Supporting Information for "Multi-layer Seismic Anisotropy Beneath Greenland"

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Additional Supporting Information (Files uploaded separately)

1. Table S1: Information about stations used in this study.
2. Table S2: Individual splitting measurements used in this study.

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Introduction

Text S1 explains the methods for the synthetic tests of parameter recovery with uneven back-azimuthal sampling.

Table S1 shows information about each of the 27 stations used in the final dataset. Table S2 presents each individual splitting measurement used in the final dataset. Table S1 and S2 are also accessible at the Brown Digital Data Repository: https://repository.library.brown.edu/studio/item/bdr:1149085/, https://doi.org/10.7910/DVN/XB4SCT

Figure S1 shows measurements of shear-wave splitting fast polarization directon as a function of back-azimuth for each of the individual stations contributing to the final set of splitting measurements used in this study. The corresponding figure for NEEM is also in the main text. Figure S2 shows measurements of delay times as a function of back-azimuth for all stations in this study. Figure S3 shows fast axis measurements from prior studies in adjacent regions of North America, in addition to those shown in Figure 7 of the main text. Figure S4 shows measurements of fast axis as a function of back-azimuth for all stations, grouped by the type of *KS phase. Figures S5-7 show results from synthetic tests that explore the recovery of model parameters corresponding to two layers of anisotropy for datasets constructed with different underlying distributions and sources/levels of noise.

Text S1.

Here, we describe the parameters and process for the synthetic tests shown in Figure 6 and S5-7 in more detail.

Goal of Synthetic Tests: The goal of these tests is to examine how recovery of model parameters is affected by the (i) starting model, (ii) sampling of multiple starting models, and (iii) the back-azimuthal sampling. To this end, we have conducted the following series of tests.

Test 1a (Fig. S5a, c-h): Can we recover the two-layer model from a sampling of two-layer models that vary only slightly? To construct the synthetic dataset for Test 1a, at every back-azimuth for which we have an observation of shear-wave splitting, we choose a predicted fast direction from the pool of 39 values that corresponds to the models that pass the F-test from the finer grid search. If the chosen fast direction is within 3° of the back-azimuth, it is eliminated, simulating the impact of avoiding null measurements. This test explores whether it is possible to recover a two-layer model from a sampling of two-layer models that vary slightly in their underlying model parameters. The recovered model parameters for the 100 tested cases overlap the distributions of input model parameters. This test shows that minor variations in underlying two-layer anisotropy do not inhibit meaningful retrieval of representative model parameters.

Test 1b (Fig. S5b, i-n): How much does additionally sampling from one or more single layer models affect the appearance of an otherwise consistent two-layer pattern? This test expands upon Test 1a by including the possibility that our synthetic dataset may sample a single layer of anisotropy in addition to the two-layer pattern. At every back-azimuth, there is a 50% chance that a measurement will sample one of the predictions corresponding to the F-test from the finer grid search, and a 50% chance that a measurement will sample a one-layer measurement drawn from one of two Gaussian distributions: one with a mean of 50° and a standard deviation of 30° and another with a mean of 115° and a standard deviation of 30°. If a measurement is within 10° of the corresponding back-azimuth, it is eliminated and a new measurement is chosen. Our calculations show that some retrieved models fall outside the distributions of input two-layer model parameters, which is not surprising since 50° of the data are now drawn from the "contaminating" one-layer models. However, the results of the grid search still resolve deep and shallow layer a-axis azimuths whose most likely values represent the two-layer distribution they are drawn from.

Test 2a (Fig. S6a, c-h): Does sampling from many different two-layer models yield a coherent result and, if so, is that result representative of any of the input models? This test explores whether grid search modeling of a synthetic dataset generated from two-layer model parameters with Gaussian distributions can retrieve the input two-layer distribution. This test is similar to that shown in Fig. 6 of the main text, except that the underlying distribution of model parameters is not related to that obtained from the grid search. The starting model distributions are given as:

- A shallow a-axis centered on a mean of 140°, with a standard deviation of 30°
- A deep a-axis centered on a mean of 180°, with a standard deviation of 30°
- A shallow dip centered on a mean of 40°, with a standard deviation of 10°
- A deep dip centered on a mean of 20°, with a standard deviation of 10°
- A shallow strength centered on a mean of 40%, with a standard deviation of 10%
- A deep strength centered on a mean of 40%, with a standard deviation of 10%

For 50 combinations of model parameters drawn from these distributions, a set of predictions are generated at the back-azimuths of the real dataset. To construct the final synthetic dataset, a value is drawn at every one of the back-azimuths from the suite of 50 model predictions. If the chosen value is within 10° of the corresponding back-azimuth, the draw is repeated to avoid a null measurement. We repeat this process 100 times, and thus conduct 100 coarse grid searches. The range of retrieved model parameters is similar to the input values. However, the introduction of the 30°, standard deviation on a-axis azimuth reduces the accuracy of model parameter retrieval. While the peak of recovered a-axes in the shallow layer in both cases is similar to the peak of the input distribution, the distributions of input and recovered a-axes in the deeper layer differ more.

Test 2b (Fig. S6b, i-n): How much does additionally sampling from one or more single layer models affect our ability to get a result from a sampling of multiple disparate two-layer models? This test adds the same Gaussian distribution around single layers as in Test 1b to the two-layer data in Test 2a, with 50% probability for drawing from the two-layer versus one-layer model predictions. As with the previous tests, this process is repeated 100 times. Comparisons of input and retrieved model parameter distributions are similar to those in Test 2a, with slightly larger differences.

Test 3 (Fig. S7): Can sampling multiple single layer models produce a grid search result that looks like a two-layer model? Test 3 assesses whether one-layer anisotropy, sampled randomly by different *KS paths, could produce an apparent pattern of fast direction with back-azimuth that results in well-constrained two-layer model parameters. The answer is no. In this test, at each back-azimuth in the real data, a fast direction is drawn at random from the distribution of our measured fast directions

(Fig. S7c). Fast directions within 10° of the back-azimuth are redrawn to avoid null measurements. We repeat this process 100 times, and conduct 100 coarse grid searches of the resulting synthetic fast directions. In contrast to the results of the previous tests, the resulting distribution of retrieved two-layer models contain model parameters across the range of possible values, and a-axis a-azimuth ranges for each layer are not well-constrained. From this test we conclude that the observed pattern of fast-direction versus back-azimuth in Greenland is not coincidental, and that two-layer anisotropy (or at least depth-varying anisotropy) is required.

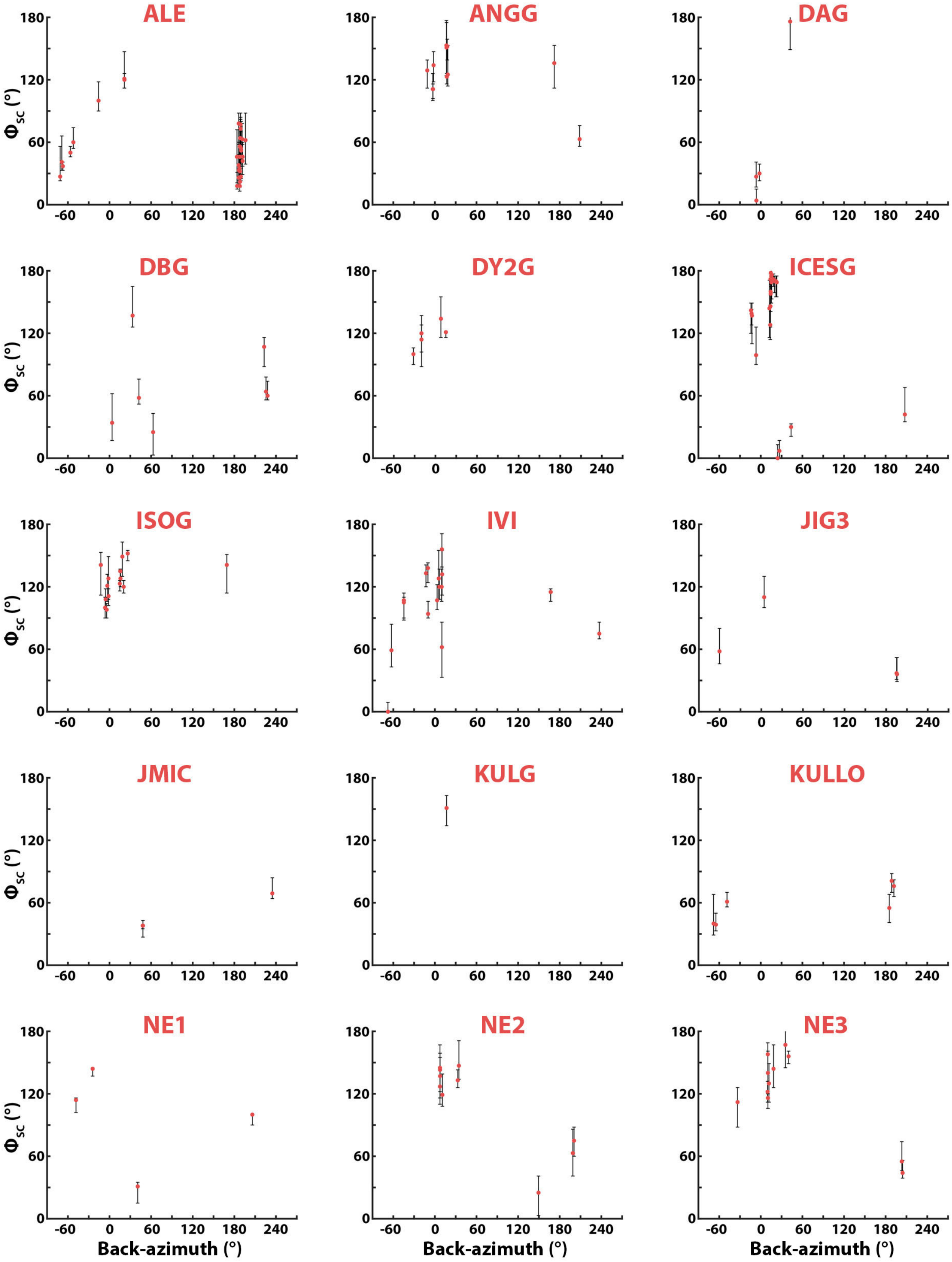

Figure S1a. Back-azimuthal variation of fast-axis measurements for all the stations used in this study, shown individually.

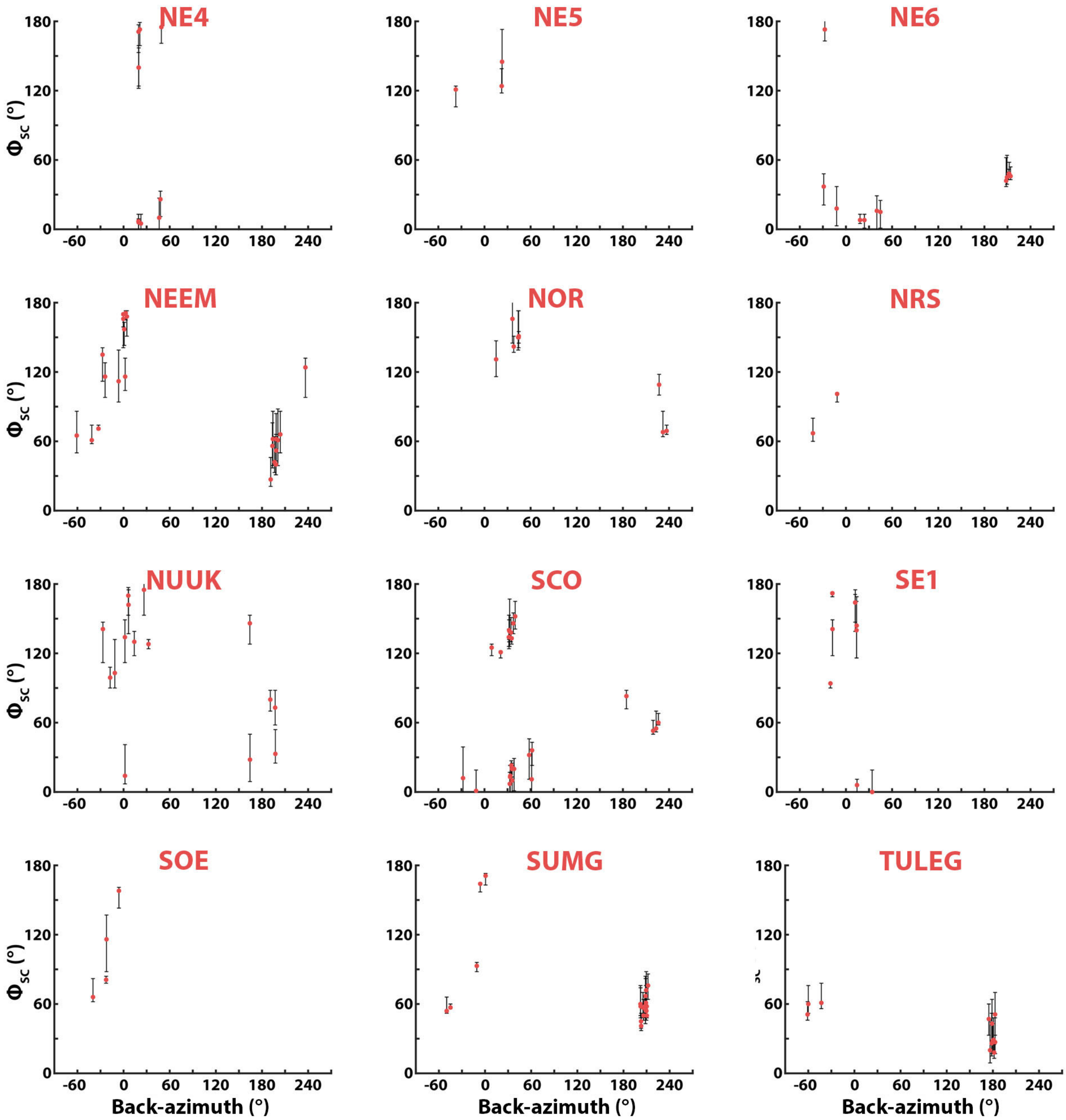

Figure S1b. Back-azimuthal variation of fast-axis measurements for all the stations used in this study, shown individually.

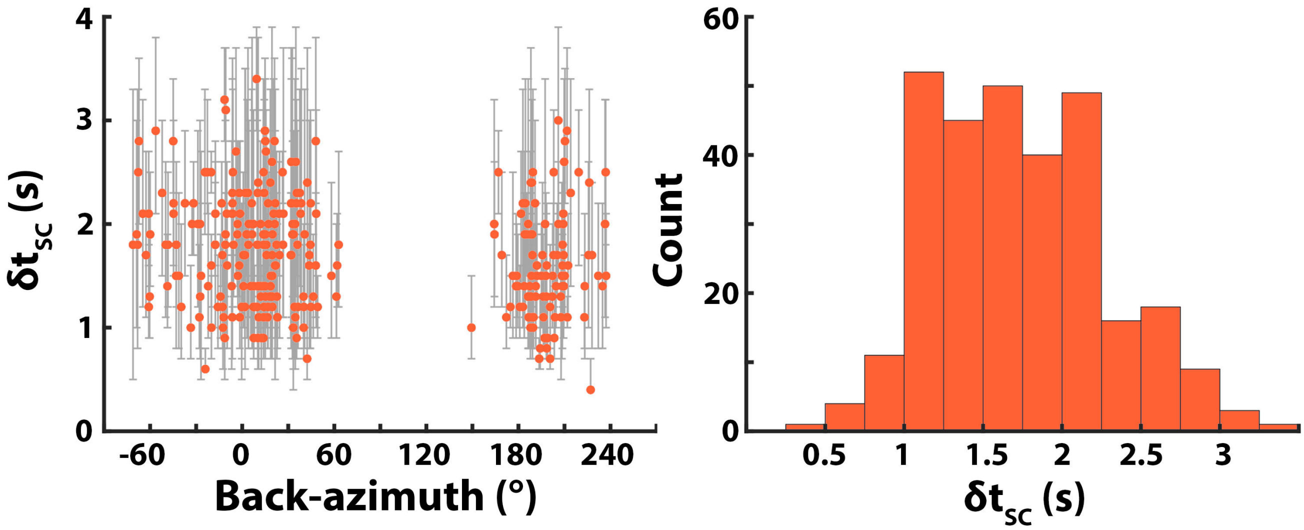

Figure S2. Back-azimuthal distribution of splitting delay times (left) and histogram showing distribution of delay times (right).

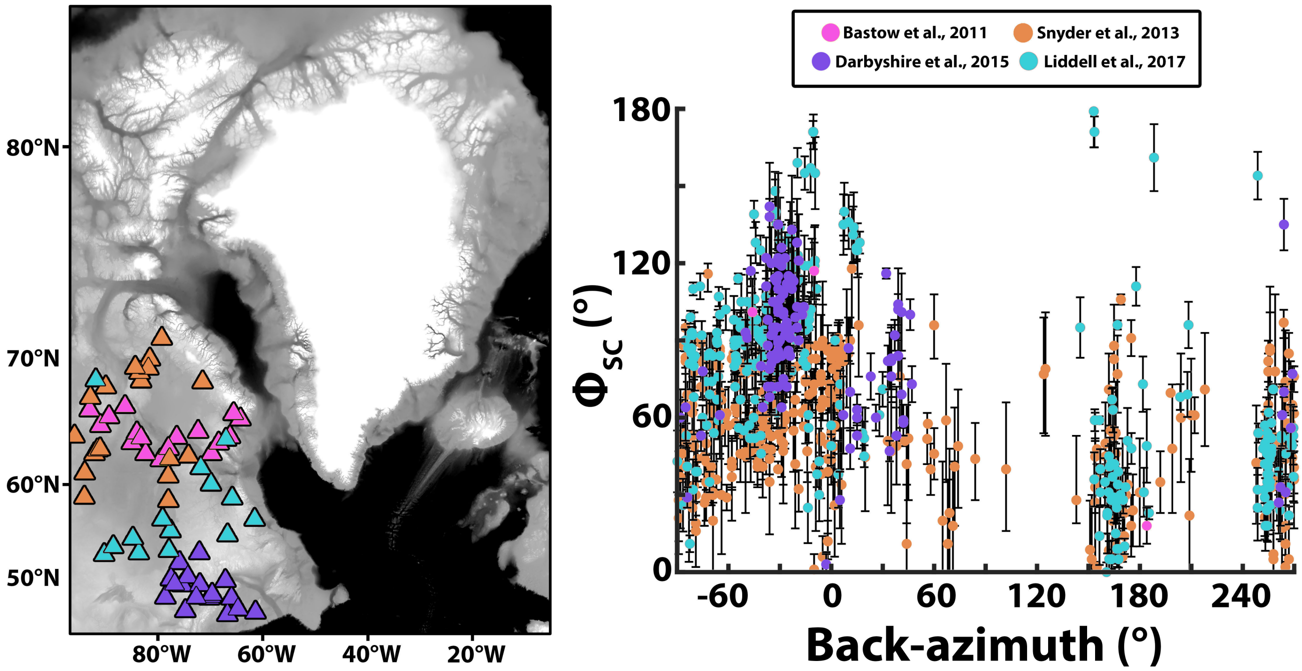

Figure S3. Left: Locations of stations outside of Greenland used in SKS splitting studies at locations somewhat geographically separated from Greenland. Colors are the same in the map and plot. Underlying map is topography. Right: Comparison of aggregate results from other studies.

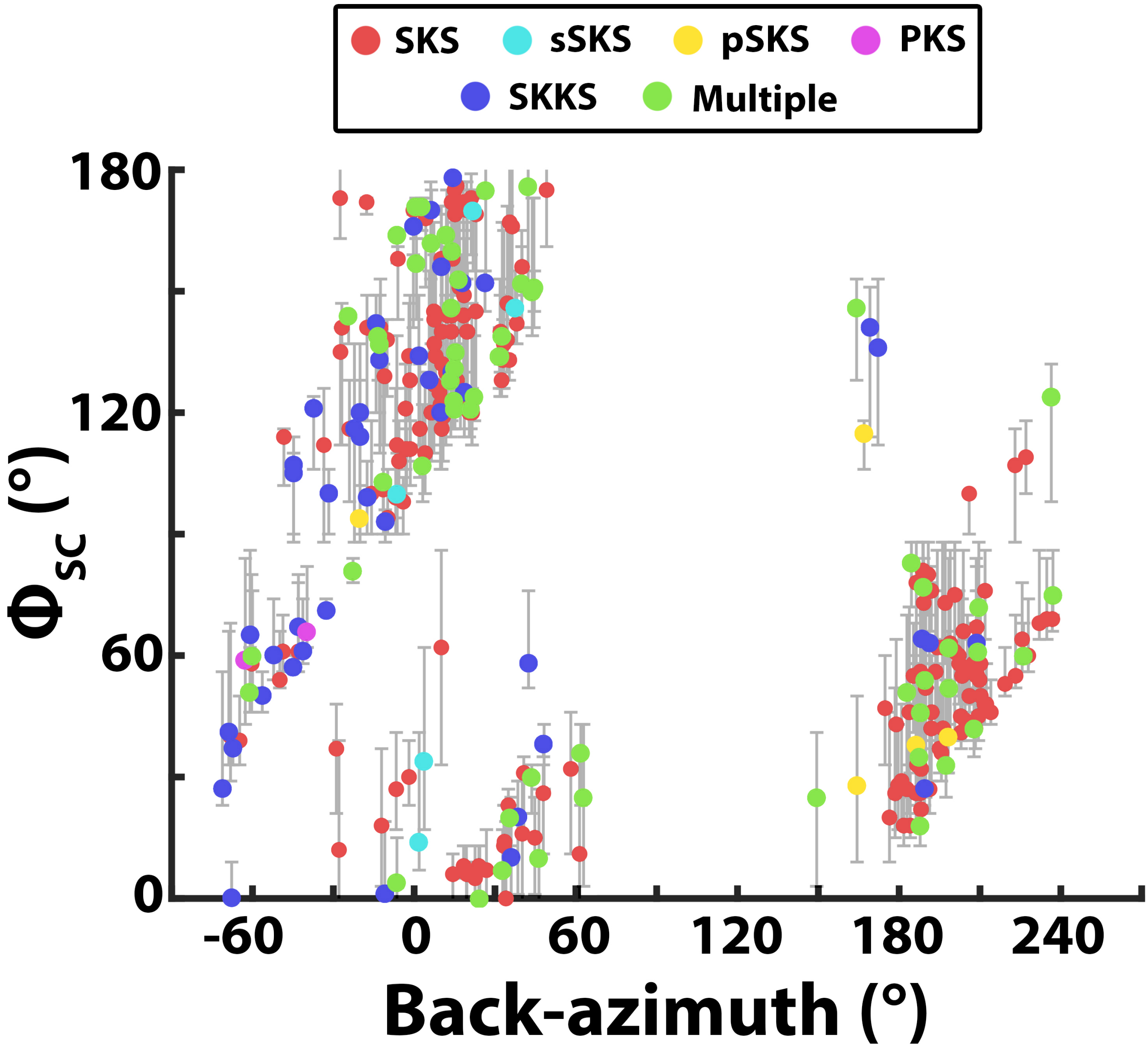

Figure S4. Back-azimuthal variation of fast axis measurements grouped by the phase the measurement was made on. A designation of "Multiple" indicates that multiple *KS phase arrivals were sufficiently close together that it was not possible to definitively say which phase the measurement was made on.

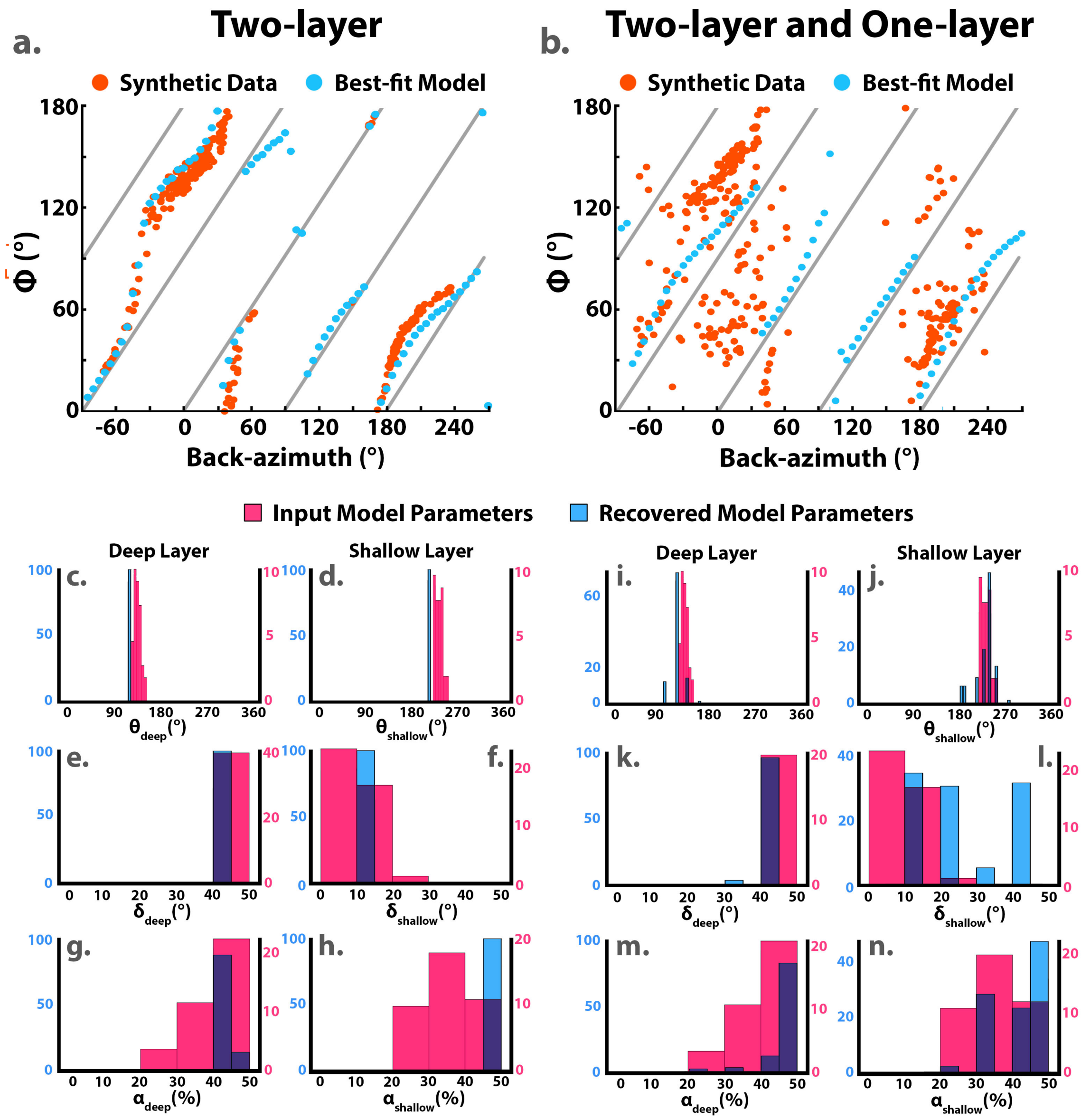

Figure S5. Figure S5. Results of synthetic tests exploring the impact of noise from 1-layer models. In Test 1a in panel (a), the synthetic fast direction at each back-azimuth is from one of the 39 two-layer models that pass the f-test from the fine gird search applied to the real data. In Test 1b in panel (b), the synthetic fast direction has a 50% chance at any back-azimuth to be drawn from the models in Test 1a, and 50% to be from a model with a single horizontal a-axis, with a-axis azimuths characterized as Gaussian distributions centered on either a mean of 50° or 115° , with a standard deviation of 30° . The synthetic data were modeled using the coarse grid of models applied to the real data. The recovered model parameters from 100 different realizations of these datasets are shown in panels (c-f) for Test 1a and (i-n) for Test 1b as blue bars, and the family of models used to generate the synthetic data are shown as pink bars.

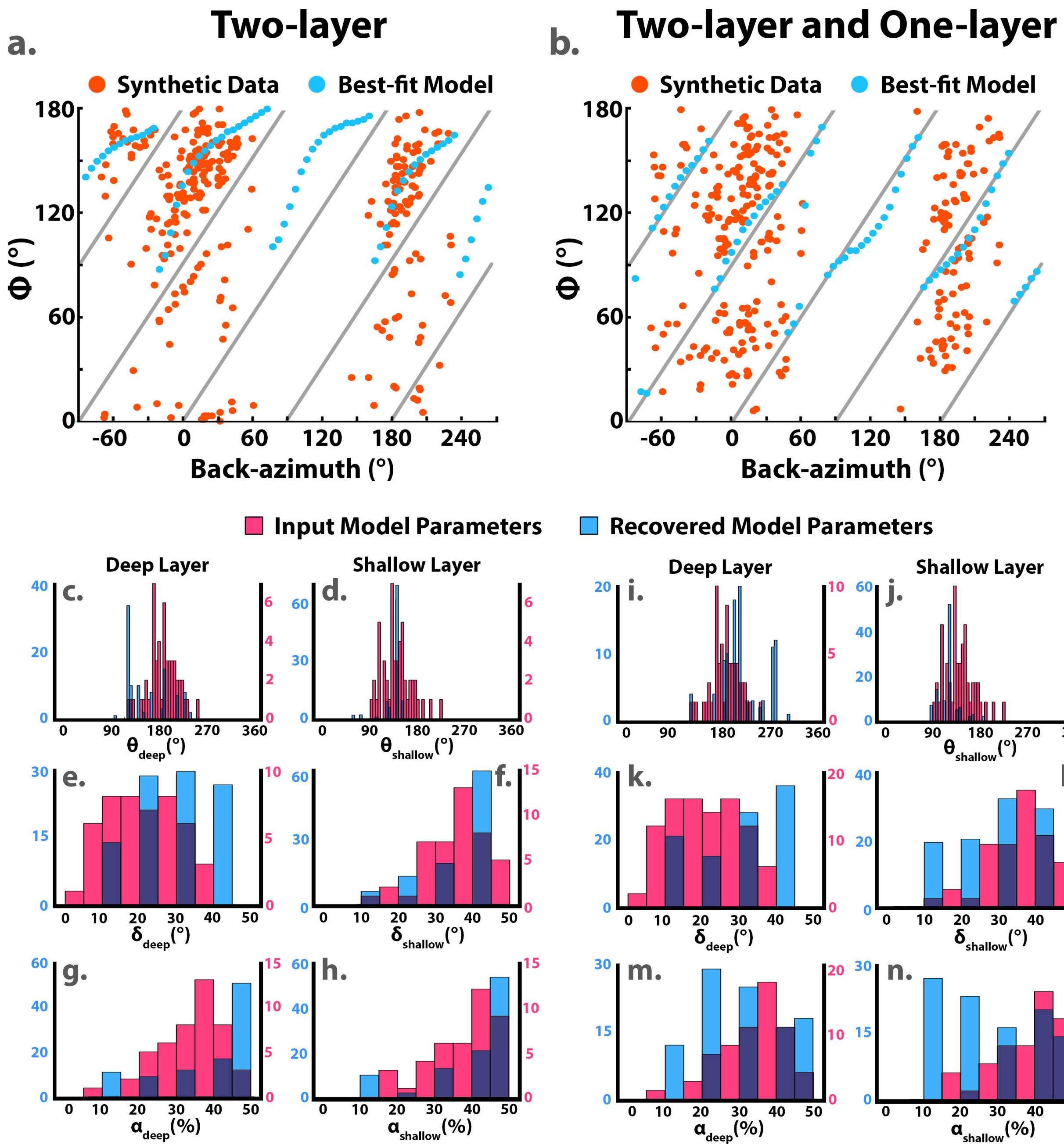

Figure S6. Synthetic test that explores how moderate random variation in two-layer model parameters impacts recovery of their distribution, without and with additional one-layer anisotropy. In Test 2a (a) this noise is due to an underlying Gaussian distribution on each of each of the six model parameters (Text S1). In Test 2b (b) the model distributions in (a) are further complicated by the addition of parameters from one-layer models, with Gaussian distributions as in Test 1b (Fig. S5b). The recovered model parameters from 100 different realizations of these datasets are shown in panels (c-f) for Test 2a and (i-n) for Test 2b as blue bars, and the family of models used to generate the synthetic data are shown as pink bars.

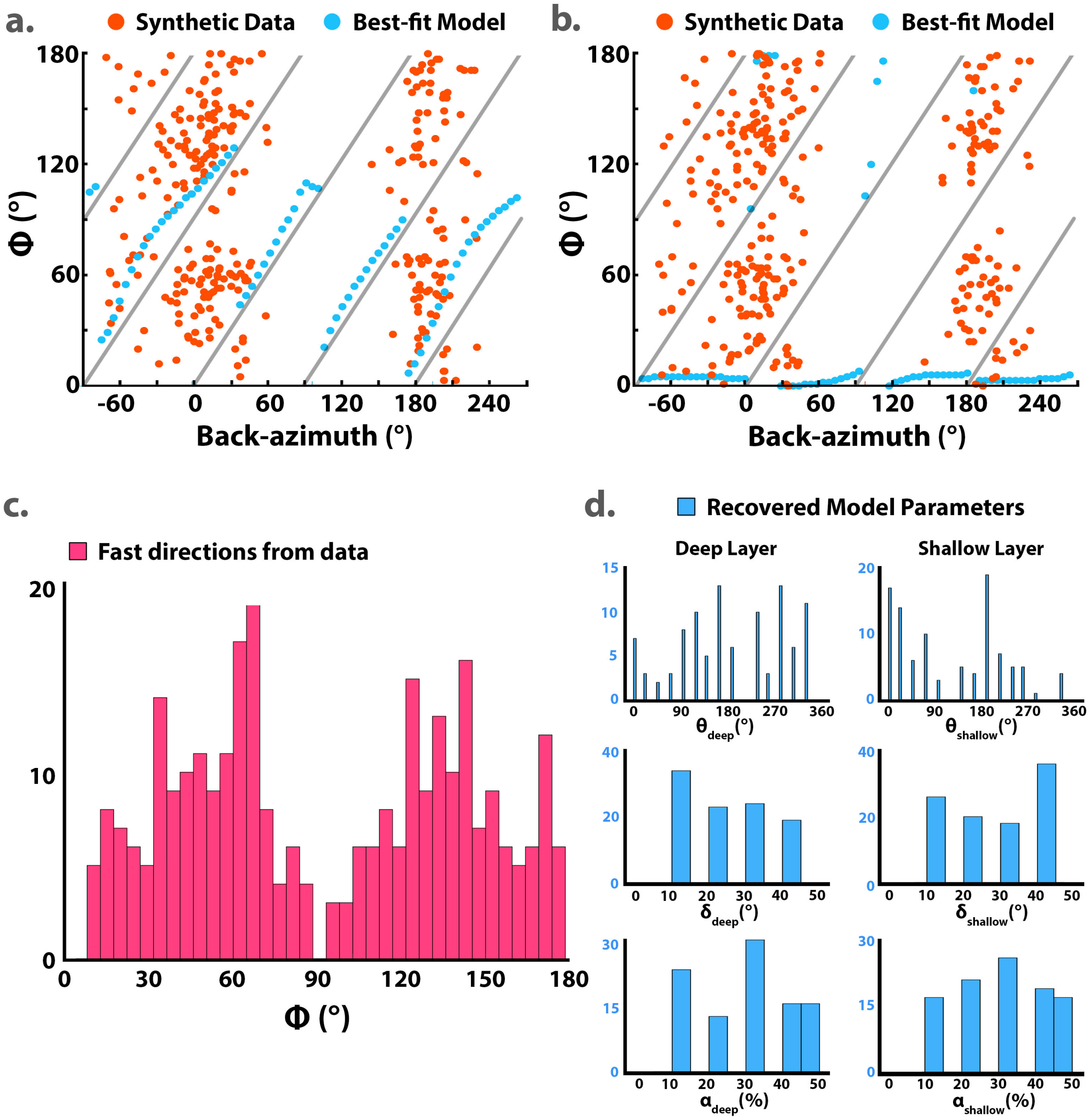

Figure S7. Synthetic tests with fast directions dataset that are drawn from a distribution of fast direction measurements that parallels the distribution of observed fast directions (See text S1). (a,b) Examples of realizations of the synthetic datasets we are fitting. (c) Distribution of our fast direction measurements, indicating the likelihood of any given fast direction in the synthetic dataset. (d) Distribution of recovered model parameters for grid searches on 100 synthetic datasets.

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