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SIM-CRUST Project - Seismic Imaging and Monitoring of the Upper Crust: Exploring the Potential Low-Enthalpy Geothermal Resources of Ireland

Nicola Piana Agostinetti[1] and Andrea Licciardi[1,2]

[1] Geophysics Section, School of Cosmic Physics, Dublin Institute for Advanced Studies, Dublin, Ireland

[2] School of Geological Sciences, University College Dublin, Ireland

piana@cp.dias.ie

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ABSTRACT

The SIM-CRUST project is focused on the development and application of passive seismic techniques to geothermal research. Controlled-source seismology has been widely used as a standard tool for geothermal exploration in the past decades. However, attenuation and scattering from complex, shallow crustal structures can blur the reconstructed image of the subsurface due to the low-energy content of the sources. Passive seismics make use of natural seismicity to explore the subsurface elastic properties. Both local and distant earthquakes can be used to evaluate seismic velocity at depth, and to constrain the presence of seismic anisotropy, which relates to both fluids and cracks in the rock matrix.

The main activities of the project are focused on two widely used techniques: the Local Earthquake Tomography and the teleseismic Receiver Function. The former technique is based on the analysis of microseismicity (Mw less than 3.0) within small (D less than 40km) regions and can be used both to build 3D model and to monitor the time-evolution of the seismic properties of the investigate volumes. The latter technique makes use of teleseismic converted waves to map sharp velocity contrasts at depth (e.g. the sediment-basement interface) with a resolving power of some hundreds of meters.

The SIM-CRUST project comprises the development of two high-density (inter-station distance less than 10km) seismic networks to explore the Donegal granite region and the Dublin basin, and it will benefit from and integrate results of the IRETHERM.

1. INTRODUCTION

Detailed models of the shallow structure of the Earth's crust are facing an increasing interest from the wide scientific and industrial community, related to the growing number of activities for the exploitation of its resources, e.g. CO_2 storage and heat extraction in low-enthalpy geothermal sites. In the latter case, a refined crustal model, in the 0-5 km depth range, is fundamental to minimize the risk of drilling not-productive boreholes. Geophysical investigations have been widely employed to reconstruct the structure of the shallow crust during the planning phase of a geothermal site, e.g. gravity and magneto-telluric surveys. Elastic properties of rocks composing the geothermal reservoir are usually modelled via active seismics experiments. Such methodology gives a high definition image of the seismic reflectors at depth, subsequently interpreted as interfaces between different geological unities using litho-stratigraphy from near-by boreholes. However, three main issues limit the potential of active seismics. First, strong shallow reflectors limit the resolution of deep interfaces. Second, deep active seismics cannot be easily operated in a heavily populated environment. Last but not least, the financial cost of an active seismic survey is quite elevated.

Passive seismic techniques result to be a valuable alternative to active seismics. Passive seismics has been widely used to reconstruct elastic models of the Earth's crust analysing natural seismicity, both local (e.g. microseismicity) and far seismic events (e.g. teleseisms). P- and S- waves generated from local events and recorded from a dense seismic network can give independent estimates of the 3D distribution of elastic properties within the crust directly beneath the network (i.e. so called "Local Earthquakes Tomography", LET). Teleseismic P-to-s converted waves can be used to image the main seismic velocity discontinuities beneath a single seismic station (i.e. so called "Receiver Function", RF, method). In particular, RF analysis can put constraints on the presence of seismic anisotropy at depth, which, in turn, is tightly related to the presence of fluids and oriented cracks within the shallow crust. Both methods can be applied to local seismic network continuously operated for a variable number of months (depending on the rate of microseismicity in the area, and on the geographical distribution of seismogenic area at teleseismic distance) and can be used to put constraints on the seismic structure of the shallow crust.

The SIM-CRUST project is focused on the development of new methodologies for both the analysis of RF data-set and the solution of the LET inverse problem. Such new techniques are tested on the seismic data recorded across Ireland in two key areas, the Donegal granite region and the Dublin basin, which have been previously identified as potential geothermal sites in Ireland.

2. METHODOLOGY

2.1 Local earthquake tomography

Local Earthquake Tomography (LET) is a non-linear and non-unique inverse problem, which makes use of P and S arrival times to depict an image (also called a "solution") of the elastic properties in a given crustal volume. Iterative linearized approaches are widely applied to solve it, but require a number of subjective choices to be made: (1) the "starting model", which is step-by-step perturbed, (2) the definition of the preferred solution, e.g. the best-fit model, the minmax model or the maximum likelihood model, (3) the method used to quantify the uncertainties associate to the preferred solution and (4) the regularization function, which is used to smooth the solution itself.

The algorithm we are developing within the SIM-CRUST project uses a trans-dimensional Markov chain Monte Carlo (McMC) to compute the posterior probability distributions of the elastic properties of the subsurface, the hypocentral parameters, and the data noise (Piana Agostinetti et al., submitted to *Geophys. J. Int.*) The method is developed in a Bayesian framework, where "a-priori" information is explored according to the Metropolis rules, to asymptotically produce a sampling from the posterior probability distribution of each investigated parameter. This approach allows us to reduce the number of "a-priori" assumptions made by the user. First, random sampling of the prior probability distribution makes the solution independent from the starting model of the McMC, after a burn-in period. Given the posterior probability distribution of each parameter, collected at the end of the McMC, a number of different estimators can be considered to produce the preferred model. The reconstruction of the posterior probability distribution of the data noise, which directly influences the uncertainties in the preferred model, gives us a robust estimation of the theoretical and experimental errors. Finally, the elastic model parameterization is considered as part of the inverse problem, so that the number of elastic parameters in the model is an unknown itself. This fact guarantees that the final resolution and smoothness of the preferred solution is completely dictated by the data.

Due to the use of repeated forward solution instead of matrix inversion, the approach sketched above can easily be applied to areas with a low rate of seismicity. In fact, linearized methods become unstable with a limited number of data due to numerical instability of the matrix inversion and derivatives computation. McMC methods can correctly exploit limited information available in a limited data-set. This behavior can be fundamental in region, like Ireland, where few seismic events of low magnitude are expected.

2.2 Receiver function

The teleseismic Receiver Function (RF) technique has proven to be an effective tool in imaging Earth's structure from the crust to the upper mantle. A P-wave generated by a teleseismic earthquake is partially converted into an S-wave as it travels through different velocity contrasts in the path between the source and a seismic station located at the surface (Fig.1). The signal generated by each of these conversions is contained in the P-wave coda recorded by the sensor and usually confined in the first seconds after the direct P arrival. Removing the source and path effect by deconvolving the vertical component from the radial and the transverse ones of the observed seismograms, allow isolating these conversions into two time series named the Radial (R) and the Transverse (T) RF (Langston, 1979; Ammon, 1991). The delay time of each conversion is a function of the depth of the interface that generates it, while the amplitude is proportional to the size of the velocity contrast at depth. In a medium that is horizontally isotropic, all the conversions due to impedance contrasts at depth are observed in the RRF while no energy should be present on the TRF. The presence of anisotropy or dipping interfaces in the subsurface causes the energy to rotate out of the plane of the incoming wave field and gives a contribution to the TRF with known pattern of variations as a function of the backazimuth (Levin & Park, 1998; Savage, 1998). To highlight this effect a good azimuthal distribution of events is required and, depending on the S/N and the quality of the site, this is achieved in at least one year of continuous recording period.

Recently, Leahy et al. (2012) have shown that just by increasing the frequency content in the observed RF one can easily increase the resolving power of the RFs data-set up to some hundreds of meters, allowing for the imaging of the seismic discontinuities in the shallow crust (0-10 km depth); other studies have successfully compared RFs with boreholes litho-stratigraphy (Amato et al., submitted to *J. Geodyn.*).

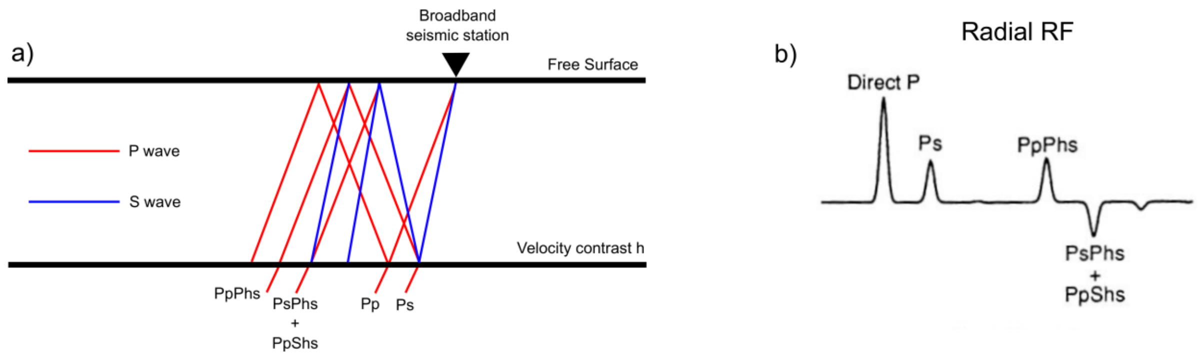

Figure 1. Diagram of ray partitioning at a seismic velocity contrast h (a) and corresponding observed Radial RF (b), modified from Ammon (1991). Upgoing travel paths are labelled with lower case letters, downgoing travel paths with upper case letters.

3. DONEGAL ARRAY

3.1 Donegal seismic network

Granites are considered a possible "reservoir" for a low-enthalpy geothermal site, where heat is actively extracted from deep crystalline rock heated by the decay of radioactive elements (i.e. Hot-Dry Rock technology). Due to this, fluids are injected at depth from a first deep borehole, and, then, circulated through fractures in the granites before being extracted from a second borehole. Artificial stimulation of the geothermal site using high-pressure injection increases the number of fractures in the granites and their interconnections. Post-orogenic granites partly outcrop along the NW Atlantic coast of Ireland in Co. Donegal. Such formation has been indicated as a possible target for a low-enthalpy geothermal site based on Hot-Dry Rocks technology (Goodman et al., 2004) and it has been selected as one of the key- area of the IRETHERM project. However, due to the lack of deep-drilled boreholes (more than 1000m deep), the heat flow density data currently available do not clearly indicate a promising site for geothermal exploitation. The granites are supposed to be buried at shallow depth in the Eastern part of Co. Donegal, where low-magnitude seismic sequences have been recorded in the past decades (Lebedev et al., 2012). Natural seismicity indicates the presence of secondary porosity, which turns out to be a viable pathway for fluid circulation.

To reconstruct the geometry of the buried granites across Eastern Donegal, we installed a seismic network that covers approximately a 40x40 km area (Fig. 2). The seismic network comprises 10 temporary seismic stations equipped with Guralp CMG-T40 broadband sensors, and a permanent seismic station equipped with a Trillium-120 sensor. Other temporary stations across Co. Donegal are also acquired and analysed to extend the area covered by our study. The seismic network will be operated for two years. Continuous recording from all the stations will be archived at DIAS and analysed using different passive seismic techniques.

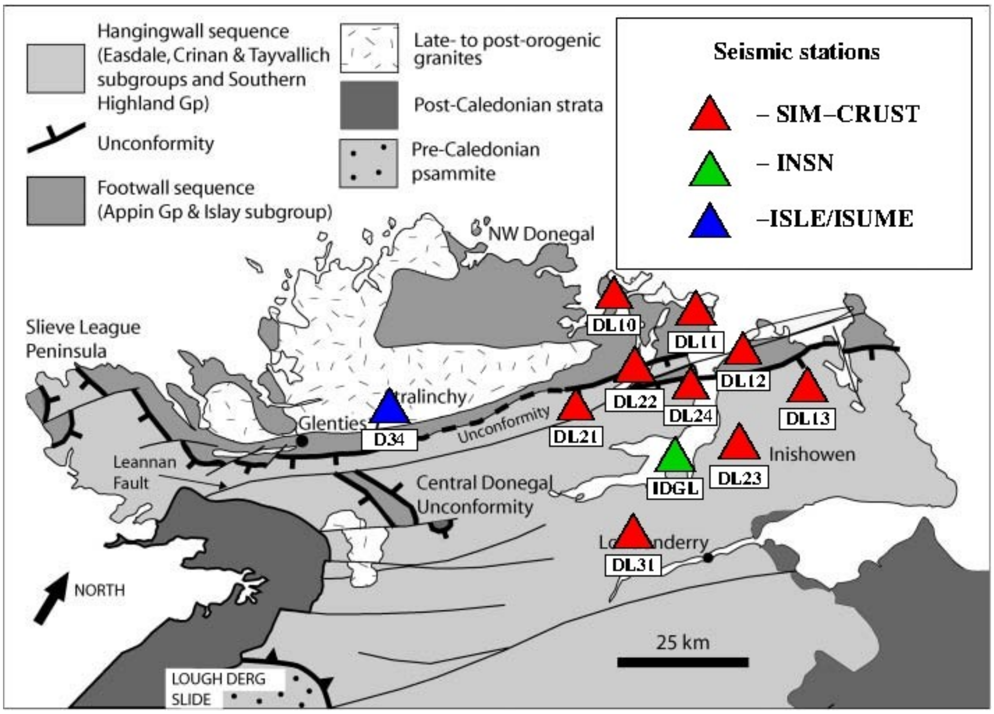

Figure 2. Map of the seismic network operated by DIAS in Donegal. Red triangles represent broadband seismic stations deployed in Co. Donegal in the framework of the SIM-CRUST project. Green and blue triangles show seismic stations belonging to the Irish National Seismic Network and project ISUME, respectively. The seismic network covers the area across the main geological structures in the region and (possibly) overlies buried granites. Modified from Hutton and Alsop (2004).

3.2 Seismic data at DL21: teleseismic, regional, local and anthropogenic events

Seismic data recorded at each station have been analysed during the first year of the project, to assess the quality of the seismic site for the detection of seismic signals of different nature. Due to the presence of low-rate microseismicity in the Northern part of Ireland, seismic records of local event have been also analysed to refine the location of seismic event in the area. Here, we present seismic signals recorded at station Dl21, near Milford (Donegal). The station is located about 6 km away from the epicentral area of the Mw=2.2 event recorded on Jan 26th 2012 (Lebedev et al., 2012)

Teleseismic data (Fig. 3a) show the arrivals from all the expected phases (P, S, SKS body waves, and Love and Rayleigh surface waves). Clear P- and S- wave on-set make these records useful for both P- and S- Receiver Function. Records of a low-magnitude regional event occurred in Scotland (Fig. 3b) display Pn arrivals. Such arrivals are usually investigated to reconstruct Vp velocity models on a 1000-km lateral scale. A local event occurred in Coleraine (about 60 km away) is clearly recognizable in the data recorded at this seismic station. This fact demonstrates the high S/N ratio for station DL21, optimal for the detection of very low-magnitude events. Finally, anomalous coherent seismic signals have been recorded throughout the seismic network (Fig. 3d). A detailed analysis of such signals allowed to precisely constrain the source location near an active quarry, suggesting an anthropic nature of these peculiar seismic waves. In addition, documented quarry blasts can be exploited to provide independent estimates of the location accuracies and uncertainties retrieved by the array.

3.3 Location of a microseisms: the Apr 29th 2014 Mw=0.8 event

Precise location of microseismicity is fundamental to reconstruct the 3D seismic properties of the beneath the seismic network and to better constrain the rock volume in which secondary porosity can be present. While microsesimicity is quite common in the eastern part of Co. Donegal, its location has been barely possible in the past, due to the lack of close seismic stations. Using a single station in the first 60 km from the epicentre can result in location error as large as 15 km (see Lebedev et al., 2012, for an example in Co. Donegal). Thus, the data recorded by the SIM-CRUST seismic network are fundamental to better locate the seismic event in Donegal and reconstruct a 3D velocity model for the area.

In Figure 4, we present the preliminary location of a small event that occurred in Co. Donegal during the deployment of the seismic network. The data show clear P- and S- arrivals (Fig. 4, right panel) that can be used to better constrain both the epicentre and the source depth. The event is located directly below one of the stations in the seismic network (Fig. 4, left panel), resulting in a source depth of 4.7 km.

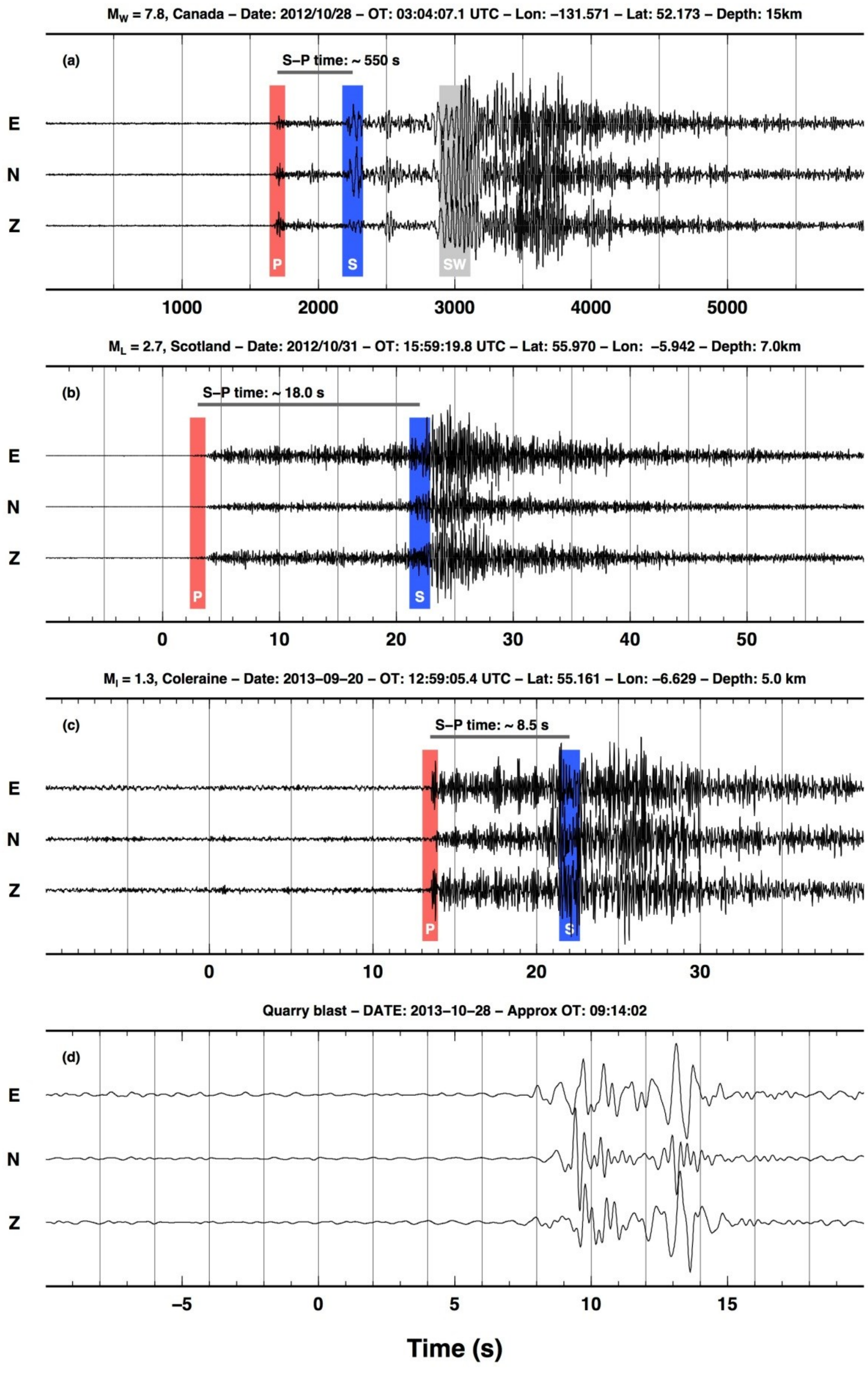

Figure 3. Examples of seismic data recorded at station DL21 (Milford, Donegal). Each panel displays three components (E- East-West, N- North-South, and Z- vertical) of the ground motion. Red and blue bars indicate P- and S- waves, respectively. The difference between S- and P- arrival time (S-P time) is proportional to the earthquake distance from the seismic station (a) Example of teleseismic event: Mw=7.8 earthquakes occurred along the Pacific coast of Canada. A grey bar indicates the Surface waves. (b) Example of regional event: Mw=2.7 earthquake occurred in Northern Scotland. (c) Example of local event: Mw=1.8 earthquake occurred near Coleraine (Northern Ireland). (d) Example of seismic waves generated from human activities: a quarry blast occurred about 10km from Milford. Data have been filtered using a low-pass filter at 4Hz.

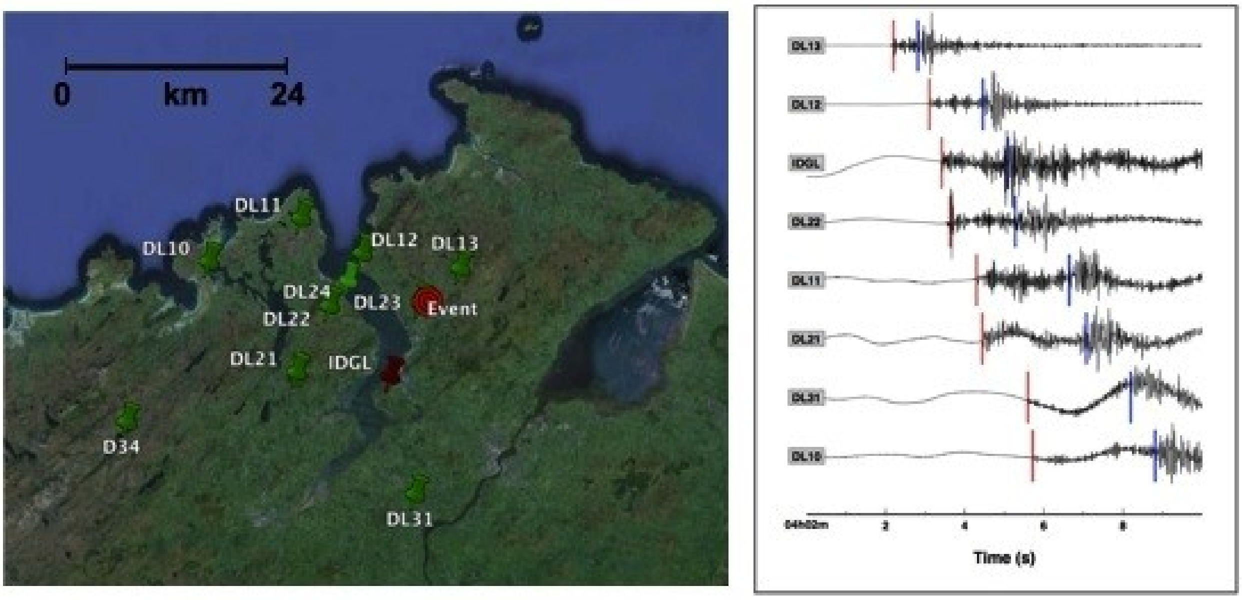

Figure 4. Location of the Mw=0.8 seismic event occurred on April 29th 2014 in Donegal. (left) Green and red pins indicate temporary and permanent seismic stations (SIM-CRUST project - temporary stations; INSN - permanent station). A red target shows preliminary location of the seismic event. (right) Vertical components of the seismic records, at different stations of the seismic network. Red and blue dashes indicate P and S seismic waves generated from the earthquake, respectively.

4. DUBLIN BASIN ARRAY

4.1 Dublin Basin seismic network

The Dublin Basin (DB) is a Carboniferous sedimentary basin located in the eastern part of Ireland, SW of Dublin (Fig. 5). In the last years, the SW margin of the basin and in particular the area close to the ENE trending Blackrock-Newcastle Fault (BNF) has been the object of interest for geothermal exploration, which led to the acquisition of two reflection seismic lines and the drilling of two ~ 1.4 km deep boreholes, from which a temperature of 130 °C at ~4 km depth has been estimated.

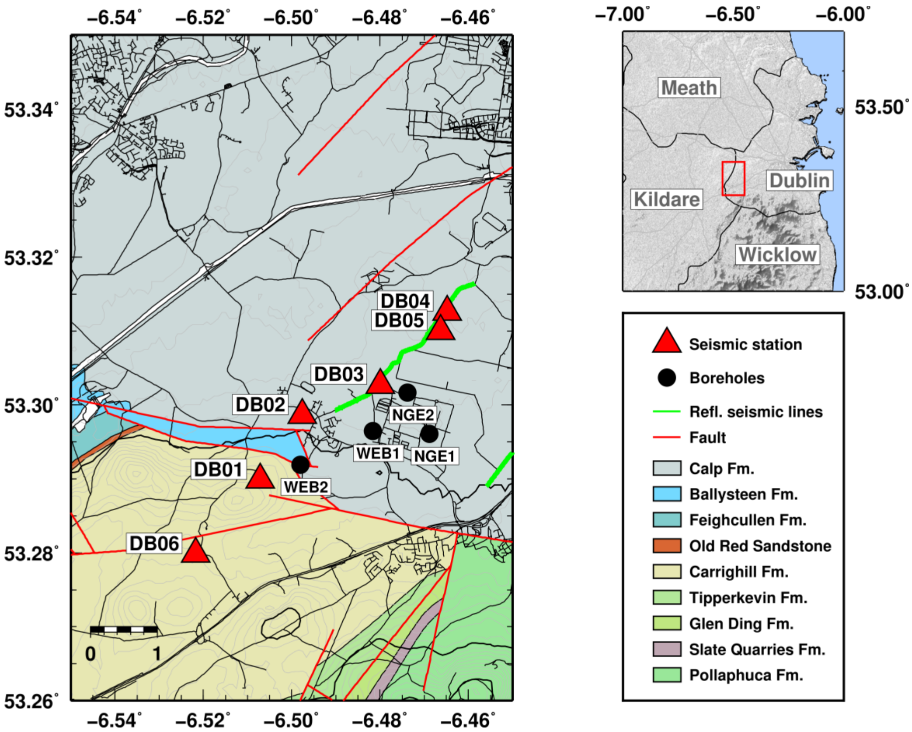

Figure 5. Location of the seismic stations deployed in the Dublin Basin and geology map of the area (left). Four stations belonging to University College Dublin (UCD) are recording since August 2013 (DB01, DB02, DB03, and DB04), DB04 has been redeployed as DB05 and DB06 has been installed in April 2014. Each of them is equipped with a broadband Guralp CMG-6TD sensor. The array is located on the south-western margin of the Dublin Basin defined by the Blackrock-Newcastle fault system and has been designed to cross it almost perpendicularly.

The geothermal potential of the DB is associated with the intense fractured rocks along the SW margin and with the presence of fluids, observed by the geophysical survey conducted by GTEnery at a depth of about 1.2 km. This high secondary porosity zone is overlain by a less porous sequence of sediments which would trap the heat at depth. This promising structural setting has been correlated with one of the shear dilatation zone described by Rothery et al. (1983) that are thought to be present along the SW margin of the DB, in the lower part of the Carboniferous succession. However, most of the area is still unexplored and the deeper geological relationship between the BNF, the sedimentary succession, and the Lower Palaeozoic basement are mostly unknown. Even the depth to the basement is poorly constrained, as none of the boreholes drilled so far have encountered it, which is hence located at a depth greater than 1.4 km in this area.

In the context of the SIM-CRUST project, an array of 5 broadband seismic stations has been deployed in the area to test the possibility of retrieving the seismic stratigraphy of the shallow crust (0-10 km depth range) by means of a high frequency teleseismic Receiver Function (RF) analysis. The closed spacing of the array will provide high resolution images of the impedance contrast at depth. The first aim of the project is to apply such technique to the geothermal exploration of the DB, providing the imaging of the complex BNF system and a precise quantification of the thickness of the Carboniferous sedimentary sequence inside the basin.

In a later phase of the study, based on the amount of high quality data, an anisotropic approach to the RF analysis will allow to constrain the presence of fluids at depth and their mapping along the length of the array.

4.2 Data

Starting in July 2013, 4 broadband seismic stations equipped with a Guralp 6TD have been deployed along the south western margin of the basin where the BNF trends WNW and is intensively displaced by other minor splay faults. During April 2014 one of the stations (DB04) has been re-deployed very close to the previous site (DB05) and the linear geometry of the array has been further extended toward SW by adding one more station (DB06) of the same type. Hence, the final configuration of the array crosses the BNF almost perpendicularly and, relying on an interstation distance of about 1 km, will allow a high resolution imaging of the transition between the SW margin to the inner portion of the sedimentary basin. The array will operate until January/February 2015, providing teleseismic data with a fairly good azimuthal coverage. We selected teleseismic events with magnitude > 5.5 and epicentral distances between 30° and 100° from a list of events occurring between July 2013 and January 2014 and performed a visual inspection of the waveforms. Only those with a clear P arrival and good S/N were retained.

The horizontal components were rotated in the RTZ coordinate system and RFs were computed with the frequency domain deconvolution method proposed by Di Bona (1998), manually selecting only those with small ringing and low amplitude in the acausal portion of the trace. The final azimuthal distribution of events for which RFs have been calculated and then selected is shown in Figure 6 for station DB03, which is the one so far with the longer recording period and higher S/N. In order to increase the azimuthal coverage we also included a number of events coming from greater epicentral distances. In these cases the exact same kind of analysis is performed over a different seismic phase (Pdiff).

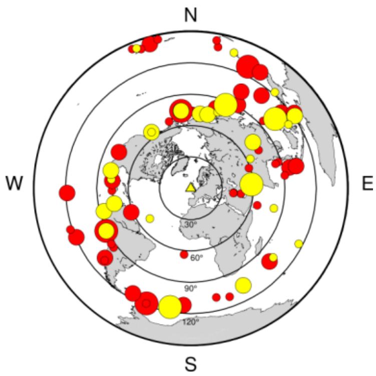

Figure 6. Azimuthal equidistant projection centered at station DB03, showing an example of the teleseismic earthquakes and RFs data-sets selection. Events from 30° to 100° of epicentral distance have been visualized for the corresponding recording period. Red circles are the events selected after a visual inspection for which RFs were computed. Yellow circles represent the final set of high S/N RFs, used for further analysis. More distant earthquakes have been included as well to fill some gaps in back-azimuthal directions.

3.2 Preliminary results

In Figure 7 we show an example of RFs computation for 4 different recorded earthquakes. The Z components of the seismograms at each station are plotted in the topmost panel and a good S/N ratio is observed for these selected events. The resulting RFs (plotted for a cutoff frequency of ~1H) are drawn in the lowermost panel together with the rotated components in the ZRT coordinate system.

The positive pulse at 0s corresponds to the direct P wave arrival, while all the following pulses are either conversions at a true velocity discontinuity or reverberatory phases (Fig. 1). The positive (blue) pulses correspond to a P to S conversion at an interface with a positive jump in velocity with the increasing depth, while the negative (red) pulses are associated with velocity inversions at depth. Despite the good S/N ratio and the relatively moderate ringing in the RFs, the resulting time series are rather complicated, and a complex ensemble of pulses are observed. This feature is consistent with what one would expect in a sedimentary basin setting, as the reverberations in the pile of sediments strongly complicate the observed waveforms. In order to increase the S/N ratio in the RFs, enhancing the true conversions and reducing the incoherent noise, one can perform a simple stack of many RFs computed from a large number of events from different backazimuth and epicentral distances. In this way, a mean RF representative of the volume of the subsurface sampled by the incoming rays can be obtained.

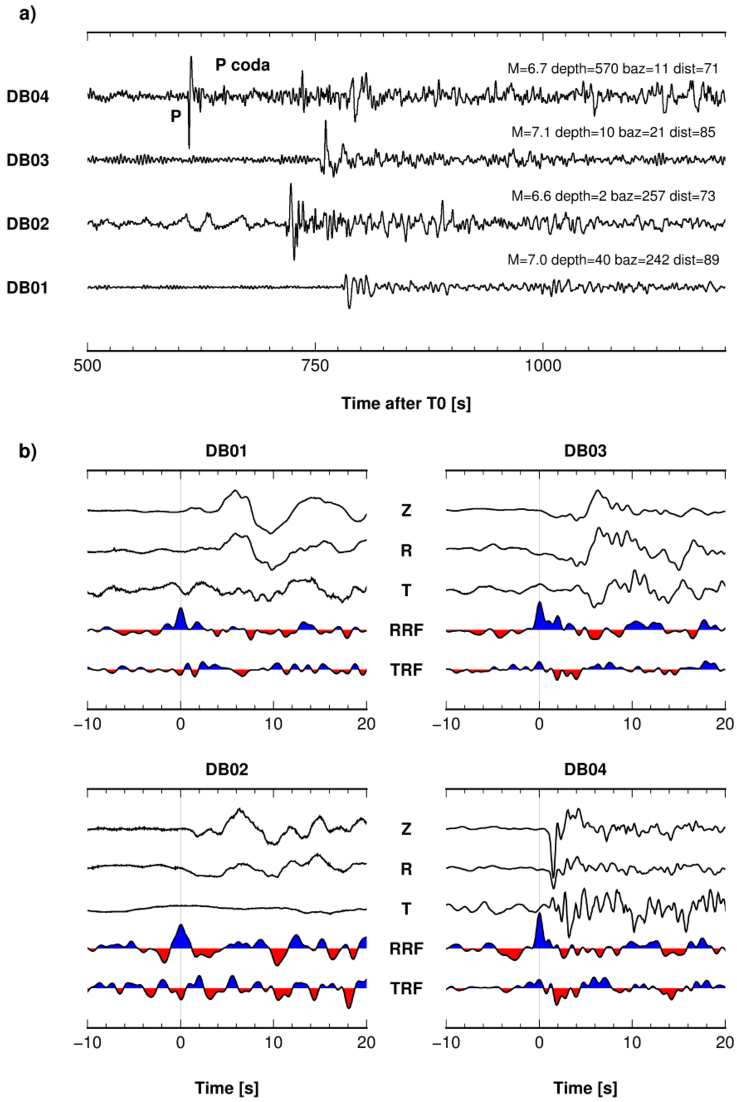

Figure 7. Example of RF computation for 4 different recorded earthquakes. a) The Z components of the seismograms are plotted for each station, with information about the events above the corresponding trace. Traces have been low pass filtered to 1 Hz. b) Rotated components of the seismograms (RTZ) and the resulting RRF and TRF for a cut-off frequency of 1Hz. The plotted time window starts 10 seconds before and ends 20 seconds after the P wave arrival for each event. Complicated waveforms are observed reflecting the complex setting of the sedimentary basin.

In this preliminary work, based on the first 6 months of data, we focus our attention on the RRFs, which in principle contain the signal generated by the isotropic structure under each station, as the analysis of the TRFs requires a more complete azimuthal coverage of events which is not available yet. To test whether the shallow structure (first 10 km) under the DB can be resolved by these data, we computed different data-sets for multiple values of the cut-off frequency, progressively increasing the frequency content in the calculated RFs, starting from ~0.5 up to ~8 Hz and then we stacked all the resulting RRFs at each station. The results are shown in Figure 8. Increasing the frequency content in the RF highlights the presence of signals in the first second after the direct P arrival. For stations DB01, DB02 and DB03, a negative pulse at about 0.3-0.5 s begins to be visible at ~4 Hz while it is not present at DB04. This is interesting because it is directly related to the location of the station with respect to the BNF. Between 0.6 and 1 s (4Hz) a positive pulse is observed at all the stations with an increasing delay time moving away from the BNF. However at 8Hz it separates in two small pulses at DB01 and DB02 while it remains a single feature at DB03 and DB04. Stations DB03 and DB04 (the two stations inside the basin) show a series of positive and negative pulses between 1 and 3 s which are not present in DB01 and DB02. These pulses can represent multiples phases from the basement of the basin. Finally the conversion at the Moho results in a clear positive pulse at 3.5-3.7 s for DB03 and DB04 at all frequencies, while is somehow attenuated at DB01 and DB02. This observed delay time for the Moho conversion is coherent with those reported by Licciardi et al. (in press.) in this area where the Moho is located at a depth of about 30-32 km.

In Figure 9 we plot the stacked RRF at 8Hz in time domain along the length of the array to examine the lateral variations of the pulses observed in Figure 8 (Fig. 9a) and, tentatively, to constrain the structural setting of the DB (Fig. 9b). The negative pulse observed in the stacked RRFs (Ps_L in Fig.9a) corresponds to a negative velocity jump with depth which seems to dip towards the inner portion of the DB and can be associated to the presence of a low velocity layer within the sediment succession. The conversion from the sediment-basement interface (Ps_B in Fig. 9a) and the associated multiples are clear at DB03 and DB04 but more difficult to recognize in the first portion of the profile. This main feature can be related to the presence of the BNF (Fig. 9b). Constraining the extension of the BNF at depth as well as its orientation requires the analysis of the TRFs which can be carried out only with a better azimuthal coverage.

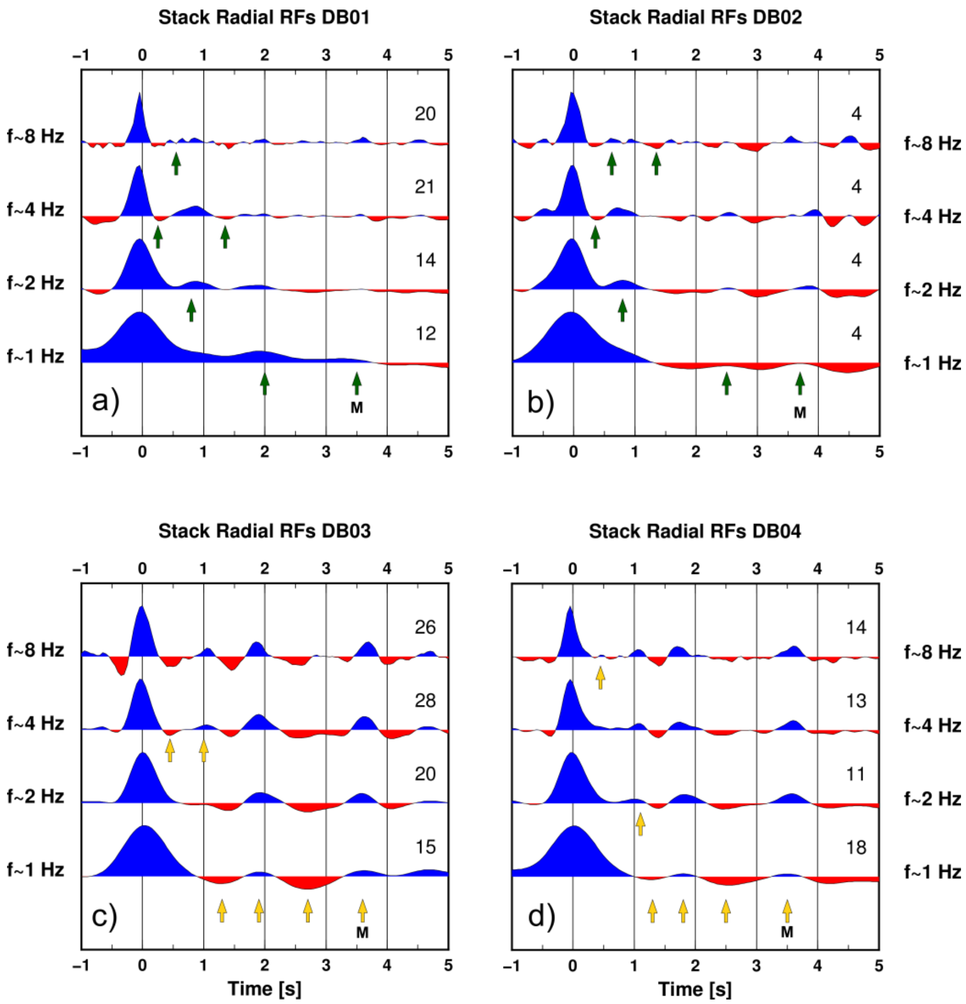

Figure 8. Stacks of RRFs at each station. The RRFs are computed and stacked for 4 different progressively increasing cut-off frequencies. The number of RFs used in each stack is indicated over the trace. Each arrow marks the onset of a particular pulse at the corresponding frequency. The presence of signal in the first second after the direct P-wave arrival is revealed for frequencies cut-off greater than 2 Hz.

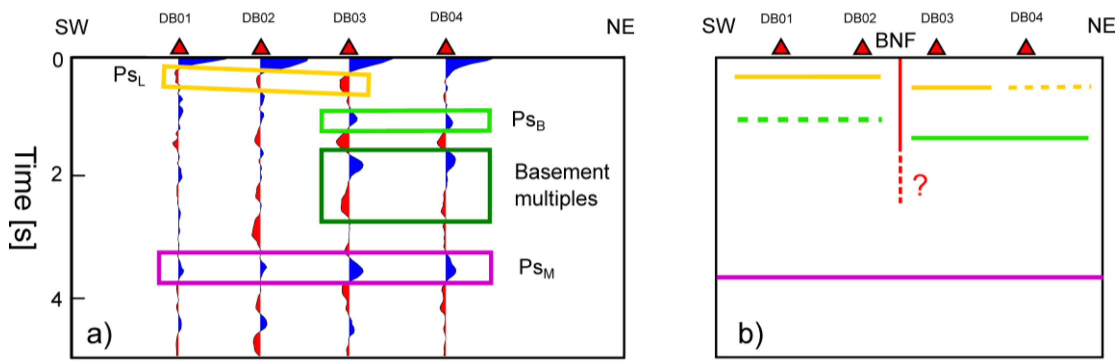

Figure 9. Profile of time-stacked RRF (8Hz) along the length of the array (a) and possible interpretation of the structural setting of the SW margin of the DB (b). Ps_L: conversion at a negative velocity jump in the sediment pile; Ps_B: conversion at the sediment-basement interface; Ps_M: conversion from the Moho. Major changes in the pulses amplitudes are related to the presence of the BNF.

5. CONCLUSIONS

Two new passive seismic arrays have been recently deployed in two potential geothermal sites in Ireland in order to retrieve the structure of the shallow crust with passive seismic methods. In this work we presented the results of different analysis conducted over the first year of recordings.

Good quality seismic data have been recorded by the Donegal array. Regional, local and anthropogenic events have been detected and microseismicity precisely located. This is of importance for the next stage of the study where a Local Earthquake Tomography approach will be used together with the RF method to better constrain the structure of the shallow crust with particular focus on the geothermal potential associated with the buried Donegal granite.

In the DB, a preliminary analysis of high frequency RFs has been conducted along the length of the recently deployed array. The results encourage the possibility of retrieving the structure of the shallow crust with teleseismic data. The presence of laterally varying structures in the first 0-10 km of the crust has been pointed out by a simple stack of high frequency RFs which has shown structural changes across the length of the array associated with the presence of the BNF. More precise constraints on the depth of the interfaces and a quantification of the S-wave velocity at depth will be obtained with a formal isotropic inversion of the stacked RRFs at each site. In this work this will be achieved by means of a probabilistic inversion using the transdimensional reversible jump Markov Chain Monte Carlo implementation of Piana Agostinetti & Malinverno (2010). The second stage of this study will be aimed to determine whether the presence of anisotropy can be detected in the shallow crust using the harmonic decomposition of the RF data-set developed by Bianchi et al. (2010), and, if so, to locate the depth and the geometries of such anisotropic structures, a key point in geothermal exploration.

Finally, all the available commercial data as boreholes logs, active seismic reflection profiles, and the magneto-telluric data recently acquired by the IRETHERM working group (www.iretherm.ie) will be integrated with our results to provide a more precise characterization of these potential geothermal sites.

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