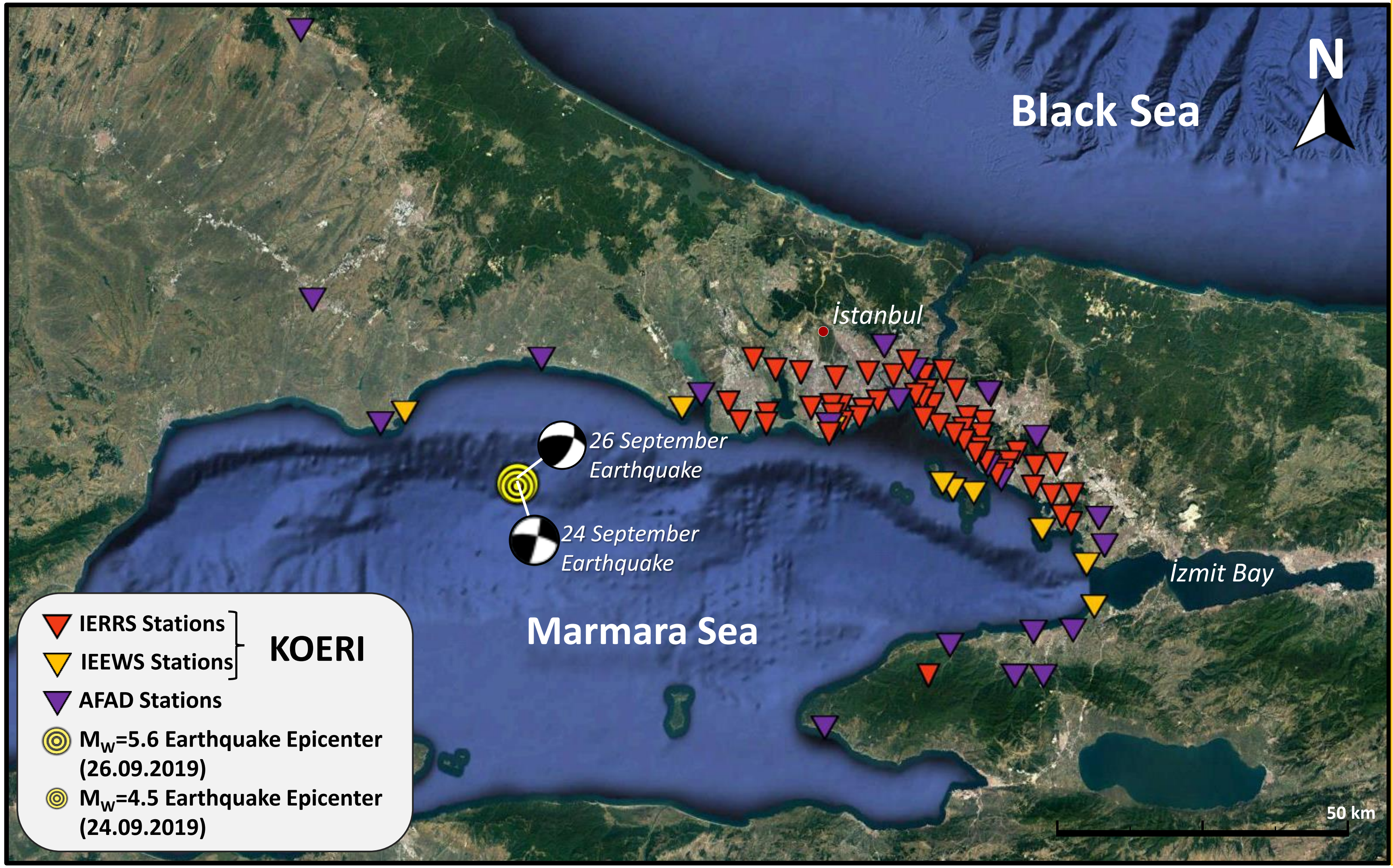
1. Earthquake Information
2. Data Compilation and Processing



II. EARTHQUAKE INFORMATION

EARTHQUAKE DATE	24 SEPTEMBER 2019	26 SEPTEMBER 2019
Moment Magnitude (M_W)	4.5 (KOERI) / 4.6 (AFAD)	5.6 (KOERI) / 5.8 (AFAD)
Local Magnitude (M_L)	4.7 (KOERI)	5.7 (KOERI)
Earthquake Depth (km)	9.8 (KOERI) / 5.91 (AFAD)	12.3 (KOERI) / 7.97 (AFAD)
Focal Mechanism	Strike-Slip Dominant	Thrust Dominant
Local Time	11:00:21 (KOERI) /11:00:22 (AFAD)	13:59:24 (KOERI) /13:59:25 (AFAD)
Earthquake Location	Off the coast of Silivri (Sea of Marmara)	Off the coast of Silivri (Sea of Marmara)
Epicenter Coordinate	40.8785 N / 28.2090 E (KOERI) 40.88360 N / 28.216 E (AFAD)	40.8823 N / 28.2095 E (KOERI) 40.8818N / 28.214E (AFAD)

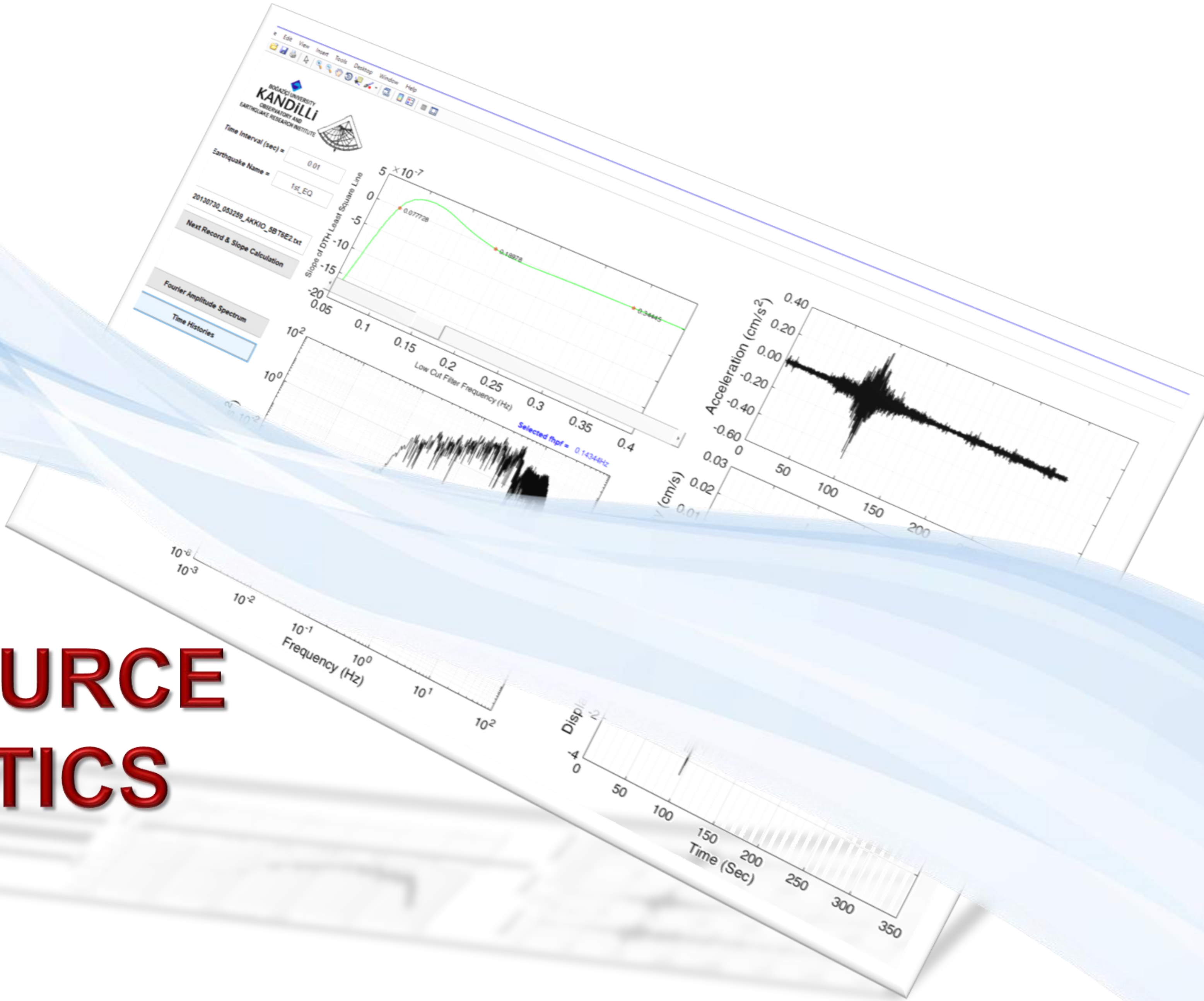
II. DATA COMPILATION & PROCESSING



Data Compilation: 148 three component recordings (444 in total) obtained at the stations of the;

- *Istanbul Earthquake Rapid Response and Early Warning operated by the Department of Earthquake Engineering of Bogazici University **(IERRS &IEEWS - KOERI)**,*
- National Strong Motion Network operated by **AFAD**

Data Processing: Acceleration time histories were processed **by applying baseline correction and high&low pass filtering by individual visual inspection.**



III. ESTIMATED SOURCE CHARACTERISTICS

III. SOURCE PARAMETERS

Corner frequency (Andrews, 1986)

$$f_c = \frac{1}{2\pi}\sqrt{\frac{\int_0^\infty V^2(f)df}{\int_0^\infty D^2(f)df}}$$

Radiuses of the seismic sources (Brune, 1970) and the circular rupture plane area**

$$r = \frac{0.37\beta}{f_c};\ A = \pi r^2$$

Average source dislocation:

$$\bar{D} = \frac{M_0}{\mu A}$$

($\mu = 3.16e^{10}$ Pa)

Source duration (Boatwright and Choy, 1992; Boore, 1983):

$$D_s = \frac{1}{f_c}$$

Static stress drop (Keilis-Borok, 1959)

$$\Delta\sigma = \frac{7M_0}{16r^3}$$

	M_0 (Nm) *	f_c (Hz)	r (km)	A (km^2)	$\bar{D}$ (m)	D_S (s)	$\Delta\sigma$ (bars)
M_W=4.5	$6.494e^{15}$	0.8 (±0.34)	1.58	7.84	0.08	1.25	7.2
M_W=5.6	$3.449e^{17}$	0.59 (±0.3)	2.15	14.52	2.36	1.69	151.8

* *KOERI-RETMC (2019a & 2019b)* ** β= Crustal shear wave velocity, *(RETMC, personal communication, 2018)*

- **Rupture areas (A)** are calculated also with empirical source scaling relationships developed by Wells and Coppersmith (1994) and Thingbaijam et al. (2017),

  4.27 km^2 (M_W=4.5) & 31.48 km^2 (M_W=5.6) Wells and Coppersmith (1994)

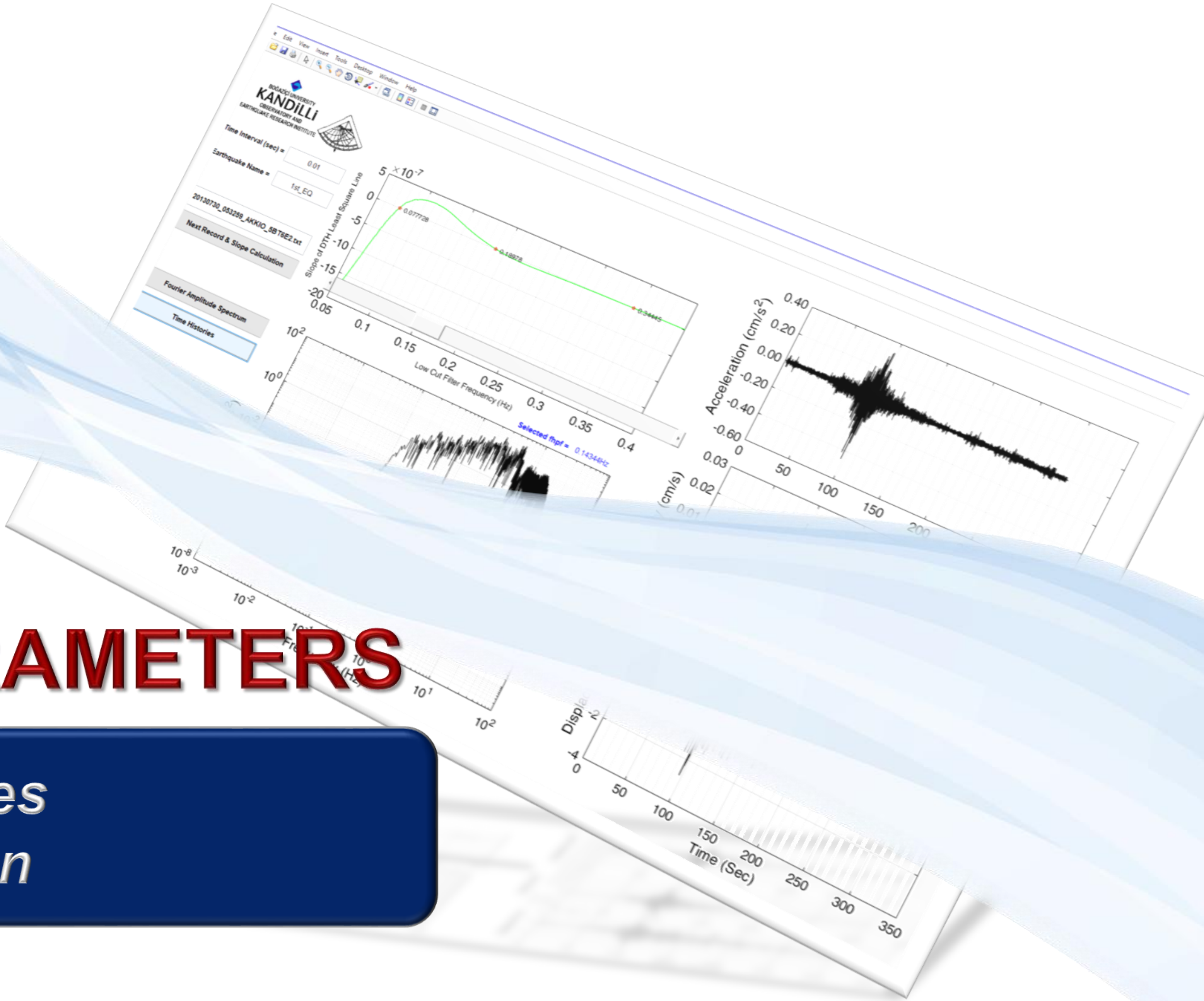
  5.66 km^2 (M_W=4.5) & 7.13 km^2 (M_W=5.6) Thingbaijam et al. (2017)

- The **average source dislocation** relationships of Thingbaijam et al. (2017) yield, *0.03 m (M_W=4.5) & 0.23 m (M_W=5.6)*

- The calculated **stress drop** for the M_W=5.6 event is exceptionally high. Some rare, very high values are also observed in some thrust dominated faults and in shallow earthquakes in the past (Allmann and Shearer, 2009).

IV. ESTIMATED DURATION PARAMETERS

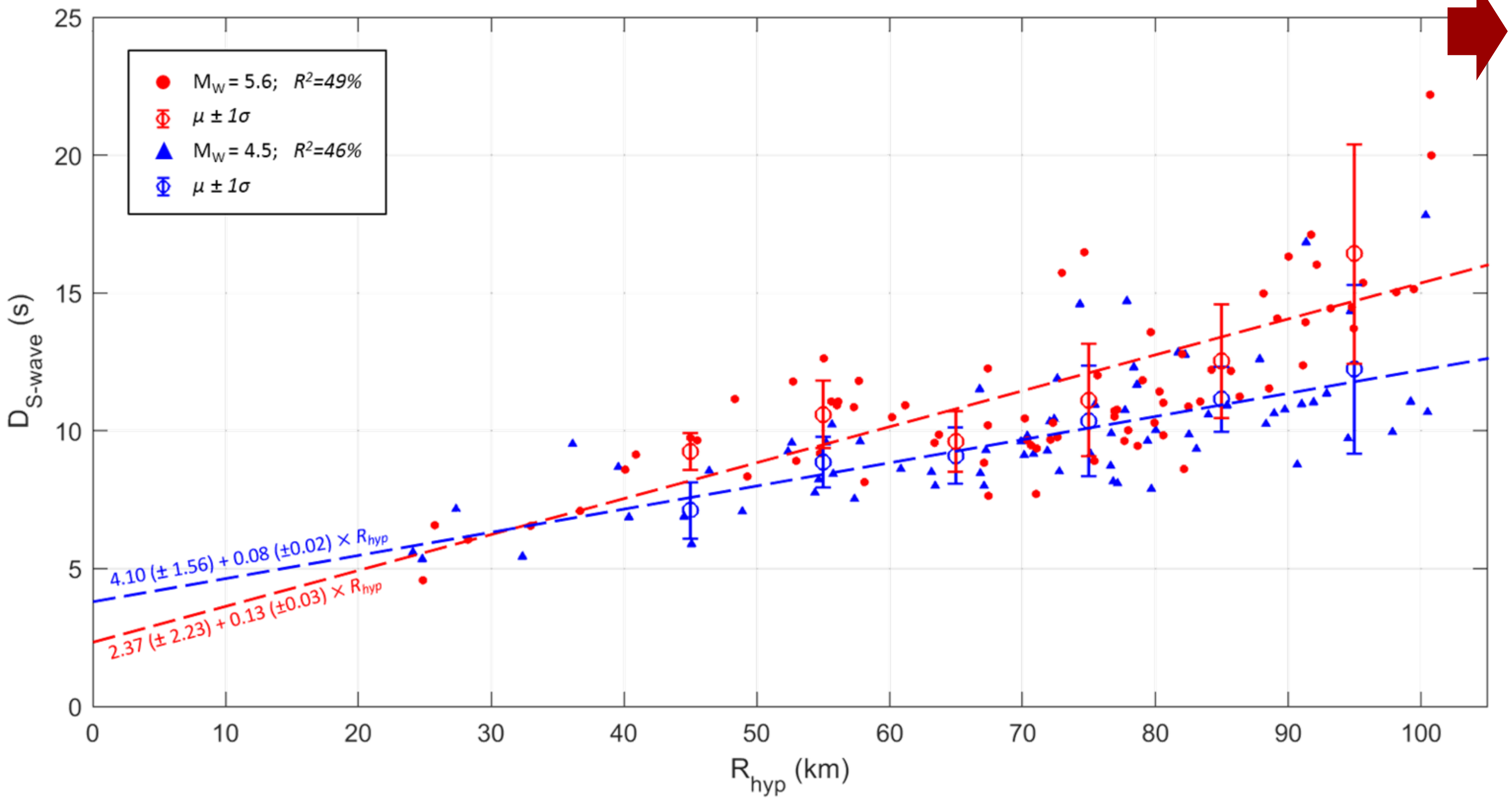
1. *Duration of S-Waves*
2. *Significant Duration*



IV. 1 DURATION OF S- WAVES

Durations of hand-picked S-wave windows are discussed in terms of their source and path components as,

$$D_{S\text{-}wave} = D_{source} + D_{path} = D_{source} + c_{path} \times R_{hyp}$$



The path component of S-wave durations is modelled linearly as $0.1 \times R_{hyp}$ for California, in seconds (Kishida et al. 2016). **0.1 in this expression matches well with the path components** of our models, which are ***0.08 (±0.02) and 0.13 (±0.03)***. In Kishida et al. (2016), source durations for events with magnitudes of $M_W \geq 4.5$ that occurred in Greece is suggesting a **10-second** source duration, while our estimations are much smaller.

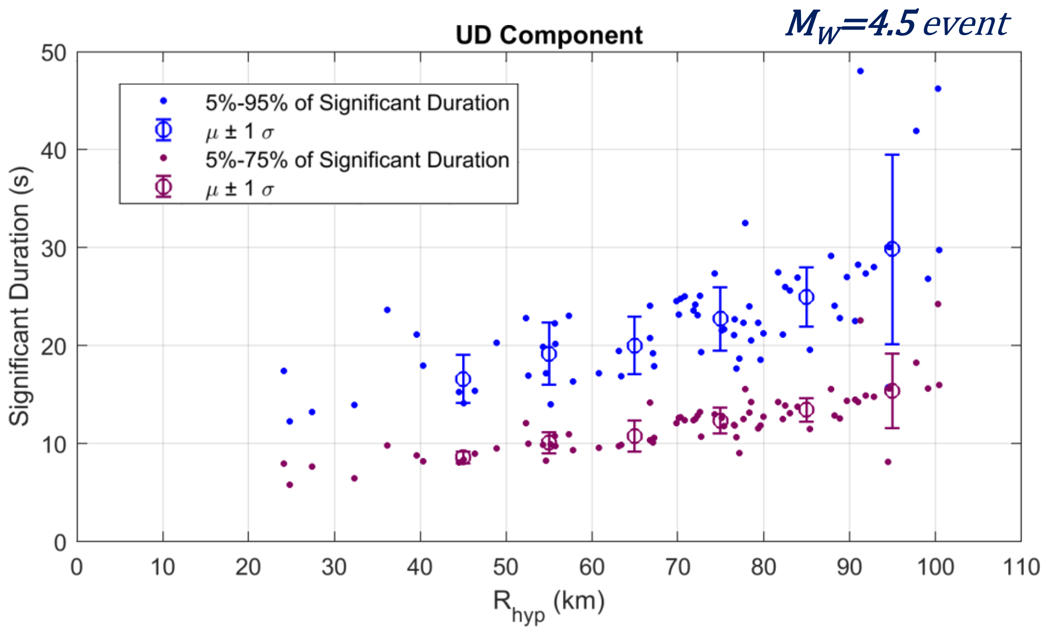
IV. 2 SIGNIFICANT DURATION

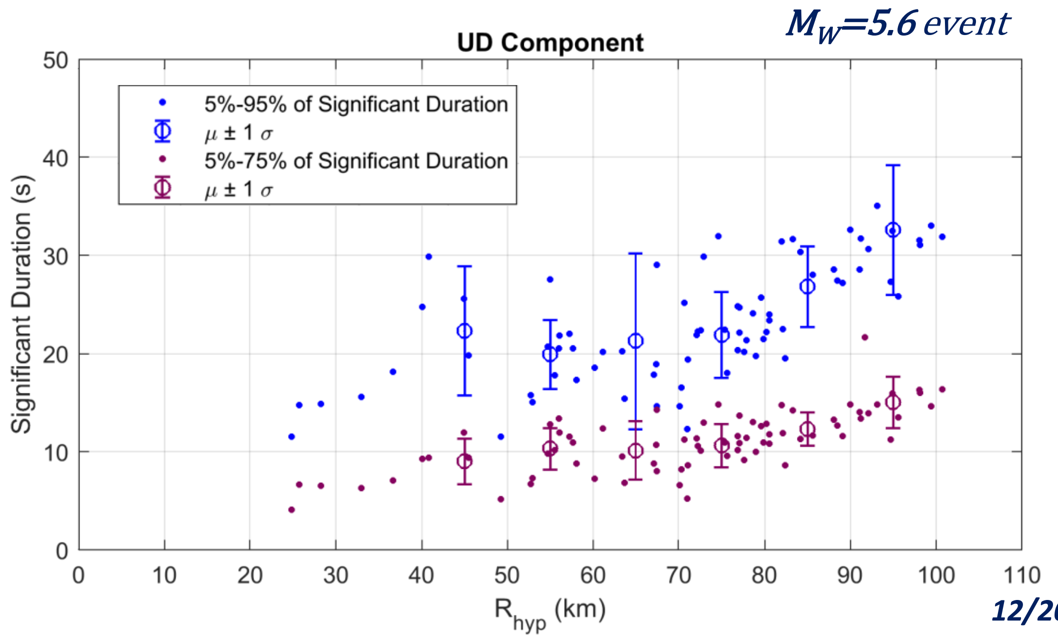
Significant duration is the b time interval across which a certain amount of energy is dissipated. Arias (1970) used the integral of the square of the ground acceleration to represent energy, known as **Arias Intensity (I_A)**,

$$I_A = \frac{\pi}{2g}\int_0^T a^2(t)dt$$

$M_W=4.5$						
	Significant Duration (5%-75%)			*Significant Duration (5%-95%)*		
	R^2 (%)	a	b	R^2 (%)	a	b
NS	25	5.24±2.98	0.03±0.04	42	14.26±4.69	0.06±0.06
EW	16	3.60±2.92	0.07±0.04	20	10.06±4.68	0.14±0.06
UD	60	2.90±1.85	0.13±0.03	41	7.00±4.60	0.22±0.06

$M_W=5.6$						
	Significant Duration (5%-75%)			*Significant Duration (5%-95%)*		
	R^2 (%)	a	b	R^2 (%)	a	b
NS	35	3.11±2.75	0.03±0.04	13	8.52±5.23	0.12±0.07
EW	11	1.77±2.94	0.06±0.04	16	6.58±5.86	0.15±0.08
UD	48	2.74±2.08	0.12±0.03	40	6.99±4.85	0.23±0.07





V. VARIATION OF GROUND MOTION PARAMETERS WITH DISTANCE

1. Procedure Scheme
2. Variation of Peak Ground Motion Parameters
3. Variation of Spectral Accelerations

V. 1 PROCEDURE SCHEME

PRELIMINARY PROCESS

Strong Ground Motion Data Compilation

Processing of Time Histories (EW & NS Records)

NEEDED &ASSUMED PARAMETERS

Moment magnitude (M_W): 4.5 and 5.6 by KOERI

Distance (R): $R_{JB} \approx R_{epi}$

Fault type (SoF): strike-slip for M_W=4.5; reverse for M_W=5.6

Average shear wave velocity ($V_{s,30}$) $\approx$ 550 m/sec

Region: Turkey in BSSA14 and KAAH15

CALCULATION OF NEEDED PARAMETERS FOR PROCESSED OBSERVED DATA

COMMONLY USED SELECTED GMPEs

- *Boore et al., 2014 (BSSA14)*
- *Akkar et al., 2014 (ASB14)*
- *Kale et al., 2015 (KAAH15)*

Calculated Parameters

PGA | **PGV** | **$S_{a\ e}$** -*Geometrical mean*-

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V. 2 PEAK SGM PARAMETERS-M_w=4.5

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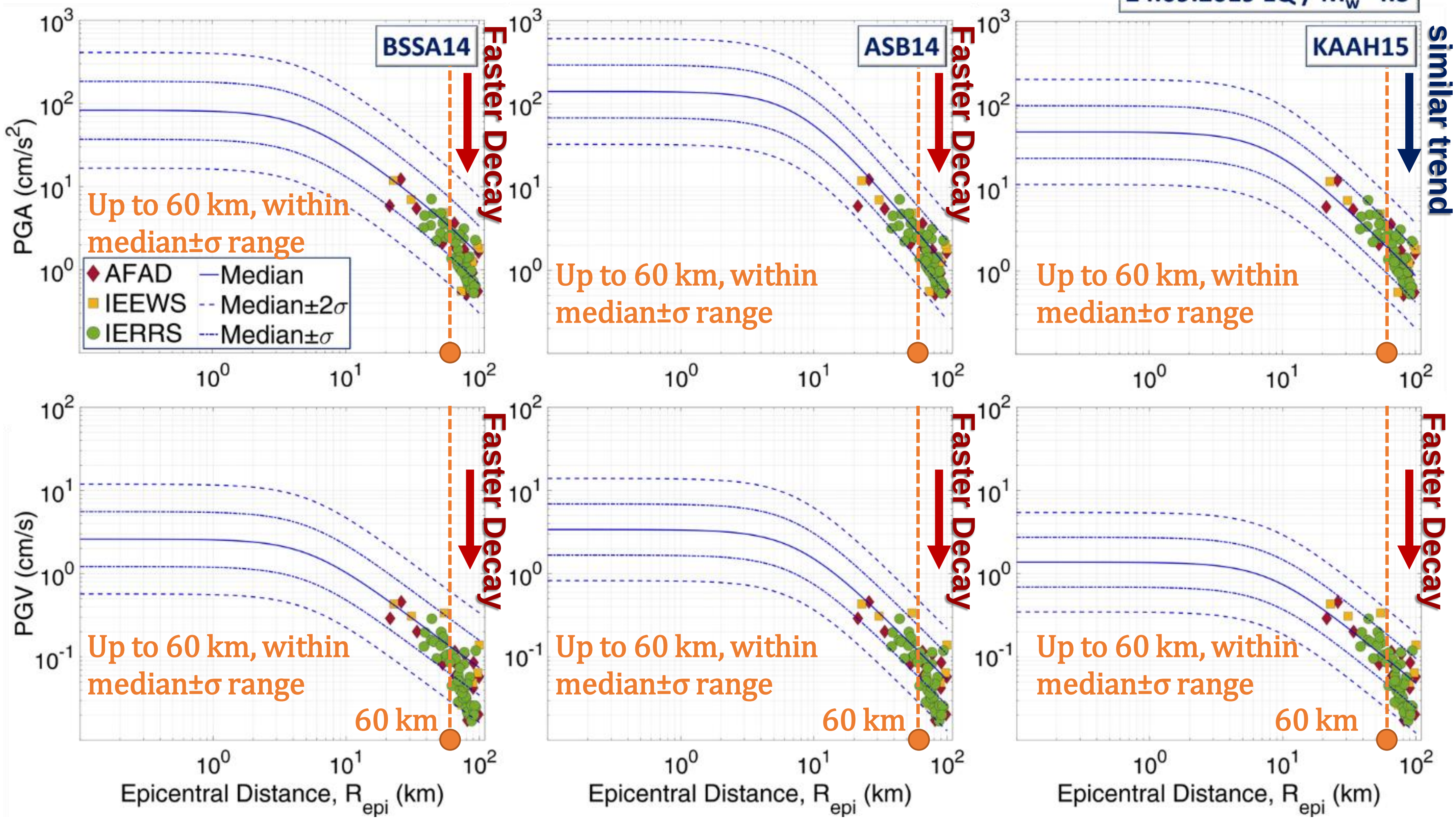
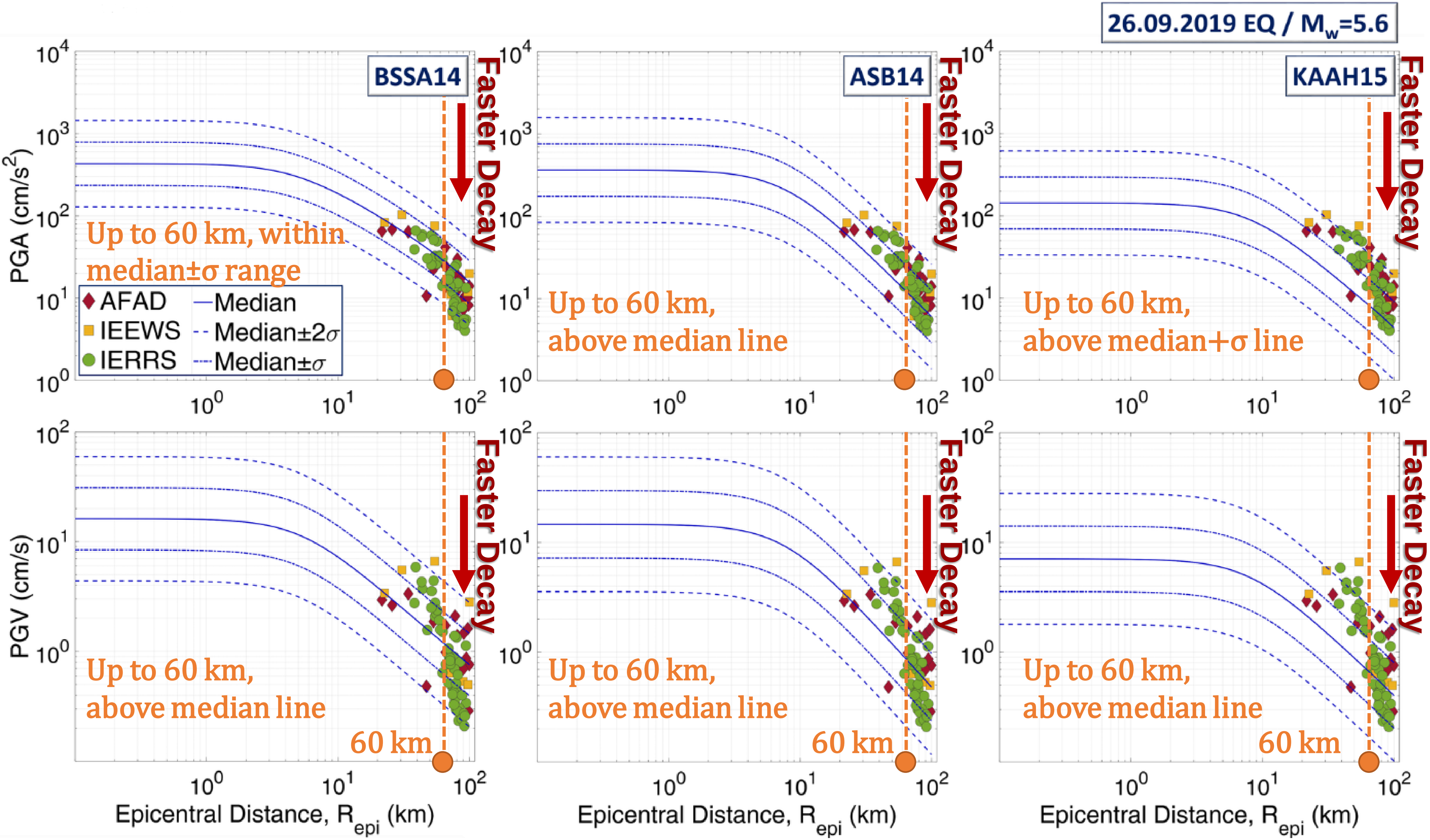
24.09.2019 EQ / M_w=4.5



All values are within median±2σ range

V. 2 PEAK SGM PARAMETERS-M_w=5.6



All values are about within median±2σ range

Some values exceed median+2σ line

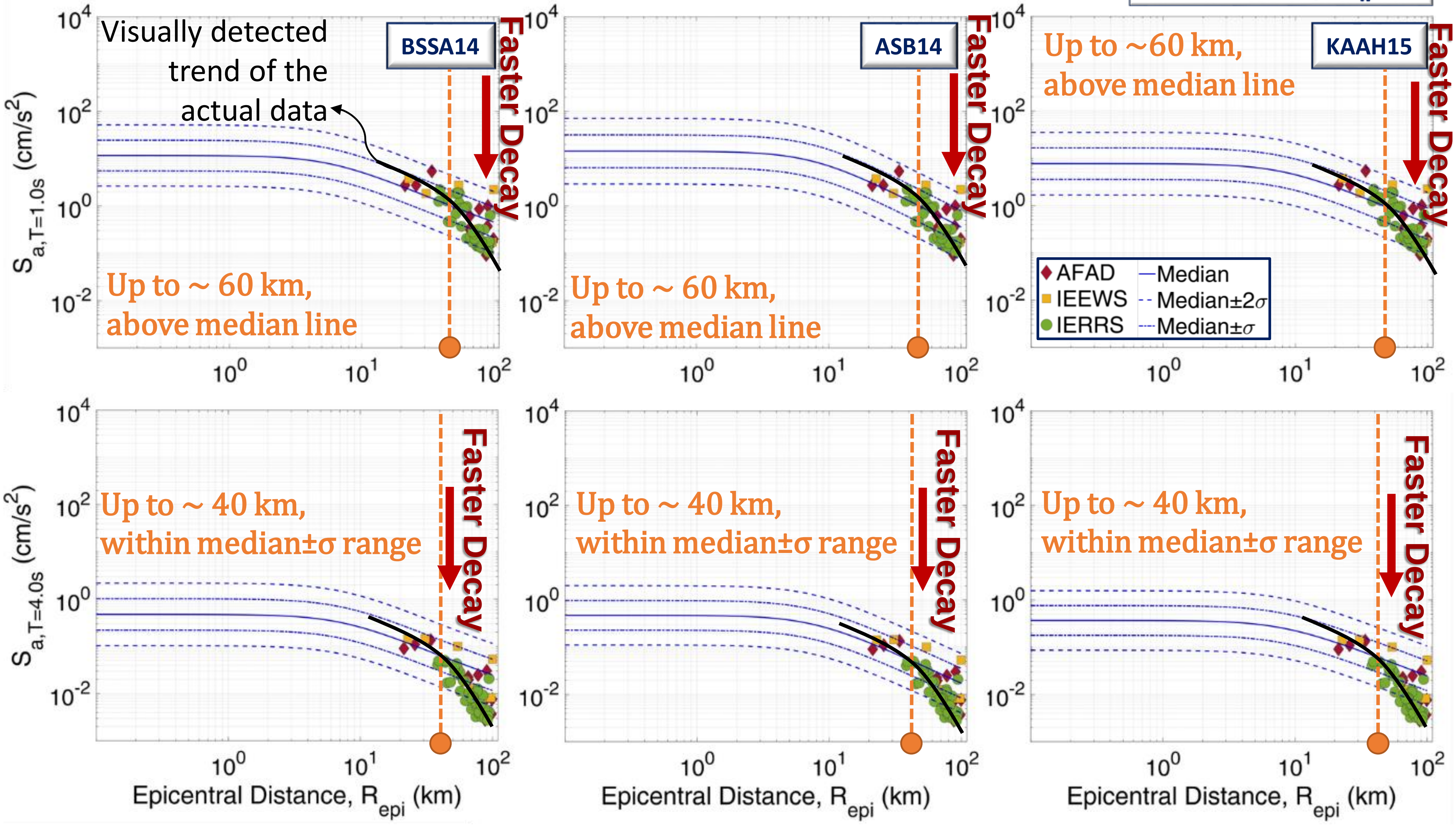
V. 2 PEAK SGM PARAMETERS

	FOR *PGA*	FOR *PGV*
$M_w = 4.5$	➢ **Up to 60 km**, observed data are **within median±σ ranges** and more proper to the emprical GMPEs. ➢ **A little bit faster attenuation** occurs in the observed PGA values especially **above the distances around 60 km** than in the GMPE lines.	➢ **Similar to PGA, up to 60 km**, observed data are **within median±σ** ranges and more proper to the emprical GMPEs. ➢ PGVs measured **at greater distances than 60 km** display **a sharp reduction** down to median-2σ line.
$M_w = 5.6$	➢ **Up to 60 km**, observed data are **above median line** and **exceed the median+2σ** line except for BSSA14. ➢ **Faster attenuation** occurs in the observed PGA values especially **above the distances around 60 km** than in the GMPE lines, resulting in incompatibility with the observed data.	➢ **Up to 60 km**, observed data are **above median line** and some values exceed the median+2σ line. However, data are seen more dispersed than PGA. ➢ PGVs measured **at greater distances than 60 km** display **a sharp reduction** down to median-2σ line.

Actual data for M_w=5.6 EQ are seen **more scattered** than observed data of M_w=4.5 Earthquake.

V. 3 SPECTRAL ACCELERATIONS

24.09.2019 EQ / M_w=4.5



All values are about within median±2σ range

Some values fall below median-2σ line at greater distances

V. 3 SPECTRAL ACCELERATIONS

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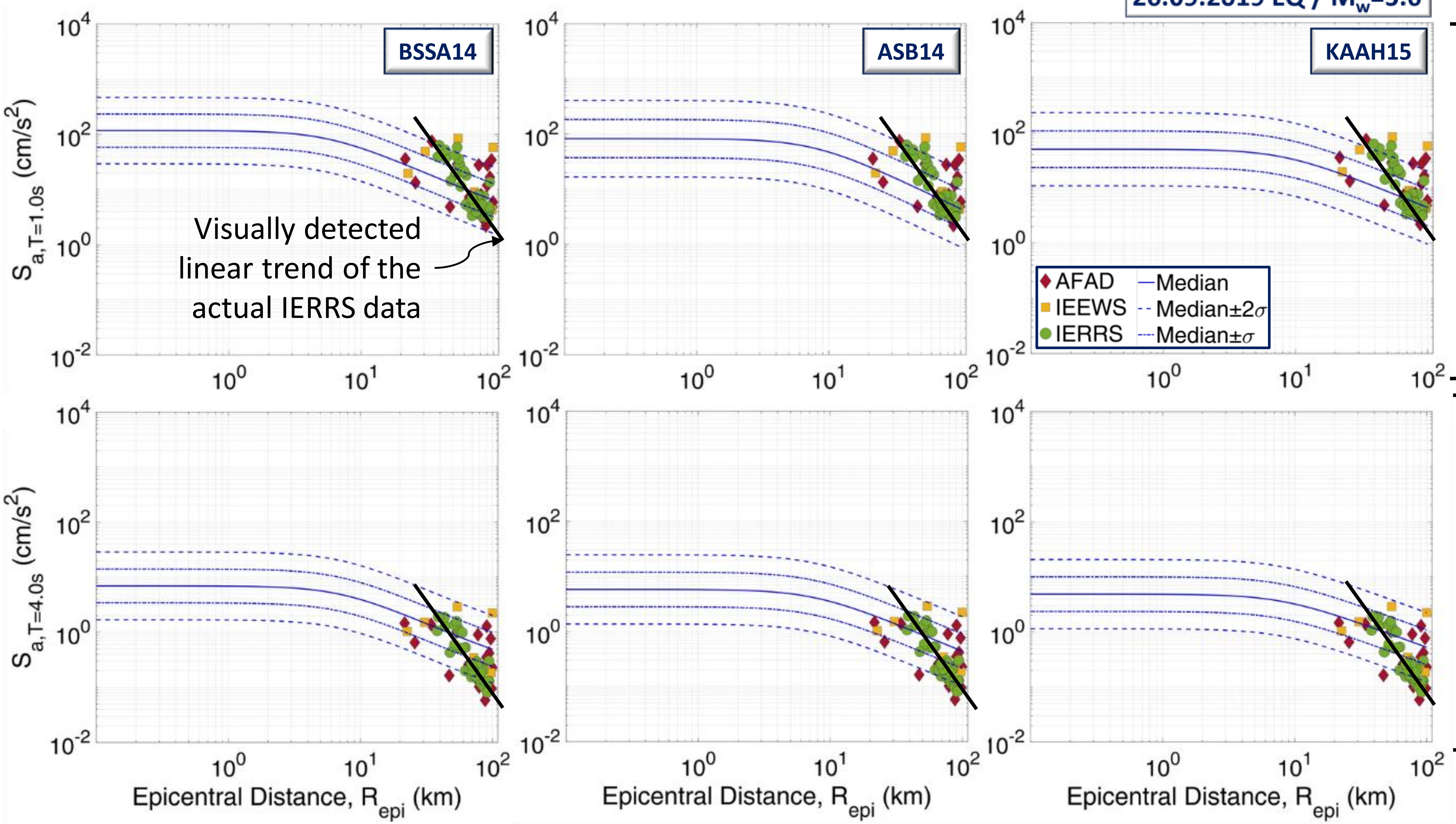
26.09.2019 EQ / M_w=5.6



Some values exceed median + 2σ line.

Some values fall below median-2σ line at greater distances

V. 3 SPECTRAL ACCELERATIONS

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	FOR $Sa\ (T = 1\ sec)$	FOR $Sa\ (T = 4\ sec)$
$M_w = 4.5$	➢ **Up to 60 km**, observed data are **above median line .** ➢ **A little bit faster attenuation** occurs in the Sa values especially **above the distances around 60 km** than in the GMPE lines.	➢ **Up to 40 km**, observed data are **within median±σ** ranges. ➢ Sa values calculated **at greater distances than 40 km** display **a faster reduction** down to median-2σ line.
$M_w = 5.6$	➢ **Any distance limit could not adapted due to dispersion of data.** ➢ However, **a linear decay** was visually detected especcially for **IERRS data.** ➢ Some values **exceed median + 2σ** line of three GMPEs.	➢ **Any distance limit could not adapted due to dispersion of data.** ➢ However, **a linear decay** was visually detected especcially for **IERRS data.** ➢ Some values **fall below median-2σ** line of three GMPEs especially at greater distances.

Actual data for M_w=5.6 EQ are seen **much more scattered** than observed data of M_w=4.5 Earthquake.

VI. ANELASTIC ATTENUATION PARAMETER

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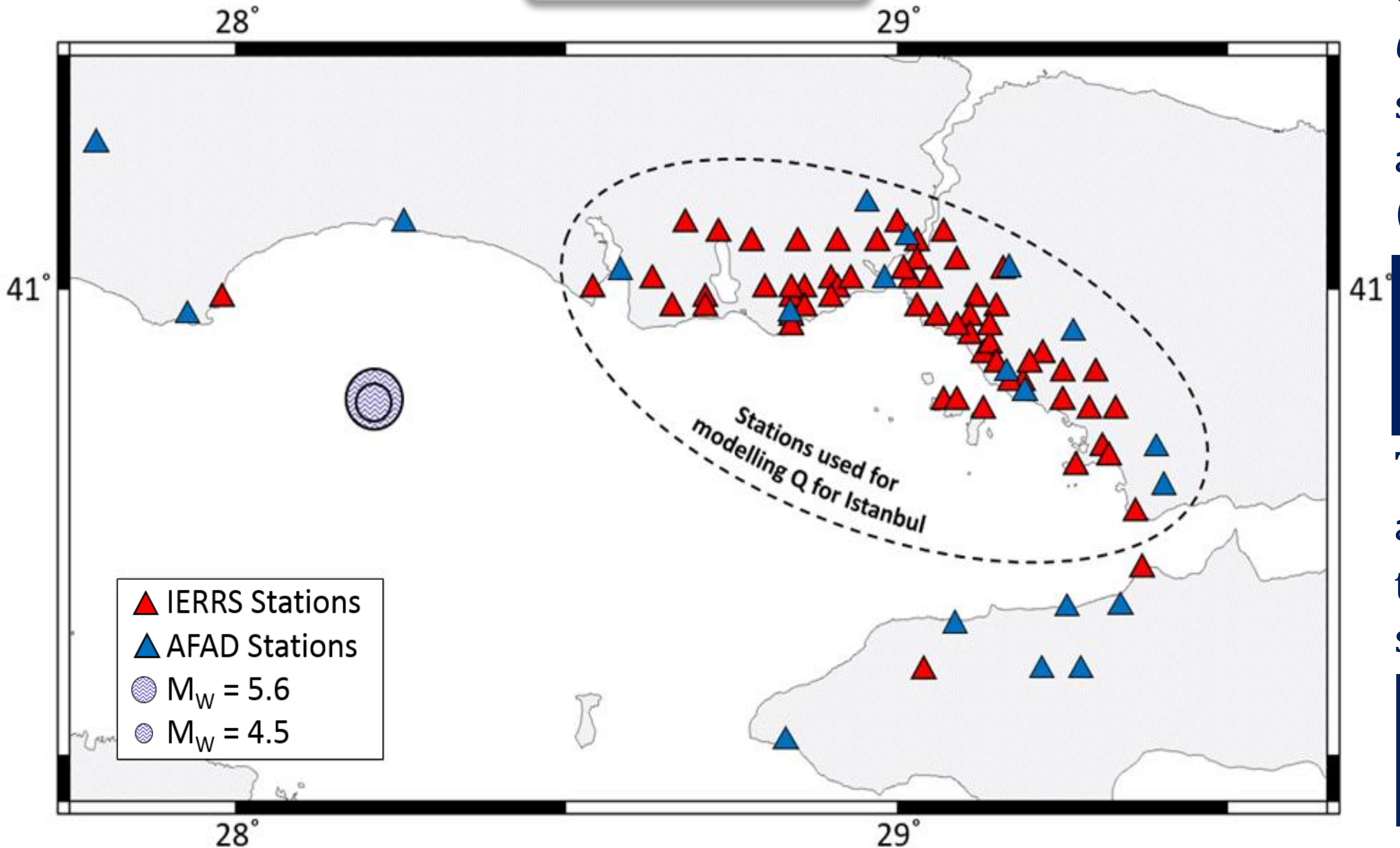
Frequency-dependent anelastic attenuation model, $Q_s(f)$, is prepared by observing the spectral decays at selected central frequencies by using the vertical components of acceleration Fourier amplitude spectra of S-waves (Anderson and Quaas, 1988),

$$Q_s(f) = Q_0 \times f^n$$



The frequency-dependent $Q_S(f)$ is calculated over the spectral amplitudes of twelve selected central frequencies with wide enough usable frequency bandwidths, between 0.5 Hz - 24 Hz.

The mean amplitudes at selected frequencies are corrected by a geometrical spreading model, $G(R_{hyp})$, expressed in the form of $R_{hyp}^{-\gamma}$. We selected the γ exponent as 1, following Frankel et al. (1990) and Horasan and Boztepe-Güney (2004). The correction is applied as,

$$u(R_{hyp}) = \ln\left[\frac{U(f,r)}{G(R_{hyp})}\right]$$

These corrected values are plotted against R_{hyp} and regressed in the $a - b \times R_{hyp}$ form. So that the b value yields the individual Qs values at each selected frequency as,

$$b = \frac{\pi f}{Q_s \beta}$$

VI. ANELASTIC ATTENUATION PARAMETER

Central frequencies (Hz)	İstanbul		Northeast of Marmara	
	M_W=4.5	M_W=5.6	M_W=4.5	M_W=5.6
1	41	39	55	56
1.5	65	61	84	81
2	88	81	109	101
2.5	112	103	135	120
3	141	131	166	136
4	217	201	243	185
6	322	305	329	313
9	414	478	383	508
12	679	850	588	614
15	972	1183	797	697
18	1140	1269	930	949
21	1440	1533	1151	1514
This study	$40\ f^{1.15}$	$31\ f^{1.30}$	$56\ f^{0.97}$	$49\ f^{1.04}$
Horasan et al. (1998) - Sea of Marmara	-		$50 \pm 1.7\ f^{1.09 \pm 0.05}$	
Horasan and Boztepe-Güney (2004) - Sea of Marmara	-		$40 \pm 5\ f^{1.03 \pm 0.06}$	
Horasan and Boztepe-Güney (2004) - Istanbul	$13 \pm 1\ f^{1.22 \pm 0.05}$		-	

- The individual Q_s values corresponding to each central frequency is shown in the table, forming the functional frequency-dependent model of $\boldsymbol{Q_s(f) = Q_0 \times f^n}$.
- The Q_S models prepared considering Istanbul has ***lower*** Q_S **values than the** Q_S **values estimated for the Northeast of Marmara**. In other words, shear waves propagating towards Istanbul were encountered by **a *higher* attenuation.** This is comparable with the model of Horasan and Boztepe-Güney (2004), pointing out on an even higher attenuation.
- **Q_S models** prepared in the past for **the Sea of Marmara** are in **very good agreement** with our models. However, while the models prepared in this study exclusively focuses on the Northeast of our region, the compared models are prepared for the whole region.

VII. CONCLUSION

VII. CONCLUSION

SOURCE PARAMETERS

- The estimated source parameters of M_W=4.5 event are in reasonable agreement with global estimations for moderate magnitude and strike-slip events. However, the stress drop and the average source dislocation of M_W=5.6 event are remarkably high when compared with earthquakes having similar characteristics. Therefore, these values can rarely be observed.

DURATION OF STRONG GROUND MOTION

- The path components of significant duration and S-wave duration models have very similar values and they also match with the global models. The 5%-75% significant duration models are very close to the S-wave duration model. In addition to this, the vertical component of the 5%-75% significant duration estimations have a very linear trend along hypocentral distance, yielding $2.90(\pm1.85) + 0.13(\pm0.03) \times R_{hyp}$ and $2.74(\pm2.08) + 0.12(\pm0.03) \times R_{hyp}$ for M_W=4.5 and M_W=5.6 events, respectively.

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VII. CONCLUSION

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VARIATION OF GROUND MOTION PARAMETERS WITH DISTANCE

- The calculated peak parameters (PGA & PGV) and spectral accelerations of the M_W=5.6 earthquake display more dispersed characteristics when compared to those of the smaller event. As a result of that, generally, the data spreads between median±2σ lines of three GMPEs.
- For this data group compiled from both earthquakes, ~60 km may be identifed as a threshold distance since the peak and spectral values begin to attenuate faster at this limit value. However, in order to verify this argument, the database in this study should be extended especially for closer distances.

ANELASTIC ATTENUATION PARAMETER

- When the recordings of stations located in Istanbul were examined as a special case, we observed that a very high attenuation exists along the path through which the shear waves travelled towards Istanbul. However, the general model prepared for the northeast of Marmara shows lower attenuation characteristics than the one in the first case.

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Background Photo: Bosphorous and İstanbul Landscape from Kandilli Observatory