WS2-4-8

伊方観測記録に基づくQ値評価の高度化

Evaluation of Q-value which based on seismic ground motion records in Ikata

電力中央研究所　原子力リスク研究センター
CRIEPI/NRRC
佐藤　浩章
Hiroaki Sato

Ikata3 SSHAC project WS2
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電力中央研究所

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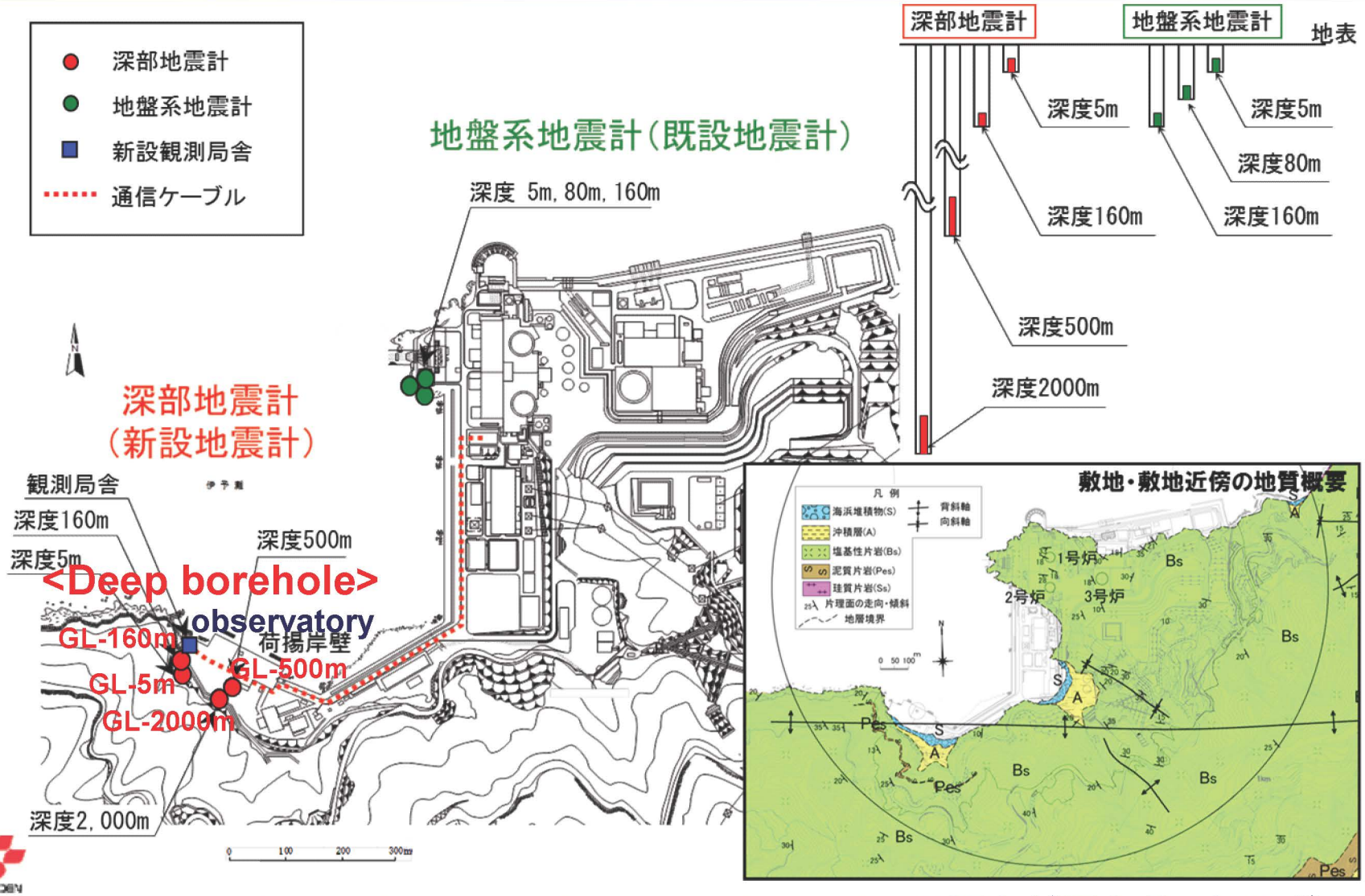
伊方発電所における深部地震観測

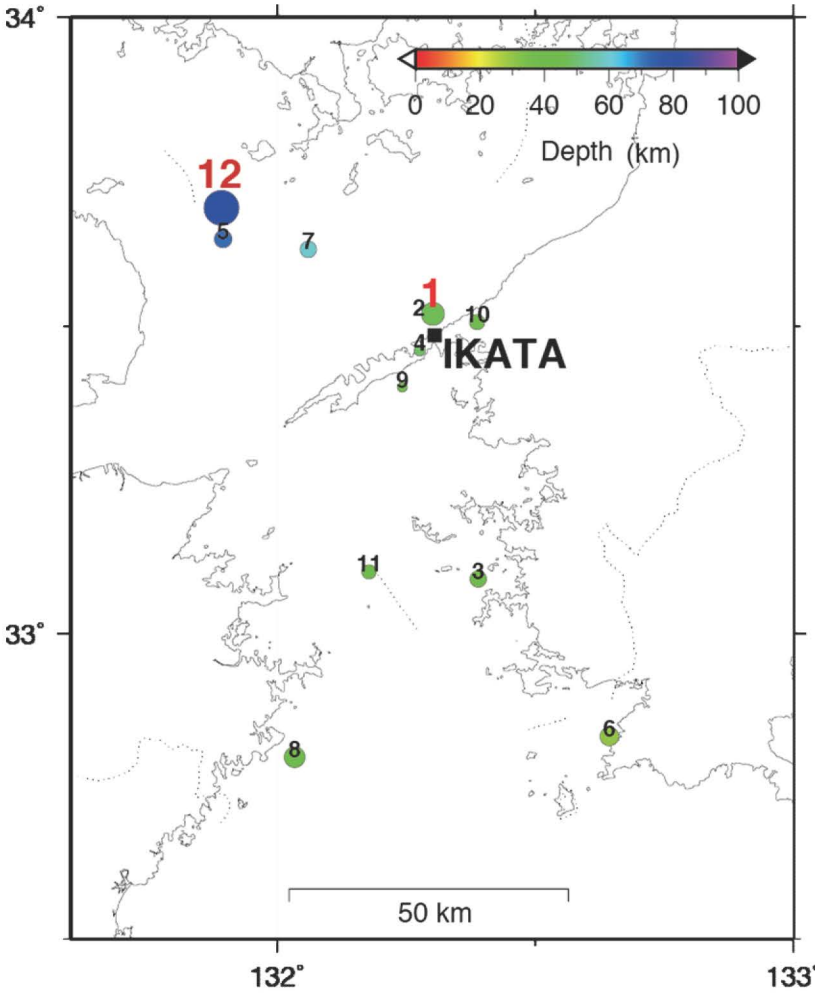
Deep borehole array observation at Ikata site



- GL(GROUND LEVEL)-5m、GL-160m、GL-500m、GL-2000mの深さが異なる4本のボーリング孔の孔底に地震計が1台ずつ設置されている。

出典: https://www.nsr.go.jp/data/000100928.pdf

観測されたおもな地震
Observed earthquake events



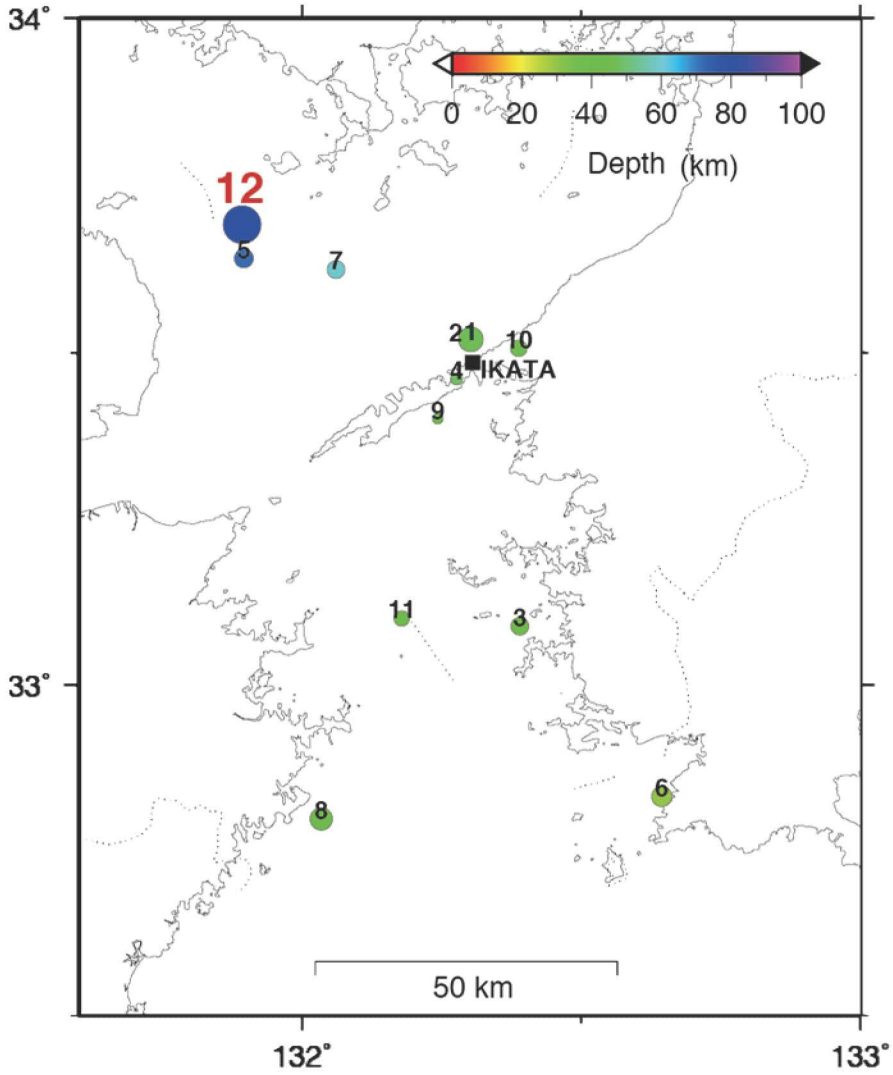
No.	LAT. (°)	LONG. (°)	Focal depth (km)	M_{JMA}	Vector PGA (Gal)			
					GL−5m	GL−160m	GL−500m	GL−2000m
1	33.520	132.301	46.6	4.5	18.4	9.6	8.5	8.5
2	33.522	132.295	45.9	3.4	4.9	2.7	2.7	3.0
3	33.089	132.388	40.8	3.4	1.9	1.1	1.2	1.0
4	33.461	132.275	48.3	2.3	0.7	0.3	0.5	0.4
5	33.641	131.894	71.7	3.6	1.8	1.1	1.3	1.6
6	32.832	132.642	30.0	3.8	0.9	0.4	0.5	0.6
7	33.625	132.059	59.2	3.4	1.7	1.2	1.2	1.1
8	32.798	132.033	42.2	4.1	1.5	1.0	1.1	1.0
9	33.401	132.241	44.8	2.1	0.6	0.3	0.4	0.4
10	33.507	132.386	45.4	3.2	1.0	0.6	0.8	0.8
11	33.101	132.177	42.1	3.0	0.8	0.5	0.4	0.3
12	33.692	131.891	80.0	6.1	100.7	53.9	55.2	74.2

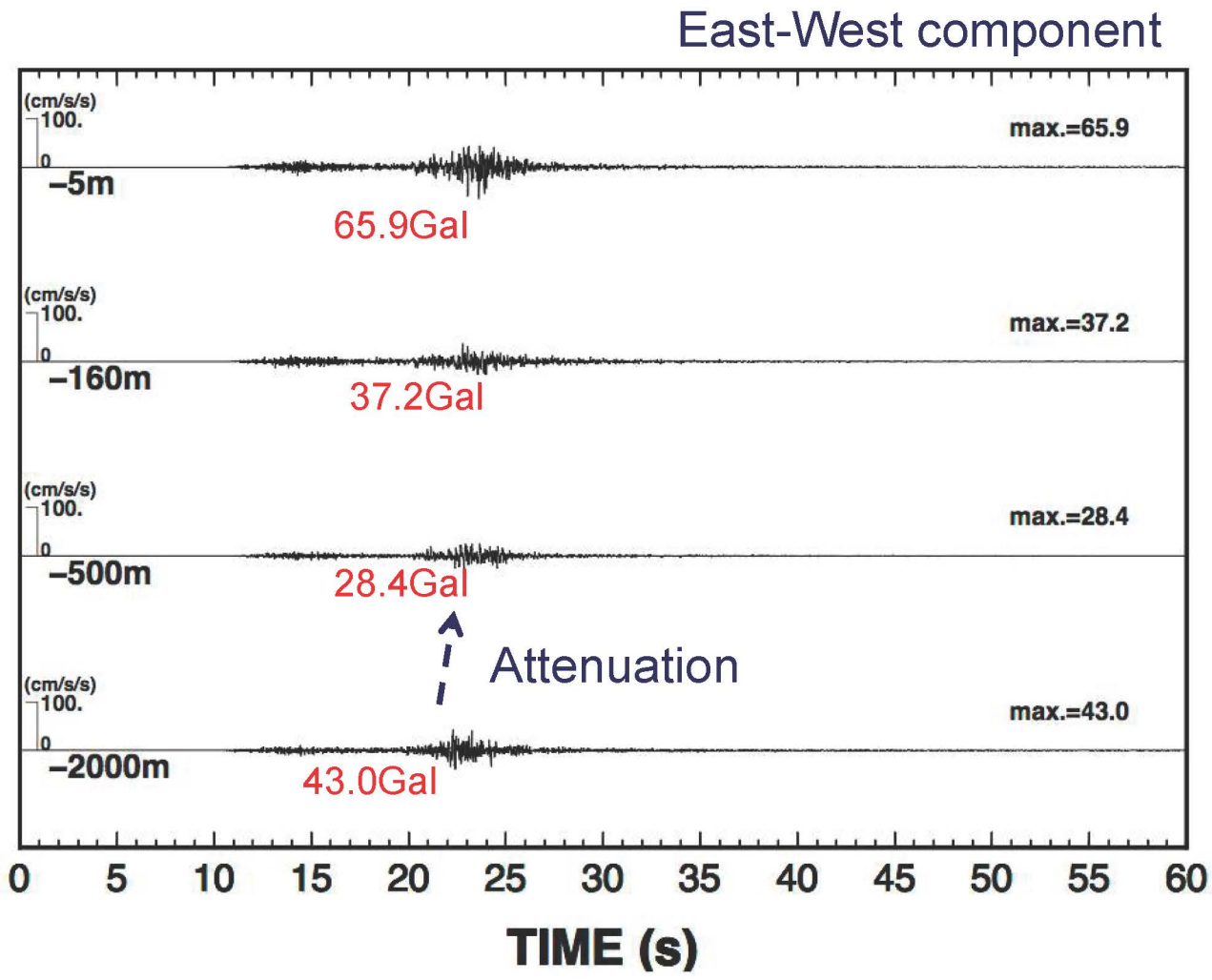
- No.12 event records(largest records) are used in this study.

◆ GL-2000mで1Gal程度の小さい記録がほとんどであるが、地表で100Gal（GL-2000mで74Gal）の記録が1つ得られている。（本研究の対象）

深部地震観測記録　- 最大加速度の最も大きな記録（No.12）-

Deep borehole array observation records –Largest records event(No.12) –





◆ 深部の地中記録（GL-2000mからGL-500m）には、加速度振幅の減少が明瞭に確認できる。

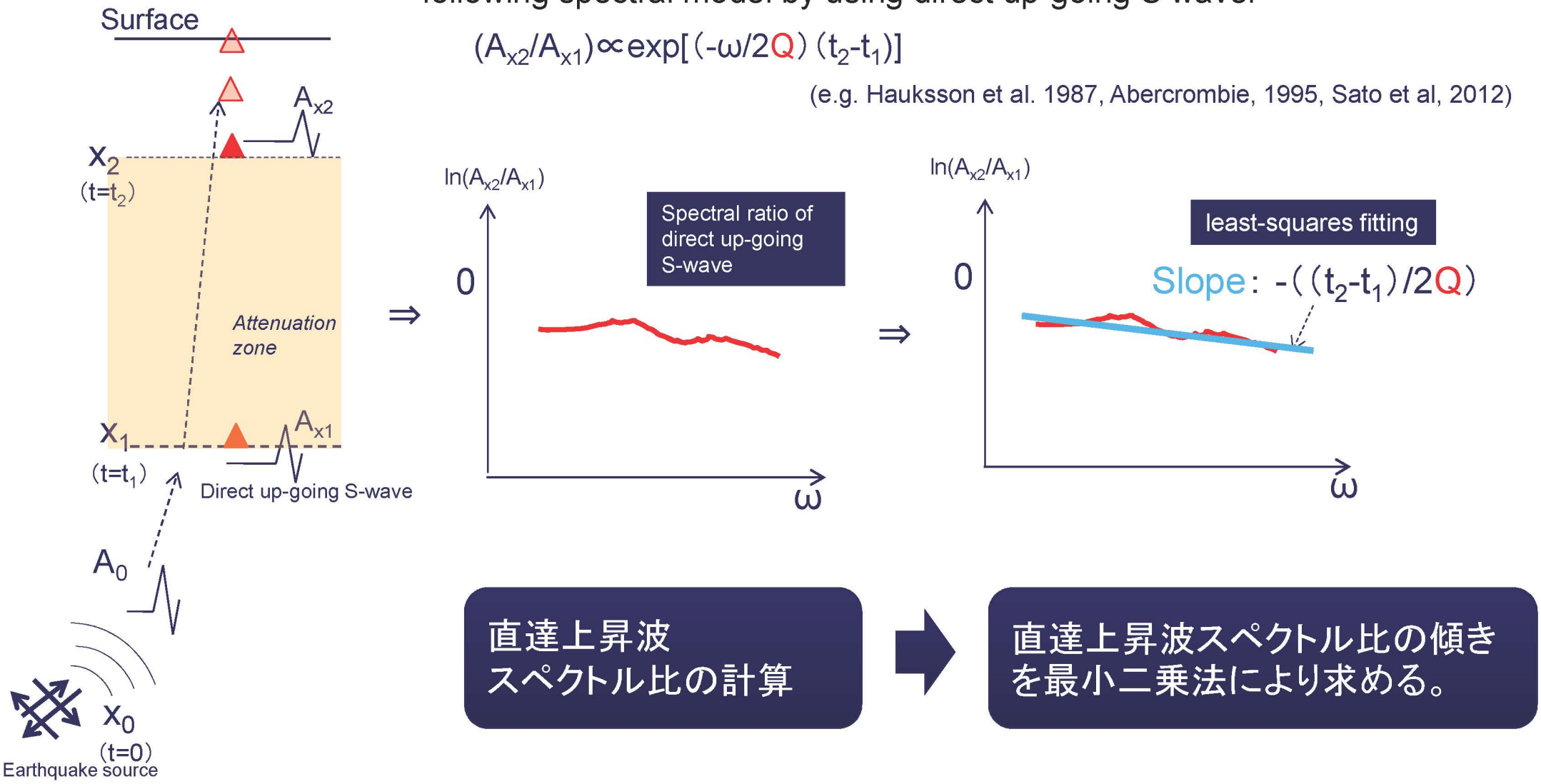
ボアホール地震記録による深部Q値（減衰）の測定　-方法-

Q (ATTENUATION) MEASUREMENTS IN DEEPER UNDERGROUND BY BOREHOLE RECORDS – METHOD –

The attenuation of seismic wave in a borehole can be determined from the following spectral model by using direct up-going S wave:

$$(A_{x2}/A_{x1}) \propto \exp[(-\omega/2Q)(t_2-t_1)]$$

(e.g. Hauksson et al. 1987, Abercrombie, 1995, Sato et al, 2012)



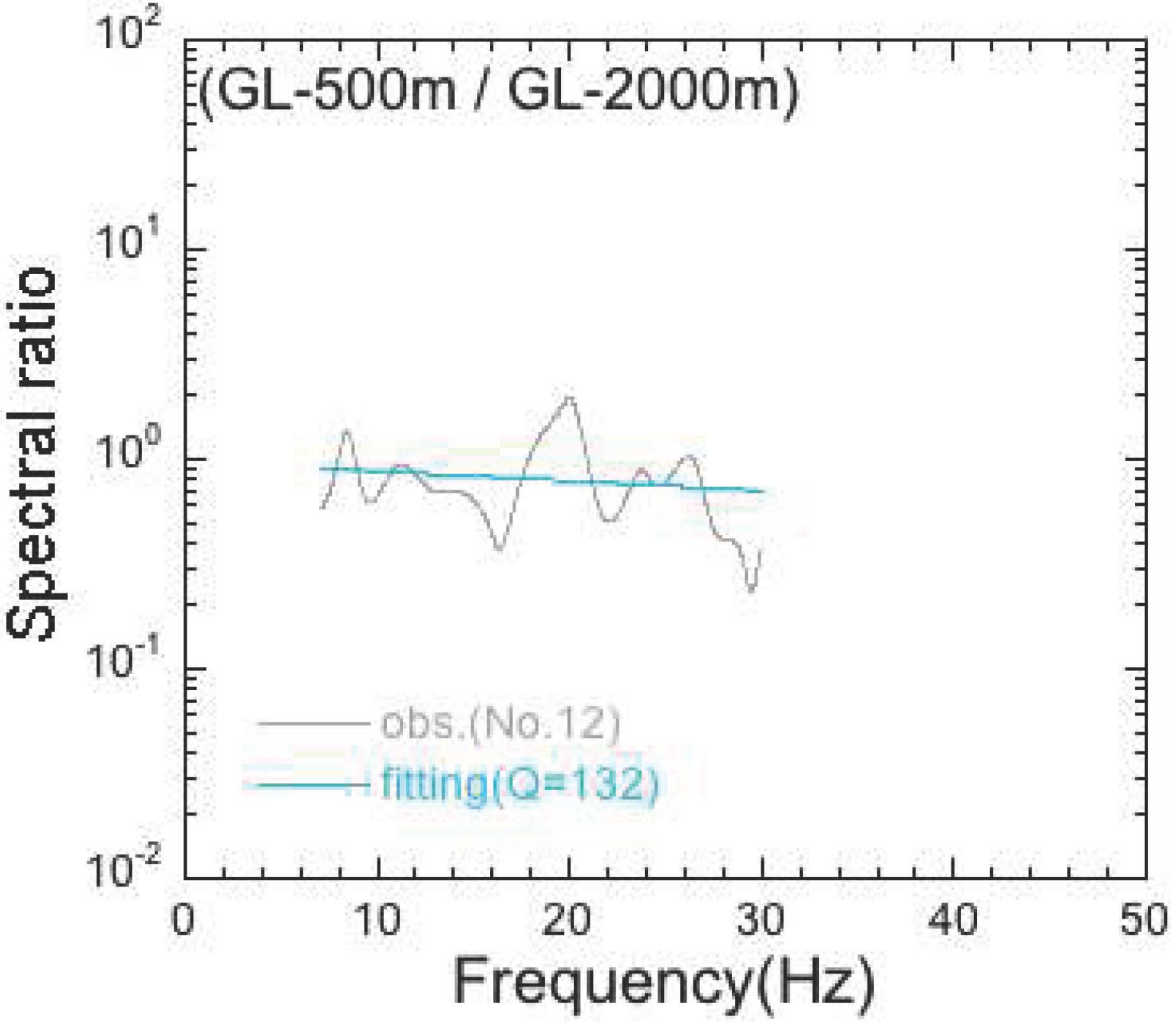
直達上昇波
スペクトル比の計算

直達上昇波スペクトル比の傾き
を最小二乗法により求める。

深部Q値（減衰）の測定結果　- 最も大きい記録の結果 –

Result of Q measurements in deeper underground –Largest records –

◆ **Figure** shows a comparison of the spectral ratio of the largest event and attenuation model of Q=132 estimated by least-squares fitting in the frequency.



✓ 最も大きい記録（No.12）の上昇波スペクトル比（7Hz～30Hz）を用いて、スペクトル減衰モデルによる最小二乗法によるフィッティングを実施した結果、Q=132が得られた。

課題：

- 地表からの反射波の影響が小さい深部に限られる。
- データが短いため、広帯域のQ値の測定が難しい。

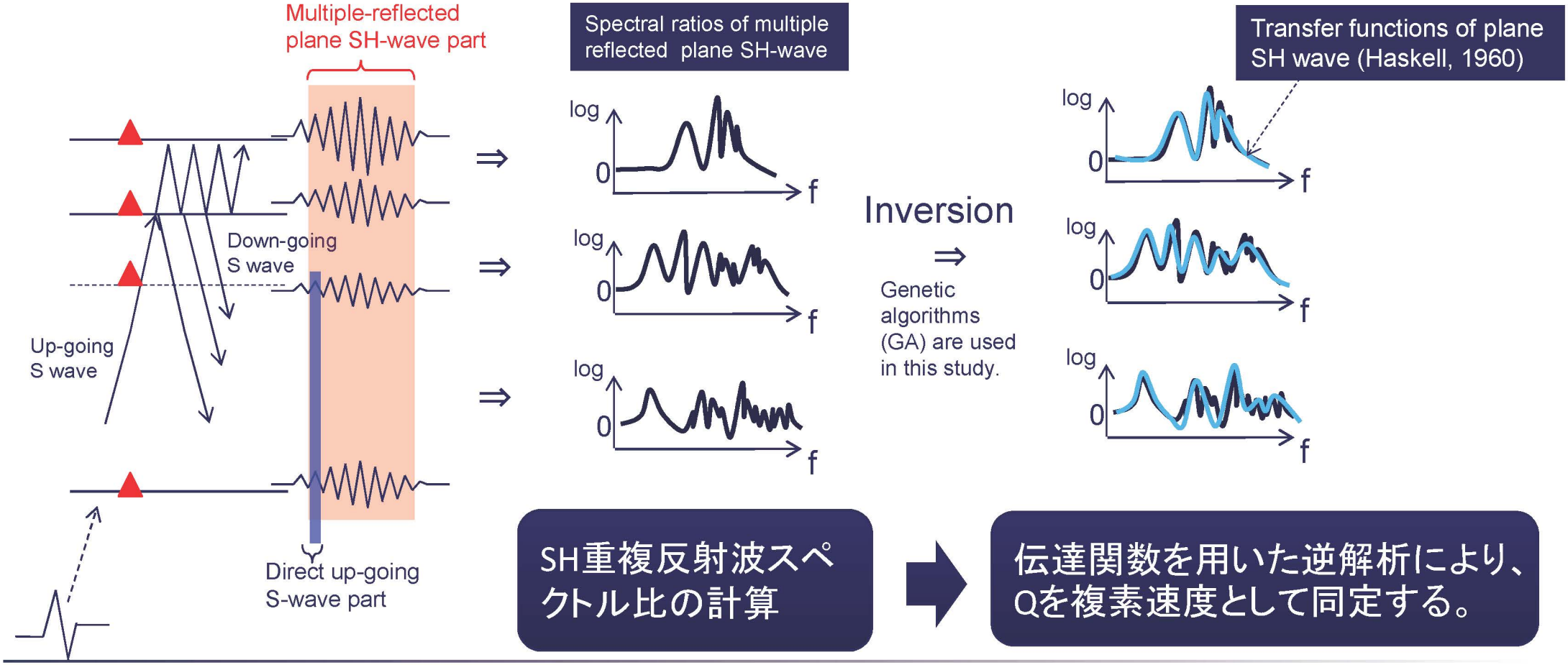
In the case of applying to
- broadband Q
- shallower underground Q

there are some difficulties in this method.

ボアホール地震記録による広帯域Q値（減衰）の測定

Measurements of broadband Q in shallower and deeper underground by borehole records

- Multiple-reflected plane SH-wave spectral-ratio inversions are often applied to an estimation of a broadband and shallower Q in underground by using borehole records.
- Q is identified as a part of complex S wave velocity: $v_s^*=v_s(1+i/2Q)$.
- For calculation of transfer functions, a layered model of S-wave velocity is needed in an inversion.



SH重複反射波スペクトル比の計算

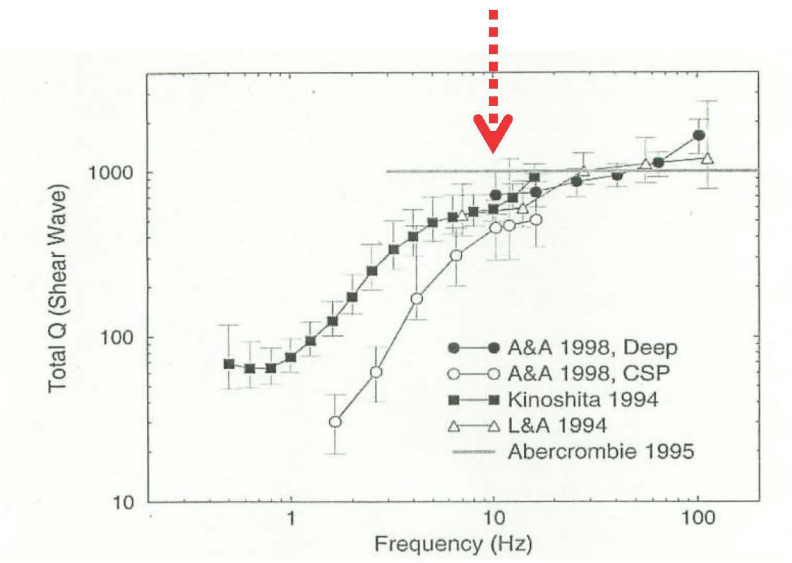
伝達関数を用いた逆解析により、Qを複素速度として同定する。

10Hz transition of broadband Q

- The rapidly increasing Q with frequency is determined in the frequency range 1 to 10 Hz.
- The increasing Q with frequency is weak between 10 and 100 Hz.
- It is clearly unwise to extrapolate Q estimates made below about 10 Hz to higher frequencies.

(Abercrombie,1998)

10 Hz



(Abercrombie, 1998)

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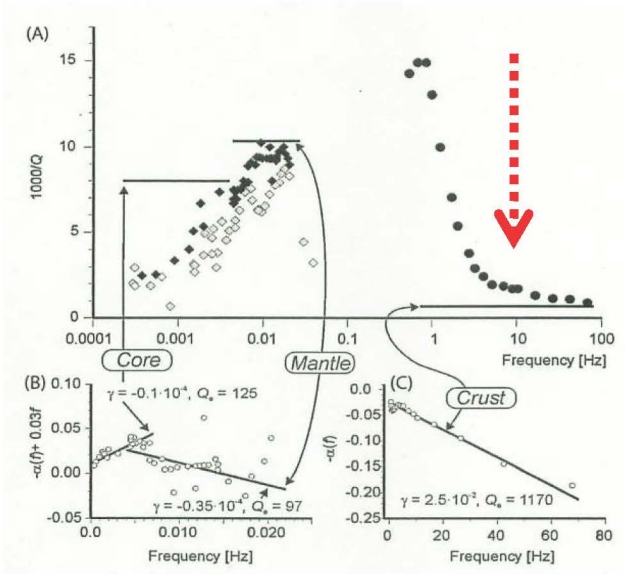
10 Hz



(Morozov, 2008)

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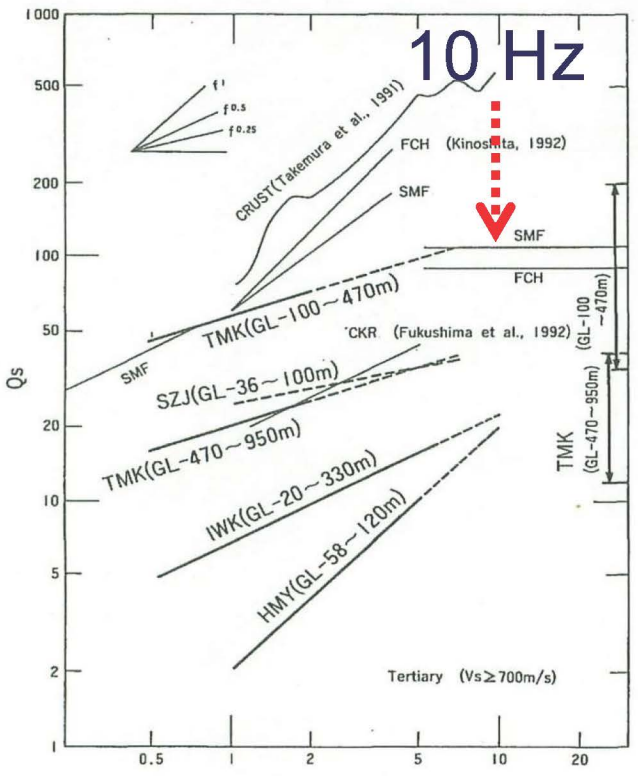
10 Hz



(Takemura et al., 1993)

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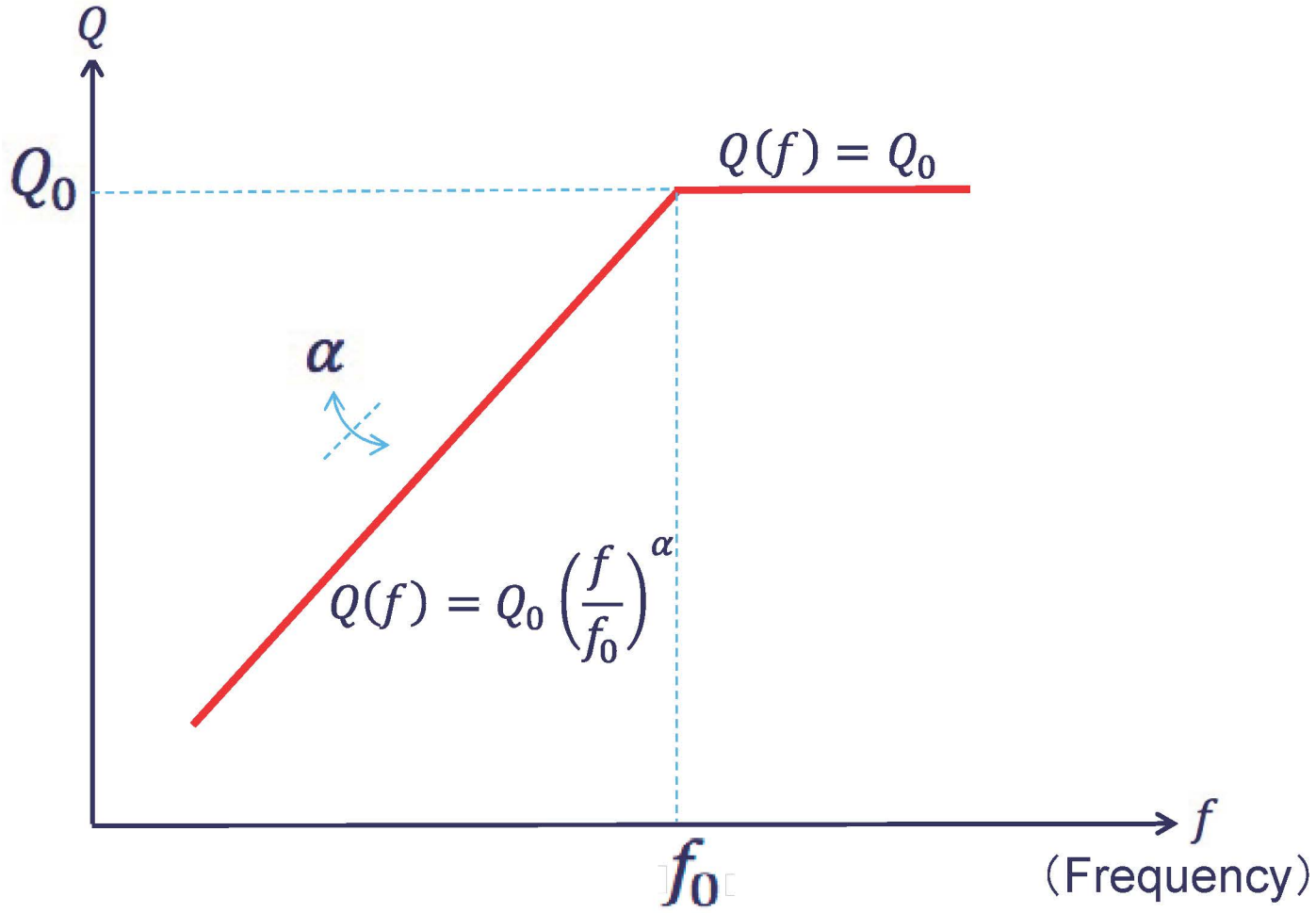
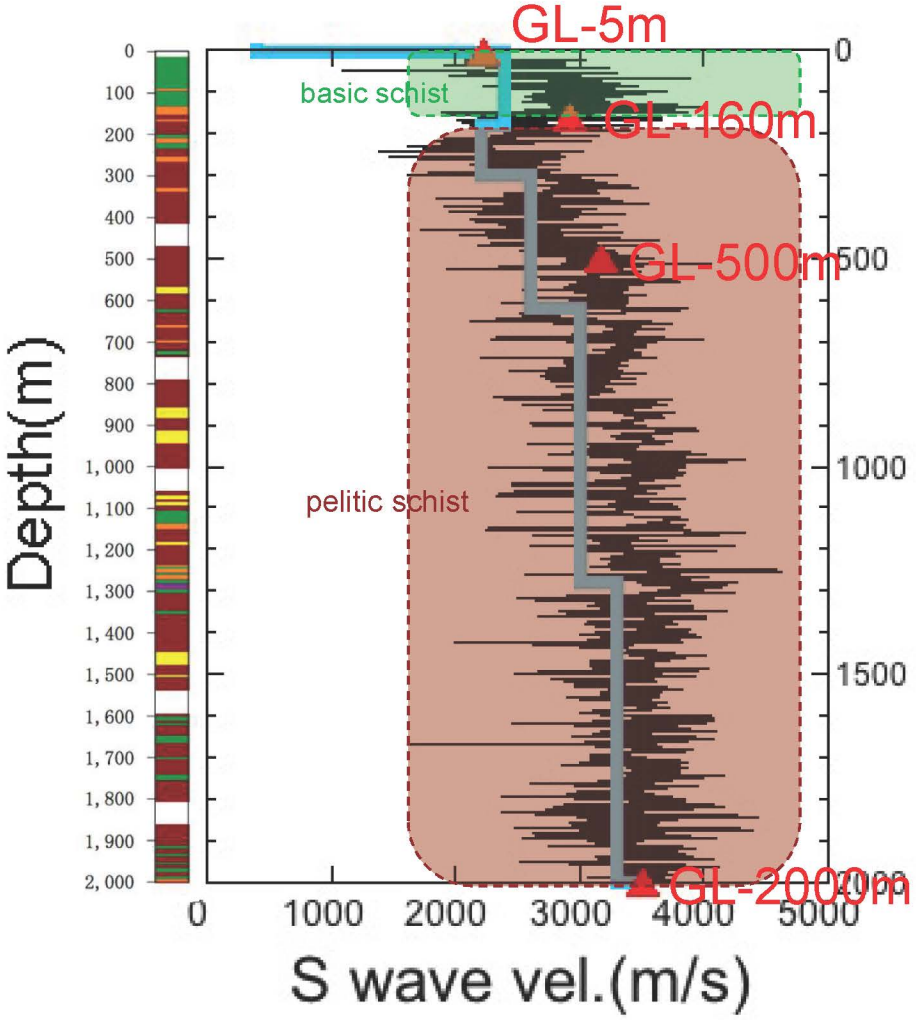
Broadband Q model

- We proposed a bi-linear frequency-dependent Q model which can consider characteristics of broadband Q such as 10 Hz transition.(Sato et al.,2006)
- In inversions using this model , it's necessary that the three parameters are identified.



Inversion

- Genetic algorithms (GA) are used in the inversion.
- Unknown parameters(Q_0,f_0,α in this study) are searched in the given areas.
- In GA, the iterations was terminated at the given generation number. (used 1000 generations in this study)



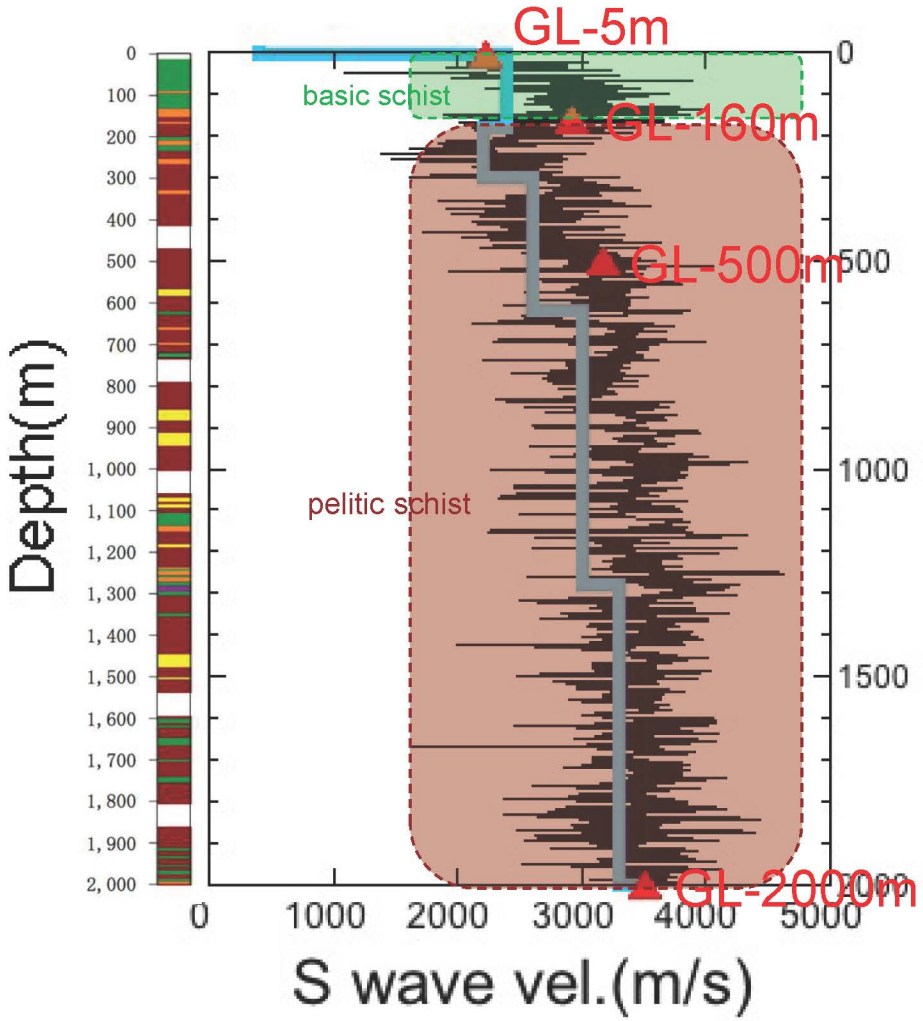
<Layered model of Ikata used in inversion>

No.	Seismo-meter	Upper depth (m)	Thick-ness(m)	Density (g/cm^3)	Vs (m/s)	Search area of Broadband Q parameters		
						Q_0	f_0	α
1		0	5	2.30	400	16.6-50	1.0-20	0.0-1.5
2	GL-5m	5	155	2.90	2400			
3	GL-160m	160	20	2.90	2400			
4		180	120	2.70	2200	50-500	1.0-20	0.0-1.5
5		300	200	2.70	2600			
6	GL-500m	500	120	2.70	2600			
7		620	660	2.70	3000			
8		1280	720	2.70	3300			
9	GL-2000m	2000	-	2.70	3500			

SH重複反射波スペクトル比の逆解析の結果 -最も大きい記録の結果–

The result of multiple-reflected plane SH-wave spectral-ratio inversions –Largest records –

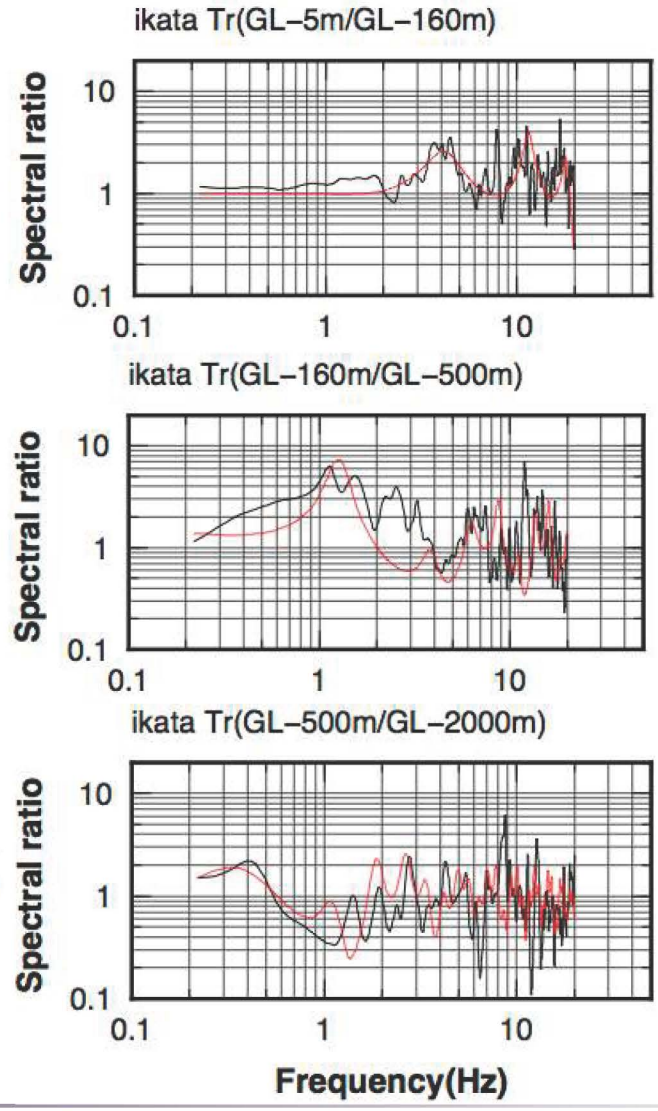
- The observed spectral-ratios of 0.3Hz to 20Hz are well explained by transfer functions with identified Q.



$$\frac{GL-5m}{GL-160m}$$

$$\frac{GL-160m}{GL-500m}$$

$$\frac{GL-500m}{GL-2000m}$$

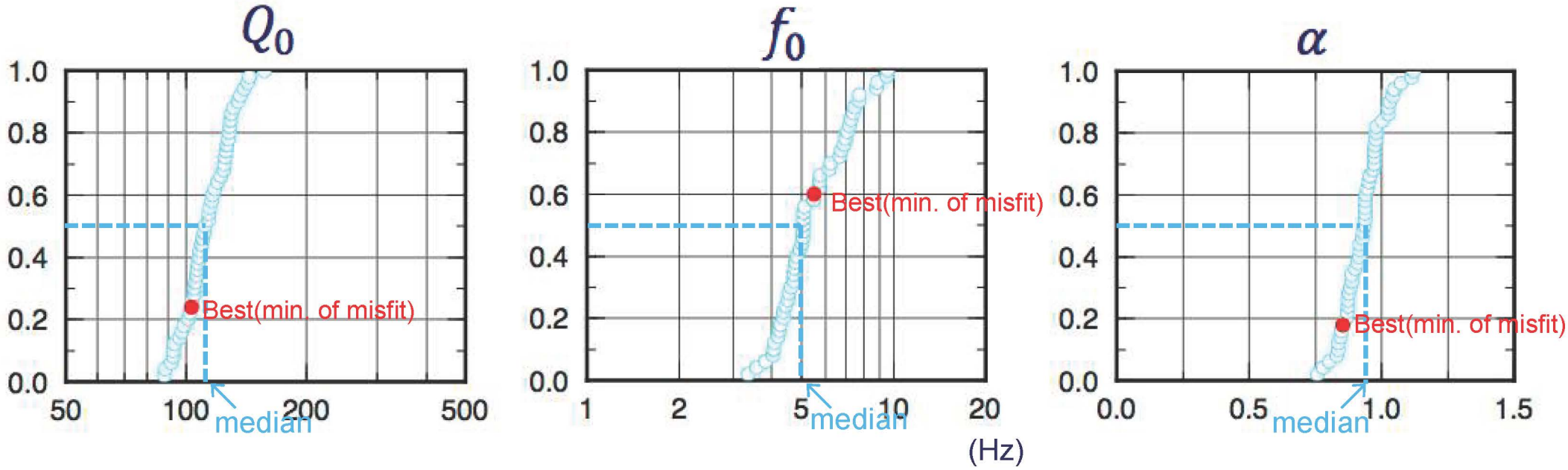


Black line:
Observed spec. ratio
Red line:
Inverted transfer func.

深部の広帯域Q値（減衰）の結果 - 最も大きい記録の結果 –

Result of broadband Q measurements in deeper underground –Largest records –

- 500 GA inversions were carried out by using different initial random numbers.
- Three parameters of broadband Q were identified in each inversions.
- The distributions of three parameters of Q from the best 50 inversion results are shown below:

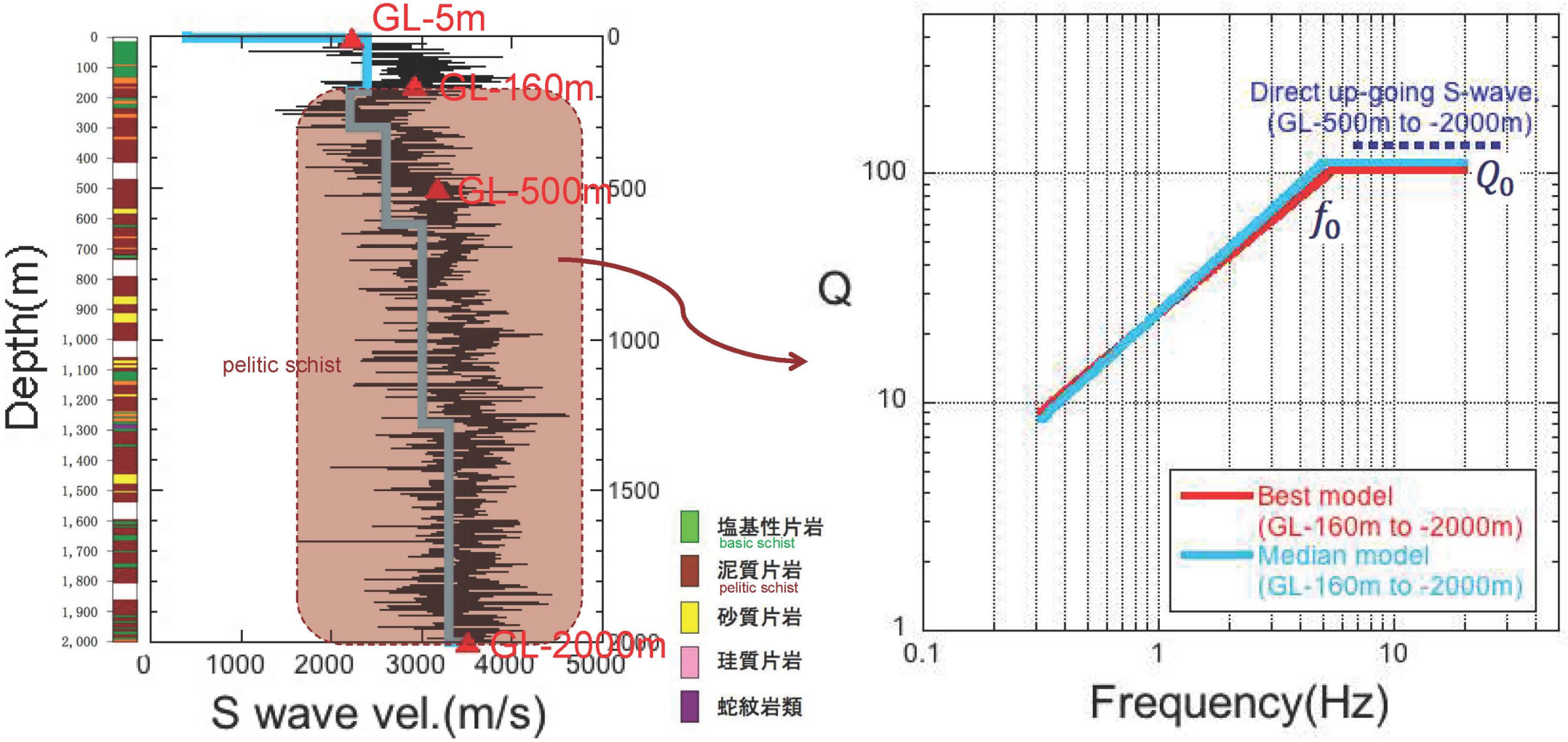


- ✓ The best inversion result is Q_0=103, f_0=5.5(Hz) and α=0.85, respectively.
- ✓ The median of each parameters are Q_0=111, f_0=5.1(Hz) and α=0.93, respectively.

深部Q値（減衰）の測定結果の比較 - 最も大きい記録の結果 –

Comparison of deeper underground Qs in Ikata site by different methods –Largest records –

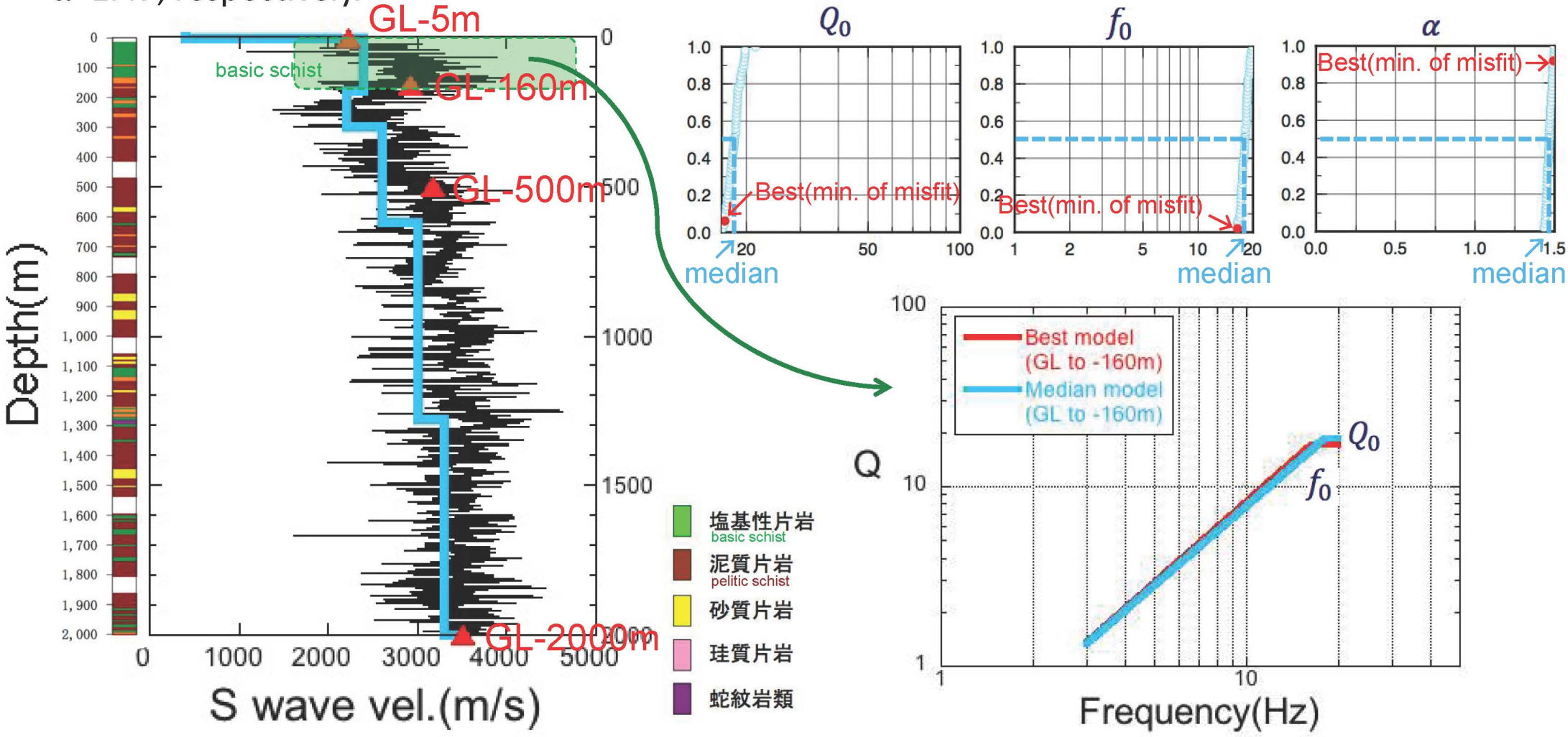
- The best inversion result and the median model are almost the same.
- In a high-frequency range, identified broadband Q_0s are in good agreement with the Q determined by direct up-going S-wave.



浅部の広帯域Q値（減衰）の測定結果 - 最も大きい記録の結果 –

Result of broadband Q measurements in shallower underground –Largest records –

- The each parameters of the best inversion result are Q_0=17.0, f_0=16.5(Hz) and α=1.49, respectively.
- The median of each parameters from the best 50 inversion results are Q_0=18.3, f_0=18.0(Hz) and α=1.47, respectively.



Near-surface Q of Rock

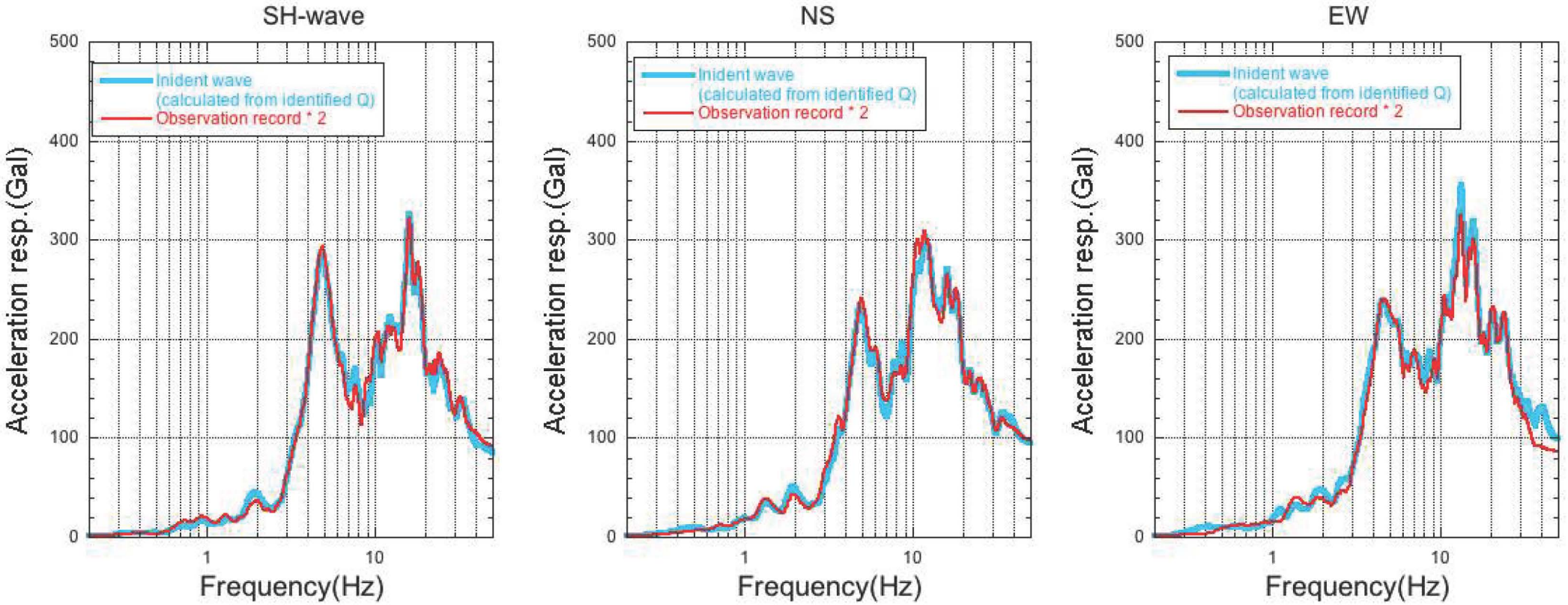
- Identified Q_0 (=18.3) shallower than GL-160m is consistent with near-surface Qs of rock in high-frequency ranges by previous researches.

Rock	Site	Q_s	Depth(m)	Vs(km/s)	Referenses
Ophiolite	Oroville	9	0 – 475	3.3	Malin et al.(1988)
		11	375 – 475		
Granite	Anza	9	0 – 150	2.8	Aster and Shearer(1991)
		26	150 – 300		
	Garner valley	12	0 – 220	2.5	Archuleta et al.(1992)
	Cajon	～21±7	0 – 2900	3.3 – 3.5	Abecrombie(1997)
Tertially rock	Parkfield	8–19	0 – 200	< 1.0	Blakeslee and Malin(1991)
		10	0 – 300	–	Jongman and Malin(1995)
		37	0 – 1000	–	

GL-2000mでの入射波加速度応答スペクトル –最も大きい記録–

Acceleration response spectra of incident waves at GL-2000m –Largest record –

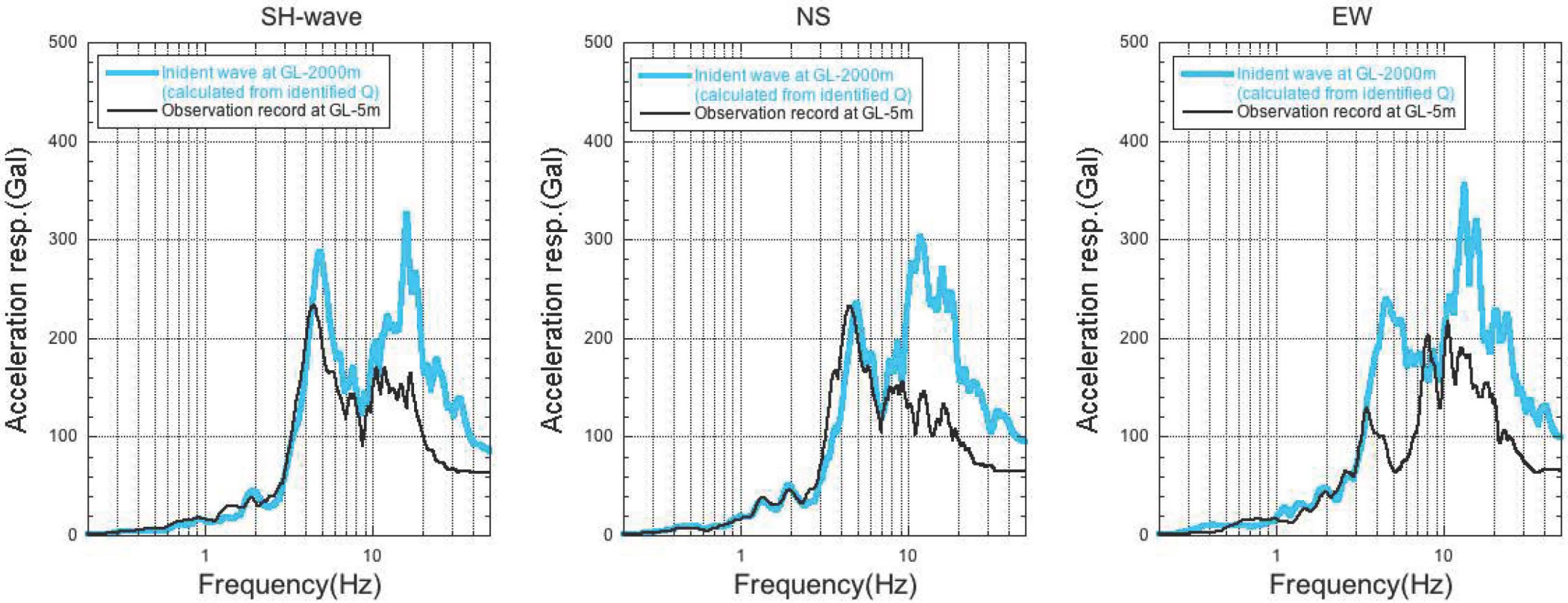
- Incident waves at GL-2000m are calculated from de-convolution of observed records at GL-2000m based on transfer functions using the identified Qs.
- Acceleration response spectra of incident waves are almost identical to the ones of two times observed records at GL-2000m.
  - GL-2000m records are free from reflected waves.



地表記録(GL-5m)とGL-2000mでの入射波の応答スペクトルの比較

Comparison of incident wave at GL-2000m and observed record at GL-5m

- Acceleration response spectra of incident waves at GL-2000m are diminished in propagating to the surface.
- During wave propagation in Ikata site, it is suggested that attenuation effects are dominant rather than amplification effects.



まとめ
CONCLUDING REMARKS

◆ ボアホール地震記録による広帯域Q値（減衰）の測定

- 最も大きな記録(No.12)のS波直達上昇波スペクトル比を用いたスペクトル減衰モデルのフィッティングから、深部Q値としてQ=132（7Hz～30Hz）を得た。
- 浅部および深部の広帯域Q値の評価のため、バイリニア周波数依存による広帯域Q値モデルを用いたSH重複反射波スペクトル比の逆解析を実施した。
- その結果、SH重複反射波スペクトル比による高周波数での深部Q値はQ=103で、S波直達上昇波スペクトル比と概ねよい一致をみた。
- 浅部（GL-160m以浅）のQ値としてQ_0=18.3が得られ、これは、既往の研究による様々な地表に近い岩盤の高周波数でのQ値の評価結果と調和的であった。

◆ GL-2000mでの入射波加速度応答スペクトルと増幅特性

- 測定したQ値を用いて、GL-2000mでの入射波加速度応答スペクトルを評価した結果、GL-2000mでの観測記録の2倍のスペクトルと一致することを示した。これは、GL-2000m位置には上層からの反射波の影響が含まれないことを示唆する。
- GL-2000mでの入射波加速度応答スペクトルは、GL-5mでの加速度応答スペクトルより大きいことを示した。これは、当該地点では地表へ地震波が伝播する過程で、増幅よりも減衰特性が卓越することを示唆する。

まとめ
CONCLUDING REMARKS

◆ **Measurements of broadband Q in shallower and deeper underground by borehole records**

- Q=132 in deeper underground was estimated by least-squares fitting of attenuation model using direct up-going S-wave spectral ratio .
- Multiple-reflected plane SH-wave spectral-ratio inversion using bi-linear frequency-dependent Q model was applied to the estimation of broadband Q in Ikata site.
- As a result, in a high-frequency range, identified broadband Q_0s are in good agreement with the Q determined by direct up-going S-wave.
- Identified Q_0（=18.3）shallower than GL-160m is consistent with near-surface Qs of rock in high-frequency ranges by previous researches.

◆ **Acceleration response spectra of incident wave at GL-2000m and response spectral amplification**

- Acceleration response spectra of incident waves are almost identical to the ones of two times observed records at GL-2000m.

  => GL-2000m records are free from reflected waves.
- Acceleration response spectra of incident waves at GL-2000m are diminished in propagating to the surface.It is suggested that attenuation effects are dominant rather than amplification effects.