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Teleseismic shear wave splitting measurements in noisy environments

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SUMMARY

High noise levels hamper teleseismic shear wave splitting measurements, which bandpass filtering does not always help. To investigate how robust splitting measurements are to noise, we analysed a set of synthetic records with known splitting parameters and added fixed levels of noise. In the presence of weak anisotropy, single-waveform splitting measurements are unreliable when operating with noisy data sets. A practical rule in terms of S/N ratio and splitting delay time parameters is that splitting is confidently detectable at $S/N > 8$, regardless of the wave's original polarization orientation. However, for the evidence of weak anisotropy to be detectable and measurable at an S/N value of 4, the backazimuth separation of the phases from the fast polarization direction needs to be higher than 20°. Stacks of individual measurements consistently yield reliable results down to S/N values of 4. Applying stacking to data from DSB (Dublin, Ireland), the fast polarization direction ϕ and lag time δt are 58° and 0.95 s. This orientation reflects surface trends of deformation in the area, as found elsewhere in the UK. Our result thus reinforces the proposed model that the detected anisotropy in the British Isles originates from lithospheric coherent deformation preserved from the last main tectonic episode.

Key words: anisotropy, shear wave splitting.

INTRODUCTION

Shear wave splitting measurements at many stations indicate seismic anisotropy (Vinnik *et al.* 1989; Silver & Chan 1991; Silver 1996). It is widely accepted that this property arises from strain-induced lattice preferred orientation (LPO) of the upper-mantle mineral components, but its physical and geological significance for stations located in di erent geodynamical environments is still much debated. Whether absolute plate motion (APM) (Vinnik *et al.* 1989) or coherent lithospheric deformation in orogenic areas (Silver & Chan 1991; Hel rich *et al.* 1994; Hel rich 1995; Silver 1996; Barruol *et al.* 1997) causes the anisotropy has further consequences. In the latter case it would point to a strong coupling present between the crust and the upper mantle in the deformational process and it would lead to inferences on the global mechanisms of plate tectonics such as the origin of its dominant driving forces (Silver 1996). Other asthenospheric candidate processes (small-scale convection cells, forced flow around deep continental roots or lithosphere–asthenosphere transition topography) might only explain local variability of the shear wave splitting parameters (Barruol *et al.* 1997). They are not, however, the main source of large-scale trends.

Within the UK, the fast shear wave polarization direction ϕ of the anisotropy commonly parallels the trend of the dominant surface structures in the area, which are mostly of Caledonian or Variscan age. This suggests the presence in the lithosphere of a 'frozen', coherent pattern of deformation, which has been preserved over geological time. As wide-angle seismic studies support a fairly constant Moho depth in the UK, variations in magnitude of the delay time δt of splitting may be related to the increasing level of basement involvement in the orogenic processes in the proximity of the Iapetus Suture Zone (Hel rich 1995). Barruol *et al.* (1997) expanded this study, bringing splitting data from a series of US stations to strengthen the frozen lithospheric deformation hypothesis. Holt (1998) has also recently shown splitting results from some Tibetan stations where the fast polarization direction is strikingly aligned with the directions of the main geological features. Processes other than lithospheric mineral LPO do not seem to provide an equally consistent fit of all the observations in continental areas, in terms of both ϕ and δt (Silver & Chan 1991; Hel rich *et al.* 1994; Silver 1996; Barruol *et al.* 1997).

In this paper we describe our investigation of seismic anisotropy using teleseismic shear wave splitting measurements at the GEOFON station DSB in Dublin, Ireland, aiming to integrate the work by Hel rich (1995) in the UK and assess the relationships between the splitting parameters and the local geology. We focus on the problems encountered in our analysis related to the particularly noisy environment. Through analysis of synthetic seismograms with known splitting parameters and added noise, we investigate the relationship between splitting measurements and noise levels. Here we show that filtering is not an e ective tactic when the signal and noise frequency bands overlap using the standard measurement technique of Silver & Chan (1991). Our modified version of the stacking processing technique of Wolfe & Silver (1998) overcomes instead the highly noisy conditions at DSB. The splitting parameters retrieved for this station support the trends in the UK proposed earlier for both ϕ and δt.

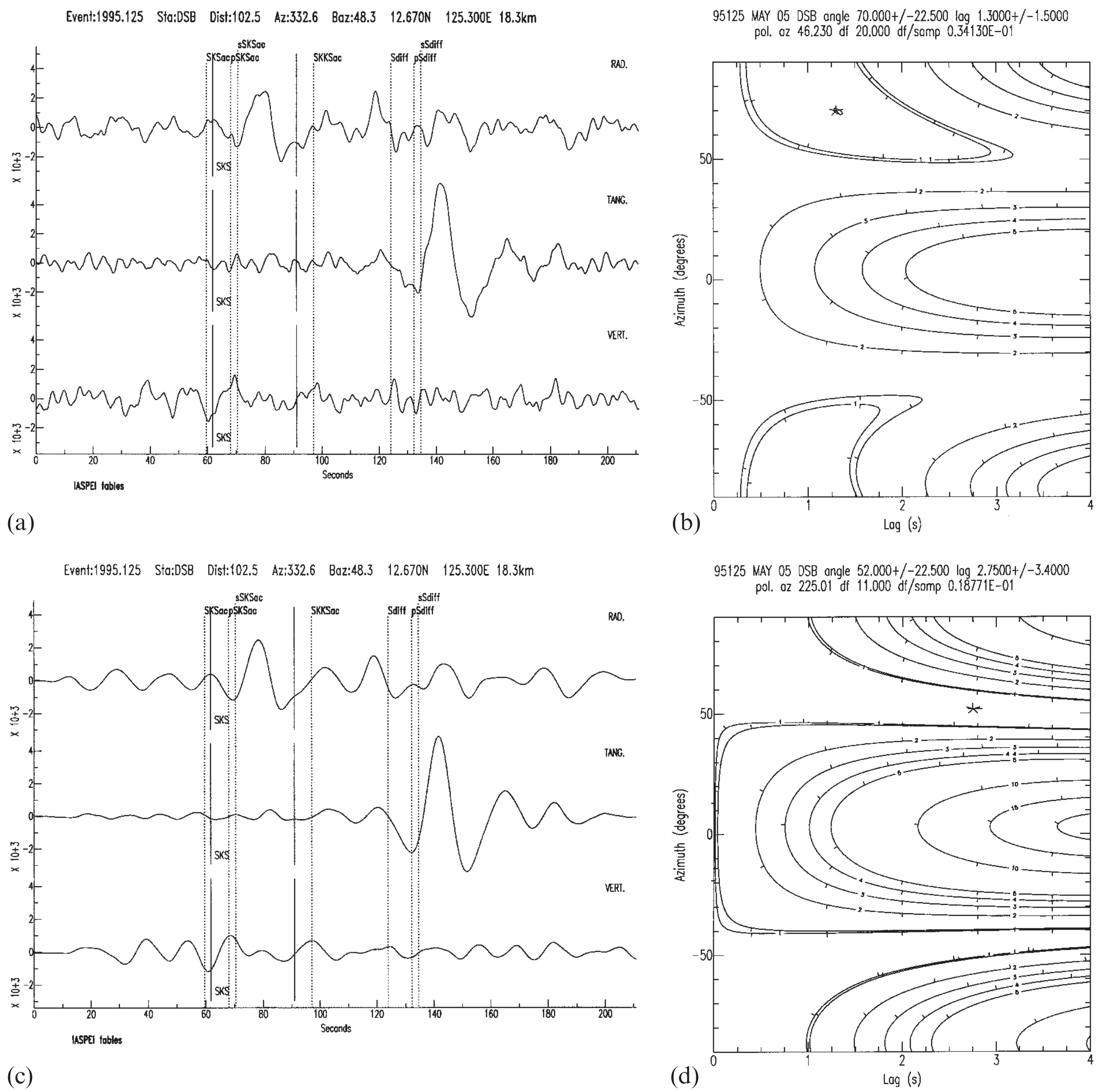

Figure 1. Example of single-waveform splitting measurements at DSB, following Silver & Chan (1991). (a) Original three-component broad-band seismogram. Horizontal components are rotated onto the radial and tangential directions. Dashed lines are theoretical arrivals from IASPEI tables; full lines are limits of picked measurement window. Unclear signal energy on the T component leads to poorly constrained measurement. (b) Plot of operator misfit. Star denotes optimal splitting parameters and double contour line marks 95 per cent confidence area. Title defines numerically $\phi \pm \sigma$ (angle), $\delta t \pm \sigma$ (lag), incoming polarization direction of shear wave (pol. az) and number of degrees of freedom (df). (c) Seismic trace after bandpass filtering with corners 0.02 and 0.1 Hz. Signal within measurement window is now more evident but its tangential component amplitude has been further reduced by the filter. (d) Misfit plot for measurement on filtered record. The result is consistent with that obtained from unfiltered waveform analysis (within the constraints of their standard deviations) but its confidence level is much degraded.

DATA AND METHODS

For our study we use records of *SKS*, *SKKS* and *PKS* from over 100 broad-band three-component seismograms recorded between January 1994 and June 1996. They are available in part from the GEOFON data centre in Potsdam, Germany and in part from the IRIS database at the University of Washington. The raw data are noisy, making the records di cult to analyse.

Individual record estimates

We used the measurement technique described by Silver & Chan (1991) to estimate the splitting parameters from individual records (Fig. 1). In the absence of anisotropy, seismograms should only bear *SKS* or *SKKS* energy on the radial component. The method seeks the inverse splitting operator which best removes the split signal from the tangential direction to the backazimuth by means of an exhaustive search. Alternatively, when the shear wave's incoming polarization is shifted from the backazimuth direction, the pair of orthogonal axes are sought which correspond to the eigenvectors of the ground particle motion matrix. Such an inverse operator describes the medium's anisotropy through the shear wave splitting parameters (ϕ, δt). The technique also provides statistical estimates of the misfits from the correct solution.

The successful application of this procedure depends on the detectability of the split signal on the tangential component, which in turn is a function of the signal-to-noise (S/N) levels of seismograms. The magnitude of δt and the angular separation between the incoming polarization direction of the waveform and ϕ control the signal energy on the tangential component. In our case, an average S/N ratio of 3 : 1 leads typically to very poorly constrained measurements with this technique, with broad uncertainty bands for both ϕ and δt, as exemplified by the contour plot of Fig. 1(b).

To determine the S/N ratio of each of our seismograms, the signal level is the maximum amplitude of the seismic trace within the measurement window on the radial component after applying the correct inverse splitting operator. The 2σ envelope value of the time-series of values within the same window on the tangential component, after removal of the split signal by such an inverse operator, gives the seismogram's noise level.

To reduce the high noise level in the data and enhance the visibility of the signal, we explored bandpass filtering of our original records. A combination of spectral analysis and filtering tests suggested optimal filter corner frequencies of 0.02 and 0.1 Hz. At higher frequencies, in fact, strong noise was overlapped with the signal, typically dominated by periods between 4 and 8 s, thus forcing the selection of such a narrow filter. Consequently, seismic energy was also lost in the process and splitting measurements on the filtered seismograms remained poorly constrained: they resemble null measurements, as the contour plot in Fig. 1(d) suggests.

Synthetic analysis

In very noisy environments the traditional splitting measurement methodology does not provide confident estimates of the parameters of anisotropy and filtering does not overcome this obstacle (see also Wolfe & Silver 1998). Narrow bandpass filtering, with an upper corner frequency within the signal's proper spectral range, also reduces signal energy. This is particularly problematic if splitting is small and hence the amplitude of the signal on the tangential component is already very limited. How much splitting can we detect in such noisy environments? Here we seek a practical but general rule for the successful application of Silver & Chan's (1991) methodology, trying also to define quantitatively the influence of filtering on these resolution limits.

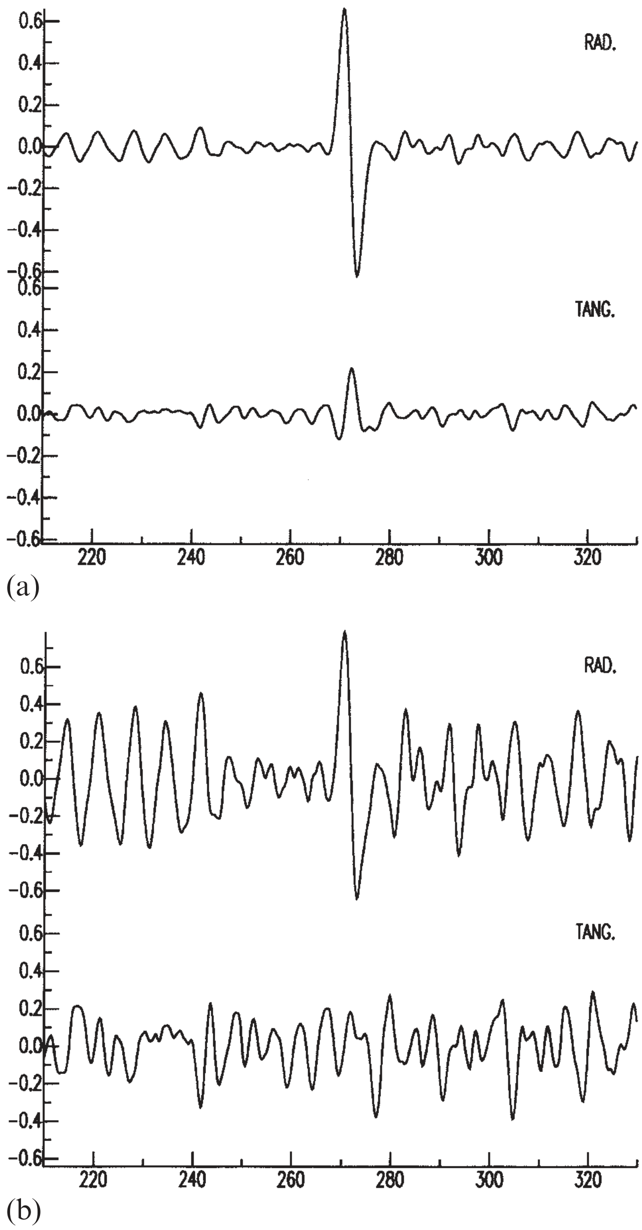

Figure 2. Synthetic seismograms. The dominant frequency of *SKS* is 0.125 Hz and the splitting parameters in these examples are (ϕ, δt) = (0°, 1 s). Backazimuth to event source is 20°. Noise generated by an autoregressive model fitted to horizontal-component oceanic noise is added to the seismic trace at di erent S/N ratios. (a) S/N ratio 10 : 1; (b) S/N ratio 2 : 1. The parameters adopted simulate well the spectral characterization of real data from DSB.

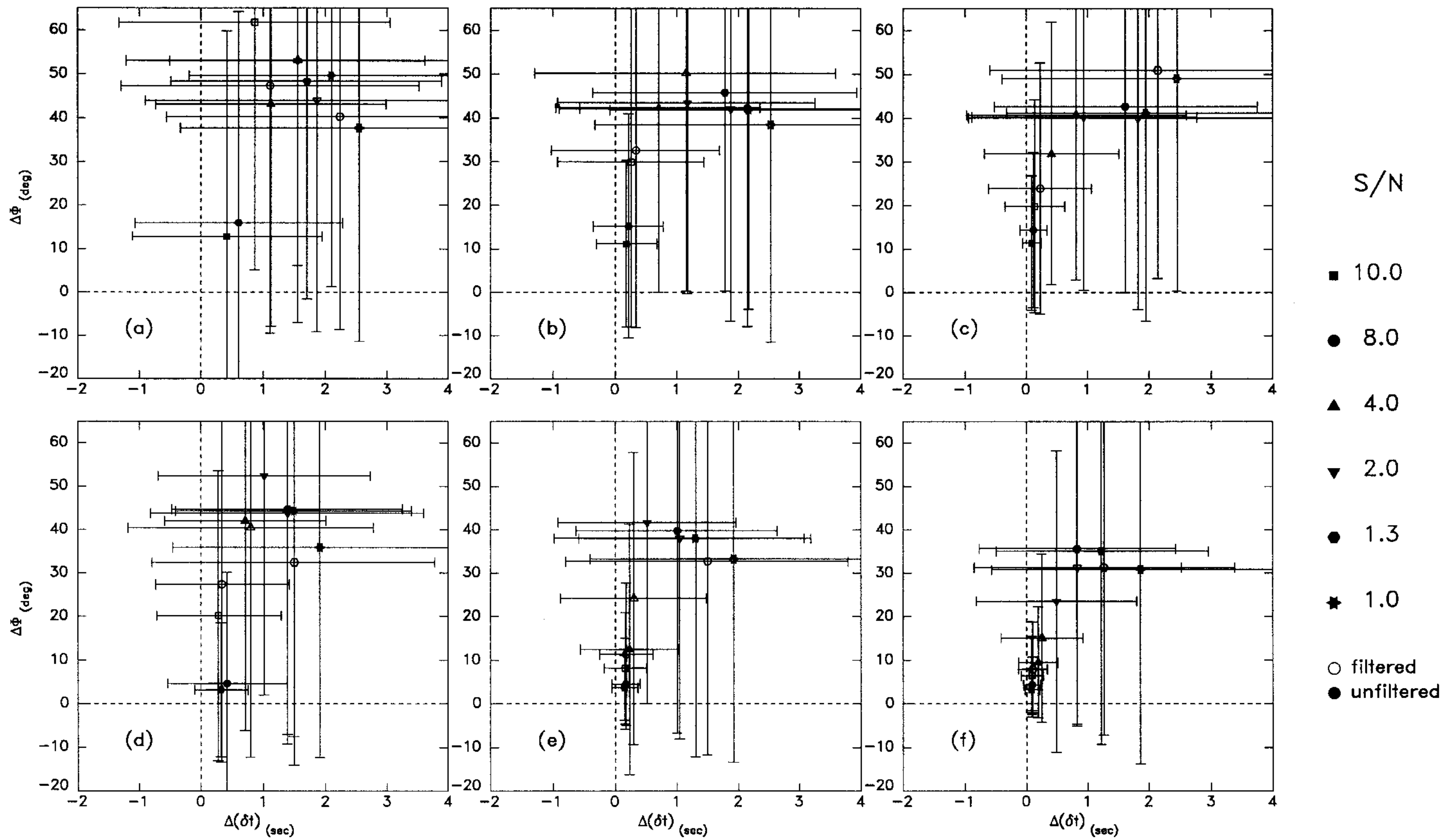

Figure 3. Diagrams summarizing the results of our synthetic analysis. Full symbols indicate results from analysis of unfiltered synthetic records, open symbols refer to bandpass filtered records in the range 0.02–0.1 Hz. Results displayed as absolute value of discrepancy with imposed parameters. Dashed lines mark the match of the measurements with input to synthetics. Plots built for increasing backazimuth separation from ϕ (left to right: $\Delta \mathrm{baz} = \pm 10^\circ$, 20°, 30°) and δt (top to bottom: $\delta t = 0.5$, 1.0, 1.5, 2.0 s). Vertical scale: absolute deviation from ϕ; horizontal scale: deviation from δt. Correct splitting characterization is detectable from unfiltered records in the presence of $S/N > 8$, regardless of the incoming polarization direction of waveforms and the strength of anisotropy. At an S/N ratio ≤ 4 at least 20° of backazimuth separation from the fast polarization direction is required. Bandpass filtering of low S/N data is only e ective at $\delta t > 1.5$ s.

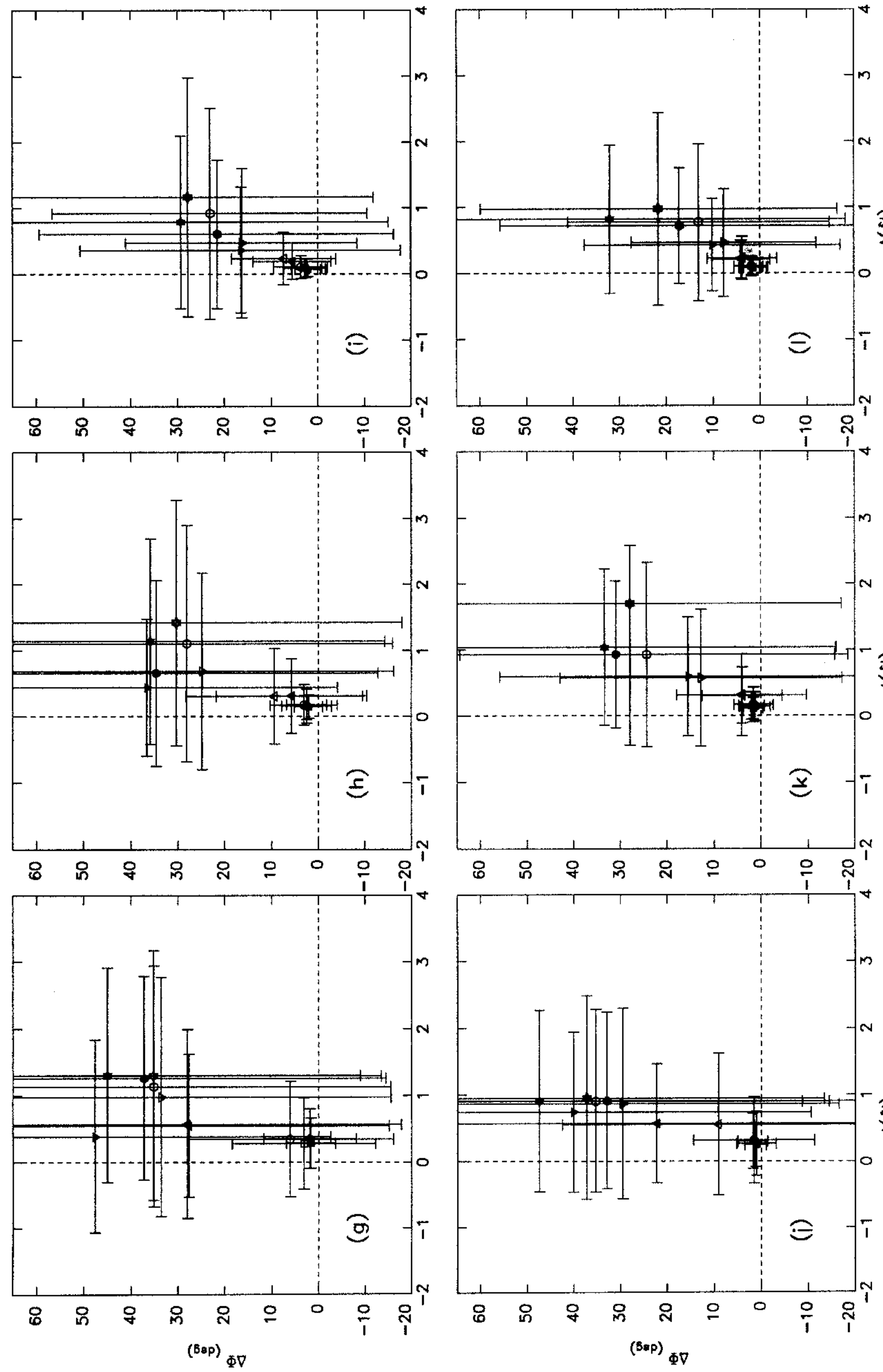

Figure 3. *(continued.)*

For di erent splitting delay times (ranging from 0.5 to 2.0 s) and backazimuth separations from ϕ ($\pm 10^\circ$, 20°, 30°) we generated synthetic seismograms with known splitting parameters by adding noise to the seismic trace at di erent S/N levels (ranging from 10:1 to 1:1) (Fig. 2). Noise functions were calculated by autoregressive models of noise at stations located in comparable environments. For each set of the above parameters we produced 50 di erent synthetics with di erent noise sequences. We analysed these groups of records in the same fashion as the real data, with and without bandpass filtering. Fig. 3 shows the results from this e ort: average values of the ϕ and δt estimates, weighted by their standard deviations, are represented for each group. The error bars on these diagrams represent the standard deviation (1σ) of the symmetrized distribution of the groups of individual measurements, with shorter bars corresponding to higher confidence in the result. As expected, uncertainties become smaller when δt and the backazimuth separation from the fast polarization direction increase, as well as when the noise level decreases.

We can summarize our findings, noting first how, in general, filtering does not result in more precise and confident estimates of the splitting parameters when splitting is small. For $\delta t \leq 1.5$ s, splitting measurements on unfiltered records with relatively high S/N yield closer solutions for ϕ to the expected value. For S/N lying under the threshold of 3:1, filtering once again is not a successful operation as it yields no significant improvement to ϕ determinations, while also leading to worse estimates of the lag time. In addition, filtering consistently gives way to a higher dispersion of individual measurements around the average, in terms of both ϕ and δt. We can relate these results to the fact that filtering seismograms with small splitting further reduces the energy of the split signal on the tangential component, thus leading to numerous apparent null measurements.

To illustrate this point note in Fig. 3a the trend of solutions for analyses on filtered seismograms bearing minimum splitting (δt 0.5 s) and characterized by a backazimuth separation from ϕ of $\pm 10^\circ$. The higher-S/N ratio events yield a weighted average measurement which departs even more from the correct and expected answer for ϕ than the estimates from lower-S/N ratio data. Examining this 'reversed' sequence in detail shows that almost all individual measurements are null, which brings a totally unconstrained value of ϕ to the averaging process.

Bandpass filtering on low S/N data, to enhance splitting parameter determinations, only becomes e ective when the δt value exceeds 1.5 s.

Quantitatively, if we consider the world average δt value of 1.0 s for *SKS* and *SKKS*, we can define the limits of resolution of the Silver & Chan (1991) technique in terms of S/N ratio: a S/N ratio of 8:1 at least is needed to retrieve consistently the correct splitting parameters from unfiltered seismograms, regardless of the waveform's initial polarization. A S/N value as low as 4:1 is only tolerable when the separation between the backazimuth and the direction of fast polarization is $\geq 20^\circ$. These limitations become more pessimistic for filtered seismograms: even an S/N ratio of 10:1 does not yield the correct answer consistently when original polarization directions di er marginally from the anisotropy axes of the medium.

Stacking procedure

The synthetic analysis confirms that we cannot reliably define the splitting parameters at DSB using the traditional single-waveform method of analysis, given the average S/N ratio of 3:1 of our data. Trying to find an alternative way to handle our noisy data, we next explored Wolfe & Silver's (1998) stacking technique, originally devised to study anisotropy at noisy oceanic stations.

The method uses individual estimates, obtained with the Silver & Chan (1991) analysis, and sums their misfit distributions after normalization, producing a combined misfit to all the available data. Moreover, good-quality measurements can be treated in the same way as poorly constrained ones and null ones, but as lower-S/N records convey less information in terms of splitting than high-S/N ones, we augmented this methodology by weighting (Fig. 4). Progressively higher weight is given in the stack to events with S/N increasing from 1:1 to 21:1. S/N ratios below and above this range can no longer influence substantially the amount of information, irrelevant or important respectively, that we can extract from records; these measurements are therefore assigned a virtually identical low and high value. Furthermore, to compensate for the e ect of overrepresented azimuths in the uneven sampling of a station, we adopted another weighting procedure. In this method every individual measurement is scaled to a factor of $1/N$, with its great-circle direction defining a wedge of $\pm 10^\circ$ in which N observations fall.

We also tested the reliability of this modified technique for detecting small anisotropy (δt 0.5 s) with di erent S/N ratios using synthetic simulations. For each S/N ratio, we built 150 synthetic seismograms with the same splitting parameters but varying backazimuth directions and processed them through bandpass filtering; we then analysed such products individually, with the Silver & Chan (1991) technique, over the same measurement window around the signal. We sorted them into 150 random combinations of 50 events each, and stacked their individual measurements, thus producing 150 simulated stacked observations for each value of S/N. An example for S/N 4:1 is given in Fig. 5. Analysing the histograms of the stack-retrieved splitting parameters for each S/N value, they all showed a narrow Gaussian-like distribution centred on the expected ϕ and δt, even down to a S/N ratio of 4:1. This result also holds when we perform the stacks of individual measurements from unfiltered synthetics instead. Our analysis

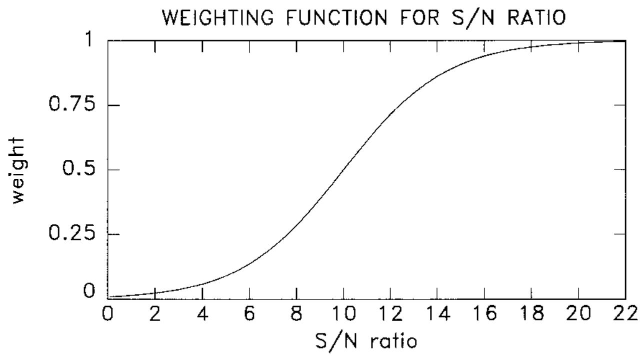

Figure 4. Weighting function to treat single-wave measurements in the stacking procedure according to their individual S/N ratio. Between S/N ratios of 1:1 and 21:1, increasing weight is given (inflection point of the curve corresponds to intermediate weight attributed to S/N 10:1); lower and higher S/N ratios adopt minimum and maximum weights.

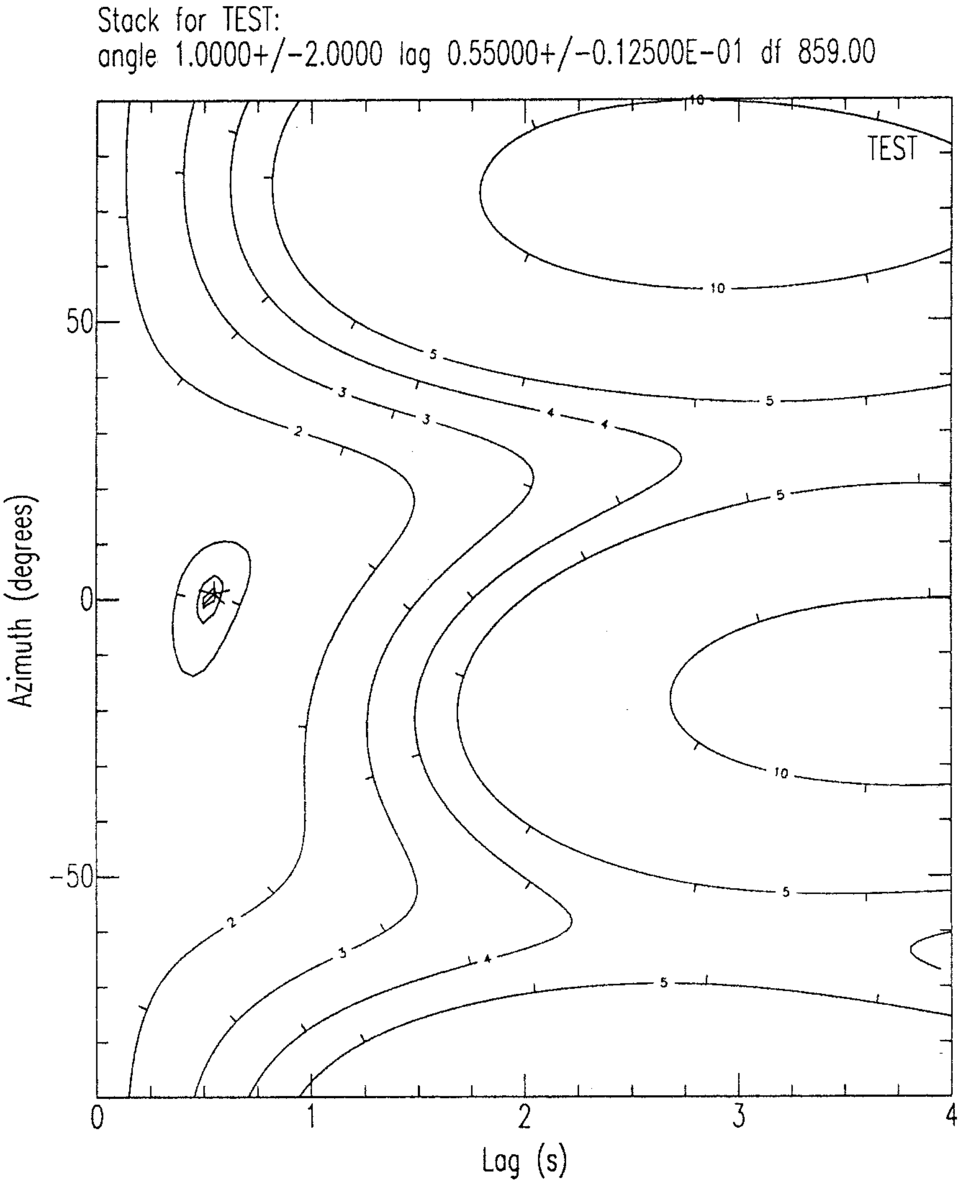

Figure 5. Example of the application of the stacking procedure to splitting analysis on synthetics. The stack combines the results of 50 single-waveform measurements on unfiltered records with S/N ratio 4 : 1 and varying incoming polarization directions with $(\phi, \delta t) = (0^\circ, 0.5\ \mathrm{s})$. Legend as in Fig. 1.

therefore demonstrates that this technique is a reliable tool for retrieving the parameters of anisotropy even with noisy data and small splitting conditions.

RESULTS AND DISCUSSION

We processed 41 splitting measurements on unfiltered DSB records with the above stacking technique. The result (Fig. 6) indicates a direction of fast polarization lying at 58° (clockwise from north) with a splitting lag time of 0.95 s. These parameters characterize the anisotropy at DSB.

The station DSB is located south of Dublin, within the north-eastern boundary of the Leinster Massif of Early Palaeozoic units intruded by the Late Caledonian Leinster Granite (Murphy 1987). According to Phillips *et al.* (1976), this area lies on the southern flank of the Iapetus Suture and hence belongs to the Avalonian domain (Soper *et al.* 1992). It displays a structural framework which is dominated by folds, faults and terrane boundaries striking along the Caledonian characteristic NE–SW direction (Phillips *et al.* 1980). These trends also find expression in similar patterns of the gravity field (Readman *et al.* 1997). Variscan deformation in the Dublin area, revealed by folding of the Visean flyschoid sequences of the Loughshinny Syncline, with axial plane traces lying typically E–W, is superficial (Le Gall 1991). The Variscan orogenic phase hence did not obliterate the previous dominant NE–SW pattern here, apparently finding deeper expression in the reactivation of transpressive basement lineaments of Caledonian origin (Le Gall 1991). A constant crustal thickness of about 30 km is found in the whole area of the British Isles (Bamford *et al.* 1978; Jacob *et al.* 1985; Lowe & Jacob 1989; Klemperer *et al.* 1991).

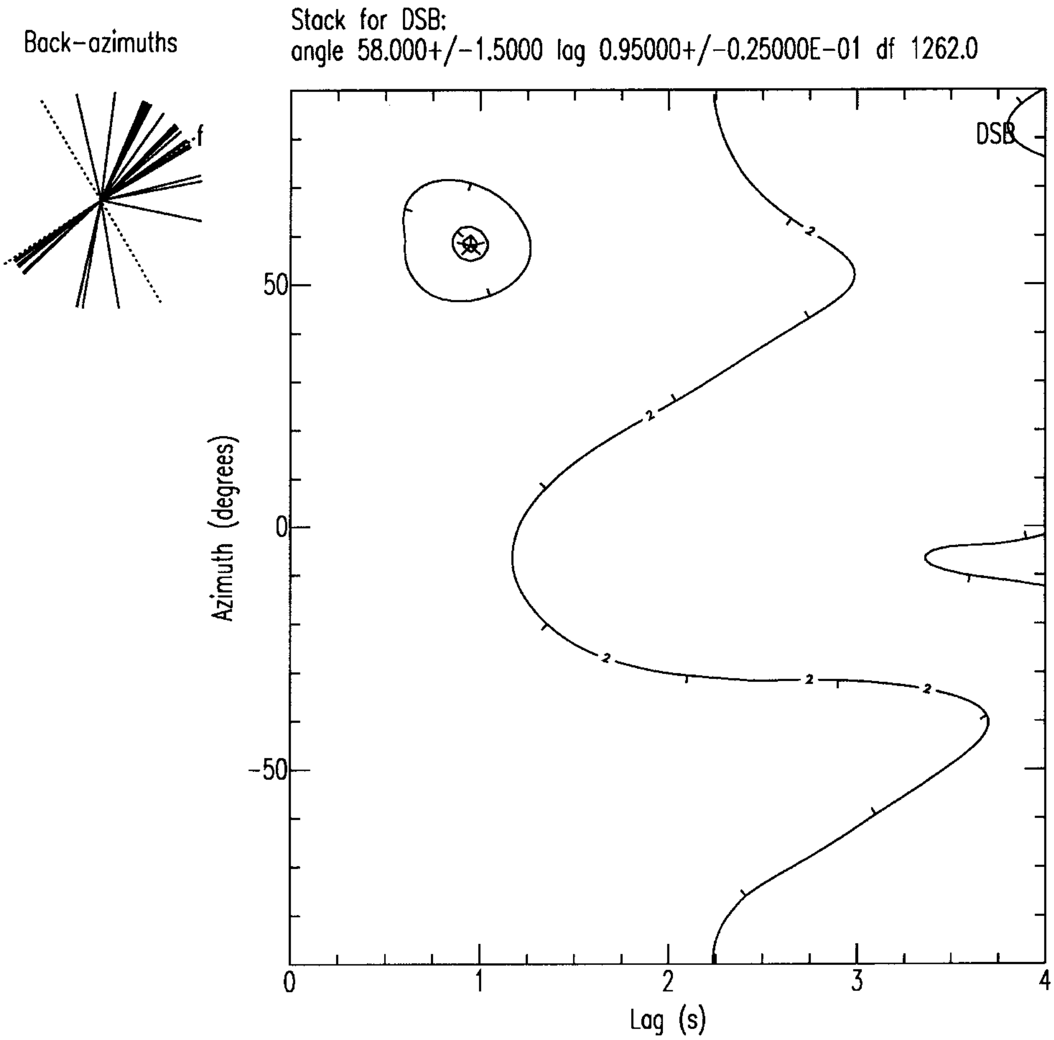

Figure 6. Stack plot giving the splitting parameters at DSB derived from a group of 41 measurements on unfiltered waveforms. Their calculated S/N ratio varies between 1.4 and 7.0, with a mean value 3.0. Azimuthal sampling of the station is represented by the direction plot in the top left corner.

Our splitting result for DSB is in line with Hel rich's (1995) inferences derived from other UK stations and further supports the hypothesis that 'frozen' lithospheric deformation, coherent with the dominant crustal tectonic fabric and dating back to the last main episode of tectonic activity in the area, is responsible for the detected seismic anisotropy. The fast polarization direction of 58° determined at DSB coincides with the dominant NE–SW tectonic pattern of the area (Figs 7a and b). The 0.95 s lag time also fits the trend of increasing δt towards the Iapetus Suture Zone (Fig. 7c). Given the regionally constant crustal thickness, this trend had been explained as related to the progressively increasing involvement of the basement in the deformation near the suture.

CONCLUSIONS

Our synthetic analysis shows the inadequacy of Silver & Chan's (1991) technique for retrieving splitting parameters when the S/N ratio is low and splitting small. Filtering is largely ine ective under these conditions. Our synthetic analysis also proved the validity of the new stacking procedure discussed by Wolfe & Silver (1998), which we augmented to avoid azimuthal bias and to be flexible in handling measurements from events with di erent S/N ratios. The technique can be reliably used, giving very confident results for splitting parameters, even where splitting is small and the S/N ratio generally very poor.

Splitting parameters at DSB were retrieved in this way, overcoming the problem posed by the station's very noisy conditions. The detected anisotropy reflects the local surface geology and supports the hypothesis of frozen coherent lithospheric deformation in the British Isles.

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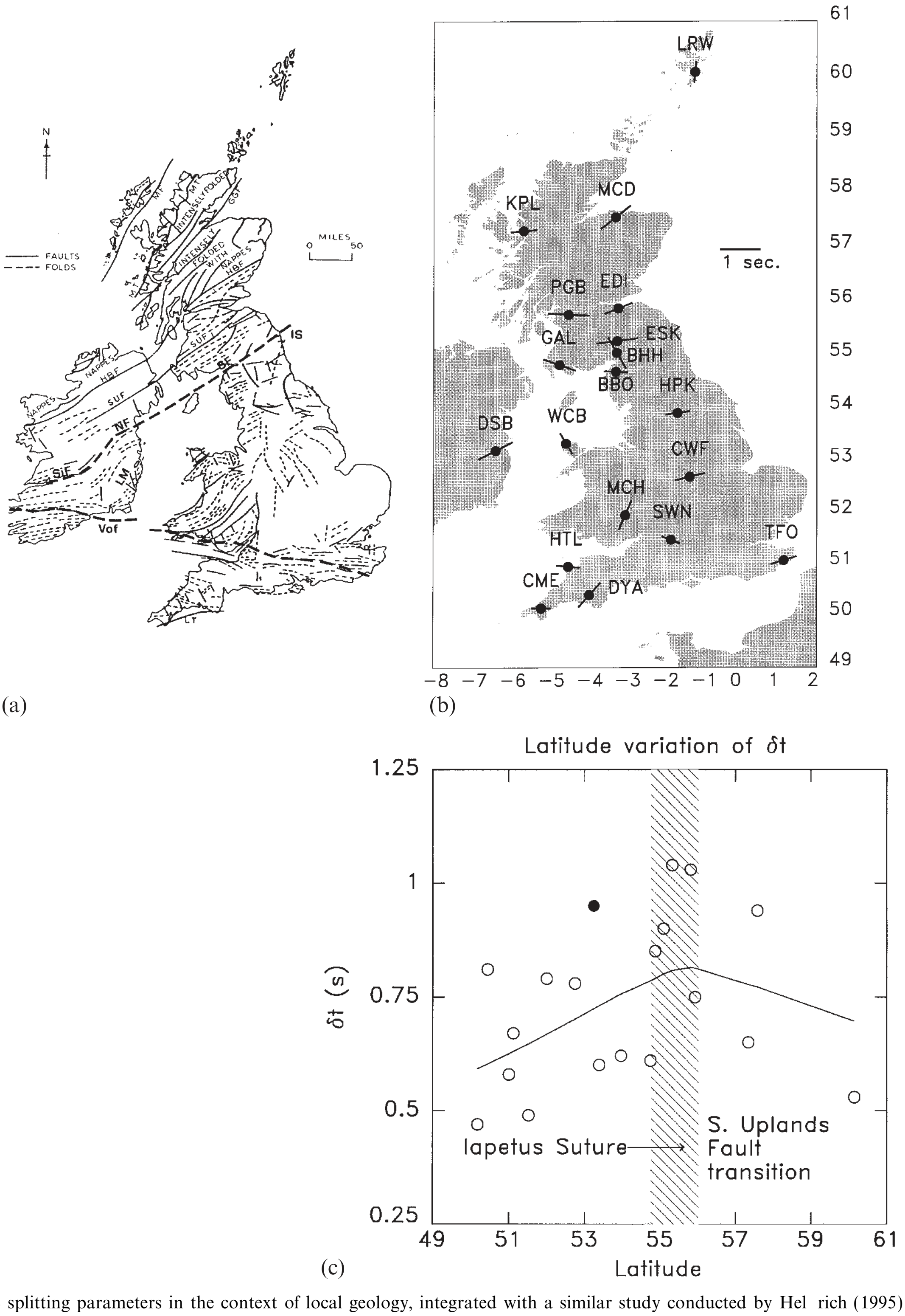

Figure 7. DSB splitting parameters in the context of local geology, integrated with a similar study conducted by Hel rich (1995) on stations of the UK network. (a) Simplified tectonic map of the British Isles from Anderson & Owen (1980) depicting main lineaments and dominant deformational trends. The Caledonian NE–SW pattern is recognizable in most part of the British Isles except in SW England and SW Ireland, where the Variscan dominant tectonic fabric trends approximately E–W. Iapetus Suture traced following Phillips *et al.* (1976). Variscan orogenic front traced following Le Gall (1991). Key: GGF—Great Glen Fault; HBF—Highland Boundary Fracture Zone; IS—Iapetus Suture; LM—Leinster Massif; LT—Lizard Thrust Zone; MF—Minch Fault; MT—Moine Thrust; NF—Navan Fault; SF—Solway Fault; SiF—Silvermines Fault; SUF—Southern Uplands Fault; Vof—Variscan orogenic front. (b) Symbolic representation of splitting measurements in the UK integrated with the result for DSB (adapted from Hel rich 1995). The fast polarization direction at DSB is also aligned with the dominant structural trend of the area. (c) Diagram from Hel rich (1995) showing the relationship between splitting delay times in the UK and station latitudes as a function of their distance from the Iapetus Suture Zone. The result for DSB is added and represented with a solid dot. The splitting delay times increase towards the Iaeptus Suture.

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