Geological Survey of Ireland Research Programme
- Short Call 2015, Final Report -

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Organisation name	Dublin Institute for Advanced Studies		
Organisation type:	☒HEI	☐Public Sector (other)	☐Private Sector
Department/section	Geophysics Section		

Project Title	Natural, man made and induced seismicity of Ireland: Discrimination and hazard
Contract No.	2015-sc-021

2. **Project information**:

Title of project	Natural, man-made and induced seismicity of Ireland : Discrimination and hazard
Did you make any formal amendment to the project workplan / budget?	☐ YES ☐ If yes, please specify: Most of the travel and materials costs in the original budget have been covered from other sources. The resulting savings of €4400.00 were used to pay interns who helped pick seismic phase arrival times on the vast seismogram database that was built in the course of the project. That budget amendment was submitted to and approved by GSI.

Project Report (*max 1500 words, excluding figures and headings*):

(i) Objectives and scientific/engineering targets beyond the state of the art

This project was essentially aimed at investigating the potential of cross-correlation based methods to detect local seismic events and discriminate between natural and man-made seismicity in order to develop automated tools that could be used for routine detection and analysis of local seismic activity in Ireland, a task currently performed manually by the analysts of the Irish National Seismic Network (INSN).

Besides that primary objective, the goal was also to take advantage of the large amount of seismic waveform data acquired in the past five years at permanent and temporary seismic arrays in Ireland (Figure 1) to improve the location of previously detected events and to identify and locate new, previously unknown events.

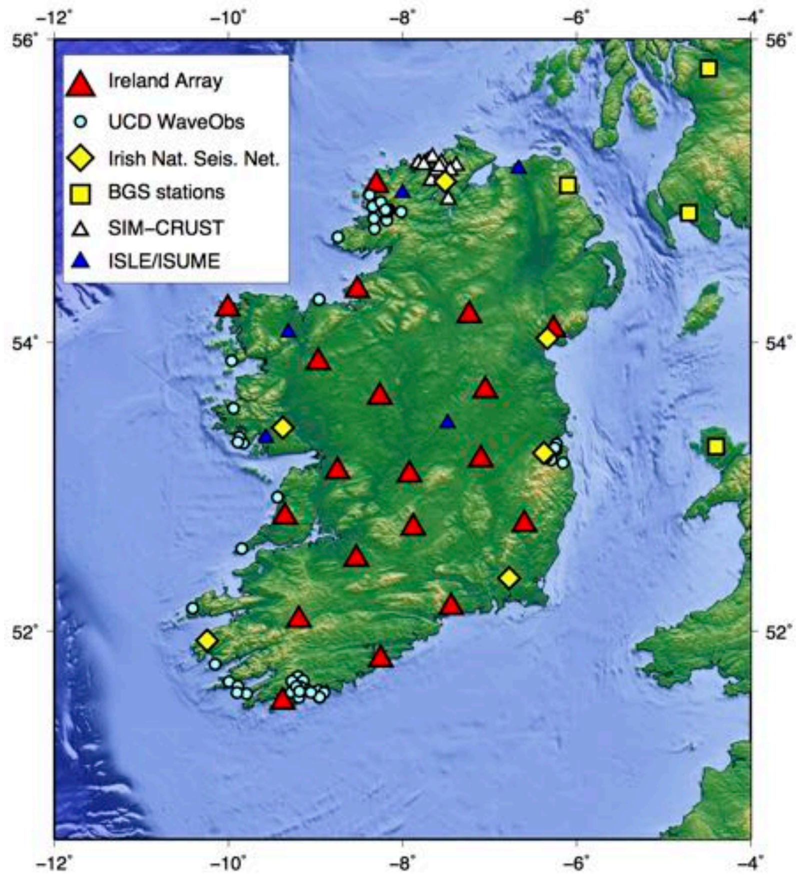

Figure 1. Temporary and permanent seismic installations used in this work.

A new 1D velocity model

A good knowledge of the seismic velocity structure is a pre-requisite to accurate earthquake location. Using an inaccurate velocity model can lead to erroneous locations and result in large uncertainties. Hence, in this work, we first built a preliminary 1D P- and S-wave velocity model for local seismic event location from linear regression of the INSN phase arrival time database for the years 2010-2016 (Figure 2). We combined that model with results from past controlled-source studies (Landes et al., 2005), considering a Vp/Vs ratio of 1.74 (Licciardi et al., 2014). The resulting new model, deduced from local data, is more adapted to the region of interest and represents, as such, an improvement over the global model (IASP91) that was used so far by the INSN (Figure 3).

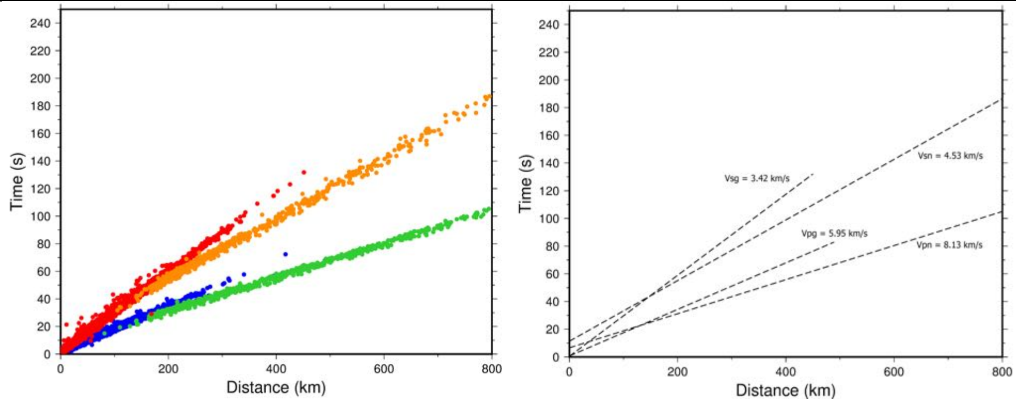

Figure 2. Upper left: Observed arrival times from the INSN phase catalogue as a function of epicentral distance for Pg (blue), Pn (green), Sg (red) and Sn (orange) waves. Upper right: Regression lines obtained from observed Pg, Pn, Sg and Sn wave arrival times and corresponding wave speeds.

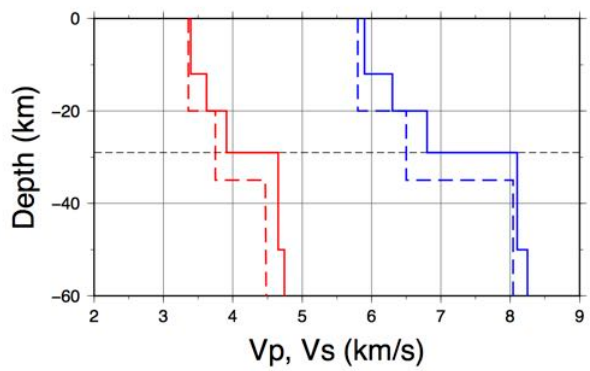

Figure 3: Comparison of IASP91 global P and S wave velocity model previously used by the INSN (red and blue dashed lines, respectively) with the one obtained in this work (solid lines). The black dashed line shows the Moho depth used to build our model, deduced from receiver function analysis (Licciardi et al., 2014).

A new waveform database

We assembled a database of waveforms recorded at temporary and permanent stations for all previously detected seismic events for the period 2010-2015. This includes 62 catalog, natural events (2010-2015) and more than 1,500 additional quarry and mine blasts (2013-2014). We also scanned the continuous data recorded during year 2011, for which no seismic event had been detected yet, and identified more than 500 new events, among which one natural earthquake (14/07/2011, 00:19, see Figure 4).

A new phase arrival time database

We manually picked P- and S-wave arrival times for all events. Given the large number of data to be analyzed, we agreed with GSI to hire two interns on this grant in order to help with that task. A total of more than 15,000 P- and 20,000 S-wave arrival times were picked in the course of this project (for year 2011, 2013 and 2014), providing an unprecedented dataset for future 3D high-resolution imaging of the crust and upper mantle beneath Ireland. The model that will be constructed using those new data will not only provide an unprecedented image of the geological structure of Ireland at depth, but will also help improve significantly the location accuracy of the Irish seismic activity.

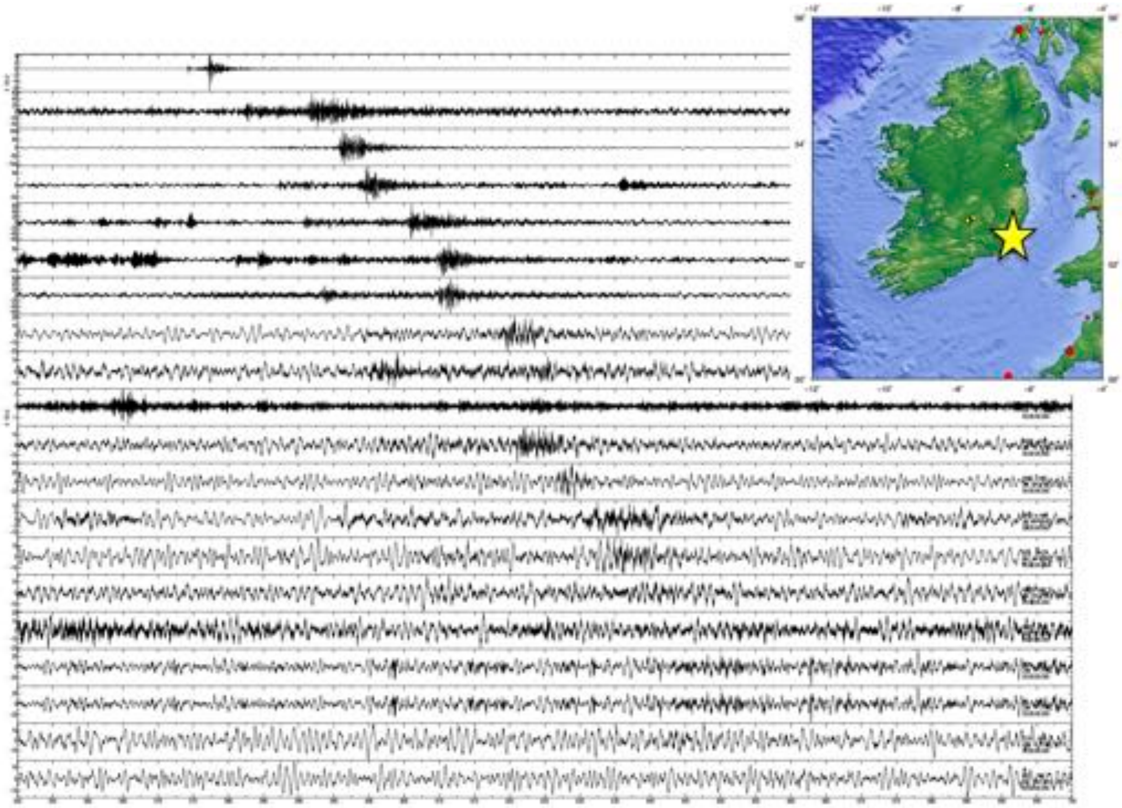

Figure 4. Waveforms recorded at IrelandArray stations for a new, previously undetected event (14/07/2011, 00:09). Traces are bandpassed filtered between 1 and 5 Hz. The inset in the upper right corner shows its location (yellow star).

Quarry blast and earthquake relocations

We relocated all events (natural and man-made) using the 1D velocity model that we built, the P- and S-wave picks performed in this work from all available seismograms recorded at permanent and temporary stations (Figure 5). Revised locations result in a less diffuse distribution, and the expected improvement is reflected by the fact that suspected blasts get located closer to known quarries after relocation, and can hence be less ambiguously attributed to a specific quarry. In addition to the quarry and mine database that we obtained from GSI and GSNI (Geological Survey of Northern Ireland) for Ireland and Northern Ireland, respectively, those new locations allowed us to identify additional active quarries by comparing their locations with quarries visible on Google Earth images. This resulted in an updated, more complete active quarry database for Ireland. The relocations also allowed us to update the INSN earthquake catalogue (Figure 6) and the new locations are now visible on the recently developed INSN website (https://insn.ie/confirmed/).

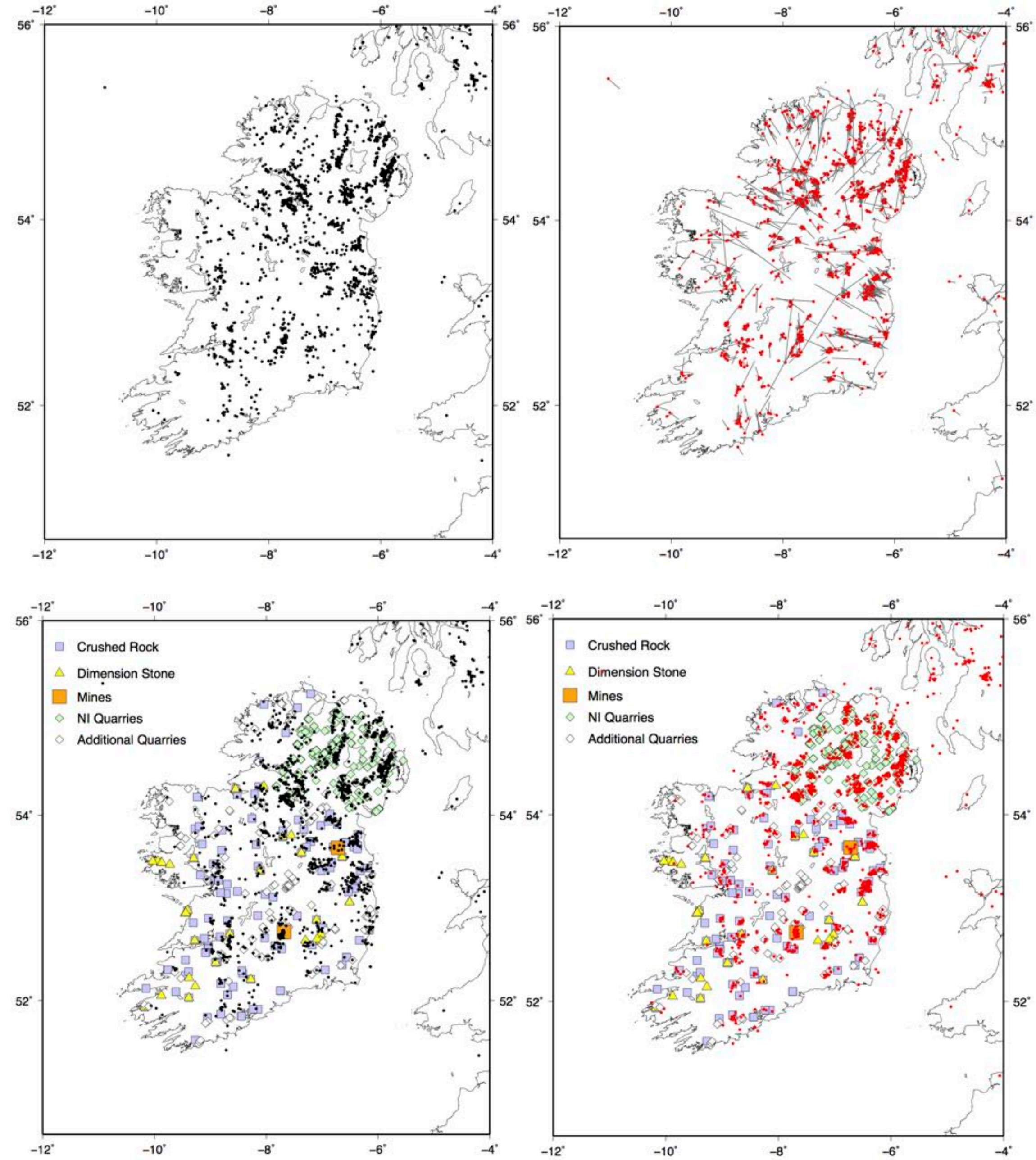

Figure 5. Upper left: preliminary INSN seismic event locations (black circles). Upper right: Relocated events (red circles); the black lines show the effect of the new 1D velocity model and additional phase picks on the epicentral locations. Lower left: Preliminary locations superimposed to the quarry map for Ireland and Northern Ireland. The "Additional quarries" were identified in this work by comparing newly detected events and Google Earth images. Lower right: Relocated events and quarry map of Ireland and Northern Ireland. Note the more focused event distribution close to known quarries after relocation.

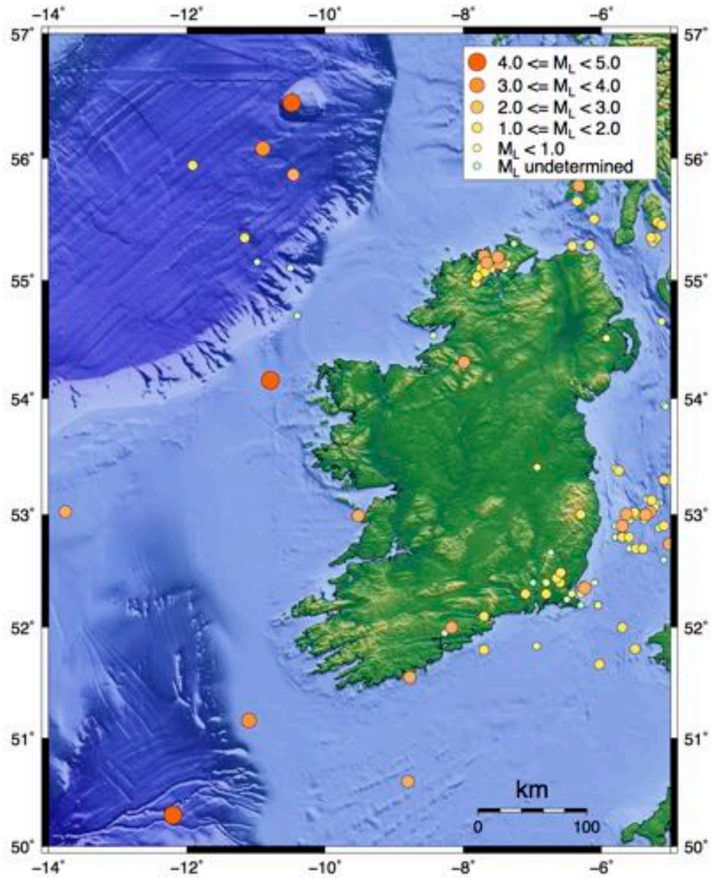

Figure 6. Relocated earthquake map of Ireland and surrounding offshore basins (1980-2016). Earthquakes were relocated using the 1D velocity model built in this work and the P and S wave arrival time data were picked on all available seismograms recorded at the permenent and temporary seismic installations shown in Figure 1.

Identification of repeating quarry blasts with waveform cross-correlation

We used cross-correlation to identify repeating events, natural or man-made, either in the existing database of previously detected events or in the continuous waveform data, in order to discover new, previously undetected ones. We primarily targeted quarry blasts, assuming that shots originating from a given quarry would produce similar waveforms, but also applied the technique to natural events. One unexpected finding of this study is that waveforms generated by blasts from a particular quarry are not necessarily highly correlated. Figure 7 shows the waveforms and associated correlation matrices of 19 events from two quarries in Co. Clare. The quarry blast nature and quarry of origin of those events can be unambiguously assessed from the preliminary locations and *a fortiori* from the relocated epicenters. Waveforms are filtered in two frequency bands, namely 2 to 8 Hz and 1 to 5 Hz, which are respectively used for cross-correlating a time window around the P-wave and around the surface wave. Although events from a specific quarry are, in some cases, associated to a high correlation coefficient, it is yet not systematic, precluding the use of the technique, as it is, to identify quarry blasts and associate them with a specific quarry. The distribution of correlation values, however, does not appear totally random and the two clusters seem to have their own signature in the correlation matrix, suggesting that some amendment to the technique, for instance using a linear combination of the different matrices, and using an appropriate weighting scheme accounting for inter-event and event-to-station distances, might be enough to design a more effective identification and discrimination tool.

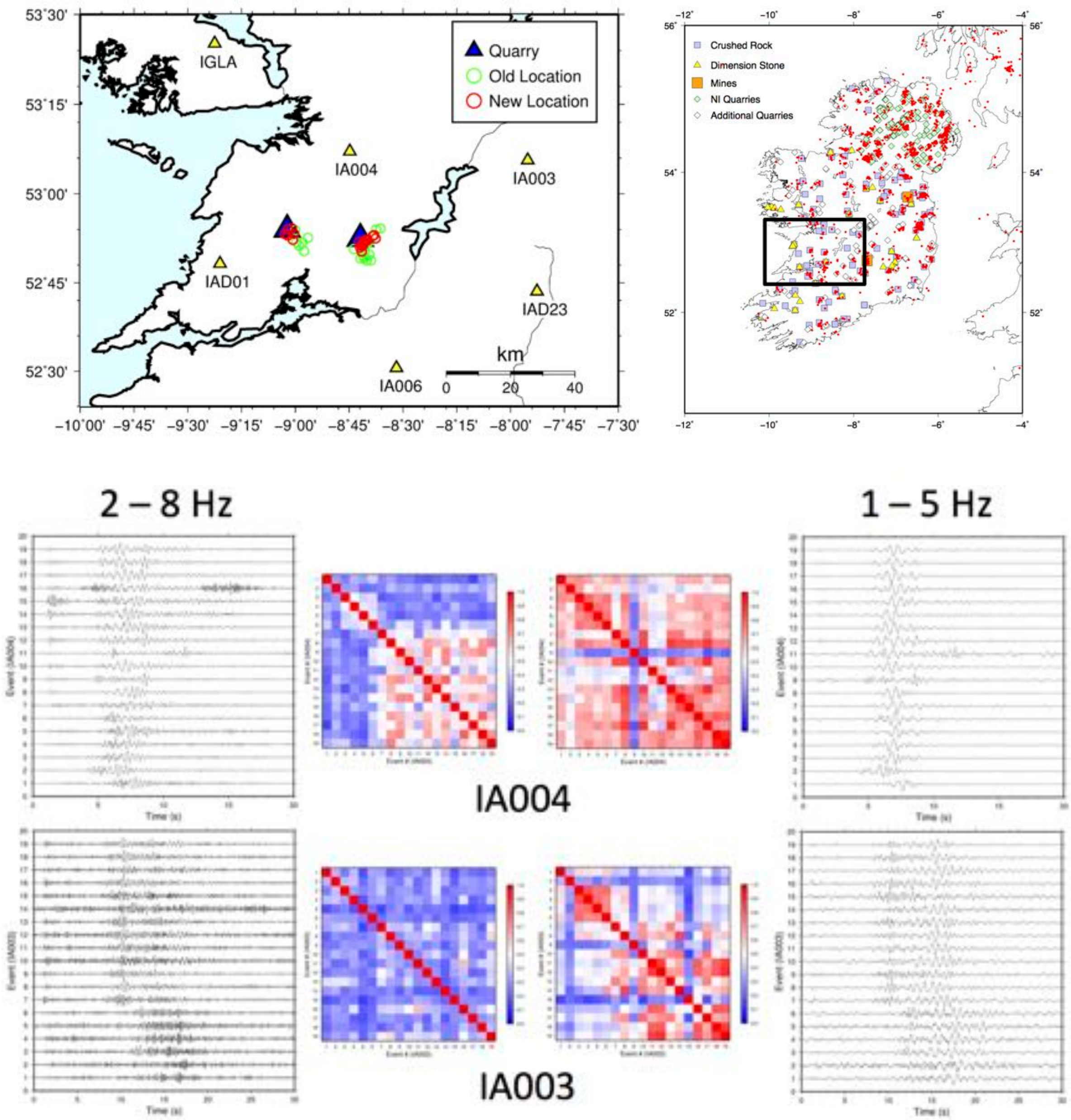

Figure 7. Upper left: Map of Ennis and Tulla quarries (Co. Clare). Old and new locations correspond to preliminary locations and relocated epicenters, respectively. Location of the study area within Ireland is shown on the right. Lower panel: Filtered waveforms and correlation matrices computed at two stations for the events shown on the map. Events 1 to 6 correspond to the westernmost quarry; events 7 to 19 correpsond to the easternmost one.

Identification of repeating earthquakes

We also computed the cross-correlation matrix at the six permanent stations of the INSN for known, catalog earthquakes. This allows the identification of clusters that can subsequently be relocated using relative location techniques. Figure 8 shows the correlation matrix calculated at IDGL, a station located in Co. Donegal, one of the most seismically active regions of the country. The 43 analyzed events for which a pick was available at IDGL since 2010 are sorted by chronological order. The large subset of highly correlated events (events 23-43) corresponds to detections performed by SIM-CRUST, a temporary, dense network of 10 broadband seismic stations deployed in 2012 by DIAS. That array allows to monitor local seismic activity with a better coverage and lower detection thresholds than permanent stations alone. Groups of repeating events can be identified from inter-event correlation values by cluster analysis. Here, we show an example of how hierarchical clustering can be used to reorder the correlation matrix so as to associate events sharing high correlation values. Figure 8 also demonstrates that clustering was successful at associating close events (see in particular the red cluster). Application to the entire event database (natural + man-made) will allow to identify groups of events that will be jointly relocated using relative location techniques.

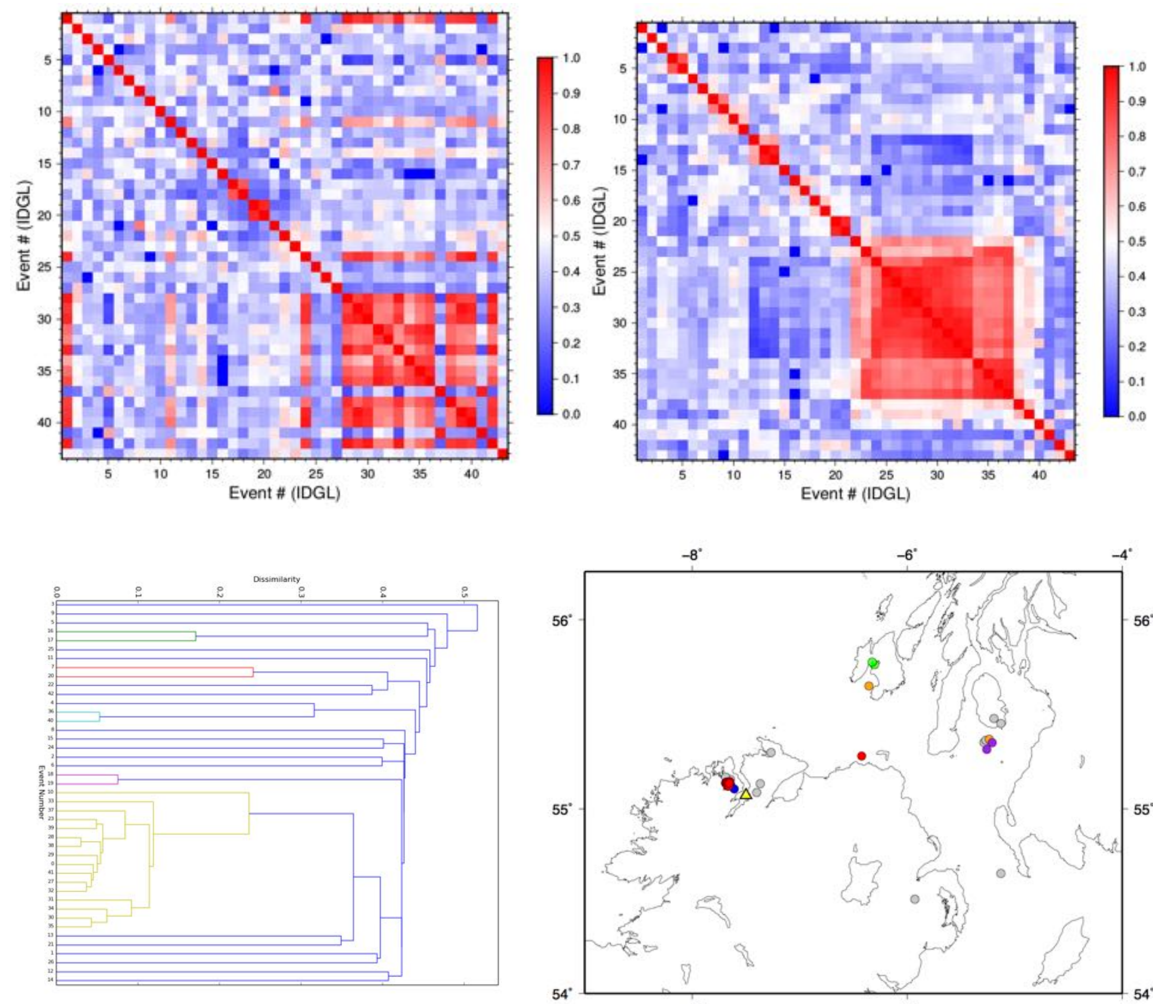

Figure 8. Upper left: Correlation matrix for the 43 events recorded at IDGL. Upper right: Re-ordered correlation matrix after event association by hierarchical clustering. Lower left: Dendrogram plot showing the principle of hierarchical clustering. Lower right: Map of the clusters identified at IDGL from hierarchical clustering. Different colors show individual clusters. Note the most prominent one shown in red. Grey circles are events not associated to a cluster.

Discrimination between natural and man-made seismicity

The data recorded by SIM-CRUST provided an opportunity to compare waveforms from natural and man-made seismic events in the same region and test the ability of cross-correlation to discriminate between them. Figure 9 shows a map of 14 earthquakes and 3 quarry blasts having occurred within the area covered by that array during the period 2013-2014, along with the observed waveforms and correlation matrices computed at IDGL permanent station. It appears quite clear that the natural events and quarry blasts respectively form two distinct families. Earthquakes all correlate well with each other, at the exception of one event located southeast of the main cluster. The three quarry blasts, as in the previous example, tend to be associated with slightly lower correlation values, but their clear lack of correlation with the natural events demonstrates that discrimination based on waveform cross-correlation is possible, providing that the nature (natural/man-made) of some events has independently been assessed. Modifications to the original technique might however be needed, as stated earlier.

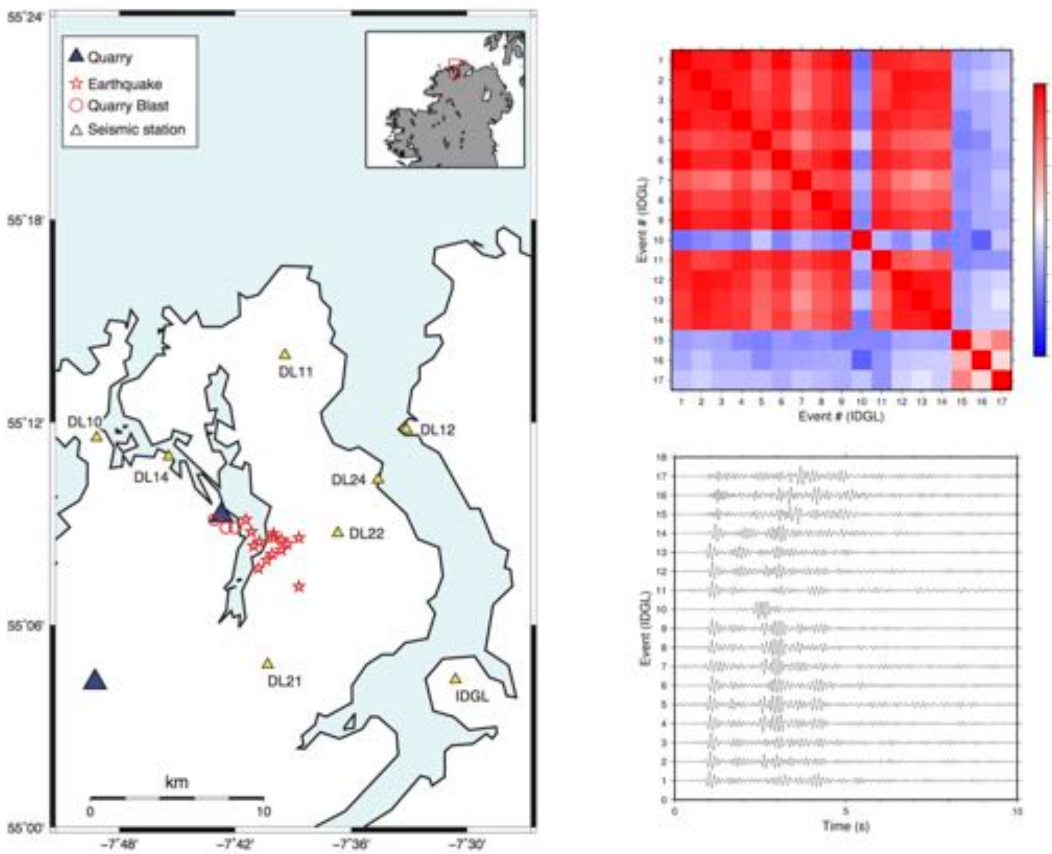

Figure 9. Left: Map showing 14 natural and 3 man-made events in the region of Donegal. Upper right: Correlation matrix for the earthquakes (1-14) and quarry blasts (15-17), for station IDGL. Lower right: Associated seismograms, filtered between 2 and 8 Hz.

New earthquake identification using cross-correlation

We also used cross-correlation using previously known events as templates to identify new events in the continuous waveform data. Figure 10 shows the waveforms of 10 new earthquakes identified in the region of Donegal using data from station IDGL, and Figure 11 the waveofrms of 3 new earthquakes identified in the region of Cork using station UGAL1 (belonging to WaveObs array, see Figure 1). Further cross-correlation using all known events as templates led to nearly 200 new detections, while the current catalogue counts 62 events in total.

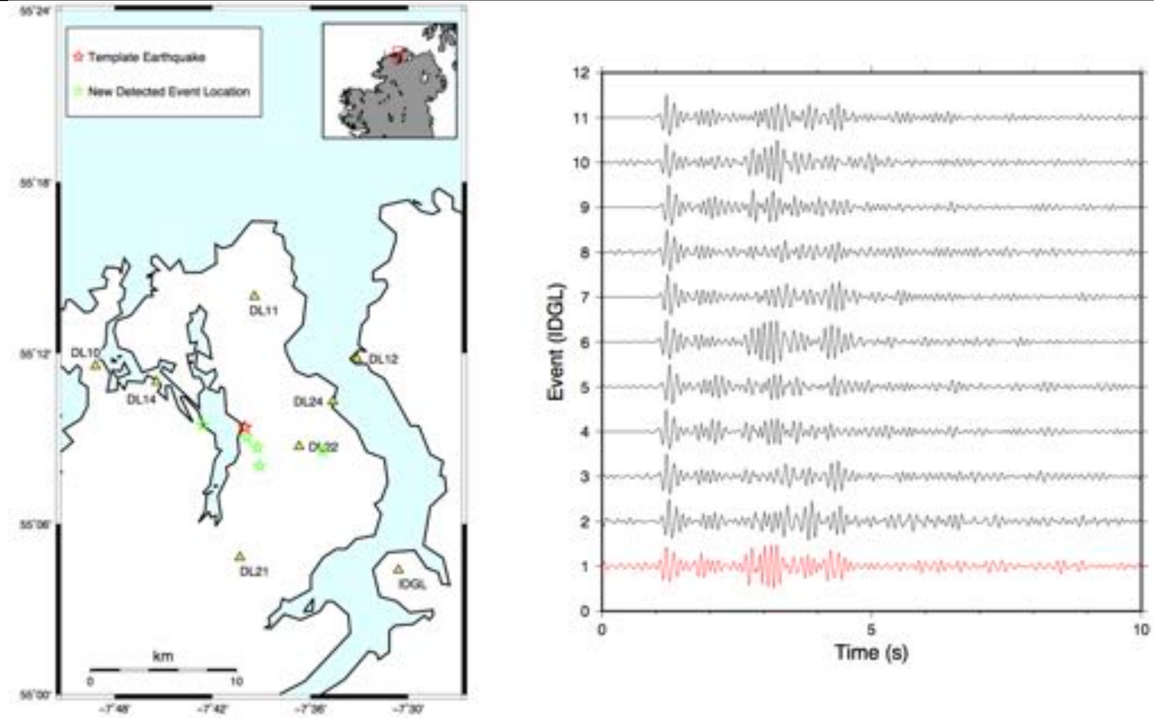

Figure 10. New detections from the continuous waveform database in the region of Donegal. Left: map of locatable events. Right: Associated seismograms for the template (red) and additional events (black).

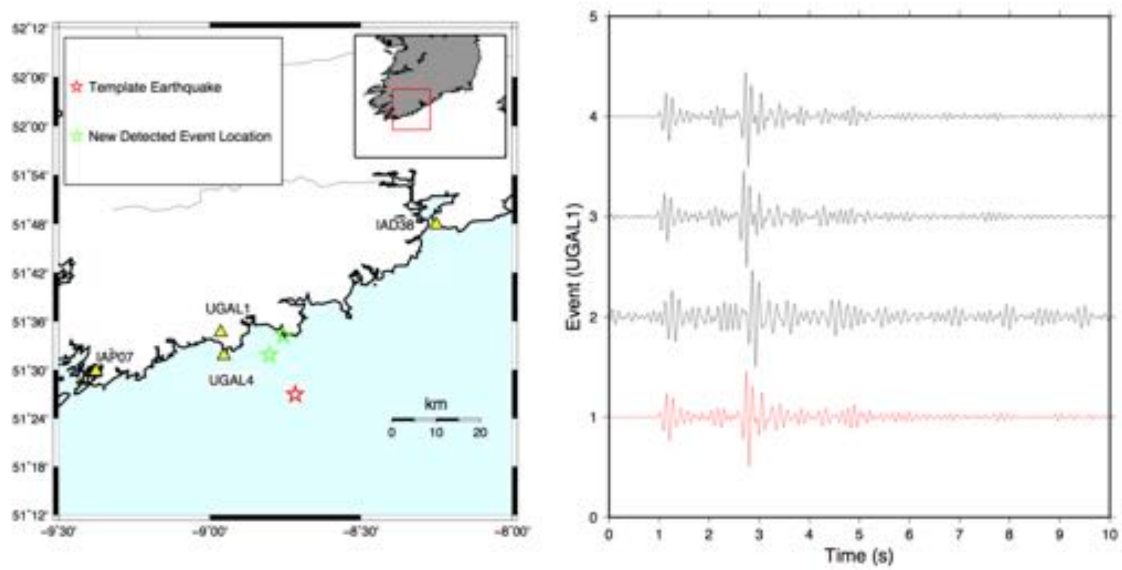

Figure 11. Same as Figure 9 in the region of Cork. Note that these are preliminary locations.

Spectral characteristics of earthquakes and quarry blasts

One goal of this project was to compute spectral ratios for quarry blasts and earthquakes in order to use them as a discriminant between natural and man-made seismicity. We computed P and S wave displacement, velocity and acceleration spectra on all components of available seismograms for which a phase pick was performed. However, due to the success of other components of the project, spectral ratios could not be computed and analyzed in the framework of this short call.

References

Landes, M., Ritter, J. R. R., Readman, P. W., O'Reilly, B. M, A review of the Irish crustal structure and signatures from the Caledonian and Variscan Orogenies, *Terra Nova*, 17, 111-120, 2005.

Licciardi, A., Piana Agostinetti, N., Lebedev, S., Schaeffer, A. J., Readman, P. W., Horan, C., Moho depth and Vp/Vs in Ireland from teleseismic receiver functions analysis, *Geophys. Journ. Int.*, 199, 561-579, 2014.

(ii) Implementation (including reference to timelines, milestones, management)

We managed to hire an experienced pre-doctoral scholar, James Grannell, for a duration of 1 year, starting on January 1st, 2016. Due to the large amount of data to process, we later decided to hire two interns, James Murphy and Andrew Baird, to help with the phase picking. Milestones were all completed in due time, although the spectral characteristics of earthquake and quarry blast waveforms have not been fully analyzed, as explained in the previous section. Note however that the spectra have all been calculated and are ready for future analysis, and in that respect represent an important output of this work. Management meetings have been held monthly, as indicated in the proposal, except in July since all the participants could not be present.

(iii) Outputs (please use bullet points)

- New, detailed earthquake catalogue for Ireland and neighbouring offshore domains for years 2010-2016.
- Online database of Irish earthquakes available on the INSN website: https://www.insn.ie/confirmed/
- Waveform database of Irish quarry and mine blasts for period 2013-2015.
- Updated database of active quarries in Ireland.
- Calalogue of more than 15,000 P- and more than 20,000 S-wave arrival times for natural and man-made seismic events having occurred in Ireland between 2010 and 2015, that will be used for 3D imaging of the crust and upper mantle beneath Ireland.
- Database of P-, S- and surface-wave spectra of natural and man-made Irish seimic events.
- Presentation of preliminary results at the 59th Irish Geological Research Meeting (IGRM) conference (Galway, 19-21 February 2016).
- Presentation of results at the European Seismological Commission (ESC) conference (5-9 September 2016, Trieste, Italy).

Impact/value of the project (M*ax 500 words*):

The new earthquake locations obtained in this work, as well as the new events detected, provide a new, accurate and more complete catalogue of seismicity that will benefit both seismotectonic and seismic hazard studies of Ireland and Great Britain. The large number of P- and S-wave arrival times that were picked in the course of the project furthermore provide a unique dataset for high-resolution, 3D seismic imaging of the region. The 3D model that will be obtained will enhance our knowledge of the geology of Ireland at depth, and will help provide more accurate seismic event locations in Ireland and its surrounding offshore basins. New detection and discrimination tools were developed, that can now be implemented for real-time monitoring to help the analysts of the INSN. Communication of results to the earth science community was achieved at one national (IGRM 2016) and two international conferences (EGU 2016, ESC 2016). We also plan to publish the results obtained in this work in at least one international journal.

Appendix 1 – Publications & Presentations:

Arroucau, P. Lebedev, S., Grannell, J., Möllhoff, M., Bean, C. J., Horan, C., Blake, T., New estimates of seismicity rates in Ireland, *35th General Assembly of the European Seismological Commission*, Trieste, Italy, 4-11 September 2016.

Grannell, J., Arroucau, P., Lebedev, S., Möllhoff, M., Bean, C. J., Horan, C., Blake, T., Towards an improved catalog of Irish seismicity in the years 2010 to 2015, *35th General Assembly of the European Seismological Commission*, Trieste, Italy, 4-11 September 2016.

Möllhoff, M., Bean, C. J., Arroucau, P., Grannell, J., Regional network performance estimation based on ambient noise amplitudes, *35th General Assembly of the European Seismological Commission*, Trieste, Italy, 4-11 September 2016.

Arroucau, P., Lebedev, S., Grannell, J., Horan, C., Blake, T., Bean, C. J., Towards a new earthquake catalog for Ireland and its near offshore domains: a joint analysis of permanent and temporary seismic array deployments, *EGU General Assembly*, Vienna, Austria, 17-22 April, 2016.

Arroucau, P. Grannell, J., Lebedev, S., Bean, C. J., Horan, C., Blake, T., The seismicity of Ireland, *59th Irish Geological Research Meeting,* Galway, Ireland, 19-21 February, 2016.

Grannell, J., Arroucau, P., Lebedev, S., Bean, C. J., Horan, C., Blake, T., Natural and man-made event detection and discrimination in Ireland, *59th Irish Geological Research Meeting,* Galway, Ireland, 19-21 February, 2016.

Appendix 2 – Any additional information not included above: