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Spatial and temporal constraints on sources of seismic anisotropy: Evidence from the Scottish highlands

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[1] Routine *SKS* splitting analyses of seismic anisotropy usually suffer from limitations in station density that hinder attempts to place spatial constraints on anisotropic fabrics. Data from a ~20 km station spacing network in Scotland show that splitting parameters vary considerably ($\delta t = 0.45 - 1.5$ s; $\phi = 49 - 128^\circ$) over short (10–20 km) length scales. Improved spatial constraints then lead to tighter temporal constraints on the anisotropic sources. Asthenospheric fabrics due to Tertiary rifting and present day plate motions do not strongly influence our results that instead correlate with lithospheric scale trends inferred from surface geology. Splitting observations track Scotland's tectonic history from the Precambrian emplacement of crustal basement and through the activation of large-scale faulting and thrusting during the Caledonian Orogeny. The shallow lithosphere beneath Scotland has preserved a fossil anisotropic signature up to hundreds of millions of years after it was formed. **Citation:** Bastow, I. D., T. J. Owens, G. Helffrich, and J. H. Knapp (2007), Spatial and temporal constraints on sources of seismic anisotropy: Evidence from the Scottish highlands, *Geophys. Res. Lett.*, *34*, L05305, doi:10.1029/2006GL028911.

1. Introduction

[2] When a shear wave encounters an anisotropic medium, it splits into two orthogonal shear waves; one traveling faster than the other. The *SKS* phase, for example, will split if it encounters an anisotropic medium on the receiver side of its path through the mantle and crust. Splitting can be quantified by the time delay (δt) between the two shear waves, and the orientation (ϕ) of the fast shear wave. Shear wave splitting monitors tectonic strains that impart a fabric on the crust and upper mantle by lattice preferred orientation of anisotropic minerals. Splitting parameters can therefore be related, for example, to asthenospheric flow [e.g., *Walker et al.*, 2005], elongate inclusions [e.g., *Kendall et al.*, 2005], fault orientations and lithospheric deformation [e.g., *Helffrich*, 1995]. However, limited station spacing in studies of shear wave splitting often hinders attempts to constrain the spatial origins of the anisotropic fabrics; there is often debate as to how much anisotropy is caused by crustal, asthenospheric and lower mantle sources [e.g., *Savage*, 1999] and to the time scales of anisotropic fabric formation and subsequent preservation.

[3] Here we present shear wave splitting parameters in the region of the Scottish Highlands using data from the 21 broadband seismological stations of the RUSH (Reflections Under the Scottish Highlands) experiment [e.g., *Asencio*, 2003, Figure 1]. Streckeisen STS-2 sensors recorded continuously at 20 s.p.s. between 2001 and 2003. Our aim is to constrain better the spatial and temporal origins of anisotropy beneath the area. Existing studies of shear wave splitting in the British Isles suggest that splitting parameters correlate strongly with tectonic features of Caledonian and Variscan age [*Helffrich*, 1995; *Restivo and Helffrich*, 1999]. However, tectonic activity associated with the opening of the Atlantic and emplacement of the British Tertiary Igneous Province (BTIP) at ~50–60 Ma, may still be affecting deeper structures beneath the Atlantic's passive margins [e.g., *Arrowsmith et al.*, 2005; *Ucisik et al.*, 2005]. The station spacing and density of the RUSH broadband network means we are able to place constraints on the source location of anisotropy in Scotland to depths shallower than the Moho. The resulting spatial constraints on anisotropy will subsequently provide clues as to the temporal origins of the anisotropic fabrics. We report on the most detailed study to date of seismic anisotropy in the Scottish Highlands; a region that last experienced major orogenesis during the Caledonian (500–420 Ma).

2. Geology of Scotland

[4] The basement of the Scottish Highlands is composed of several geological terranes, juxtaposed by a series of tectonic events culminating in the Caledonian Orogeny in Early Paleozoic time [*Craig*, 1991]. In the far NW part of the study area (Figure 1) Precambrian Lewisian basement out-crops at the surface and is cross-cut by the E–W to NW–SE trending dolerite Scourie dyke complex that was emplaced ~2.4 Ga. The zone was subsequently deformed by discrete subvertical, sinistral oblique-slip, amphibolite facies shear zones of Laxfordian (~1750 Ma) age [e.g., *Park*, 1991]. To the east of this region, the Moine thrust belt (Figure 1) forms the NW margin of the Caledonian orogenic belt on mainland Scotland [e.g., *Coward*, 1985; *Butler and Coward*, 1984]. The orogenic foreland comprises the Lewisian basement, over which the Torridon sandstone group and a cover of Cambro–Ordovician sediments were thrust ~100 km in a WNW direction 430–410 Ma during the Silurian [e.g., *Butler*, 2004].

[5] In the center of the study area, a major lithospheric-scale strike-slip fault [e.g., *Canning et al.*, 1998], the Great Glen Fault (GGF), bisects the metamorphic Caledonides in Scotland near vertically. Strike slip motion is thought to have dissected the nappe pile during Devonian–Early Carboniferous time (416–299 Ma). The Highland Boundary

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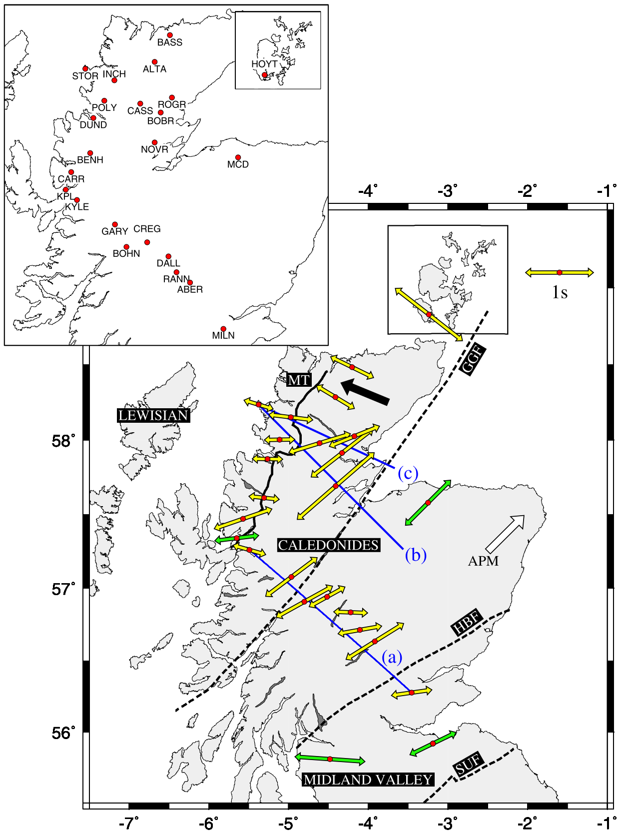

Figure 1. Shear wave splitting results in the region of the Scottish Highlands. The orientation of the arrows shows the alignment of faster shear waves and the length of the arrow is proportional to the magnitude of the splitting. Green arrows are results from the study of *Helffrich* [1995]. Yellow arrows are RUSH stations. MT, Moine Thrust; GGF, Great Glen Fault; HBF, Highland Boundary Fault; SUF, Southern Uplands Fault; APM, Absolute Plate Motion (open arrow). The black arrow shows the WNW motion of material by thrust tectonics during the Silurian. The blue lines are the orientations of the cross-sections shown in Figures 3a, 3b. and 3c respectively. The top left inset shows the names and the locations of the RUSH stations, in addition to stations MCD and KPL from the study of *Helffrich* [1995].

Fault (HBF) marks the southerly extent of the metamorphic Caledonides. To the south of the HBF, softer sedimentary rocks of the Devonian and Carboniferous periods form the so-called Midland Valley, which is bound to the south by the Southern Uplands Fault (SUF). The Caledonian Orogeny was concluded by the closure of the Iapetus ocean; the Iapetus suture lies approximately 100 km south of our study area at ~55°*N*. Rifting in Permian–Triassic time separated North America from Eurasia; since when, no significant tectonic activity has affected Scotland. An overview of the geology of Scotland is available from *Craig* [1991, and references therein]. Our closely spaced seismic stations traverse many of the major geological boundaries in Scotland. Thus, we will be able to detect short length scale variations in seismic anisotropy, should they exist in Scotland.

3. Data Analysis

[6] We analyzed *SKS* and *PKS* data from the 21 RUSH experiment stations for earthquakes of $M \geq 5.5$ that occurred at distances $\geq 88°$ in order to avoid contamination by other *S* wave phases. Splitting parameters (δt, ϕ) were then determined for individual earthquakes using the method of *Silver and Chan* [1991]. A total of 232 phases were chosen from 35 earthquakes where *SKS* or *PKS* phase energy was visible above the noise level; other seismograms were eliminated from the analysis. In order to linearize particle motion after correction for single layer anisotropy, bandpass filtering with corner frequencies 0.04 and 0.15 Hz was usually required to remove the high levels of microseismic and cultural noise in the data. In cases of excellent signal-to-noise earthquakes, this approach gives robust measurements on individual seismograms (see auxiliary materials).[1] However, more often in the noisy environment of Scotland, this resulted in splitting parameters with large associated errors (≥ 0.5 s in δt, $\geq 20°$ in ϕ) for individual earthquakes. We instead carry out our analysis on unfiltered seismograms and adopt the stacking procedure of *Restivo and Helffrich* [1999]. In the stacking procedure, high signal-to-noise ratio measurements are given more weight. Additionally, to compensate for the effects of over-represented backazimuths in the uneven sampling of a station, every individual measurement is scaled to a factor of $1/N$, with its backazimuth defining a wedge of $\pm 10°$ in which N observations fall. One stacking result is illustrated in Figure 2 for station BOBR; $\phi = 67 \pm 1°$, $\delta t = 1.35 \pm 0.08$ s. The backazimuth distribution of the earthquakes used in the stack is also shown. In applying the stacking procedure we are assuming a single homogeneous anisotropic layer, rather than considering a two layer case [e.g., *Silver and Savage*, 1994]. Our approach is valid, however, since a detailed study of *SKS* splitting at permanent stations in the British Isles reveals little dependence on incoming backazimuth [*Helffrich*, 1995]. Additionally, using the method of *VanDecar and Crosson* [1990], we compute relative arrival-times for *PKP* phases arriving from backazimuths corresponding to the fast and slow shear wave orientations. Relative arrival-times vary only by ≤ 0.25 s at our stations (see auxiliary material); the absence of significant variations further substantiates our assumption that the fast axis of anisotropy is either horizontal or sub-horizontal beneath Scotland. Finally, comparison of the stacking results with the highest quality individual measurements shows the results to be consistent. Thus, the stacking method allows us to develop lower error estimates of the variations in anisotropy across the region.

4. Results

[7] Results are summarized in Table 1 and Figure 1. In the NW part of the study area (BENH, STOR, INCH, POLY, DUND) ϕ is consistently oriented ~E–W, approx-

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2006GL028911.

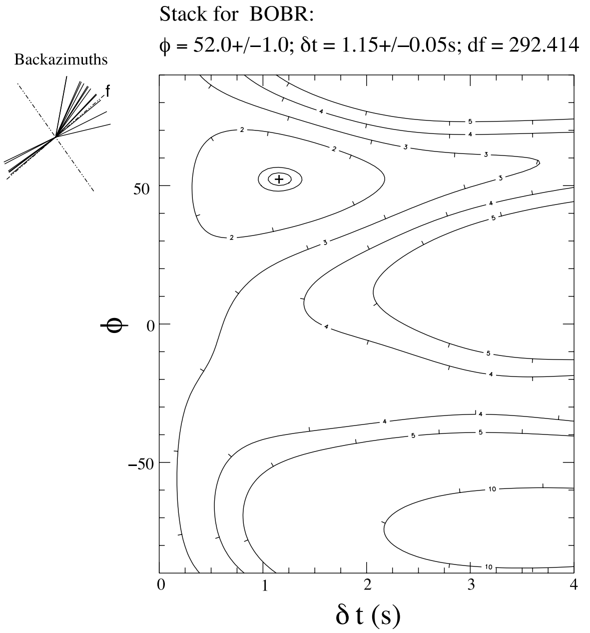

Figure 2. Example of the application of the stacking procedure of *Restivo and Helffrich* [1999] to RUSH station BOBR. The result is obtained from 19 individual results computed from un-filtered waveforms. df is the number of degrees of freedom. The backazimuth distribution of the earthquakes used is shown in the top left hand corner, where f is the orientation of the fast shear wave.

imately coincident with the orientation of the tectonic fabric in the Scourie Dyke complex that outcrops in this area; δt is ~0.5 s. Stations ALTA, BASS and HOYT, located on Cambrian sediments and Torridonian–Devonian sandstones, have ϕ oriented NW-SE to WNW–ESE, coincident with the direction of material transport by the Moine thrust; δt is ~0.75–1 s. Moving south towards the GGF, ϕ rotates into a NE–SW trend (Figure 1), approximately coincident with the strike of the surface expression of the fault; δt increases to ≥1 s. Figures 3a and 3b illustrate the variation in δt as a function of distance along profiles that traverse major terrane boundaries, as discussed below. Figure 3c illustrates the rotation in ϕ from E–W and WNW–ESE orientations towards the NE–SE Caledonian trend.

[8] We observe changes in splitting parameters over very short distances in Scotland; Figure 3a shows a ~0.35 s increase in δt between stations BOHN and CREG. The stations are only separated by a distance of ~20 km so Fresnel zone arguments [e.g., *Alsina and Snieder*, 1995] suggest that the observed difference in δt is accrued in the crust. However, observed splits of up to 1.5 s approaching the GGF require a thicker anisotropic layer.

5. Discussion

[9] Patterns of anisotropy can be due to the preferential alignment of minerals in the crust and/or mantle, or the preferential alignment of inclusions of fluid or melt, or some combination of these mechanisms. A range of plausible processes could lead to such anisotropy, including: (1) asthenospheric flow in the direction of absolute plate motion (APM); (2) anisotropy due to the flow of material along the Mid-Atlantic ridge at the time of opening of the ocean; and/or (3) a pre-existing fossil anisotropy frozen in the lithosphere. Most of these can be eliminated, however. The absolute plate motion of the Eurasian Plate is ~22 mm/yr in a direction N45.16E (HS2-NUVEL1 model of *Gripp and Gordon* [1990]). We cannot relate our results collectively to this orientation. Stations such as NOVR and GARY (Figure 1) are nearly parallel, while ALTA and BASS are approximately perpendicular, thus ruling out anisotropy due to the motion of the Eurasian Plate over the mantle. *Ucisik et al.* [2005] suggest an asthenospheric flow hypothesis to explain shear wave splitting parameters at stations on the east coast of Greenland. Lateral flow of asthenospheric material along the Mid-Atlantic ridge at the time of opening

Table 1. *SKS* Shear Wave Splitting Parameters and Station Locations for RUSH Stations[a]

Station	Latitude/Longitude, deg	ϕ, deg	σ_ϕ, deg	δt, s	$\sigma_{\delta t}$, s	N
ABER	56.63/−3.92	58	5	1.00	0.18	13
ALTA	58.29/−4.41	−59	2	0.65	0.03	14
BASS	58.48/−4.20	−64	2	0.70	0.05	7
BENH	57.61/−5.31	−84	9	0.45	0.15	8
BOBR	57.91/−4.33	52	1	1.15	0.05	19
BOHN	56.91/−4.80	61	4	0.95	0.28	9
CARR	57.47/−5.57	71	1	0.90	0.05	9
CASS	57.98/−4.61	73	5	0.95	0.15	11
CREG	56.94/−4.52	61	6	0.60	0.15	9
DALL	56.83/−4.22	−88	4	0.50	0.05	12
DUND	57.87/−5.26	−89	7	0.45	0.05	9
GARY	57.08/−4.96	53	4	0.95	0.25	9
HOYT	58.83/−3.24	−52	1	1.25	0.08	12
INCH	58.15/−4.97	−83	5	0.65	0.10	16
KYLE	57.26/−5.49	−74	6	0.50	0.05	5
MILN	56.28/−3.45	82	4	0.60	0.05	15
NOVR	57.69/−4.41	49	4	1.50	0.18	9
RANN	56.71/−4.11	80	4	0.65	0.05	12
ROGR	58.03/−4.17	68	5	0.80	0.10	10
POLY	58.00/−5.11	89	7	0.45	0.08	18
STOR	58.24/−5.38	−73	5	0.45	0.05	18

[a] σ_ϕ and $\sigma_{\delta t}$ are the errors associated with each measurement. N is the number of individual measurements used to constrain the splitting parameters.

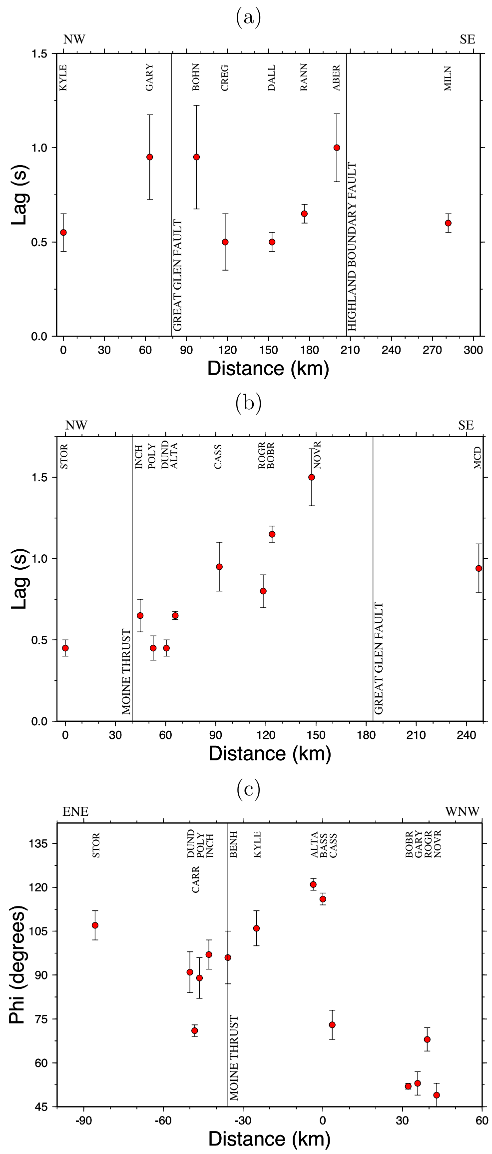

Figure 3. Shear wave splitting parameters plotted as functions of distance along lines (a) through the Great Glen (GGF) and Highland Boundary (HBF) faults; (b) through the GGF to the north of Figure 3a; and (c) perpendicular to the Moine Thrust (MT). The orientations of the profiles are shown in Figure 1.

of the ocean is inferred to have induced a N–S fabric in the lithosphere. In Scotland this hypothesis would most likely be applicable to the stations in the far NW part of the study area where we observe E–W oriented fast shear waves. ϕ is perpendicular to the continental margin that lies $\geq$150 km farther away from our stations than for their Greenland counterparts. The asthenospheric flow hypothesis is not, therefore, favored here.

[10] Instead, the anisotropy in Scotland is most likely a lithospheric fossil anisotropy. Splitting parameters in the Scottish Highlands closely mirror the trends of geological features exposed at the surface, consistent with the hypothesis of *Silver and Chan* [1991] that splitting under continents monitors the lithosphere's remnant strain from the last previous deformation event. *Helffrich* [1995] showed this to be an appropriate model for the British Isles, but our increased station density in the Scottish Highlands offers the opportunity to place tighter constraints on the depth extent of anisotropy beneath the study area, in addition to increased spatial coverage of the various geological terranes.

[11] Estimates of the amount of splitting that can be accrued in the crust vary from 0.1–0.3 s [*Silver*, 1996] to 0.1–0.5 s [e.g., *Barruol and Mainprice*, 1993]. In areas where schists have steeply dipping foliation, crustal contribution to shear wave splitting can be especially high [e.g., *Godfrey et al.*, 2000]. Thus the increase in δt on approach to the GGF (which divides the metamorphic Caledonides) can be attributed plausibly to an increase in the intensity of crustal deformation near the fault. Near the GGF, however, the large splits observed ($\sim$1–1.5 s) require an anisotropic layer that is thicker than the crust. BIRPS seismic profiling [e.g., *Klemperer and Peddy*, 1992] indicates that the GGF could be a vertical boundary in the crust and mantle. The general rotation in ϕ towards the strike of the GGF, and the accompanying increase in δt on approach to the fault is, therefore, consistent with its lithospheric scale. *SKS*/*PKS* waves arriving at stations such as ROGR, BOBR and MCD (Figure 1) sample the deeper portions of GGF deformation, while closer stations such as BOHN, GARY and NOVR are additionally affected by the intensely deformed crustal signature of the fault.

[12] In other areas of Scotland, deformation observed at the surface cannot so easily be extrapolated to mantle depths. The Scourie dykes, for example, in the NW part of the study area were thought to have been emplaced at 10–20 km depth [e.g., *Dickinson and Watson*, 1976]. Our observations of $\delta t \approx 0.5$ s at these stations are consistent with published upper estimates for crustal anisotropy. Anisotropy beneath Archaean continental regions is not thought to be created (or, alternatively, is not preserved) during initial continental formation [e.g., *Fouch et al.*, 2004] so it appears that anisotropy formed in this region and has survived since the last major significant tectonic reworking in the Lewisian. To the east of the Scourie dykes and Laxfordian deformation zone, the region affected by Silurian WNW thrusting events exhibits larger splitting: $\delta t \approx 0.75$–1 s (ALTA, BASS and HOYT). There is some debate as to the depth extent of deformation by the Moine. *Soper and Barber* [1982] suggested that the thrust cuts steeply down into the mantle, whereas *Barr et al.* [1986] and *Butler* [1986] view the deformation as "thin-skinned". In this region, to explain δt in the crust alone would require an implausible 8.1–11.6% anisotropy in the 30 km thick crust so we conclude that a deeper lithospheric layer of anisotropy, which may or may not be related to the Moine, is contributing to our results.

6. Conclusions

[13] We have investigated seismic anisotropy beneath a closely spaced seismic network in Scotland via shear wave splitting analysis of teleseismic *SKS* and *PKS* phases. The results show considerable variations in the strength (δt 0.5–1.5 s) and orientation of anisotropy. Rapid spatial variations in ϕ and δt confirm strong contributions by crustal anisotropic layers. However, large values of δt near the GGF, for

example, require a thicker anisotropic layer that is consistent with independent geological estimates of displacement on the GGF. Surprisingly, asthenospheric fabrics due to Tertiary rifting and present day plate motions do not seem to affect our results. Instead, by placing tight spatial constraints on anisotropy, we show that our observations track Scotland's tectonic history from the Precambrian emplacement of crustal basement, and through the activation of large-scale faulting and thrusting during the Caledonian. The shallow lithosphere beneath Scotland has preserved a fossil anisotropic signature, up to hundreds of millions of years after it was formed.

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