



Data-oriented constraint on the interpretation of S receiver function and its application to observations of seismic discontinuities in the lithosphere-asthenosphere system

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10 4 **to observations of seismic discontinuities in the lithosphere-asthenosphere system**
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15 Summary

16 This paper aims to improve the robustness of interpretation in the S receiver function
17 (SRF), a technique commonly used to retrieve forward scattering of S -to- P converted waves
18 (Sdp) originated from the lithosphere-asthenosphere system (LAS) beneath the stations.
19 Although the SRF does not suffer interferences from backward scattering waves such as the
20 first multiples from the Moho, one major drawback in the method is that Sdp phases can
21 interfere with P coda waves and it is conceivable that these signal-generated noise may be
22 misinterpreted as Sdp phase from the LAS beneath seismic stations. Through systematic
23 analysis of full-waveform synthetics and SRFs from catalogued source parameters, we find
24 that the strong P coda waves before the S wave in the longitudinal-component waveforms
25 result in unwanted signal-generated noise before the S wave in the synthetic SRFs. If the
26 mean amplitude of SRFs after the S wave is large, dubious signal-generated noise before the
27 S arrival are strong as well. In this study, we honor the level of these unwanted signal-
28 generated noise and devise data-oriented screening criteria to minimize the interference
29 between P coda waves and genuine S -to- P converted waves. The first criterion is LQR, a
30 direct measure of the amplitude ratio between longitudinal P coda waves and radial S wave in
31 the waveform data. The second criterion is AMP, the amplitude of SRFs after the S arrival.
32 We illustrate that these criteria effectively measure the energy level of mantle waves such as
33 the SP wave. With synthetics and real data, we demonstrate the effectiveness of LQR and
34 AMP criteria in minimizing these unwanted signal-generated noise in the stacked SRFs down
35 to 1–2%, improving detection threshold and interpretation of Sdp phases from seismic
36 discontinuities in the LAS.

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38 **Key words:** Body waves; Structure of the Earth; Wave propagation, Wave scattering and
39 diffraction; Coda waves

41 **1 Introduction**

42 Oceanic lithosphere is typically thought to be the outcome of melting of undepleted
43 mantle and subsequent cooling, whereas continental lithosphere, especially beneath the
44 cratons, is often considered as the result of large-scale plume melting, stacking oceanic
45 lithospheres or/and arc collision (e.g. Lee *et al.* 2010). Small-scale convective instability,
46 episodes of metasomatism and hydration, among other mechanisms, potentially facilitate the
47 modification and disruption of oceanic and continental lithosphere. Unraveling robust seismic
48 signature with the lithosphere-asthenosphere system (LAS) is crucial to understanding of the
49 **formation**, modification and destruction of the plates and the formation of continents. For
50 instance, the lithosphere-asthenosphere boundary (LAB), a mechanical boundary separating
51 the rigid lithosphere and underlying viscous asthenosphere is thought to be the result of a
52 simple thermal boundary due to long-term cooling. Seismic LAB from such a thermal
53 boundary is considered smooth and gradual, where the velocity reduction with depth takes
54 place over a transition thickness on the order of 50 km (Fischer *et al.* 2010). However, recent
55 efforts have demonstrated that seismic LAB can be much sharper (e.g. Rychert *et al.* 2007;
56 Kawakatsu *et al.* 2009; Tharimena *et al.* 2017). Beneath the continents and many localities in
57 the oceans, seismic discontinuities have also been observed at depth ranges much shallower
58 than expected, and the nature of such mid-lithospheric discontinuities (MLDs) remains
59 elusive (e.g. Karato 2012; Schmerr 2012; Selway *et al.* 2015).

60 Therefore, it is clear that a robust and high-resolution seismic detection and
61 characterization of LAB or/and MLDs can revolutionize our understandings of plate tectonics
62 (e.g. Eaton *et al.* 2009; Fischer *et al.* 2010; Kawakatsu & Utada 2017). In the last decade, the
63 depth and spatial resolution of the seismic discontinuities are greatly improved, thanks to the
64 explosion of seismic data and progression of varieties of seismic techniques, including
65 teleseismic *P*-to-*S* receiver function (PRF) (e.g. Langston 1977; Rondenay 2009) and *S*-to-*P*

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3 66 receiver function (SRF) (e.g. Farra & Vinnik 2000), *ScS* reverberations (e.g. Bagley &
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5 67 Revenaugh 2008), and multiple *S*-wave triplications (e.g. Tan & Helmberger 2007) and
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7 68 underside *SS* precursors (e.g. Rychert & Shearer 2011; Schmerr 2012). Among these
8
9 69 methods, PRF and SRF provide the highest resolution of seismic discontinuities in the LAS
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11 70 because of the use of relatively high-frequency waves (e.g. 0.1–1.0 Hz) in the analysis.
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14 71 While the PRF and SRF methods can effectively detect converted phases (*Pds* or *Sdp*,
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16 72 where ‘*d*’ marks the depth or location of the conversion) through source normalization (or
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18 73 deconvolution) and stacking, they are not without issues. For example, the PRF suffers
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20 74 interferences from backward scattering waves such as the first multiples from the Moho,
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22 75 making it difficult to identify converted-phase arrivals within the LAS. On the other hand, the
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24 76 SRF, by construction, separates the converted phases from the multiples (e.g. Ferra & Vinnik
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26 77 2000), and it is preferable to identify robust signal from the LAS. However, one major
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28 78 drawback is that *Sdp* converted waves can be interfered by *P* coda waves, which consist of
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30 79 multiple mantle *P* waves (e.g. Wilson *et al.* 2006), multiples of reflections between the
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32 80 surface and the transition zone (e.g. Bock 1994) or/and *S*-to-*P* scattering waves within the
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34 81 crust and lithosphere between the source and the receiver (e.g. Vinnik & Romanowicz 1991).
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36 82 Depending on the strength of scatters as well as epicentral distance, azimuth, earthquake
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38 83 source depth, and source mechanisms, the amplitudes and timings of these *P* coda waves may
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40 84 vary and a significant level of wave energy preceding the *S*-wave arrival can be erroneously
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42 85 taken as *S*-to-*P* phases converted beneath the stations. Therefore, a robust identification and
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44 86 interpretation of *S*-to-*P* converted waves in the SRF are not necessarily trivial, and data
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46 87 selection criteria can become the key to provide a more robust determination of sharp
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48 88 features in the LAS.
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56 89 The purpose of this paper is thus to introduce simple but effective screening criteria for
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58 90 the data selection and therefore removal of data or SRFs with strong unwanted signal-
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3 91 generated noise. We will first briefly review data selection criteria established in the
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5 92 literatures (e.g. Kumar *et al.* 2005; Yuan *et al.* 2006; Wilson *et al.* 2006; Abt *et al.* 2010;
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8 93 Kind *et al.* 2015; Shen *et al.* 2017). To devise an objective criterion to minimize the
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10 94 interference from *P* coda waves, as a proof of concept, we first examine scenario of SRFs
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12 95 recorded in South Korea seismic network, sitting on a geologically stable continental
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14 96 platform (Fig. 1). Through systematic analysis of full-waveform synthetics and SRFs from
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16 97 catalogued teleseismic earthquakes in 2005–2015 (Takeuchi *et al.* 1996; Kawai *et al.* 2006),
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18 98 we demonstrate the usage and effectiveness of the new data screening and selection criteria
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20 99 against previous efforts (e.g. Wilson *et al.* 2006) with synthetics as well as observed SRFs in
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24 100 South Korea.

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28 102 **2 Construction of SRF and previous efforts in the data selection criteria**

30 103 The calculation of SRF involves two important steps, that are (1) coordinate rotation,
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33 104 which isolates *Sdp* phase from the incident *S* wave, and (2) deconvolution, which removes
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35 105 source and propagation path effects (e.g. Farra & Vinnik 2000). Three-component north-east-
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37 106 vertical (N–E–Z) data are rotated to L–Q–T (or *P–SV–SH*) ray coordinate system (see also
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39 107 Rondenay 2009). While both of these coordinate systems are frequently implemented in past
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41 108 SRF studies (see review by Rondenay 2009; Kind *et al.* 2012), as demonstrated by
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43 109 Svenningsen & Jacobsen (2004) and discussed by Rondenay (2009), the difference of SRFs
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45 110 constructed in these two coordinate systems is minimum and much less than 1% (see Fig. 3 in
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47 111 Svenningsen & Jacobsen (2004)). Since the aim of this paper is to design the metrics to
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49 112 indicate the level of unwanted signal-generated noise prior to the *S* wave, we choose to
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51 113 discuss and illustrate the usage of our designed metrics in the L–Q–T system throughout this
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56 114 paper.

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3 115 As the L component is dominated by the *P* wave, Q and T components mostly contain
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5 116 energies from *SV* and *SH* waves, respectively. SRFs are then computed by deconvolving the
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7 117 *S* waveform in the Q component from the corresponding L component, in either time domain
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9 118 or frequency domain. To improve the signal-to-noise ratio (SNR), SRFs are binned and
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11 119 stacked. Throughout the paper, we will illustrate the usage and performance of our data-
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13 120 oriented screening criteria with the time-domain Wiener deconvolution method (Robinson &
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15 121 Treitel 1967), whereas examples with the frequency-domain deconvolution of various water
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17 122 levels can be referred to the Supplementary Information.

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21 123 Earlier works put emphasis on the selection of earthquakes in restricted epicentral
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23 124 distances or/and source depths (e.g. Wilson *et al.* 2006; Yuan *et al.* 2006). In an attempt to
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25 125 evaluate the robustness of the observed *Sdp* phases, Yuan *et al.* (2006) performed full
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27 126 waveform synthetics (Wang 1999) and suggested optimal epicentral distances of 55°–85° for
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29 127 the construction of SRF, which avoid post-critical incoming *S* wave. However, the synthetic
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31 128 waveforms only include downgoing waves and upgoing waves were excluded. Consequently,
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33 129 the influence of surface-reflected *P* waves on the *Sdp* detection cannot be evaluated. On the
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35 130 other hand, Wilson *et al.* (2006) conducted full waveform synthetics (Fuchs & Müller 1971)
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37 131 and quantitatively measured the energy level before the *S* wave in the SRFs. They suggested
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39 132 a data selection criterion for the SRF at restricted epicentral distances of 60°–75° and source
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41 133 depths of 300 km or less.

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46 134 The criterion by Wilson *et al.* (2006) was however based on synthetics from a single
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48 135 thrust-fault source mechanism and an one-dimensional (1-D) velocity model with a relatively
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50 136 thick crust of 70 km. Therefore, the established criterion needs not necessarily be the most
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52 137 general choice. As *P* coda waves can consist of multiple mantle *P* waves or/and *S*-to-*P*
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54 138 scattering waves within the crust and lithosphere between the source and the receiver, the
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56 139 amplitude and timing of these *P* coda waves not only depend on source depth (Wilson *et al.*
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3 140 2006), but it may also depend on the strength of scatters and source-receiver geometry and
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5 141 source mechanisms, or effectively the radiation pattern. Nevertheless, these data selection
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7 142 criteria have been commonly used in the SRF analysis, sometimes with a minor adjustment
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9 143 on either the range of epicentral distance or/and source depth (e.g. Hansen *et al.* 2009; Abt *et*
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11 144 *al.* 2010; Ford *et al.* 2010; Lekic & Fischer 2014; Hopper & Fischer 2015).

145 To improve the robustness and interpretation of the SRF and establish a more general
146 data selection scheme, our focus is to expand the work by Wilson *et al.* (2006) and establish
147 data-oriented selection criteria. In particular, by either contrasting the energy level between
148 the *S*-wave arrival in the Q-component waveform and *P* coda waves in the L-component
149 waveform, or measuring the amplitude of the SRF after the *S* wave, we introduce more direct
150 and general selection and screening criteria that do not necessarily rely on a specific choice of
151 the epicentral distance or source parameters, but honor the level of unwanted signal-
152 generated noise before the *S* wave.

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154 **3 Design and construction of new data selection criteria for the SRF**

155 As discussed in previous sections, multiple mantle *P* waves or *S*-to-*P* scattering within
156 the crust and mantle between the source and receiver (Vinnik & Romonowicz 1991; Bock
157 1994; Wilson *et al.* 2006) can form the *P* coda waves. Depending on the amplitude of these *P*
158 coda waves preceding the *S*-wave arrival, they can interfere with converted waves, *Sdp*, from
159 the LAS beneath seismic stations, or even being erroneously identified as *Sdp*. Depending
160 upon the epicentral distance, source depth and mechanism, the level of interference can vary.
161 In other words, the energy level of *P* coda waves can be large even for a shallow event. Since
162 the effect of diverse source mechanism or radiation pattern on the excitation of these *P* coda
163 waves was not explored by Wilson *et al.* (2006), we conduct a systematic investigation

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3 164 through full waveform synthetics and examine the impact of realistic source mechanisms, or
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5 165 more importantly, the radiation pattern on the excitation and amplitude of *P* coda waves.
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9 166 As a proof of concept, we consider **observations of one station** from the South Korea
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11 167 seismic network (Lim *et al.* 2018) and examine full waveform synthetics from earthquakes
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13 168 with magnitude larger than 5.5 between 2004 and 2013 from the global CMT **catalogue**
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15 169 (Dziewonski *et al.* 1981; Ekström *et al.* 2012), located at the distances of 60°–85° from the
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17 seismic network (Fig. 1). **The event magnitude threshold of 5.5 allows detection of clear *S*-**
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19 **wave arrivals and identification of *S_{mp}* arrivals from the Moho beneath the continental**
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21 **platform in South Korea.** Since most stations generally contain quality waveform data from
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23 172 200–400 earthquakes after data quality control and screening, we randomly select 300
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25 173 earthquakes in our synthetic test. As expected in most realistic scenarios, synthetics data are
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27 174 predominantly from shallow events. Synthetic waveforms are computed with the Direct
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29 175 Solution Method (Takeuchi *et al.* 1996; Kawai *et al.* 2006) using the 1-D IASP91 model
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31 176 (Kennett & Engdahl 1991) as well as a modified IASP91 model (denoted as ‘L70’), which
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33 177 **includes a 35 km thick high-velocity mantle lid with a 7.5% shear velocity increase below**
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35 **Moho, a low velocity zone with a 9% shear velocity reduction beneath 70 km depth, and a**
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37 178 **small 1.5% shear velocity increase beneath 120 km depth** (Fig. S1; Table S1).
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45 181 To calculate synthetic SRFs, we first rotate synthetic waveforms with a time window of
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47 182 100 s prior to and 100 s after the *S* wave to the radial-tangential-vertical (R–T–Z) system
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49 183 using the **theoretical** event back-azimuth. Theoretical incidence angle of the *S* wave
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51 184 **computed from the IASP91 model** is used to rotate waveforms into the ray coordinate system
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53 185 in the L–Q–T components (e.g. Rondenay 2009) before deconvolution (e.g. Kind *et al.* 2012;
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55 186 Shen *et al.* 2017). The waveforms in the Q component (e.g. the parent waveform) are
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57 187 windowed 10 s before and 35 s after the *S*-wave arrival and tapered with a 15% Hanning
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3 188 taper at both ends of the signal window. The L- and Q-component waveforms are then
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5 189 deconvolved by the parent waveform through the time-domain Wiener deconvolution method,
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8 190 which involves spiking of the output time series with the parent waveform and construction
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10 191 of Wiener-filter time series (Robinson & Treitel 1967). **Minimum regularization with a white**
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12 192 **noise of 0.01% is applied in the calculation.** Such a time series is then convolved with L- and
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14 193 Q-component waveforms to obtain L- and Q-component SRFs, **respectively.** The resulting
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16 194 SRFs are bandpass filtered at 3–50 s and normalized by the spike in the Q-component at zero
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18 195 time. Hereafter, we will refer our discussion in the L-component SRFs.

22 196 **3.1 Inspections of synthetic SRFs**

26 197 Figs 2a and b display stacked synthetic SRF record sections, which consist of 300
27
28 198 individual SRFs, stacked with a 1°-distance bin and aligned along the *S* arrival at zero time.
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30 199 Synthetics are computed with the IASP91 model (Fig. 2a) and the L70 model (Fig. 2b). The
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32 200 converted waves from the Conrad (*SCp*) and the Moho (*SMp*) have a negative polarity and
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34 201 they arrive at about 4–5 s before the *S* wave (Fig. 2). Crustal multiples (e.g. *SCpPCP* and
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36 202 *SMpPMP*) and other mantle waves such as *SP*, *sSP*, *pSPPP*, *sSPPPP* and *pSPPPPP* arrive at
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38 203 about 5–60 s after the *S* wave (Fig. 2). Converted waves at the upper mantle seismic
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40 204 discontinuities from incident *ScS* and *SKS* waves (e.g. *ScS410p*, *ScS660p*, *SKS410p* and
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42 205 *SKS660p*) have a very different moveout from the *SMp* and they are less visible than those
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44 206 shown in Yuan *et al.* (2006). On the other hand, as pointed out by Wilson *et al.* (2006), we
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46 207 can observe spurious but consistent energies before the *SMp* arrival that are not associated
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48 208 with converted waves from local structure beneath the receivers. Therefore, it is important to
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50 209 set up a general data selection scheme to minimize these spurious arrivals.

57 210 After systematically inspecting synthetic waveforms and the resulting SRFs, we use
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59 211 Fig. 3 to illustrate the motivation of our designated data selection criteria. **We consider two**

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 3 212 earthquakes (events 1 and 2) such that their epicentral distances are comparable at $\sim 67^\circ$ and
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 5 213 the SNR of the S waves in the Q component are also similar (Fig. 1a, red beachballs).
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 7 214 However, regardless of the choice of IASP91 model or L70 model (Fig. S1), the P coda
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 9 215 waves in the L -component waveforms are comparably stronger in event 2 than those in event
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 11 216 1, arguing the effect of radiation pattern on the amplitude of these P coda waves. When
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 13 217 examining their SRFs, those from event 1 display clear SMp or/and SLp with otherwise weak
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 15 218 energy prior to the S wave (Figs 3a and b). On the other hand, SRFs from event 2 display
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 17 219 strong and spurious energy before and after the S wave (e.g. Figs 3c and d). It is noteworthy
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 19 220 to emphasize that, as the deconvolution scheme, data windowing and tapering procedures are
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 21 221 exactly the same between event 1 and event 2, strong spurious energy before the S wave in
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 23 222 the SRF directly corroborates with strong P coda waves in the L -component waveform of
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 25 223 event 2 (see also Figs S2 and S3 for the results with different windowing schemes). As noted
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 27 224 earlier, it is conceivable that these dubious signals may be mistakenly interpreted as Sdp
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 29 225 waves beneath seismic stations.
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226 3.2 Measurement of LQR and AMP and construction of stacked SRFs

227 Motivated by observation, we devise measures of LQR, the amplitude ratio between L -
 228 component P coda waves and Q -component S waves, and AMP, the amplitude of SRFs after
 229 the S -wave arrival. We then systematically test how the LQR and AMP thresholds may be
 230 used to detect and retain robust Sdp waves while minimizing dubious energies in the SRFs
 231 (Fig. 3). Here, we define LQR as

$$232 \quad \text{LQR} = \text{RMS}(L[t_3 \ t_4]) / \text{Max}(Q[t_1 \ t_2]), \quad (1)$$

233 where $\text{Max}(Q[t_1 t_2])$ measures the peak amplitude of the S wave in the Q-component data
 234 window defined by t_1 and t_2 , and $\text{RMS}(L[t_3 t_4])$ measures the RMS amplitude of the P coda in
 235 the L-component time window defined by t_3 and t_4 . On the other hand, the AMP is defined as

$$236 \quad \text{AMP} = \text{RMS}(\text{SRF}[t_5 t_6]), \quad (2)$$

237 where $\text{RMS}(\text{SRF}[t_5 t_6])$ measures the RMS amplitude of the SRF in the time window defined
 238 by t_5 and t_6 with respect to the S arrival. In the subsequent analysis and demonstration, we set
 239 $t_1 = -5$ s, $t_2 = 10$ s, $t_3 = -60$ s, $t_4 = -20$ s, $t_5 = 20$ s, and $t_6 = 100$ s. Note that the choice of t_3 and
 240 t_4 is such that they do not include potential Sdp arrivals in the LAS.

241 After measuring the LQR and AMP against all synthetic SRFs, we observe that SRFs
 242 with the lowest LQR typically fall in the distance range of 60° – 66° and those with the lowest
 243 AMP are typically in the distance range of 70° – 77° . However, to fully take advantage of the
 244 slant stack technique, it is important to ensure effective noise removal and to minimise data
 245 selection bias in epicentral distance. Therefore, it is more desirable that selected SRFs are
 246 evenly distributed within the entire distance range of 60° – 85° and are not falling in a narrow
 247 distance range. Consequently, synthetic SRFs in each 1° -distance bin are first selected
 248 according to a designated data selection threshold and subsequently stacked. The error is then
 249 estimated by the bootstrap method (Efron & Tibshiran 1998).

250 In the following tests, we systematically examine how different LQR and AMP
 251 thresholds determine the quality of the stacked SRFs. To determine the effectiveness of each
 252 data selection criteria in mitigating signal-generated noise, we sum stacked SRFs of each 1° -
 253 distance bin and measure the RMS amplitude of the summed SRF before the SMp arrival
 254 (denoted as AMP1). The AMP1 is defined as

$$255 \quad \text{AMP1} = \text{RMS}(\text{SRF}[t_7 t_8]), \quad (3)$$

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3 256 where $\text{RMS}(\text{SRF}[t_7 t_8])$ measures the RMS amplitude of the SRF in the time window defined
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5 257 by t_7 and t_8 with respect to the S arrival. Here, we set $t_7 = -60$ s and $t_8 = -20$ s.
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9 258 **3.3 Evaluating the efficacy of the LQR and AMP criteria**

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12 259 In order to investigate the efficacy of LQR and AMP criteria for the SRFs, we consider
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14 260 two principles to judge the quality of stacked SRFs. First, if the data selection criterion is
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16 261 effective, we expect that the signal-generated noise before the S arrival shall be minimized.
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18 262 This can be visually inspected and quantitatively examined through the measurement of
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20 263 AMP1. Second, if the data selection criterion is effective, the amplitude of stacked SRFs
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22 264 against epicentral distance should follow closely the theoretical S -to- P transmission
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24 265 coefficient (Aki & Richards 2002) with minimum perturbation.
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30 266 **3.3.1 Presence/absence of signal-generated noise before S -wave arrival**

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33 267 To highlight how the data selection criteria influence signal-generated noise, synthetic
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35 268 SRFs with 25% lowest and 25% highest LQR (or AMP) in each distance bin are selected and
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37 269 subsequently stacked. For comparison, we also present stacked SRFs with the criterion by
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39 270 Wilson *et al.* (2006) and those with 25% randomly selected SRFs. Stacked SRF images at
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41 271 60° – 85° from the IASP91 model (Kennett & Engdahl 1991) and L70 model (Fig. S1) are
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43 272 shown in Fig. 4, whereas the sum of stacked SRFs and their 95% confidence interval are
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45 273 displayed in Figs 5a and 5b, respectively. For comparisons, stacked SRF waveforms (Figs
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47 274 5c–f) and stacked SRF images (Figs S4–7) with different parent window length (case 1; -10 s
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49 275 before and 15 s after the S wave), tapering (case 2; 5% Hanning taper), deconvolution scheme
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51 276 and regularization (cases 3 and 4; frequency-domain deconvolution with water level of 0.05%
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53 277 and 0.2%, respectively) are also presented for comparisons.
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3 278 For the IASP91 model, the first signal before the S arrival is a negative SMp phase
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5 279 arriving at about 4 s before the S arrival (Figs 4a–f and 5a). While the SMp signal can be
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8 280 consistently detected with different data selection criteria (Figs 4a–f and 5a), the amplitudes
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10 281 of SMp with the highest LQR and AMP criteria are much stronger and more variable than
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12 282 those with the lowest LQR or AMP criteria (Fig. 5a). In particular, signals up to 6–8% with
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14 283 positive amplitude can be detected before the SMp at the 95% confidence level (Fig. 5a).
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16 284 However, these signals are dubious as they do not corroborate with the absence of any sharp
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18 285 velocity gradient below the Moho (Fig. S1). While the criterion by Wilson *et al.* (2006) does
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20 286 a better job in reducing the amplitude of these dubious signals down to 3–4% (Fig. 5a), the
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22 287 lowest LQR and AMP criteria appear to be the most effective, minimizing dubious arrivals at
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24 288 the amplitude level of 1–2%, typically insignificant at the 95% confidence level (Fig. 5a).
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28 289 For the L70 model, we can observe a consistent, but positive signal arriving at about 9 s
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30 290 before the S arrival (Figs 4g–l and 5b). As expected, it is the S -to- P converted arrival (SLp)
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32 291 from the negative velocity discontinuity at the depth of 70 km (Fig. S1). Such a SLp signal
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34 292 has the same polarity and comparable strength as those used in *previous* studies to infer LAB
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36 293 or MLDs in the LAS (e.g., Eaton *et al.*, 2009; Abt *et al.*, 2010; Kumar *et al.*, 2012; Shen *et al.*,
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38 294 2015; Shen *et al.*, 2017). However, except the lowest LQR or AMP criteria, all other data
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40 295 selection criteria produce strong oscillations throughout the entire SRF stacks (Figs 4g–l),
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42 296 following slowness very similar to the SP wave. Even the SLp appears to be detected in this
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44 297 circumstance, the quality of the detection is low with incorrect amplitude and very large
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46 298 uncertainties (Fig. 5b). With the lowest LQR or AMP criteria, the SLp signal appears more
47
48 299 robust with the smallest bootstrap uncertainties (Fig. 5b). It is evident that the signal-
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50 300 generated noise before the S arrival are much weaker in the stacked SRFs produced with the
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52 301 criteria of the lowest LQR (Figs 4g and 5b) or AMP (Figs 4i and 5b) than those produced
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3 302 with the highest LQR (Figs 4h and 5b), the highest AMP (Figs 4j and 5b), the criterion by
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5 303 Wilson *et al.* (2006) (Figs 4k and 5b) or with random data selection (Figs 4l and 5b).
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8 304 These observations can be concluded with alternative window length of the parent
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10 305 waveform (case 1; Figs 5c and S4), tapering (case 2; Figs 5d and S5) or deconvolution
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12 306 scheme (e.g. frequency-domain water-level deconvolution) with different regularization
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14 307 (cases 3 and 4; Figs. 5e, 5f, S6, and S7). Stacked SRFs produced with the criteria of the
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16 308 lowest LQR or AMP are stable, regardless specific choices of these data processing
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18 309 procedures. Evidently, stacked SRFs with other criteria vary more substantially with the
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20 310 choice of data processing routines. More critically, while a stronger regularization does
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22 311 minimize amplitude oscillation (e.g. case 4; Fig. 5f), strong signal-generated noise arriving
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24 312 before the *SLp* arrival remains.
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30 313 To quantitatively assess the quality of stacked SRF and the effectiveness of data
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32 314 selection criteria in mitigating the signal-generated noise, we compute AMP1 to measure the
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34 315 RMS amplitude in the designated time window before the *S* arrival. We systematically select
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36 316 a subset of all synthetic SRFs by varying the percentage threshold (10–50%) of the lowest
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38 317 and highest LQR or AMP, generate the summed SRF and calculate AMP1. As shown in Fig.
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40 318 6, the value of AMP1 generally decreases with increasing percentage threshold of six
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42 319 different criteria. At 25% threshold, AMP1 of the lowest LQR or AMP is lower than that of
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44 320 the highest LQR or AMP by more than a factor of 4 (Fig. 6). Also, at 25% threshold and
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46 321 higher, AMP1 of the lowest LQR or AMP is less than AMP1 of all SRFs (Fig. 6a). In
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48 322 particular, we find that the SRFs constructed with the lowest AMP generally display a lower
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50 323 level of AMP1, and the improvement is even more substantial for the synthetic SRFs from
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52 324 the L70 model (Fig. 6b). AMP1 of the lowest AMP for the L70 model is lower by a factor of
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54 325 2 or less than that measured against the summed SRF of the entire SRF dataset (Fig. 6b).
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3 326 In the case of random data selection, the value of AMP1 does not show appreciable
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5 327 difference with respect to the percentage threshold (Fig. 6), whereas the criterion of Wilson *et*
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7 328 *al.* (2006) does not seem to improve AMP1 upon those from random data selection (Fig. 6),
8
9 329 which is not unexpected as synthetic data are predominantly from shallow events. In a way,
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11 330 even with a smaller volume of the entire synthetic SRFs (e.g., 25% or less), the lowest LQR
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13 331 or AMP criterion achieves a much lower AMP1 than that of Wilson *et al.* (2006)'s using 50%
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15 332 of the entire synthetic SRFs. **Notably, depending on the exact data selection threshold, AMP1**
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17 333 **with lowest LQR or lowest AMP criteria can be 20–50% lower than AMP1 of all events (Fig.**
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19 334 **6).**

25 335 3.3.2 Validating the amplitude of the *S-to-P* converted waves

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28 336 To further verify the robustness of the converted phases beneath the receiver and assess
29
30 337 the stability of the signal, we measure the amplitudes of *Sdp* (e.g. *SMp* and *SLp*) and compare
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32 338 them against the theoretical *S-to-P* transmission coefficient (Aki & Richards 2002). If the
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34 339 amplitudes of *Sdp* from the stacked SRFs follow closely to the theoretical transmission
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36 340 coefficients, we consider that the data selection criteria are effective in removing signal-
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38 341 generated noise and recovering a truthful detection. Fig. 7a shows distance-dependent
39
40 342 amplitudes of *SMp* measured against stacked SRFs of six different criteria for the IASP91
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42 343 model. On the other hand, Figs 7c and 7d show distance-dependent amplitudes of *SMp* and
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44 344 *SLp* measured against stacked SRFs of different criteria for the L70 model, respectively. Fig.
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46 345 7b shows the amplitudes of the SRFs measured in the same time window as that used in Fig.
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48 346 7d for comparison. Since we do not expect a truthful detection of *SLp* for the IASP91 model,
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50 347 the measurements are indicative of the level of signal-generated noise.

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52 348 Typically, the highest LQR or AMP criterion results in unstable estimate of *SMp*
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54 349 amplitudes (e.g. Figs 4 and 5), and their amplitudes strongly deviate from the theoretical

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3 350 predictions (Figs 7a and c). Stacked SRFs from the random data selection or from the
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5 351 criterion of Wilson *et al.* (2006) also suffer similar distortion, but to a less degree (Fig. 7). On
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8 352 the other hand, given the selection criteria of 25% lowest LQR or AMP, the amplitude of
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10 353 *SMp* follows closely to theoretical calculation against distance (Figs 7a and c). Similarly, the
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12 354 amplitude of *SLp* against distance generally follows theoretical prediction when the data
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14 355 selection criteria of 25% lowest LQR or AMP are implemented (Fig. 7d). Our results indicate
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16 356 that the lowest LQR or AMP is useful for detecting *SLp* phases and retaining their amplitudes
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18 357 by reducing the dubious signals before the *S* wave. We note that the average amplitude within
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20 358 the time window for expected *SLp* arrivals is typically on the order of 2% for the lowest
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22 359 LQR, and of ~1% for the lowest AMP (Fig. 7b). Therefore, we suggest 2% as the minimum
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24 360 amplitude threshold above which the robust identification of local *Sdp* converted waves
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26 361 within the LAS can be made and interpreted.

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32 362 In summary, we find that the SRFs constructed with the lowest LQR or AMP generally
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34 363 display a lower level of spurious energy before the *S* wave while the SRFs with the highest
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36 364 LQR or AMP, as expected, displays a higher level of signal generated noise (Figs 4–7). The
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38 365 improvement appears more substantial in the case where synthetic SRFs are computed from
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40 366 the L70 model (Fig. 6b). While the calculation of SRF can be influenced by the choice of
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42 367 time window and tapering in the parent waveform as well as the deconvolution scheme (e.g.
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44 368 Lekic & Fischer 2017), the performance of LQR and AMP data selection criteria does not
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46 369 depend on such specific choices. This characteristic makes the LQR and AMP very desirable
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48 370 since stacked SRFs with low LQR and low AMP are always very stable.

371 3.3.3 The sources of *P* coda waves?

372 To investigate the source of these *P* coda waves, we first examine if the attributes
373 such as LQR or AMP depend on epicentral distance, event back azimuth or source

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3 374 parameters. However, we do not observe any obvious selection bias in event epicentral
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5 375 distance or back azimuth against the criteria such as LQR and AMP (Fig. S8), nor do we find
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7 376 dependence of LQR or AMP on earthquake source mechanism (Fig. S9), suggesting that
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10 377 LQR and AMP, or the level of P coda waves, are predominantly dictated by the radiation
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12 378 pattern. In this regard, while we do not specifically include SV/SH amplitude ratio in the data
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14 379 selection criteria, high LQR or AMP criterion more often corresponds to data with a low
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16 380 SV/SH ratio (< 1) and low LQR or AMP typically corresponds to data with a high SV/SH
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18 381 ratio (> 1) (Fig. 8).
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23 382 It has been argued by Wilson *et al.* (2006) that P -coda waves can come from
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25 383 multiples such as $pPPP$, $pPPPP$ or/and $sPPPP$ from deep events (> 300 km) and they may
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27 384 interfere with Sdp phases. However, for most practical analysis on the LAS, only those from
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29 385 really deep events of 450 km or deeper may directly interfere with Sdp from the LAS since
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32 386 these multiples, in most instances, arrive at least 1–2 minutes before the S arrival. Similar
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34 387 lines of arguments have been also pointed out by Vinnik & Romanowicz (1991). This
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36 388 assertion can be supported by the fact that P radiation patterns computed with the slowness
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38 389 such as $pPPPP$ wave do not distinguish against LQR or AMP (Fig. 9). This is also consistent
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41 390 with our observation that, when shallow events dominate the synthetic dataset, Wilson *et al.*
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43 391 (2006)'s criterion does not necessarily outperform data selection scheme of random choice
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45 392 (Figs 5b–f; see also Figs S4–7).
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49 393 As shown in Figs 4g–l, signal-generated noise before the S arrival appear to follow very
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51 394 similar slowness as those mantle waves such as SP , sSP , $sSPPP$, and $sSPPPP$, apparently
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53 395 forming precursors of these mantle waves and interfering with Sdp phases in the LAS. It is
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55 396 conceivable that energies prior to the S wave in the stacked SRF are likely to be scattering
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58 397 waves such as $S\bullet P$ and $SP\bullet P$, where $S\bullet P$ denotes S -to- P scattering wave from the free surface
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3 398 and $SP\bullet P$ denotes SP -to- P scattering wave from the scatter in the crust (Vinnik 1981; Vinnik
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5 399 & Romanowicz 1991). Depending on the lead time of scattering waves with respect to the S
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7 400 wave, the area of scattering is expected to be at least 25° from the receiver, and typically in
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9 401 the range of 30° – 40° from the receiver (see Fig. 8a of Vinnik & Romanowicz (1991)), with
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11 402 the raypaths of S and P waves in the $S\bullet P$ (or $SP\bullet P$) arriving in different vertical planes. As
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13 403 our wave propagation simulation is done with a laterally homogeneous and spherically
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15 404 symmetric earth model (Kawai *et al.* 2006) with a finite duration S wave, spherical waves
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17 405 propagating off the vertical plane defined by the source and receiver likely result in scattering
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19 406 waves such as $S\bullet P$.

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25 407 If $S\bullet P$ or/and $SP\bullet P$ scattering waves are indeed the cause of these signal-generated
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27 408 noise observed in SRFs, the SV radiation pattern in the area of scattering will directly control
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29 409 the amplitude of $S\bullet P$ and $SP\bullet P$ scattering waves (Vinnik & Romanowicz 1991). To validate
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31 410 this, we assume that the scattering area is near the surface reflection point of SP wave and
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33 411 compute SV radiation pattern with the slowness of SP wave in our synthetic dataset. As
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35 412 shown in Fig. 10, the SV radiation patterns against the lowest LQR and AMP criteria are
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37 413 generally much weaker than those against the highest LQR and AMP criteria. Effectively,
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39 414 LQR and AMP criteria help select data with weakest SV radiation pattern in the scattering
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41 415 area. Following the same line of reasoning, it is conceivable that $S\bullet P$ scattering waves can
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43 416 come from internal boundaries such as the Moho. While a more elaborated investigation
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45 417 should be done in the future, this is consistent with our simulation that signal-generated noise
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47 418 in SRF are much stronger in the L70 model, which includes a larger velocity contrast across
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49 419 the Moho than the IASP91 model as well as an additional velocity reduction at 70 km depth
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51 420 (Fig. S1).

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3 421 Evidently, there is no lateral variation in surface topography, internal boundary or
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5 422 velocity in our simulation, and it is difficult to precisely estimate the scattering potential
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7 423 without invoking 2-D or 3-D full waveform modelling. It is also possible that signal-
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9 424 generated noise in 2-D or 3-D models are less coherent and do not add constructively.
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11 425 However, our data-oriented screening criteria such as LQR or AMP are designed to honor the
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13 426 data and provide direct and straightforward attributes to measure the level of these spurious
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15 427 energies. With lowest LQR or/and AMP, SRFs with strong signal-generated noise are
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17 428 effectively removed, improving the quality of stacked SRF and the detection of true *Sdp*
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19 429 arrivals in the LAS beneath seismic stations.
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27 431 **4 Application to South Korea seismic data: detection and characterization of seismic** 28 29 432 **discontinuities in the LAS**

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33 433 Our synthetic tests have demonstrated that the effectiveness of LQR and AMP could
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35 434 serve as general data selection criteria for the construction of SRF. Here we apply these new
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37 435 data selection criteria to the dataset recorded by South Korea seismic network (Fig. 1) (Lim
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39 436 *et al.* 2018) and illustrate its effectiveness in real datasets. We select earthquake magnitudes
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41 437 greater than 5.5 within the epicentral distance range of 60°–85° from the seismic network. To
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43 438 construct the SRF, we follow exactly the same scheme detailed in the synthetic test in Section
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45 439 3, but highlight a few key additional steps here to screen noisy data. First, when rotating
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47 440 three-component waveforms into L-Q-T coordinate system, the incidence angle of the
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49 441 incoming *S* wave is determined by maximizing the *SV*-wave energy on the Q component
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51 442 within the time window spanning ± 2 s on either side of the theoretical *S*-wave onset. If the
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53 443 difference between the observed incidence angle and the predicted one (from IASP91)
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55 444 exceeds 25°, the waveforms are rejected. Secondly, data are also removed if the SNR of the *S*
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3 445 wave in the Q component is less than 5. Thirdly, if the peak SRF amplitude in the L
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5 446 component is larger than 0.5 or if the mean amplitude of the SRF in the L component is
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7 447 larger than 50% of its peak amplitude, such SRFs are apparently oscillatory throughout the
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9 448 entire time window and they are also rejected.
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13 449 As an example, we examine stacked SRFs at station TJN in South Korea seismic
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15 450 network (Fig. 1b) in detail. We process waveform data from 917 events in January 2005–
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17 451 January 2015 (Lim *et al.* 2018) and, after preliminary data quality control detailed earlier,
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19 452 316 SRFs are retained and they are filtered at 3–50 s before subsequent data selection
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21 453 analysis. Here we measure LQR and AMP against the observed SRFs exactly the same way
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23 454 as discussed in Section 3. In general, the lowest LQR and AMP against the observed SRFs
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25 455 are typically higher than that against synthetic SRFs because of noise. With the nominal
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27 456 percentage threshold of 25%, we finally retain about 80 SRFs.
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33 457 To illustrate how the stability of the SRF and detection of *SMp* and *SLp* depend on the
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35 458 data selection criteria, Fig. 11 (and Fig. S10) displays stacked SRF images constructed with
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37 459 the same six different data-selection criteria as discussed in the synthetic test in Section 3
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39 460 (e.g. Fig. 4). With the lowest LQR or AMP criterion (Figs 11a and c), we can reasonably
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41 461 track a consistent signal with negative amplitude with respect to epicentral distance, arriving
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43 462 about 4 s before the *S* arrival, presumably *Sdp* from the Moho (*SMp*). However, it is less
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45 463 trivial to track *SMp* in stacked SRF image with the Wilson *et al.* (2006)'s criterion (Fig. 11e)
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47 464 or random selection criterion (Fig. 11f), and very difficult to do so against those constructed
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49 465 with the highest LQR or AMP criterion (Figs 11b and d). These observations can also be
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51 466 made against stacked SRF images using a stronger regularization of 1% white noise (Figs
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55 467 S13 and S14).
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Stacking the SRFs shown in Fig. 11, Figs 12a and b displays summed SRF waveforms and their bootstrapped uncertainties against the six different data-selection criteria and data selection threshold of 25% and 50%, respectively. Again, using the lowest LQR, AMP or Wilson *et al.* (2006)'s criterion, detection of *SMp* can be made at the 95% confidence level (Fig. 12). With the highest LQR or AMP criterion, the *SMp* can be barely detected at the 95% confidence level with large uncertainties (Fig. 12a and b). Even with a stronger regularisation (1% white noise), *SMp* still possesses large uncertainties (Fig. 12c). It is important to note that the uncertainties of SRF with low LQR and AMP are much smaller than those with high LQR or AMP or random selection (Fig. 12). In principle, a consistent detection of *SMp* with small amplitude uncertainties serves as a very good indication on the quality of stacked SRF. Furthermore, with the lowest LQR or AMP criterion, a positive signal arriving at about 8 s before the *S* arrival, possibly *SLp* from the LAS, can be detected at 95% confidence level (Fig. 12), whereas such a *SLp* arrival cannot be detected otherwise with statistical significance (Fig. 12). We note that the amplitude of detected *SLp* is about 5–7%, considerably exceeding the 1–2% amplitude threshold for robust *SLp* detection with the lowest LQR or AMP criterion (e.g. Figs 4 and 5b).

Considering three data-selection criteria such as the lowest LQR, AMP and Wilson *et al.* (2006), Fig. 13 further examines distance-dependent amplitudes of detected *SMp* and *SLp* and they are compared against theoretical *S*-to-*P* transmission coefficient (Aki & Richards 2002) from the L70 model (Fig. S1). Here we do not seek an optimal fit to the data, but simply show if the amplitude measurements in general follow the theoretical trend against epicentral distance. While there are still substantial amplitude fluctuations with respect to theoretical prediction against epicentral distance, in this particular example at station TJN, measurements from the lowest AMP criterion follows closest to the theoretical trend,

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3 492 regardless the degree of regularization (Figs 13a and b vs. Figs 13c and d). As expected, the
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5 493 amplitude of *SMp* and *SLp* is notably modulated by the degree of regularization.
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8 494 At least locally beneath the station TJN, a relatively sharp boundary with a negative
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10 495 velocity gradient is robustly identified in the LAS beneath the old Korea craton (Lee *et al.*
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12 496 1998). While the exact nature and spatial extent of such a boundary deserves further analysis
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14 497 and discussion, it is beyond the scope of this paper and we will detail the findings beneath the
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16 498 entire Korea network in a subsequent paper. Also, another key potential source of
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18 499 contamination on SRFs is scattering from laterally-varying structure (Lekic & Fischer 2017).
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23 500 Lastly, Fig. 14 displays AMP1 against data-selection percentage threshold for six
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25 501 different criteria. Similar to what we observe in the synthetics (Fig. 6), the results from real
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27 502 data analysis at station TJN also show that not only AMP1 decreases with increasing
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29 503 percentage threshold, but the lowest LQR or AMP criterion gives the lowest AMP1 than
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31 504 Wilson *et al.* (2006) or the random data selection does (Fig. 14), compatible with synthetic
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33 505 test in Section 3 (Fig. 6). Despite the criterion of Wilson *et al.* (2006) restrains SRFs within
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35 506 60° – 75° from shallow events, the lowest LQR or AMP criterion does concern SRFs across
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37 507 the entire distance range of 60° – 85° , including a few SRFs from deep earthquakes as well.
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39 508 Furthermore, since the level of random noise reduction is proportional to the square-root of
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41 509 SRF number in the stacks, there is a trade-off between eliminating random noise and signal-
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43 510 generated noise. While random noise can be reduced by stacking, it is not the case for signal-
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45 511 generated noise. In comparison to the cases shown in Figs 11 and 12, while we can still detect
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47 512 *SMp* and *SLp* at 95% confidence level with a higher percentage threshold of 50%, the
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49 513 uncertainty of SRF amplitude does not decrease as expected for random noise (Figs S11 and
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51 514 S12). By inspection, if N is the data selection percentage threshold, multiplying AMP1 in Fig.
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53 515 6 (noise free) with the square root of $100/N$ generally reproduces the pattern of AMP1 shown
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3 516 in Fig. 14. This can be useful in the discussion on how to properly select N against random
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5 517 noise with respect to data quality and noise level.
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9 518 In the case of our test, permanent station TJN provides about 300 quality data over 10
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11 519 years after data prescreening. As we present the result with 25% selection threshold (or ~75
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13 520 traces) for the detection of the *SLp* phase (Figs 11–13), we find a 15% selection threshold (or
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15 521 ~45 traces) with the low AMP criteria can still provide consistent SRF and *SLp* detection.
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17 522 Concerning typical PASSCAL experiments or temporal arrays over a 2-year period,
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19 523 depending on the aperture of the array, the number of stations, background noise level and
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21 524 the scale of lateral heterogeneity in the LAS, it is conceivable that a network of 5 stations can
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23 525 record 45 traces with low LQR and produce reasonably robust SRF stacks.
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28 526 As evident in the synthetic test and real data analysis, high SNR of the *S* wave in the Q-
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30 527 component seismogram by itself does not necessarily warrant the quality of stacked SRFs.
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32 528 The data selection criterion proposed by Wilson *et al.* (2006) is favorable for a specific focal
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34 529 mechanism, but it is not necessarily a general scheme that takes into account the effect of
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36 530 radiation pattern on the excitation of mantle *P* coda waves or/and scattering waves between
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38 531 the source and receiver in the L-component seismogram. In this study, the LQR criterion, by
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40 532 design, makes a direct amplitude measurement of the scattering wave in the L component and
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42 533 contrasts it against the amplitude of the *S* wave in the Q component. Obviously, the
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44 534 application of LQR criteria in real data analysis slightly depends on the choice of
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46 535 measurement time window, which may be adapted. Alternatively, the AMP data selection
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48 536 criterion makes a direct assessment on the amplitude of *SP*, *sSP* and other related multiples in
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50 537 the SRF, making it an ideal proxy to indicate the strength of scattering waves away from the
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52 538 receiver side (e.g., Vinnik & Romonowicz 1991). Finally, these data selection criteria can be
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54 539 easily adapted to a different coordinate system (e.g., *P-SV-SH*) when desired.
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5 541 **5 Conclusions**

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7 542 Teleseismic scattered waves such as *S*-to-*P* converted phases (*Sdp*) provide enhanced
8 543 sensitivity to localized velocity gradients across the lithospheric discontinuities. In this study,
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10 544 through systematic analysis of full-waveform synthetic waveforms and SRFs from
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12 545 catalogued earthquake focal mechanism and depth, we find that the strong *P* coda waves
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14 546 before the *S* wave recorded in the L component could result in the dubious *Sdp* phases in the
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16 547 synthetic SRFs before the *S* arrival. Furthermore, if the mean amplitude of SRFs after the *S*
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18 548 wave is large, dubious signals of SRFs before the *S* arrival become strong as well. Such
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20 549 signal-generated noise before the *S* arrival can be mistakenly interpreted as *Sdp* phase derived
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22 550 from lithosphere-asthenosphere system (LAS) beneath seismic stations.
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28 551 To minimize the interference of *P* coda waves on *Sdp* phases in the LAS, we devise
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30 552 data-oriented criteria such as LQR, the amplitude ratio between *P* coda waves of the L-
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32 553 component waveform and the *S* wave of the Q-component waveform, and AMP, the
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34 554 amplitude of SRFs after the *S* arrival. These screening criteria provide a direct and
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36 555 straightforward attribute to measure and indicate the level of spurious energies before the *S*
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38 556 arrival in the SRF. With low LQR or AMP, regardless of the choice of deconvolution scheme,
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40 557 tapering or/and data windowing, unwanted signal-generated noise are largely removed, which
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42 558 improves the detection and quality of locally converted *Sdp* in the LAS. With the criteria
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44 559 such as the lowest LQR or AMP, the minimum amplitude threshold above which robust *SLp*
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46 560 can be detected is reduced down to about 1–2%, smaller than the amplitude threshold of 3–4%
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48 561 by the criterion of Wilson *et al.* (2006). The effectiveness of these criteria largely manifests
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50 562 the amplitude of *SP* wave as well as the control of *SV* radiation pattern in the scattering area
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52 563 on the amplitude of signal-generated noise due to *S*-to-*P* scattering (Vinnik & Romanowicz
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54 564 1991). Applying the newly designed selection criteria to real data in the South Korea seismic
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3 565 network, we demonstrate that the lowest LQR or AMP criterion provides robust detection of
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5 566 *SLp* beneath the test station TJN, offering a great potential to better characterize seismic
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4

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23
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29
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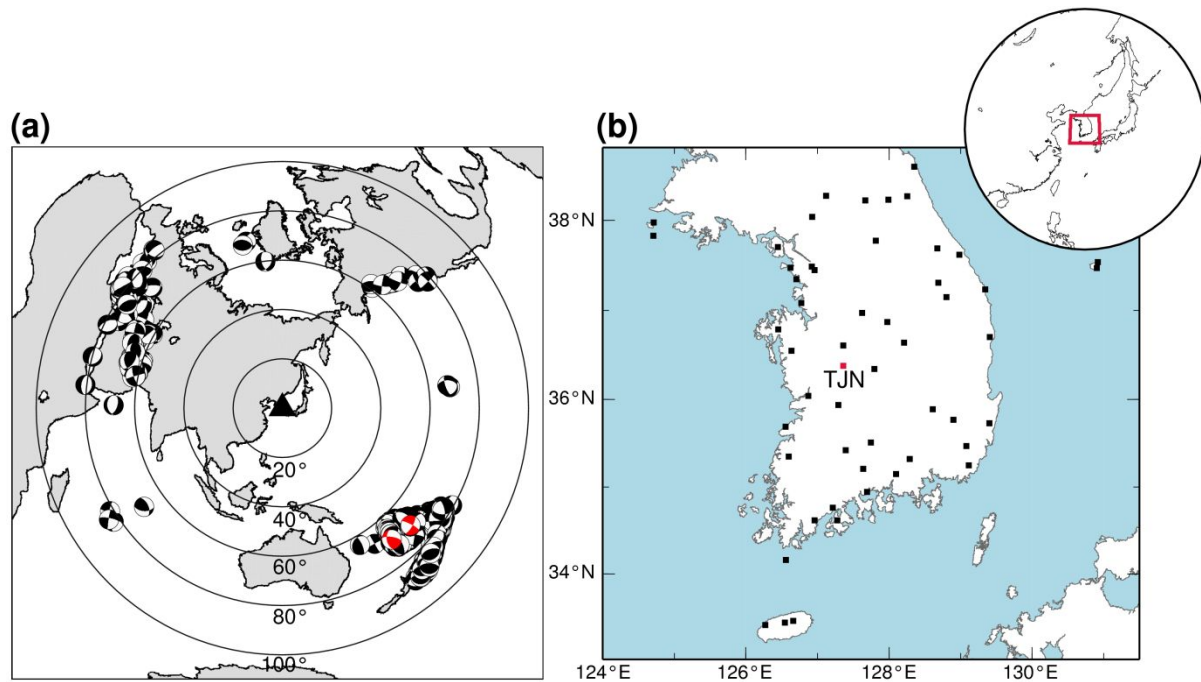
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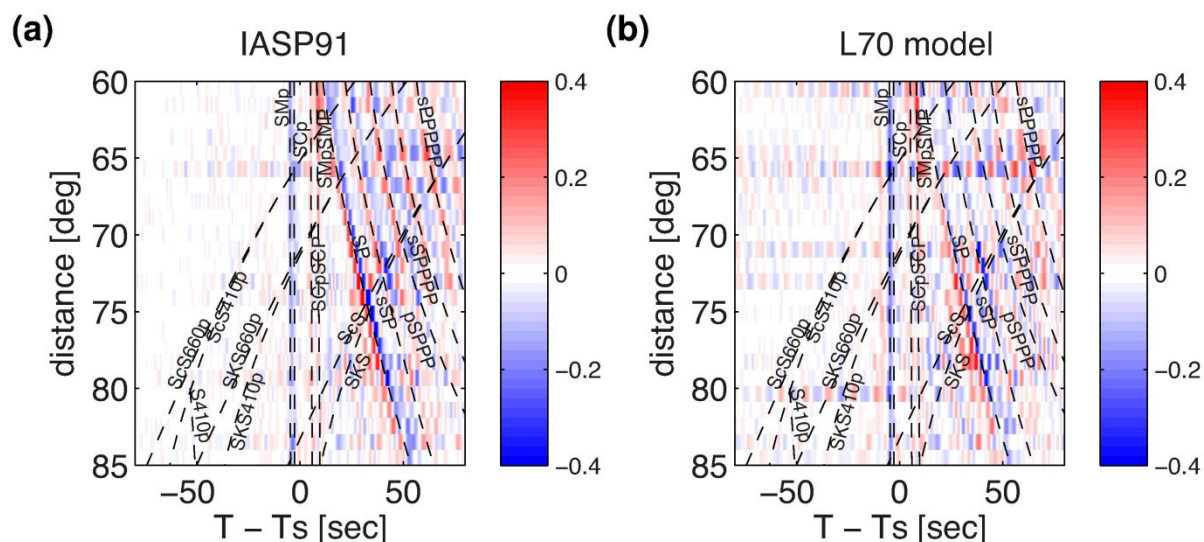
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727 **Figures**

728

729 **Figure 1.** Distribution of earthquakes with magnitude greater than 5.5 and South Korea
 730 seismic network. (a) Distribution of earthquakes within the epicentral distances of 60°–85°
 731 from the center of the Korean seismic network (black triangle). The Centroid Moment Tensor
 732 (CMT) solutions of the events are from Dziewonski *et al.* (1981) and Ekstrom *et al.* (2012).
 733 **Two earthquakes for synthetics in Fig. 3 are highlighted in red.** (b) South Korea seismic
 734 network. Broadband seismic stations are shown in black squares, and the only station is
 735 labelled with the station ID (TJN).



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737 **Figure 2.** Stacks of 300 synthetic SRFs as a function of the epicentral distance of 60°–85°.

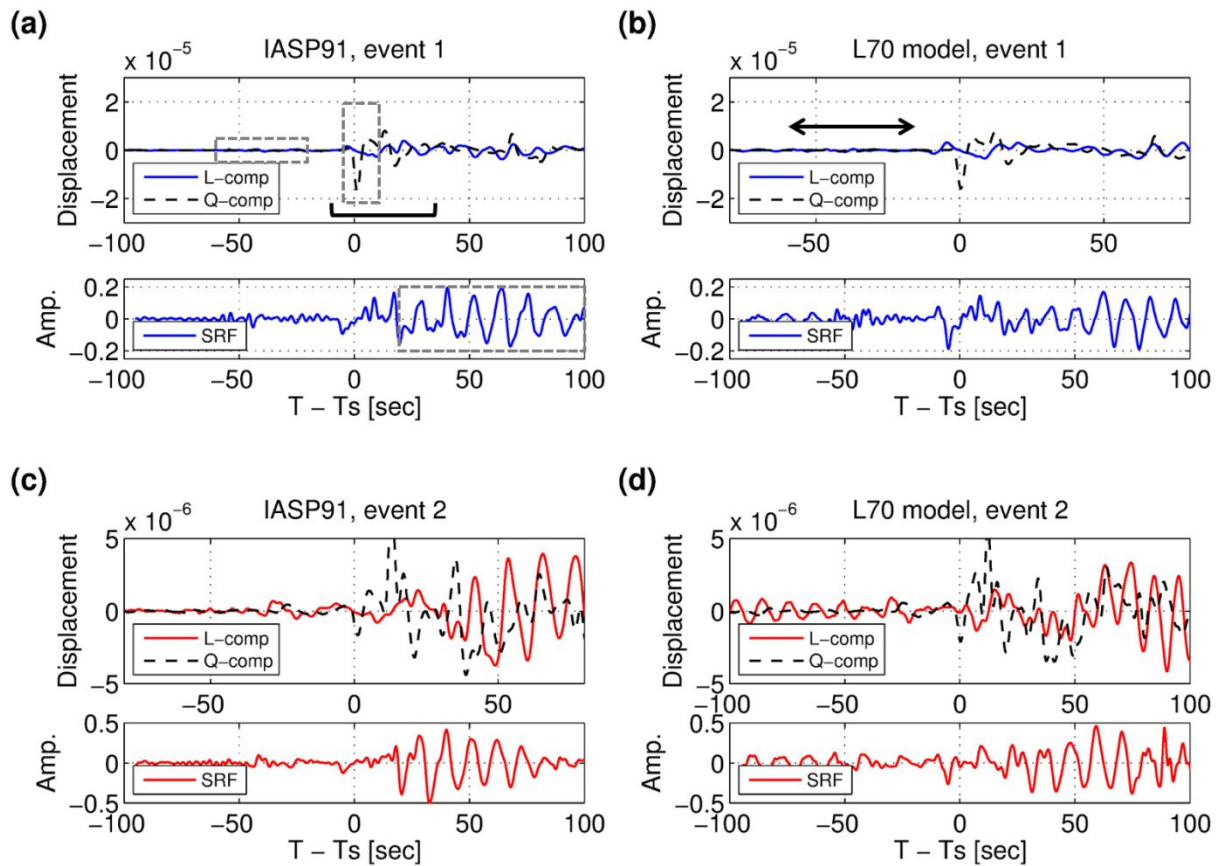
738 The SRFs are binned with a distance of a 1° window and stacked, and their amplitudes are

739 displayed in blue-to-red color. Theoretical phase arrival times from the IASP91 model

740 (Kennett & Engdahl 1991) are marked as dashed lines with phase names labeled. (a)

741 Synthetic SRFs calculated from the IASP91 model (Kennett & Engdahl 1991). (b) Synthetic

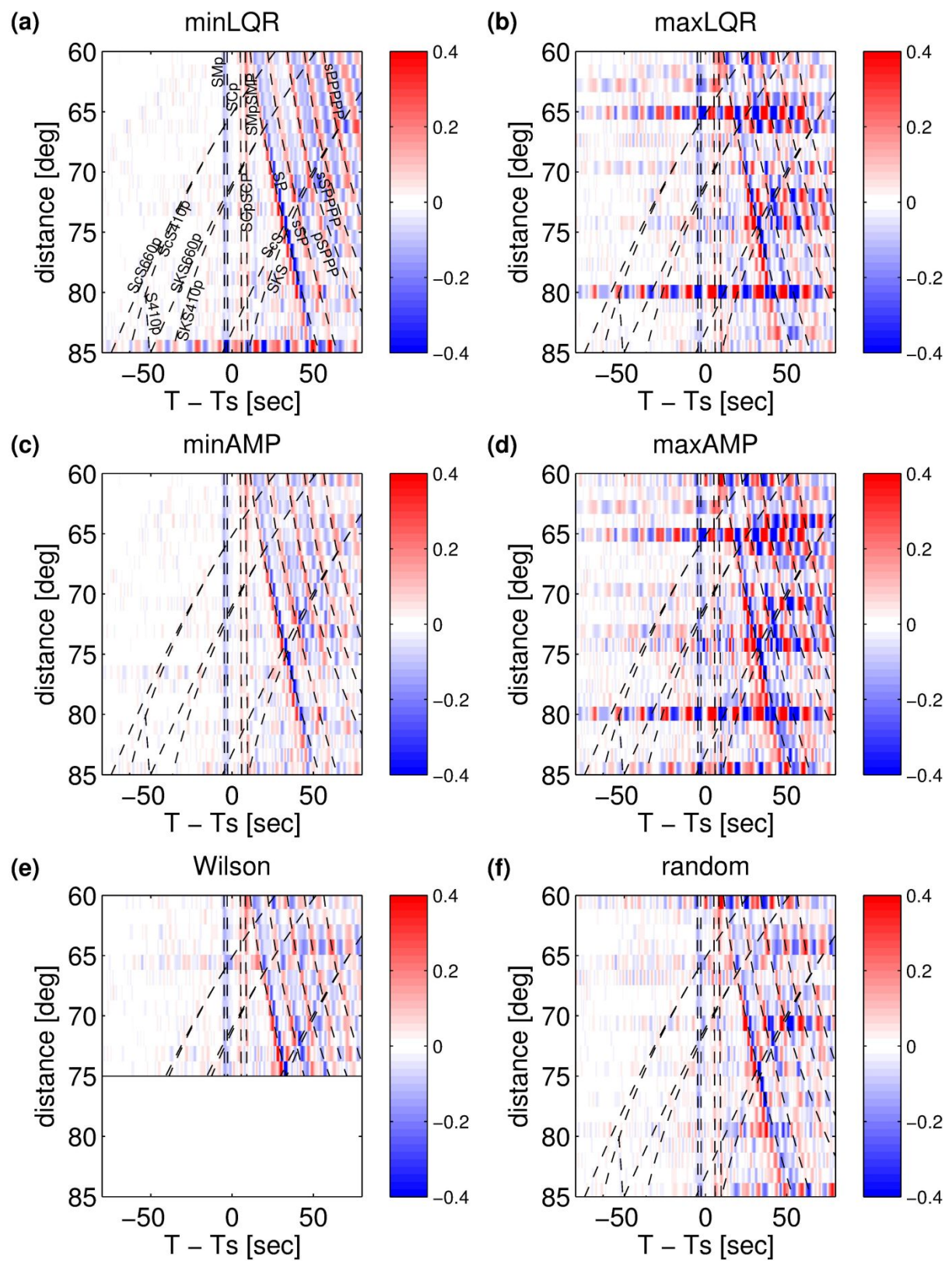
742 SRFs from L70 model (Fig. S1).



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744 **Figure 3.** Examples showing *P* coda waves and their influence on signal-generated noise in
 745 the SRF. Gray dashed boxes in panel (a) indicate how LQR is measured from the L- and Q-
 746 component synthetic seismograms and how AMP is measured from synthetic SRF. Synthetic
 747 waveforms are computed from **two** earthquake sources (Fig. 1a, **red beachballs**) using the
 748 IASP91 (Kennett & Engdahl 1991) (a and c) and the L70 model (Fig. S1) (b and d). **S-wave**
 749 **arrivals are aligned at zero time in the Q-component waveforms (dashed lines), and a time**
 750 **window for *P* coda waves are marked in a panel b (double arrow).** Time-domain Wiener
 751 deconvolution method **with minimum regularization (0.01% white noise)** is performed within
 752 the parent waveform time window of 10 s before and 35 s after the *S* arrival (**black bar in a**
 753 **panel a**). Note the amplitude scale of SRF in case 2 is higher than that in case 1. See Figs S2
 754 and S3 for cases for the time window of [-10 s 15 s] and [-10 s 10 s] with respect to *S* arrival,
 755 respectively.

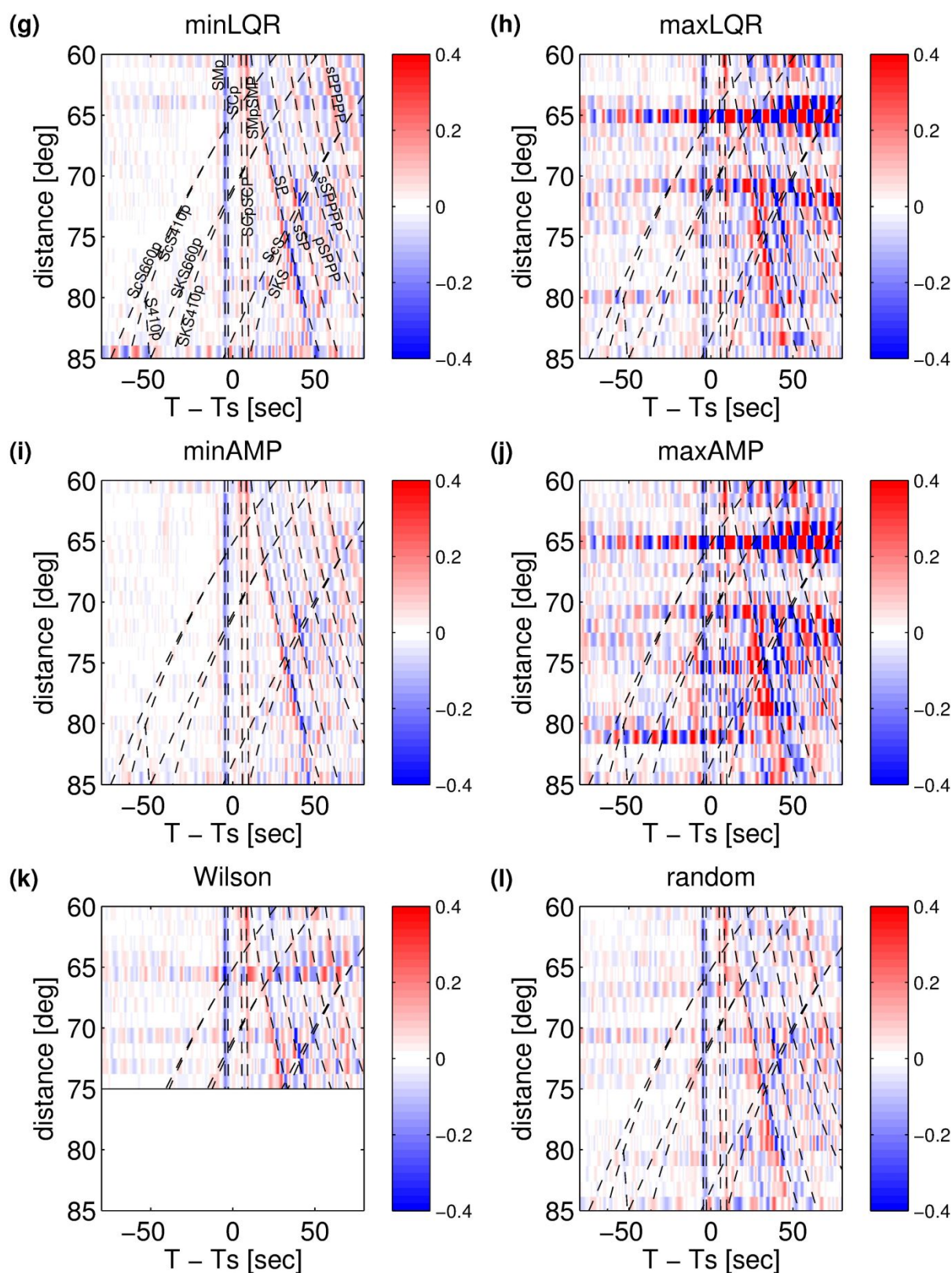
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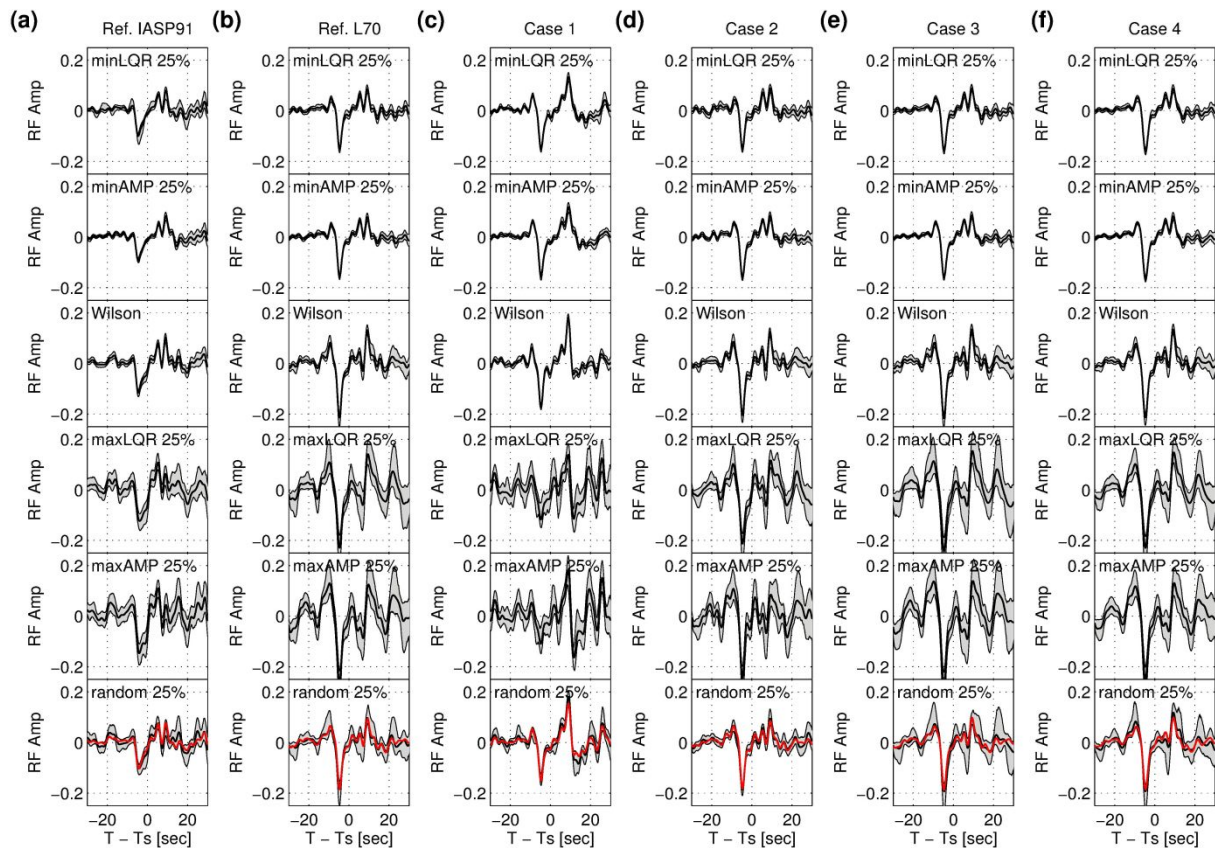
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761 **Figure 4.** Images of synthetic SRFs for the IASP91 model (a–f) and L70 model (g–l) against

762 epicentral distance and six data selection criteria. The SRFs are plotted in the same way as

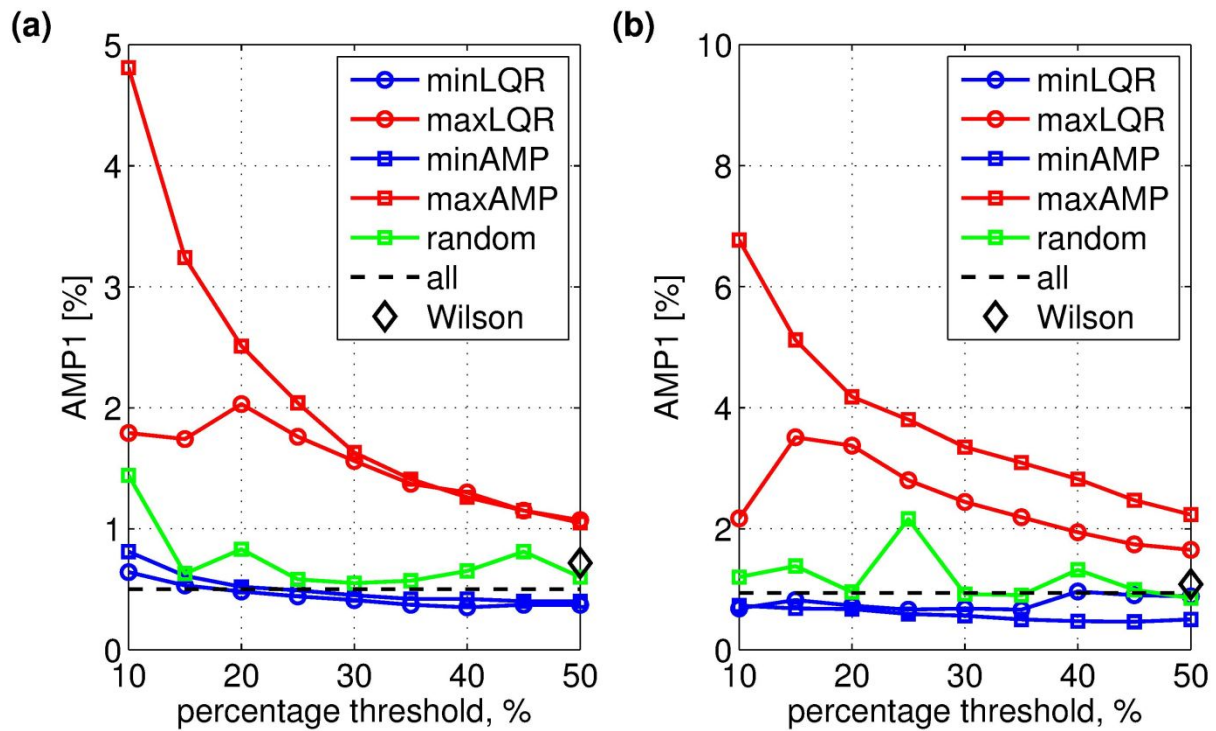
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3 763 Fig. 2. (a, g) Stacked SRFs with the 25% lowest LQR. (b, h) Stacked SRFs with the 25%
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5 764 highest LQR. (c, i) Stacked SRFs with the 25% lowest AMP. (d, j) Stacked SRFs with the
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7 765 25% highest AMP. (e, k) Stacked SRFs with the criterion by Wilson *et al.* (2006). Note that
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9 766 Wilson *et al.* (2006) used restricted epicentral distances of 60° – 75° for earthquakes with focal
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11 767 depths shallower than 300 km. (f, l) Stacked SRFs with 25% random data selection. Dashed
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14 768 lines indicate phase arrival times predicted by the IASP91 model.
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771 **Figure 5.** Stacked SRFs for various cases against six data selection criteria: 25% lowest LQR,
 772 25% lowest AMP, the criterion by Wilson *et al.* (2006), 25% highest LQR, and 25% highest
 773 AMP, and 25% random data selection, from the top to bottom rows, respectively. Gray
 774 region indicates bootstrap error estimates of the SRFs. (a) Stacked SRFs for IASP91 model.
 775 (b) Stacked SRFs for L70 model. (c) Stacked SRFs for the case 1; same as (b) but with the
 776 window of parent waveform -10 s before and 15 s after the *S* wave. (d) Stacked SRFs for the
 777 case 2; same as (b) but with the Hanning tapering window of 5%. (e) Stacked SRFs for the
 778 case 3; same as (b), but with frequency-domain water-level deconvolution and water level of
 779 0.05%. (f) Stacked SRFs for the case 4; same as (b), but with frequency-domain water-level
 780 deconvolution and water level of 0.2%. Note stacked SRFs without any selection criteria are
 781 shown in red lines for comparisons. The stack of all traces is shown in red in the bottom
 782 panel.

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784

785 **Figure 6.** Root-mean-square (RMS) amplitudes of the synthetic SRFs at -60 to -20 s with

786 respect to the S arrival (AMP1 in %), plotted against data-selection ratios (10–50%). (a)

787 AMP1 for IASP91 model (Kennett & Engdahl 1991) with six criteria, which are lowest LQR

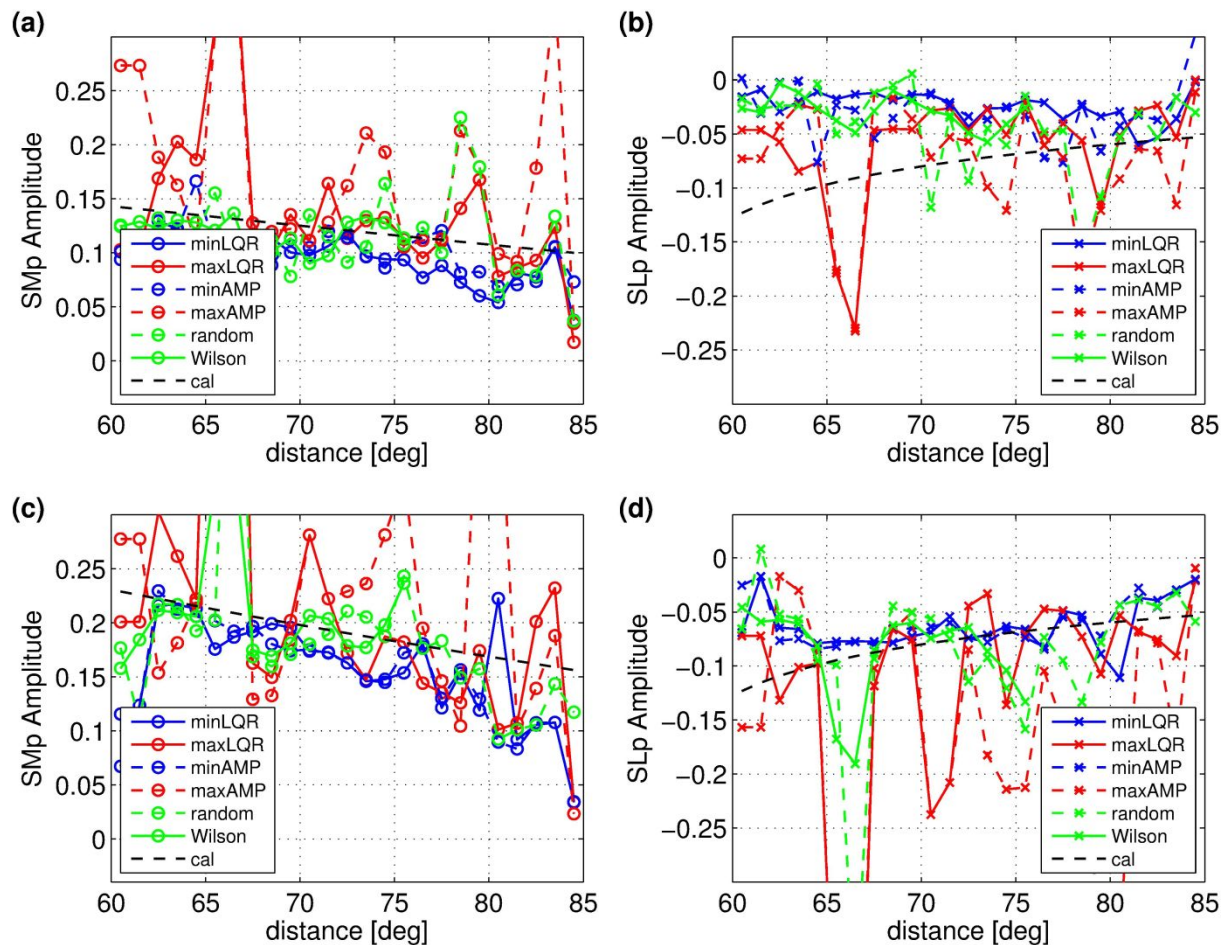
788 (blue circle), highest LQR (red circle), lowest AMP (blue square), highest AMP (red square),

789 random data selection (green square) and the criterion by Wilson *et al.* (2006) (black

790 diamond), in addition to all SRFs (black dashed line). (b) AMP1 for L70 model (Fig. S1)

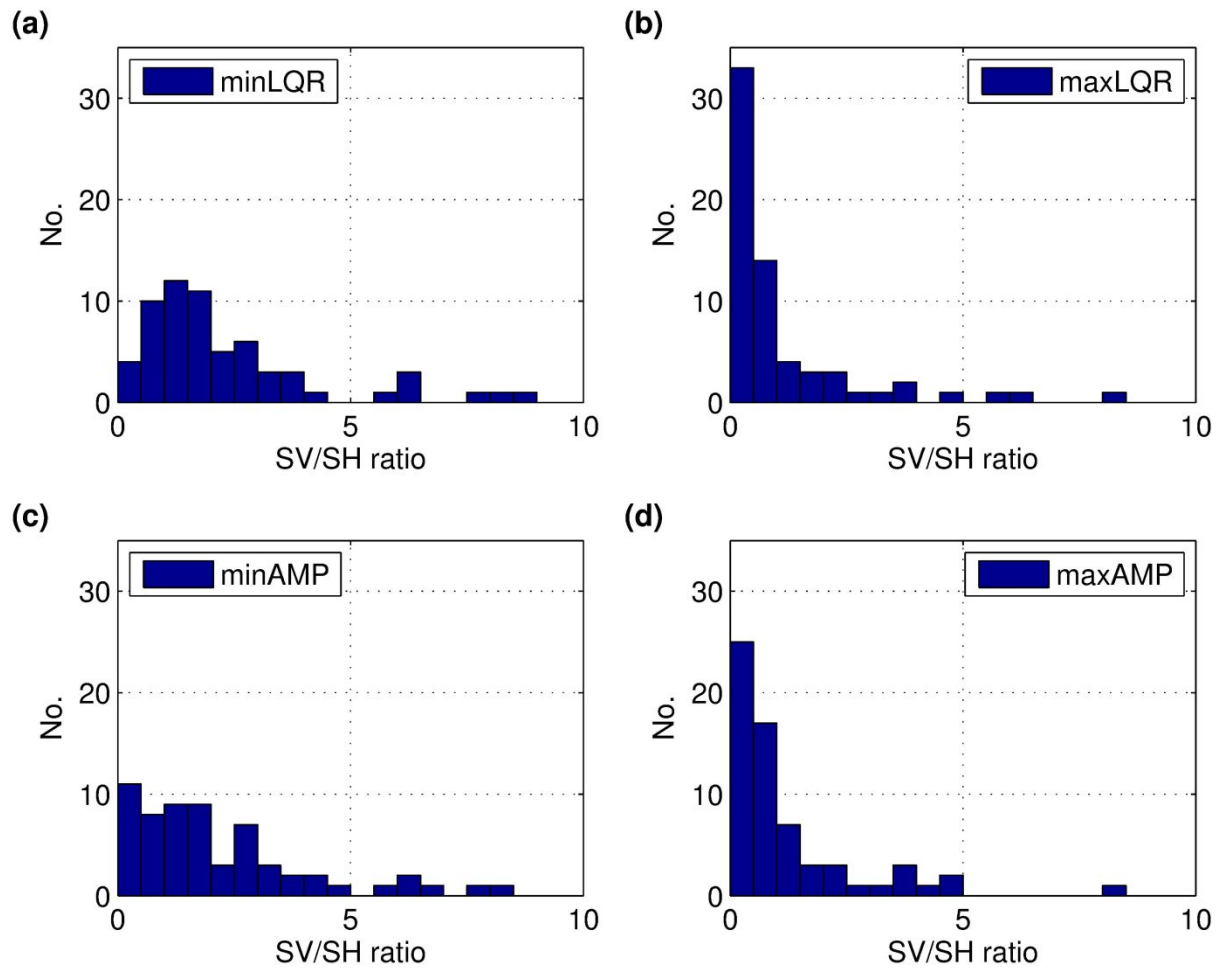
791 with the same criteria as (a).

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794 **Figure 7.** Amplitudes of SMp and SLp phases from the synthetic SRFs, plotted against the
 795 epicentral distance for the six different data selection criteria. The measured amplitudes are
 796 compared with the theoretical transmission coefficients (Aki & Richards 2002), shown in
 797 black dashed line. (a) Distance-dependent amplitude of SMp from IASP91 model (Kennett &
 798 Engdahl 1991). (b) Distance-dependent amplitude of SLp from IASP91 model. (c) Distance-
 799 dependent amplitude of SMp from L70 model (Fig. S1). (d) Distance-dependent amplitude of
 800 SLp from L70 model. Note that the theoretical calculation of SLp transmission coefficient
 801 from the L70 model is reproduced in Fig. 7b for comparison. In the absence of a negative
 802 velocity contrast in the IASP91 model, notable amplitude peak, especially with the highest
 803 LQR or AMP criteria, can still be identified and potentially misinterpreted as SLp signal in
 804 the LAS. Lowest LQR or AMP criteria substantially minimize these dubious signals.

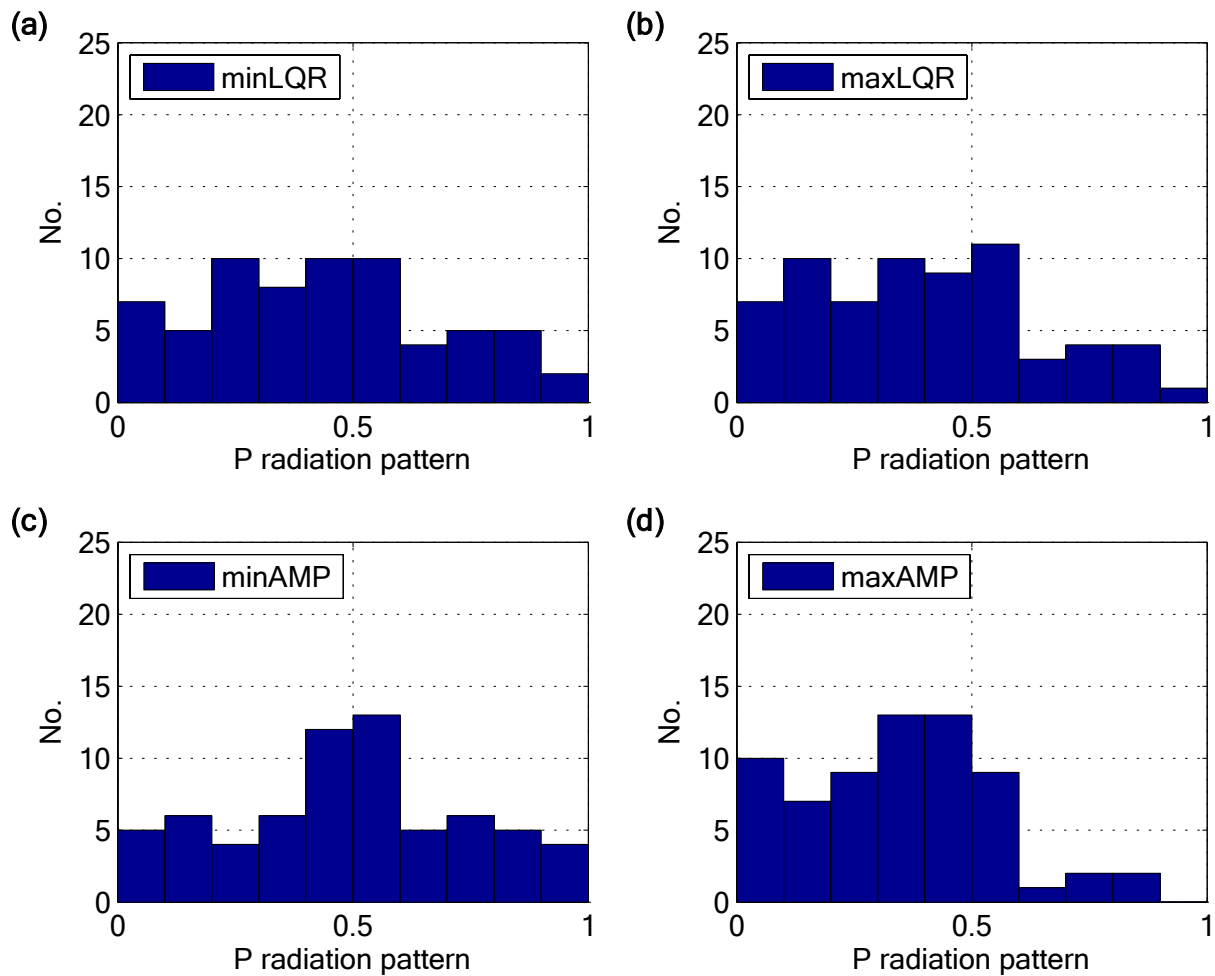


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806 **Figure 8.** Histograms of SV/SH ratio against four data selection criteria; (a) 25% lowest LQR,

807 (b) 25% highest LQR, (c) 25% lowest AMP, and (d) 25% highest AMP.

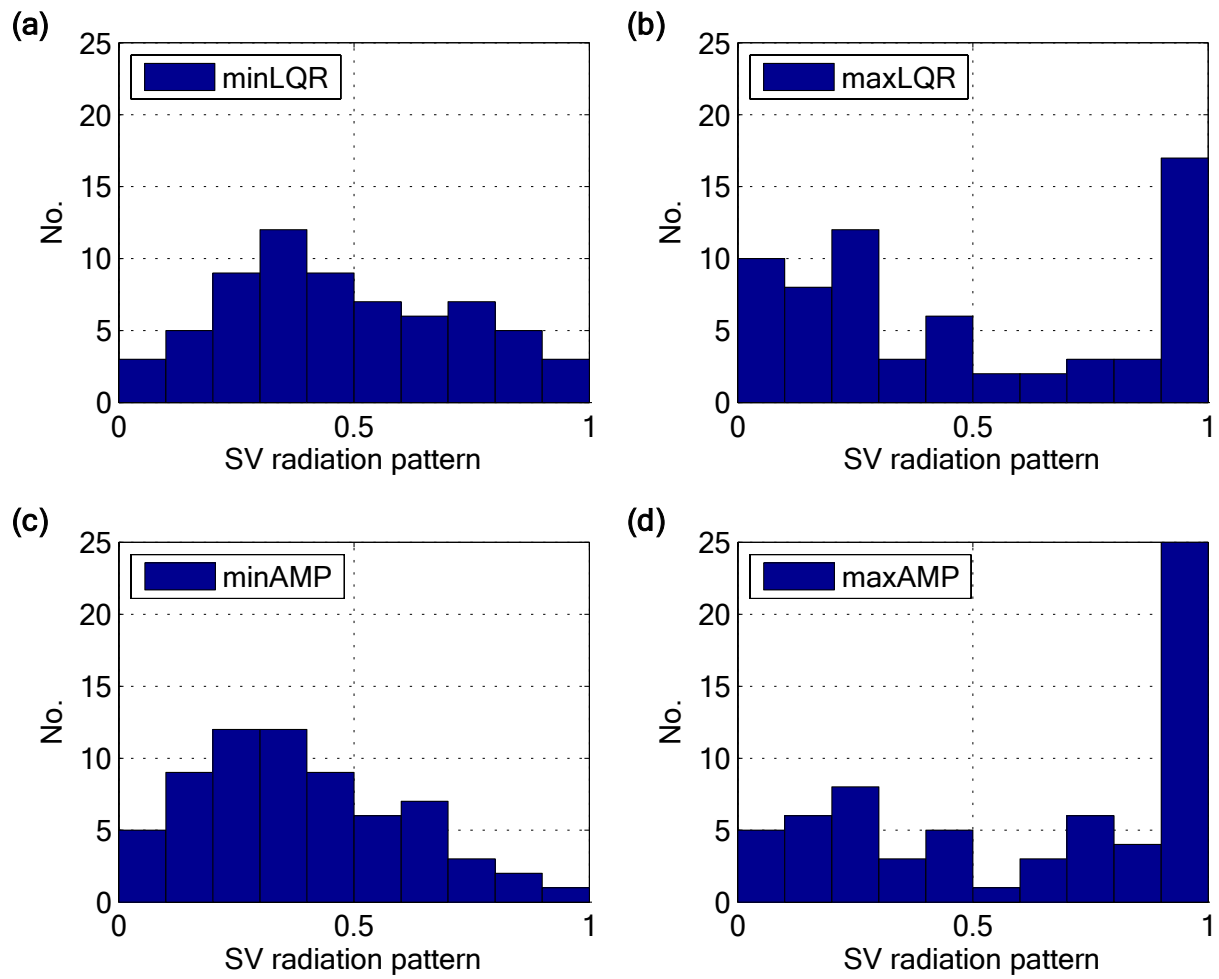
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810 **Figure 9.** Histograms of P radiation pattern against four data selection criteria; (a) 25%
 811 lowest LQR, (b) 25% highest LQR, (c) 25% lowest AMP, and (d) 25% highest AMP. **The P**
 812 **radiation pattern is computed with the slowness of $pPPPP$ against focal mechanisms of**
 813 **selected events.**

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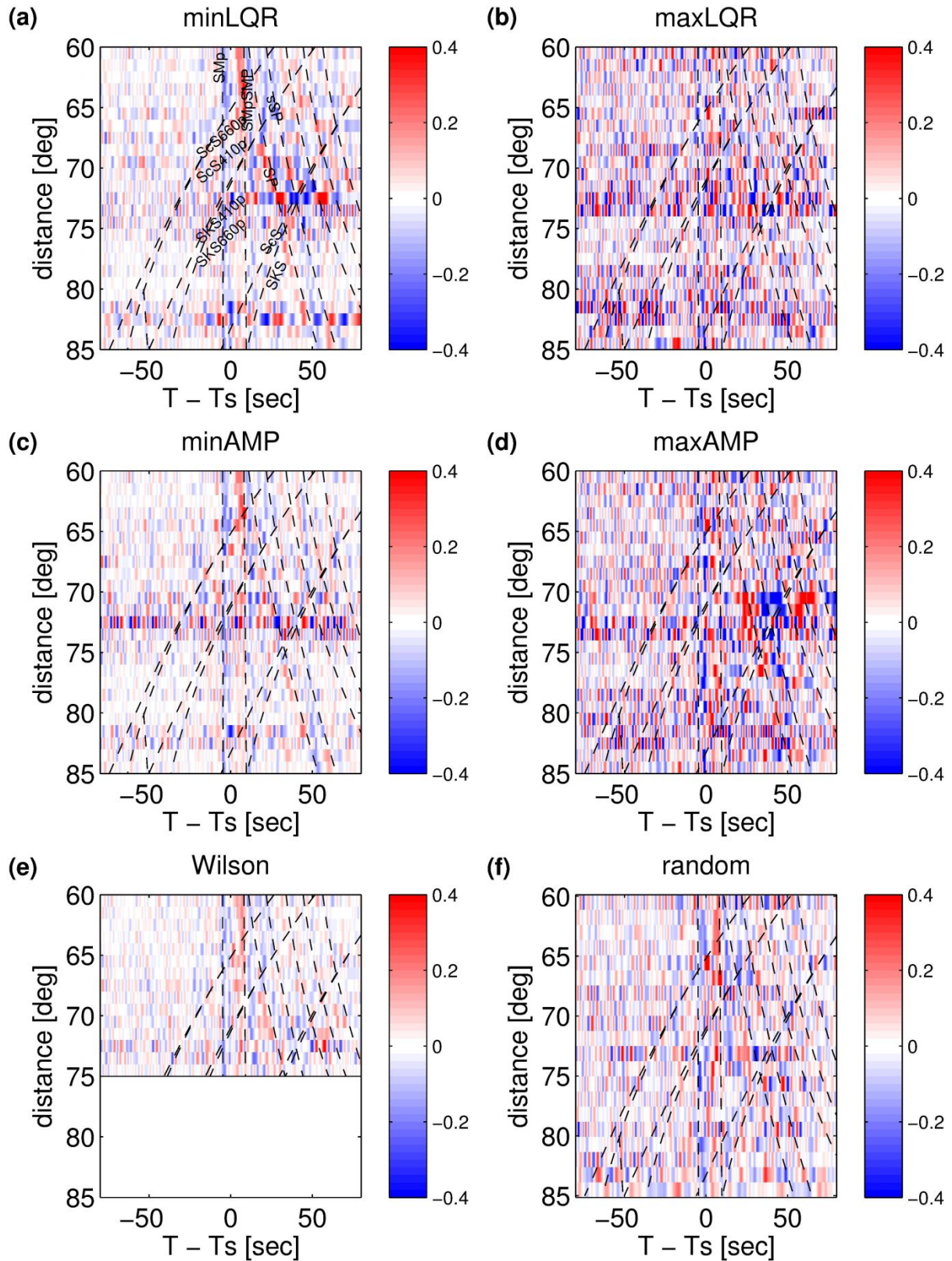


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816 **Figure 10.** Histograms of SV radiation pattern against four data selection criteria; (a) 25%817 lowest LQR, (b) 25% highest LQR, (c) 25% lowest AMP, and (d) 25% highest AMP. The SV 818 radiation pattern is computed with the slowness of SP wave against focal mechanisms of

819 selected events.

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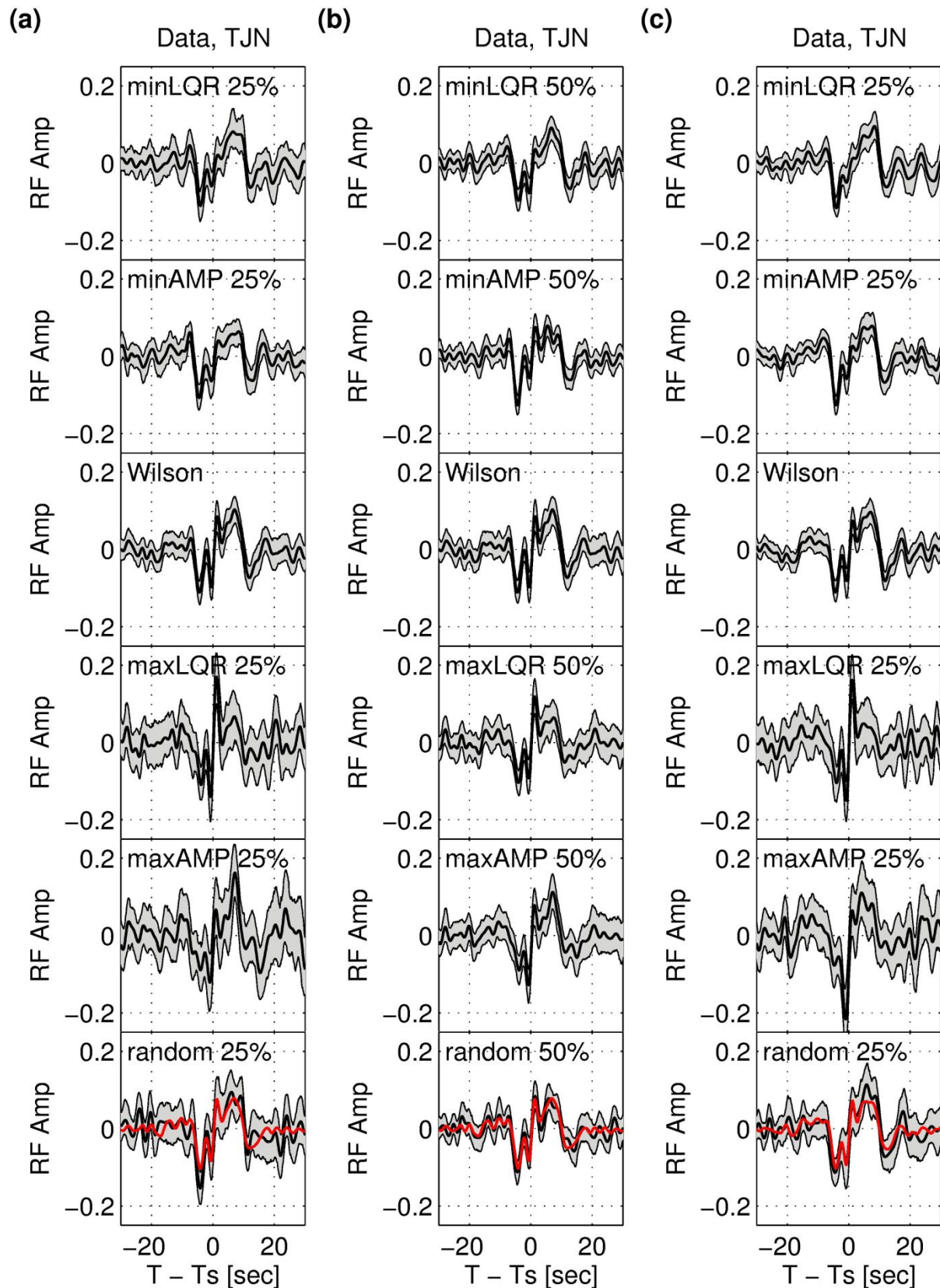
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822 **Figure 11.** Images of SRFs for station TJN as a function of the distance of 60°–85° with six

823 different data selection criteria. The SRFs are plotted in the same way as Fig. 2. (a) Stacked

824 SRFs with the 25% lowest LQR. (b) Stacked SRFs with the 25% highest LQR. (c) Stacked

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3 825 SRFs with the 25% lowest AMP. (d) Stacked SRFs with the 25% highest AMP. (e) Stacked
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5 826 SRFs with the criterion by Wilson *et al.* (2006). (f) Stacked SRFs with 25% random data
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7 827 selection. Dashed lines indicate phase arrival times predicted by the IASP91 model. See Fig.
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10 828 S10 for the images of -30–30 s time window.
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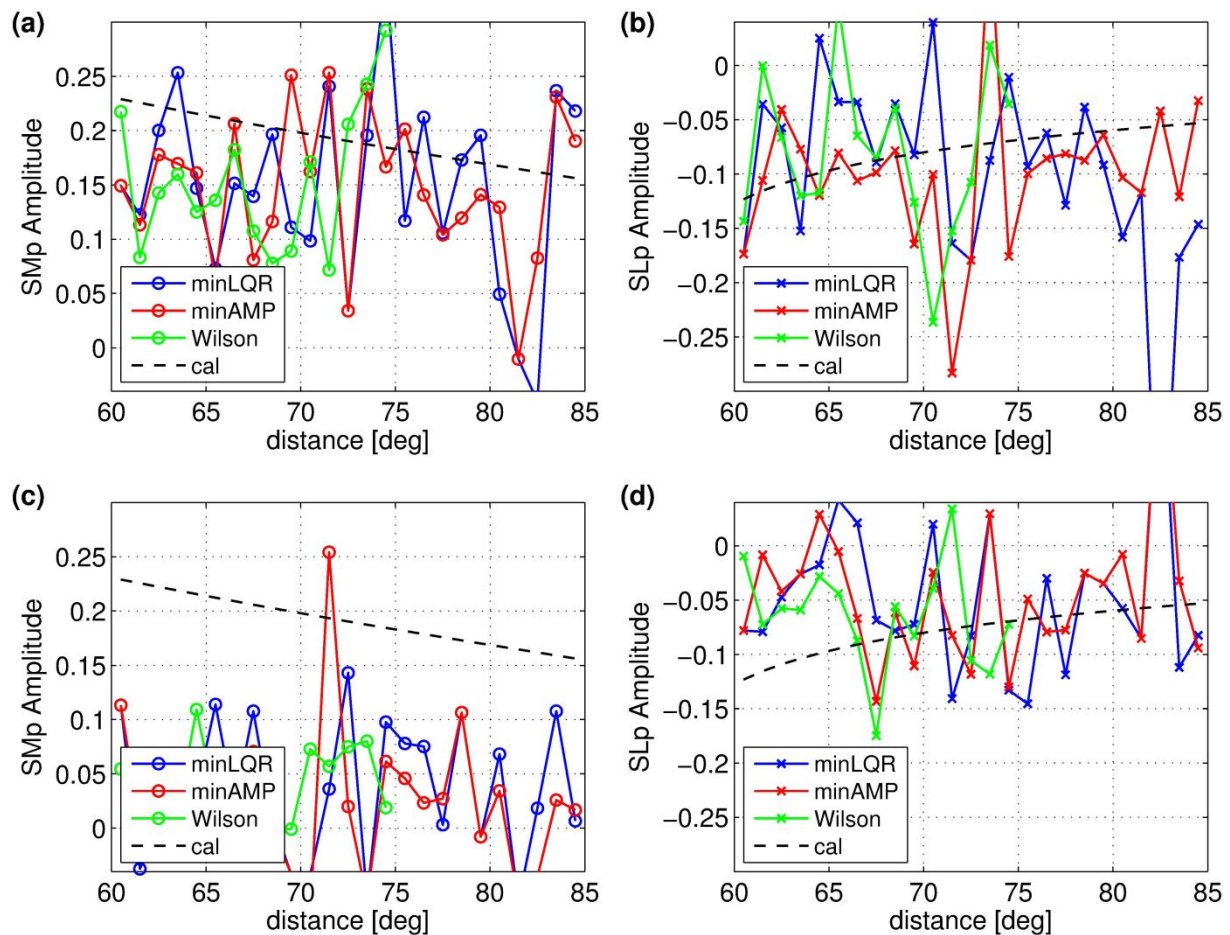


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830 **Figure 12.** Stacked SRFs for station **TJN** with six data selection criteria with (a) a percentage
 831 threshold of 25%, (b) 50 %, and (b) 25% with a stronger regularization (1% white noise).

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3 832 Gray region indicates bootstrap error estimates of the SRFs. The six data selection criteria are
4
5 833 as follows: 25% lowest LQR, 25% lowest AMP, the criterion by Wilson *et al.* (2006), 25%
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7 834 highest LQR, and 25% highest AMP, and 25% random data selection, from the top to bottom
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10 835 rows, respectively.
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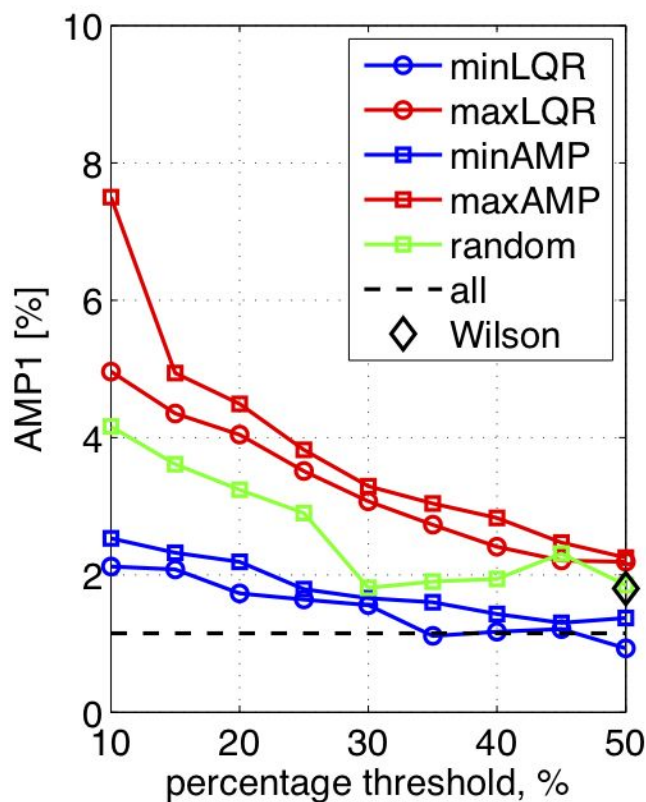
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838 **Figure 13.** Amplitudes of SMp and SLp phases from the SRFs for station **TJN**, plotted against
 839 the distance of 60° – 85° for three different data selection criteria (25% lowest LQR, 25%
 840 lowest AMP, and the criterion by Wilson *et al.* (2006)). The measured amplitudes are
 841 compared with the theoretical transmission coefficients (Aki & Richards 2002), shown in
 842 black dashed line. (a) Distance-dependent amplitude of SMp . (b) Distance-dependent
 843 amplitude of SLp . (c) Distance-dependent amplitude of SMp with a strong regularization (1%
 844 white noise). (d) Distance-dependent amplitude of SLp with a strong regularization (1% white
 845 noise).

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847

848 **Figure 14.** Root-mean-square (RMS) amplitudes of the SRFs at -60 to -20 s with respect to
 849 the *S* arrival (AMP1 in %) for station TJN, plotted against data-selection ratios (10–50%).

850 The six data selection criteria are as follows: lowest LQR (blue circle), highest LQR (red
 851 circle), lowest AMP (blue square), highest AMP (red square), random data selection (green
 852 square) and the criterion by Wilson *et al.* (2006) (black diamond), in addition to all SRFs
 853 (black dashed line).

854 **Supporting Information**

855

856 Additional Supporting Information may be found in the online version of this article:

857

858 Supporting Information file includes **one table and 14** figures providing velocity models for
859 synthetic tests (Fig. S1), illustrations showing how the synthetic SRFs are constructed with
860 our proposed data selection criteria for shorter time windows for the time-domain Wiener
861 deconvolution (Figs S2 and S3), effect of using different data windowing and tapering length
862 (Figs **S4 and S5**, respectively), effect of using various water levels in the alternative
863 frequency-domain deconvolution (Figs **S6 and S7**), histograms of epicentral distance and
864 event back-azimuth (Fig. **S8**) as well as source parameters (Fig. **S9**) against data selection
865 criteria, **and** an alternative 50% threshold for six data selection criteria for the SRFs from
866 station TJN (Figs **S11 and S12**) **in addition to 25% threshold (Fig. S10). SRFs images with**
867 **25% threshold and a strong regularization (1% white noise) are shown in Figs S13 and S14.**

868

869 **Table S1. Velocity models.**

870

871 **Figure S1.** Velocity models. The 1-D IASP91 model (Kennett & Engdahl 1991) is shown in
872 black, and the L70 model is shown in red. The L70 model **includes a 35 km thick high-**
873 **velocity mantle lid with a 7.5% shear velocity increase below Moho, a low velocity zone with**
874 **a 9% shear velocity reduction beneath 70 km depth, and a small 1.5% shear velocity increase**
875 **beneath 120 km depth. See also Table S1.**

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877 **Figure S2.** Examples showing *P* coda waves and their influence on signal-generated noise in
878 the SRF. Gray dashed boxes in panel (a) indicate how LQR is measured from the L- and Q-

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3 879 component synthetic seismograms and how AMP is measured from synthetic SRF. Synthetic
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5 880 waveforms are computed from catalogued earthquake **sources** using the IASP91 (Kennett &
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7 881 Engdahl 1991) (a and c) and the L70 **model** (b and d). Time-domain Wiener deconvolution
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9 882 method is performed with the parent waveform time window of 10 s before and 15 s after the
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11 883 *S* arrival (**black bar in a panel a**). Note the amplitude scale of SRF in **event 2** is higher than
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13 884 that in **event 1**.
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19 886 **Figure S3.** Examples showing *P* coda waves and their influence on signal-generated noise in
20
21 887 the SRF. Gray dashed boxes in panel (a) indicate how LQR is measured from the L- and Q-
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23 888 component synthetic seismograms and how AMP is measured from synthetic SRF. Synthetic
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25 889 waveforms are computed from catalogued earthquake **sources** using the IASP91 (Kennett &
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27 890 Engdahl 1991) (a and c) and the L70 **model** (b and d). Time-domain Wiener deconvolution
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29 891 method is performed with the parent waveform time window of 10 s before and 10 s after the
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31 892 *S* arrival (**black bar in a panel a**). Note the amplitude scale of SRF in **event 2** is higher than
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33 893 that in **event 1**.
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39 895 **Figure S4.** Images of synthetic SRFs **for the case 1 from the L70 model** as a function of the
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41 896 distance of 60°–85° with following six data selection criteria; (a) 25% lowest LQR, (b) 25%
42
43 897 highest LQR, (c) 25% lowest AMP, (d) 25% highest AMP, (e) criterion by Wilson *et al.*
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45 898 (2006), and (f) 25% random data selection. The parent waveforms are windowed 10 s before
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47 899 and 15 s after the *S*-wave arrival and tapered with a 15% Hanning taper at both ends of the
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49 900 signal window. Dashed lines indicate phase arrival times predicted by the IASP91 model
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51 901 (Kennett & Engdahl 1991). The SRFs are plotted in the same way as Fig. 2.
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3 903 **Figure S5.** Images of synthetic SRFs for the case 2 from the L70 model as a function of the
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5 904 epicentral distance of 60° – 85° with six different data selection criteria. The parent waveforms
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7 905 are windowed 10 s before and 35 s after the *S*-wave arrival and tapered with a 5% Hanning
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9 906 taper at both ends of the signal window. See a caption of Fig. S4 for more detail.

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14 908 **Figure S6.** Images of synthetic SRFs for the case 3 from the L70 model as a function of the
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16 909 epicentral distance of 60° – 85° with six different data selection criteria. The parent waveforms
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18 910 are windowed 10 s before and 35 s after the *S*-wave arrival and tapered with a 15% Hanning
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20 911 taper at both ends of the signal window. The frequency-domain deconvolution is done with a
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22 912 water level of 0.05%. See a caption of Fig. S4 for more detail.

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27 914 **Figure S7.** Images of synthetic SRFs for the case 4 from the L70 model as a function of the
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29 915 distance of 60° – 85° with six different data selection criteria. The parent waveforms are
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31 916 windowed 10 s before and 35 s after the *S*-wave arrival and tapered with a 15% Hanning
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33 917 taper at both ends of the signal window. The frequency-domain deconvolution is done with a
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35 918 water level of 0.2%. See a caption of Fig. S4 for more detail.

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40 920 **Figure S8.** Histograms of epicentral distance and back azimuth against six data selection
41
42 921 criteria. LQR and AMP data selection criteria with a percentage threshold of 25% result in
43
44 922 negligible data selection bias in back azimuthal and epicentral distance.

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49 924 **Figure S9.** Histograms of earthquake source parameters (dip, strike and rake) against four
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51 925 data selection criteria; (a, e, f) 25% lowest LQR, (b, f, j) 25% highest LQR, (c, g, k) 25%
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53 926 lowest AMP, and (d, h, l) 25% highest AMP. LQR and AMP data selection criteria result in
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55 927 negligible data selection preference in source parameters.

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929 **Figure S10.** Images of SRFs for station **TJN** as a function of the epicentral distance of 60° –
930 85° with following six data selection criteria; (a) 25% lowest LQR, (b) 25% highest LQR, (c)
931 25% lowest AMP, (d) 25% highest AMP, (e) criterion by Wilson *et al.* (2006), and (f) 25%
932 random data selection. The parent waveforms are windowed 10 s before and 35 s after the *S*-
933 wave arrival and tapered with a 15% Hanning taper at both ends of the signal window. See a
934 caption of Fig. S4 for more detail. See also Fig. 10 for the images of -80–80 s window.

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936 **Figure S11.** Images of SRFs for station **TJN** as a function of the distance of 60° – 85° with
937 following six data selection criteria; (a) 50% lowest LQR, (b) 50% highest LQR, (c) 50%
938 lowest AMP, (d) 50% highest AMP, (e) criterion by Wilson *et al.* (2006), and (f) 50%
939 random data selection. The parent waveforms are windowed 10 s before and 35 s after the *S*-
940 wave arrival and tapered with a 15% Hanning taper at both ends of the signal window. See a
941 caption of Fig. S4 for more detail. See Fig. S12 for the images plotted for -30–30 s window.

942

943 **Figure S12.** Images of SRFs for station **TJN** as a function of the distance of 60° – 85° with
944 following six data selection criteria; (a) 50% lowest LQR, (b) 50% highest LQR, (c) 50%
945 lowest AMP, (d) 50% highest AMP, (e) criterion by Wilson *et al.* (2006), and (f) 50%
946 random data selection. The parent waveforms are windowed 10 s before and 35 s after the *S*-
947 wave arrival and tapered with a 15% Hanning taper at both ends of the signal window. See a
948 caption of Fig. S4 for more detail.

949

950 **Figure S13.** Images of SRFs for station **TJN** as a function of the distance of 60° – 85° with
951 following six data selection criteria; (a) 25% lowest LQR, (b) 25% highest LQR, (c) 25%
952 lowest AMP, (d) 25% highest AMP, (e) criterion by Wilson *et al.* (2006), and (f) 25%

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3 953 random data selection. The parent waveforms are windowed 10 s before and 35 s after the *S*-
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5 954 wave arrival and tapered with a 15% Hanning taper at both ends of the signal window. Time
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7 955 domain wiener deconvolution is done with a strong regularization of 1% white noise. See
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10 956 Fig. S14 for the images plotted for -30–30 s window.
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12 957

14 958 **Figure S14.** Images of SRFs for station **TJN** as a function of the distance of 60°–85° with
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16 following six data selection criteria; (a) 25% lowest LQR, (b) 25% highest LQR, (c) 25%
17 959 lowest AMP, (d) 25% highest AMP, (e) criterion by Wilson *et al.* (2006), and (f) 25%
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19 960 random data selection. The parent waveforms are windowed 10 s before and 35 s after the *S*-
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21 961 wave arrival and tapered with a 15% Hanning taper at both ends of the signal window. Time
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23 962 domain wiener deconvolution is done with a strong regularization of 1% white noise.
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8 3 **Data-oriented constraint on the interpretation of *S* receiver function and its application**
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10 4 **to observations of seismic discontinuities in the lithosphere-asthenosphere system**
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14 6 Xuzhang Shen¹, YoungHee Kim^{2*}, Teh-Ru Alex Song³, and Hobin Lim²
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15 Summary

16 This paper aims to improve the robustness of interpretation in the S receiver function
17 (SRF), a technique commonly used to retrieve forward scattering of S -to- P converted waves
18 (Sdp) originated from the lithosphere-asthenosphere system (LAS) beneath the stations.
19 Although the SRF does not suffer interferences from backward scattering waves such as the
20 first multiples from the Moho, one major drawback in the method is that Sdp phases can
21 interfere with P coda waves and it is conceivable that these signal-generated noise may be
22 misinterpreted as Sdp phase from the LAS beneath seismic stations. Through systematic
23 analysis of full-waveform synthetics and SRFs from catalogued source parameters, we find
24 that the strong P coda waves before the S wave in the longitudinal-component waveforms
25 result in unwanted signal-generated noise before the S wave in the synthetic SRFs. If the
26 mean amplitude of SRFs after the S wave is large, dubious signal-generated noise before the
27 S arrival are strong as well. In this study, we honor the level of these unwanted signal-
28 generated noise and devise data-oriented screening criteria to minimize the interference
29 between P coda waves and genuine S -to- P converted waves. The first criterion is LQR, a
30 direct measure of the amplitude ratio between longitudinal P coda waves and radial S wave in
31 the waveform data. The second criterion is AMP, the amplitude of SRFs after the S arrival.
32 We illustrate that these criteria effectively measure the energy level of mantle waves such as
33 the SP wave. With synthetics and real data, we demonstrate the effectiveness of LQR and
34 AMP criteria in minimizing these unwanted signal-generated noise in the stacked SRFs down
35 to 1–2%, improving detection threshold and interpretation of Sdp phases from seismic
36 discontinuities in the LAS.

37
38 **Key words:** Body waves; Structure of the Earth; Wave propagation, Wave scattering and
39 diffraction; Coda waves

41 **1 Introduction**

42 Oceanic lithosphere is typically thought to be the outcome of melting of undepleted
43 mantle and subsequent cooling, whereas continental lithosphere, especially beneath the
44 cratons, is often considered as the result of large-scale plume melting, stacking oceanic
45 lithospheres or/and arc collision (e.g. Lee *et al.* 2010). Small-scale convective instability,
46 episodes of metasomatism and hydration, among other mechanisms, potentially facilitate the
47 modification and disruption of oceanic and continental lithosphere. Unraveling robust seismic
48 signature with the lithosphere-asthenosphere system (LAS) is crucial to understanding of the
49 formation, modification and destruction of the plates and the formation of continents. For
50 instance, the lithosphere-asthenosphere boundary (LAB), a mechanical boundary separating
51 the rigid lithosphere and underlying viscous asthenosphere is thought to be the result of a
52 simple thermal boundary due to long-term cooling. Seismic LAB from such a thermal
53 boundary is considered smooth and gradual, where the velocity reduction with depth takes
54 place over a transition thickness on the order of 50 km (Fischer *et al.* 2010). However, recent
55 efforts have demonstrated that seismic LAB can be much sharper (e.g. Rychert *et al.* 2007;
56 Kawakatsu *et al.* 2009; Tharimena *et al.* 2017). Beneath the continents and many localities in
57 the oceans, seismic discontinuities have also been observed at depth ranges much shallower
58 than expected, and the nature of such mid-lithospheric discontinuities (MLDs) remains
59 elusive (e.g. Karato 2012; Schmerr 2012; Selway *et al.* 2015).

60 Therefore, it is clear that a robust and high-resolution seismic detection and
61 characterization of LAB or/and MLDs can revolutionize our understandings of plate tectonics
62 (e.g. Eaton *et al.* 2009; Fischer *et al.* 2010; Kawakatsu & Utada 2017). In the last decade, the
63 depth and spatial resolution of the seismic discontinuities are greatly improved, thanks to the
64 explosion of seismic data and progression of varieties of seismic techniques, including
65 teleseismic *P*-to-*S* receiver function (PRF) (e.g. Langston 1977; Rondenay 2009) and *S*-to-*P*

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3 66 receiver function (SRF) (e.g. Farra & Vinnik 2000), *ScS* reverberations (e.g. Bagley &
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5 67 Revenaugh 2008), and multiple *S*-wave triplications (e.g. Tan & Helmberger 2007) and
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7 68 underside *SS* precursors (e.g. Rychert & Shearer 2011; Schmerr 2012). Among these
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9 69 methods, PRF and SRF provide the highest resolution of seismic discontinuities in the LAS
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11 70 because of the use of relatively high-frequency waves (e.g. 0.1–1.0 Hz) in the analysis.
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14 71 While the PRF and SRF methods can effectively detect converted phases (*Pds* or *Sdp*,
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16 72 where ‘*d*’ marks the depth or location of the conversion) through source normalization (or
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18 73 deconvolution) and stacking, they are not without issues. For example, the PRF suffers
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20 74 interferences from backward scattering waves such as the first multiples from the Moho,
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22 75 making it difficult to identify converted-phase arrivals within the LAS. On the other hand, the
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24 76 SRF, by construction, separates the converted phases from the multiples (e.g. Ferra & Vinnik
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26 77 2000), and it is preferable to identify robust signal from the LAS. However, one major
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28 78 drawback is that *Sdp* converted waves can be interfered by *P* coda waves, which consist of
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30 79 multiple mantle *P* waves (e.g. Wilson *et al.* 2006), multiples of reflections between the
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32 80 surface and the transition zone (e.g. Bock 1994) or/and *S*-to-*P* scattering waves within the
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34 81 crust and lithosphere between the source and the receiver (e.g. Vinnik & Romanowicz 1991).
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36 82 Depending on the strength of scatters as well as epicentral distance, azimuth, earthquake
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38 83 source depth, and source mechanisms, the amplitudes and timings of these *P* coda waves may
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40 84 vary and a significant level of wave energy preceding the *S*-wave arrival can be erroneously
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42 85 taken as *S*-to-*P* phases converted beneath the stations. Therefore, a robust identification and
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44 86 interpretation of *S*-to-*P* converted waves in the SRF are not necessarily trivial, and data
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46 87 selection criteria can become the key to provide a more robust determination of sharp
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48 88 features in the LAS.
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56 89 The purpose of this paper is thus to introduce simple but effective screening criteria for
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58 90 the data selection and therefore removal of data or SRFs with strong unwanted signal-
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3 91 generated noise. We will first briefly review data selection criteria established in the
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5 92 literatures (e.g. Kumar *et al.* 2005; Yuan *et al.* 2006; Wilson *et al.* 2006; Abt *et al.* 2010;
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8 93 Kind *et al.* 2015; Shen *et al.* 2017). To devise an objective criterion to minimize the
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10 94 interference from *P* coda waves, as a proof of concept, we first examine scenario of SRFs
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12 95 recorded in South Korea seismic network, sitting on a geologically stable continental
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14 96 platform (Fig. 1). Through systematic analysis of full-waveform synthetics and SRFs from
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16 97 catalogued teleseismic earthquakes in 2005–2015 (Takeuchi *et al.* 1996; Kawai *et al.* 2006),
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18 98 we demonstrate the usage and effectiveness of the new data screening and selection criteria
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20 99 against previous efforts (e.g. Wilson *et al.* 2006) with synthetics as well as observed SRFs in
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24 100 South Korea.

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28 102 **2 Construction of SRF and previous efforts in the data selection criteria**

30 103 The calculation of SRF involves two important steps, that are (1) coordinate rotation,
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33 104 which isolates *Sdp* phase from the incident *S* wave, and (2) deconvolution, which removes
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35 105 source and propagation path effects (e.g. Farra & Vinnik 2000). Three-component north-east-
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37 106 vertical (N–E–Z) data are rotated to L–Q–T (or *P–SV–SH*) ray coordinate system (see also
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39 107 Rondenay 2009). While both of these coordinate systems are frequently implemented in past
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41 108 SRF studies (see review by Rondenay 2009; Kind *et al.* 2012), as demonstrated by
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43 109 Svenningsen & Jacobsen (2004) and discussed by Rondenay (2009), the difference of SRFs
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45 110 constructed in these two coordinate systems is minimum and much less than 1% (see Fig. 3 in
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47 111 Svenningsen & Jacobsen (2004)). Since the aim of this paper is to design the metrics to
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49 112 indicate the level of unwanted signal-generated noise prior to the *S* wave, we choose to
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51 113 discuss and illustrate the usage of our designed metrics in the L–Q–T system throughout this
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56 114 paper.

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3 115 As the L component is dominated by the P wave, Q and T components mostly contain
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5 116 energies from SV and SH waves, respectively. SRFs are then computed by deconvolving the
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7 117 S waveform in the Q component from the corresponding L component, in either time domain
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9 118 or frequency domain. To improve the signal-to-noise ratio (SNR), SRFs are binned and
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11 119 stacked. Throughout the paper, we will illustrate the usage and performance of our data-
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13 120 oriented screening criteria with the time-domain Wiener deconvolution method (Robinson &
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15 121 Treitel 1967), whereas examples with the frequency-domain deconvolution of various water
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17 122 levels can be referred to the Supplementary Information.

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19 123 Earlier works put emphasis on the selection of earthquakes in restricted epicentral
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21 124 distances or/and source depths (e.g. Wilson *et al.* 2006; Yuan *et al.* 2006). In an attempt to
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23 125 evaluate the robustness of the observed Sdp phases, Yuan *et al.* (2006) performed full
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25 126 waveform synthetics (Wang 1999) and suggested optimal epicentral distances of 55° – 85° for
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27 127 the construction of SRF, which avoid post-critical incoming S wave. However, the synthetic
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29 128 waveforms only include downgoing waves and upgoing waves were excluded. Consequently,
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31 129 the influence of surface-reflected P waves on the Sdp detection cannot be evaluated. On the
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33 130 other hand, Wilson *et al.* (2006) conducted full waveform synthetics (Fuchs & Müller 1971)
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35 131 and quantitatively measured the energy level before the S wave in the SRFs. They suggested
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37 132 a data selection criterion for the SRF at restricted epicentral distances of 60° – 75° and source
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39 133 depths of 300 km or less.

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41 134 The criterion by Wilson *et al.* (2006) was however based on synthetics from a single
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43 135 thrust-fault source mechanism and an one-dimensional (1-D) velocity model with a relatively
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45 136 thick crust of 70 km. Therefore, the established criterion needs not necessarily be the most
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47 137 general choice. As P coda waves can consist of multiple mantle P waves or/and S -to- P
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49 138 scattering waves within the crust and lithosphere between the source and the receiver, the
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51 139 amplitude and timing of these P coda waves not only depend on source depth (Wilson *et al.*
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3 140 2006), but it may also depend on the strength of scatters and source-receiver geometry and
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5 141 source mechanisms, or effectively the radiation pattern. Nevertheless, these data selection
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7 142 criteria have been commonly used in the SRF analysis, sometimes with a minor adjustment
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9 143 on either the range of epicentral distance or/and source depth (e.g. Hansen *et al.* 2009; Abt *et*
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11 144 *al.* 2010; Ford *et al.* 2010; Lekic & Fischer 2014; Hopper & Fischer 2015).

145 To improve the robustness and interpretation of the SRF and establish a more general
146 data selection scheme, our focus is to expand the work by Wilson *et al.* (2006) and establish
147 data-oriented selection criteria. In particular, by either contrasting the energy level between
148 the *S*-wave arrival in the Q-component waveform and *P* coda waves in the L-component
149 waveform, or measuring the amplitude of the SRF after the *S* wave, we introduce more direct
150 and general selection and screening criteria that do not necessarily rely on a specific choice of
151 the epicentral distance or source parameters, but honor the level of unwanted signal-
152 generated noise before the *S* wave.

153

154 **3 Design and construction of new data selection criteria for the SRF**

155 As discussed in previous sections, multiple mantle *P* waves or *S*-to-*P* scattering within
156 the crust and mantle between the source and receiver (Vinnik & Romonowicz 1991; Bock
157 1994; Wilson *et al.* 2006) can form the *P* coda waves. Depending on the amplitude of these *P*
158 coda waves preceding the *S*-wave arrival, they can interfere with converted waves, *Sdp*, from
159 the LAS beneath seismic stations, or even being erroneously identified as *Sdp*. Depending
160 upon the epicentral distance, source depth and mechanism, the level of interference can vary.
161 In other words, the energy level of *P* coda waves can be large even for a shallow event. Since
162 the effect of diverse source mechanism or radiation pattern on the excitation of these *P* coda
163 waves was not explored by Wilson *et al.* (2006), we conduct a systematic investigation

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3 164 through full waveform synthetics and examine the impact of realistic source mechanisms, or
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5 165 more importantly, the radiation pattern on the excitation and amplitude of P coda waves.
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9 166 As a proof of concept, we consider observations of one station from the South Korea
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11 167 seismic network (Lim *et al.* 2018) and examine full waveform synthetics from earthquakes
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13 168 with magnitude larger than 5.5 between 2004 and 2013 from the global CMT catalogue
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15 169 (Dziewonski *et al.* 1981; Ekström *et al.* 2012), located at the distances of 60° – 85° from the
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17 170 seismic network (Fig. 1). The event magnitude threshold of 5.5 allows detection of clear S -
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19 171 wave arrivals and identification of SMp arrivals from the Moho beneath the continental
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21 172 platform in South Korea. Since most stations generally contain quality waveform data from
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23 173 200–400 earthquakes after data quality control and screening, we randomly select 300
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25 174 earthquakes in our synthetic test. As expected in most realistic scenarios, synthetics data are
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27 175 predominantly from shallow events. Synthetic waveforms are computed with the Direct
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29 176 Solution Method (Takeuchi *et al.* 1996; Kawai *et al.* 2006) using the 1-D IASP91 model
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31 177 (Kennett & Engdahl 1991) as well as a modified IASP91 model (denoted as ‘L70’), which
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33 178 includes a 35 km thick high-velocity mantle lid with a 7.5% shear velocity increase below
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35 179 Moho, a low velocity zone with a 9% shear velocity reduction beneath 70 km depth, and a
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37 180 small 1.5% shear velocity increase beneath 120 km depth (Fig. S1; Table S1).
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44 181 To calculate synthetic SRFs, we first rotate synthetic waveforms with a time window of
45
46 182 100 s prior to and 100 s after the S wave to the radial-tangential-vertical (R–T–Z) system
47
48 183 using the theoretical event back-azimuth. Theoretical incidence angle of the S wave
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50 184 computed from the IASP91 model is used to rotate waveforms into the ray coordinate system
51
52 185 in the L–Q–T components (e.g. Rondenay 2009) before deconvolution (e.g. Kind *et al.* 2012;
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54 186 Shen *et al.* 2017). The waveforms in the Q component (e.g. the parent waveform) are
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56 187 windowed 10 s before and 35 s after the S -wave arrival and tapered with a 15% Hanning
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3 188 taper at both ends of the signal window. The L- and Q-component waveforms are then
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5 189 deconvolved by the parent waveform through the time-domain Wiener deconvolution method,
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8 190 which involves spiking of the output time series with the parent waveform and construction
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10 191 of Wiener-filter time series (Robinson & Treitel 1967). Minimum regularization with a white
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12 192 noise of 0.01% is applied in the calculation. Such a time series is then convolved with L- and
13
14 193 Q-component waveforms to obtain L- and Q-component SRFs, respectively. The resulting
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17 194 SRFs are bandpass filtered at 3–50 s and normalized by the spike in the Q-component at zero
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19 195 time. Hereafter, we will refer our discussion in the L-component SRFs.

22 196 **3.1 Inspections of synthetic SRFs**

26 197 Figs 2a and b display stacked synthetic SRF record sections, which consist of 300
27
28 198 individual SRFs, stacked with a 1°-distance bin and aligned along the *S* arrival at zero time.
29
30 199 Synthetics are computed with the IASP91 model (Fig. 2a) and the L70 model (Fig. 2b). The
31
32 200 converted waves from the Conrad (*SCp*) and the Moho (*SMp*) have a negative polarity and
33
34 201 they arrive at about 4–5 s before the *S* wave (Fig. 2). Crustal multiples (e.g. *SCpPCP* and
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36 202 *SMpPMP*) and other mantle waves such as *SP*, *sSP*, *pSPPP*, *sSPPPP* and *pSPPPPP* arrive at
37
38 203 about 5–60 s after the *S* wave (Fig. 2). Converted waves at the upper mantle seismic
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40 204 discontinuities from incident *ScS* and *SKS* waves (e.g. *ScS410p*, *ScS660p*, *SKS410p* and
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42 205 *SKS660p*) have a very different moveout from the *SMp* and they are less visible than those
43
44 206 shown in Yuan *et al.* (2006). On the other hand, as pointed out by Wilson *et al.* (2006), we
45
46 207 can observe spurious but consistent energies before the *SMp* arrival that are not associated
47
48 208 with converted waves from local structure beneath the receivers. Therefore, it is important to
49
50 209 set up a general data selection scheme to minimize these spurious arrivals.

57 210 After systematically inspecting synthetic waveforms and the resulting SRFs, we use
58
59 211 Fig. 3 to illustrate the motivation of our designated data selection criteria. We consider two

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 2
 3 212 earthquakes (events 1 and 2) such that their epicentral distances are comparable at $\sim 67^\circ$ and
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 5 213 the SNR of the S waves in the Q component are also similar (Fig. 1a, red beachballs).
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 7 214 However, regardless of the choice of IASP91 model or L70 model (Fig. S1), the P coda
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 9 215 waves in the L-component waveforms are comparably stronger in event 2 than those in event
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 11 216 1, arguing the effect of radiation pattern on the amplitude of these P coda waves. When
 12
 13 217 examining their SRFs, those from event 1 display clear SMp or/and SLp with otherwise weak
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 15 218 energy prior to the S wave (Figs 3a and b). On the other hand, SRFs from event 2 display
 16
 17 219 strong and spurious energy before and after the S wave (e.g. Figs 3c and d). It is noteworthy
 18
 19 220 to emphasize that, as the deconvolution scheme, data windowing and tapering procedures are
 20
 21 221 exactly the same between event 1 and event 2, strong spurious energy before the S wave in
 22
 23 222 the SRF directly corroborates with strong P coda waves in the L-component waveform of
 24
 25 223 event 2 (see also Figs S2 and S3 for the results with different windowing schemes). As noted
 26
 27 224 earlier, it is conceivable that these dubious signals may be mistakenly interpreted as Sdp
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 29 225 waves beneath seismic stations.
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226 3.2 Measurement of LQR and AMP and construction of stacked SRFs

227 Motivated by observation, we devise measures of LQR, the amplitude ratio between L-
 228 component P coda waves and Q-component S waves, and AMP, the amplitude of SRFs after
 229 the S -wave arrival. We then systematically test how the LQR and AMP thresholds may be
 230 used to detect and retain robust Sdp waves while minimizing dubious energies in the SRFs
 231 (Fig. 3). Here, we define LQR as

$$232 \quad \text{LQR} = \text{RMS}(\text{L}[t_3 \ t_4]) / \text{Max}(\text{Q}[t_1 \ t_2]), \quad (1)$$

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3 233 where $\text{Max}(Q[t_1 t_2])$ measures the peak amplitude of the S wave in the Q-component data
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5 234 window defined by t_1 and t_2 , and $\text{RMS}(L[t_3 t_4])$ measures the RMS amplitude of the P coda in
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7
8 235 the L-component time window defined by t_3 and t_4 . On the other hand, the AMP is defined as
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$$10$$

$$11 \quad 236 \quad \text{AMP} = \text{RMS}(\text{SRF}[t_5 t_6]), \quad (2)$$

$$12$$

$$13$$

14
15 237 where $\text{RMS}(\text{SRF}[t_5 t_6])$ measures the RMS amplitude of the SRF in the time window defined
16
17 238 by t_5 and t_6 with respect to the S arrival. In the subsequent analysis and demonstration, we set
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19 239 $t_1 = -5$ s, $t_2 = 10$ s, $t_3 = -60$ s, $t_4 = -20$ s, $t_5 = 20$ s, and $t_6 = 100$ s. Note that the choice of t_3 and
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21 240 t_4 is such that they do not include potential Sdp arrivals in the LAS.
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25 241 After measuring the LQR and AMP against all synthetic SRFs, we observe that SRFs
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27 242 with the lowest LQR typically fall in the distance range of 60° – 66° and those with the lowest
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29 243 AMP are typically in the distance range of 70° – 77° . However, to fully take advantage of the
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31 244 slant stack technique, it is important to ensure effective noise removal and to minimise data
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33 245 selection bias in epicentral distance. Therefore, it is more desirable that selected SRFs are
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35 246 evenly distributed within the entire distance range of 60° – 85° and are not falling in a narrow
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37 247 distance range. Consequently, synthetic SRFs in each 1° -distance bin are first selected
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39 248 according to a designated data selection threshold and subsequently stacked. The error is then
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41 249 estimated by the bootstrap method (Efron & Tibshiran 1998).
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47 250 In the following tests, we systematically examine how different LQR and AMP
48
49 251 thresholds determine the quality of the stacked SRFs. To determine the effectiveness of each
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51 252 data selection criteria in mitigating signal-generated noise, we sum stacked SRFs of each 1° -
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53 253 distance bin and measure the RMS amplitude of the summed SRF before the SMp arrival
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55 254 (denoted as AMP1). The AMP1 is defined as
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$$59 \quad 255 \quad \text{AMP1} = \text{RMS}(\text{SRF}[t_7 t_8]), \quad (3)$$

$$60$$

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3 256 where $\text{RMS}(\text{SRF}[t_7 t_8])$ measures the RMS amplitude of the SRF in the time window defined
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5 257 by t_7 and t_8 with respect to the S arrival. Here, we set $t_7 = -60$ s and $t_8 = -20$ s.
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9 258 **3.3 Evaluating the efficacy of the LQR and AMP criteria**

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11
12 259 In order to investigate the efficacy of LQR and AMP criteria for the SRFs, we consider
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14 260 two principles to judge the quality of stacked SRFs. First, if the data selection criterion is
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16 261 effective, we expect that the signal-generated noise before the S arrival shall be minimized.
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18 262 This can be visually inspected and quantitatively examined through the measurement of
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20 263 AMP1. Second, if the data selection criterion is effective, the amplitude of stacked SRFs
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22 264 against epicentral distance should follow closely the theoretical S -to- P transmission
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24 265 coefficient (Aki & Richards 2002) with minimum perturbation.
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30 266 **3.3.1 Presence/absence of signal-generated noise before S -wave arrival**

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33 267 To highlight how the data selection criteria influence signal-generated noise, synthetic
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35 268 SRFs with 25% lowest and 25% highest LQR (or AMP) in each distance bin are selected and
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37 269 subsequently stacked. For comparison, we also present stacked SRFs with the criterion by
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39 270 Wilson *et al.* (2006) and those with 25% randomly selected SRFs. Stacked SRF images at
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41 271 60° – 85° from the IASP91 model (Kennett & Engdahl 1991) and L70 model (Fig. S1) are
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43 272 shown in Fig. 4, whereas the sum of stacked SRFs and their 95% confidence interval are
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45 273 displayed in Figs 5a and 5b, respectively. For comparisons, stacked SRF waveforms (Figs
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47 274 5c–f) and stacked SRF images (Figs S4–7) with different parent window length (case 1; -10 s
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49 275 before and 15 s after the S wave), tapering (case 2; 5% Hanning taper), deconvolution scheme
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51 276 and regularization (cases 3 and 4; frequency-domain deconvolution with water level of 0.05%
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53 277 and 0.2%, respectively) are also presented for comparisons.
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3 278 For the IASP91 model, the first signal before the S arrival is a negative SMp phase
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5 279 arriving at about 4 s before the S arrival (Figs 4a–f and 5a). While the SMp signal can be
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8 280 consistently detected with different data selection criteria (Figs 4a–f and 5a), the amplitudes
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10 281 of SMp with the highest LQR and AMP criteria are much stronger and more variable than
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12 282 those with the lowest LQR or AMP criteria (Fig. 5a). In particular, signals up to 6–8% with
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14 283 positive amplitude can be detected before the SMp at the 95% confidence level (Fig. 5a).
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16 284 However, these signals are dubious as they do not corroborate with the absence of any sharp
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19 285 velocity gradient below the Moho (Fig. S1). While the criterion by Wilson *et al.* (2006) does
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21 286 a better job in reducing the amplitude of these dubious signals down to 3–4% (Fig. 5a), the
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23 287 lowest LQR and AMP criteria appear to be the most effective, minimizing dubious arrivals at
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25
26 288 the amplitude level of 1–2%, typically insignificant at the 95% confidence level (Fig. 5a).

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28 289 For the L70 model, we can observe a consistent, but positive signal arriving at about 9 s
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30 290 before the S arrival (Figs 4g–l and 5b). As expected, it is the S -to- P converted arrival (SLp)
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32 291 from the negative velocity discontinuity at the depth of 70 km (Fig. S1). Such a SLp signal
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34 292 has the same polarity and comparable strength as those used in previous studies to infer LAB
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36 293 or MLDs in the LAS (e.g., Eaton *et al.*, 2009; Abt *et al.*, 2010; Kumar *et al.*, 2012; Shen *et al.*,
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38 294 2015; Shen *et al.*, 2017). However, except the lowest LQR or AMP criteria, all other data
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40 295 selection criteria produce strong oscillations throughout the entire SRF stacks (Figs 4g–l),
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42 296 following slowness very similar to the SP wave. Even the SLp appears to be detected in this
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44 297 circumstance, the quality of the detection is low with incorrect amplitude and very large
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46 298 uncertainties (Fig. 5b). With the lowest LQR or AMP criteria, the SLp signal appears more
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48 299 robust with the smallest bootstrap uncertainties (Fig. 5b). It is evident that the signal-
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50 300 generated noise before the S arrival are much weaker in the stacked SRFs produced with the
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52 301 criteria of the lowest LQR (Figs 4g and 5b) or AMP (Figs 4i and 5b) than those produced
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3 302 with the highest LQR (Figs 4h and 5b), the highest AMP (Figs 4j and 5b), the criterion by
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5 303 Wilson *et al.* (2006) (Figs 4k and 5b) or with random data selection (Figs 4l and 5b).
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8 304 These observations can be concluded with alternative window length of the parent
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10 305 waveform (case 1; Figs 5c and S4), tapering (case 2; Figs 5d and S5) or deconvolution
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12 306 scheme (e.g. frequency-domain water-level deconvolution) with different regularization
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14 307 (cases 3 and 4; Figs. 5e, 5f, S6, and S7). Stacked SRFs produced with the criteria of the
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16 308 lowest LQR or AMP are stable, regardless specific choices of these data processing
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18 309 procedures. Evidently, stacked SRFs with other criteria vary more substantially with the
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20 310 choice of data processing routines. More critically, while a stronger regularization does
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22 311 minimize amplitude oscillation (e.g. case 4; Fig. 5f), strong signal-generated noise arriving
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24 312 before the SLp arrival remains.
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30 313 To quantitatively assess the quality of stacked SRF and the effectiveness of data
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32 314 selection criteria in mitigating the signal-generated noise, we compute AMP1 to measure the
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34 315 RMS amplitude in the designated time window before the S arrival. We systematically select
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36 316 a subset of all synthetic SRFs by varying the percentage threshold (10–50%) of the lowest
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38 317 and highest LQR or AMP, generate the summed SRF and calculate AMP1. As shown in Fig.
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40 318 6, the value of AMP1 generally decreases with increasing percentage threshold of six
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42 319 different criteria. At 25% threshold, AMP1 of the lowest LQR or AMP is lower than that of
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44 320 the highest LQR or AMP by more than a factor of 4 (Fig. 6). Also, at 25% threshold and
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46 321 higher, AMP1 of the lowest LQR or AMP is less than AMP1 of all SRFs (Fig. 6a). In
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48 322 particular, we find that the SRFs constructed with the lowest AMP generally display a lower
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50 323 level of AMP1, and the improvement is even more substantial for the synthetic SRFs from
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52 324 the L70 model (Fig. 6b). AMP1 of the lowest AMP for the L70 model is lower by a factor of
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54 325 2 or less than that measured against the summed SRF of the entire SRF dataset (Fig. 6b).
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3 326 In the case of random data selection, the value of AMP1 does not show appreciable
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5 327 difference with respect to the percentage threshold (Fig. 6), whereas the criterion of Wilson *et*
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7 328 *al.* (2006) does not seem to improve AMP1 upon those from random data selection (Fig. 6),
8
9 329 which is not unexpected as synthetic data are predominantly from shallow events. In a way,
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11 330 even with a smaller volume of the entire synthetic SRFs (e.g., 25% or less), the lowest LQR
12
13 331 or AMP criterion achieves a much lower AMP1 than that of Wilson *et al.* (2006)'s using 50%
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15 332 of the entire synthetic SRFs. Notably, depending on the exact data selection threshold, AMP1
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17 333 with lowest LQR or lowest AMP criteria can be 20–50% lower than AMP1 of all events (Fig.
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19 334 6).

25 335 3.3.2 Validating the amplitude of the *S-to-P* converted waves

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28 336 To further verify the robustness of the converted phases beneath the receiver and assess
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30 337 the stability of the signal, we measure the amplitudes of *Sdp* (e.g. *SMp* and *SLp*) and compare
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32 338 them against the theoretical *S-to-P* transmission coefficient (Aki & Richards 2002). If the
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34 339 amplitudes of *Sdp* from the stacked SRFs follow closely to the theoretical transmission
35
36 340 coefficients, we consider that the data selection criteria are effective in removing signal-
37
38 341 generated noise and recovering a truthful detection. Fig. 7a shows distance-dependent
39
40 342 amplitudes of *SMp* measured against stacked SRFs of six different criteria for the IASP91
41
42 343 model. On the other hand, Figs 7c and 7d show distance-dependent amplitudes of *SMp* and
43
44 344 *SLp* measured against stacked SRFs of different criteria for the L70 model, respectively. Fig.
45
46 345 7b shows the amplitudes of the SRFs measured in the same time window as that used in Fig.
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48 346 7d for comparison. Since we do not expect a truthful detection of *SLp* for the IASP91 model,
49
50 347 the measurements are indicative of the level of signal-generated noise.

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52 348 Typically, the highest LQR or AMP criterion results in unstable estimate of *SMp*
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54 349 amplitudes (e.g. Figs 4 and 5), and their amplitudes strongly deviate from the theoretical

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3 350 predictions (Figs 7a and c). Stacked SRFs from the random data selection or from the
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5 351 criterion of Wilson *et al.* (2006) also suffer similar distortion, but to a less degree (Fig. 7). On
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8 352 the other hand, given the selection criteria of 25% lowest LQR or AMP, the amplitude of
9
10 353 *SMp* follows closely to theoretical calculation against distance (Figs 7a and c). Similarly, the
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12 354 amplitude of *SLp* against distance generally follows theoretical prediction when the data
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14 355 selection criteria of 25% lowest LQR or AMP are implemented (Fig. 7d). Our results indicate
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16 356 that the lowest LQR or AMP is useful for detecting *SLp* phases and retaining their amplitudes
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18 357 by reducing the dubious signals before the *S* wave. We note that the average amplitude within
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20 358 the time window for expected *SLp* arrivals is typically on the order of 2% for the lowest
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22 359 LQR, and of ~1% for the lowest AMP (Fig. 7b). Therefore, we suggest 2% as the minimum
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24 360 amplitude threshold above which the robust identification of local *Sdp* converted waves
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26 361 within the LAS can be made and interpreted.

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32 362 In summary, we find that the SRFs constructed with the lowest LQR or AMP generally
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34 363 display a lower level of spurious energy before the *S* wave while the SRFs with the highest
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36 364 LQR or AMP, as expected, displays a higher level of signal generated noise (Figs 4–7). The
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38 365 improvement appears more substantial in the case where synthetic SRFs are computed from
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40 366 the L70 model (Fig. 6b). While the calculation of SRF can be influenced by the choice of
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42 367 time window and tapering in the parent waveform as well as the deconvolution scheme (e.g.
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44 368 Lekic & Fischer 2017), the performance of LQR and AMP data selection criteria does not
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46 369 depend on such specific choices. This characteristic makes the LQR and AMP very desirable
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48 370 since stacked SRFs with low LQR and low AMP are always very stable.

371 3.3.3 The sources of *P* coda waves?

372 To investigate the source of these *P* coda waves, we first examine if the attributes
373 such as LQR or AMP depend on epicentral distance, event back azimuth or source

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3 374 parameters. However, we do not observe any obvious selection bias in event epicentral
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5 375 distance or back azimuth against the criteria such as LQR and AMP (Fig. S8), nor do we find
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8 376 dependence of LQR or AMP on earthquake source mechanism (Fig. S9), suggesting that
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10 377 LQR and AMP, or the level of P coda waves, are predominantly dictated by the radiation
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12 378 pattern. In this regard, while we do not specifically include SV/SH amplitude ratio in the data
13
14 379 selection criteria, high LQR or AMP criterion more often corresponds to data with a low
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16
17 380 SV/SH ratio (< 1) and low LQR or AMP typically corresponds to data with a high SV/SH
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19 381 ratio (> 1) (Fig. 8).
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23 382 It has been argued by Wilson *et al.* (2006) that P -coda waves can come from
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25 383 multiples such as $pPPP$, $pPPPP$ or/and $sPPPP$ from deep events (> 300 km) and they may
26
27 384 interfere with Sdp phases. However, for most practical analysis on the LAS, only those from
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29 385 really deep events of 450 km or deeper may directly interfere with Sdp from the LAS since
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32 386 these multiples, in most instances, arrive at least 1–2 minutes before the S arrival. Similar
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34 387 lines of arguments have been also pointed out by Vinnik & Romanowicz (1991). This
35
36 388 assertion can be supported by the fact that P radiation patterns computed with the slowness
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39 389 such as $pPPPP$ wave do not distinguish against LQR or AMP (Fig. 9). This is also consistent
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41 390 with our observation that, when shallow events dominate the synthetic dataset, Wilson *et al.*
42
43 391 (2006)'s criterion does not necessarily outperform data selection scheme of random choice
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45 392 (Figs 5b–f; see also Figs S4–7).
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49 393 As shown in Figs 4g–l, signal-generated noise before the S arrival appear to follow very
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51 394 similar slowness as those mantle waves such as SP , sSP , $sSPPP$, and $sSPPPP$, apparently
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53 395 forming precursors of these mantle waves and interfering with Sdp phases in the LAS. It is
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55 396 conceivable that energies prior to the S wave in the stacked SRF are likely to be scattering
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58 397 waves such as $S\bullet P$ and $SP\bullet P$, where $S\bullet P$ denotes S -to- P scattering wave from the free surface
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3 398 and $SP\bullet P$ denotes SP -to- P scattering wave from the scatter in the crust (Vinnik 1981; Vinnik
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5 399 & Romanowicz 1991). Depending on the lead time of scattering waves with respect to the S
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7 400 wave, the area of scattering is expected to be at least 25° from the receiver, and typically in
8
9 401 the range of 30° – 40° from the receiver (see Fig. 8a of Vinnik & Romanowicz (1991)), with
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11 402 the raypaths of S and P waves in the $S\bullet P$ (or $SP\bullet P$) arriving in different vertical planes. As
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13 403 our wave propagation simulation is done with a laterally homogeneous and spherically
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15 404 symmetric earth model (Kawai *et al.* 2006) with a finite duration S wave, spherical waves
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17 405 propagating off the vertical plane defined by the source and receiver likely result in scattering
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19 406 waves such as $S\bullet P$.

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25 407 If $S\bullet P$ or/and $SP\bullet P$ scattering waves are indeed the cause of these signal-generated
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27 408 noise observed in SRFs, the SV radiation pattern in the area of scattering will directly control
28
29 409 the amplitude of $S\bullet P$ and $SP\bullet P$ scattering waves (Vinnik & Romanowicz 1991). To validate
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31 410 this, we assume that the scattering area is near the surface reflection point of SP wave and
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33 411 compute SV radiation pattern with the slowness of SP wave in our synthetic dataset. As
34
35 412 shown in Fig. 10, the SV radiation patterns against the lowest LQR and AMP criteria are
36
37 413 generally much weaker than those against the highest LQR and AMP criteria. Effectively,
38
39 414 LQR and AMP criteria help select data with weakest SV radiation pattern in the scattering
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41 415 area. Following the same line of reasoning, it is conceivable that $S\bullet P$ scattering waves can
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43 416 come from internal boundaries such as the Moho. While a more elaborated investigation
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45 417 should be done in the future, this is consistent with our simulation that signal-generated noise
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47 418 in SRF are much stronger in the L70 model, which includes a larger velocity contrast across
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49 419 the Moho than the IASP91 model as well as an additional velocity reduction at 70 km depth
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51 420 (Fig. S1).

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3 421 Evidently, there is no lateral variation in surface topography, internal boundary or
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5 422 velocity in our simulation, and it is difficult to precisely estimate the scattering potential
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7 423 without invoking 2-D or 3-D full waveform modelling. It is also possible that signal-
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9 424 generated noise in 2-D or 3-D models are less coherent and do not add constructively.
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11 425 However, our data-oriented screening criteria such as LQR or AMP are designed to honor the
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13 426 data and provide direct and straightforward attributes to measure the level of these spurious
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15 427 energies. With lowest LQR or/and AMP, SRFs with strong signal-generated noise are
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17 428 effectively removed, improving the quality of stacked SRF and the detection of true *Sdp*
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19 429 arrivals in the LAS beneath seismic stations.
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27 431 **4 Application to South Korea seismic data: detection and characterization of seismic** 28 29 432 **discontinuities in the LAS**

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33 433 Our synthetic tests have demonstrated that the effectiveness of LQR and AMP could
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35 434 serve as general data selection criteria for the construction of SRF. Here we apply these new
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37 435 data selection criteria to the dataset recorded by South Korea seismic network (Fig. 1) (Lim
38
39 436 *et al.* 2018) and illustrate its effectiveness in real datasets. We select earthquake magnitudes
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41 437 greater than 5.5 within the epicentral distance range of 60°–85° from the seismic network. To
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43 438 construct the SRF, we follow exactly the same scheme detailed in the synthetic test in Section
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45 439 3, but highlight a few key additional steps here to screen noisy data. First, when rotating
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47 440 three-component waveforms into L-Q-T coordinate system, the incidence angle of the
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49 441 incoming *S* wave is determined by maximizing the *SV*-wave energy on the Q component
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51 442 within the time window spanning ± 2 s on either side of the theoretical *S*-wave onset. If the
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53 443 difference between the observed incidence angle and the predicted one (from IASP91)
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55 444 exceeds 25°, the waveforms are rejected. Secondly, data are also removed if the SNR of the *S*
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3 445 wave in the Q component is less than 5. Thirdly, if the peak SRF amplitude in the L
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5 446 component is larger than 0.5 or if the mean amplitude of the SRF in the L component is
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7 447 larger than 50% of its peak amplitude, such SRFs are apparently oscillatory throughout the
8
9 448 entire time window and they are also rejected.
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13 449 As an example, we examine stacked SRFs at station TJN in South Korea seismic
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15 450 network (Fig. 1b) in detail. We process waveform data from 917 events in January 2005–
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17 451 January 2015 (Lim *et al.* 2018) and, after preliminary data quality control detailed earlier,
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19 452 316 SRFs are retained and they are filtered at 3–50 s before subsequent data selection
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21 453 analysis. Here we measure LQR and AMP against the observed SRFs exactly the same way
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23 454 as discussed in Section 3. In general, the lowest LQR and AMP against the observed SRFs
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25 455 are typically higher than that against synthetic SRFs because of noise. With the nominal
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27 456 percentage threshold of 25%, we finally retain about 80 SRFs.
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33 457 To illustrate how the stability of the SRF and detection of SMp and SLp depend on the
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35 458 data selection criteria, Fig. 11 (and Fig. S10) displays stacked SRF images constructed with
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37 459 the same six different data-selection criteria as discussed in the synthetic test in Section 3
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39 460 (e.g. Fig. 4). With the lowest LQR or AMP criterion (Figs 11a and c), we can reasonably
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41 461 track a consistent signal with negative amplitude with respect to epicentral distance, arriving
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43 462 about 4 s before the S arrival, presumably Sdp from the Moho (SMp). However, it is less
44
45 463 trivial to track SMp in stacked SRF image with the Wilson *et al.* (2006)'s criterion (Fig. 11e)
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47 464 or random selection criterion (Fig. 11f), and very difficult to do so against those constructed
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49 465 with the highest LQR or AMP criterion (Figs 11b and d). These observations can also be
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51 466 made against stacked SRF images using a stronger regularization of 1% white noise (Figs
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55 467 S13 and S14).
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3 468 Stacking the SRFs shown in Fig. 11, Figs 12a and b displays summed SRF waveforms
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6 469 and their bootstrapped uncertainties against the six different data-selection criteria and data
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8 470 selection threshold of 25% and 50%, respectively. Again, using the lowest LQR, AMP or
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10 471 Wilson *et al.* (2006)'s criterion, detection of *SMp* can be made at the 95% confidence level
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12 472 (Fig. 12). With the highest LQR or AMP criterion, the *SMp* can be barely detected at the 95%
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14 473 confidence level with large uncertainties (Fig. 12a and b). Even with a stronger regularisation
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16 474 (1% white noise), *SMp* still possesses large uncertainties (Fig. 12c). It is important to note
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18 475 that the uncertainties of SRF with low LQR and AMP are much smaller than those with high
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20 476 LQR or AMP or random selection (Fig. 12). In principle, a consistent detection of *SMp* with
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22 477 small amplitude uncertainties serves as a very good indication on the quality of stacked SRF.
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24 478 Furthermore, with the lowest LQR or AMP criterion, a positive signal arriving at about 8 s
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26 479 before the *S* arrival, possibly *SLp* from the LAS, can be detected at 95% confidence level
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28 480 (Fig. 12), whereas such a *SLp* arrival cannot be detected otherwise with statistical
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30 481 significance (Fig. 12). We note that the amplitude of detected *SLp* is about 5–7%,
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32 482 considerably exceeding the 1–2% amplitude threshold for robust *SLp* detection with the
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34 483 lowest LQR or AMP criterion (e.g. Figs 4 and 5b).

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41 484 Considering three data-selection criteria such as the lowest LQR, AMP and Wilson *et*
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43 485 *al.* (2006), Fig. 13 further examines distance-dependent amplitudes of detected *SMp* and *SLp*
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45 486 and they are compared against theoretical *S*-to-*P* transmission coefficient (Aki & Richards
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47 487 2002) from the L70 model (Fig. S1). Here we do not seek an optimal fit to the data, but
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49 488 simply show if the amplitude measurements in general follow the theoretical trend against
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51 489 epicentral distance. While there are still substantial amplitude fluctuations with respect to
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53 490 theoretical prediction against epicentral distance, in this particular example at station TJN,
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55 491 measurements from the lowest AMP criterion follows closest to the theoretical trend,
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3 492 regardless the degree of regularization (Figs 13a and b vs. Figs 13c and d). As expected, the
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5 493 amplitude of SMp and SLp is notably modulated by the degree of regularization.
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8 494 At least locally beneath the station TJN, a relatively sharp boundary with a negative
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10 495 velocity gradient is robustly identified in the LAS beneath the old Korea craton (Lee *et al.*
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12 496 1998). While the exact nature and spatial extent of such a boundary deserves further analysis
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14 497 and discussion, it is beyond the scope of this paper and we will detail the findings beneath the
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16 498 entire Korea network in a subsequent paper. Also, another key potential source of
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18 499 contamination on SRFs is scattering from laterally-varying structure (Lekic & Fischer 2017).
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23 500 Lastly, Fig. 14 displays AMP1 against data-selection percentage threshold for six
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25 501 different criteria. Similar to what we observe in the synthetics (Fig. 6), the results from real
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27 502 data analysis at station TJN also show that not only AMP1 decreases with increasing
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29 503 percentage threshold, but the lowest LQR or AMP criterion gives the lowest AMP1 than
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31 504 Wilson *et al.* (2006) or the random data selection does (Fig. 14), compatible with synthetic
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33 505 test in Section 3 (Fig. 6). Despite the criterion of Wilson *et al.* (2006) restrains SRFs within
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35 506 60° – 75° from shallow events, the lowest LQR or AMP criterion does concern SRFs across
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37 507 the entire distance range of 60° – 85° , including a few SRFs from deep earthquakes as well.
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39 508 Furthermore, since the level of random noise reduction is proportional to the square-root of
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41 509 SRF number in the stacks, there is a trade-off between eliminating random noise and signal-
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43 510 generated noise. While random noise can be reduced by stacking, it is not the case for signal-
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45 511 generated noise. In comparison to the cases shown in Figs 11 and 12, while we can still detect
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47 512 SMp and SLp at 95% confidence level with a higher percentage threshold of 50%, the
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49 513 uncertainty of SRF amplitude does not decrease as expected for random noise (Figs S11 and
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51 514 S12). By inspection, if N is the data selection percentage threshold, multiplying AMP1 in Fig.
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53 515 6 (noise free) with the square root of $100/N$ generally reproduces the pattern of AMP1 shown
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3 516 in Fig. 14. This can be useful in the discussion on how to properly select N against random
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5 517 noise with respect to data quality and noise level.
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9 518 In the case of our test, permanent station TJN provides about 300 quality data over 10
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11 519 years after data prescreening. As we present the result with 25% selection threshold (or ~75
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13 520 traces) for the detection of the *SLp* phase (Figs 11–13), we find a 15% selection threshold (or
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15 521 ~45 traces) with the low AMP criteria can still provide consistent SRF and *SLp* detection.
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17 522 Concerning typical PASSCAL experiments or temporal arrays over a 2-year period,
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19 523 depending on the aperture of the array, the number of stations, background noise level and
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21 524 the scale of lateral heterogeneity in the LAS, it is conceivable that a network of 5 stations can
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23 525 record 45 traces with low LQR and produce reasonably robust SRF stacks.
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28 526 As evident in the synthetic test and real data analysis, high SNR of the *S* wave in the Q-
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30 527 component seismogram by itself does not necessarily warrant the quality of stacked SRFs.
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32 528 The data selection criterion proposed by Wilson *et al.* (2006) is favorable for a specific focal
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34 529 mechanism, but it is not necessarily a general scheme that takes into account the effect of
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36 530 radiation pattern on the excitation of mantle *P* coda waves or/and scattering waves between
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38 531 the source and receiver in the L-component seismogram. In this study, the LQR criterion, by
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40 532 design, makes a direct amplitude measurement of the scattering wave in the L component and
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42 533 contrasts it against the amplitude of the *S* wave in the Q component. Obviously, the
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44 534 application of LQR criteria in real data analysis slightly depends on the choice of
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46 535 measurement time window, which may be adapted. Alternatively, the AMP data selection
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48 536 criterion makes a direct assessment on the amplitude of *SP*, *sSP* and other related multiples in
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50 537 the SRF, making it an ideal proxy to indicate the strength of scattering waves away from the
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52 538 receiver side (e.g., Vinnik & Romonowicz 1991). Finally, these data selection criteria can be
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54 539 easily adapted to a different coordinate system (e.g., *P-SV-SH*) when desired.
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6 541 **5 Conclusions**
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8 542 Teleseismic scattered waves such as *S*-to-*P* converted phases (*Sdp*) provide enhanced
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10 543 sensitivity to localized velocity gradients across the lithospheric discontinuities. In this study,
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12 544 through systematic analysis of full-waveform synthetic waveforms and SRFs from
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14 545 catalogued earthquake focal mechanism and depth, we find that the strong *P* coda waves
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16 546 before the *S* wave recorded in the L component could result in the dubious *Sdp* phases in the
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18 547 synthetic SRFs before the *S* arrival. Furthermore, if the mean amplitude of SRFs after the *S*
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20 548 wave is large, dubious signals of SRFs before the *S* arrival become strong as well. Such
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22 549 signal-generated noise before the *S* arrival can be mistakenly interpreted as *Sdp* phase derived
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24 550 from lithosphere-asthenosphere system (LAS) beneath seismic stations.
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28 551 To minimize the interference of *P* coda waves on *Sdp* phases in the LAS, we devise
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30 552 data-oriented criteria such as LQR, the amplitude ratio between *P* coda waves of the L-
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32 553 component waveform and the *S* wave of the Q-component waveform, and AMP, the
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34 554 amplitude of SRFs after the *S* arrival. These screening criteria provide a direct and
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36 555 straightforward attribute to measure and indicate the level of spurious energies before the *S*
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38 556 arrival in the SRF. With low LQR or AMP, regardless of the choice of deconvolution scheme,
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40 557 tapering or/and data windowing, unwanted signal-generated noise are largely removed, which
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42 558 improves the detection and quality of locally converted *Sdp* in the LAS. With the criteria
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44 559 such as the lowest LQR or AMP, the minimum amplitude threshold above which robust *SLp*
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46 560 can be detected is reduced down to about 1–2%, smaller than the amplitude threshold of 3–4%
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48 561 by the criterion of Wilson *et al.* (2006). The effectiveness of these criteria largely manifests
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50 562 the amplitude of *SP* wave as well as the control of *SV* radiation pattern in the scattering area
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52 563 on the amplitude of signal-generated noise due to *S*-to-*P* scattering (Vinnik & Romanowicz
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54 564 1991). Applying the newly designed selection criteria to real data in the South Korea seismic
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3 565 network, we demonstrate that the lowest LQR or AMP criterion provides robust detection of
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5 566 *SLp* beneath the test station TJN, offering a great potential to better characterize seismic
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8 567 discontinuities in the LAS.
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4

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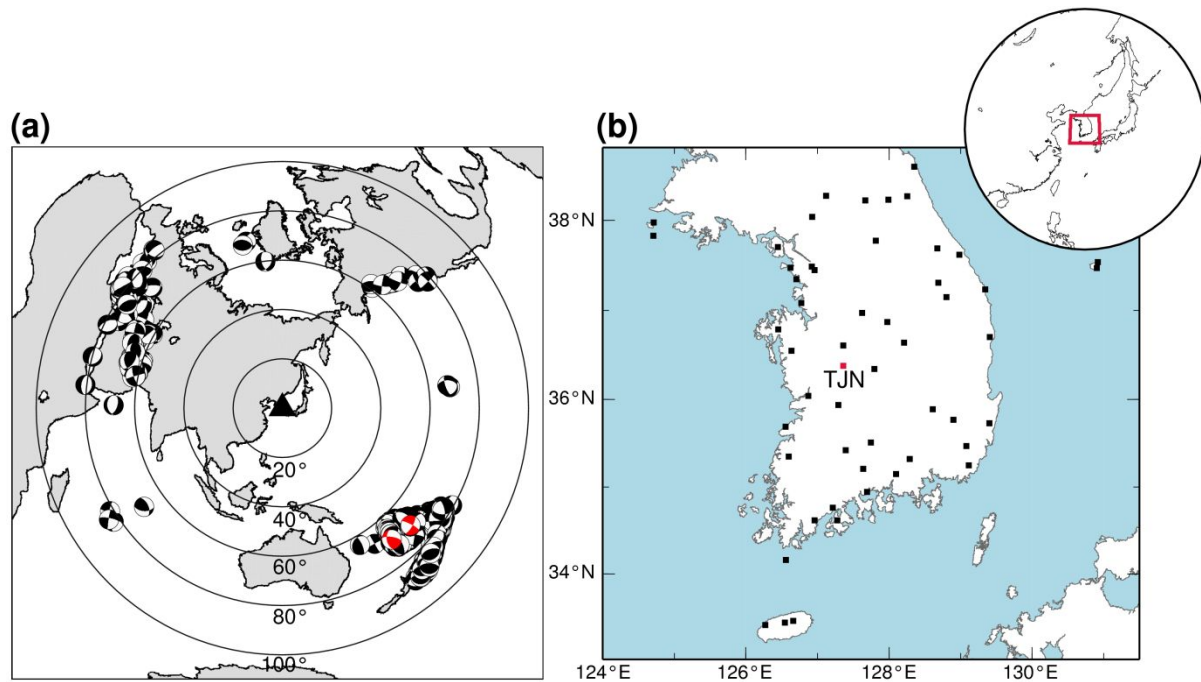
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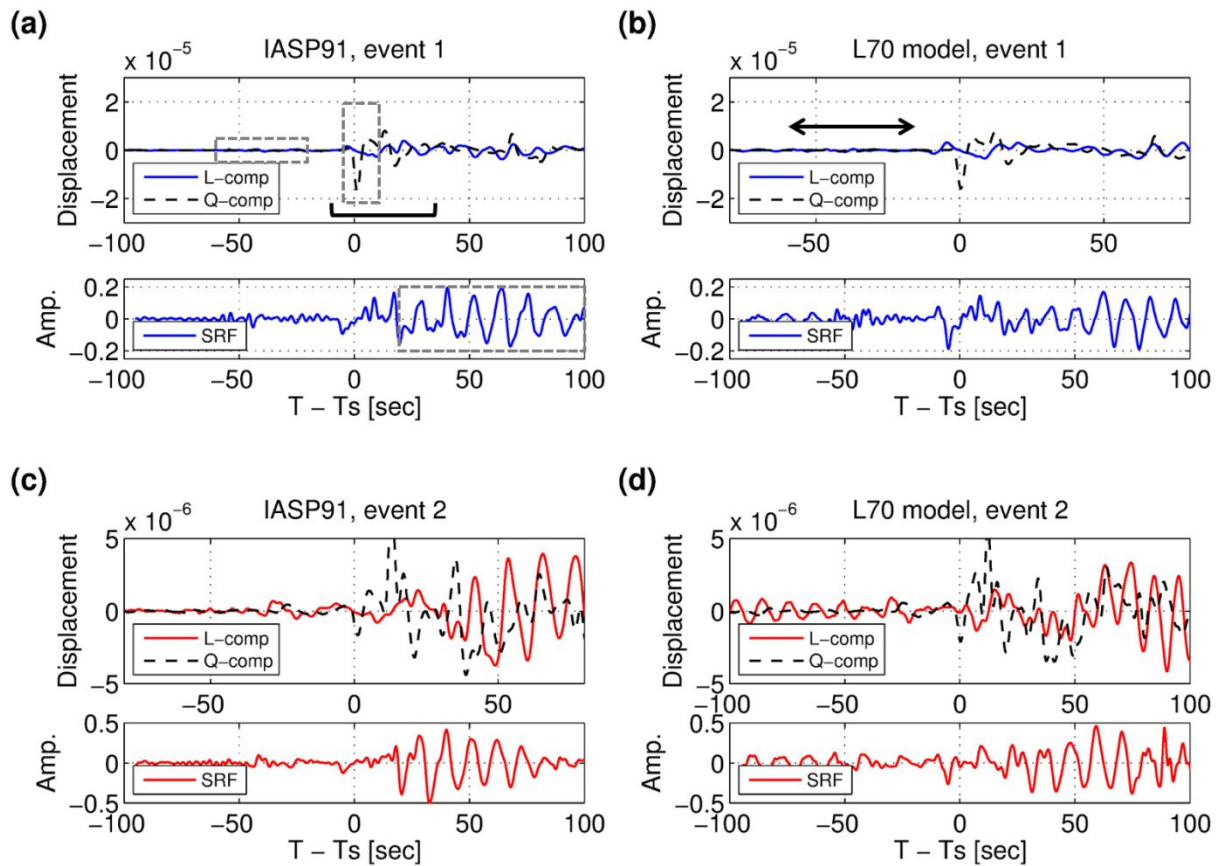
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727 **Figures**

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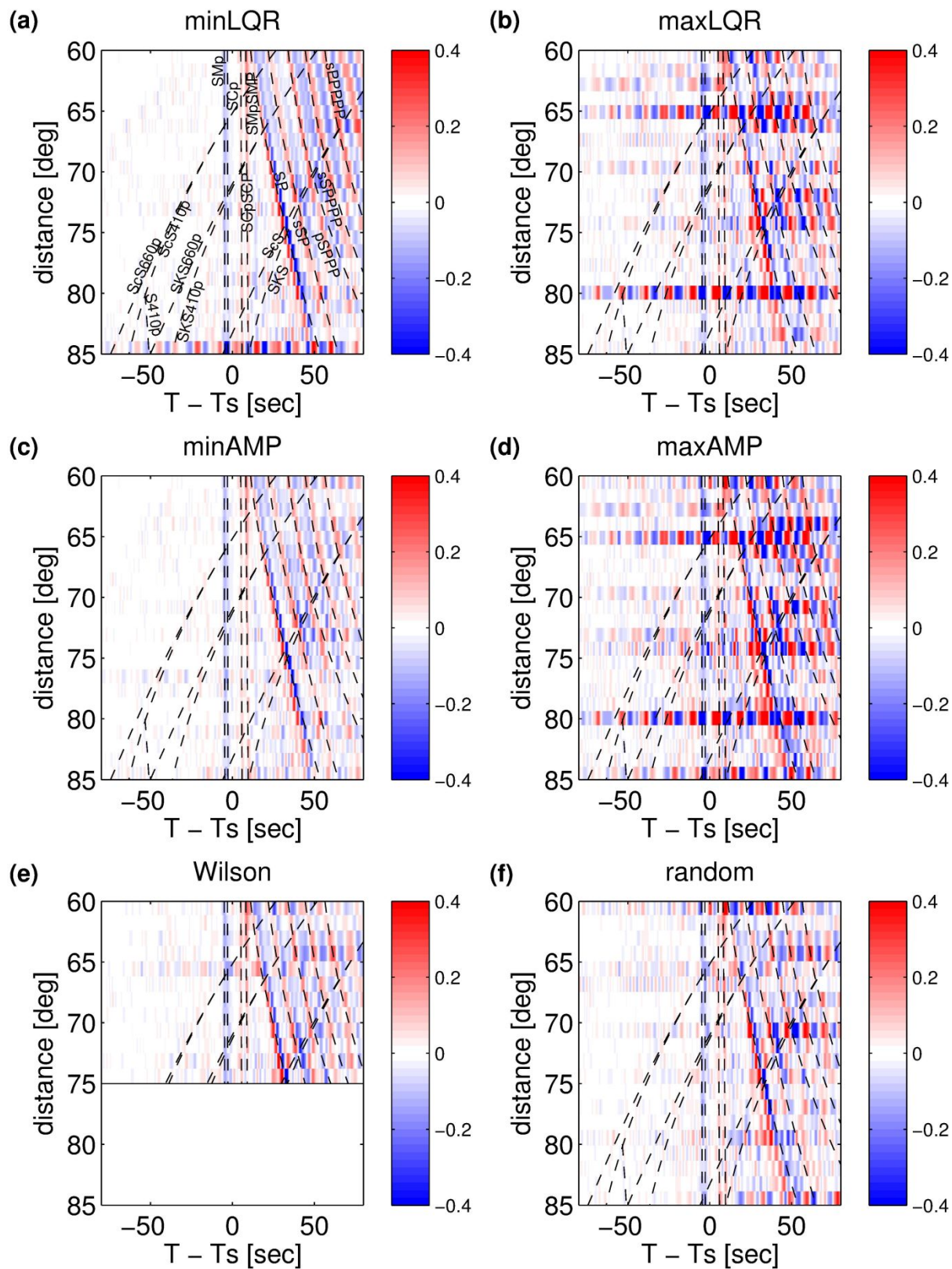
729 **Figure 1.** Distribution of earthquakes with magnitude greater than 5.5 and South Korea
 730 seismic network. (a) Distribution of earthquakes within the epicentral distances of 60°–85°
 731 from the center of the Korean seismic network (black triangle). The Centroid Moment Tensor
 732 (CMT) solutions of the events are from Dziewonski *et al.* (1981) and Ekstrom *et al.* (2012).
 733 Two earthquakes for synthetics in Fig. 3 are highlighted in red. (b) South Korea seismic
 734 network. Broadband seismic stations are shown in black squares, and the only station is
 735 labelled with the station ID (TJN).



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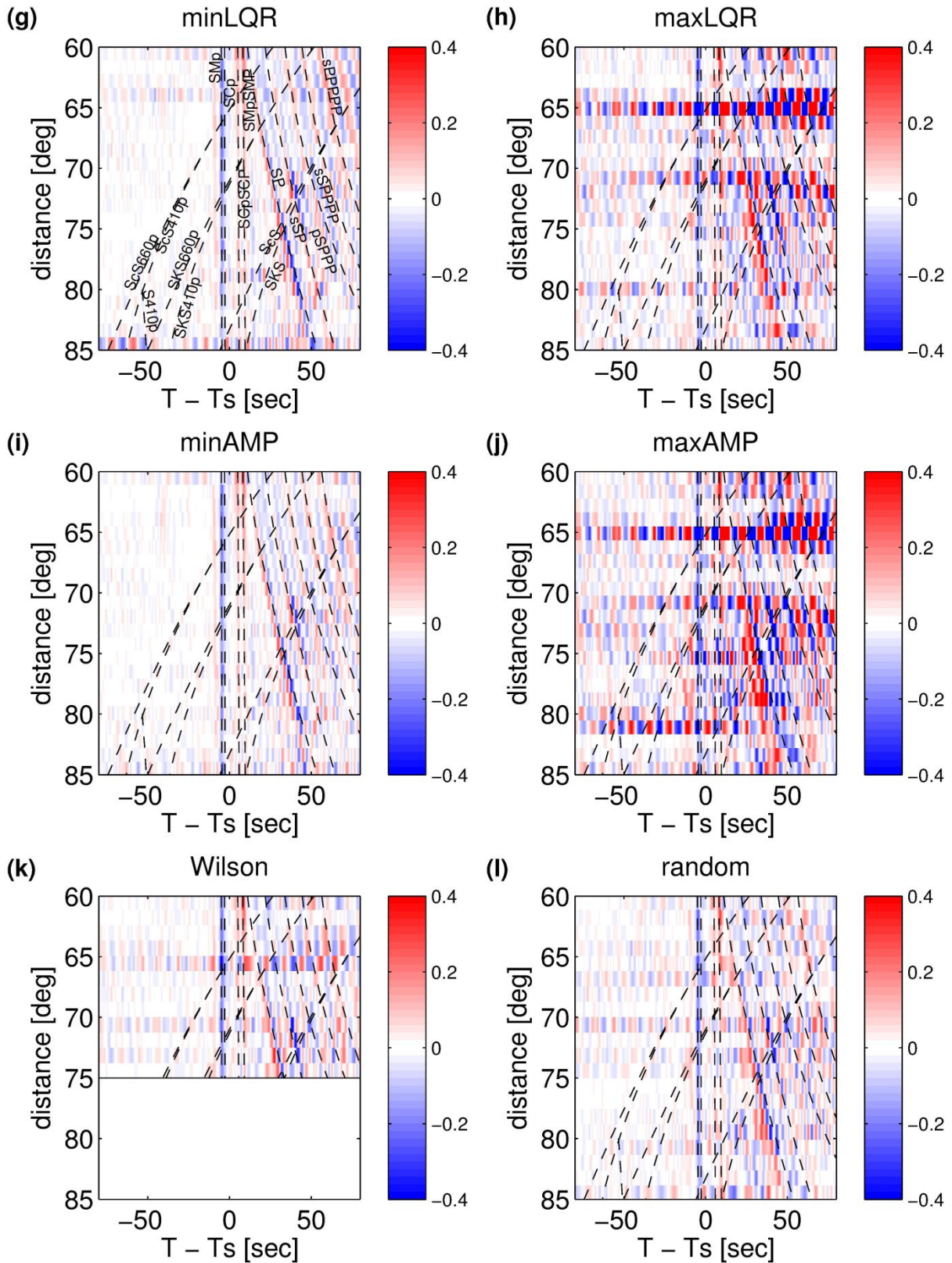
744 **Figure 3.** Examples showing *P* coda waves and their influence on signal-generated noise in
 745 the SRF. Gray dashed boxes in panel (a) indicate how LQR is measured from the L- and Q-
 746 component synthetic seismograms and how AMP is measured from synthetic SRF. Synthetic
 747 waveforms are computed from two earthquake sources (Fig. 1a, red beachballs) using the
 748 IASP91 (Kennett & Engdahl 1991) (a and c) and the L70 model (Fig. S1) (b and d). *S*-wave
 749 arrivals are aligned at zero time in the Q-component waveforms (dashed lines), and a time
 750 window for *P* coda waves are marked in a panel b (double arrow). Time-domain Wiener
 751 deconvolution method with minimum regularization (0.01% white noise) is performed within
 752 the parent waveform time window of 10 s before and 35 s after the *S* arrival (black bar in a
 753 panel a). Note the amplitude scale of SRF in case 2 is higher than that in case 1. See Figs S2
 754 and S3 for cases for the time window of [-10 s 15 s] and [-10 s 10 s] with respect to *S* arrival,
 755 respectively.

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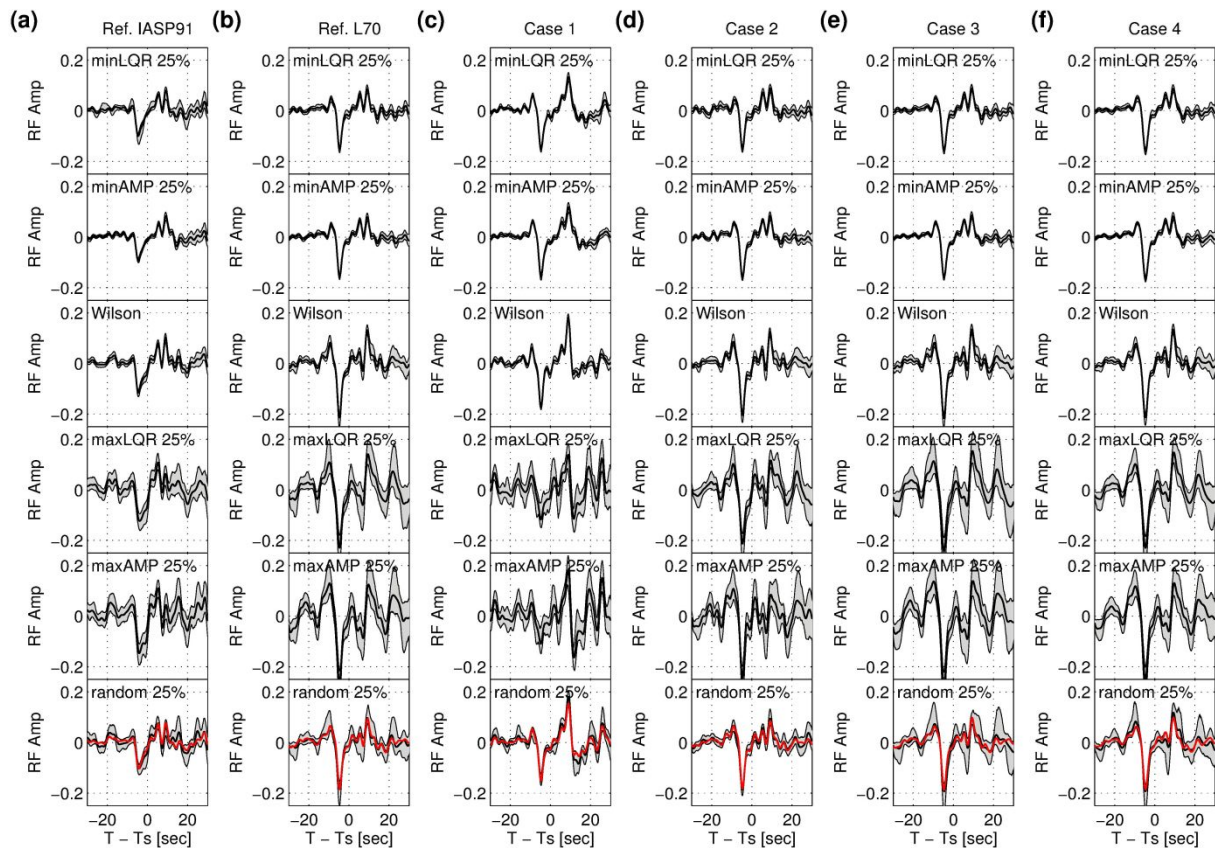
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761 **Figure 4.** Images of synthetic SRFs for the IASP91 model (a–f) and L70 model (g–l) against

762 epicentral distance and six data selection criteria. The SRFs are plotted in the same way as

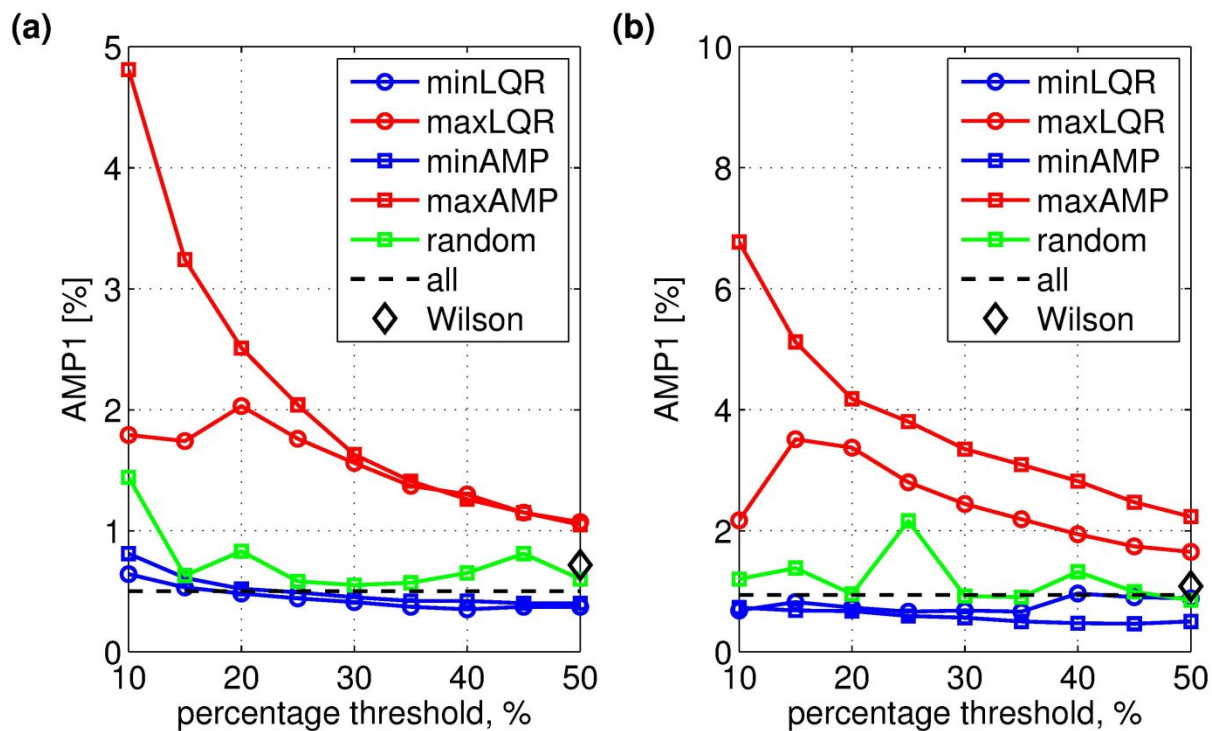
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3 763 Fig. 2. (a, g) Stacked SRFs with the 25% lowest LQR. (b, h) Stacked SRFs with the 25%
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5 764 highest LQR. (c, i) Stacked SRFs with the 25% lowest AMP. (d, j) Stacked SRFs with the
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7 765 25% highest AMP. (e, k) Stacked SRFs with the criterion by Wilson *et al.* (2006). Note that
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9 766 Wilson *et al.* (2006) used restricted epicentral distances of 60° – 75° for earthquakes with focal
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11 767 depths shallower than 300 km. (f, l) Stacked SRFs with 25% random data selection. Dashed
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14 768 lines indicate phase arrival times predicted by the IASP91 model.
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771 **Figure 5.** Stacked SRFs for various cases against six data selection criteria: 25% lowest LQR,
 772 25% lowest AMP, the criterion by Wilson *et al.* (2006), 25% highest LQR, and 25% highest
 773 AMP, and 25% random data selection, from the top to bottom rows, respectively. Gray
 774 region indicates bootstrap error estimates of the SRFs. (a) Stacked SRFs for IASP91 model.
 775 (b) Stacked SRFs for L70 model. (c) Stacked SRFs for the case 1; same as (b) but with the
 776 window of parent waveform -10 s before and 15 s after the *S* wave. (d) Stacked SRFs for the
 777 case 2; same as (b) but with the Hanning tapering window of 5%. (e) Stacked SRFs for the
 778 case 3; same as (b), but with frequency-domain water-level deconvolution and water level of
 779 0.05%. (f) Stacked SRFs for the case 4; same as (b), but with frequency-domain water-level
 780 deconvolution and water level of 0.2%. Note stacked SRFs without any selection criteria are
 781 shown in red lines for comparisons. The stack of all traces is shown in red in the bottom
 782 panel.

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785 **Figure 6.** Root-mean-square (RMS) amplitudes of the synthetic SRFs at -60 to -20 s with786 respect to the *S* arrival (AMP1 in %), plotted against data-selection ratios (10–50%). (a)

787 AMP1 for IASP91 model (Kennett & Engdahl 1991) with six criteria, which are lowest LQR

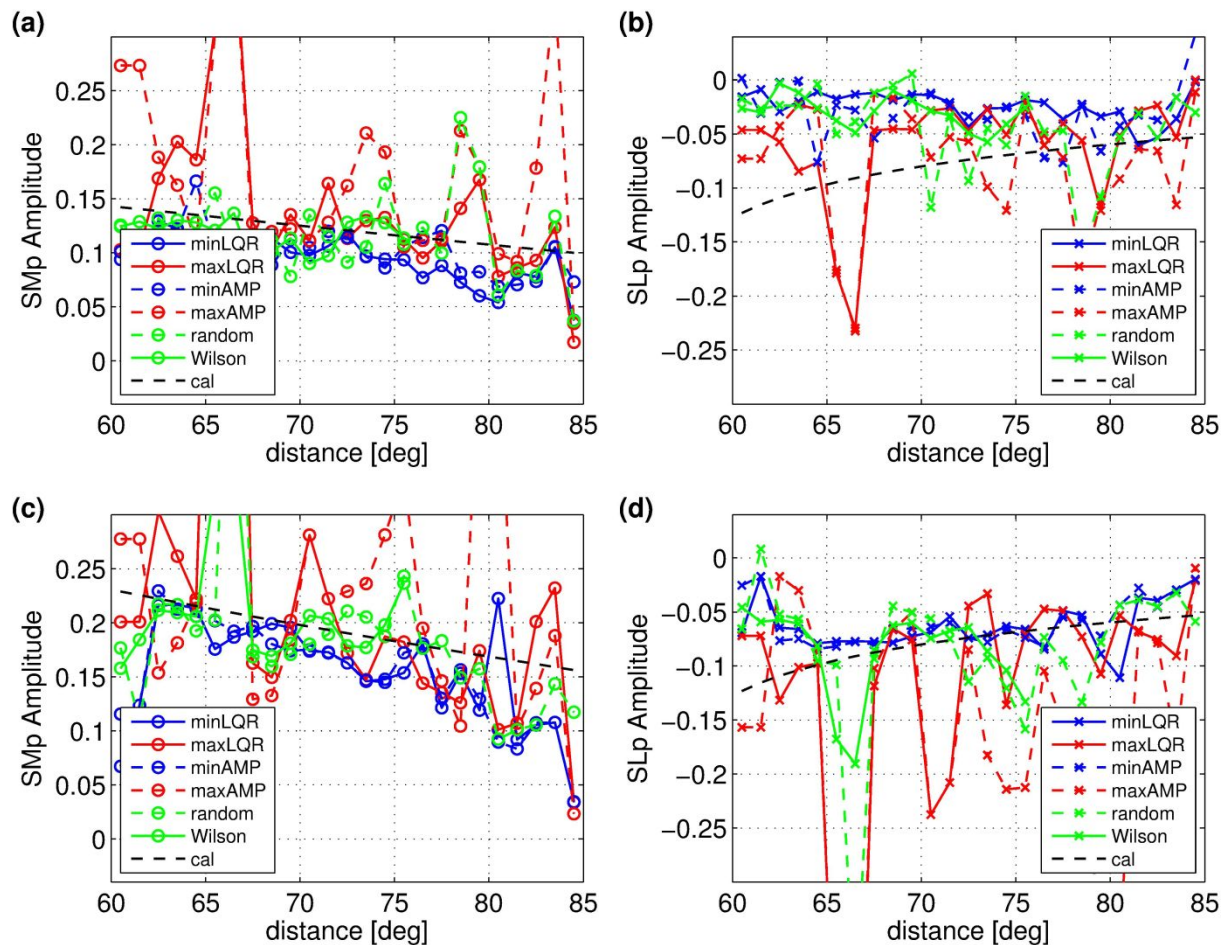
788 (blue circle), highest LQR (red circle), lowest AMP (blue square), highest AMP (red square),

789 random data selection (green square) and the criterion by Wilson *et al.* (2006) (black

790 diamond), in addition to all SRFs (black dashed line). (b) AMP1 for L70 model (Fig. S1)

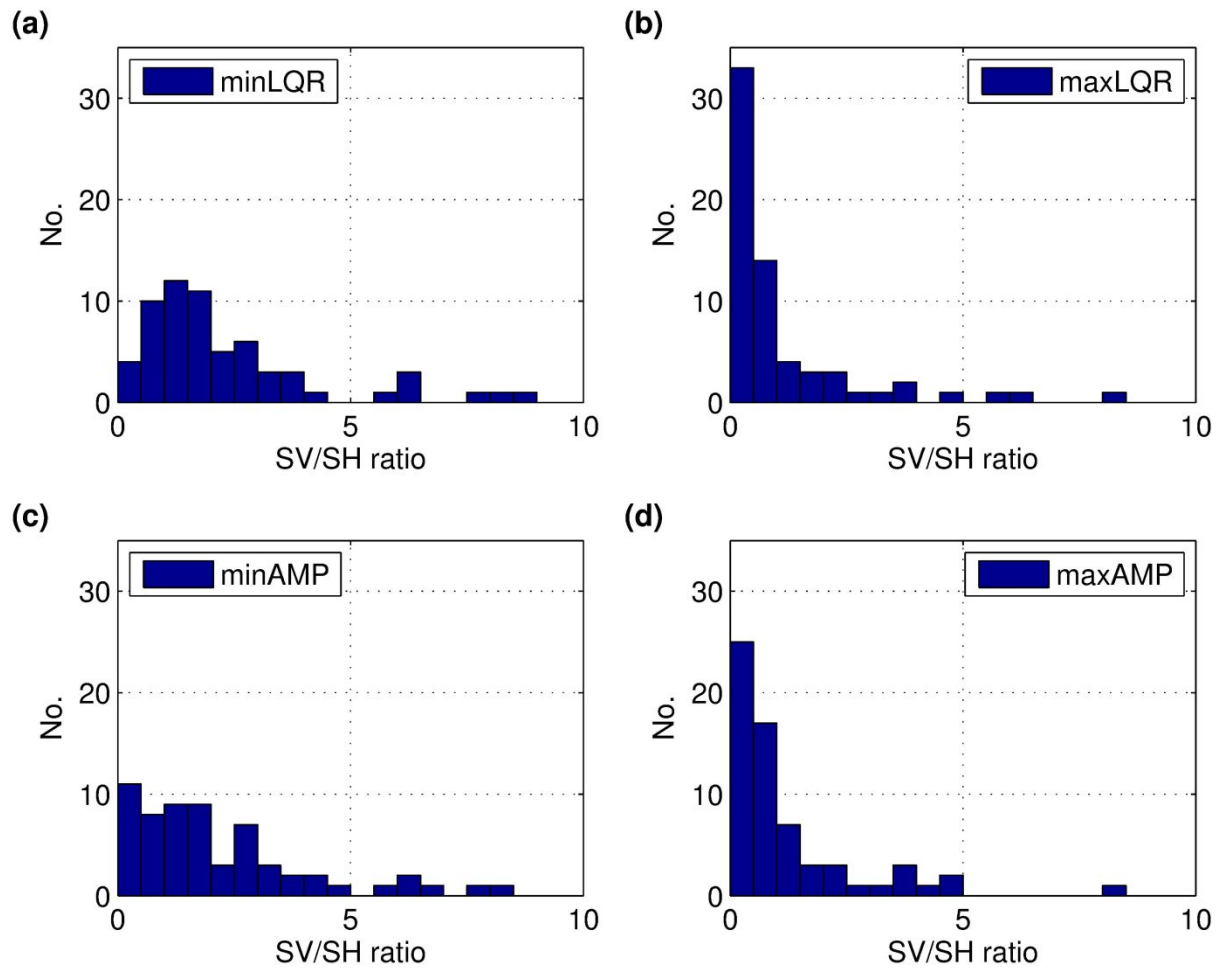
791 with the same criteria as (a).

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794 **Figure 7.** Amplitudes of SMp and SLp phases from the synthetic SRFs, plotted against the
 795 epicentral distance for the six different data selection criteria. The measured amplitudes are
 796 compared with the theoretical transmission coefficients (Aki & Richards 2002), shown in
 797 black dashed line. (a) Distance-dependent amplitude of SMp from IASP91 model (Kennett &
 798 Engdahl 1991). (b) Distance-dependent amplitude of SLp from IASP91 model. (c) Distance-
 799 dependent amplitude of SMp from L70 model (Fig. S1). (d) Distance-dependent amplitude of
 800 SLp from L70 model. Note that the theoretical calculation of SLp transmission coefficient
 801 from the L70 model is reproduced in Fig. 7b for comparison. In the absence of a negative
 802 velocity contrast in the IASP91 model, notable amplitude peak, especially with the highest
 803 LQR or AMP criteria, can still be identified and potentially misinterpreted as SLp signal in
 804 the LAS. Lowest LQR or AMP criteria substantially minimize these dubious signals.

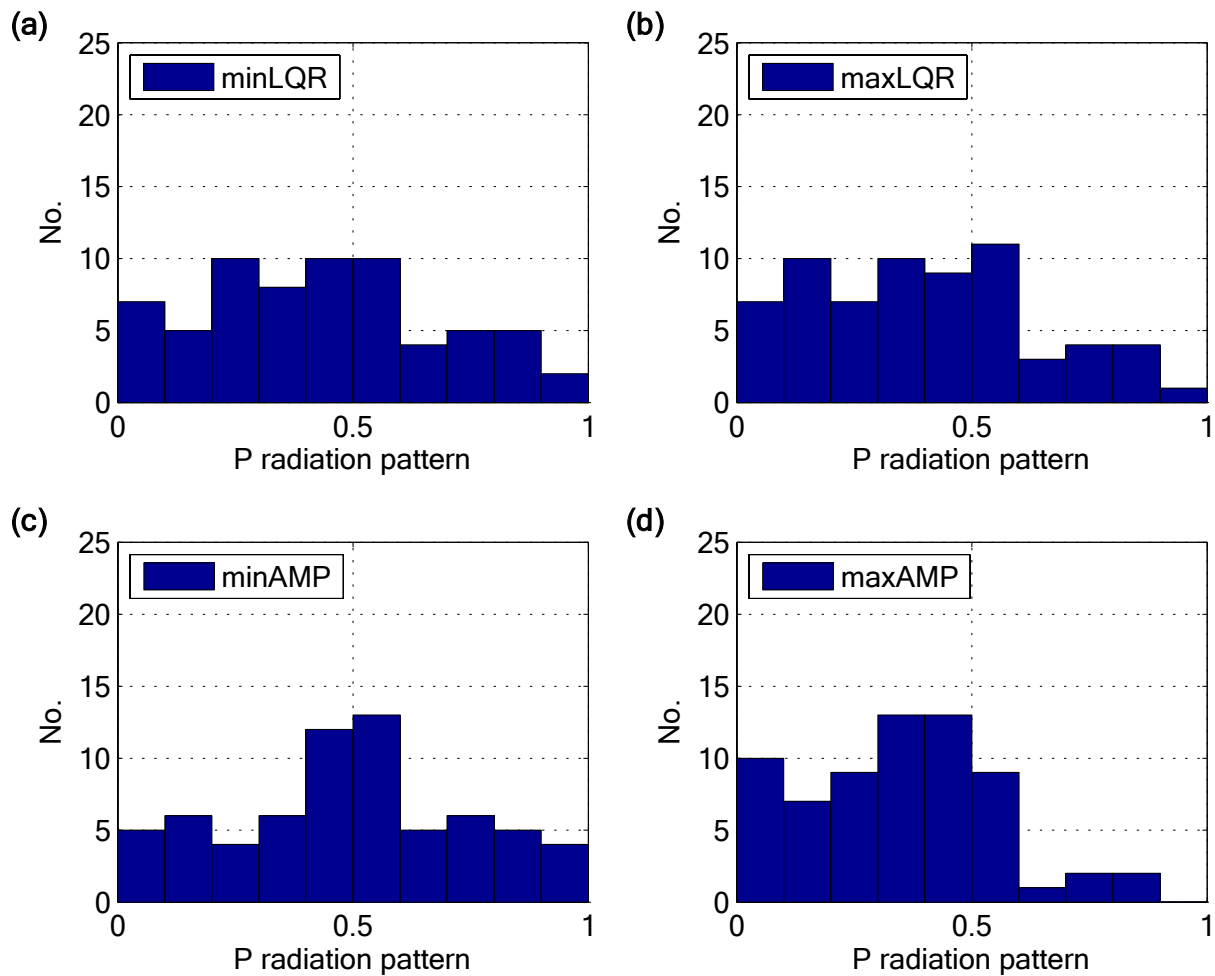


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806 **Figure 8.** Histograms of SV/SH ratio against four data selection criteria; (a) 25% lowest LQR,

807 (b) 25% highest LQR, (c) 25% lowest AMP, and (d) 25% highest AMP.

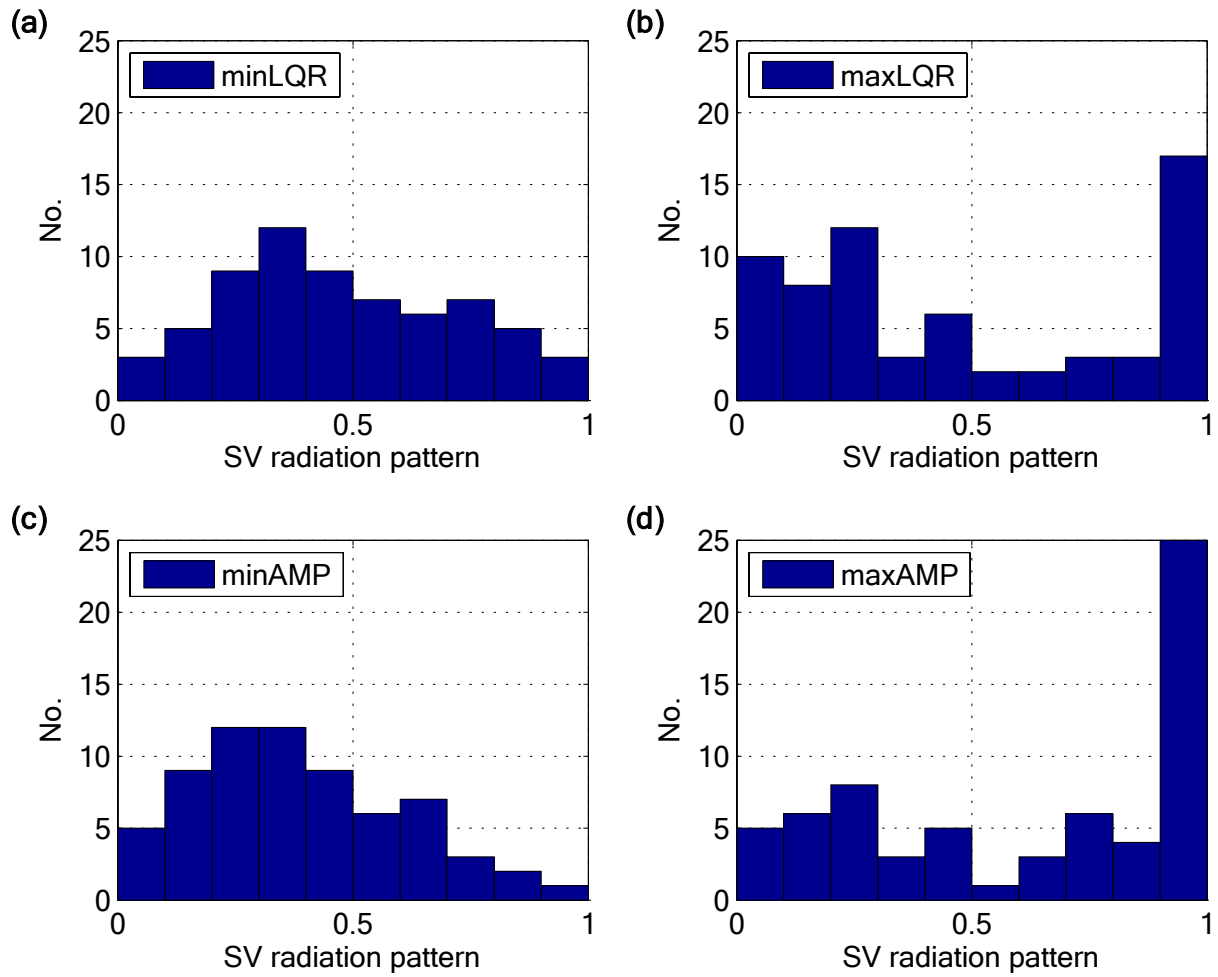
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810 **Figure 9.** Histograms of P radiation pattern against four data selection criteria; (a) 25%
 811 lowest LQR, (b) 25% highest LQR, (c) 25% lowest AMP, and (d) 25% highest AMP. The P
 812 radiation pattern is computed with the slowness of $pPPPP$ against focal mechanisms of
 813 selected events.

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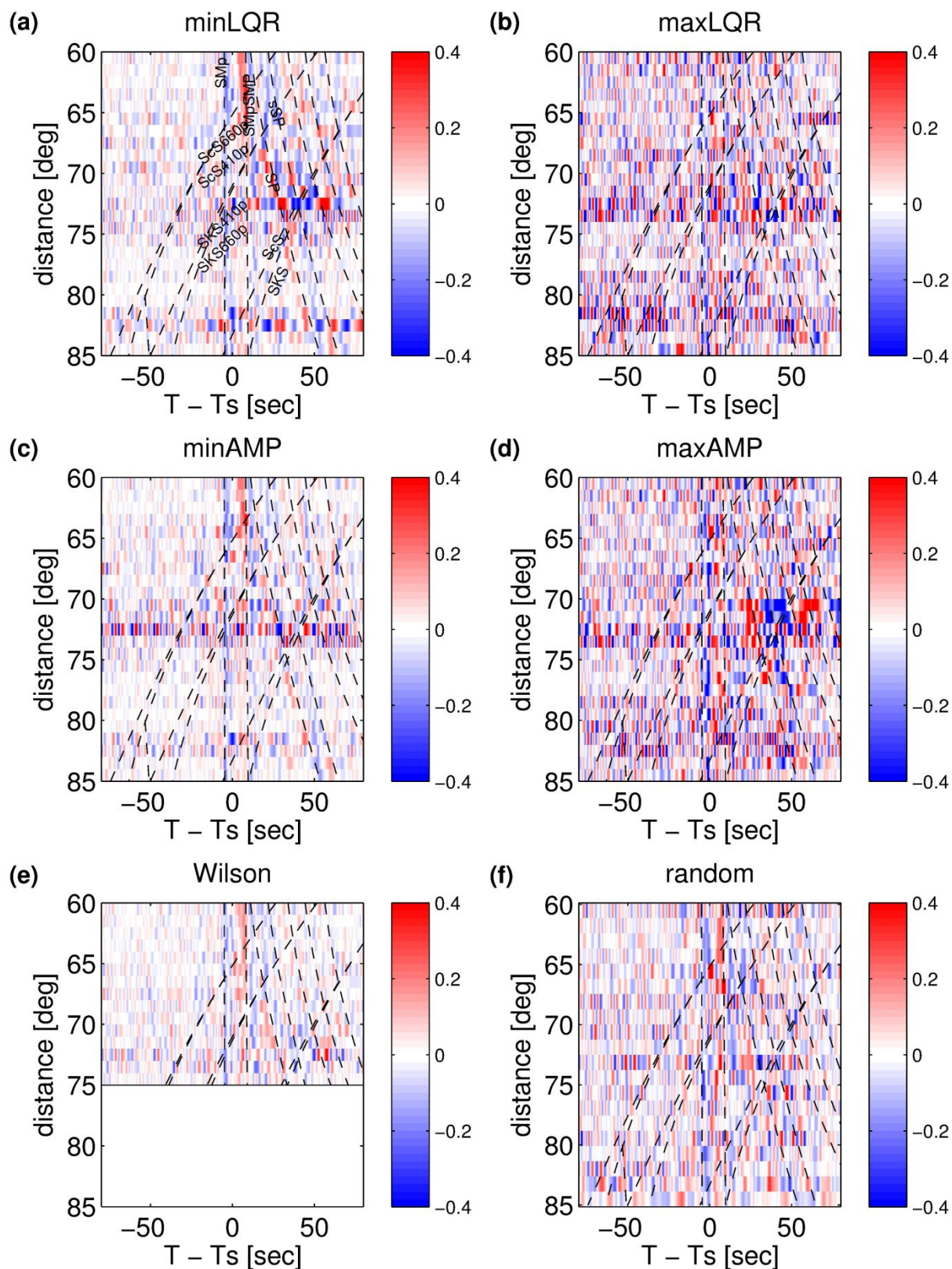


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816 **Figure 10.** Histograms of SV radiation pattern against four data selection criteria; (a) 25%817 lowest LQR, (b) 25% highest LQR, (c) 25% lowest AMP, and (d) 25% highest AMP. The SV 818 radiation pattern is computed with the slowness of SP wave against focal mechanisms of

819 selected events.

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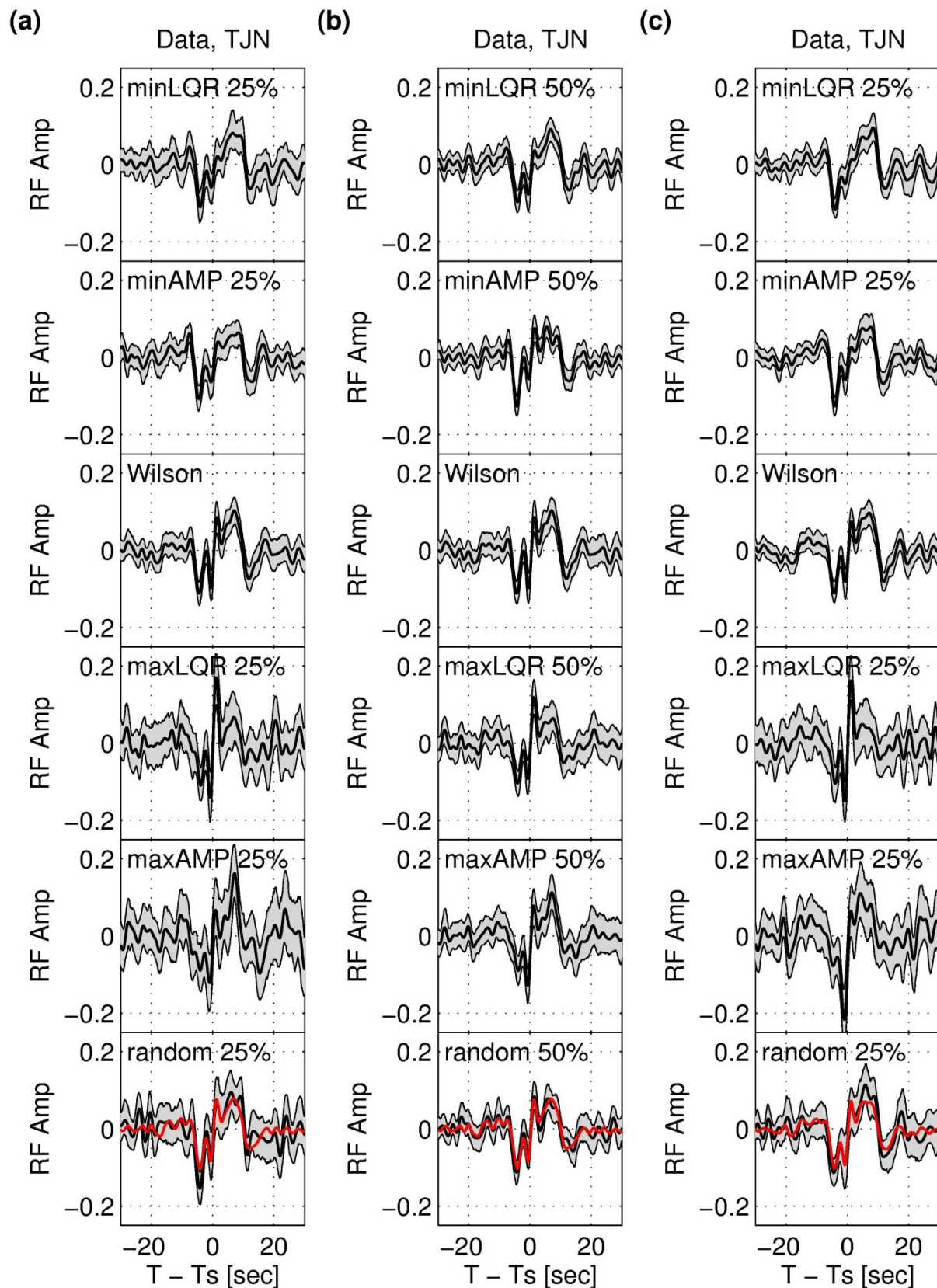
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822 **Figure 11.** Images of SRFs for station TJN as a function of the distance of 60°–85° with six

823 different data selection criteria. The SRFs are plotted in the same way as Fig. 2. (a) Stacked

824 SRFs with the 25% lowest LQR. (b) Stacked SRFs with the 25% highest LQR. (c) Stacked

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3 825 SRFs with the 25% lowest AMP. (d) Stacked SRFs with the 25% highest AMP. (e) Stacked
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5 826 SRFs with the criterion by Wilson *et al.* (2006). (f) Stacked SRFs with 25% random data
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7 827 selection. Dashed lines indicate phase arrival times predicted by the IASP91 model. See Fig.
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9 828 S10 for the images of -30–30 s time window.
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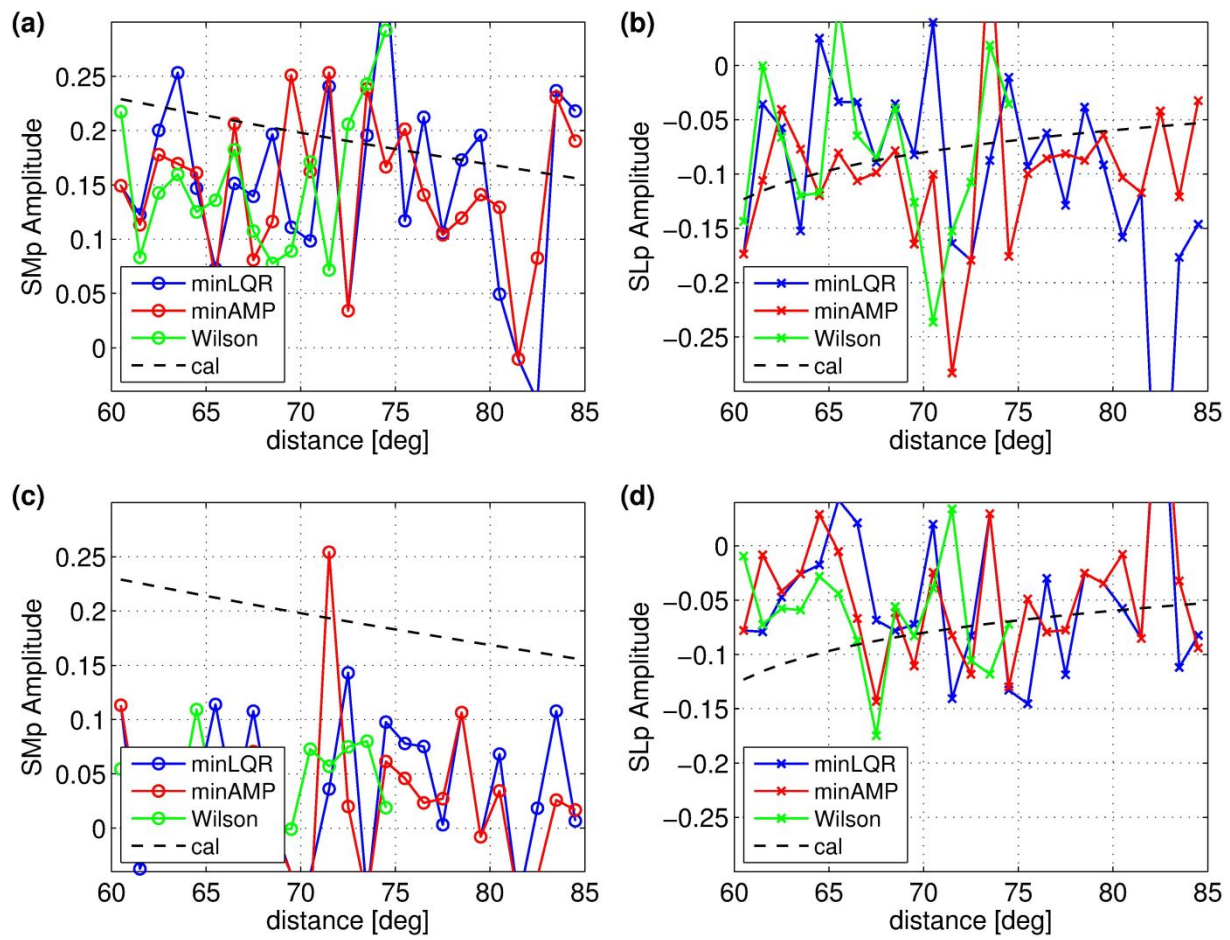


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830 **Figure 12.** Stacked SRFs for station TJN with six data selection criteria with (a) a percentage
 831 threshold of 25%, (b) 50 %, and (b) 25% with a stronger regularization (1% white noise).

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3 832 Gray region indicates bootstrap error estimates of the SRFs. The six data selection criteria are
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5 833 as follows: 25% lowest LQR, 25% lowest AMP, the criterion by Wilson *et al.* (2006), 25%
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7 834 highest LQR, and 25% highest AMP, and 25% random data selection, from the top to bottom
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10 835 rows, respectively.

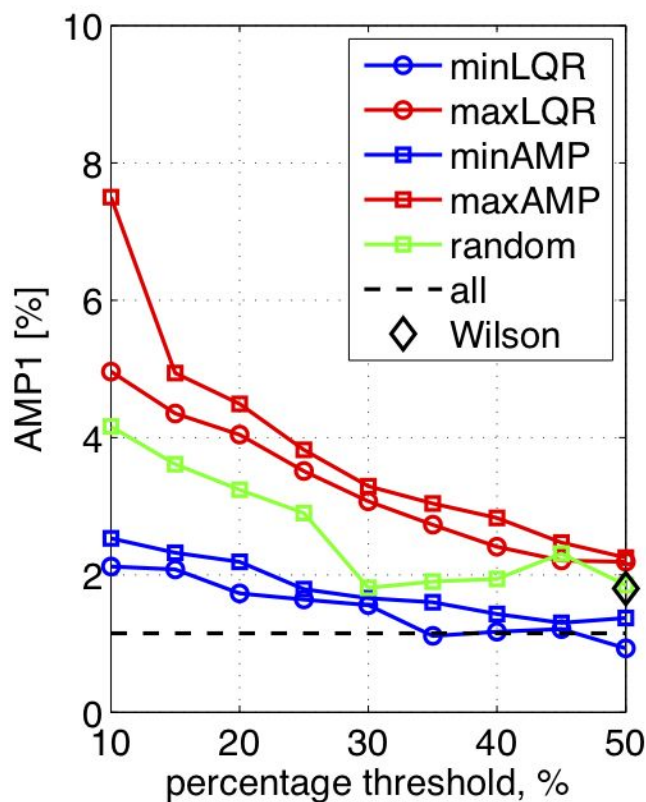
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838 **Figure 13.** Amplitudes of SMp and SLp phases from the SRFs for station TJN, plotted against
 839 the distance of 60° – 85° for three different data selection criteria (25% lowest LQR, 25%
 840 lowest AMP, and the criterion by Wilson *et al.* (2006)). The measured amplitudes are
 841 compared with the theoretical transmission coefficients (Aki & Richards 2002), shown in
 842 black dashed line. (a) Distance-dependent amplitude of SMp . (b) Distance-dependent
 843 amplitude of SLp . (c) Distance-dependent amplitude of SMp with a strong regularization (1%
 844 white noise). (d) Distance-dependent amplitude of SLp with a strong regularization (1% white
 845 noise).

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848 **Figure 14.** Root-mean-square (RMS) amplitudes of the SRFs at -60 to -20 s with respect to
 849 the S arrival (AMP1 in %) for station TJN, plotted against data-selection ratios (10–50%).
 850 The six data selection criteria are as follows: lowest LQR (blue circle), highest LQR (red
 851 circle), lowest AMP (blue square), highest AMP (red square), random data selection (green
 852 square) and the criterion by Wilson *et al.* (2006) (black diamond), in addition to all SRFs
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3 **854 Supporting Information**
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8 856 Additional Supporting Information may be found in the online version of this article:
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12 858 Supporting Information file includes one table and 14 figures providing velocity models for
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14 859 synthetic tests (Fig. S1), illustrations showing how the synthetic SRFs are constructed with
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17 860 our proposed data selection criteria for shorter time windows for the time-domain Wiener
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19 861 deconvolution (Figs S2 and S3), effect of using different data windowing and tapering length
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21 862 (Figs S4 and S5, respectively), effect of using various water levels in the alternative
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23 863 frequency-domain deconvolution (Figs S6 and S7), histograms of epicentral distance and
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25 864 event back-azimuth (Fig. S8) as well as source parameters (Fig. S9) against data selection
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27 865 criteria, and an alternative 50% threshold for six data selection criteria for the SRFs from
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29 866 station TJN (Figs S11 and S12) in addition to 25% threshold (Fig. S10). SRFs images with
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31 867 25% threshold and a strong regularization (1% white noise) are shown in Figs S13 and S14.
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37 869 **Table S1.** Velocity models.
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42 871 **Figure S1.** Velocity models. The 1-D IASP91 model (Kennett & Engdahl 1991) is shown in
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44 872 black, and the L70 model is shown in red. The L70 model includes a 35 km thick high-
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46 873 velocity mantle lid with a 7.5% shear velocity increase below Moho, a low velocity zone with
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48 874 a 9% shear velocity reduction beneath 70 km depth, and a small 1.5% shear velocity increase
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50 875 beneath 120 km depth. See also Table S1.
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56 877 **Figure S2.** Examples showing *P* coda waves and their influence on signal-generated noise in
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58 878 the SRF. Gray dashed boxes in panel (a) indicate how LQR is measured from the L- and Q-
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5 880 waveforms are computed from catalogued earthquake sources using the IASP91 (Kennett &
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7 881 Engdahl 1991) (a and c) and the L70 model (b and d). Time-domain Wiener deconvolution
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10 882 method is performed with the parent waveform time window of 10 s before and 15 s after the
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12 883 *S* arrival (black bar in a panel a). Note the amplitude scale of SRF in event 2 is higher than
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14 884 that in event 1.
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19 886 **Figure S3.** Examples showing *P* coda waves and their influence on signal-generated noise in
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21 887 the SRF. Gray dashed boxes in panel (a) indicate how LQR is measured from the L- and Q-
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23 888 component synthetic seismograms and how AMP is measured from synthetic SRF. Synthetic
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25 889 waveforms are computed from catalogued earthquake sources using the IASP91 (Kennett &
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27 890 Engdahl 1991) (a and c) and the L70 model (b and d). Time-domain Wiener deconvolution
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29 891 method is performed with the parent waveform time window of 10 s before and 10 s after the
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31 892 *S* arrival (black bar in a panel a). Note the amplitude scale of SRF in event 2 is higher than
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33 893 that in event 1.
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38 895 **Figure S4.** Images of synthetic SRFs for the case 1 from the L70 model as a function of the
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40 896 distance of 60°–85° with following six data selection criteria; (a) 25% lowest LQR, (b) 25%
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42 897 highest LQR, (c) 25% lowest AMP, (d) 25% highest AMP, (e) criterion by Wilson *et al.*
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44 898 (2006), and (f) 25% random data selection. The parent waveforms are windowed 10 s before
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46 899 and 15 s after the *S*-wave arrival and tapered with a 15% Hanning taper at both ends of the
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48 900 signal window. Dashed lines indicate phase arrival times predicted by the IASP91 model
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50 901 (Kennett & Engdahl 1991). The SRFs are plotted in the same way as Fig. 2.
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3 903 **Figure S5.** Images of synthetic SRFs for the case 2 from the L70 model as a function of the
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5 904 epicentral distance of 60° – 85° with six different data selection criteria. The parent waveforms
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7 905 are windowed 10 s before and 35 s after the *S*-wave arrival and tapered with a 5% Hanning
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9 906 taper at both ends of the signal window. See a caption of Fig. S4 for more detail.

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14 908 **Figure S6.** Images of synthetic SRFs for the case 3 from the L70 model as a function of the
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16 909 epicentral distance of 60° – 85° with six different data selection criteria. The parent waveforms
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18 910 are windowed 10 s before and 35 s after the *S*-wave arrival and tapered with a 15% Hanning
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20 911 taper at both ends of the signal window. The frequency-domain deconvolution is done with a
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22 912 water level of 0.05%. See a caption of Fig. S4 for more detail.

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26 914 **Figure S7.** Images of synthetic SRFs for the case 4 from the L70 model as a function of the
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28 915 distance of 60° – 85° with six different data selection criteria. The parent waveforms are
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30 916 windowed 10 s before and 35 s after the *S*-wave arrival and tapered with a 15% Hanning
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32 917 taper at both ends of the signal window. The frequency-domain deconvolution is done with a
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34 918 water level of 0.2%. See a caption of Fig. S4 for more detail.

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38 920 **Figure S8.** Histograms of epicentral distance and back azimuth against six data selection
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40 921 criteria. LQR and AMP data selection criteria with a percentage threshold of 25% result in
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42 922 negligible data selection bias in back azimuthal and epicentral distance.

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46 924 **Figure S9.** Histograms of earthquake source parameters (dip, strike and rake) against four
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48 925 data selection criteria; (a, e, f) 25% lowest LQR, (b, f, j) 25% highest LQR, (c, g, k) 25%
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50 926 lowest AMP, and (d, h, l) 25% highest AMP. LQR and AMP data selection criteria result in
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52 927 negligible data selection preference in source parameters.

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929 **Figure S10.** Images of SRFs for station TJN as a function of the epicentral distance of 60° –
930 85° with following six data selection criteria; (a) 25% lowest LQR, (b) 25% highest LQR, (c)
931 25% lowest AMP, (d) 25% highest AMP, (e) criterion by Wilson *et al.* (2006), and (f) 25%
932 random data selection. The parent waveforms are windowed 10 s before and 35 s after the *S*-
933 wave arrival and tapered with a 15% Hanning taper at both ends of the signal window. See a
934 caption of Fig. S4 for more detail. See also Fig. 10 for the images of -80–80 s window.

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936 **Figure S11.** Images of SRFs for station TJN as a function of the distance of 60° – 85° with
937 following six data selection criteria; (a) 50% lowest LQR, (b) 50% highest LQR, (c) 50%
938 lowest AMP, (d) 50% highest AMP, (e) criterion by Wilson *et al.* (2006), and (f) 50%
939 random data selection. The parent waveforms are windowed 10 s before and 35 s after the *S*-
940 wave arrival and tapered with a 15% Hanning taper at both ends of the signal window. See a
941 caption of Fig. S4 for more detail. See Fig. S12 for the images plotted for -30–30 s window.

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943 **Figure S12.** Images of SRFs for station TJN as a function of the distance of 60° – 85° with
944 following six data selection criteria; (a) 50% lowest LQR, (b) 50% highest LQR, (c) 50%
945 lowest AMP, (d) 50% highest AMP, (e) criterion by Wilson *et al.* (2006), and (f) 50%
946 random data selection. The parent waveforms are windowed 10 s before and 35 s after the *S*-
947 wave arrival and tapered with a 15% Hanning taper at both ends of the signal window. See a
948 caption of Fig. S4 for more detail.

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950 **Figure S13.** Images of SRFs for station TJN as a function of the distance of 60° – 85° with
951 following six data selection criteria; (a) 25% lowest LQR, (b) 25% highest LQR, (c) 25%
952 lowest AMP, (d) 25% highest AMP, (e) criterion by Wilson *et al.* (2006), and (f) 25%

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3 953 random data selection. The parent waveforms are windowed 10 s before and 35 s after the *S*-
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5 954 wave arrival and tapered with a 15% Hanning taper at both ends of the signal window. Time
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10 956 Fig. S14 for the images plotted for -30–30 s window.

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14 958 **Figure S14.** Images of SRFs for station TJN as a function of the distance of 60°–85° with
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16 959 following six data selection criteria; (a) 25% lowest LQR, (b) 25% highest LQR, (c) 25%
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18 960 lowest AMP, (d) 25% highest AMP, (e) criterion by Wilson *et al.* (2006), and (f) 25%
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20 961 random data selection. The parent waveforms are windowed 10 s before and 35 s after the *S*-
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9 3 **Data-oriented constraint on the interpretation of *S* receiver function and its application to**
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11 4 **observations of seismic discontinuities in the lithosphere-asthenosphere system**
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14 5 Xuzhang Shen¹, YoungHee Kim^{2*}, Teh-Ru Alex Song³, and Hobin Lim²
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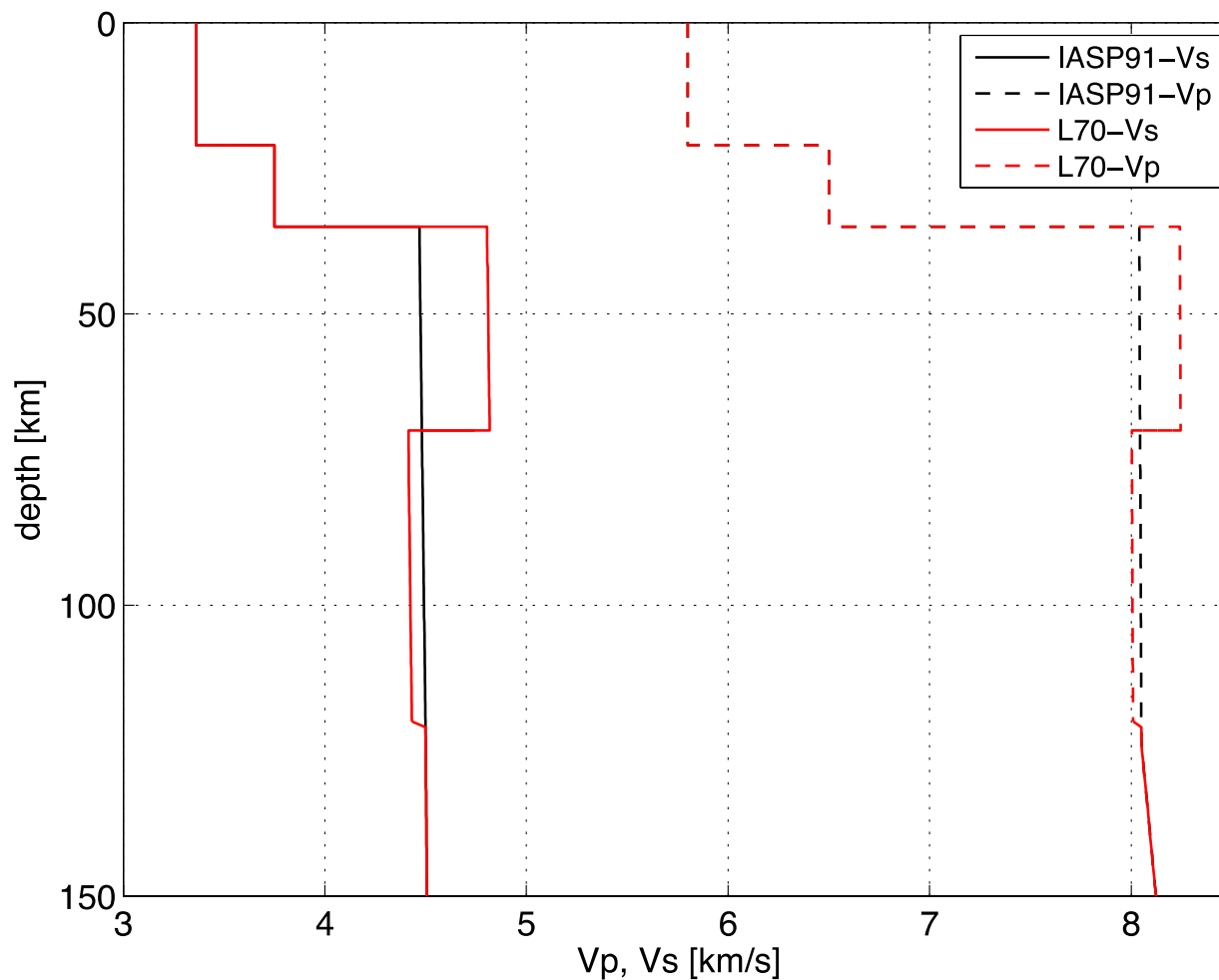
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15 26 (Fig. S8) as well as source parameters (Fig. S9) against data selection criteria, and an alternative
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17 27 50% threshold for six data selection criteria for the SRFs from station TJN (Figs S11 and S12) in
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19 28 addition to 25% threshold (Fig. S10). SRFs images with 25% threshold and a strong
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21 29 regularization (1% white noise) are shown in Figs S13 and S14.
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31 **Table S1.** Velocity models.

IASP91 model^a				L70 model			
Depth	Vp	Vs	Density	Depth	Vp	Vs	Density
(km)	(km/s)	(km /s)	(g/cm ³)	(km)	(km/s)	(km /s)	(g/cm ³)
0	5.800	3.360	2.7200	0	5.8000	3.3600	2.7200
20	5.800	3.360	2.7200	20	5.8000	3.3600	2.7200
20	6.500	3.750	2.9200	20	6.5000	3.7500	2.9200
35	6.500	3.750	2.9200	35	6.5000	3.7500	2.9200
35	8.040	4.470	3.3198	35	8.2596	4.8053	3.3797
77.5	8.045	4.485	3.3455	70	8.2637	4.8141	3.3758
120	8.050	4.500	3.3713	70	8.0020	4.4187	3.3758
165	8.175	4.509	3.3985	120	8.0500	4.5000	3.3713
210	8.300	4.518	3.4258	165	8.1750	4.5090	3.3985
				210	8.3000	4.5180	3.4258

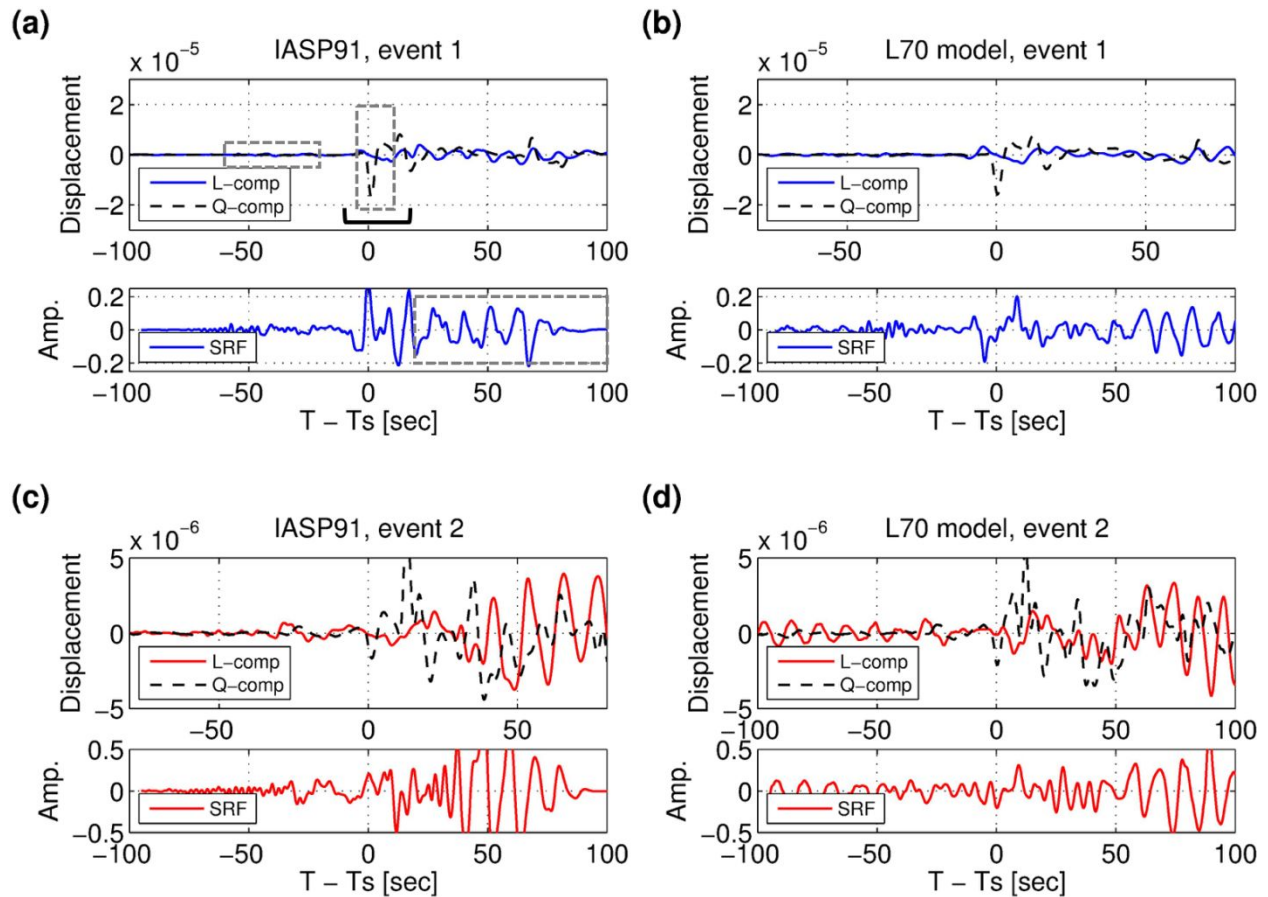
32 ^a Kennett & Engdahl (1991)

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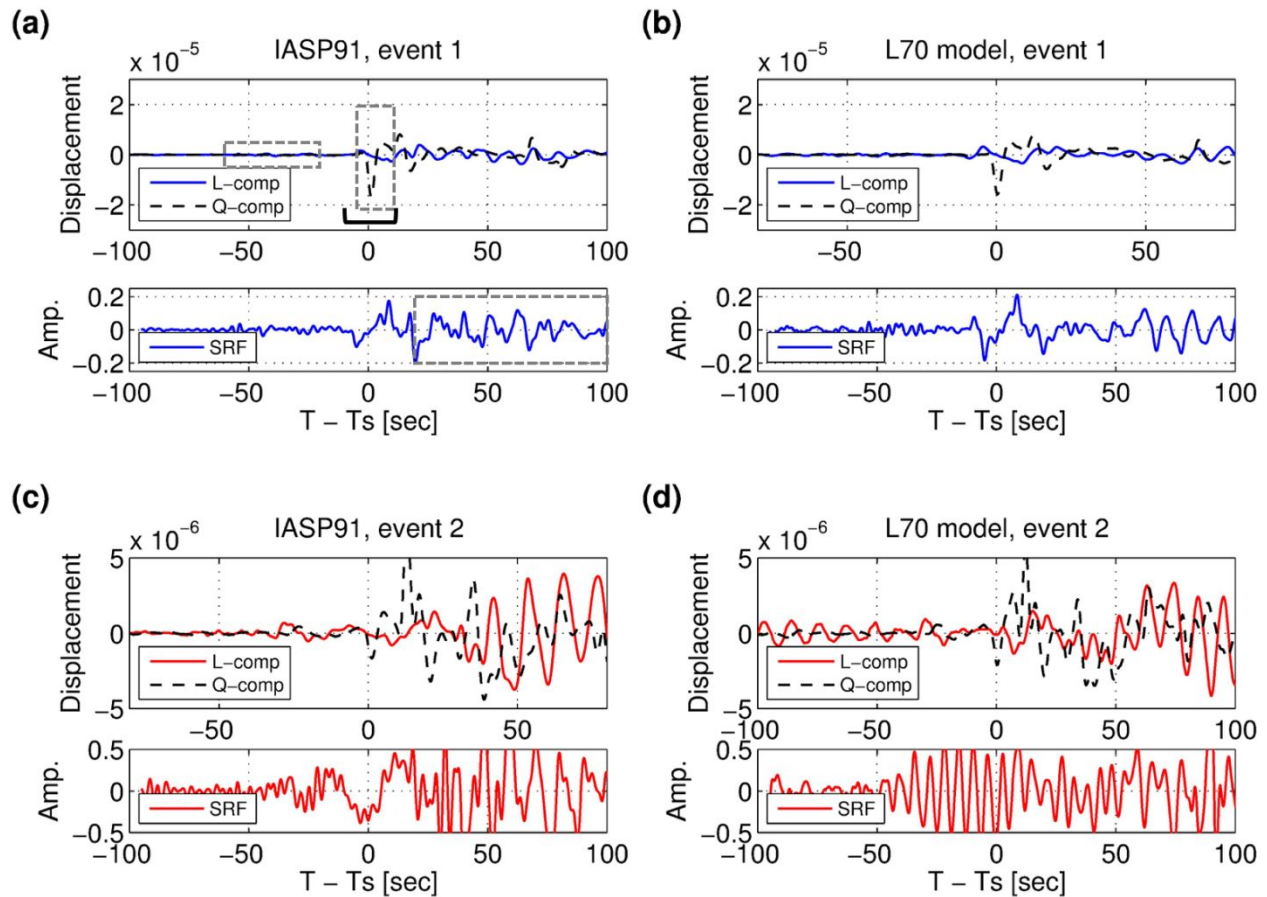
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35 **Figure S1.** Velocity models. The 1-D IASP91 model (Kennett & Engdahl 1991) is shown in
 36 black, and the L70 model is shown in red. The L70 model includes a 35 km thick high-velocity
 37 mantle lid with a 7.5% shear velocity increase below Moho, a low velocity zone with a 9% shear
 38 velocity reduction beneath 70 km depth, and a small 1.5% shear velocity increase beneath 120
 39 km depth. See also Table S1.



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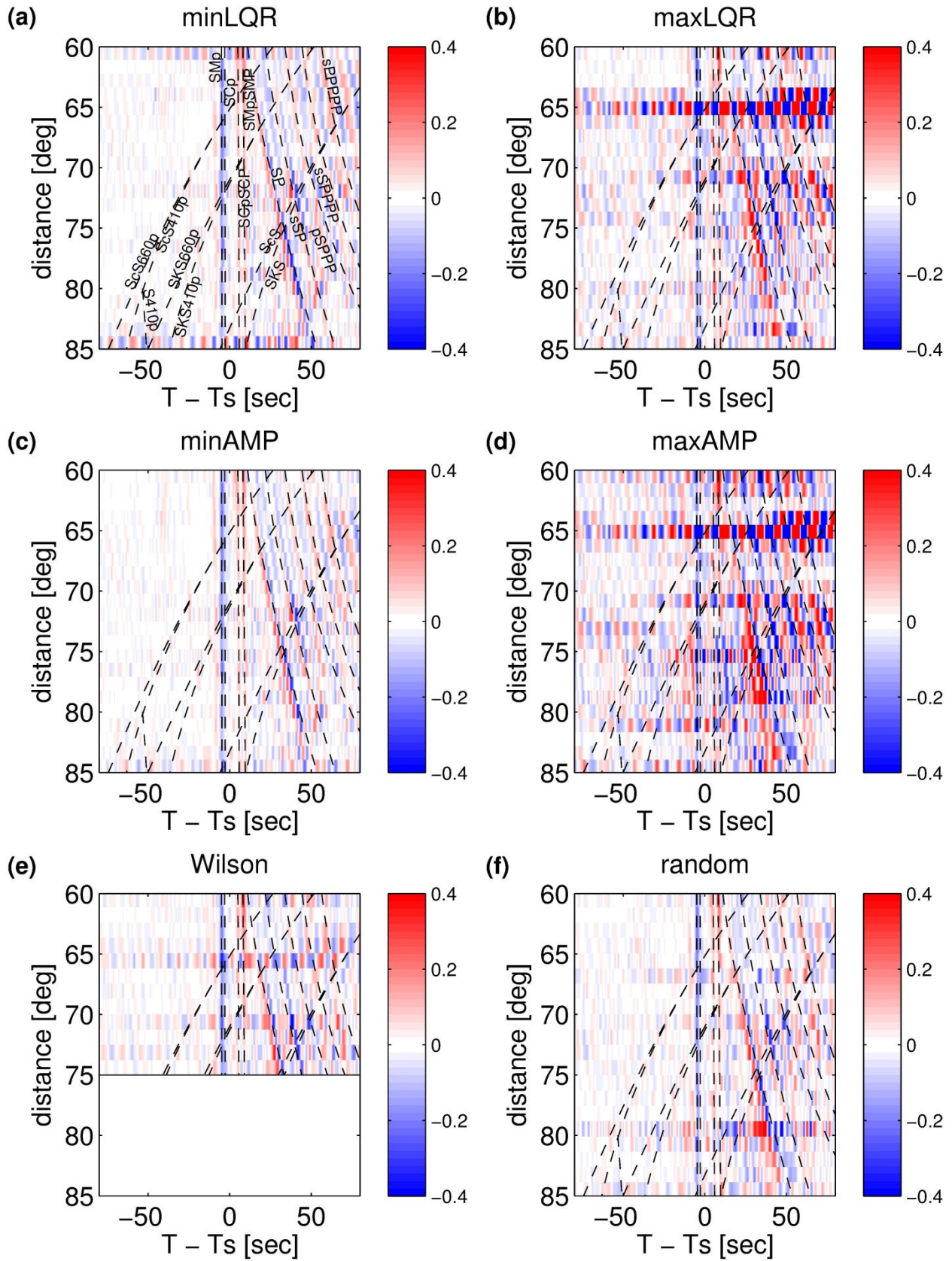
41 **Figure S2.** Examples showing *P* coda waves and their influence on signal-generated noise in the
 42 SRF. Gray dashed boxes in panel (a) indicate how LQR is measured from the L- and Q-
 43 component synthetic seismograms and how AMP is measured from synthetic SRF. Synthetic
 44 waveforms are computed from catalogued earthquake sources using the IASP91 (Kennett &
 45 Engdahl 1991) (a and c) and the L70 model (b and d). Time-domain Wiener deconvolution
 46 method is performed with the parent waveform time window of 10 s before and 15 s after the *S*
 47 arrival (black bar in a panel a). Note the amplitude scale of SRF in event 2 is higher than that in
 48 event 1.



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50 **Figure S3.** Examples showing *P* coda waves and their influence on signal-generated noise in the
 51 SRF. Gray dashed boxes in panel (a) indicate how LQR is measured from the L- and Q-
 52 component synthetic seismograms and how AMP is measured from synthetic SRF. Synthetic
 53 waveforms are computed from catalogued earthquake sources using the IASP91 (Kennett &
 54 Engdahl 1991) (a and c) and the L70 model (b and d). Time-domain Wiener deconvolution
 55 method is performed with the parent waveform time window of 10 s before and 10 s after the *S*
 56 arrival (black bar in a panel a). Note the amplitude scale of SRF in event 2 is higher than that in
 57 event 1.

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4 59 **Figure S4.** Images of synthetic SRFs for the case 1 from the L70 model as a function of the
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6 60 distance of 60° – 85° with following six data selection criteria; (a) 25% lowest LQR, (b) 25%
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8 61 highest LQR, (c) 25% lowest AMP, (d) 25% highest AMP, (e) criterion by Wilson *et al.* (2006),
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10 62 and (f) 25% random data selection. The parent waveforms are windowed 10 s before and 15 s
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12 63 after the *S*-wave arrival and tapered with a 15% Hanning taper at both ends of the signal window.
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14 64 Dashed lines indicate phase arrival times predicted by the IASP91 model (Kennett & Engdahl
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16 65 1991). The SRFs are plotted in the same way as Fig. 2.
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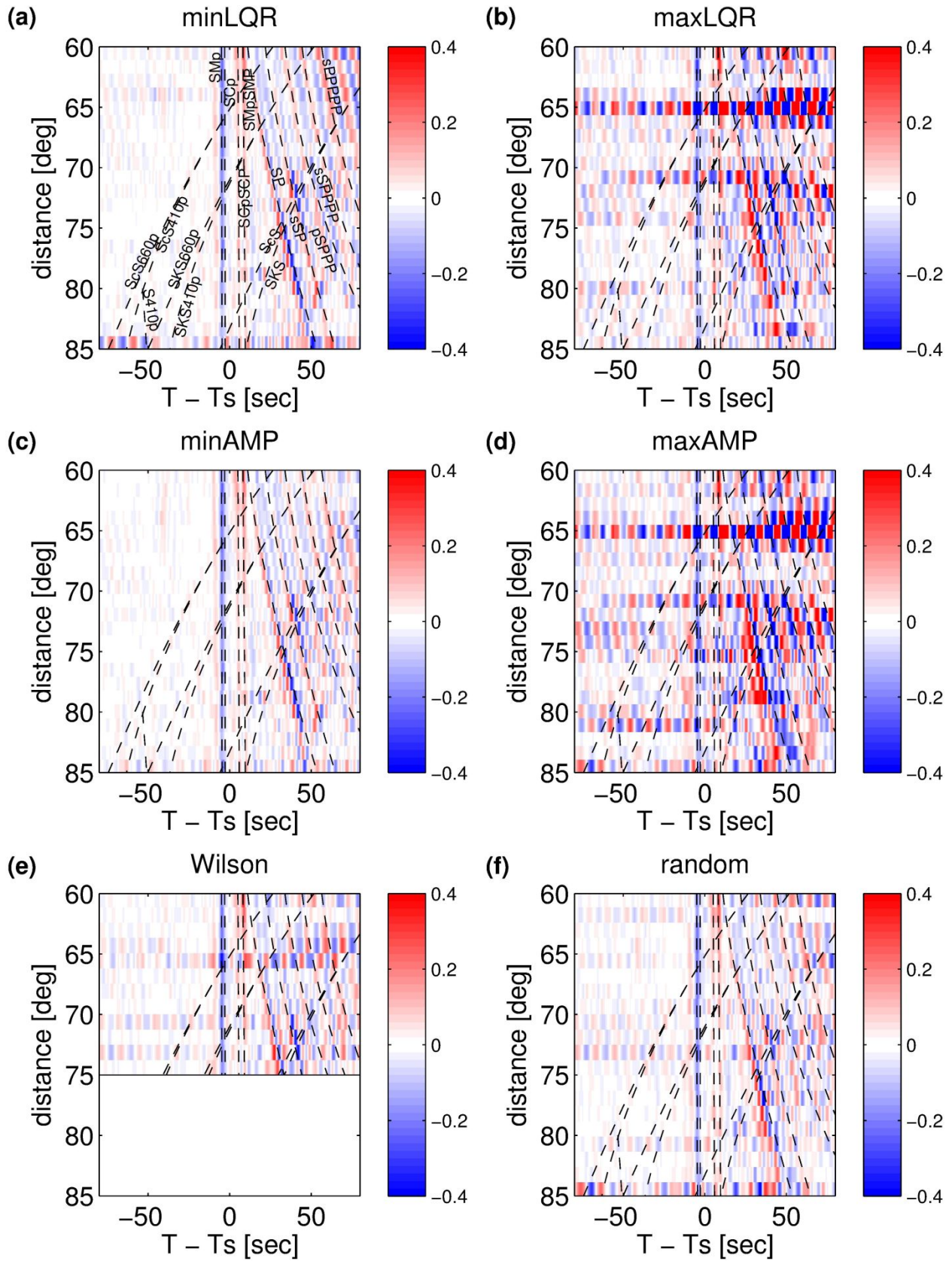
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3 68 **Figure S5.** Images of synthetic SRFs for the case 2 from the L70 model as a function of the
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5 69 epicentral distance of 60° – 85° with six different data selection criteria. The parent waveforms
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7 70 are windowed 10 s before and 35 s after the *S*-wave arrival and tapered with a 5% Hanning taper
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9 71 at both ends of the signal window. See a caption of Fig. S4 for more detail.
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3 74 **Figure S6.** Images of synthetic SRFs for the case 3 from the L70 model as a function of the
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5 75 epicentral distance of 60° – 85° with six different data selection criteria. The parent waveforms
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7 76 are windowed 10 s before and 35 s after the *S*-wave arrival and tapered with a 15% Hanning
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10 77 taper at both ends of the signal window. The frequency-domain deconvolution is done with a
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12 78 water level of 0.05%. See a caption of Fig. S4 for more detail.
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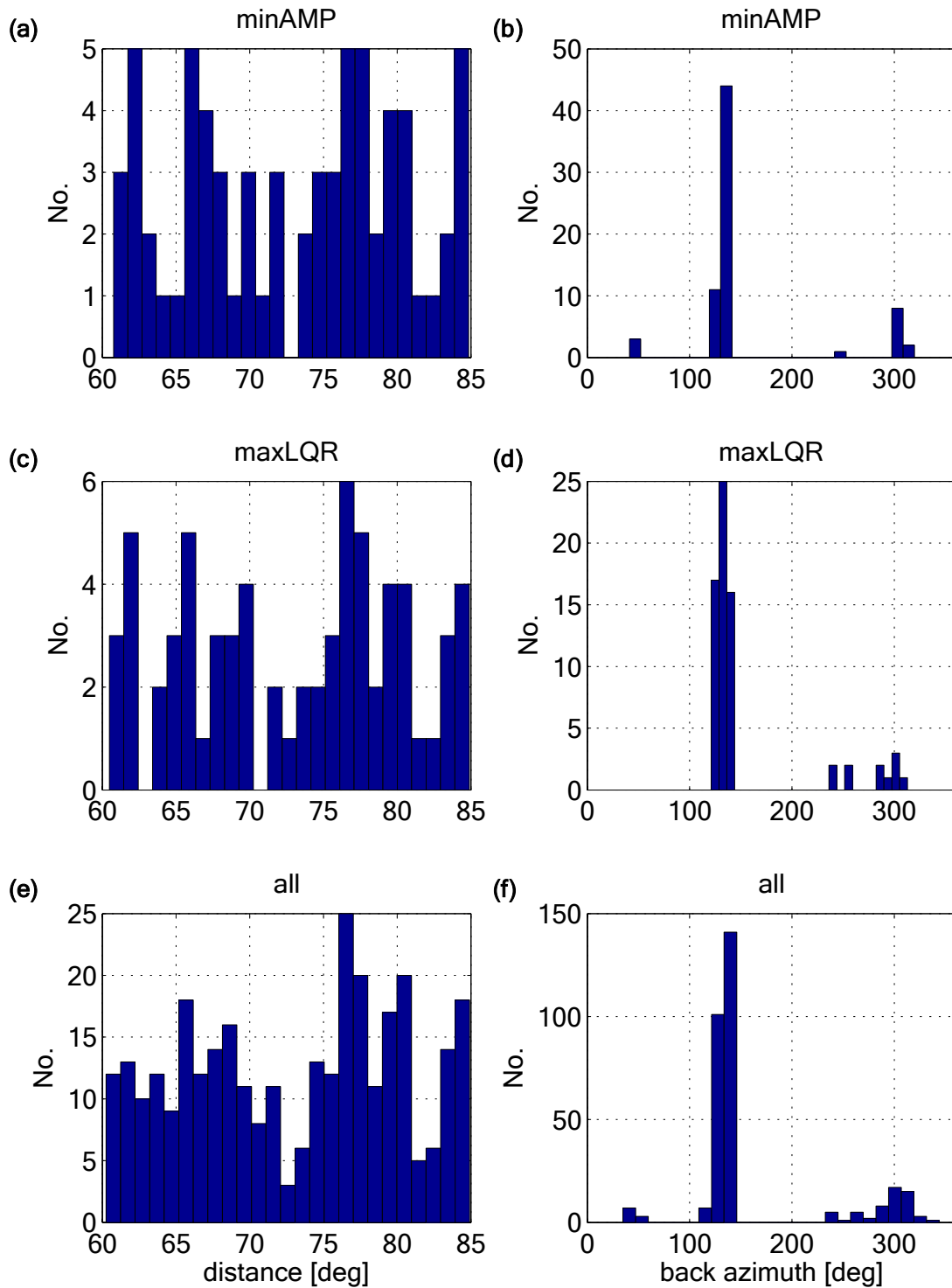


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3 81 **Figure S7.** Images of synthetic SRFs for the case 4 from the L70 model as a function of the
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5 82 distance of 60° – 85° with six different data selection criteria. The parent waveforms are
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7 83 windowed 10 s before and 35 s after the *S*-wave arrival and tapered with a 15% Hanning taper at
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9 84 both ends of the signal window. The frequency-domain deconvolution is done with a water level
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12 85 of 0.2%. See a caption of Fig. S4 for more detail.
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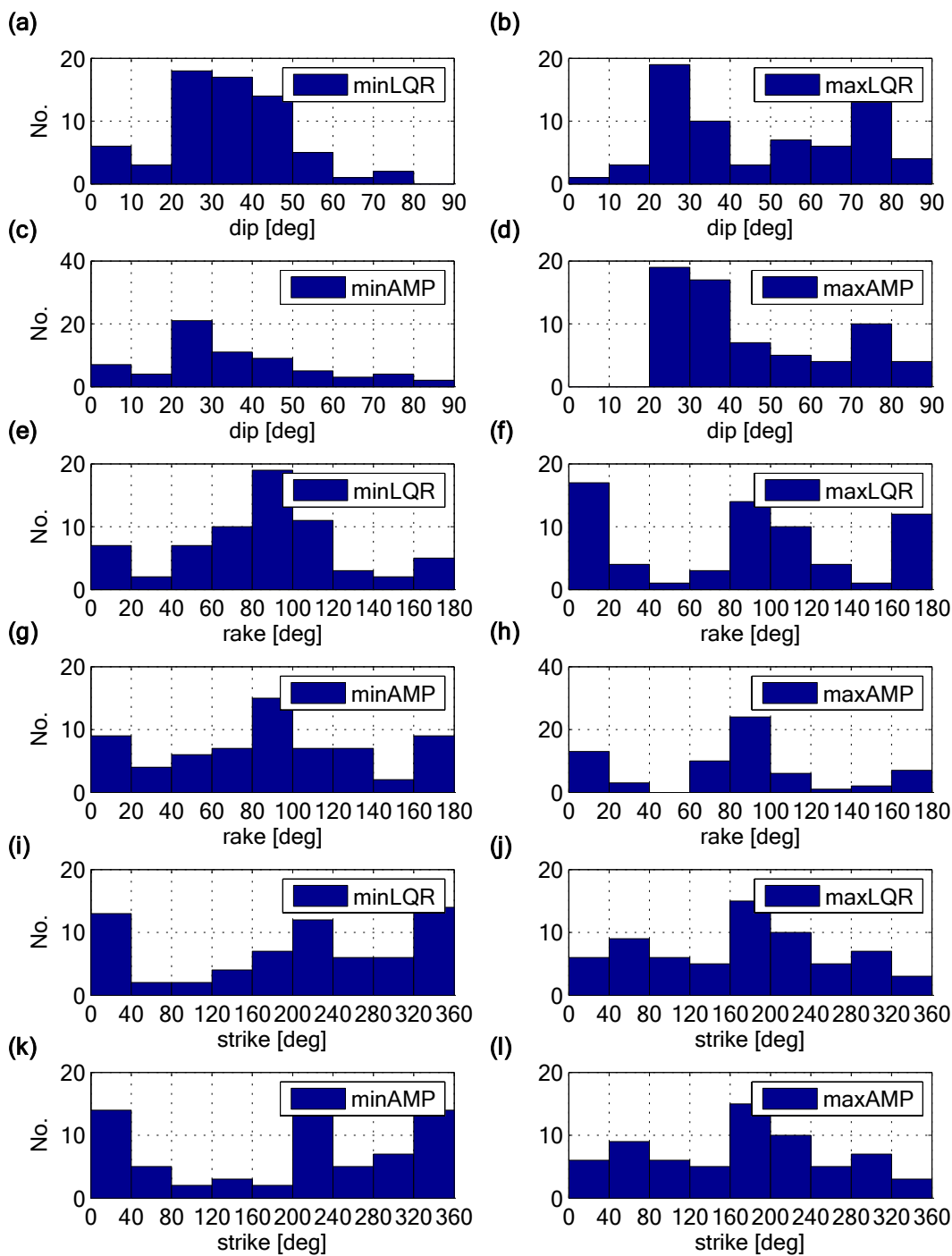


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88 **Figure S8.** Histograms of epicentral distance and back azimuth against six data selection criteria.

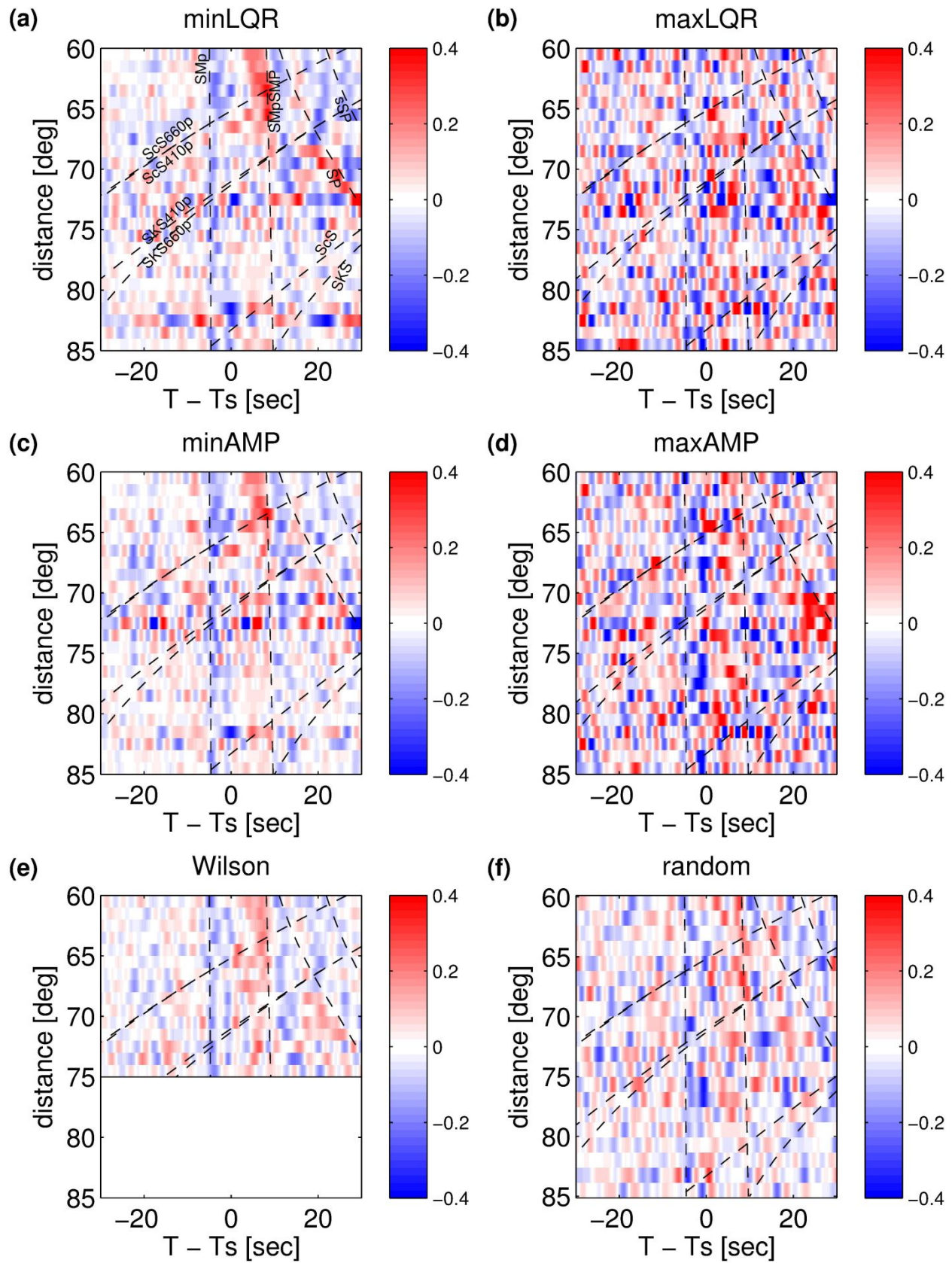
89 LQR and AMP data selection criteria with a percentage threshold of 25% result in negligible

90 data selection bias in back azimuthal and epicentral distance.

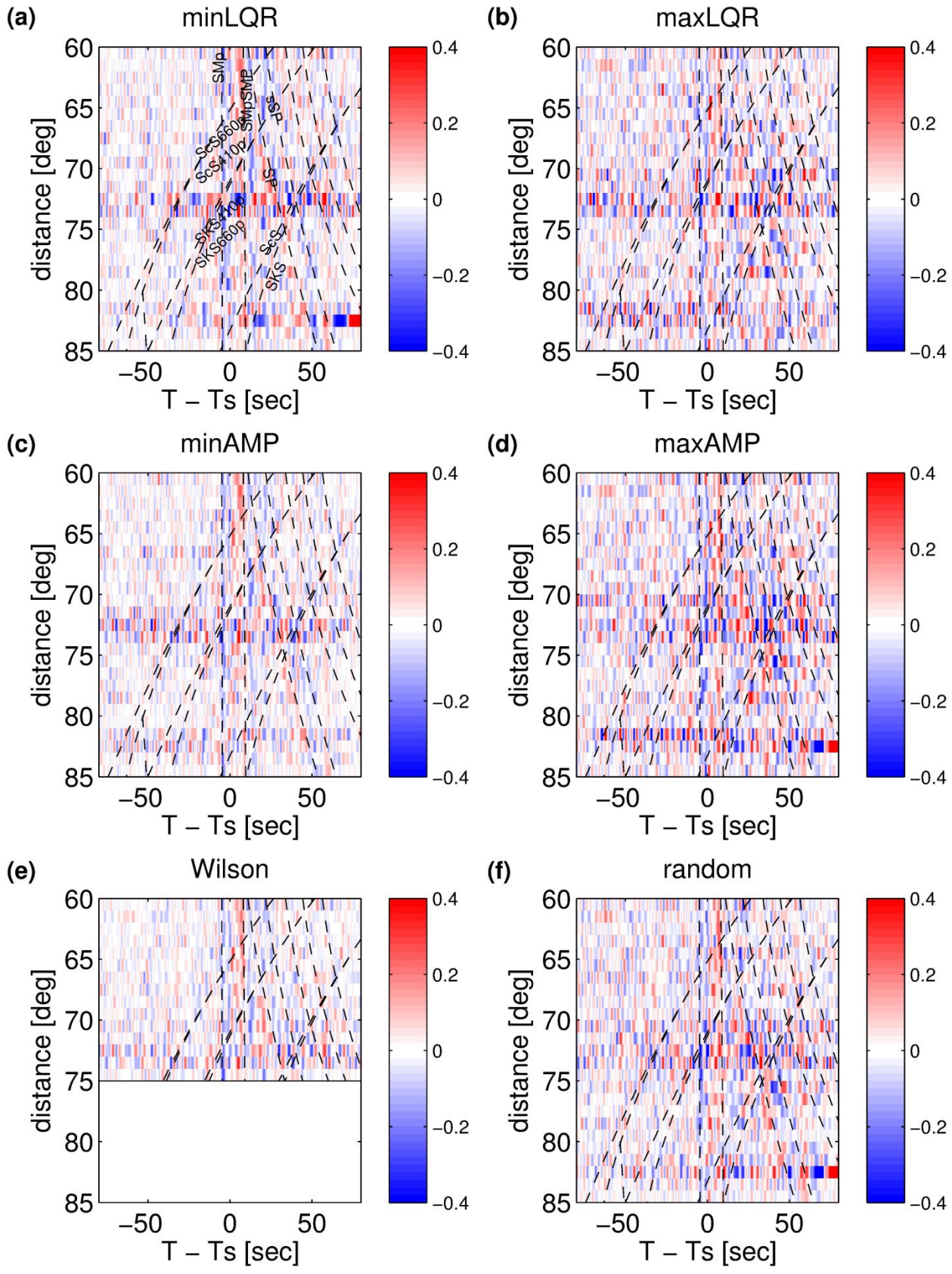


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92 **Figure S9.** Histograms of earthquake source parameters (dip, strike and rake) against four data
 93 selection criteria; (a, e, i) 25% lowest LQR, (b, f, j) 25% highest LQR, (c, g, k) 25% lowest
 94 AMP, and (d, h, l) 25% highest AMP. LQR and AMP data selection criteria result in negligible
 95 data selection preference in source parameters.

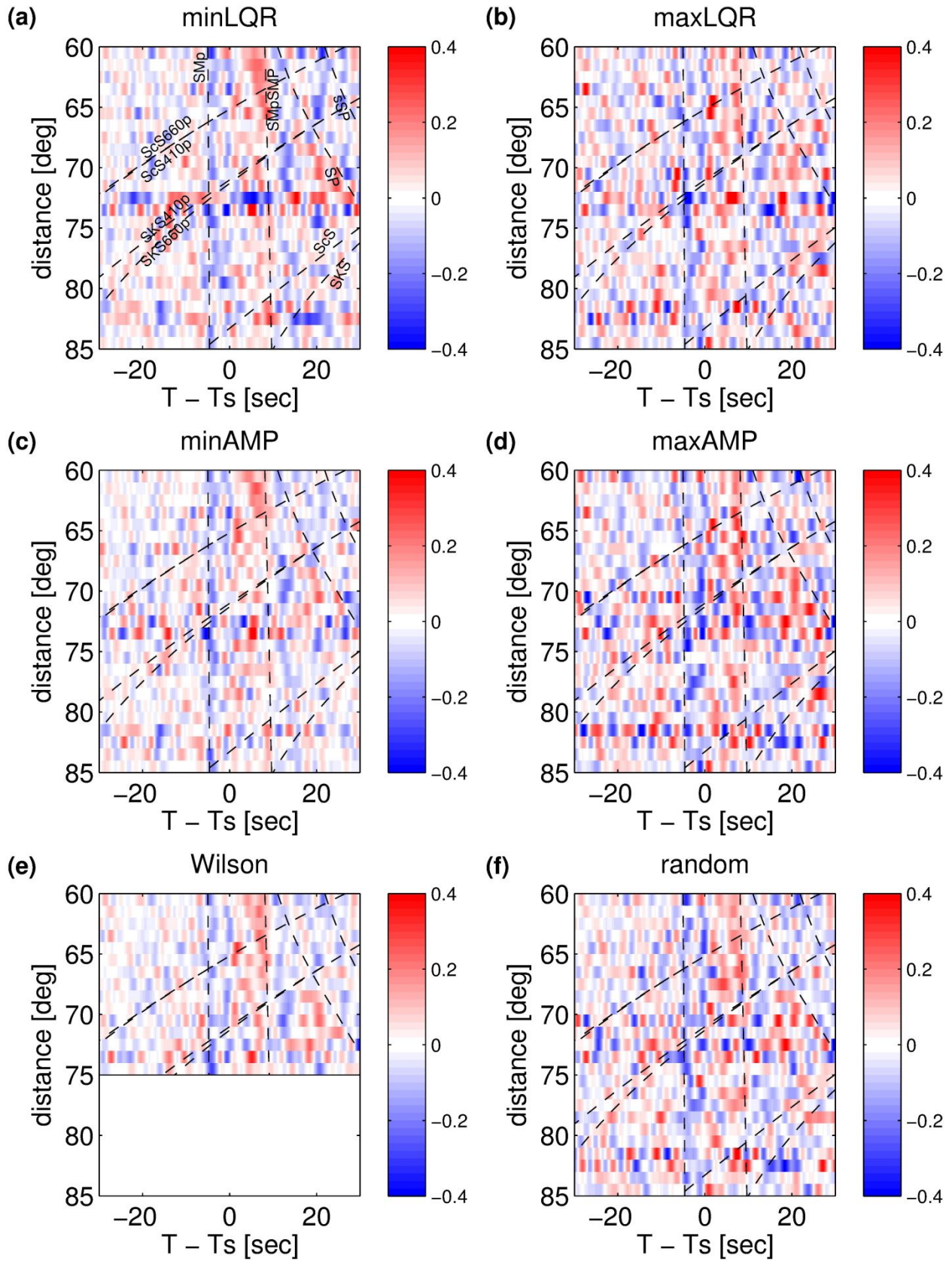


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3 97 **Figure S10.** Images of SRFs for station TJN as a function of the epicentral distance of 60° – 85°
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5 98 with following six data selection criteria; (a) 25% lowest LQR, (b) 25% highest LQR, (c) 25%
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7 99 lowest AMP, (d) 25% highest AMP, (e) criterion by Wilson *et al.* (2006), and (f) 25% random
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10 100 data selection. The parent waveforms are windowed 10 s before and 35 s after the *S*-wave arrival
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12 101 and tapered with a 15% Hanning taper at both ends of the signal window. Time domain wiener
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14 102 deconvolution is done with minimum regularization of 0.01% white noise. See a caption of Fig.
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16 103 S4 for more detail. See also Fig. 10 for the images of -80–80 s window.
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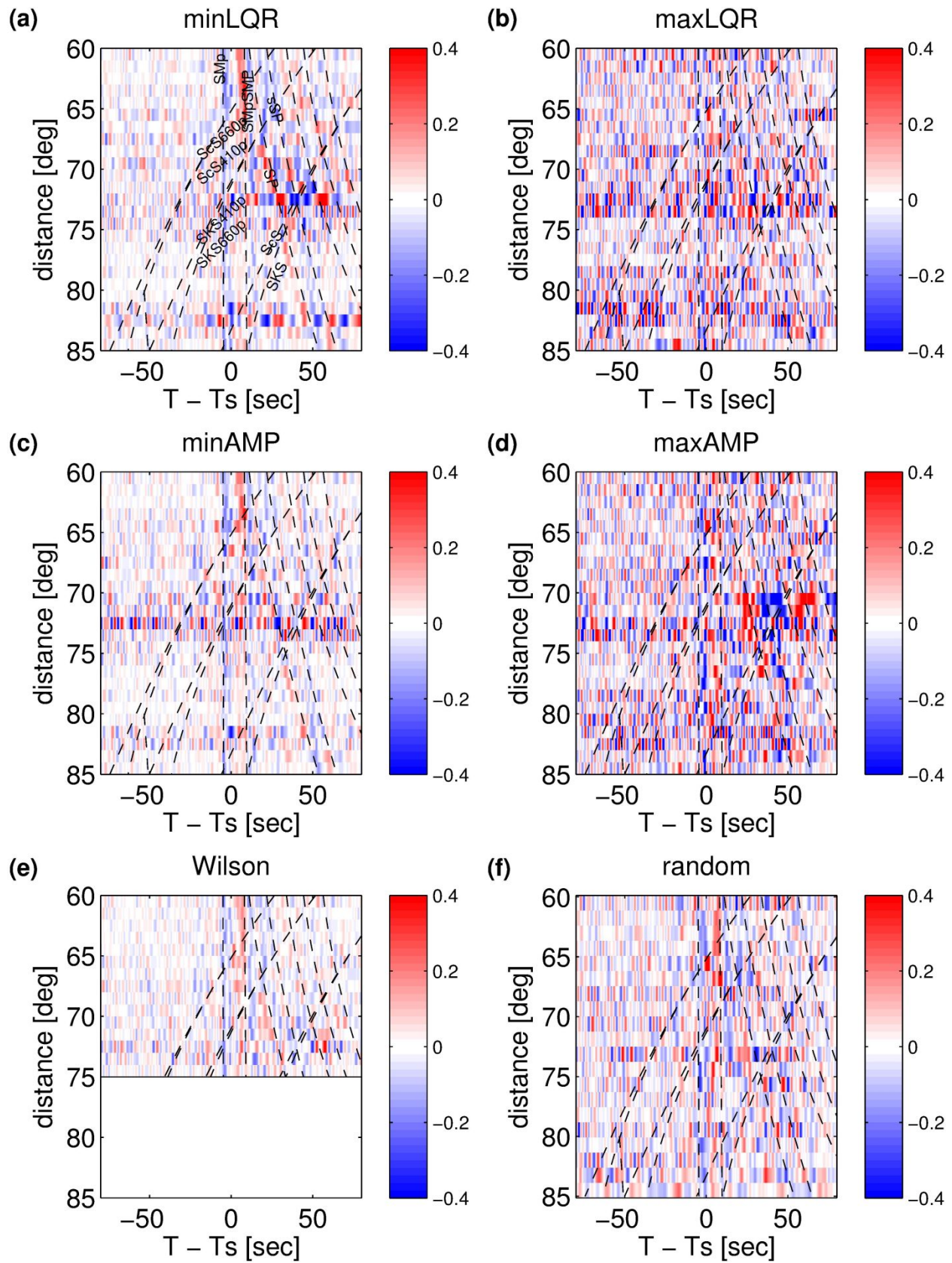


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3 105 **Figure S11.** Images of SRFs for station TJN as a function of the distance of 60° – 85° with
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5 106 following six data selection criteria; (a) 50% lowest LQR, (b) 50% highest LQR, (c) 50% lowest
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7 107 AMP, (d) 50% highest AMP, (e) criterion by Wilson *et al.* (2006), and (f) 50% random data
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9 108 selection. The parent waveforms are windowed 10 s before and 35 s after the *S*-wave arrival and
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11 109 tapered with a 15% Hanning taper at both ends of the signal window. Time domain wiener
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13 110 deconvolution is done with minimum regularization of 0.01% white noise. See a caption of Fig.
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15 111 S4 for more detail. See Fig. S12 for the images plotted for -30–30 s window.
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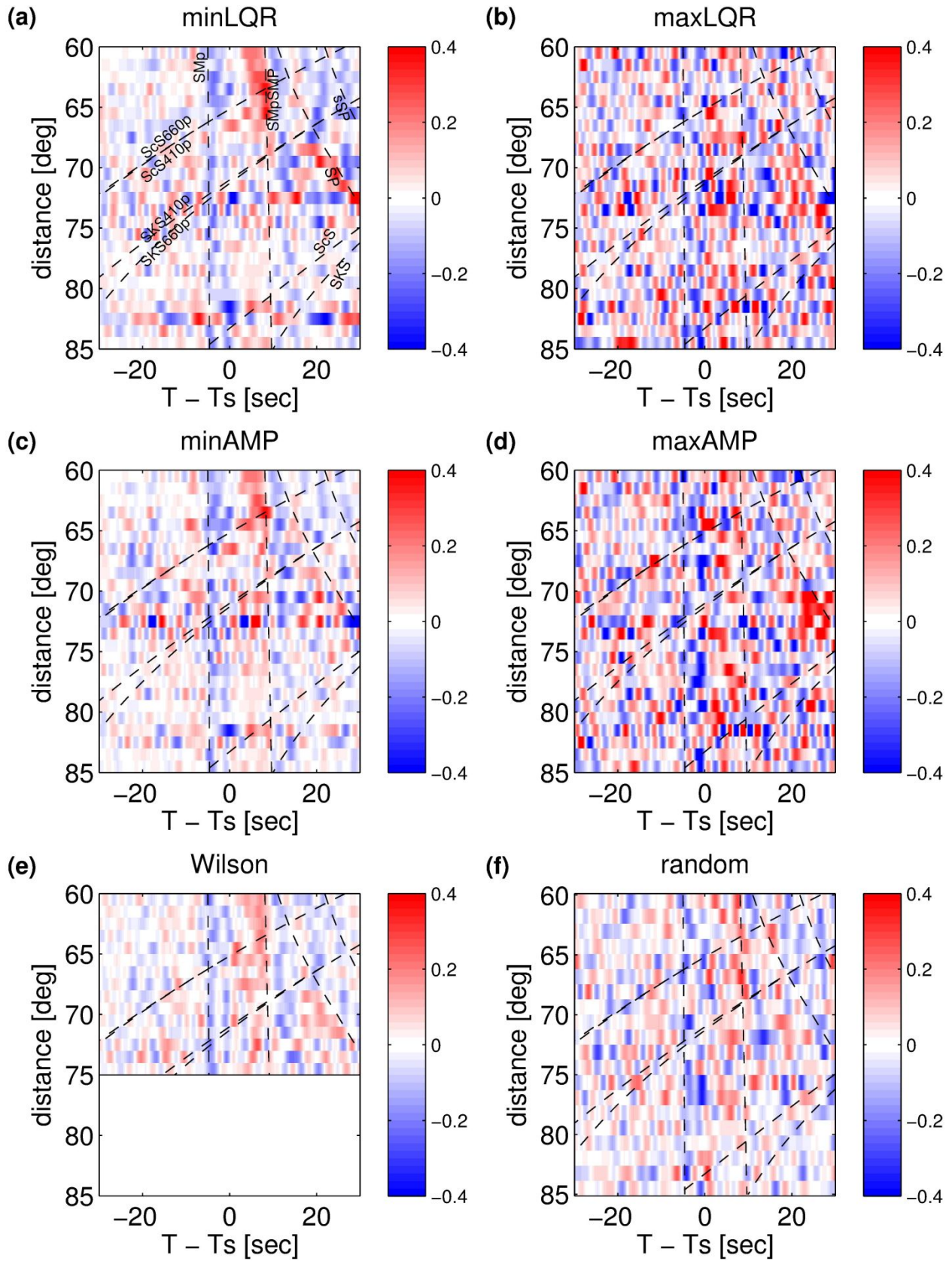


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3 113 **Figure S12.** Images of SRFs for station TJN as a function of the distance of 60° – 85° with
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5 114 following six data selection criteria; (a) 50% lowest LQR, (b) 50% highest LQR, (c) 50% lowest
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7 115 AMP, (d) 50% highest AMP, (e) criterion by Wilson *et al.* (2006), and (f) 50% random data
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9 116 selection. The parent waveforms are windowed 10 s before and 35 s after the *S*-wave arrival and
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11 117 tapered with a 15% Hanning taper at both ends of the signal window. Time domain wiener
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13 118 deconvolution is done with minimum regularization of 0.01% white noise. See a caption of Fig.
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15 119 S4 for more detail.
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3 121 **Figure S13.** Images of SRFs for station TJN as a function of the distance of 60° – 85° with
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5 122 following six data selection criteria; (a) 25% lowest LQR, (b) 25% highest LQR, (c) 25% lowest
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7 123 AMP, (d) 25% highest AMP, (e) criterion by Wilson *et al.* (2006), and (f) 25% random data
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9 124 selection. The parent waveforms are windowed 10 s before and 35 s after the *S*-wave arrival and
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11 125 tapered with a 15% Hanning taper at both ends of the signal window. Time domain wiener
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13 126 deconvolution is done with a strong regularization of 1% white noise. See Fig. S14 for the
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15 127 images plotted for -30–30 s window.
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3 129 **Figure S14.** Images of SRFs for station TJN as a function of the distance of 60°–85° with
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5 130 following six data selection criteria; (a) 25% lowest LQR, (b) 25% highest LQR, (c) 25% lowest
6
7 131 AMP, (d) 25% highest AMP, (e) criterion by Wilson *et al.* (2006), and (f) 25% random data
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9 132 selection. The parent waveforms are windowed 10 s before and 35 s after the *S*-wave arrival and
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11 133 tapered with a 15% Hanning taper at both ends of the signal window. Time domain wiener
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13 134 deconvolution is done with a strong regularization of 1% white noise.
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21 136 **Reference**

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