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Seismicity of Ireland, and why it is so low: How the thickness of the lithosphere controls intraplate seismicity

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SUMMARY

Ireland and neighbouring Britain share much of their tectonic history and are both far from active plate boundaries at present. Their seismicity shows surprising lateral variations, with very few earthquakes in Ireland but many low-to-moderate ones in the adjacent western Britain. Understanding the cause of these variations is important for our understanding of the basic mechanisms of the intraplate seismicity distributions and for regional hazard assessment. The distribution of microseismicity within Ireland and its underlying causes have been uncertain due to the sparsity of the data sampling of the island, until recently. Here, we use the data from numerous recently deployed seismic stations in Ireland and map its seismicity in greater detail than previously. The majority of detectable seismic events are quarry and mine blasts. These can be discriminated from tectonic events using a combination of the waveform data, event origin times, and the epicentres' proximity to quarries and mines, catalogued or identified from the satellite imagery. Our new map of natural seismicity shows many more events than known previously but confirms that the earthquakes are concentrated primarily in the northernmost part of the island, with fewer events along its southern coast and very few deeper inland. Comparing the seismicity with the recently published surface wave tomography of Ireland and Britain, we observe a strong correspondence between seismicity and the phase velocities at periods sampling the lithospheric thickness. Ireland has relatively thick, cold and, by inference, mechanically strong lithosphere and has very few earthquakes. Most Irish earthquakes are in the north of the island, the one place where its lithosphere is thinner, warmer and, thus, weaker. Western Britain also has relatively thin lithosphere and numerous earthquakes. By contrast, southeastern England and, probably, eastern Scotland have thicker lithosphere and, also, few earthquakes. The distribution of earthquakes in Ireland and Britain is, thus, controlled primarily by the thickness and mechanical strength of the lithosphere. The thicker, colder, stronger lithosphere undergoes less deformation and features fewer earthquakes than thinner, weaker lithosphere that deforms more easily. Ireland and Britain are tectonically stable and the variations in the lithospheric thickness variations across them are estimated to be in a 75–110 km range. Our results thus indicate that moderate variations in the lithospheric thickness within stable continental interiors can exert substantial control on the distributions of seismicity and seismic hazard—in Ireland, Britain and elsewhere around the world.

Key words: Europe; Seismicity and tectonics; Seismic tomography; Surface waves and free oscillations; Dynamics of lithosphere and mantle; Intra-plate processes.

1 INTRODUCTION

Most of the Earth's seismicity occurs either at plate boundaries or in areas of pervasive lithospheric deformation (Gutenberg & Richter 1949; Engdahl *et al.* 2020), the latter often considered diffuse plate boundaries (Gordon 1998). Stable continental areas—those largely unaffected by currently active plate-boundary processes—undergo little deformation and feature low seismicity rates. Notable exceptions, such as the 1811–1812 sequence of *M*7–8 earthquakes in the New Madrid Seismic Zone, central United States (e.g. Johnston

1996) or the M7–8 palaeoearthquakes in the Fennoscandian Craton at 9–11 ka (e.g. Muir-Wood 1989a), are rare but highlight the importance of understanding the seismicity in the low-strain regions.

1.1 Seismicity in stable continental regions

Tectonic stress in the stable continental lithosphere is produced by the transmission of plate-boundary stresses into the plate interior, by the forces exerted upon the lithosphere by the convecting sublithospheric mantle, and by the lateral variations of the surface elevation and lithospheric density (Zoback & Zoback 1989; Bird *et al.* 2008; Becker *et al.* 2015; Calais *et al.* 2016). The tectonic stress varies slowly in time and smoothly in space, due to the gradual variations in the underlying processes (e.g. Calais *et al.* 2016). Most of the central and eastern North America, for example, is characterized by NE to ENE orientation of maximum horizontal compression, coinciding with the absolute plate motion and ridge-push directions for North America (Zoback & Zoback 1989).

In western Europe—north of the Alps and Pyrenees and south and southwest of Scandinavia—the dominant large-scale stress pattern shows a NW–NNW orientation of maximum horizontal compression, roughly parallel to the relative plate motion of Africa with respect to Eurasia and to the ridge push from the Mid Atlantic Ridge (Müller *et al.* 1992; Heidbach *et al.* 2007). The prevailing tectonic stress pattern in western Europe is thus controlled by plate boundary forces—the North Atlantic Ridge push and the compression associated with the Africa–Europe collision (Müller *et al.* 1992).

The correlation of stress orientations and plate motions indicates that the first-order intraplate stress patterns are the result of the same forces that drive plate motions (Sykes & Sbar 1973; Heidbach *et al.* 2007). Second-order and transient patterns can modify the stress field at regional scales. These patterns can result from regional variations in the lithospheric structure and strength, deglaciation or lithospheric flexure (e.g. Sykes 1978; Muir-Wood 1989a; Heidbach *et al.* 2007; Calais *et al.* 2016).

The tectonic loading in stable regions gives rise to strain accumulation that is slow but sufficient to maintain low-magnitude seismicity. Many stable continental regions show scattered low-to-moderate-magnitude earthquakes, whereas others show little seismic activity (e.g. Schulte & Mooney 2005). The rare large earthquakes in these regions do not follow the recurrence patterns typical of the plate-boundary settings and may be due to transient perturbations of local stress or fault strength—including glacial, hydrological or sedimentary load change or the fluid pore pressure increase at seismogenic depths—releasing elastic energy from a pre-stressed lithosphere (Calais *et al.* 2016). The transient perturbations, along with the long-term tectonic loading, can also affect the occurrence and distribution of low-magnitude seismicity.

1.2 Seismicity and lithospheric thickness and strength

Pervasive deformation of the lithosphere occurs primarily where the mantle lithosphere is thin, warm and, thus, mechanically weak (e.g. Kusznir & Park 1984; Burov & Diament 1995; Liu & Zoback 1997). Even though the mantle lithosphere in these locations is warm, the upper crust above it is cooled from the Earth's surface and is sufficiently cold and brittle to host a seismogenic layer of, typically, around 15 km thick. Deformation within the seismogenic layer produces earthquakes. Strongly deforming areas in southern Europe, for example, including the Aegean region and much of Italy, have warm, thin lithosphere (e.g. Tesauro *et al.* 2009; Pasyanos *et al.* 2014; El-Sharkawy *et al.* 2020) and feature high seismicity rates (Fig. 1).

At the opposite end of the spectrum, stable cratons have thick, cold and mechanically strong lithosphere. The East European Craton in eastern and northern Europe, for instance, has thick, cold lithosphere (e.g. Legendre *et al.* 2012; Artemieva 2019), undergoes little deformation and shows very low seismicity (Fig. 1). Comparisons of global seismicity and lithospheric seismic velocities, taken from tomographic models, confirm that the seismicity rates in continental intraplate regions are correlated with the seismic velocities within them, with the thick, cold and strong lithosphere of cratons showing the highest seismic velocities and the lowest seismicity (Mooney *et al.* 2012).

Relatively subtle lithospheric strength variations—away from the end members of the thick, stable cratonic lithosphere and areas of pervasive active deformation—can also have a strong effect on seismicity. In the central Aegean Sea, for example, the lithospheric block beneath the Cyclades Islands has—at present—a thinner crust and a thicker, colder and, by inference, stronger mantle lithosphere, as evidenced by higher seismic velocities, compared to that of the northern Aegean Sea (e.g. Endrun *et al.* 2008, 2011; Tirel *et al.* 2013). This matches the much lower distributed seismicity in the Cyclades compared to that in the neighbouring northern Aegean (e.g. Papazachos 1990; Tirel *et al.* 2004).

The thickness and temperature of the mantle lithosphere—in other words, the local geotherm—were shown to have an effect on the thickness of the seismogenic layer (Maggi *et al.* 2000; Jackson *et al.* 2021), which triggered a stimulating debate on the vertical distribution of the mechanical strength of the lithosphere at different temporal and spatial scales (Jackson 2002; Handy & Brune 2004; Burov & Watts 2006; Schmalholz *et al.* 2009). The local geotherm also has an effect on the total deformation of the lithosphere: thicker, colder and, thus, mechanically stronger lithosphere is likely to deform less and, thus, feature weaker seismicity compared to thinner, warmer and mechanically weaker lithosphere. It is this relationship—between the lateral variations in the lithospheric strength and those in the rates of deformation and seismicity—that is of primary importance in this study.

1.3 Ireland and Britain

Ireland and Britain lie near the stable western margin of Eurasia (the margin itself is delineated by the bathymetry contrast halfway from Ireland and Britain to Iceland, which indicates a change from stretched continental to oceanic crust, Fig. 1). They were formed in the Caledonian Orogeny in the course of the assembly of the supercontinent Pangea (McKerrow *et al.* 2000; Woodcock & Strachan 2000; Holland & Sanders 2009). The associated closure of the Iapetus Ocean is recorded in the NE–SW structural trends that feature prominently in the tectonic set-up of Ireland and Britain (Phillips *et al.* 1976; Chew 2009; Chew & Stillman 2009; Fig. 2). Lithospheric stretching and hyperextension in the submerged basins west and northwest of Ireland occurred in the course of the protracted, late Palaeozoic–Mesozoic breakup of Pangea (O'Reilly *et al.* 2006; Naylor & Shannon 2011). Stretched continental lithosphere now extends a few hundred kilometres west and northwest of Ireland and Britain, beneath the Northeast Atlantic Ocean. Further west and northwest, the oceanic lithosphere of the NE Atlantic basin was created by the seafloor spreading that started in the late Cretaceous and was accompanied by the development of volcanic continental margins in the early Cenozoic (Vogt *et al.* 1998). The Iceland

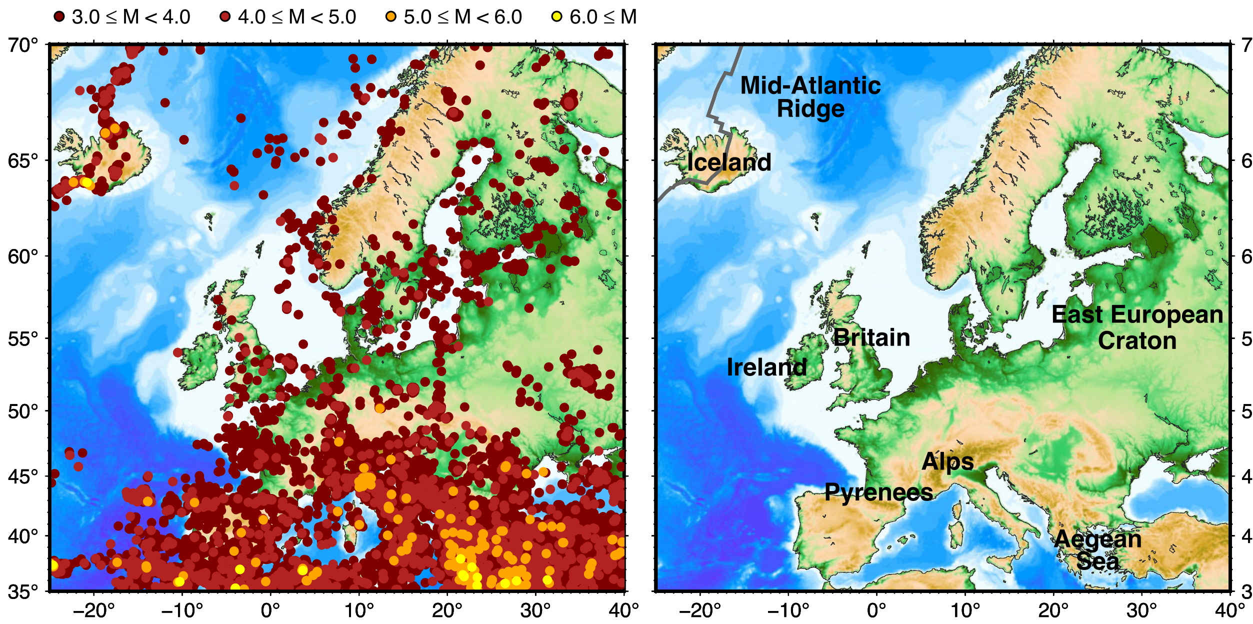

Figure 1. Seismicity map of Europe, showing earthquakes with magnitude $M \geq 3.0$, according to the International Seismological Centre (ISC) catalogue (Storchak *et al.* 2020).

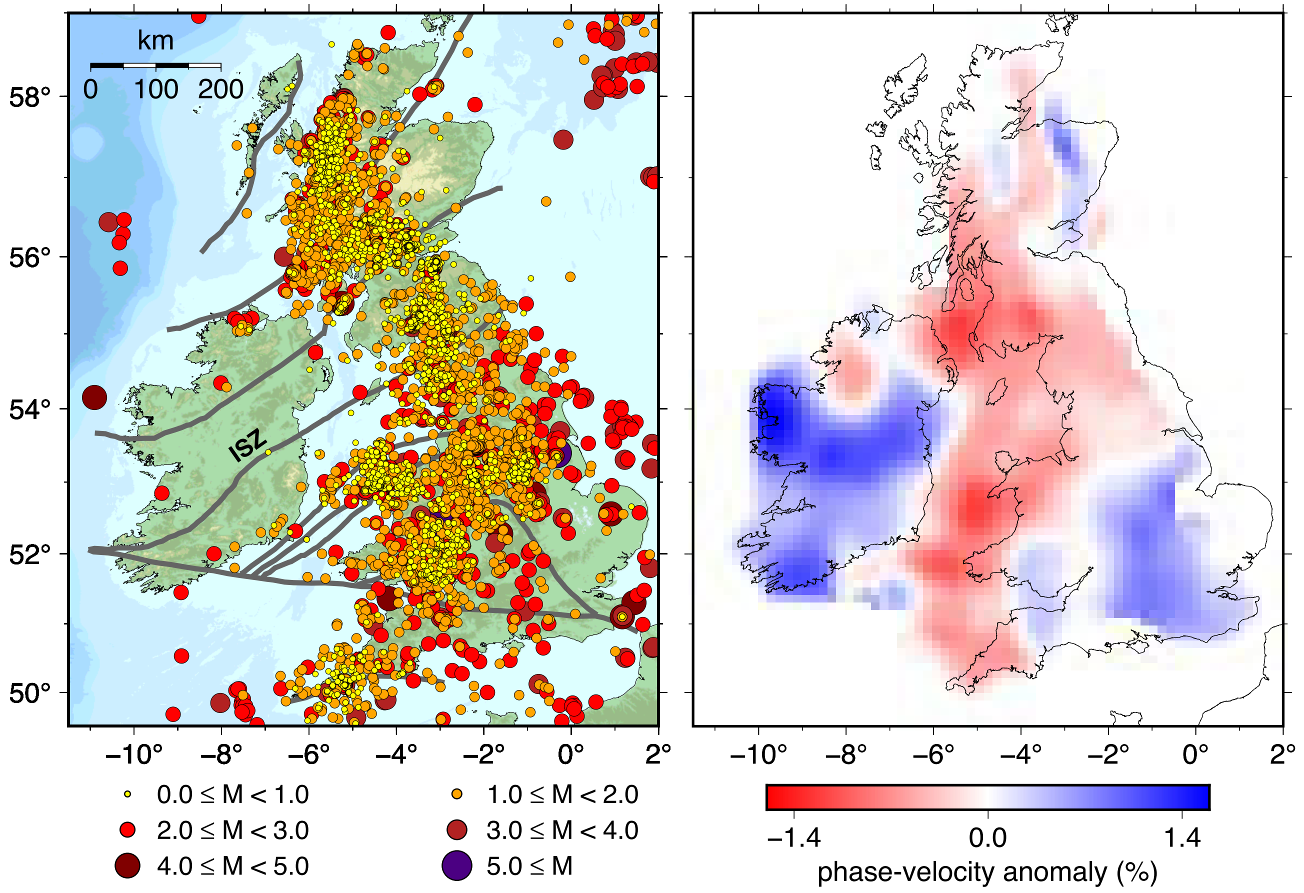

Figure 2. Left-hand panel: seismicity of Ireland and Great Britain according to the BGS seismicity catalogue (e.g. Baptie 2018). The grey lines show major geological boundaries (after Tomlinson *et al.* 2006), including the Iapetus Suture Zone (ISZ, e.g. Holland & Sanders 2009). Right: phase velocities of Rayleigh surface waves at a 64 s period (Bonadio *et al.* 2021). Phase-velocity anomalies are relative to the 4.03 km s^{-1} regional average. Rayleigh waves at the period sample primarily the 60–130 km depth range (e.g. Lebedev *et al.* 2013), and the phase velocities reflect variations in the lithospheric thickness, with higher velocities indicating thicker lithosphere. High velocities across much of Ireland and within the London-Brabant Platform in the southeast of Great Britain indicate thicker, colder and stronger lithosphere.

Plume activity in the early Cenozoic is thought to have caused uplift, volcanism and magmatic underplating in Ireland, Britain and surroundings (White & Lovell 1997).

The NE–SW tectonic boundaries, including the Iapetus Suture Zone, extend continuously from Ireland to Britain across the Irish Sea. This reflects a shared tectonic history of the islands but does not necessarily imply the same structure of the deep crust or the mantle lithosphere. The crustal thickness in Ireland shows mild variations around 30 km, known from controlled source profiles and passive seismic data (e.g. Landes *et al.* 2005; Kelly *et al.* 2007; Licciardi *et al.* 2014; Bonadio *et al.* 2021). Beneath Great Britain, the crustal thickness is somewhat greater, on average, and more variable, ranging between 30 and 36 km beneath most of the island (e.g. Kelly *et al.* 2007; Baykiev *et al.* 2018; Licciardi *et al.* 2020).

The thickness of Ireland's and Britain's lithosphere was long assumed to be relatively uniform, mostly due to the lack of evidence to the contrary. In a departure from this view, Landes *et al.* (2007) proposed a model in which Ireland's lithosphere thinned from 85 km in the south to as little as 55 km in the north, based on the analysis of *S*-wave receiver functions from an array in southcentral Ireland. Fullea *et al.* (2014) used gravity and elevation data to build a lithospheric model of Ireland that showed lithospheric thickness variations in the 75–110 km range, with the thinnest lithosphere in the north of the island. In agreement with this pattern, the greatest surface heat flow and the shallowest Curie depth values are also mapped in the north of the island (Mather & Fullea 2019).

The recent growth in the number of broad-band seismic stations, in particular in Ireland, yielded data for more detailed and accurate imaging of the lithosphere than possible previously. Surface wave tomography (e.g., Zhang et al. 2009) exploits the waves' strong sensitivity to the lithospheric structure and is particularly suitable to image it. Surface-wave tomography of Ireland and Britain using the recently collected data from networks across Ireland and Britain has revealed surprisingly strong lateral variations in their lithospheric thickness (Bonadio *et al.* 2021, 2023), with relatively thick lithosphere beneath most of Ireland, except for its northern part, and beneath southeastern Britain.

1.4 Seismicity of Ireland and Britain

Both Britain and Ireland have relatively low seismicity, compared to many other areas in Europe (Fig. 1). Seismicity of Ireland is particularly low, and the fact that it is so much lower than in neighbouring Britain is surprising. This contrast has been long recognised based on historical seismicity (O'Reilly 1884; Davison 1924; Richardson 1975; Musson 1996; Baptie *et al.* 2016). The global seismicity map of Mallet & Mallet (1858)—pre-instrumental and compiled based on reports of felt earthquakes—showed relatively low seismicity in Britain and lower, yet, in Ireland (see, also, this map reproduced by Beroza & Kanamori 2015). O'Reilly (1884) catalogued historical earthquakes in Britain and Ireland, 1426–1880, and compiled his 'Earthquake map of the British Islands,' using colour to represent geographical variations in the frequency of the earthquake occurrence. He reported that Great Britain was by far more subject to earthquake activity than Ireland. As an explanation for this contrast, he proposed the existence of barriers (in modern terms, major faults) between them, 'preventing the extension of earthquake action from Great Britain to Ireland.' An alternative explanation he proposed was the absence, beneath Ireland, of 'active foci capable of producing earthquakes in the present geological order of things.'

Gutenberg & Richter (1949) discussed the minor seismicity of the Caledonian areas in Europe and reasoned that 'it is highly improbable that these shocks represent any persistence of the Caledonian orogeny to the present time. Stresses of more recent origin have produced fractures in the Caledonian mass, or have rejuvenated old faults of Caledonian age'.

Over the last few decades, synthesis of growing geophysical datasets in the framework of plate tectonics showed how the large-scale regional stress patterns are shaped by plate-boundary forces (Sykes & Sbar 1973; Müller *et al.* 1992; Heidbach *et al.* 2007). With Ireland and Britain much closer to each other than their distance from any plate boundaries, the dominant tectonic stress patterns in both are likely to be similar. Numerous faults have been mapped in both Britain and Ireland, but there are no indications in the seismicity or geodetic data for substantial slips on any faults between the two islands that would decouple their deformation (e.g. Anderson *et al.* 2018; Rodríguez-Salgado *et al.* 2020). Thus, in spite of the progress in our understanding of the regional crustal structure and tectonic stress and of the seismogenesis in general, a conclusive explanation of Ireland's surprisingly low seismicity rate has remained elusive.

The seismicity map of O'Reilly (1884) was intended to bring out new geological relations, complementary to the maps of the geological formations. In general terms, this remains an important goal today. As we show in this paper, it is the lateral variations in the thickness and temperature and, therefore, the mechanical strength of the lithosphere that are likely to control the lateral distribution of seismicity in Ireland and Britain. The lithospheric strength is related to the processes of the evolution of the islands, in the sense that the thicker lithospheric blocks with the greatest mechanical strength may have been incorporated into the landmass during its assembly. The lithospheric thickness variations, however, cannot be inferred from the geological formations seen at the surface, and this has obscured their relationship to seismicity rates up until now.

Although the low level of seismicity in Ireland is well known, the abundance and distribution of micro-earthquakes ($M < 3.0$) has been uncertain due to a possible instrumental bias, with far fewer seismic stations deployed in Ireland compared to Britain, until recently. In recent years, however, the number of stations in Ireland has increased substantially.

This paper reports on the results of the Science Foundation Ireland-funded project 'Structure and seismicity of Ireland's crust' (2014–2018), whose first goal was to use the newly abundant data to establish the patterns of seismicity in Ireland more accurately than possible previously. Another goal was to analyse the seismicity in the context of new lithospheric imaging—which also used the newly available seismic data—and establish the causes for the surprisingly strong variations in the seismicity rates between and within Ireland and Great Britain.

2 DATA

Prior to 2010, there was one broad-band seismic station on the island of Ireland, the permanent station DSB near Dublin, operated jointly by the GEOFON network (GEOFON Data Centre 1993) and the Dublin Institute for Advanced Studies (DIAS). Another permanent station, VAL on Valentia Island, was wide-band (periods up to 30 s). A few short period stations were operated at different times in the Republic of Ireland (ROI) and Northern Ireland (NI) by DIAS and the British Geological Survey (BGS), respectively.

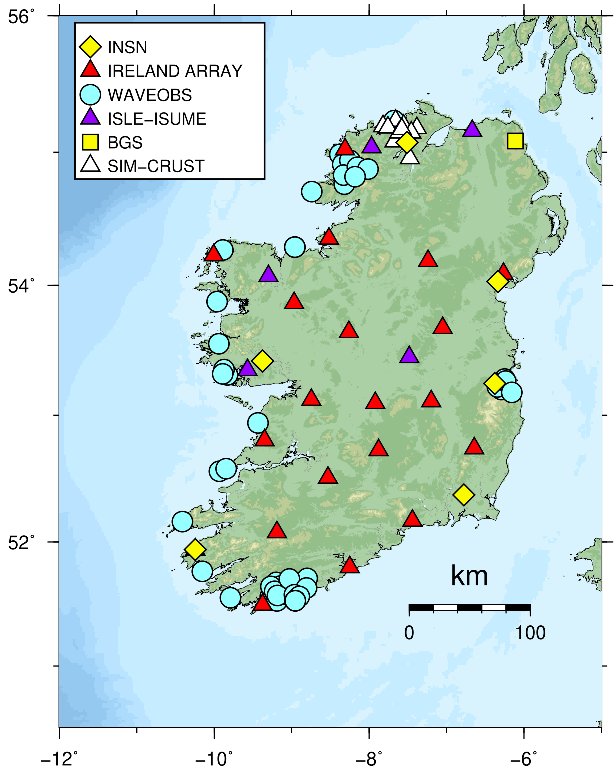

Figure 3. Seismic stations that operated in Ireland in 2010–2020. The Irish National Seismic Network (INSN 1993; Blake *et al.* 2012) comprised 6 permanent broad-band stations. Ireland Array (Lebedev *et al.* 2012, 2022) comprised 20 broad-band stations, most of them operating from their deployment in 2010–2012 to 2021–2022, and some of them changing their location once. The wideband stations of the ISUME (O'Donnell *et al.* 2011; Polat *et al.* 2012) and SIM-CRUST (Licciardi *et al.* 2014; Piana Agostinetti & Licciardi 2015) experiments operated for a few years each. The wideband stations of the WaveObs arrays (Möllhoff & Bean 2016) operated for periods from less than a year to a few years.

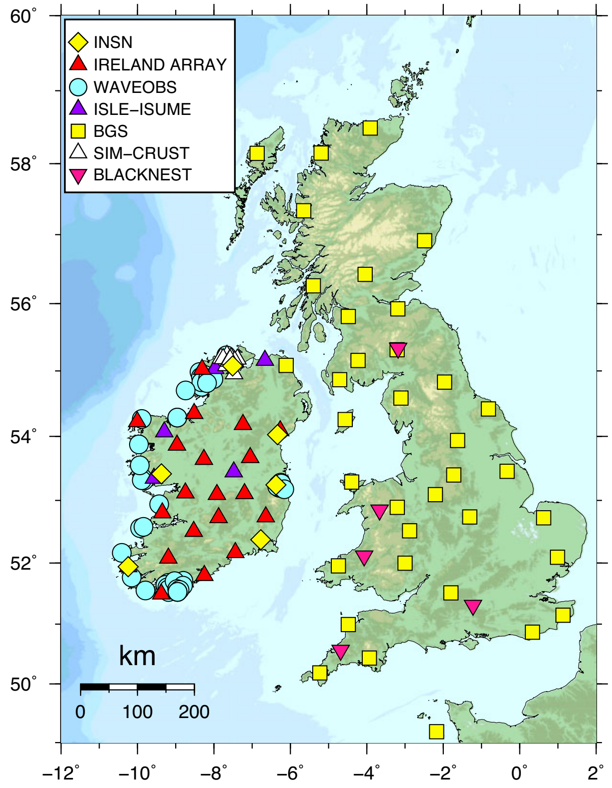

Figure 4. Seismic station coverage of Great Britain and Ireland. The broad-band stations in Great Britain belong to the United Kingdom network operated by the British Geological Survey (e.g. Baptie 2018) and to the Blacknest Array (AWE 2020). The stations in Ireland are as in Fig. 3.

In 2002–2005, the Irish Seismic Lithospheric Experiment (ISLE) deployed wide-band (30 s) stations in SW Ireland (Landes *et al.* 2004; Wawerzinek *et al.* 2008). ISLE was followed by the Irish Seismological Upper Mantle Experiment (ISUME) that installed the same instruments across the island of Ireland in 2006 (O'Donnell *et al.* 2011; Polat *et al.* 2012), some of them recording for many years and used in this study (Fig. 3).

In 2010–2012, Ireland Array (Lebedev *et al.* 2012, 2022) deployed 20 broad-band (120 s) stations across ROI, with most of the stations recording continuously until 2021–2022 (www.irelandarray.ie). At the same time, the Irish National Seismic Network (INSN; Dublin Institute for Advanced Studies 1993) installed five new permanent broad-band stations (Blake *et al.* 2012), making it six for INSN in total, including DSB. The five new installations included an upgrade of the station VAL from a wide-band to a broad-band (240 s) instrument and deployments of 240-s instruments at four new locations. Broad-band stations of the UK Seismograph Network, operated by the BGS (e.g. Baptie 2018), complement the coverage in Northern Ireland and across Britain (Fig. 4). Recent temporary, wide-band deployments in Ireland, including the Dublin Basin array (30-s stations, Licciardi & Piana Agostinetti 2017), WaveOBS (60-s and 30-s stations, Möllhoff & Bean 2016), and, in particular, the SIM-CRUST array deployment collocated with the cluster of seismicity in Donegal (30-s stations, Piana Agostinetti & Licciardi 2015; Riva *et al.* 2022) recorded important additional data.

Thanks to the recent growth in the number of stations in Ireland, we can now map its seismicity using an unprecedentedly dense data coverage. Fig. 5, for example, shows the recordings of a newly detected natural earthquake in Co. Wexford, southeastern Ireland, at the stations of Ireland Array (Fig. 3), and Fig. 6 shows Ireland Array seismograms of a quarry blast in Co. Tipperary (Fig. 7).

3 SEISMICITY OF IRELAND

We used the newly dense coverage of Ireland with seismic stations to relocate known seismic events and to detect numerous new ones. In this section, we briefly describe the data analysis and present a map of natural earthquakes in Ireland for 2010–2016, displaying seismicity patterns across the island in detail.

At the time of the analysis, there were six permanent INSN stations streaming data continuously to the data centre at DIAS, which operated INSN, monitoring the seismic activity in Ireland. (At present, the network is deploying additional permanent stations.) The data were processed in real time using the SeisComP3 detection, location and database management software suite (Weber *et al.* 2007; Helmholtz-Centre Potsdam 2008). Because not all events are detected by SeisComP3, the data were also scanned daily by analysts. The SeisComP3 event location was performed using its default one-dimensional seismic velocity model, iasp91 (Kennett & Engdahl 1991). Fig. 8 shows these preliminary locations for all the events detected by INSN in 2013–2014, the initial time period

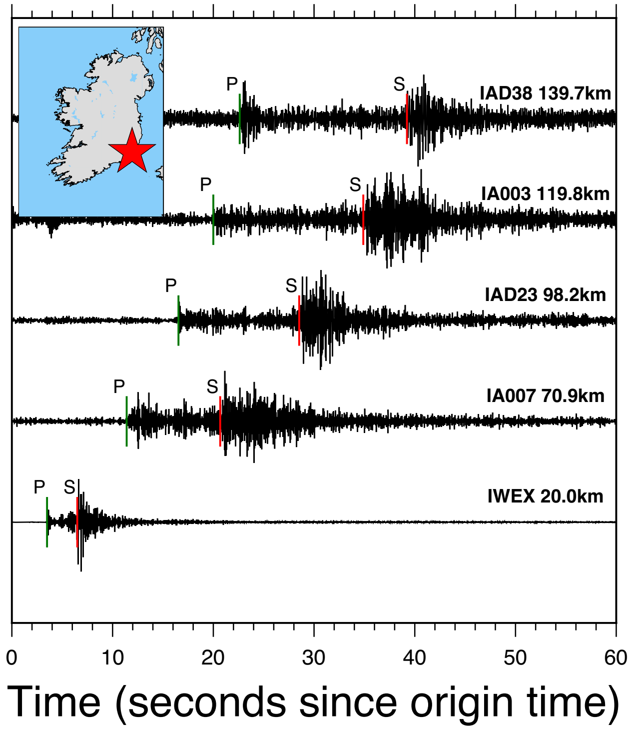

Figure 5. Recordings of a tectonic earthquake of 14 July 2011 (00:09 UST), in Co. Wexford, southeastern Ireland, at the vertical components of the Ireland Array stations and the INSN station IWEX.

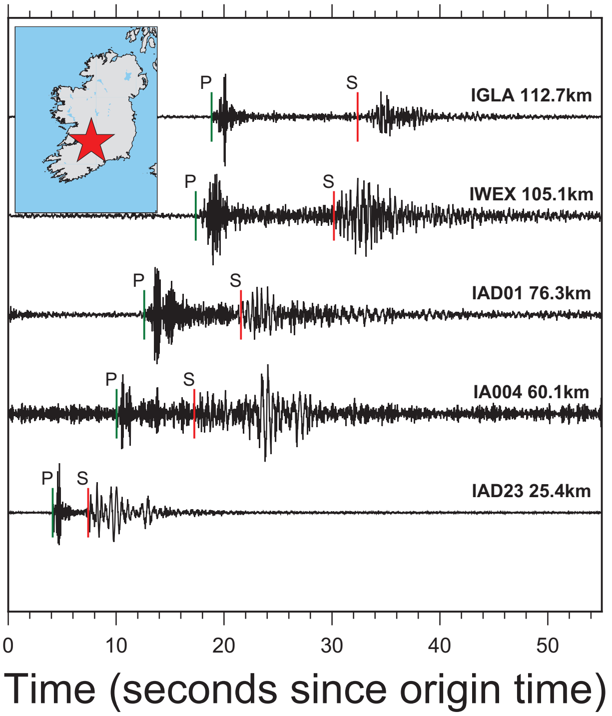

Figure 6. Recordings of a 13 July 2011, quarry blast in Co. Tipperary at the vertical components of the Ireland Array and INSN (IWEX, IGLA) seismic stations.

Figure 7. A Google Earth image of a quarry in Co. Tipperary and the estimated location of an event, close to the quarry (circle). The event is a quarry blast, and its true epicentre is at the quarry itself.

we analysed, including both natural and anthropogenic events (1401 events in total).

In this study, we relocated the events using all available waveform data from temporary and permanent networks in Ireland and from the adjacent stations of the BGS network. We then discriminated between natural and man-made events and, finally, used cross-correlation of continuous data with template earthquake waveforms to detect a large number of new, previously unknown micro-earthquakes.

The time–distance plot in Fig. 8 shows our manual picks of Pg, Pn, Sg and Sn for the events shown on the map. Linear regression of the Pg, Pn, Sg and Sn picks yields estimates of the crustal and uppermost-mantle seismic velocities, as well as the Moho depth. The velocities obtained are 5.95 km s^{-1} (Pg), 8.13 km s^{-1} (Pn), 3.42 km s^{-1} (Sg) and 4.57 km s^{-1} (Sn). The Pn value is slightly higher than the global average of 8.09 km s^{-1} (Christensen & Mooney 1995). This indicates relatively cold uppermost mantle, which is likely to be due, in large part, to the crust being relatively thin and the uppermost mantle sampled by Pn waves—relatively shallow. The crustal thickness obtained is 29 km, in close agreement with the results of active source studies (e.g. Landes *et al.* 2005). The Wadati diagram analysis also confirms the average Vp/Vs ratio of 1.74, obtained previously from receiver-function analysis (Licciardi *et al.* 2014).

The 1-D seismic velocity model described above was used for the event relocation (Arroucau *et al.* 2017). The SeisComP3 software suite was used for relocating and determining magnitudes for all the events. Magnitudes were determined manually by measuring the maximum zero-to-peak amplitudes on the horizontal components of Woods–Anderson simulated seismograms for each event. An additional 2 Hz high-pass filter was applied to the Woods–Anderson simulated seismograms in order to suppress microseismic noise.

Most seismic events detected in Ireland are quarry blasts. They occur only during daylight hours, and many quarries fire at specific times, such as on the hour. A large proportion of the remaining events are mine blasts, which can occur day and night.

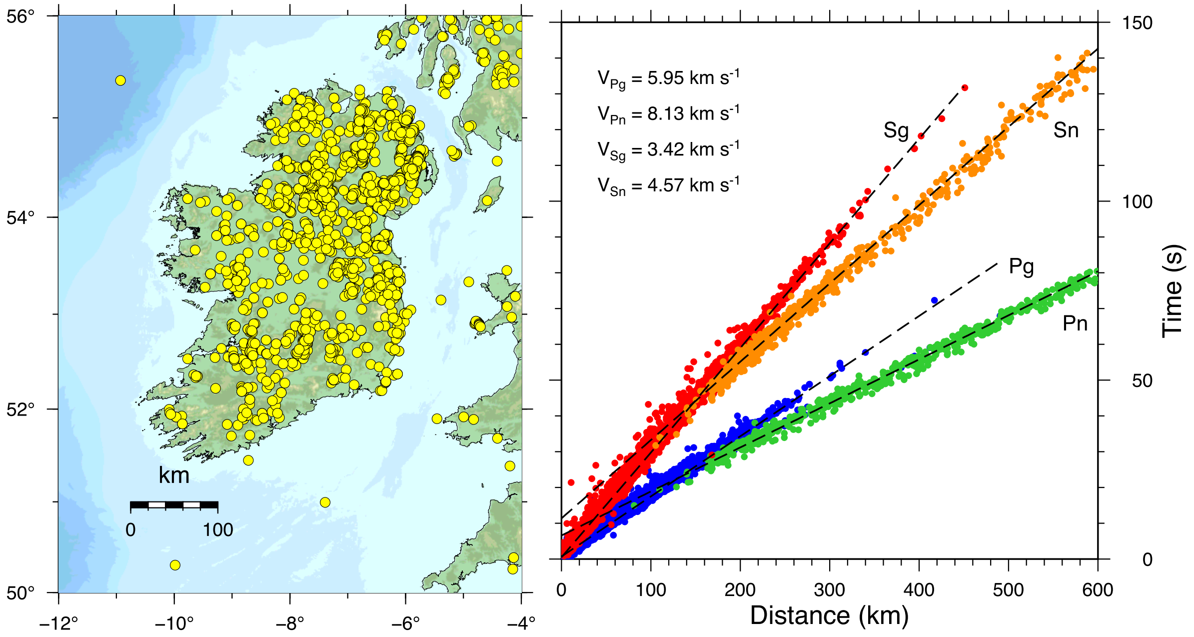

Figure 8. Left-hand panel: preliminary locations of all the events detected by INSN in 2013–2014, including natural and anthropogenic events. Right-hand panel: time–distance plot for Pn, Pg, Sn and Sg arrivals, manually picked by the INSN analysts for these events. Preliminary velocities for the crust and mantle, as well as the Moho depth, were inferred by linear regression (black lines).

We discriminated between natural and man-made events using a set of complementary lines of evidence. The origin time of the events provides one useful discriminant for whether they are likely to be natural or man-made. An origin-time histogram for 2013–2014 shows that a vast majority of the events occurred during the working hours of the day (Fig. 9). A scatter plot of the origin times also shows two systematic, 1-hr shifts in the Spring and in the Autumn, coinciding with the beginning and the end of the summer time (daylight saving time).

Another discriminant is given by the improved event locations, obtained using the complete dataset and the preliminary one-dimensional seismic velocity model. Fig. 10 shows the initial (left-hand panel) and relocated (right-hand panel) epicentres of the 2013–2014 events. The relocated events tend to converge into clusters, compared to the more diffuse initial distribution. The locations of these clusters coincide, in most cases, with the locations of known quarries and mines (Fig. 10, right-hand panel). The presence of quarries at the epicentres of the man-made events was verified using Google Earth imagery, which shows the quarries clearly (Fig. 7). As for the mines, the locations of the two Zn-Pb mines operating in the country at the time are well known—the Tara mines near Navan in eastern Ireland (Mills *et al.* 1987) and the now-closed Lisheen mine in south-central Ireland (Wilkinson *et al.* 2005).

Waveform analysis provides further useful discriminants. Contrary to our initial expectations, *P*/*S* (or *P*/*Lg*) amplitude ratios (e.g. Kim *et al.* 1993) did not provide an effective discriminant in Ireland, with local quarry blasts generating substantial *S*-wave energy. Instead, the spectral ratio discriminant, which involved calculating the ratio of the spectral amplitudes averaged across two non-overlapping frequency bands within the *S*-wave train, was found to be more effective (e.g. Hedlin *et al.* 1990; Koch 2002). The waveform-based event discrimination in Ireland (e.g. Grannell *et al.* 2019) is described in detail in a forthcoming publication.

Prior to this study, INSN's Irish seismicity catalogue for the period 1980–2016 included 144 natural earthquakes. Here, we used waveforms of known events—those known previously and those identified by our own analysis—as templates and detected numerous new micro-earthquakes in Ireland and surroundings. We used continuous, vertical-component seismograms recorded at over 50 permanent and temporary stations in Ireland and Great Britain from 2010 to 2016 (Fig. 3). Selecting 62 events—local magnitudes 0.6–4.0—as templates, we systematically cross-correlated the continuous data from all the stations with the waveform templates (e.g. Schaff & Waldhauser 2010; Zhang & Wen 2015).

This yielded the detection of 218 new natural earthquakes in 2010–2016, of which 131 were recorded at 3 or more stations and successfully located. These earthquakes are distributed as clusters in the vicinity of the template events (Fig. 11). The methodology has proven to be successful at identifying low magnitude events in relatively noisy conditions. The limitation of the template cross-correlation technique is that it detects repeating events in the same areas but does not identify new seismically active areas. A geographical bias could also result from the uneven distribution of stations across Ireland. Any unidentified seismicity clusters in Ireland, however, would have to feature only events well below M_L 2.0 and would not change significantly the main patterns of seismicity distribution mapped here (see also seismicity maps with different magnitude cut-offs in Section 4).

Most of the newly detected events are in Co. Donegal in the north of Ireland, the most seismically active area of the island (Fig. 12). Figs 13 and 14 show examples of the waveforms of the template events and the new events detected using the procedure in Co. Donegal and Co. Cork, respectively. The low magnitude earthquake detections in Ireland by waveform template matching will be presented in detail in a forthcoming publication (e.g. Arroucau *et al.* 2017; Grannell *et al.* 2019).

Fig. 15 displays our map of the seismicity of Ireland. The seismic event catalogue continues to be updated with new events at the INSN website (www.insn.ie), with the discrimination and detection procedures developed in this project contributing to the INSN routines.

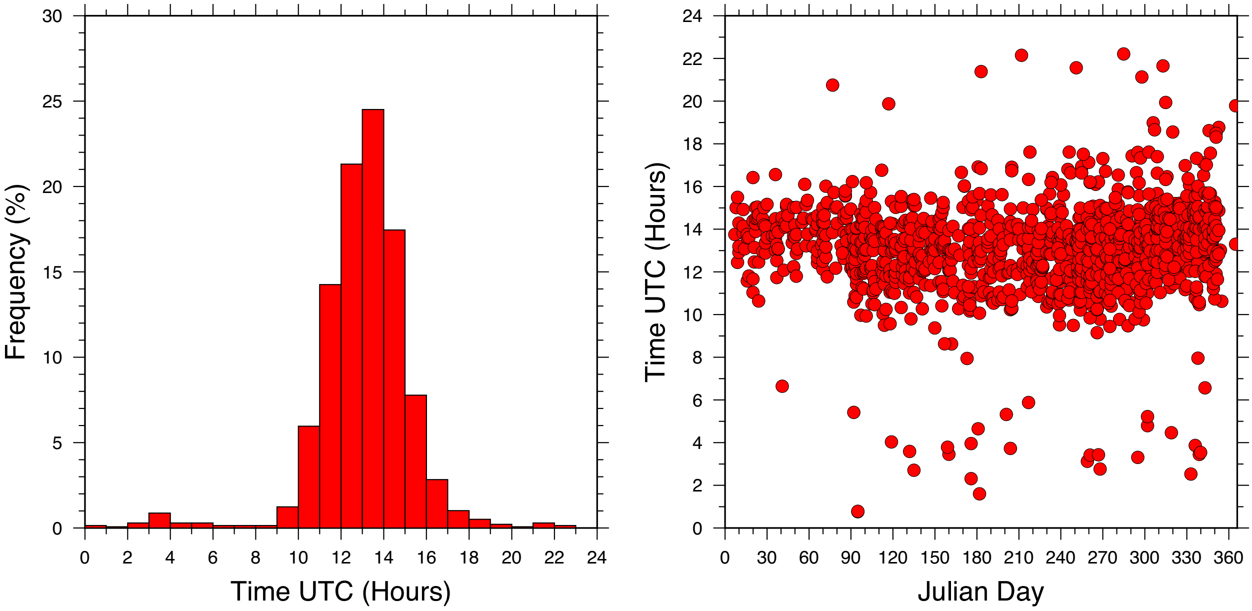

Figure 9. Left-hand panel: a histogram of the origin times of the seismic events in 2013–2014, plotted in Fig. 8. Right-hand panel: the dates and the GMT origin times of the events. Note the systematic shifts at the beginning and the end of the summer time (daylight saving time) period.

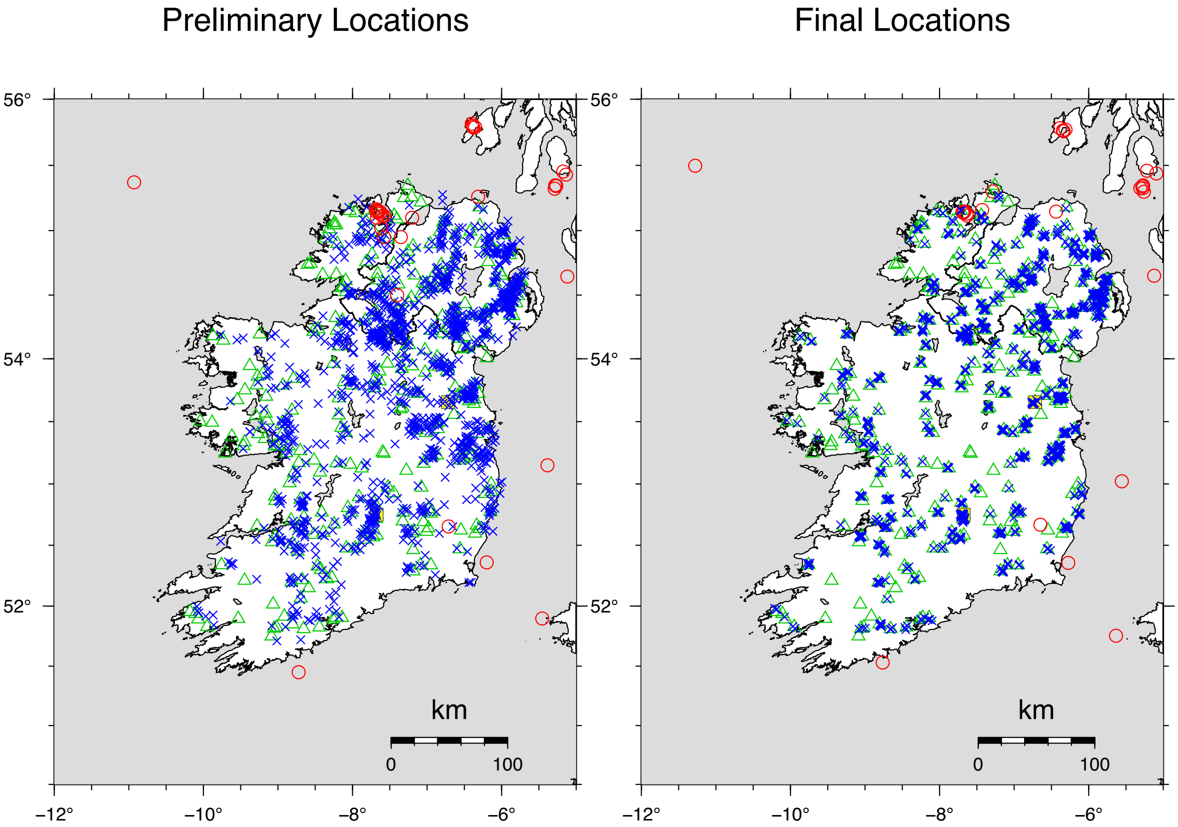

Figure 10. Left: initial locations of the natural (circles) and man-made (crosses) seismicity in 2013–2014. Right: relocations using the complete data set and the improved estimated velocity model. The locations of quarries and mines are superimposed as triangles.

Ongoing improvements in the seismicity detection and analysis will facilitate reliable monitoring and further research on the seismicity (Möllhoff *et al.* 2019).

The main patterns of the seismicity of Ireland can now be considered established and no longer biased by insufficient data sampling. Most of Ireland's natural earthquakes occur in northern Co. Donegal in the north of the island. The other notable seismicity area is along the island's southern coast, from Co. Cork in the west to Co. Wexford in the east. The largest local earthquake recorded around Ireland and its near offshore was M_L 4.0 off the west coast of Ireland on the 6th of June 2012, whereas the largest onshore event was M_L 2.5, occurring in Co. Donegal on the 26th of January 2012.

The rare earthquakes elsewhere onshore Ireland include those south of the primary Donegal cluster (in southern Donegal and along the border of Co. Leitrim in ROI and Co. Fermanagh in NI) and east of it (in Co. Derry and Co. Antrim, Northern Ireland). Ireland's largest earthquakes occur offshore to the west of the island, with occasional smaller earthquakes along the western coast as well. The Irish Sea, east of Ireland, also shows more and larger earthquakes than the adjacent eastern Ireland.

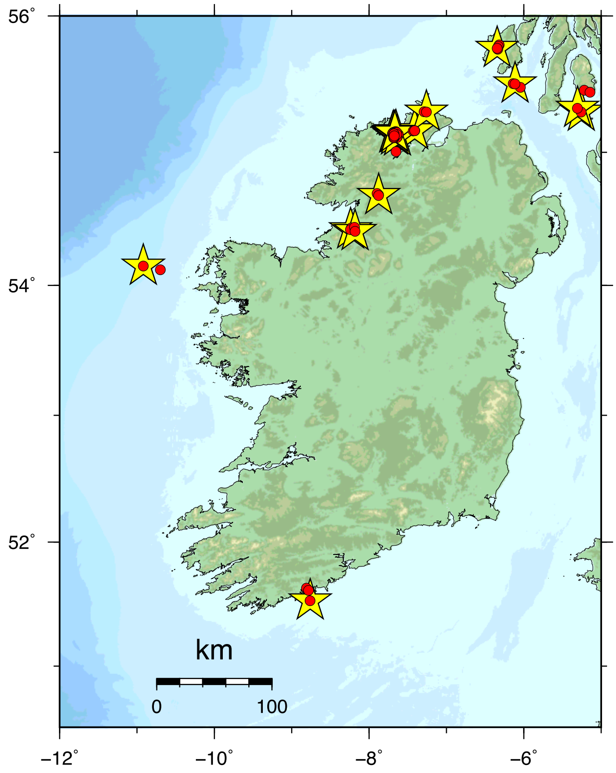

Figure 11. The template events (stars) and the earthquakes (circles) detected using cross-correlation of the template waveforms with continuous seismograms. In total, 131 previously unknown natural earthquakes were detected and successfully located. A large majority of the events are located in Co Donegal in the north of the island and plot on top of each other at this scale. Fig. 12 zooms on Donegal and the multiple seismicity clusters there, each with many earthquakes.

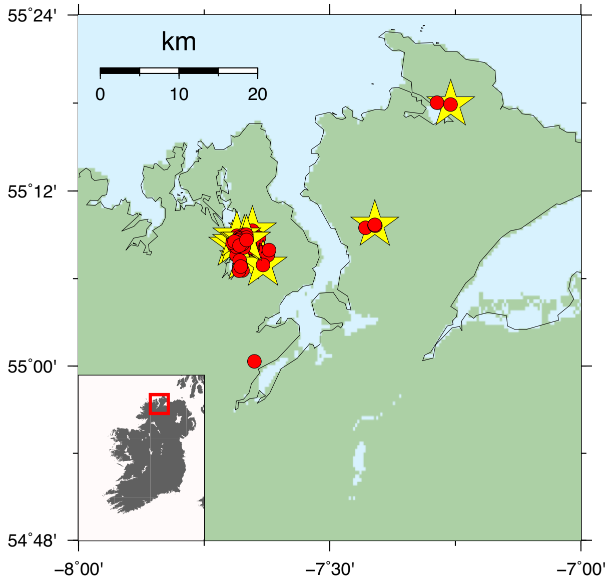

Figure 12. The template events (stars) and the earthquakes (circles) detected using cross-correlation of the template waveforms with continuous seismograms in the northern Co. Donegal.

4 DISCUSSION

Britain and Ireland present a classic example of intraplate seismicity (e.g. Musson 2007). An improved understanding of the puzzling distribution of their earthquakes can shed new light on the basic intraplate seismicity mechanisms. The seismicity also has an increasing economic and societal importance on the islands themselves, given the continuous development of potentially vulnerable infrastructure and the importance of the knowledge of baseline seismicity for the monitoring of the induced seismicity associated, for example, with deep geothermal energy production (Musson 2007; Baptie *et al.* 2016).

The tectonic stress that gives rise to most of the seismicity is likely to be transmitted from the plate boundaries, with regional modifications of the stress pattern due to laterally varying lithospheric strength and deformation. To the south–southeast of Ireland and Britain, subduction and continental collision occur at the Pyrenees and the Alps, with north–south and northwest–southeast compression. To the northwest, the Mid Atlantic Ridge produces a southeast-ward ridge push. The resulting regional tectonic stress pattern is the northwest and north–northwest oriented maximum horizontal compression across western Europe, including Britain and Ireland (Müller *et al.* 1992; Heidbach *et al.* 2007). Focal mechanisms of earthquakes in the United Kingdom show that they occur predominantly on strike-slip faults—with NNW–SSE compression and ENE–WSW tension—and on thrust faults, with NNW–SSE compression (Main *et al.* 1999; Baptie 2010). The stress orientation with the maximum NNW–SSE compression is consistent with the measurements of different types from the World Stress Map 2008 release (Heidbach *et al.* 2008) and with the tectonic stress being transmitted from plate boundaries.

Systematic spatial variation in *P*- and *T*-axes orientation are also present (Baptie 2010), with the northwest–southeast compression in England and Wales changing to approximately north–south compression and east–west extension in northwest Scotland. Baptie (2010) interpreted this as modification of the principal stress directions due to plate-boundary forces by local stress conditions due to glacio-isostatic adjustment in northwestern Scotland. Alternatively, regional variations in the stress pattern can be caused by the lateral variations in the strength and deformation of the lithosphere.

The variations in the seismicity rates across Ireland and Britain can be expected to result from variations either in the local stress or in the mechanical strength of the lithosphere—or a combination of both. Notable variations in seismicity can be seen both within Britain and within Ireland (Fig. 2), with the most striking contrast being that between the two islands. Reviewing the earthquake distribution across the islands and its relationship to geological structure, Musson (2007) noted: 'The problem can be summarized neatly with one question: why is Ireland so aseismic?'

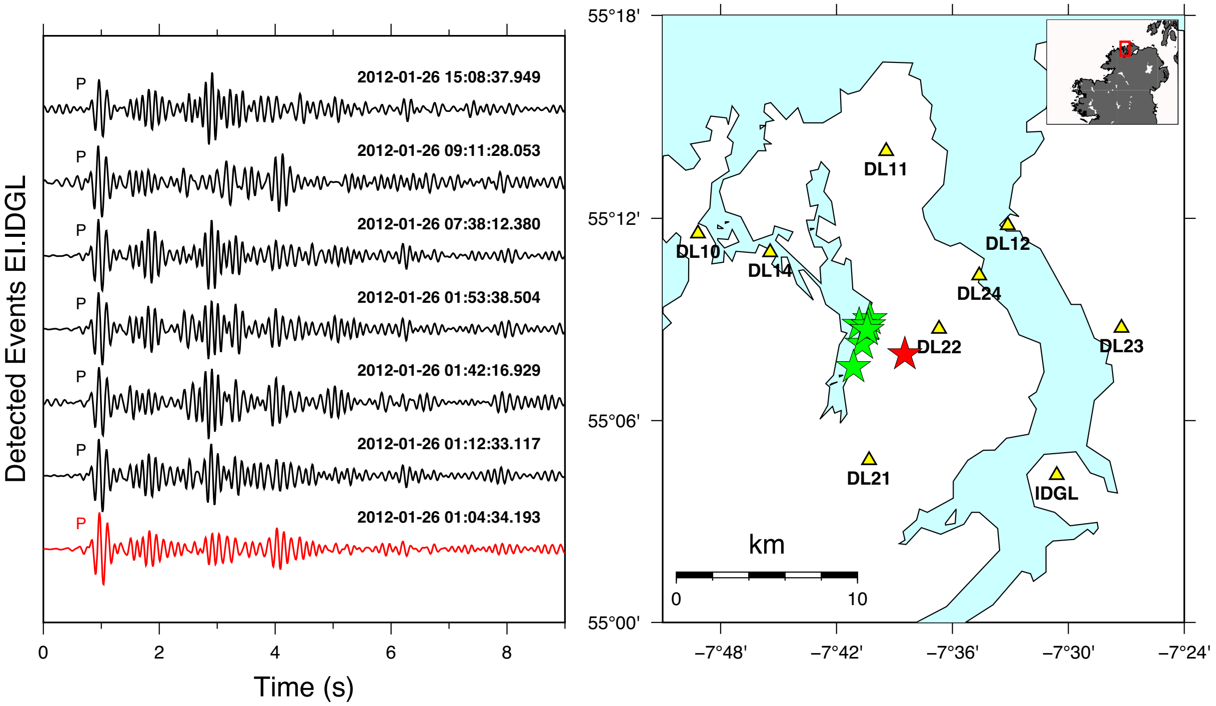

Figure 13. Seismograms of the newly detected events (black) identified by cross-correlating continuous recordings with seismograms from a template event (red) in Co. Donegal. The recordings are from the INSN station IDGL. Seismic stations in the region are plotted as triangles.

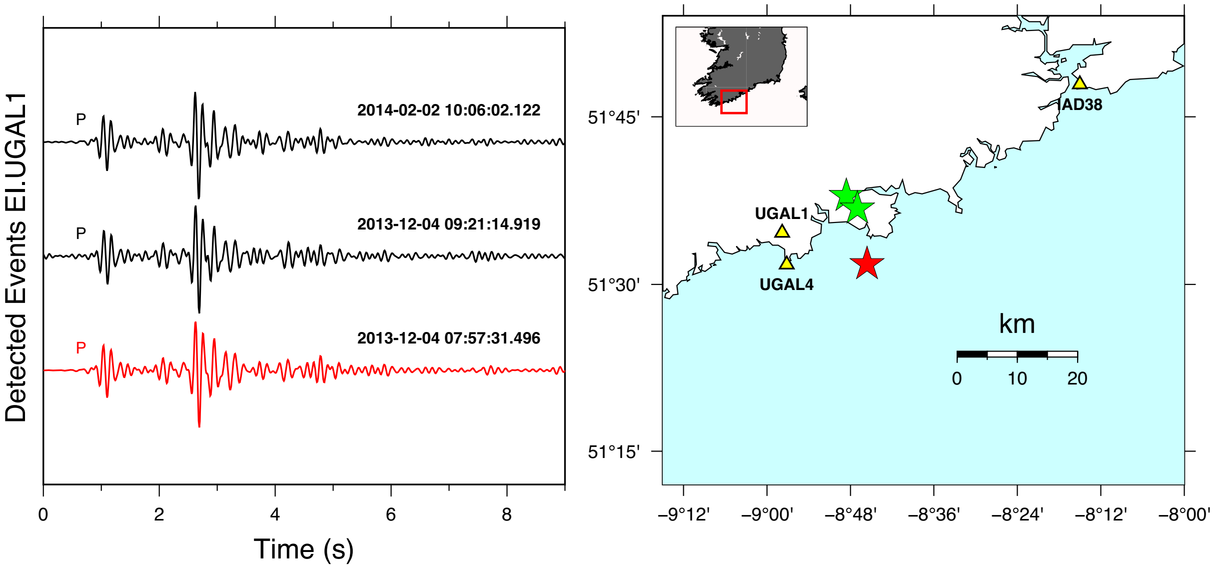

Figure 14. Seismograms of the newly detected events (black) identified by cross-correlating continuous recordings with seismograms from a template event (red) in Co. Cork.

A number of explanations have been put forward, starting with the hypotheses by O'Reilly (1884) that the deformation of the two islands was decoupled by slip on major faults between them or, alternatively, that suitable seismogenic faults existed beneath Britain but not Ireland. Neither of these hypotheses is supported by now available geological and seismic data, which show numerous faults beneath and around both Ireland and Britain and an absence of substantial movement along any faults between the islands (e.g. Anderson *et al.* 2018; Rodríguez-Salgado *et al.* 2020).

More recent explanations for the unevenly distributed seismicity included uneven distribution of the Palaeogene–Neogene deformation (Muir-Wood 1989b; Ove Arup 1993; Musson 2000); postglacial rebound (Hobbs 1927; Kolderup 1930; Musson 1996; Main *et al.* 1999; Muir-Wood 2000); distribution of major fault systems (Davison 1924; Chadwick *et al.* 1996) and mantle convection associated with the thermal heterogeneity in the sublithospheric mantle (Bott & Bott 2004; Arrowsmith *et al.* 2005). The postglacial rebound and the forces exerted onto the lithosphere by the convecting

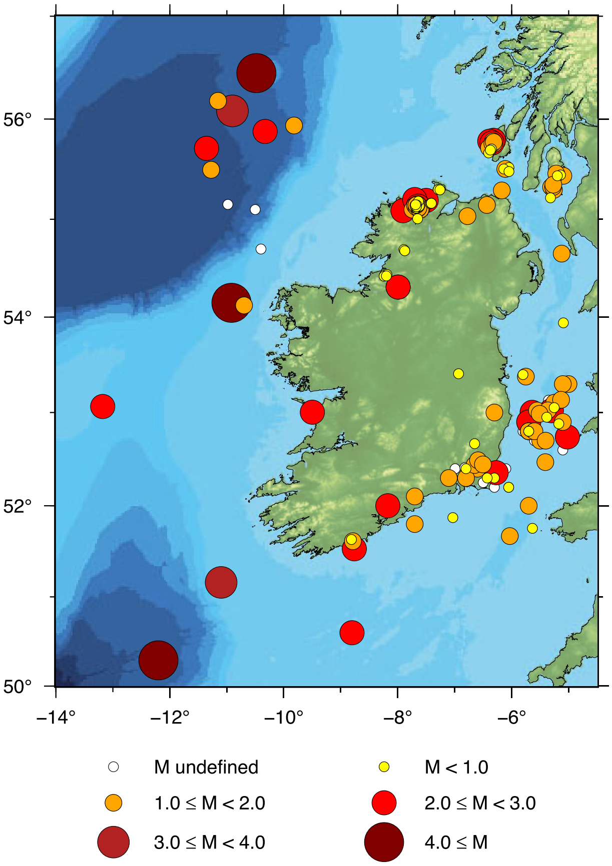

Figure 15. The natural seismicity map for Ireland and surroundings for the period 1980–2016. Events that occurred from 2010 to 2016 were relocated using all available data from temporary and permanent stations. The seismicity map is now updated routinely on the INSN website (https://www.insn.ie).

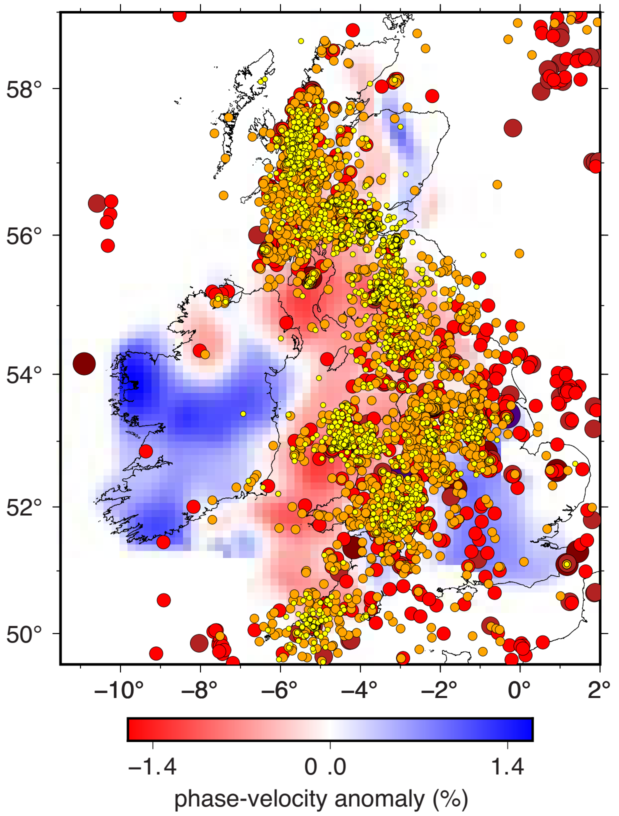

Figure 16. Seismicity of Ireland and Great Britain according to the BGS seismicity catalogue (e.g. Baptie 2018), superimposed on a map of 64 s, Rayleigh-wave phase velocity anomalies (Bonadio *et al.* 2021). Phase-velocity anomalies are relative to the 4.03 km s^{-1} regional average. Rayleigh waves at the period sample primarily the 60–130 km depth range, and the phase velocities reflect variations in the lithospheric thickness. High velocities across much of Ireland and within the London Platform in the southeast of Great Britain indicate thicker, colder, stronger lithosphere.

sublithospheric mantle are, indeed, likely to contribute to the lithospheric stress. Yet, neither the lateral variations in the amount of the rebound nor the asthenospheric heterogeneity suggested by seismic tomography show a close match to the seismicity distribution (Musson 2007). Musson (2007) proposed that the key to seismicity in the region was, instead, a complex pattern of fault reactivation related to the interaction of strong and weak crustal blocks.

Our results support the essential role of the lateral variations in the mechanical strength. They show that it is the thickness of the lithosphere that is the primary controlling factor (Fig. 16), with the uppermost mantle and the lower crust being colder and stronger (e.g. Burov & Watts 2006; Jackson *et al.* 2021) and, thus, deforming less where the lithosphere is thicker.

The regional-scale structure of the mantle lithosphere across Britain and Ireland was poorly known until recently. Active and passive-source seismic imaging studies provided extensive evidence on the structure of the crust, onshore and offshore the islands (e.g. Edwards & Blundell 1984; Klemperer & Hobbs 1991; Landes *et al.* 2005; O'Reilly *et al.* 2006; Shaw Champion *et al.* 2006; Tomlinson *et al.* 2006; Kelly *et al.* 2007; Polat *et al.* 2012; Nicolson *et al.* 2014; Watremez *et al.* 2018; Prada *et al.* 2019). They resolved detailed structure of sedimentary basins, moderate lateral variations in the crystalline crust structure and a relatively flat Moho across the islands. In the upper mantle, notable anomalies have been reported by traveltime tomography studies (Arrowsmith *et al.* 2005; Wawerzinek *et al.* 2008; O'Donnell *et al.* 2011). The structure of the mantle lithosphere, specifically, was studied only in parts of the region, such as by the *S*-wave receiver function study using an array in southcentral Ireland (Landes *et al.* 2007). The inference from this study that Ireland's lithosphere thins from 85 km in the south to as little as 55 km in the north was intriguing but difficult to reconcile with the observed topography (Fullea *et al.* 2014). Petrological modelling of gravity and elevation data in Ireland (Fullea *et al.* 2014) yielded lithospheric thickness variations in the 75–110 km range. In European-scale seismic models, Ireland and Britain normally fall at the boundary of the study region (e.g. Meier *et al.* 2016; El-Sharkawy *et al.* 2020) and in larger- and global-scale, seismic or multiparameter petrological models (e.g. Legendre *et al.* 2012; Fullea *et al.* 2021), the islands' lithosphere is averaged with that of their surroundings too strongly for any accurate inferences on its regional scale structure.

Bonadio *et al.* (2021) performed regional surface wave tomography using the newly available data from Ireland Array (Lebedev *et al.* 2012), INSN (Blake *et al.* 2012) and other networks in Ireland and available data in Britain and Northern Ireland (e.g. Baptie 2018). Their optimal-resolution-tomography method solved the optimal-resolution problem as posed by Backus & Gilbert (1970) and provided maps of the averaging length of the imaging, which varied from as short as 39 km in central Ireland to as long as ∼250 km in some of its coastal areas, increasing the most at the edges of the region sampled with data, as expected (Bonadio *et al.*

2021). The phase-velocity maps indicated substantial lateral variations in the lithospheric thickness across the islands. Fig. 2 shows phase-velocity variations at a 64 s period. Rayleigh waves at this period are particularly sensitive to the lithospheric thickness and temperature (e.g. Lebedev *et al.* 2013), so that the phase-velocity map presents a proxy for their lateral variations, with higher velocities indicating thicker, colder lithosphere (Bonadio *et al.* 2021). In order to calculate the absolute lithospheric thickness from surface wave data, it is necessary to combine Rayleigh and Love wave measurements and isolate the signal of the isotropic-average seismic velocity variations—which reflect the temperature, thickness and composition of the lithosphere—from that of seismic anisotropy (Bartzsch *et al.* 2011; Bonadio *et al.* 2018; Ravenna & Lebedev 2018; Ravenna *et al.* 2018; Fullea *et al.* 2021). Thermodynamic inversion (Fullea *et al.* 2012, 2021; Xu *et al.* 2023) of the surface wave data sets is work in progress and reveals lithospheric thickness variations across Ireland and Britain from as thin as 75–85 km in the low-phase-velocity areas (Fig. 2) to as thick as 95–110 km in the high-phase-velocity areas (Chambers *et al.* 2022; Bonadio *et al.* 2023). Fig. 17 shows the results of the thermodynamic inversions in a thinner-lithosphere and a thicker-lithosphere locations, yielding 83 and 100 km lithospheric thicknesses, respectively. The regional variations in the lithospheric thickness are moderate but their strong match with the earthquake distribution (Fig. 16) indicates that it is such differences that control the distribution of seismicity.

Our results provide simple answers to the long-standing basic questions of why Ireland is so aseismic and what the primary control is on the variations in seismicity across Britain. A detailed examination of the seismicity also prompts some interesting new questions. A great majority of micro-earthquakes with $M < 2.0$ occur in the areas of relatively thin lithosphere (Fig. 16). Their distribution in the thin-lithosphere areas, however, is uneven. For example, there are seismicity gaps in the Irish Sea, which has a thin lithosphere. This is likely to be due to regional variations of the tectonic stress pattern (Baptie 2010), probably caused by the lateral variations in the strength and the deformation rate of the lithosphere.

Most larger events of magnitude 3 and over occur in the thin-lithosphere areas, with none known in Ireland or (north-)eastern Scotland (Fig. 18). Many of them, however, align along the western boundary of the London-Brabant Platform in England, with a number of them within the platform, on what appears to be relatively thick lithosphere (Fig. 18). It may be that the occurrence of larger events on thicker lithosphere is facilitated by its colder geotherm and, consequently, a thicker seismogenic layer in the crust. Main *et al.* (1999) showed that the largest earthquakes in the United Kingdom nucleate in the mid to lower crust (13–26 km), consistent with a relatively low geothermal gradient. Yet, the larger events (Fig. 18) tend to occur in certain parts of only this particular tectonic block—the London-Brabant Platform in southeastern England—and their origin may relate to particular properties of the crust and mantle lithosphere in this particular location. An important problem for the future is to map with more certainty the lithospheric thickness and geotherm in southern and southeastern England—sampled relatively sparsely with currently available surface wave data sets, as are large parts of Scotland (Bonadio *et al.* 2021; Fig. 2)—and to investigate the local crustal and lithospheric properties and their relationship to the occurrence of these larger events.

Our results also have useful general implications for the distributions of intraplate seismicity globally. It has been observed at global (Mooney *et al.* 2012) and regional (Rocha *et al.* 2016) scales that seismicity in cratons that have the thick, cold and mechanically strong lithosphere is generally weaker than in adjacent continental areas with thin lithosphere. Seismicity in a number of regions has also been compared with the surface heatflow, which is indicative of the temperature and, thus, thickness of the lithosphere. Liu & Zoback (1997) pointed out that heatflow in the New Madrid seismic zone appeared to be elevated (about 60 $\mathrm{mW\,m^{-2}}$) relative to the background regional value of 45 $\mathrm{mW\,m^{-2}}$ and proposed that it was the temperature in the lower crust and upper mantle that localized the seismicity there. Holford *et al.* (2011) compared seismicity and heatflow measurements in southeastern Australia and suggested that active intraplate deformation there was localized and controlled by the thermal properties of the crust and upper mantle. Bezada & Smale (2019) detected a strong correlation between intraplate seismicity across Australia and the variations in the attenuation of teleseismic *P* waves, which they argued to reflect those in the thickness of the lithospheric mantle (see also Bezada 2017). Their map of attenuation did not show a complete agreement with the lithospheric thickness variations inferred from seismic tomography (e.g. de Laat *et al.* 2023; Haynes *et al.* 2020), probably due to the substantial contribution of sub-lithospheric mantle to the total attenuation measured. Nevertheless, the high seismicity in the areas with thin lithosphere along the eastern coast of Australia showed a clear contrast with low seismicity in the central, cratonic parts of the continent. Bezada & Smale (2019) inferred that the lithospheric mantle structure exerted first-order controls on the localization of intraplate seismicity.

Our observations in Ireland and Britain provide important new evidence on the influence of the lithospheric thickness, temperature and strength on the distribution of seismicity. Using surface wave tomography, we can map relatively subtle variations in the lithospheric thickness. These variations can by quantified accurately using thermodynamic inversions of the surface wave data for temperature at depth. Our results show that even moderate lateral variations in the thickness of the lithosphere—only up to 20–30 km—are sufficient to create strong heterogeneity in the distribution of seismicity and to control which areas have numerous earthquakes and which are aseismic, such as most of Ireland.

5 CONCLUSIONS

The distribution of seismicity in Ireland can now be considered well established and not biased by insufficient data sampling. The majority of the island's natural earthquakes occur in its northernmost part (in Co. Donegal). Another seismicity area is along its southern coast. Earthquakes elsewhere onshore Ireland are rare and include those south and east of the primary Donegal cluster. Ireland's largest earthquakes occur offshore to the west of the island, with occasional smaller earthquakes along the western coast as well. The Irish Sea, east of Ireland, also shows more and larger earthquakes than the adjacent eastern Ireland.

The distribution of seismicity across Ireland and Britain shows a remarkable match with the thickness, temperature and, by inference, mechanical strength of the lithosphere. Recent surface wave tomography indicates thicker, colder lithosphere beneath most of Ireland, southeastern England and, probably, eastern Scotland—the areas with very few earthquakes. By contrast, western Britain and northernmost Ireland have thinner, warmer lithosphere and feature numerous earthquakes. Our results indicate that moderate variations in the lithospheric thickness exert substantial control on the

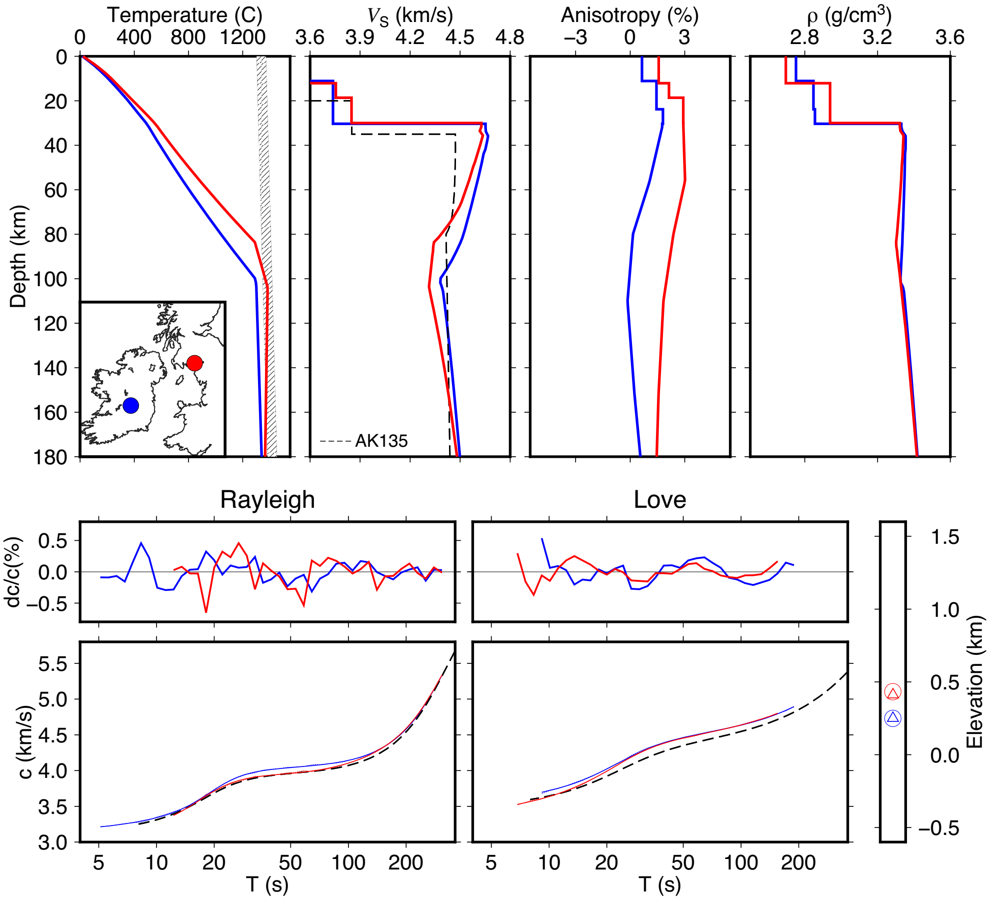

Figure 17. Lithospheric temperature and thickness at two example locations with thinner (red) and thicker (blue) lithosphere determined by thermodynamic inversions of surface wave data (Bonadio *et al.* 2023). Rayleigh wave (Bonadio *et al.* 2021) and Love wave (Bonadio 2019) dispersion curves were inverted for a best-fitting conductive geotherm within the lithosphere, temperature within the asthenosphere and a radial anisotropy profile using thermodynamic inversion (Fullea *et al.* 2021; Xu *et al*. 2023), which also fits the surface elevation (bottom right). Bottom: synthetic (solid lines) and observed (dashed) phase-velocity curves. Middle: the relative misfit between the two. The resulting lithospheric thicknesses at the two locations are 83 and 100 km.

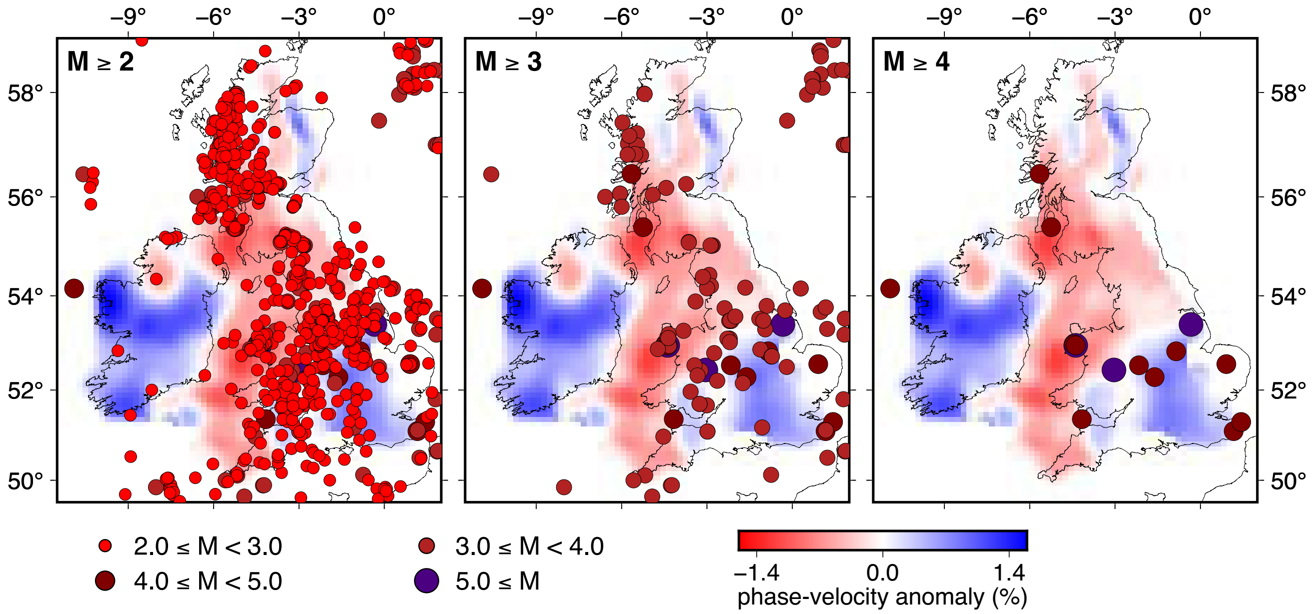

Figure 18. Seismicity of Ireland and Great Britain according to the BGS seismicity catalogue (e.g. Baptie 2018), with different minimum magnitude cut-offs. The 64-s Rayleigh-wave phase-velocity anomalies in the background are as in Fig. 16.

distributions of seismicity and seismic hazard in stable continental interiors.

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DATA AVAILABILITY

The Ireland Array and INSN data can be downloaded via FDSN web services at GFZ FDSNWS and IRIS FDSNWS (doi:10.14470/0G7565901444 and doi:10.7914/SN/EI, respectively). The BGS data are distributed via the BGS data servers. The catalogues of tectonic earthquakes, quarry blasts and mine blasts associated with this study are published at https://zenodo.org/record/7888353. doi:10.5281/zenodo.7888353

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