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Moho depth and V_p/V_s in Ireland from teleseismic receiver functions analysis

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SUMMARY

This work presents a teleseismic *P*-wave receiver function study on 34 stations deployed across Ireland in order to determine the first-order crustal properties, thickness (*H*) and mean crustal V_p/V_s, over the entire island. We apply the $H - V_p/V_s$ stacking method, which exploits the information contained in both the *Ps* and the multiple phases from the free-surface. In this way, we obtain the first Moho depth and V_p/V_s maps of Ireland based on a uniform distribution of measurements. The results are used to examine in detail the lateral variation of crustal thickness and V_p/V_s ratio across the major terrane boundaries in Ireland. Our results show a good agreement with the available previous estimates from onshore wide-angle/refraction experiments and add new information in poorly constrained areas such as Northern Ireland and the NW coast of Ireland. The mean V_p/V_s ratio is 1.73 ± 0.05 with a consistently low ($\approx$1.70) value in the Leinster domain and in central Ireland. The mean crustal thickness is 30.9 ± 2.3 km. The southern portion of the island shows a nearly flat Moho at a depth of 32–33 km, while north of the Southern Uplands Fault, a relatively higher spatial frequency variation in Moho topography exists with values ranging from 28 to 32 km. This reflects the complex history of multiphase terranes accretion during the Caledonian orogeny, although locally, the superposition of more recent geological processes is not excluded. Crossing the Iapetus Suture Zone, our results support the presence of a 'transitional' Moho, that is, a 3–4 km smooth seismic transition between crust and mantle, while Moho depth remains constant. Anomalous values in Northern Ireland are interpreted as evidence of a 5- to 6-km-thick high *S*-wave velocity layer just above the Moho.

Key words: Composition of the continental crust; Body waves; Crustal structure.

1 INTRODUCTION

The Mohorovičić discontinuity (Moho), which separates the crust from the underlying upper mantle, is a major feature in the Earth's structure and its depth represents one of the fundamental parameters in geophysical modelling of the lithosphere. Accurate estimates of the Moho depth allow the construction of precise crustal velocity models and provide insights on tectonic and geodynamical reconstructions.

In Ireland, the Moho depth has been investigated through deep offshore seismic reflection lines (Freeman *et al.* 1988; Snyder & Flack 1990; Klemperer & Hobbs 1991; Klemperer *et al.* 1991; O'Reilly *et al.* 1995) and with refraction/wide-angle onshore experiments (Jacob *et al.* 1985; Lowe & Jacob 1989; Masson *et al.* 1998; Landes *et al.* 2000; Hodgson 2001; Fig. 1). Most of the available results have been compiled in different Moho depth maps of the British Isles over the last 15 yr (Chadwick & Pharaoh 1998; Landes *et al.* 2005; Kelly *et al.* 2007; Davis *et al.* 2012). For onshore Ireland, a smooth trend of crustal thinning directed S–N has been inferred from the integration of all the available active seismic experiments with values ranging from 32 to 28.5 km (Landes *et al.* 2005). However, Moho depth estimates obtained with the refraction/wide-angle seismic methods, rely on the interpretation of *Pn* and *PmP* phases, which are more sensitive to lateral velocity variations than to the Moho depth variations and are sometimes difficult to pick in the observed data (Zhu & Kanamori 2000). Moreover, the onshore coverage of active seismic experiments in Ireland is confined to the southern portion of the island while a few and sparse measurements are available to the north of the Iapetus Suture Zone (ISZ).

More recently, Ireland has became the object of an increasing number of passive seismic studies using different approaches, from traveltime analysis (Masson *et al.* 1999), shear wave splitting measurements (Do *et al.* 2006), tomography (Wawerzinek *et al.* 2008; O'Donnell *et al.* 2011; Polat *et al.* 2012) and receiver functions (RFs;

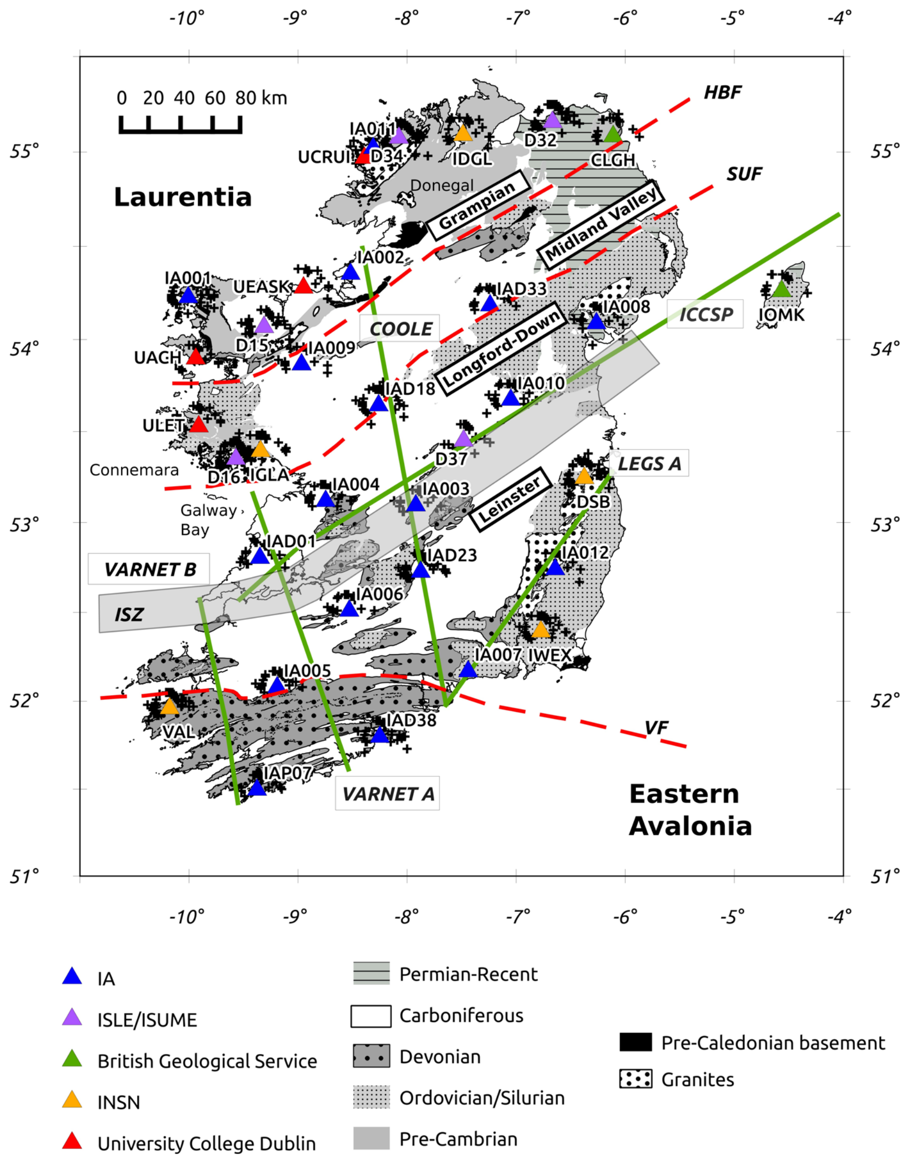

Figure 1. Geology sketch map of Ireland, modified after O'Reilly *et al.* (2010) and location of the 34 broad-band seismic stations used in this study. We integrated permanent (BGS, and INSN) with temporary (IA, UCD, ISLE/ISUME) networks to increase the spatial density. Crosses are the piercing points at a depth of 30 km for the events used to compute the corresponding receiver function. Green lines identify the location of onshore active seismic profiles: ICSSP 1982 (Jacob *et al.* 1985), COOLE 1985 (Lowe & Jacob 1989), VARNET 1996 lines A (Landes *et al.* 2000) and B (Masson *et al.* 1998), LEGS 1999 line A (Hodgson 2001). Grey shaded: Iapetus Suture Zone (ISZ). Dashed red lines, main tectonic lineaments: HBF, Highland Boundary Fault; SUF, Southern Uplands Fault; VF, Variscan Front.

Landes *et al.* 2006; Shaw Champion *et al.* 2006; Davis *et al.* 2012). Among these techniques, the RF method (Langston 1979; Ammon 1991) has proven to be a powerful seismological tool to estimate first-order bulk crustal structure and composition (Zandt & Ammon 1995; Chevrot & Van Der Hilst 2000). The *P* wave generated by a teleseismic earthquake is converted to *S* wave at velocity discontinuities beneath the seismic station. This information is encoded in the first seconds of the *P*-coda of the recorded horizonal seismograms. The deconvolution of the vertical seismogram (which approximates the source function) from the horizontal ones allows to reconstruct a time-series of *P*-to-*S* converted phases. The analysis of the delay times of the converted phases from the Moho (*Ps*), with respect to the direct *P*-wave arrival, can be used to constrain the crustal thickness (*H*) and the composition of the crust when jointly considered with its first crustal multiple (*PpPs*). In the RF stacking algorithm proposed by Zhu & Kanamori (2000), the existing trade-off between crustal thickness and velocity is strongly reduced in the by including in the analysis additional multiple phases (*PpSs* + *PsPs*). In this way, robust estimates of crustal thickness and V_p/V_s ratio can be obtained. This method has been applied in SW Ireland by Landes *et al.* (2006), who used 21 teleseismic events to compute RFs at 10 broad-band stations belonging to the Irish Seismic Lithospheric Experiment (ISLE; Landes *et al.* 2004). Shaw Champion *et al.* (2006), performed an RF study using five broad-band stations (of which three were located in Ireland), revealing a possible high-velocity layer at the base of the crust between Ireland and the United Kingdom, as proposed by the remodelling of the CSSP/ICSSP profile of Al-Kindi *et al.* (2003). Finally, Davis *et al.* (2012) studied the regional crustal structure of the British Isles through the analysis of RFs from 51 broad-band stations distributed across Ireland (five), United Kingdom (36) and continental northern Europe. These RF studies showed a general good agreement with the existing Moho depth estimates in Ireland and contributed to add new information on the bulk crustal composition (V_p/V_s ratio), which was previously constrained only by lower crustal xenoliths studies (Van den Berg *et al.* 2005) and by the interpretation of the *S*-wave data from the VARNET profiles (Hauser *et al.* 2008).

Although recently, many RF studies contributed to increase the number of onshore crustal thickness estimates for the United Kingdom (Tomlinson *et al.* 2003, 2006; Di Leo *et al.* 2009; Davis *et al.* 2012), the total amount of information is still poor and unevenly distributed across Ireland. In particular, to the north of the ISZ, the values of crustal thickness are constrained only by one active seismic profile (COOLE in Fig. 1) and by three RF point measurements.

The main aim of this study is to obtain Moho depth estimates uniformly distributed over the island, relying on the recent increase in the number of onshore seismic stations in Ireland. Data from recently deployed instruments belonging to various networks and from stations of previous seismic experiments are used. RFs are computed at each site and, through the application of the $H - V_p/V_s$ method of Zhu & Kanamori (2000), we obtained robust single-station estimates of crustal thickness and V_p/V_s ratio, which we compared with previous results, where available. This new set of results is used to produce the first well-constrained maps of Moho depth and V_p/V_s in Ireland.

1.1 Geological framework

Ireland's crust is the result of a complex geological history, which began in the Palaeozoic with the oblique closure of the Iapetus Ocean leading to the multiple phase continental collision between Laurentian and Eastern Avalonian terranes in the context of the Caledonian orogeny. The sinistral–transpressive deformation regime associated with the subduction–collision process is thought not to have produced a huge amount of crustal shortening in this area (Soper *et al.* 1992; Chew & Stillman 2009), but is responsible of the regional NE–SW trends of Ireland's structures and main tectonic lineaments (Readman *et al.* 1997; Fig. 1). The Highland Boundary Fault (HBF) separates the Grampian domain, which includes Pre-Cambrian rocks belonging to the Dalradian Supergroup (the old margin of Laurentia), from the Midland Valley terrane to the south. Today it is widely accepted that the Carboniferous deposit in the Midland Valley are floored by rocks belonging to an older oceanic arc that collided with the Laurentia margin during the southward directed subduction in the Grampian orogeny (ca. 470 Ma; Dewey & Ryan 1990; Chew *et al.* 2010). The development of an accretionary wedge between Laurentia and Avalonia is documented today by the Ordovician and Silurian sediments in the Longford-Down terrane (Graham 2009). Hence, the Souther Uplands Fault (SUF) represents the boundary between two different sectors of the accretionary complex. The continental collision between Laurentia and Avalonia (early Devonian, the Acadian phase) left its trace in the ISZ (Phillips *et al.* 1976; McKerrow & Soper 1989), which in Ireland separates the Leinster domain (Avalonian crust) to the south, from the Longford-Down accretionary complex to the north. The late stages (late Silurian-early Devonian) of the Caledonian orogeny involved granitic magmatism, which dates the end of oceanic plate subduction (O'Reilly *et al.* 2012). Through an integrated analysis of geological, seismological and geochemical data an 'incipient delamination' model has been proposed to explain the evolution of the Irish crust soon after the soft collisional processes occurred in the Acadian phase (O'Reilly *et al.* 2010, 2012). This involves the partial melting of the accretionary prism and the migration of a silica-rich melt through the crust leading to the emplacement of granites across the ISZ. In the mid- to late Devonian the beginning of the Variscan orogenic cycle affected the southern portion of Ireland and is responsible for the formation of the sedimentary basins until the early Carboniferous (Sevastopulo & Wyse Jackson 2009). These basins underwent a tectonic inversion during the compressional phase in the late Carboniferous–early Permian, which contributed to the E–W trend observed in the structures of the sedimentary cover sequences in southern Ireland (Readman *et al.* 1997; Graham 2009). During the late Palaeozoic and Mesozoic, several phases of lithospheric stretching and associated hyperextension affected the basins west of Ireland (O'Reilly *et al.* 2006; Naylor & Shannon 2011) and led to the opening of the North Atlantic Ocean in the Cretaceous and to the extrusion of flood basalts forming the British Tertiary Volcanic Province (BTVP; Mussett *et al.* 1988; Preston 2009), which extends on the west coast of Scotland and in Northern Ireland. In this area, the presence of a hot, low-density asthenospheric plume spreading from Iceland has been suggested (Jones *et al.* 2002; Al-Kindi *et al.* 2003; Arrowsmith *et al.* 2005) and is thought to support the present-day topography in the northwest part of the British Isles (Davis *et al.* 2012). Finally, it has been proposed (Barton 1992; Al-Kindi *et al.* 2003; Shaw Champion *et al.* 2006) that the presence of such a plume could have generated a thick high-velocity layer ($Vp = 7.2$–$7.8\ \mathrm{km\,s^{-1}}$) of magmatic underplated material at the base of the crust.

2 DATA AND METHODS

We used teleseismic data recorded at 34 broad-band seismic stations in Ireland. Most of the instruments belong to the Ireland Array (IA) network (http://www.dias.ie/ireland_array/; Lebedev *et al.* 2012). In order to further increase the station density and to fill some geographical gaps, especially in Northern Ireland, we also included five permanent stations of the Irish National Seismic Network (INSN) and two of the British Geological Survey (BGS). Moreover, four stations belonging to the University College Dublin (UCD) network and five from previous Irish passive seismic experiments, the ISLE (Landes *et al.* 2004, 2006; Wawerzinek *et al.* 2008) and the Irish Seismic Upper Mantle Experiment (ISUME; O'Donnell *et al.* 2011; Polat *et al.* 2012), have also been included. The final station distribution results in an unprecedented geographical coverage of the whole island (Fig. 1). For each station, we selected, by visual inspection, a subset of earthquakes with acceptable S/N ratio from a list of about 2200 teleseismic events with $M_w \geq 5.5$ occurring between 2004 September and 2012 December at epicentral distances ranging from 30° to 100°. A total number of almost 7000 three-component waveforms were finally selected for all the stations used in this study and constitute the final data set for RFs calculation. The number of selected earthquakes is proportional to the recording period of each station. In this study, it varies between 6 yr at station DSB and less than 6 months at IA011. However, for the majority of the considered stations, at least one and a half years of recordings is achieved allowing for a fairly good azimuthal coverage. Two examples of final selection for station DSB (permanent) and IA003 (temporary) are shown in Fig. 2.

The conversion from *P*- to *S*-waves due to a subsurface impedance contrast is at the base of the teleseismic RF method. Removing the source and path effects by deconvolving the vertical component

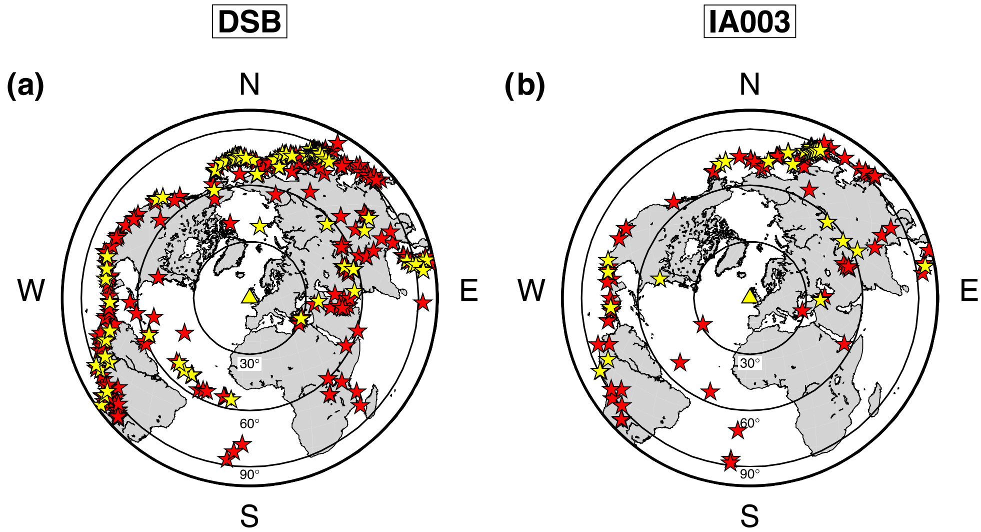

Figure 2. Azimuthal equidistant projection centred at station DSB (a) and IA003 (b), showing an example of the teleseismic earthquakes and RF data sets selection for 6 yr and 1 yr and 6 months, respectively. Events from 30° to 100° of epicentral distance have been visualized for the corresponding recording period. Red stars are the events selected after a visual inspection for which RFs were computed. Yellow stars represent the final set of high S/N RFs, used for further analysis.

from the radial and the transverse ones, allows the construction of two time-series made of converted waves at depth (i.e. the radial and transverse RFs), beneath a broad-band three-component seismic station (Langston 1979; Ammon 1991). The horizontal components of the seismograms are rotated in the ZRT coordinate system and we selected a 120-s-long time window centred at the *P*-wave arrival. RFs are computed at this stage through a frequency-domain deconvolution using the method proposed by Di Bona (1998). This method allows for variance estimation of each single RF considering both the contribution of the pre-signal noise and the noise involved in the frequency-domain deconvolution itself. We used a Gaussian filter with low-pass frequency of ≈1 Hz to rule out the effect of high-frequency noise. At this point, another visual inspection on the calculated RFs is performed, retaining only those with acceptable S/N. From of a total of 6870 calculated RFs, 1263 (20 per cent of the total) were selected, representing the final RF data set. Each single station is classified as good, medium or poor quality, based on the presence and coherence of the multiple phases with respect to the backazimuth (BAZ; Chevrot & Van Der Hilst 2000; Tomlinson *et al.* 2006; Piana Agostinetti & Amato 2009). Stations for which both *PpPs* and *PpSs* + *PsPs* multiples are clearly observable from most BAZ are classified as good. Medium-quality stations usually show the presence of multiples only from some BAZ, while for poor-quality stations, the multiples are difficult to recognize. At the base of this kind of classification, however, is the fact that the *Ps* conversion originating at the Moho is present and coherent from all BAZ, showing only minor variations in amplitude or delay time with respect to the direct *P*-wave arrival. For this reason, stations IA002 and IA007, for which *Ps* was difficult to recognize or highly variable, have been excluded from further analysis. Fig. 3 shows an example for each of the proposed classes of quality. Radial RFs have been binned in BAZ with bins of 20° and with 50 per cent overlap. Station D16 shows the presence of a positive pulse at around 3.8 s after the direct *P*-wave arrival and multiple phases in the range 11.5–15.5 s for almost all BAZ, it has been classified as good quality. Medium-quality class is represented by station IA005 where a positive pulse is found at around 4 s delay time and a first multiple is clear and coherent at ≈13 s for almost all BAZ, while a negative pulse associated with the *PpSs* + *PsPs* phases is seen just for some BAZs (especially in the interval 0°–45°) at ≈17 s. Finally, for station IAD38, no clear multiples are observed, although a positive pulse at around 4 s is present even if slightly more variable in delay time compared to the two previous stations. This station has been classified as poor quality. The stacked radial RF as a function of quality for all the stations used in this study are plotted in Fig. 4.

Seismic properties of the crust, such as its thickness (H) and bulk V_p/V_s ratio can be directly retrieved from RFs by the analysis of the arrival times of the primary converted *Ps* coming from the Moho and its crustal multiples, assuming the *P*-wave velocity in the crust is known (Zandt & Ammon 1995; Chevrot & Van Der Hilst 2000). Zhu & Kanamori (2000) proposed an RF stacking algorithm to estimate H and V_p/V_s at each individual station. This technique (with various modifications) has been extensively used to determine first-order crustal structure and composition (Nair *et al.* 2006; Tomlinson *et al.* 2006; Lombardi *et al.* 2008; Piana Agostinetti & Amato 2009; Davis *et al.* 2012) due to its straightforward implementation, its ability to automatically process a large number of RFs and the possibility to estimate errors associated with the results. Through a grid search in the $H - V_p/V_s$ domain, we look for the values of H and V_p/V_s that maximize the stacking function:

$$S(H, V_p/V_s) = \sum_{j=1}^{N} w_1 r_j(t_1) + w_2 r_j(t_2) - w_3 r_j(t_3), \tag{1}$$

where the stack is performed over N, the total number of RFs for that station. Here, r_j is the j-th observed radial RF at times t_1, t_2, t_3, the predicted arrival times for phases *Ps*, *PpPs* and *PpSs* + *PsPs*, respectively, calculated using the current values of $(H, V_p/V_s)$, while w_1, w_2 and w_3 are the weighting factors associated with each phase. In principle, the maximum value of $S(H, V_p/V_s)$ is found when the correct couple of H and V_p/V_s are used in the grid search and so the three phases are stacked coherently. This method makes use of a fixed *a priori* crustal V_p value as the parameter H is more sensitive to V_p/V_s changes than to absolute V_p variations (Zhu & Kanamori 2000). The sensitivity of the results on V_p is explored choosing three different mean crustal V_p values corresponding to 6.25, 6.50 and

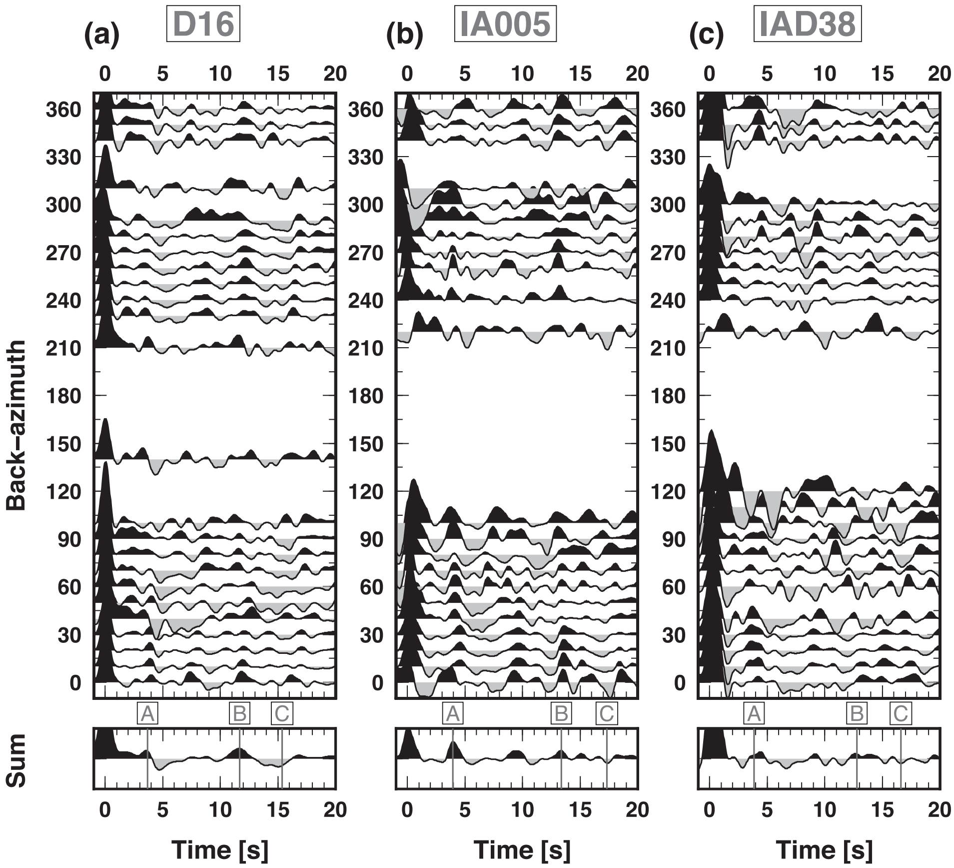

Figure 3. Examples of receiver functions data set plotted as a function of backazimuth (BAZ). The radial RFs are stacked in bins of 20° width for BAZ, with 50 per cent overlap. Black is used for drawing positive amplitude (increase of velocity with depth) while grey for negative. The sum of all the observed RF is plotted in the bottom panel for each station. Red lines correspond to the calculated delay times with respect to the direct *P*-wave arrival ($t = 0$ s) using H, and V_p/V_s as computed with the Zhu & Kanamori (2000) method, for the three phases *Ps* (A), *PpPs* (B) and *PpSs* + *PsPs* (C) and for a fixed crustal $V_p = 6.5\,\mathrm{km\,s^{-1}}$. (a) Data set for station D16, classified as good quality; (b) station IA005 (medium quality); (c) station IAD38 (poor quality).

$6.75\,\mathrm{km\,s^{-1}}$ (Dugda *et al.* 2005). This particular range of values is chosen accordingly to that reported in Landes *et al.* (2005; 6.25–6.50 $\mathrm{km\,s^{-1}}$), from refraction studies onshore Ireland, although we extended it up to $6.75\,\mathrm{km\,s^{-1}}$. The H parameter is allowed to vary between 20 and 50 km and the V_p/V_s parameter between 1.65 and 1.90. Accordingly with the qualitative ranking, the weighting factors have been set as $w_1 = 0.4$ and $w_2 = w_3 = 0.3$. This choice differs from that of the original work of Zhu & Kanamori (2000; $w_1 = 0.7$, $w_2 = 0.2$, $w_3 = 0.1$), and is instead more similar to that proposed by Chevrot & Van Der Hilst (2000) and Lombardi *et al.* (2008). These authors suggest the use of an equal phases weighting in the $H - V_p/V_s$ stack to exploit all the information included in the multiple phases. This choice could be misleading in the presence of a deep (>40 km) and strongly dipping (>10°) Moho, resulting in errors greater than 3 km in H and 0.06 in V_p/V_s (Lombardi *et al.* 2008). However, in the area considered in this study, this should not be the case, so an equal phases weighting should provide more accurate estimates of the parameters in the grid search when multiples are present, and a more coherent behaviour of the errors estimates, as the errors should be large when the multiples are not well developed and vice versa. As briefly introduced, the grid search method of Zhu & Kanamori (2000), although widely used, suffers from a number of limitations. This method is valid under a 1-D approximation of isotropic and flat stratified media. It also assumes that the highest amplitude pulse after the direct *P*-wave arrival corresponds to that coming from the Moho, which could not always be the case especially when strong velocity contrasts are found within the crust. A qualitative assessment of the contribution from 3-D structure in the crust can be done by looking at the energy contained in the transverse RFs, which should be zero in case of perfectly isotropic and flat media (Levin & Park 1998). In this study we found that for almost the totality of the considered stations the amplitudes on the transverse RFs are significantly smaller than that on the radial RFs, so we considered the 1-D approximation valid in most of the cases. Exceptions exist however and generally correspond to stations classified as poor quality. As, for most of the stations the 1-D approximation holds and we are interested in the first-order isotropic feature or Ireland's crust, the attention is focused on the radial RFs.

In this work, the errors associated with H and V_p/V_s are estimated with a bootstrap resampling technique (Efron & Tibshirani 1991), which has often been applied to the same kind of analysis (Chevrot & Van Der Hilst 2000; Julià & Mejia 2004; Lombardi *et al.* 2008; Piana Agostinetti & Amato 2009). The grid search is repeated a hundred of times using an ensemble of RF randomly selected from the original data set, where each newly composed RF data set has the same number of RF as the original one. In this way, from the empirical distribution of values it is possible to obtain a standard deviation that is representative of the original unknown distribution. Fig. 5 shows the results of the $H - V_p/V_s$ stack analysis for three high-quality stations (D15, D16 and D37) and for a medium quality one (IA005). $S(H, V_p/V_s)$ is plotted for $V_p = 6.5\,\mathrm{km\,s^{-1}}$ (Fig. 5a).

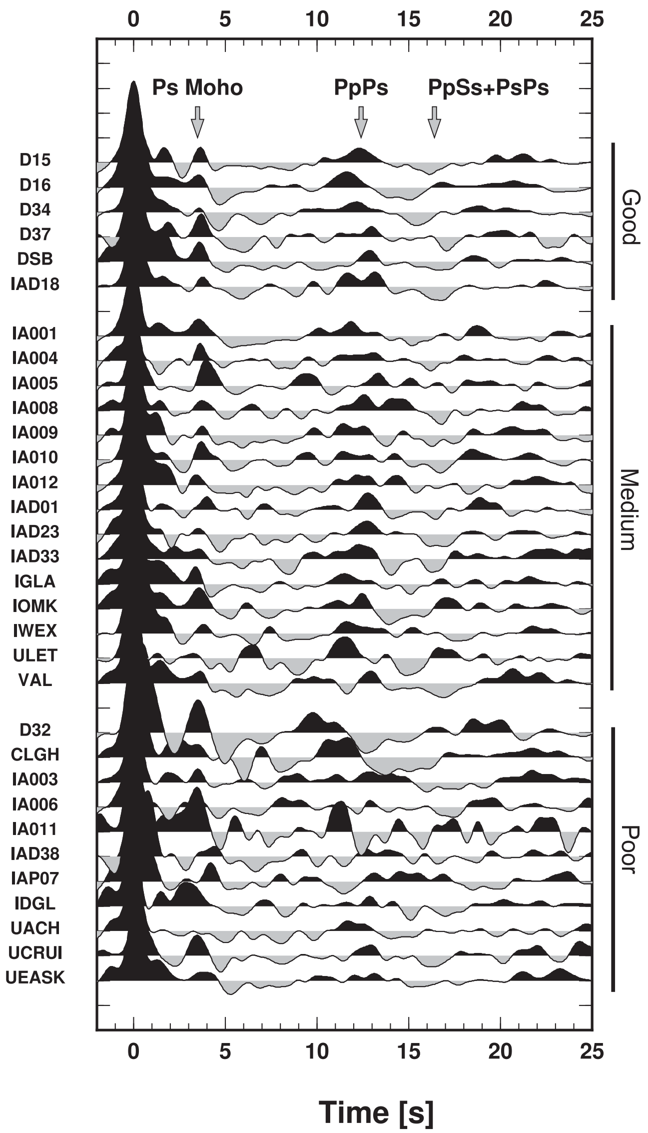

Figure 4. Stacked RFs as a function of station quality. The *Ps* Moho phase arrives between 3.5 and 4 s delay time. Multiple phases (*PpPs* and *PpSs* + *PsPs*) are found in the interval 11–18 s. Clear *PpPs* arrivals are observed for stations of good and medium quality, while these are more ambiguous for poor-quality stations.

Each star represents the maximum of the stacking function for a different crustal V_p. On average, a change in V_p of 0.25 km s^{-1} will cause a change of ≈1.4 km in H and ≈0.01 in V_p/V_s (Table S1) with maximum observed variation of 1.8 km and 0.03, respectively. The results of each single bootstrap iteration are drawn as green dots and their final distribution is used to evaluate uncertainties on the resulting parameters. On average $\sigma \approx 1.4$ km for H and $\sigma \approx 0.04$ for V_p/V_s. The $H - V_p/V_s$ stacks for all the stations used in this study is shown in Fig. S1. For the high-quality stations, errors are low and the values of the bootstrap resampling are clustered around the maximum of the stacking function. For station IA005, a medium-quality station, the results are slightly more spread, resulting in higher errors. The retrieved couple of parameters is used to compute the predicted arrival times for *Ps*, *PpPs* and *PpSs* + *PsPs*, to asses the reliability of the results (Fig. 5b). A consistent behaviour is obtained for all the good-quality and for most of the medium-quality stations.

3 RESULTS

Table 1 summarizes the results obtained by the application of the Zhu & Kanamori (2000) method for a fixed value of $V_p = 6.5$ km s^{-1}. The complete summary of results (for $V_p = 6.25$ km s^{-1} and $V_p = 6.75$ km s^{-1}) is reported in Table S1. Of the 34 stations that compose our data set, two were discarded due to the presence of a strongly varying or not well-developed Moho *Ps* phase, 18 were classified as medium quality, six as good and eight as poor. The bootstrap errors analysis found that 1σ error on Moho depth varies between 0.3 and 3.1 km while 1σ error on V_p/V_s varies between 0.01 and 0.09. However, the imposed frequency content in the data set (hence the width of the pulses in the RFs) implies an error on the observed delay time for the considered phases. The presented bootstrap error analysis is insensitive to this aspect and some unrealistic very low errors can be obtained for large and coherent data sets (high-quality stations). For this reason, we set the minimum value for the errors on H and V_p/V_s to 0.8 km and 0.02, respectively. Usually, good- and medium-quality stations also show smaller errors on H and V_p/V_s although some exceptions exist. The *Ps* phase originating at the Moho generally arrives between 3.5 and 4 s after the direct *P* arrivals in the radial RFs and little variations in delay time are observed across the studied region. The *PpPs* and *PpSs* + *PsPs* phases, on the other hand, are found in the 11.5–16.5 s interval and show larger delay time variations. They are identified as a positive pulse followed by a generally broader negative pulse as large as 2 s for some stations. Many stations are characterized by the presence of a positive pulse in the first 2 s of the radial RFs, which in some cases can reach the same amplitude as the *Ps* Moho pulse. However, no clear multiple phases possibly associated with the presence of an intracrustal layer can be uniquely observed in the later portion of the RFs for most of the sites. Moreover, the presence of this pulse in the observed RFs does not preclude a correct estimation of Moho depth and V_p/V_s for all the considered stations. For stations CLGH, D32, IA003 and IDGL, the resulting maxima of the stacking function were found on the edge of the explored V_p/V_s parameter space, resulting in ambiguous picking of the correct pair of H and V_p/V_s values. For this reason the trade-off over a broader range of parameters has been explored (Fig. S2). Very low V_p/V_s (1.55) are found for CLGH and IDGL while H does not change much. The bimodal distribution for stations IDGL and D32 is investigated in the next section, while for IA003 the results don't change. However, based on this *a posteriori* analysis, the quality for stations IDGL, CLGH and D32 has been lowered from medium to poor.

3.1 Moho depth

Interpolation of the punctual measurements in Table 1 at each site results in the Moho depth map of Fig. 6, which is the first onshore crustal thickness map of Ireland compiled from a uniform distribution of measurements. Each station is plotted as a circle with size depending on quality as discussed before.

On a regional scale two first-order different patterns in Moho topography can be identified. The first one characterizes the southern portion of Ireland and consists of a nearly flat Moho, with associated depths that vary, on average, between 32 and 33 km with stations IAP07 and IA003 (poor quality) showing the maximum values of 35.8 ± 1.6 km and 34.4 ± 1.3 km in this area. The second pattern reflects a higher spatial frequency variation in Moho topography and is confined in the northern part of Ireland. Here, the crustal thickness has a broader range of variation with values spanning the 23–32 km

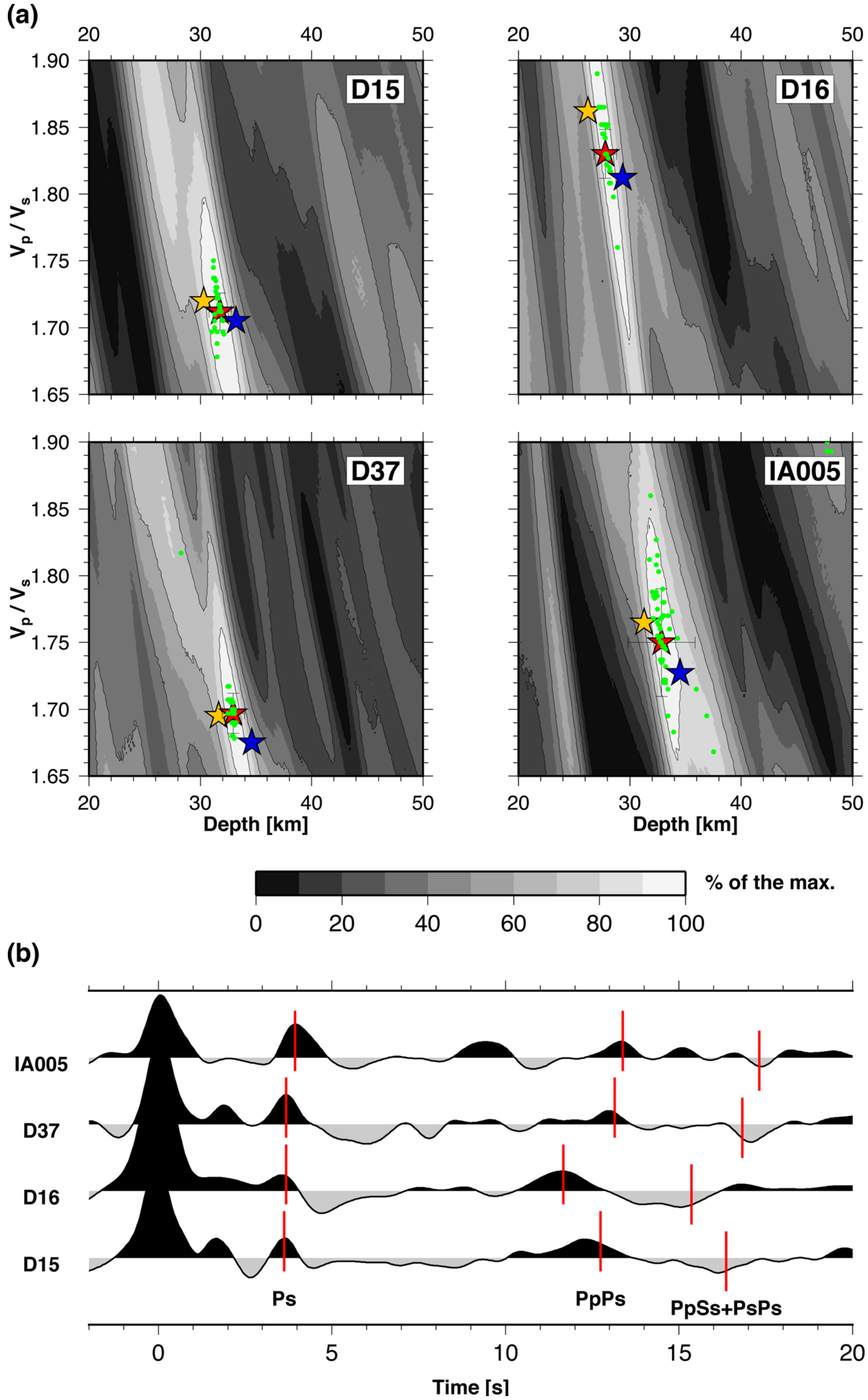

Figure 5. Zhu & Kanamori (2000) $H - V_p/V_s$ stacking results for stations D15, D16, D37 and IA005. (a) Stacking function for a fixed crustal V_p of 6.5 km s^{-1}. Grey scale is the amplitude of the stacking function expressed as percentage of the absolute maximum value. Contours are drawn every 20 per cent starting from 10 per cent. Stars represent the max values of $S(H, V_p/V_s)$ for V_p equal to 6.25 (yellow), 6.50 (red) and 6.75 (blue) km s^{-1}. Each green dot is the result of a single bootstrap iteration from which vertical and horizontal bars (1σ confidence interval) are calculated and plotted only for $V_p = 6.5$ km s^{-1}. (b) Observed stacked receiver functions for each station. The red lines mark the arrival for the *Ps*, *PpPs* and *PpSs* + *PsPs* calculated for the couple of values corresponding to the maximum of the associated stacking function for $V_p = 6.5$ km s^{-1} (red star).

interval and with a mean value of 29.3 ± 2.0 km. In particular, two areas of relative thinner crust are located along the NW and NE coasts. To have a better view on the regional lateral crustal thickness variations, in Fig. 7 our results are projected along three vertical profiles across Ireland, whose locations are indicated in Fig. 6. In all of these profiles, the $H - V_p/V_s$ stacking results is plotted as a function of crustal V_p in order to illustrate how the Moho depth estimates are influenced by the *a priori* choice of crustal velocity. As expected, increasing the mean *P*-wave velocity in the crust, results in a higher value of Moho depth. For this reason the following

Table 1. Location of the stations used in this study, quality (Q_u), number of RFs at each site (n) and results of the grid search (H and V_p/V_s) with the associated errors for a fixed crustal V_p of 6.5 km s^{-1}.

Station	Sens.	Network	Lon.	Lat.	Q_u	n	H (km)	σ_H	V_p/V_s	σ_{V_p/V_s}
CLGH	Trill. T240	BGS	−6.1106	55.0828	P	17	29.8	0.8	1.65	0.03
D15	CMG40T	ISLE/ISUME	−9.3119	54.0672	G	43	31.8	0.8	1.71	0.02
D16	CMG40T	ISLE/ISUME	−9.5700	53.3500	G	49	27.8	0.8	1.83	0.02
D32	CMG40T	ISLE/ISUME	−6.6670	55.1580	P	57	22.9	1.1	1.90	0.03
D34	CMG40T	ISLE/ISUME	−8.0400	55.0540	G	80	30.1	0.8	1.75	0.03
D37	CMG40T	ISLE/ISUME	−7.4822	53.4499	G	27	33.0	0.8	1.70	0.02
DSB	STS-2	INSN	−6.3755	53.2450	G	85	32.0	0.8	1.69	0.02
IA001	Trill. 120PA	IA	−10.0068	54.2277	M	66	28.9	0.8	1.76	0.03
IA003	Trill. 120PA	IA	−7.9202	53.0942	P	29	34.4	1.3	1.65	0.02
IA004	Trill. 120PA	IA	−8.7468	53.1188	M	29	31.9	0.8	1.70	0.02
IA005	Trill. 120PA	IA	−9.1912	52.0786	M	37	32.8	2.7	1.75	0.04
IA006	Trill. 120PA	IA	−8.5304	52.5093	P	29	32.7	0.8	1.70	0.03
IA008	Trill. 120PA	IA	−6.2644	54.0875	M	29	30.1	1.9	1.83	0.05
IA009	Trill. 120PA	IA	−8.9680	53.8649	M	19	31.4	1.5	1.73	0.06
IA010	Trill. 120PA	IA	−7.0495	53.6731	M	33	32.2	2.0	1.73	0.05
IA011	Trill. 120PA	IA	−8.3109	55.0215	P	5	29.2	3.1	1.73	0.04
IA012	Trill. 120PA	IA	−6.6423	52.7406	M	25	31.3	1.6	1.70	0.02
IAD01	Trill. 120PA	IA	−9.3502	52.8037	M	36	31.0	2.0	1.78	0.04
IAD18	Trill. 120PA	IA	−8.2613	53.6428	G	46	32.4	1.5	1.75	0.04
IAD23	Trill. 120PA	IA	−7.8762	52.7260	M	50	33.2	0.9	1.68	0.05
IAD33	Trill. 120PA	IA	−7.2388	54.1838	M	27	30.7	2.6	1.74	0.07
IAD38	Trill. 120PA	IA	−8.2501	51.7982	P	42	31.0	3.1	1.77	0.07
IAP07	Trill. 120PA	IA	−9.3764	51.4965	P	21	35.8	1.6	1.72	0.03
IDGL	Trill. T240	INSN	−7.4875	55.0893	P	32	29.6	2.9	1.65	0.04
IGLA	Trill. T240	INSN	−9.3447	53.3929	M	33	28.6	0.8	1.75	0.02
IOMK	CMG3T	BGS	−4.5662	54.2605	M	14	30.4	1.6	1.73	0.05
IWEX	Trill. T240	INSN	−6.7732	52.3929	M	45	33.7	1.4	1.70	0.03
UACH	3ESPDC	UCD	−9.9621	53.8758	P	30	29.4	1.2	1.72	0.09
UCRUI	3ESPDC	UCD	−8.3771	54.9846	P	17	31.5	1.9	1.69	0.06
UEASK	3ESPDC	UCD	−8.9583	54.2894	P	23	28.9	2.0	1.79	0.07
ULET	3ESPDC	UCD	−9.9413	53.5519	M	24	29.0	0.8	1.72	0.04
VAL	Trill. T240	INSN	−10.1780	51.9600	M	69	32.8	2.8	1.68	0.07

comments refer to the red stars (V_p equal to 6.5 km s^{-1}), remembering that, as discussed in the previous section, a change of 0.25 km s^{-1} in V_p leads to an average difference of about 1.4 km in Moho depth. Profile AA′ (Fig. 7a) runs in the SSW–NNE direction from the easternmost edge of the Variscan front to the Inishowen Peninsula in Co. Donegal, crossing all the four major tectonic structures of Ireland (black vertical lines in Fig. 7). A smooth trend of crustal thinning is observed from S to N. A mean value of 32.6 ± 1.0 km is found in the first 260 km of the profile, while moving northwards, the mean value of Moho depth is 29.2 ± 2.5 km. In more detail, station IAD38 is located on the Devonian deformed sedimentary sequence south of the Variscan front. Here, reverberations from the base of the sedimentary basin are responsible for the poor quality of the RFs and the large error bars by masking any sign of crustal multiples. Stations IWEX, IA006, IAD23, IA012, IA003 and DSB are located between the Variscan front and the ISZ, and belong to the Leinster domain. For these stations, quality varies with no discernible patterns from low to high. Station IAD23 has been classified as medium quality although, as we will comment later, the *Ps* Moho pulse was characterized by a small amplitude. Moving to the north of the ISZ in the Longford-Down domain (D37, IAD18, IA010, IA008) quality increases in the observed RFs that show clearer *Ps* Moho and multiple phases. The average Moho depth in this portion of the profile is still 32 km, but from station IA008 ($X = 300$ km) northwards a shallowing of the Moho to about 30 km depth is observed, which continues in the Midland Valley (IAD33) and in the Grampian domain (IA011, D34, IDGL, CLGH, D32). Station D32 in County Antrim (Northern Ireland) shows a value of 22.9 ± 1.1 km, which represents the smallest crustal thickness estimate of this study. Profile CC′ has been designed to look more in detail at this region.

Profile BB′ (Fig. 7b) is oriented SSE–NNW and crosses from S to N, the VF, Galway Bay, Connemara and the HBF. For the first 200 km of the profile the mean crustal thickness is about 32–33 km, while, just after Galway Bay it diminishes to 28–29 km until station IA001 at the end of the profile. As with profile AA′, no evidence of Moho depth variations are observed across the ISZ, between stations in the Leinster (IA005 and IA006) and Longford-Down (IAD01 and IA004) domains. Moving to the north, from about 210 km along the profile, a cluster of stations with a relatively thinned crust are observed from Connemara and further north. This cluster includes stations D16, IGLA, ULET, UACH and IA001 and yields a mean value of 28.7 ± 0.5 km.

Profile AA′ and BB′ both suggest a N–S trend of smooth crustal thinning with a change in Moho depth of about 4 km in a distance of ≈50 km, which results in a south gently dipping Moho inclined less than 5°. In both profiles this 50-km-long region, which marks the boundary between two different patterns of Moho depth, is geographically well correlated with the location of the Southern Uplands Fault, which separates a southern sector of thicker crust from a distinct northern sector where a thinner crust is observed.

The last profile, CC′ (Fig. 7c) crosses the NE part of Ireland following a W–E direction. It includes six stations belonging to the Grampian domain located north of the HBF. Differences in

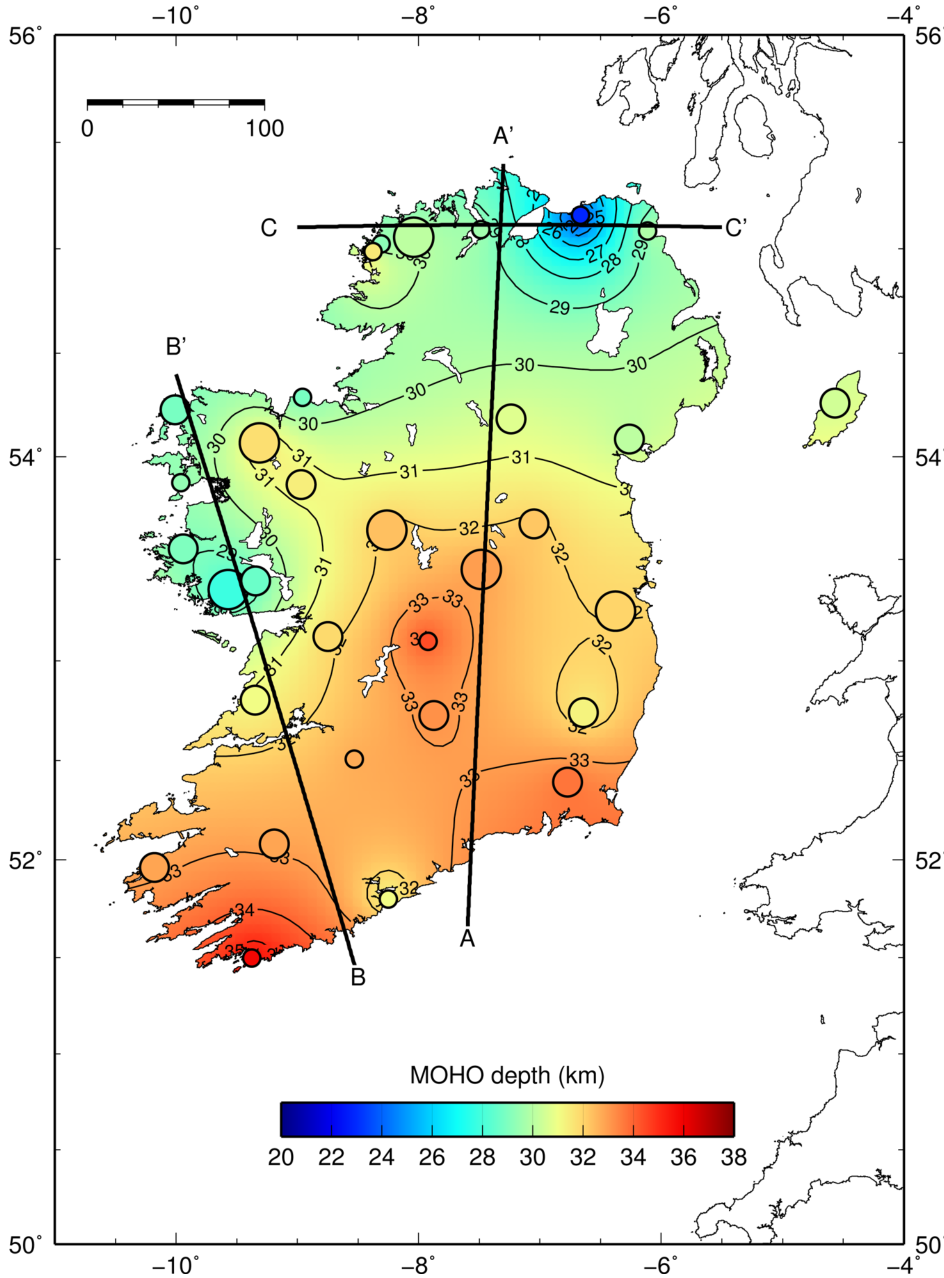

Figure 6. Interpolated Moho depth map of Ireland. Individual point measurements are those reported in Table 1 for V_p equal to 6.5 km s^{-1}. Stations are indicated by circles with size proportional to quality.

the outcropping rocks exist, with D34, IDGL and CLGH being on the Dalradian Supergroup rocks, IA011 and UCRUI on the Siluro-Devonian Donegal Granite and D32 located on an olivine basalt lava extruded in the early Cenozoic. The main *S*-wave velocity discontinuity appears to be shallower (22.9 ± 1.1 km depth) than at the surrounding stations, where a mean value of ≈30 km has been retrieved from the $H - V_p/V_s$ stacks. In particular, stations CLGH and IDGL exhibit values of 29.8 ± 0.4 and 29.6 ± 2.9 km, respectively, implying a Moho offset of about 6–7 km over a distance of 35–50 km. Airy isostasy would require a difference in topography of about 1.2–1.4 km, which is not observed. Differences in lithospheric thickness or dynamically supported topography could explain such an inconsistency. Here we note that such short-wavelength variations in crustal thickness are difficult to explain as recent lithospheric modelling of Ireland have constrained the lithospheric thickness to approximately 105 ± 15 km with a smooth thinning from S to N (Fullea *et al.* 2014; Jones *et al.* 2014). Given that, to maintain the observed topography, the Moho offset between D32 and the surrounding stations would require a thinning of the lithosphere of about 30 km (Jones *et al.* 2014) over the same distance. Apparent thinning of the crust beneath D32 is investigated in more detail. The $H - V_p/V_s$ stacks for stations D32 and IDGL are shown in Fig. 8. They both show a bimodal distribution of the stacking function, and the results of the bootstrap resampling are spread over two possible maxima, where one corresponds to H values of about 23–24 km for IDGL and 26–28 km for D32. Station CLGH does not show this kind of behaviour but has the presence of a broad *Ps* Moho pulse centred at 3 s and a fairly smeared maximum

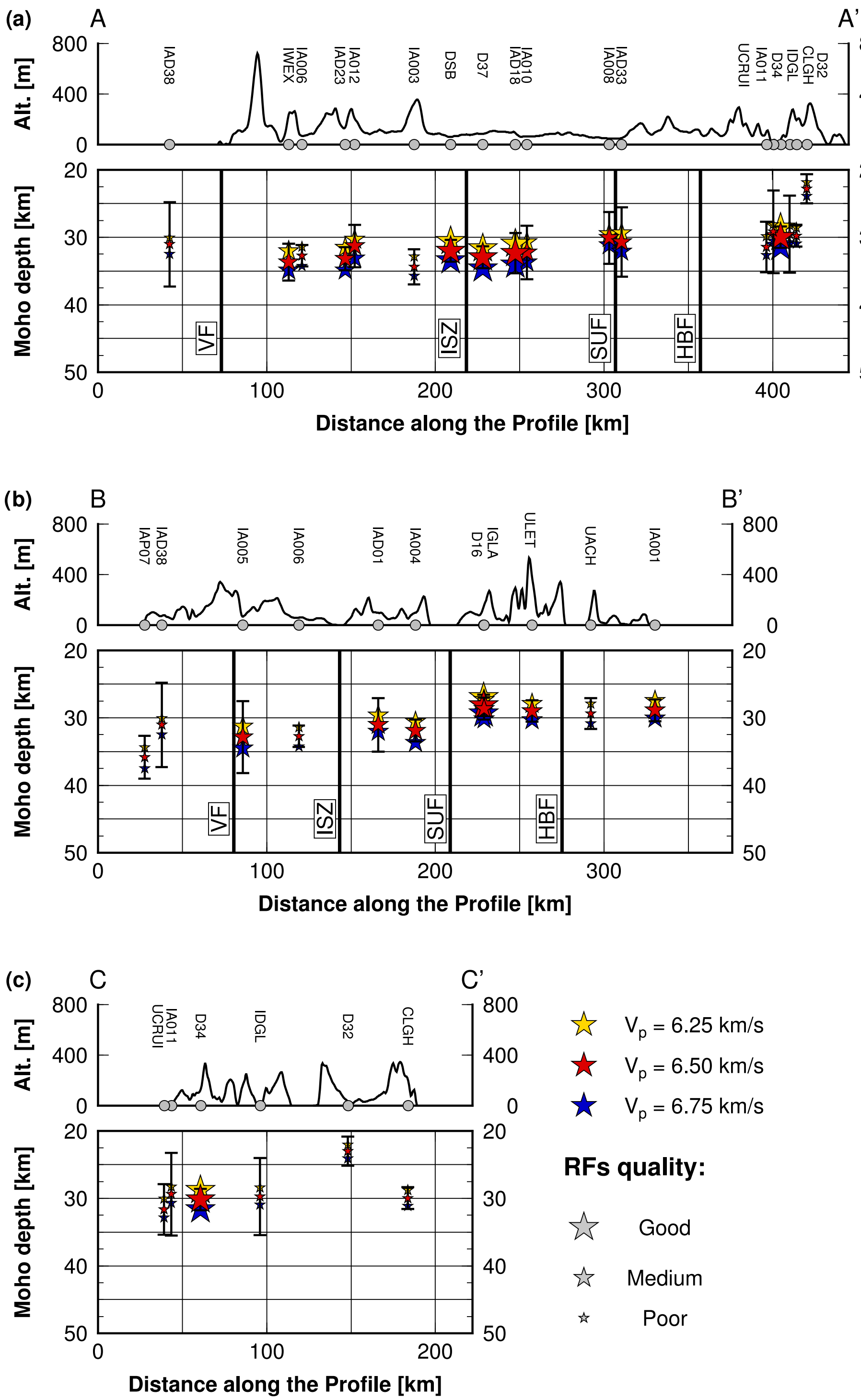

Figure 7. Moho depth variations along the three vertical profiles shown in Fig. 6. Stars are coloured by V_p as in the legend and in Fig. 5. Size is proportional to station quality. Vertical bars stand for 2σ deviation from bootstrap resampling technique. Black vertical lines correspond to the location of the main Irish tectonic features shown in Fig. 1.

in the stacking function. In addition to this, the transverse RFs for station D32 contain a non-negligible amount of energy between 1 and 3 s delay time, which is not observed for IDGL and CLGH but that could indicate the presence of anisotropy or dipping interfaces at middle to lower crustal depths. For these reasons we associate the second maximum of the stacking function to the Moho interface for stations D32, giving a crustal thickness of about 28 km and a V_p/V_s around 1.8.

Finally, as appear from Figs 7(a) and (b), no major crustal thickness variations have been observed across the ISZ. Fig. 9 shows a profile of stacked radial RFs in time domain across the ISZ, in order to illustrate the results in this area. The profile crosses the

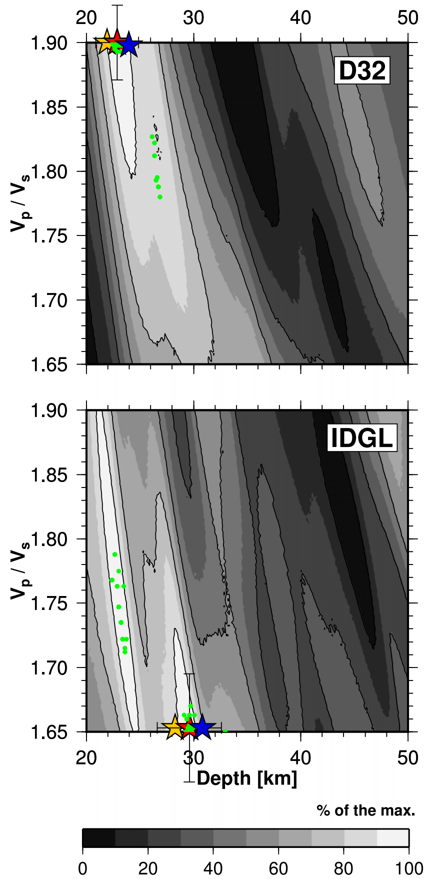

Figure 8. Zhu & Kanamori (2000) stacking functions as in Fig. 5 but for station D32 (top panel) and IDGL (bottom panel). Results of the bootstrap analysis (green dots) are spread over two maxima corresponding to H values of ≈23 and 26–28 km for D32 and at 22–24 and ≈30 km for IDGL.

ISZ almost perpendicularly in central Ireland and includes stations belonging to the East Avalonian and Laurentian Terranes. Stations IA006, IAD23 and IA003, the closest to the south of the ISZ, don't show the presence of a well-developed *Ps* pulse, as instead is observed for stations directly to the north of the ISZ (e.g. D37 and IA10).

3.1.1 Comparison with previous studies

In Ireland, information about Moho geometry is based on a non-uniform distribution of active seismic profiles (Landes *et al.* 2005) and on some single-station measurements obtained with RFs. In this section, the results from this study are compared with the available estimates to discuss the common features or discrepancies along the four main seismic profiles carried out onshore Ireland in the last decades (Fig. 10). This comparison includes crustal thickness estimates from the interpretation of the refraction profiles (white symbols in Fig. 10) and from the RF analysis carried out by Landes *et al.* (2006), Davis *et al.* (2012) and Shaw Champion *et al.* (2006, grey symbols in Fig. 10). The same $H - V_p/V_s$ stacking method has been used by these three authors although some differences exist in the chosen crustal *P*-wave velocities. However, with respect to our results, this would translate to a maximum difference in crustal thickness of about 1 km, so a comparison is to be considered feasible on a regional scale. The profile in Fig. 10(a) follows the trace of the ICSSP (Irish Caledonian Suture Seismic Project) line (Jacob *et al.* 1985), which was planned as the SW Irish onshore extension of the CSSP profile (Bott *et al.* 1985). We considered the two as a single profile, which runs almost parallel to the ISZ in the Midland Valley domain of Ireland, from Galway Bay in the SW, through the Isle of Man and to the United Kingdom in the NE (Fig. 1). The authors found an almost constant value of about 32 km for the crustal thickness from the analysis of the seismic section and a Moho transition zone of about 3–4 km in the central and eastern parts of Ireland. Our results match the first feature extremely well (Fig. 10a) and are qualitatively consistent with the second, at least for the central part of Ireland where the absence of a well-developed *Ps* pulse from the Moho has been observed in the RFs (Fig. 9). Also, when compared with previous RF studies, our findings are in good agreement along the whole length of the profile. In Fig. 10(b) the trace of the VARNET-A (VARiscan NETwork; Landes *et al.* 2000) refraction profile is extended northwestwards up

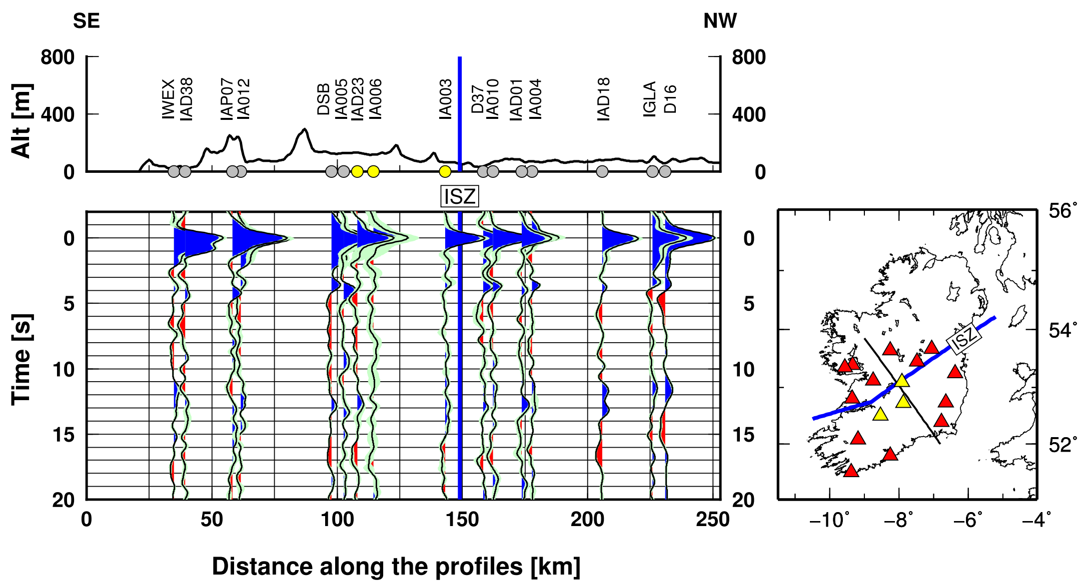

Figure 9. Profile of stacked radial receiver functions across the ISZ. Yellow triangles in the inset map and yellow dots on the profile indicate three stations for which a clear *Ps* Moho pulse is not observed.

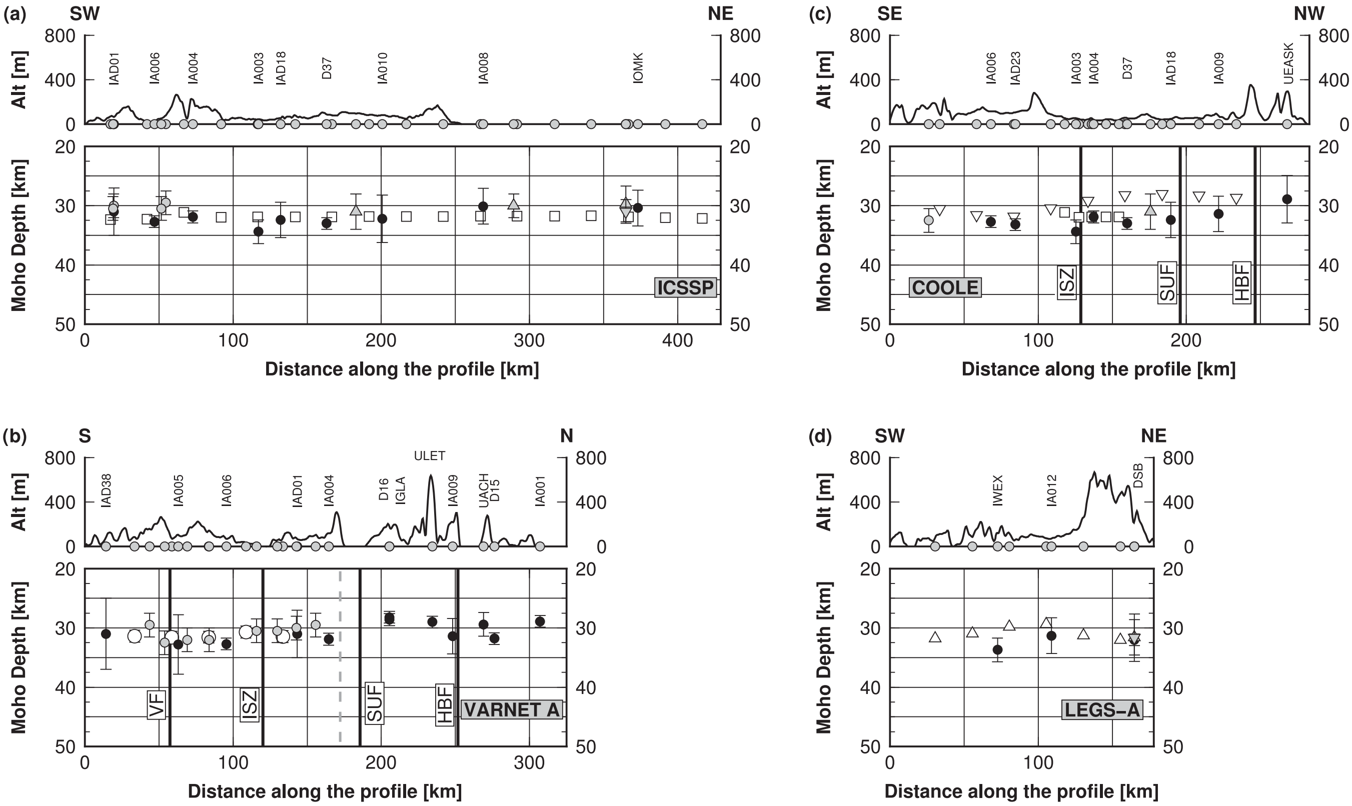

Figure 10. Comparison of Moho depth estimates with previous studies along four onshore active seismic profiles in Ireland: (a) ICSSP (Jacob *et al.* 1985); (b) VARNET-A (Landes *et al.* 2000) and its prosecution to the north after the grey dashed line; (c) COOLE (Lowe & Jacob 1989); (d)LEGS-A (Hodgson 2001). Black circles are the results of this study (for V_p equal to 6.5 km s^{-1}, with 2σ deviation). Grey symbols indicate previous RF studies: circles (Landes *et al.* 2006), triangles (Davis *et al.* 2012), inverted triangles (Shaw Champion *et al.* 2006). White symbols refers to active seismic experiments: squares are for ICSSP, circles for VARNET-A, inverted triangles for COOLE. Black vertical lines, major tectonic features.

to IA001 crossing, from SE to NW, the Leinster, Longford-Down, Midland Valley and Grampian domains. The profile was shot to investigate the influence of the Variscan and Caledonian orogenies on the southern Irish crust. A first-order comparison of results shows a fairly good match also with the RF study of Landes *et al.* (2006) yielding a crustal thickness in the 33–30 km range. However, different choices of crustal V_p at each station influence the final Moho depth values and, hence the discrepancy between the results of this work and previous estimations. Although this RF study was aimed to retrieve only the regional structure, a closer look at the profile confirms also a second-order feature in this area pointed out by the VARNET-A experiment, which is the topographic high of the Moho under the Shannon estuary. Station IAD01 at $X = 140$ km shows a slightly shallower Moho than the surrounding stations (IA006, IA005). However given the modelling uncertainties the interpretations of these features remains speculative. The shallowing of the Moho north of the SUF found in this study is reported again on the NW prosecution of the VARNET-A profile. With respect to Fig. 7(a), stations IA009 ($X = 245$ km) and D15 ($X = 275$ km) are also included to show that the observed slight crustal thinning is confined to the westernmost stations in this area (D16, IGLA, ULET, UACH, IA001). This feature robustly correlates with the available offshore reflections profiles WIRE 1 (Klemperer *et al.* 1991) and RAPIDS (O'Reilly *et al.* 1995), where values of Moho depth between 25 and 28 km have been found just off the coast between D16 and IA001. The profile in Fig. 10(c) is traced over the COOLE'85-1 (Caledonian Onshore-Offshore Lithospheric Experiment) refraction line (Lowe & Jacob 1989). This seismic experiment was designed to look in more detail at the structure of the crust across the ISZ and was shot almost perpendicular to the older ICSSP profile. A transitional 2-km-thick crust–mantle boundary was found by the authors along the whole length of the line, together with an S–N directed shallowing in its depth from 32 to 28 km observed north of the proposed trace of the ISZ. In the first 100 km of the profile, stations IA006 and IAD23 match quite well the depth of 32 km found by the COOLE experiment, while in the remaining part of the profile, some discrepancies exist. Stations IA003, IA004, D37, IAD18 and IA009 indicate that an average crustal thickness of 32 km is found from 0 to 225 km, although also the associated errors increase northwards. The maximum difference in Moho depth between the results of this study and the COOLE estimates is of about 4 km at station D37 ($X = 160$ km). The RF Moho depth value at station CKWD of Davis *et al.* (2012; 31.0 ± 1.7 km) is closer to that observed at D37, also considering the smaller crustal V_p (6.3 km s^{-1}) used by these authors. The observed discrepancy is mainly confined between the ISZ to the south and the HBF to the north where, just at the end of the profile, station UEASK seems to be more similar to COOLE with a value of 28.9 ± 2 km. Moreover, a difference of about 2–3 km in Moho depth is observed when comparing the results of ICSSP with COOLE at their intersection (inverted triangles and squares in Fig. 10c). In order to match the result of the COOLE profile an unrealistic crustal V_p of 5.75 km s^{-1} should be used in the grid search for at least four stations in central Ireland (IA003, IA004, D37, IAD18), so the trade-off effect between V_p and crustal thickness can be ruled out as an explanation for this difference, which is likely due to the difficulties in the identification of the *PmP*

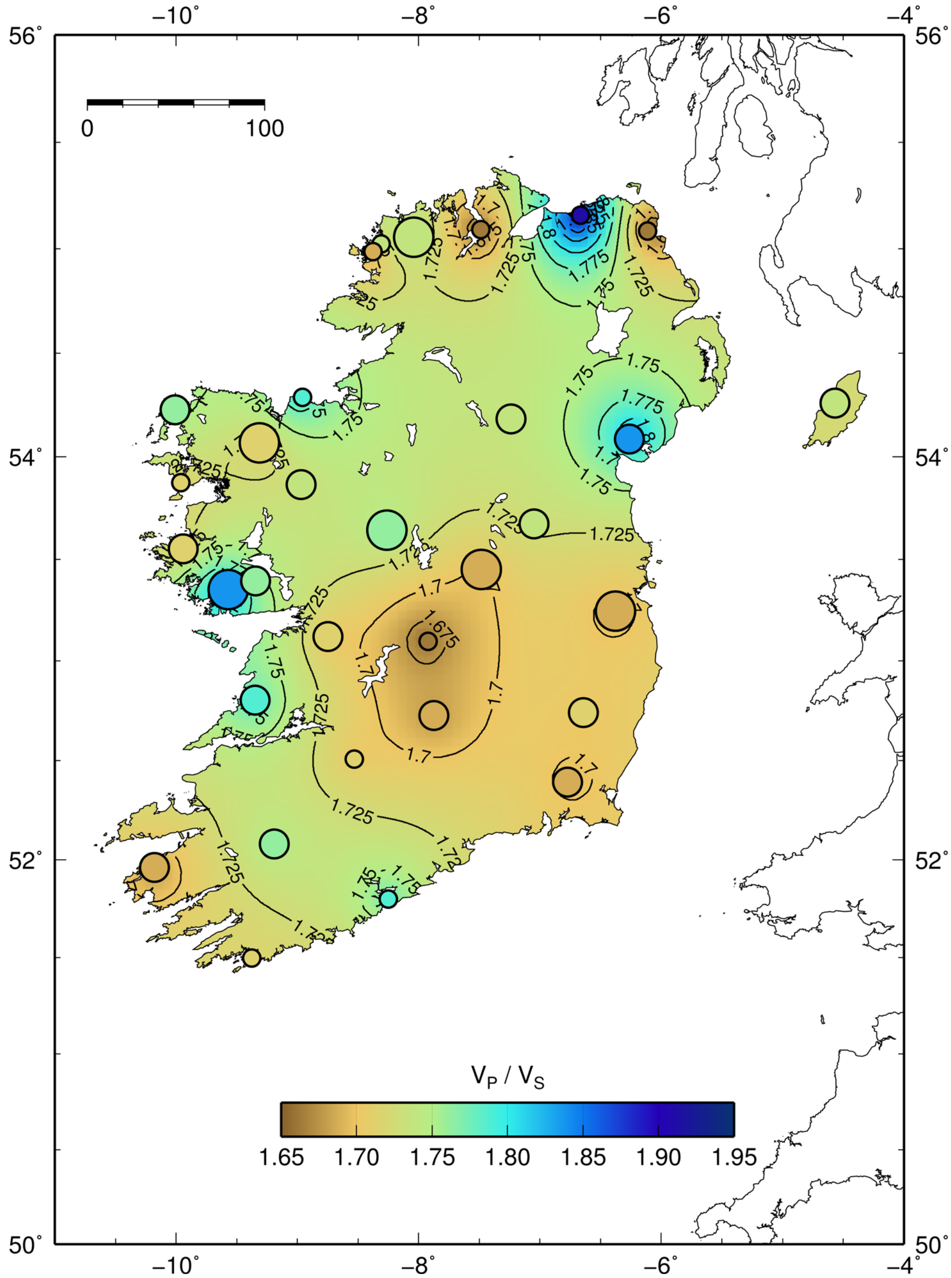

Figure 11. Interpolated map for V_p/V_s ratio in Ireland. Individual point measurements are those reported in Table 1 for V_p equal to $6.5\,\mathrm{km\,s^{-1}}$. Stations are indicated by circles with size proportional to quality.

(reflection from the Moho) and *Pn* (head-waves travelling across the crust–mantle boundary) phases, encountered by the authors Lowe & Jacob (1989).

The Leinster Granite Seismics (LEGS) is the latest onshore refraction experiment in Ireland and was carried out in 1999 (Hodgson 2001) to determine the dimensions and the extension of the Leinster granite batholith, SW of Dublin. Stations IWEX, IA012 and DSB are located on the trace of LEGS-A, one of the three profiles acquired during the experiment (Fig. 1). An acceptable agreement is achieved also from this comparison (Fig. 10d) especially for stations IA012 and DSB. IWEX results in a slightly deeper Moho than that observed over the LEGS-A experiment. The shallowing of the crust–mantle boundary towards the central part of the LEGS-A profile has been attributed to the emplacement history of the Leinster Granite by Hodgson (2001). Considering the errors associated with our estimates, this second-order feature is not well resolved, even though some similar trend is observed between IWEX and IA012. The value of 32 ± 0.3 obtained at station DSB compares well with those of Davis *et al.* (2012) and Shaw Champion *et al.* (2006) with 31.6 ± 1.7 km and with min/max values of 29.4/33.9 km, respectively.

In the northern part of Ireland, with the exception of the COOLE refraction line, not many constraints exist on our results, although the few available punctual measurements of Moho depth obtained with RFs have shown to be consistent with our findings (Fig. 10). Station GNP (located just 3 km away from D34) has been used in Davis *et al.* (2012) and Shaw Champion *et al.* (2006) give two distinct Moho depth estimates of 26.9 ± 1.2 km and 29.6/34.2 km, respectively, while D34 shows a value of 30.4 ± 0.6. This difference can be attributed to the small number of RFs used in the two previous studies ($N = 3$ and 4 RFs, respectively, where we used 80 RF for station D34).

Despite these small discrepancies in the comparisons, the crustal thickness estimates presented in this study have shown to provide robust constraints on the first-order Moho topography. The general good agreement with previous studies, gives good confidence to the results obtained where no other information exists, as in NNE and WNW of Ireland.

3.2 Variations of V_p/V_s ratio

Fig. 11 shows the interpolated map of V_p/V_s ratio across Ireland. Variations of the V_p/V_s ratio are in the range of 1.65–1.90 with mean value of 1.73 ± 0.05. The two extreme values are found at stations IA003 and D32, respectively, where a deep (≈34 km) and a shallow (≈ 23 km) Moho are also observed. We investigated the trade-off at these two stations (Figs 8 and S2) finding that, for station IA003 (poor quality), the range of plausible V_p/V_s is indeed close to the observed one (1.65), while for D32 picking the second maximum in the stacking function would give a V_p/V_s value between 1.78 and 1.84. Hence, the estimated values span the range of V_p/V_s observed with RFs in local and regional studies of the British Isle (1.65–1.88; Landes *et al.* 2006; Tomlinson *et al.* 2006; Di Leo *et al.* 2009; Davis *et al.* 2012) and more generally, those representative of crustal rocks (Christensen 1996). In this analysis, the inferred V_p/V_s at each station represents a bulk value for the entire crust, averaged over different crustal compositions and a separation between the effect of each compositional layer is difficult to extract. Moreover, single-station estimates are strongly affected by the local geological settings. The relationship between H and V_p/V_s can be examined as a function of different tectonic provinces to extract information about the evolution of the crust in the context of regional geodynamics (Chevrot & Van Der Hilst 2000). When only the good- and medium-quality stations are considered, the resulting clusters overlap but some robust features can be noted (Fig. 12), as for example, the

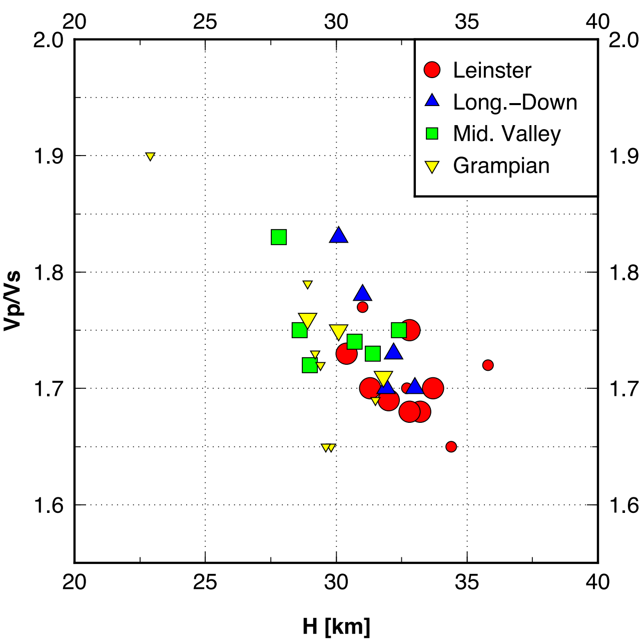

Figure 12. Measured H and V_p/V_s plotted with different colours for each of the four terranes in Ireland. Larger symbols are used for good- and medium-quality stations.

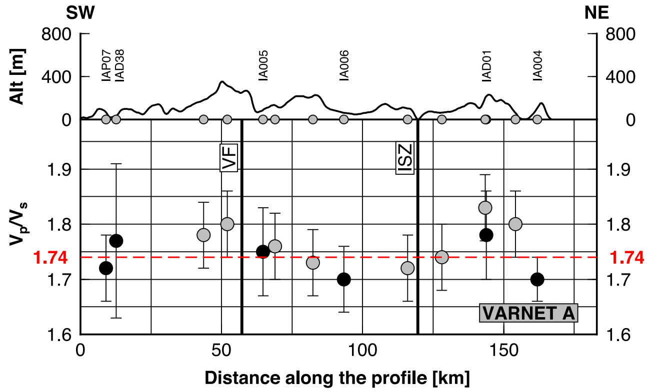

Figure 13. V_p/V_s profile along the trace of VARNET-A. Black circles, this study. Grey circles, Landes *et al.* (2006) from RFs. Errors are plotted as 2σ deviation. In dashed red a mean value of 1.74 can explain all the observed results.

general trend of increasing V_p/V_s when crustal thickness decreases, typical of the Phanerozoic tectonic provinces (Chevrot & Van Der Hilst 2000).

3.2.1 *Leinster*

The most robust feature in Fig. 12 is represented by the low V_p/V_s reported for stations in the Leinster domain with a representative mean of 1.70 ± 0.03, while crustal thickness is generally > 31 km except for IOMK, which shows a relatively lower value (≈30 km). This area is well constrained in terms of V_p/V_s from previous studies especially in SW Ireland (Landes *et al.* 2006; Hauser *et al.* 2008). The RF study of Landes *et al.* (2006) is colocated along the VARNET experiments in SW Ireland. When compared to the results of this study (Fig. 13), every observed variation is included in the 2σ error bars, indicating that a uniform value of 1.74 can easily explain the observations along the VARNET line. The V_p/V_s estimates for stations VAL, DSB and IOMK (Table 1) match those of Davis *et al.* (2012, ; V_p/V_s equals to 1.72 ± 0.03, 1.64 ± 0.02 and 1.70 ± 0.03, respectively) within the errors. Station GIM (on the Isle of Man) has been used also by Tomlinson *et al.* (2006) and gives a value of 1.68 ± 0.05 consistent with the estimate at IOMK. In the Leinster domain, despite the heterogeneous geological landscape (Fig. 1), the V_p/V_s ratio is low and fairly constant, showing a minor increase along the VARNET-A seismic line (Fig. 11).

3.2.2 *Longford-Down*

In the Longford-Down domain Moho depth decreases with increasing V_p/V_s, which ranges from 1.83 at IA008 to 1.70 for stations in central Ireland (IA004, D37) close to the ISZ (Fig. 9). In fact, despite the poor quality of stations IA006 and IA003, the cluster around the ISZ (IA006, IAD23, IA003, IA004 and D37) represents a region of very low V_p/V_s. This is in agreement with the trend observed on the southern side of the UK prosecution of the ISZ (Tomlinson *et al.* 2006; Davis *et al.* 2012). The mean V_p/V_s value in the Longford-Down is 1.75 ± 0.06 representative of a higher variability, compared to the Leinster domain. The lateral transition between IAD01 (1.78) and IA004 (1.70) corresponds to that observed by Landes *et al.* (2006) within the errors. No previous crustal V_p/V_s estimates are available north of the ISZ except for the few measurements carried out by Davis *et al.* (2012). Station IA010 can be directly compared with CKWD (1.73 ± 0.04) obtaining a close agreement. Stations IA008 has a higher V_p/V_s (1.83 ± 0.05) compared to SLNM (1.73 ± 0.02), however in the latter case, the estimate is based on less events (six) than this study (29). The composition of the lower crust in central Ireland is constrained by that of the Central Irish Xenolith Suite (CIXS; Van den Berg *et al.* 2005), with values of Poisson's ratio as low as 0.25 (V_p/V_s ≈1.73). This observation is in agreement with the first-order inferred low V_p/V_s values in central Ireland, however no vertical resolution is implied in our V_p/V_s measurements and a direct comparison is not possible.

3.2.3 Midland Valley

In the Midland Valley, the bimodal distribution for crustal thickness (Fig. 12) corresponds with higher variability in H north of the SUF described in the previous section (Fig. 6), while V_p/V_s is fairly constant over the whole terrane (mean value 1.74 ± 0.04) with the exception of D16 (1.83). No major variations in the mean V_p/V_s values are observed between the Longford-Down and the Midland Valley domain, although the V_p/V_s in the BTVP (norteastern part of the terrane) is not constrained due to the lack of seismic stations.

3.2.4 Grampian

Moving north of the HBF, a complex and heterogeneous pattern of V_p/V_s is observed and represented by a mean value of 1.74 ± 0.09. As discussed, the mean crustal thickness value is similar to the one observed in Connemara, with the exception given by D15. V_p/V_s estimates are strongly influenced by the local geological settings, and given the errors associated with the measurements and the low quality of many of the stations here, a clustering of values is very difficult. The bulk crustal composition is however similar to that of the Midland Valley, if stations IDGL and CLGH are excluded given their strong trade-off on V_p/V_s. Considering the second maximum of the stacking function at station D32, the resulting V_p/V_s of about 1.80 is strongly influenced by the presence of Cenozoic basalts belonging to the Northern Ireland portion of the BTVP. The only constraint of V_p/V_s in this area is given by the estimate obtained with just three RFs at station GNP (1.86 ± 0.02; Davis *et al.* 2012), while our closest station, D34 (good quality, 80 RFs) shows a lower V_p/V_s of 1.75 ± 0.03, which is supported by the surrounding IA011 (1.73 ± 0.04) and UCRUI (1.69 ± 0.06), although with less events and lower quality.

4 DISCUSSIONS

In this work, we tried to expand the present-day information about crustal thickness and V_p/V_s ratio in Ireland exploiting the recent improved seismic coverage of the island, with the aim of mapping the first-order structure of the crust on a regional scale. Although the $H - V_p/V_s$ stacking method used in this study suffers from a number of limitations, it assures robust, punctual estimates of mean crustal thickness and V_p/V_s ratio in regions with simple Moho geometries. As shown in the previous sections, our results are in broad agreement with a number of onshore seismic studies carried out in Ireland, and add new insights in areas where no information was previously available. The hypothesis of a Moho characterized by a regional-scale simple geometry in Ireland is widely accepted by many authors (Lowe & Jacob 1989; Landes *et al.* 2005) and is in agreement with the results of this study. A mean value of 30.9 ± 2.3 km is representative of the regional crustal thickness although some lateral smooth variations exist (Figs 6 and 7).

A general smooth S–N trend of crustal thinning has been observed in this study with depths varying between 33 and 28 km on average. In particular, we identified two different patterns of Moho depth variation geographically separated by the SUF. The first one in the southern portion of Ireland consists of a nearly flat Moho at a depth of 32–33 km. The second, is confined to the northern part of the island and is represented by a relatively higher spatial frequency variation in Moho topography with depths in the range 28–32 km. Locally, two areas of thinned crust have been observed along the northern portion of the W and NE coasts. Anisotropic Rayleigh-wave tomography of Ireland (Polat *et al.* 2012) has shown an NE–SW fast-propagation direction in the middle to lower crust, which corresponds to the main structural Caledonian trend in Ireland and something similar has been observed with *SKS* splitting measurements (Do *et al.* 2006). These observations led to the idea that the Irish crust remained stable since the early Carboniferous (O'Reilly *et al.* 2012). If this concept is extended to the crust–mantle boundary, then the observed slight changes in crustal thickness must be ascribed to differences due to the Caledonian orogeny. This is in agreement with our observation of two different patterns of Moho variation divided by the SUF (Figs 7a and b), implying that the latter represents a major discontinuity in the crustal structure of Ireland. In this view, the relatively higher variability in crustal thickness north of the SUF, reflects the multiphase nature of terrane accretion during the Caledonian orogeny suggesting that the Moho partly preserved its original features although rather smoothed. No first-order changes in Moho depth have been observed directly across the ISZ, as is proposed by the interpretation of the COOLE experiment (Fig. 10c). In this study, a broad, smooth and transitional region between Avalonian (32–33 km Moho depth) and Laurentian (28–30 km) domains can be imaged between the ISZ and the SUF in central Ireland (Fig. 7a) and possibly up to the HBF moving to the NW from IWEX to D15 (Fig. 6). The former feature spatially corresponds to the 'crustal deformation zone' identified as a region of low resistivity at middle to lower crustal depth (Rao *et al.* 2007) and characterized by a series of SSE dipping reflectors by Lowe & Jacob (1989) at the same depths. In the model proposed by O'Reilly *et al.* (2012), soon after the continental collision (Acadian phase) the small amount of shortening in a transpressional (sinistral) regime induced the formation of horizontal cracks developed in the uppermost brittle mantle, suddenly intruded by mafic magma coming from a small amount of partial melting of the subducted lithosphere. The symmetric (with respect to the proposed trace of the ISZ) pattern of 32–33 km in Moho depth identified in this study, is consistent with this hypothesis and identifies the broad region around the ISZ as the one where the higher amount of crustal and lithospheric shortening occurred in the Acadian phase. The smooth SW–NE transition to the Laurentian margin pattern in Moho depth (28–30 km) observed in Fig. 7(a) indicates that the intensity of this process decreases northeastwards in agreement with a sinistral transpressional regime. The Moho depth variations observed across the Galway Bay, however, are relatively less smooth, possibly indicating that here the Moho represents an older feature, although smoothed, related to the accrection of a forearc basin and an island arc with the related obduction of an ophiolite complex over the margin of Laurentia in the Grampian phase (Chew *et al.* 2010; Hollis *et al.* 2012).

An alternative explanation of our results might consider the geodynamic evolution of Ireland during the Mesozoic. The Mesozoic hyperextension regime and the related lithospheric thinning that affected the western margin of Europe (Woodcock & Strachan 2000; O'Reilly *et al.* 2006; Davis *et al.* 2012) could have played a role in the observed thinning of the crust onshore Ireland, in particular could explain the retrieved estimates for the cluster of station along the W coast. In this case, the differential stretching that led to the formation of the Rockall Trough (Hauser *et al.* 1995) and to the thinned crust observed offshore by the WIRE1 (Klemperer *et al.* 1991) and RAPIDS (O'Reilly *et al.* 1995) reflection profiles had an effect also on the north-westernmost part of continental Ireland. This effect did not involve however, the more internal part of the island where stations D15 and IA009 (further inland) show a Moho 3–4 km deeper than that along the coast. However, the more recent Mesozoic extension would have overprinted the older Caledonian trend resulting in an NW–SE orientation of the anisotropic fast axis in the crust. This does not match the observations reported by Polat *et al.* (2012) although along the north part of the W coast the coverage is limited to two stations, one of which being D15, does not show a thinned crust in this study.

An anomalous value for H ($\approx$23 km) is observed at station D32, which is located in Northern Ireland in the BTVP. The surrounding stations IDGL and CLGH give estimates of 29.6 $\pm$ 2.9 and 29.8 $\pm$ 0.4 km, respectively. However, a bimodal distribution of the stacking functions is observed at stations D32 and IDGL suggesting the presence of two interfaces located at 22–24 km and 27–29 km. The reflection Moho map of Chadwick & Pharaoh (1998) reports values of 26–27 km for the North Channel between Northern Ireland and Scotland with a NW trend of crustal thinning. A zone of relatively thinned crust in this area is also confirmed by the Moho depth map of Kelly *et al.* (2007) and by the results from the RF study of Davis *et al.* (2012), where north of the HBF in Scotland, values of Moho depth <27 km have been observed. The presence of a high-velocity layer of magmatic underplated material at the base of the crust and related to the activity of the proto-Icelandic plume has been invoked by Tomlinson *et al.* (2006) to explain discrepancies in the order of 7 km between their RF Moho depth estimates and the refraction Moho of the LISPB profile (Barton 1992). In this case a high-velocity contrast between the top of this layer and the above lower crust could lead to an underestimation of the actual crustal thickness from RFs. Here we propose the same explanation for the results at D32 and IDGL suggesting the presence of a 5- to 6-km-thick high-velocity layer just above the Moho which pinches out to the west as this feature is not observed at station D34 (good quality and Moho depth of $\approx$30 km). At station CLGH, a broad *Ps* Moho pulse is observed from some BAZ and a stronger $H - V_p/V_s$ trade-off exists in the grid search, so the extension to the east of this layer is more ambiguous. However this interpretation remains speculative as is not uniquely constrained by the $H - V_p/V_s$ stacking method used in this study.

The V_p/V_s ratio of the rocks at depth is strictly related to their intrinsic mineralogical composition (Christensen 1996). For rocks with $SiO_2 > 55$ per cent a linear relationship between SiO_2 content and V_p/V_s (Poisson's ratio, σ) exists (Christensen 1996). Previous estimates in the British Isles have shown that little variation in crustal V_p/V_s occurs and that the mean value is generally between 1.73 and 1.75 (Assumpção & Bamford 1978; Tomlinson *et al.* 2006; Hauser *et al.* 2008; Di Leo *et al.* 2009; Davis *et al.* 2012; O'Reilly *et al.* 2012), smaller than the mean global average for the continental crust of 1.768 (Christensen & Mooney 1995; Christensen 1996). Our mean value of 1.73 ± 0.05 confirms this view, even if the spatial distribution of values is not homogeneous (Fig. 11). The composition of the lower crustal samples of the CIXS gives a constraint over the amount of SiO_2 in the lower part of the crust in Central Ireland. These xenoliths consists mainly of metapelites, with σ as low as 0.25 ($V_p/V_s = 1.73$; Van den Berg *et al.* 2005). Seismic studies on V_p/V_s in SW Ireland have been correlated with the CIXS by Hauser *et al.* (2008) and have highlighted a silica-rich composition of the upper crust (SiO_2 $\approx$75 per cent) and a more silica-depleted lower crust (SiO_2 $\approx$64 per cent), which is however more felsic than the global average. In the 'incipient delamination' model proposed by O'Reilly *et al.* (2010, 2012) the high silica content inferred across the ISZ in the Irish crust is proposed to derive from the partial melting of the metapelitic accretionary wedge in the context of the Caledonian orogeny, and to the subsequent migration of a SiO_2-rich melt through the crust, leading to the emplacement of granites in the late Silurian–early Devonian. This model can explain the low V_p/V_s observed in the Leinster domain and around the ISZ in central Ireland (including stations IA004 and D37 belonging to the Longford-Down terrane) that corresponds to a granite–granodiorite composition of the crust (Christensen 1996). In addition, the distribution of low values in the Leinster domain and in central Ireland is geographically well correlated with the location of a broad negative Bouguer anomaly associated with the Leinster batholith and with its buried extension towards the SW, and with a smaller negative anomaly in central Ireland (the Central Midland low; Readman *et al.* 1997). The slightly higher V_p/V_s in the SW match the observations of Landes *et al.* (2006) and those of Hauser *et al.* (2008). Averaging their vertical distribution of V_p/V_s over the entire crust an increasing trend from S to N is obtained along the VARNET-A line, from 1.72 south of the VF to 1.74 at the VF and 1.75 north of the ISZ. Stations IAP07, IA005 and IAD01 are representative of this trend, while IA006 and IA004 (more to the east) show slightly lower V_p/V_s values ($\approx$1.70), more similar to the Leinster domain cluster. This is also in agreement with the pattern in gravity anomalies observed in this region by Readman *et al.* (1997) with a S–N trend of increasing Bouguer anomalies along the VARNET-A profile. In the context of the 'incipient delamination model', this would imply either a higher amount of SiO_2 in the middle to upper crust or a thinner lower crust in central Ireland compared to the SW. However, a thick gradational crust–mantle transition is inferred in central Ireland (Fig. 9), which is consistent with the highly reflective lower crust observed in the seismic experiments and described by O'Reilly *et al.* (2012). Therefore, a plausible conclusion is that melting of the accretionary wedge must have been more intense in central Ireland with respect to the SW. The elliptical negative anomaly described by Readman *et al.* (1997) in the extreme SW of Ireland, correlates well with the low V_p/V_s at station VAL (1.68) although the large errors of this estimate. This anomaly has been interpreted either as a thicker wedge of Devonian sediments or as a granite body related to the Leinster batholith (see Readman *et al.* 1997, and references therein). This is difficult to discriminate as both the arguments can explain the observed low V_p/V_s. The Longford-Down and the Midland-Valley terranes show very similar bulk crustal composition with averaged values of 1.74 $\pm$ 0.05 and 1.75 $\pm$ 0.04, which resemble the experimental value for metagraywacke (Christensen 1996). This can reflect a different composition of the original rocks building this section of the accretionary complex with an increased contribution of mafic minerals or again a weaker contribution from partial melting with respect to region around the ISZ in central Ireland. This is difficult to unravel, as no constraints exist in this part of the island on the vertical distribution of V_p/V_s. Moreover, the resulting averaged values for these two domains are affected by local geology, which can contribute to the higher observed V_p/V_s. In the Longford-Down terrane, for example, IA008 sits on top of the Tertiary volcanic centres of Slieve Gullion and Carlingford where the gabbroic component of the igneous complex can explain the observed values of 1.83 $\pm$ 0.05 (Christensen 1996), which also corresponds to a positive Bouguer anomaly (Readman *et al.* 1997). In Connemara, rock formations with very different low and high V_p/V_s ratio, such as quartzite (1.502), granites (1.710), marbles (1.841) and gabbros (1.858; Christensen 1996), crop out one near-by the other and can give rise to the observed heterogeneous distribution of results, in contrast to the more uniform values of stations (IA009,IAD18 and IAD33) located more to the east (Fig. 11). As pointed out in the previous section, although in the Grampian domain the mean V_p/V_s value resembles those observed in the Midland-Valley and in the Longford-Down domains, the low quality of most of the stations does not allow to robustly constrain the bulk crustal composition, which therefore will not be discussed further.

5 CONCLUSIONS

We have presented a regional RF study on 34 broad-band stations uniformly distributed across Ireland. By applying the $H - V_p/V_s$ stacking method (Zhu & Kanamori 2000), we retrieved the first-order crustal properties, thickness and V_p/V_s, and we examined their variations across the major terrane boundaries in the island. Interpolation of single-station estimates results in the first available Moho depth and V_p/V_s maps for Ireland based on a uniform distribution of measurements. In general a good agreement has been found with previous studies where available, and we added new information in poorly constrained areas, such as in the northern part of the island. The main findings of this study are summarized in the following points:

(1) The crust in Ireland is 30.9 ± 2.3 km thick on average with a smooth S–N trend of crustal thinning (from 32–33 km to 28–29 km).

(2) The mean V_p/V_s ratio is 1.73 ± 0.05. A consistent pattern of low V_p/V_s ($\approx$1.70) is found in the Leinster domain and in central Ireland where the crust is more silica-rich than in the northern terranes.

(3) No major crustal thickness variations are observed across the ISZ where, however the presence of a gradational crust–mantle boundary is suggested in central Ireland.

(4) The region south of the SUF is characterized by a nearly flat Moho at a depth of 32–33 km, while to the north a relatively higher spatial frequency variation exists in Moho topography with two areas of relatively thinned crust (28–30 km) along the northern part of the W and the NE coasts. These two patterns of variation reflect the multiphase nature of terrane accretion during the Caledonian orogeny, although rather smoothed.

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SUPPORTING INFORMATION

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

Figure S1. $H - V_p/V_s$ stacks for all the stations considered in this study. Grey scale is the amplitude of the stacking function expressed as percentage of the absolute maximum value. Contours are drawn every 20 per cent starting from 10 per cent. The red star represent the maximum of the stacking function for $V_p = 6.5\,\mathrm{km\,s^{-1}}$.

Figure S2. $H - V_p = V_s$ stacks over a broader range of parameters for stations CLGH, D32, IA003 and IDGL which had the maximum value over the edge of the parameter space. Stars represent the max values of $S(H, V_p = V_s)$ for V_p equal to 6.25 (yellow), 6.50 (red) and 6.75 (blue) $\mathrm{km\,s^{-1}}$. Each green dot is the result of a single bootstrap iteration from which vertical and horizontal bars (1σ confidence interval) are calculated and plotted only for $V_p = 6.5\,\mathrm{km\,s^{-1}}$.

Table S1. Location of the stations used in this study, quality (Q_u) and results of the grid search (H and V_p/V_s) with the associated errors for three tested V_p (6.25, 6.50 and 6.75 $\mathrm{km\,s^{-1}}$) (http://mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/gji/ggu277/-/DC1).

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