Anisotropic Rayleigh-wave tomography of Ireland’s crust: Implications for crustal accretion and evolution within the Caledonian Orogen

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[1] The Irish landmass, now at the western extremity of the Eurasian Plate, was formed in the Caledonian Orogeny during the Palaeozoic assembly of Pangea. The associated closure of the Iapetus Ocean is recorded in the NE–SW structural trends that dominate the tectonic set-up of Ireland today. The deep-crustal dynamics of the orogeny and the effect on the crust of the subsequent extension and magmatism in the North Atlantic are debated. Fabrics within deep crustal rocks preserve a record of deformation during and after the continental collisions. Here, we measured Rayleigh-wave phase velocities using seismograms recorded by permanent and temporary intermediate-band stations in Ireland and inverted the data for phase-velocity maps, including azimuthal anisotropy. The observed isotropic phase-velocity heterogeneity reflects moderate crustal thickness and seismic velocity variations across Ireland. Anisotropy of Rayleigh waves at 10–20 s periods shows a NE–SW fast-propagation direction and is largest (up to 2%) at a 15 s period, at which Rayleigh waves sample primarily the middle and lower crust. The NE–SW trend of the deep-crustal anisotropic fabric is parallel to tectonic trends, in particular the Iapetus Suture Zone, which indicates that suture-parallel flow in the middle and lower crust accommodated the continental collision.

The apparent preservation of the Caledonian-age fabric also shows that the deep crust of the Eurasian margin in Ireland was neither stretched by the NW–SE extension associated with the opening of the North Atlantic, nor modified significantly by the Cenozoic magmatism in the region.


1. Introduction

[2] The Caledonian Orogen spans the entire North Atlantic region, extending from Scandinavia to Britain and Ireland and towards the Gulf of Mexico in North America. Comparable in its scale to the Alpine–Himalayan orogenic system active today, the Caledonian Orogen was assembled by complex, multiphase accretion processes. The tectonic influence of separate Taconic, Scandian and Acadian events is recognised from Scotland, through Ireland, to Newfoundland and into Maine and Massachusetts [e.g., Hall et al., 1998; McKerrow et al., 2000]. These various, diachronous orogenic events were associated with the assembly of Pangea during the Palaeozoic Era. Major continental suture zones developed in the course of accretion of the different terranes that included Laurentia, Gondwana and Avalon.

[3] One of these important suture zones is the Iapetus Suture Zone [e.g., Phillips et al., 1976; McKerrow and Soper, 1989] that straddles the Irish landmass (Figure 1). Acadian deformation (mid Devonian, ~400 Ma) in what is now the British and Irish Isles involved a “soft collisional” process [Woodcock and Strachan, 2000], principally due to the oblique plate convergence. The obliquity of the continental collision generated transpressive deformation fabrics in surface rock, diagnostic of left lateral (sinistral) motion. Oblique collision may also account for the absence of evidence for large amounts of crustal thickening related to the Acadian deformation [Chew and Stillman, 2009; B. M. O’Reilly, F. Hauser, and P. W. Readman, The fine-scale seismic structure of the upper lithosphere within accreted Caledonian lithosphere: implications for the origins of the “Newer Granites”, submitted to Journal of the Geological Society, 2011]. Acadian deformation in Britain and Ireland is temporally coincident with copious granitic melt production and magmatism within the crust.

[4] The subsequent beginning of the Variscan orogenic cycle in the mid to late Devonian led to the development of sedimentary basins in Ireland that continued into the early Carboniferous [Sevastopulo and Wyse Jackson, 2009], whereas the NNW–SSE directed compression that followed during the late Carboniferous–early Permian led to tectonic inversion of these sedimentary basins, with the intensity of deformation greatest in the south [Readman et al., 1997; Graham, 2009]. Finally, lithospheric stretching and associated hyper-extension in the basins west of Ireland occurred in the North Atlantic [O’Reilly et al., 2006; Naylor and Shannon, 2011] due to the protracted breakup of the Pangaea supercontinent during the late Palaeozoic and Mesozoic, the onset of seafloor spreading in the late Cretaceous and, ultimately, to the development of volcanic continental margins in the early Cenozoic [Vogt et al., 1998]. Iceland Plume activity in the Cenozoic has also been proposed to have caused magmatism and significant magmatic underplating in the British and Irish Isles [White and Lovell, 1997].

[5] In this paper we investigate if and how the signature of these past geological events is imprinted in the fabric and seismic anisotropy of Ireland’s crust. Controlled source seismic experiments show that in spite of Ireland’s complex
orogenic history, the continental Moho beneath it is remarkably flat (~30–32 km), particularly across the major terrane boundaries [Jacob et al., 1985; Lowe and Jacob, 1989; Masson et al., 1998; Landes et al., 2000; Shaw Champion et al., 2006; Kelly et al., 2007; Hauser et al., 2008]. It seems that the bulk seismic geometry of the crust retains no memory of its geologically complex deformation history. One explanation for this is that pervasive ductile flow in the mid-lower crust and uppermost mantle—heated during an orogeny—erased any pre-existing or developing Moho topography [Tirel et al., 2008]. Anisotropic fabric within the crust would preserve a record of flow during the last major deformation episode [e.g., Deschamps et al., 2008; Endrun et al., 2011]. Here we examine such record using the azimuthal anisotropy of seismic Rayleigh waves.

2. Data and Measurements

The recent Irish Seismic Lithospheric Experiment (ISLE) [Do et al., 2006; Landes et al., 2006] and the subsequent Irish Seismological Upper Mantle Experiment (ISUME) have, for the first time, covered much of Ireland with intermediate-band seismic stations. We used data recorded at two permanent stations (DSB, VAL) and 22 temporary sites. A total of about 8 stations were moved around to occupy each site for at least one year (Figure 1). All stations were equipped with Guralp CMG-40T (eigenperiod 30 s) seismometers, except for DSB (Streckeisen STS-2, eigenperiod 120 s). ISLE and ISUME data have been recorded from 2002 to 2005 and from 2006 to present, respectively.

Phase velocities of Rayleigh waves were measured by using an inter-station technique [Meier et al., 2004] that combines cross-correlation with an efficient scheme of filtering and windowing of the signal in the frequency and time domains, providing accurate measurements in broad period ranges (in this study, the long-period measurement limit was effectively set by the period range of the instruments; the number of measurements at periods longer than 30 s was too small for imaging, due to the instrumental noise at these periods). For each station pair, we chose earthquake sources located approximately on the same great circle path with the stations, the differences between station–event and station–station azimuths being less than 10 degrees (the azimuth difference was taken into account in the phase-velocity calculations). Rayleigh-wave diffraction and the interference of the fundamental and higher modes can bias inter-station dispersion measurements [e.g., Friederich et al., 2000; Pedersen, 2006]. These frequency-dependent effects, however, also cause irregularities and roughness of measured curves, and selection of only the smooth portions of the curves (Figure 2) reduces measurement biases. We also routinely verified the consistency of measurements made using waves arriving from the opposite directions. A systematic inconsistency was detected for only one pair (D36–P07), and the measurements for this pair were discarded (Figure S1 in the auxiliary material).

Averaging over many dispersion curves, derived from events in different source regions, is another essential condition for the derivation of robust and accurate measurements. Inter-station phase-velocity curves in our dataset were averaged from tens of “one-event measurements” at almost all frequencies, with a minimum of 5 one-event measurements at any given frequency (Figure 2). (An average over few one-event dispersion curves is unlikely to be robust, and station pairs with few measurements were not included in the dataset.)

The final dataset comprises phase-velocity curves for 43 different paths (Figure 1). Most of the dispersion curves cover the 10–30 s period range and thus sample the entire crust (~30 km thick in this part of Europe). The path coverage varies somewhat with period (Figure S2); the path density is greater in the west–central part than in the eastern part of the study region (Figure 1).

3. Azimuthal Anisotropy

The Rayleigh-wave measurements were used to compute phase-velocity maps, including azimuthal anisotropy, in the period range of 10–30 s (Figure 3). The theoretical relation between slight perturbations $\delta C$ in the phase velocity $C$ of these waves and the azimuth $\Psi$ of their propagation direction is given by Smith and Dahlen [1973]:

$$
\delta C(T, \Psi) = C_0(T) + A_1(T)\cos(2\Psi) + A_2(T)\sin(2\Psi) + A_3(T)\cos(4\Psi) + A_4(T)\sin(4\Psi),
$$

where $C_0(T)$ is the mean phase velocity and $A_1(T), A_2(T), A_3(T), A_4(T)$ are coefficients that depend on the period $T$.

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1. Auxiliary materials are available in the HTML. doi:10.1029/2012GL051014.
where $T$ is the wave period, $C_0$ is the isotropic phase velocity perturbation, and $A_1$, $A_2$, $A_3$ and $A_4$ are the variables that parameterize azimuthal anisotropy.

The dispersion data were inverted separately at each wave period for the distributions of the isotropic phase velocity perturbations and the four anisotropy coefficients (equation (1)), all parameterized at the knots of the same triangular grid with a nearly-uniform spacing of around 100 km. The inversion was performed using the LSQR algorithm of Paige and Saunders [1982], with smoothing and slight norm damping [Lebedev and van der Hilst, 2008]. Anisotropy patterns can be resolved reliably only at scale lengths longer than those of the isotropic heterogeneity [Darbyshire and Lebedev, 2009]; both the $2\Psi$ and $4\Psi$ anisotropy patterns were smoothed more strongly than the isotropic phase-velocity variations. The effect of smoothing is illustrated in Figure S3. A series of test inversions was performed while excluding an increasing portion of the data that were least well fit by the tomographic models (possible “outlier” measurements). The main patterns were robust with the percentage of excluded data varying from 0 to 50% (Figure S4). Our preferred models in Figure 3 were computed with 15% of “outlier” measurements excluded.

The phase velocity maps (Figure 3) reveal isotropic phase-velocity heterogeneity of around 2%. This reflects the moderate crustal-thickness variability and crustal shear velocity heterogeneity, consistent in amplitude with independent measurements from controlled-source experiments at mid to lower crustal depths in the region [Hauser et al., 2008; O’Reilly et al., 2010].

Azimuthal anisotropy (Figure 3 displays its $\pi$-periodic, “$2\Psi$” pattern) shows a consistently NE–SW fast-propagation direction at periods that sample the crust. The amplitude of phase-velocity anisotropy shows a clear maximum at periods near 15 s, indicating that it is due to shear-velocity anisotropy within the middle and lower crust (Figure 3). Somewhat surprisingly, the data require no phase-velocity anisotropy at longer periods (25–30 s) that sample primarily the uppermost mantle (anisotropy in the tomographic solutions at these periods is very small and is not plotted in Figure 3).

With its strong smoothness constraints, our inversion was aimed at extracting the dominant, large-scale regional anisotropy pattern, which can be determined reliably from the available data. Smaller-scale anisotropy variations may be present in addition to this large-scale pattern; they may be determined in the future when data sampling across Ireland improves further.

Interestingly, we also found that the $4\Psi$ terms (see equation (1)), often neglected in surface-wave anisotropy imaging, are required by our dataset to be substantially non-zero. A comparison of variance reductions from a series of test inversions shows that both the $2\Psi$ and $4\Psi$ terms are needed to fit the data, with the $4\Psi$ terms alone providing a somewhat greater variance reduction than the $2\Psi$ terms alone (Table S1). Importantly, the fast-propagation directions given by the $2\Psi$ terms change if the $4\Psi$ terms are not included in the solution or forced to be zero (Figure S4). In order to verify that this is not due to a small proportion of highly anomalous measurements, we performed inversions with and without the $4\Psi$ terms while excluding a progressively larger percentage of “outliers”. We observed that the $4\Psi$ terms are needed to fit our dataset even if only the most mutually consistent 50% of the data are inverted.

In the case of mantle peridotites, undersaturated in silica and rich in olivine and pyroxene, nearly all of the directional variations in phase velocities can probably be described by the $2\Psi$ terms [Smith and Dahlen, 1973; Montagner and Nataf, 1986], although non-zero $4\Psi$ terms have also been reported [Trampert and Woodhouse, 2003]. The silica-rich nature of the continental crust, in contrast, as inferred from Poisson’s ratios and verified by the geochemistry of the metapelitic xenoliths [Christensen, 1996; Hauser et al., 2008] may well cause its basic anisotropic properties to be different from those of the mantle, with both the $2\Psi$ and $4\Psi$ terms being important, at least in some locations.

4. Discussion and Conclusions

The fast-propagation direction resolved at periods of 10–20 s is orientated parallel to the prominent Caledonian NE–SW structural fabrics observed geologically at the surface [Chew, 2009; Chew and Stillman, 2009] and defined by
high frequency variation in the gravity field [Readman et al., 1997]. While this is not surprising for shorter periods (10 s) that are sensitive to structure in the upper-middle crust, at longer periods (15–20 s) that resolve the middle to lower crustal depths the orientation is identical. This indicates that anisotropic fabrics with a Caledonian orientation persist throughout the entire crust.

[18] The fast-propagation directions of anisotropy (defined by the $2\Psi$ terms, Figure 3) probably reflect the orientation of the major axis of the finite strain ellipsoid, due to regional Caledonian (Acadian) pure shear. It may also, at least in part, reflect a paleo-flow direction within a ductile mid to lower crust, driven by Caledonian stresses, and related to the emplacement of the Acadian (~400 Ma) “Newer Granite Suite” (B. M. O’Reilly et al., The fine-scale seismic structure of the upper lithosphere within accreted Caledonian lithosphere: Implications for the origins of the “Newer Granites”, submitted to Journal of the Geological Society, 2011).

[19] The observed anisotropy pattern also indicates that the effects of the Variscan compressional tectonics and the subsequent Mesozoic to Cenozoic lithospheric extension, manifest as large-scale hyper-extended sedimentary basins in the neighbouring North Atlantic, including just offshore Ireland [O’Reilly et al., 2006; Naylor and Shannon, 2011], did not overprint the older Caledonian fabrics developed throughout the crust. An orthogonal, NW–SE direction for anisotropy, parallel to the predominant Mesozoic tectonic extension direction, would be anticipated, particularly in the middle and lower, ductile part of the crust, if this were the case.

[20] These overall results are consistent with the available geological and geophysical evidence. The remarkable correlation between the petrophysical and petrological properties of a suite of mid to lower crustal metapelitic xenoliths from central Ireland [van den Berg et al., 2005] and the seismic properties, derived from controlled-source imaging, support a Caledonian accretion model for the crustal development [Hauser et al., 2008; O’Reilly et al., 2010]. This model implies that continental crustal growth ensued from a subduction related process during the closure of the Iapetus Ocean, which culminated at the Acadian Orogeny. Since early Carboniferous time, the crust has remained relatively stable, with little subsequent modification.

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References


