IRECCSEM: Evaluating Ireland's potential for onshore carbon sequestration and storage using electromagnetics

1. Introduction

Carbon capture, sequestration and long-term storage (CCS) is a critically important, but intellectually and technologically challenging, bridging technology for assisting humanity to migrate from its dependence on fossil fuels to green energy over the next half century. Appraising natural reservoirs and monitoring the sequestration of carbon in them holds unique problems that test the geosciences to their limits. Appropriate aquifers have to be discovered and geometrically, structurally and petro-physically defined, CO_2 has to be carefully monitored during injection, and must then be even more carefully monitored post-injection over the long term ensure that 99% of it remains securely confined for a period of greater than 100 years to meet the standards defined in the U.S. DOE's Carbon Sequestration Roadmap and Program Plan (Plasynski, Deel et al. 2007) and by the EU's recent CCS Directive 2009/31/EC.

Geophysical methods have a key role in each of these challenges. In order for these methods to be reliable, it is necessary to study in depth the most critical aspects of them; their sensitivity, resolution, precision and repeatability. In this context, electromagnetic methods stand out as particularly promising, especially when the storage targets are deep saline formations.

Electromagnetic methods are known for characterizing and monitoring natural reservoirs given that they are sensitive to reservoir physical property variations (electrical conductors in case of aquifers and resistors in case of hydrocarbons). They complement seismic methods, and offer information not obtainable through any other approach. In the case of CO_2 injection into saline formations, laboratory measurements demonstrate that there will be large increases in resistivity, of factors of two or greater, as the saline fluids are displaced by CO_2 (Fig. 1). Such changes are observable on the surface using appropriately-designed electromagnetic surveys, either using natural-sources (MT) or man-made sources (CSEM).

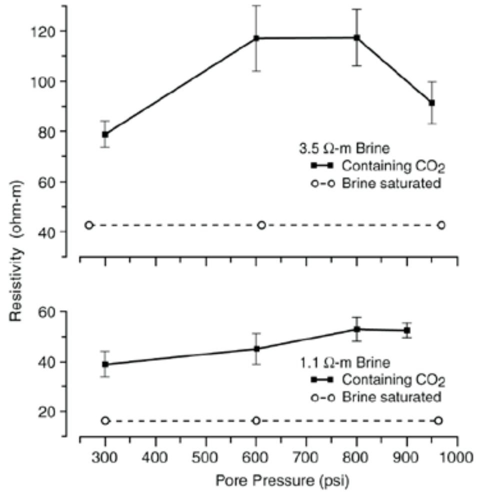

Figure 1: Changes in resistivity of brine-filled rock formations, of varying saline content, as CO_2 is injected into them. (Taken from Myer (2001)).

Archie's Law well approximates the resistivity of a porous rock, given the rock and fluid resistivities (see Section 4). Typical values for porous rocks, saline fluids and for a CO_2 fluid show a significant increase in bulk resistivity with increasing CO_2 saturation (Fig. 2). In addition, as the CO_2 becomes dissolved in the saline solution over time, both resistivity and viscosity will vary linearly according to the relations

$$\sigma_S(X_{CO_2},T)=\sigma_S(0,T)(1-6.0X_{CO_2})\left(\frac{T+19.5}{T_0+19.5}\right)$$

$$\eta_S(X_{CO_2},T)=\eta_S(0,T)(1+4.65X_{CO_2})\left(\frac{T+19.5}{T_0+19.5}\right)$$

where subscript S denotes salinity, σ_S is the electrical conductivity, η_S the viscosity, T_0 and T are the initial and final temperatures (in °C), and X_{CO_2} is the molar fraction of dissolved CO_2

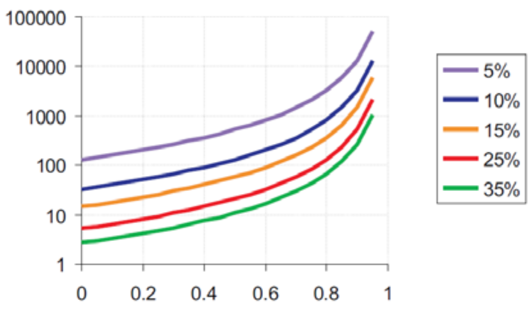

Figure 2: Bulk electrical resistivity with increasing CO_2 saturation and varying porosity from 5% to 35%

(Fleury and Deschamps, 2008). Thus, EM monitoring holds the potential to estimate, through proxy, the time variation of viscosity – a highly critical parameter required for understanding CO_2 migration but one that cannot be measured remotely by any other means. Other important strengths of electromagnetic methods are their versatility and low cost.

2. Spanish EM survey at Hontomin CCS test site

Spanish scientists have embarked upon aquifer characterization at the Hontomin CO_2 Technical Development Plant as a prelude to CCS. CO_2 will be injected into a dolomitized layer located at some 1450 m depth. A large number of experiments are in progress, and one component is electromagnetic (EM) mapping being conducted by the EM group of the University of Barcelona (Prof. J. Ledo and colleagues Prof. P. Queralt and A. Marcuello). Its scope is the development of EM methods for the characterization, modelling and monitoring of CO_2 geological storage. Jones is a collaborator on this project; he is the official external supervisor of the Ph.D. student, Xènia Ogaya, and is giving expert advice to the project participants at all stages of the work. Jones will profit from this research and will bring the discovered knowledge to bear to address identical problems in Ireland. Ledo is an official Collaborator in IRECCSEM.

3. Electromagnetic methods

Electromagnetic methods utilize the propagation of electromagnetic waves in the Earth's interior to infer the distribution of the electrical resistivity in geological formations. The following techniques are the most common:

- Shallow Electromagnetic Induction methods (EM-1);
- Electrical Tomography (ERT),
- Time Domain Electromagnetic Surveys (TDEM),
- Controlled Source Audiomagnetotellurics (CSAMT, frequency range 10^4 Hz – 1 Hz) and
- Natural Source Magnetotellurics (AMT for high frequencies 10 kHz – 10 Hz and MT for lower frequencies 100 Hz – 0.001 Hz).

These methods are characterized by their sensitivity to physical parameters that can be related to rock porosity and permeability, and their suitability for studying targets at different scales.

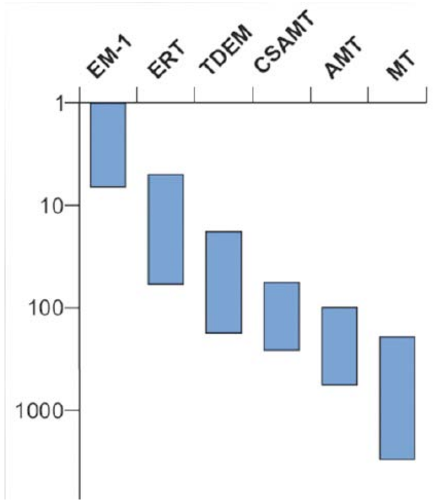

Figure 3: Typical penetration depths for each EM technique. MT is required to reach depths where CO_2 is injected (>800 m).

Penetration depth depends on the frequency of the EM fields considered and the electrical resistivity of the subsoil. Figure 3 shows the approximate skin depth of the different techniques. Magnetotelluric techniques (MT, AMT and CSAMT) are the only ones that can provide information at depths relevant for CO_2 injection (>800 m). Moreover, the responses have a tensorial character, and thus are more sensitive to lateral effects; this is key for determining the dominant directionality of the geological structures or injection processes being imaged.

4. Sensitivity of electrical resistivity to porosity in sandstone

The electrical resistivity of sedimentary rocks is a very strong function of the porosity of the rock matrix, as generally the rock matrix is resistive, and the interstitial fluid – a saline brine – is conductive. The common mathematical description used is *Archie's Law* (Archie 1942), given in its most general form by

$$\rho_r = a \cdot \phi^{-m} \cdot S_f^{-n} \cdot \rho_f$$

where ρ_r is the composite resistivity of the rock (inverse of conductivity, σ), a is a proportionality constant, φ is the porosity of the rock, m is the cementation factor, S_f is the fluid saturation, n is the saturation exponent, and ρ_f is the fluid resistivity. Taking commonly adopted values for *a*, *m*, and *n* of 1, 2 and 1 respectively, and assuming a fluid resistivity equal to that of seawater (0.3 Ωm), gives a porosity-resistivity relationship as shown in Figs. 4 (black lines). Note that Archie's Law does not include any sensitivity to the rock matrix resistivity, which is assumed to be infinite, hence at low porosities (<2.5%) the composite rock resistivity becomes far too high – greater than the assumed 1,000 Ωm of the Ross Sandstone Formation in this simulation, one potential CCS target in the Clare Basin of Ireland.

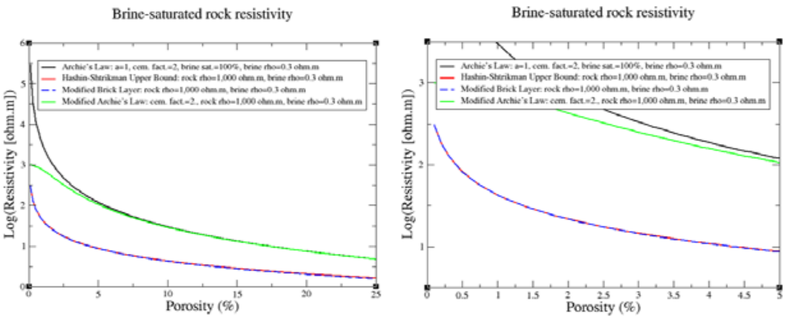

Figure 4: Variations of resistivity with porosity for different geometries of interconnection. Black line: Archie's Law. Green line: Modified Archie's Law. Red line: Hashin-Shtrikman Upper Bound. Dashed blue line: Modified Brick Layer (Note that the two plots are for the same data but have different abscissa and ordinates.)

There are a number of approaches to take the actual host rock resistivity into account. One useful description is given by Hashin-Shtrikman (HS) extremal bounds (Hashin and Shtrikman 1963) – the upper bound gives the smallest resistivity that could be observed (Figs. 4, red lines, underneath MBL dashed blue lines). Another useful description is that of the Modified Brick Layer (MBL) model (Schilling, Partzsch et al. 1997), which was proposed to take account particularly of low porosity effects often underestimated using Archie's Law (Figs. 4, dashed blue lines on top of the HS upper bound lines). Many other mathematical descriptions exist, and Glover et al. (2000) gives an excellent review together with a proposed modified Archie's Law particularly applicable at low porosities (Figs. 4, green lines).

5. Application to Ireland

The majority of Ireland's CCS storage potential is in saline aquifers in its sedimentary basins (Fig. 5, Lewis et al., 2009). However, this potential is unquantified as virtually none of the basins have been adequately characterized. Of these basins, within the Republic the onshore portion of the Clare Basin and the Northwest Carboniferous Basin can be characterized through appropriate land-based EM techniques, both controlled and natural-source.

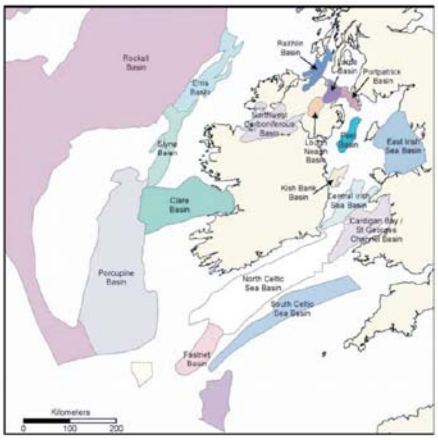

Figure 5: Sedimentary basins of Ireland

6. Clare Basin

A cross-section through the Clare Basin is shown in Fig. 6 (M. Holdstock, pers. comm., 2010). This section is based on old seismic data and the boreholes shown. The Ross Sandstone Formation is the potential CO_2 aquifer below the sealing Gull Island Formation. Potential also exists in the basement Dinantian Limestone Formation beneath the sealing Clare Shale Formation. Although the storage capacity within the Clare Basin was rated as "*unquantified*" by Lewis et al. (2009) given the paucity of geological data, the onshore part of the Clare Basin was recently excluded as a potential candidate for CO_2 sequestering due to very low permeabilities being found in the Ross Sandstone Formation due to its tight character, as determined on core samples retrieved during shallow drilling programs (Farrelly, Loske et al. 2008).

Recent onshore drilling into the Clare Basin in the Loop peninsula through Griffith and Statoil financing to Professor Pat Shannon and Dr. Peter Haughton is yielding further petrophysical information, and the proprietary resistivity logs will be made available to us as a contribution to IRECCSEM.

Unknown however is just how pervasive this tight character is, and whether basement Dinantian limestones beneath the Clare Shale formation represent a possible target.

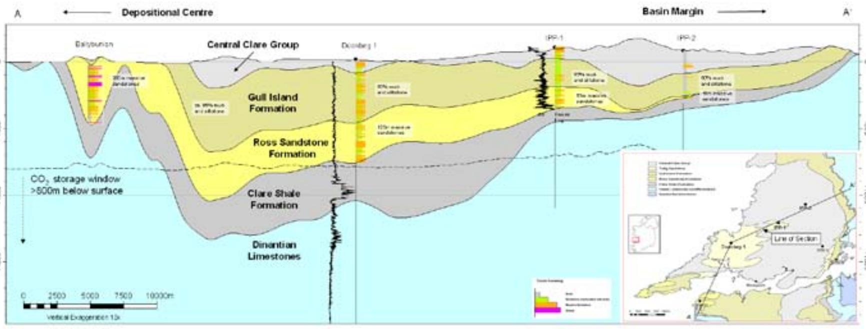

Figure 6: Cross-section of the Clare Basin (from M. Holdstock, pers. comm., 2010)

6.1 Borehole information

Two 150 m boreholes 09-04 and 09-05 were drilled in the Clare Basin for the GSI in 2009 at coordinates (126517,158683) and (87405,145406) respectively. The well-log information comprise velocities (both Vp and Vs), electrical resistivity, and lithology. Based on the lithology, 09-04 sampled from the top of the Ross Sandstone Formation through it intersecting the Clare Shale Formation at approx. 89.5 m depth (Fig. 7a). In contrast, borehole 09-05 does not intersect the Clare Shale Formation (Fig. 7b) and stays entirely within the Ross Sandstone.

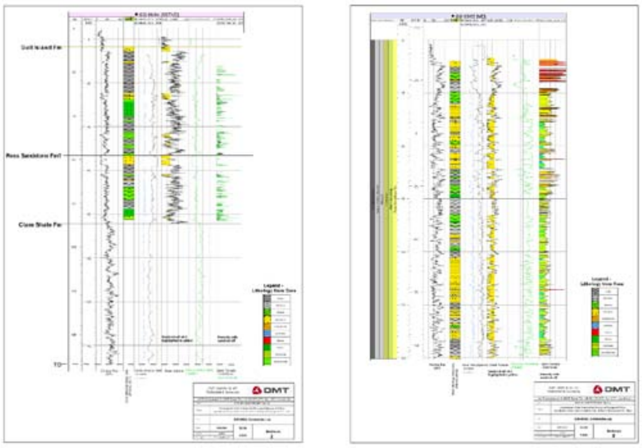

Figure 7: Borehole information for boreholes 09-04 (left) and 09-05 (right)

The resistivity logs from the two boreholes are shown in Fig. 8, together with 5 m averages of log10(resistivities). The Ross Sandstone Formation has generally a resistivity of 200–400 Ωm, whereas the Clare Shale Formation's resistivity is ~15 Ωm.

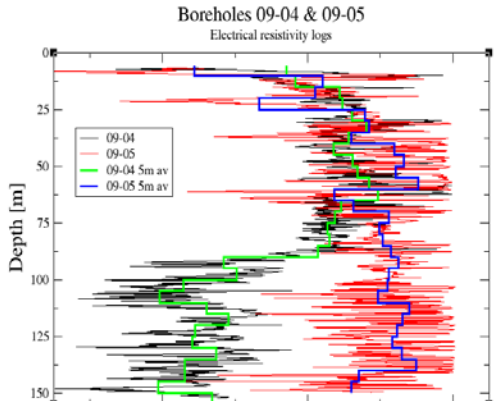

Figure 8: Electrical resistivity logs from drill-holes 09-04 and 09-05

This ability of electrical resistivity to discriminate between these two lithologies is not true of seismic techniques. Figures 9 show the cross-plots between log(resistivity) and the two velocities, Vp (Fig 9a) and Vs (Fig. 9b), for borehole 09-04, with the data above 89.5 m depth in blue (Ross Sandstone Formation) and the data from below 89.5 m in red (Clare Shale Formation). Whereas for electrical resistivity there is a clear separation between the two on either side of 1.75 log units, the observed ranges for both velocities significantly overlap for both formations.

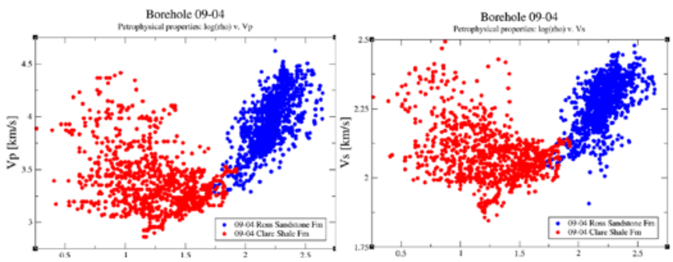

Figure 9: Cross-plot between Log(resistivity) and Vp (left) and Vs (right)

6.2 Clare Basin pilot MT survey

A NE-SW trending pilot magnetotelluric profile, funded by DIAS and GSI, was undertaken to coincide with three boreholes drilled in the Clare Basin (Fig. 10). To achieve uniform resolution of the geological structures of interest, the survey was designed with high frequency AMT sites located within 600 m to 800 m of each. This distance was based on the results of forward modelling of synthetic AMT data using known resistivities of various lithologies from the borehole data. Thirty-two individual AMT sites and 10 coincident MT sites were recorded in the survey area between June 21 and July 3, 2010. The main profile trends NE-SW in between boreholes Doonbeg-1 and IPP-2, with a small cross-profile trending NW-SE across the position of borehole IPP-1 (Fig. 10).

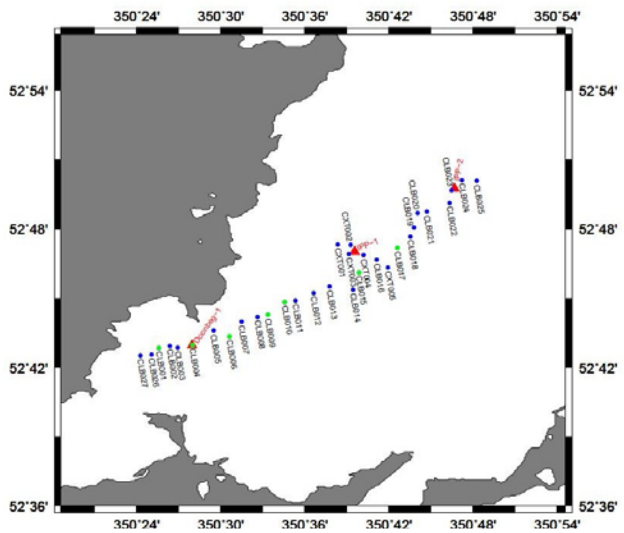

Figure 10: Locations of the MT sites measured for the pilot survey of the Clare Basin. Also shown are the drillhole locations

6.3 One-dimensional models

One dimensional (1-D) inversions of 27 AMT soundings along the main NE-SW trending profile were performed using Occam (Constable et al., 1987). The stitched-1D geoelectric model is shown in Fig. 11, with geological interpretation of the various electrical units, which exhibits three distinct layers across the Clare Basin. The interpreted geoelectric model (Fig. 12) correlates well with the interpreted geological cross-section of Holdstock, based on seismic and borehole data (top of Fig. 11). These three geoelectric layers comprise:

Layer 1: The Gull Island Formation (as well as the overlying Central Clare Group) is sensed as a layer of relatively high resistivity and constant thickness (approx. 400 m) across the profile with some thinning towards the eastern part of the profile, near borehole IPP-2. In general, the resistivity of this layer is of the order of 1,000 Ωm.

Layer 2: The Ross Sandstone Formation is well imaged as the second geoelectric layer, with a basal depth that varies across the profile, from a maximum of 1,200 m depth in the western part of the profile to 500 m depth in the east. Excellent agreement is observed between the lithological logs and the depth to the base of the Ross Sandstone Formation at the borehole localities. However it is noted that the depth to the base of the Ross Sandstone in the MT model is somewhat deeper (by about 400 m) in the region between boreholes Doonbeg-1 and IPP-1 than interpreted in Holdstock's model. The sandstone's resistivity in the MT models is in the region of 50–100 Ωm across the profile, which is somewhat lower than the average resistivity from the borehole logs (200–400 Ωm). These lower values are consistent with porosities of between 0.5% (Modified Brick layer model) to 5% (Archie's Law), depending on the model chosen to describe the geometry of interconnection.

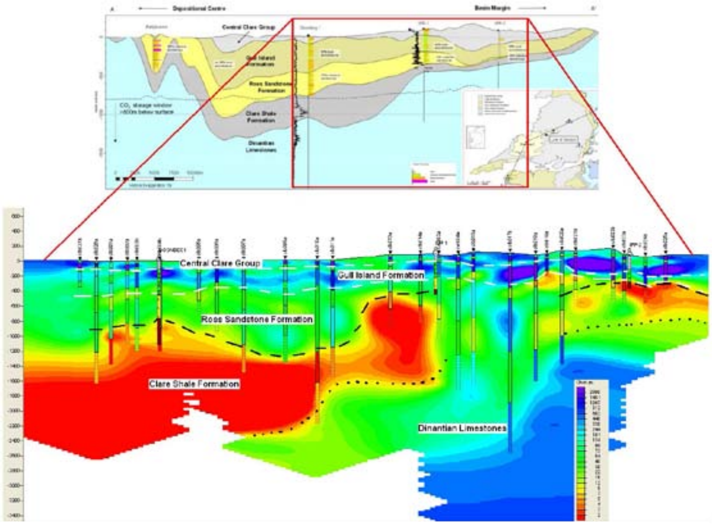

Figure 11: Model of the Clare Basin resistivity structure from stitching the 1D Occam models together

Layer 3: The Clare Shale Formation is well imaged and interpreted as the highly conductive third geoelectric layer in the model. The top of the Clare Shale is clearly defined by an order of magnitude decrease in electrical resistivity compared with the overlying Ross sandstones. The magnetotelluric model indicates low resistivities (high conductivities) in the region of 2–5 Ωm for the Clare Shale, in comparison with an average of ~15 Ωm from the borehole logs. The base of the Clare Shale formation is not defined from the AMT data.

6.5 Two-dimensional model

A preliminary two-dimensional (2-D) model has been derived using the AMT and deeper-probing MT data together (Fig. 12). For the sedimentary part the model essentially repeats the main conclusions from the 1-D modelling, but the longer periods from MT allow resolution of structures within the basement, which generally is highly resistive. Significant lateral variability in resistivity exists within the Ross Sandstone Formation indicative of highly laterally-varying porosity and permeability.

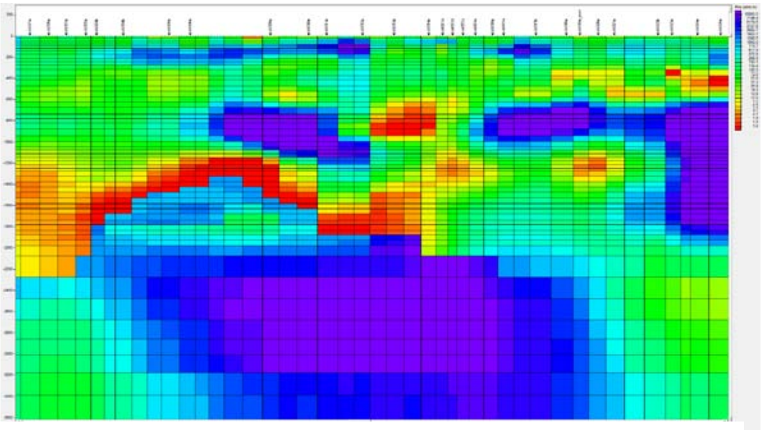

Figure 12: 2D preliminary resistivity model of the AMT and MT data from the Clare Basin pilot survey. Note anomalous low resistivity region in basement beneath Clare Shales anticline.

Of significant note however is that there is the intriguing suggestion of a moderate resistivity region within the basement Dinantian Limestones of around 100 Ωm compared to some 1,000s Ωm for the bulk of the limestone. This anomalous region lies at depths of 1,600-1,800 m within the imaged basement anticlinal structure that results in an anticline in also the Clare Shale Formation – a known seal for a potential reservoir within the Dinantian Limestone. A resistivity of 100 Ωm implies a porosity of between 0.5% (MBL model) to 5% (Archie's Law). Parameters of the potential reservoir are though only poorly resolved by the existing AMT/MT data, and further data are required.

7. Proposed programme of activity

The project will have two threads. One of these will be acquisition of new, high-resolution AMT/MT data in the two target sedimentary basins in the Republic, namely the Clare Basin and the Northwest Carboniferous Basin. The other will be development of new and novel EM acquisition technologies and monitoring tools. All three project members, Jones, the PDF and the PhD student, plus Dr. M. Muller will take part in all three activities. Jones will lead the tool development, the PDF will lead the first phase of data acquisition (Clare Basin) and the PhD student will lead the second phase of data acquisition (Northwest Carboniferous Basin). The timeframe of the project is shown in the Gantt chart (Fig. 13).

As well as obtaining new, key data on the potential for sequestering CO_2 in onshore reservoirs and developing new and novel EM acquisition and monitoring tools for CCS applications, a minimum of four international journal papers will be written, a graduate student will earn a PhD, and a PDF will be trained in methods of advanced research.

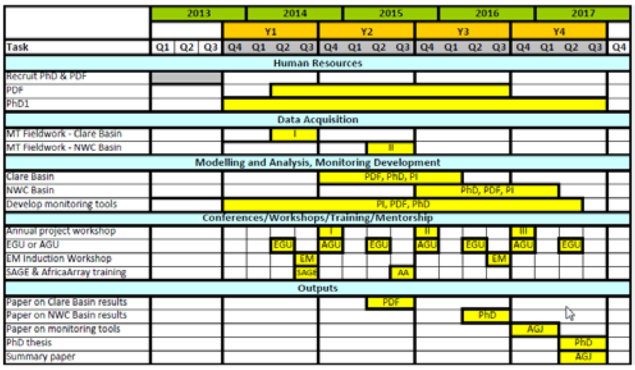

Figure 13: Gannt chart for IRECCSEM project

7.1 New data acquisition programme

New AMT and MT data will be acquired in the Clare Basin and in the Northwest Carboniferous Basin. Two field seasons are planned, for Spring/Summer 2014 and 2015. Data will first be acquired in the Clare Basin, to extend those from the 2010 pilot survey. Subsequently, data will be acquired in the Northwest Carboniferous Basin. In both cases, 50 days of fieldwork is planned, which should result in new, high-quality AMT/MT data at over 100 sites in each basin in the frequency range 10,000 Hz to 0.1 Hz with a nominal site spacing of 500 m. The data will be acquired with AMT and MT instrumentation owned by DIAS (11 Phoenix broadband recorders (MTU-V5a), 36 MT coils (MTC-50) and 18 AMT coils (MTC-30)). Fieldwork will be undertaken primarily by the PDF and PhD student, assisted by the full time, dedicated MT technician employed by DIAS. Given the high resolution required of subsurface structures, the emphasis will be on very high data quality at each site, rather than a lot of coverage with average quality data. This will entail 2 overnight recordings for AMT signals (the best AMT data occurs at night (Garcia and Jones 2002)), and 3 or 4 nights continuous recording for MT signals, rather than 1 for AMT and 2 for MT as is more common and as is the plan for IRETHERM acquisition . Given anthropogenic noise, a test recording will be undertaken at each site immediately after installation, and where necessary sites will be abandoned if they are deemed to be too noisy. We anticipate a “loss” of up to 30% of the sites installed by adopting strict criteria for acceptance. With 18 AMT coils owned by DIAS acquisition can be made at 6 AMT sites simultaneously, and with 2 nights recording per site this means effectively 3 AMT sites/day, totalling nominally 150 sites in the field season. However, site abandonment at the 30% rate is anticipated, hence the estimate of ~100 sites per field season. The other 5 MTU-V5 recorders owned by DIAS will be used for MT, and with 3-4 nights/site this is effectively 1.3 sites/day, or approx. 60 sites in the 50 days. There will not be any site losses, as the MT data will be acquired at prior AMT sites that exhibit high quality data. Thus, more than half of the AMT sites will be complemented by lower frequency MT data, i.e., nominally 1 km site spacing of the MT sites.

The data will be processed, analysed and modelled using the tools available to the MT group in DIAS; one of the largest academic groups in the world. Jones is the most published and cited scientist in MT (see CV), and has a global reputation in data analysis (e.g., Jones and Jödicke 1984; Jones 1989; Garcia and Jones 2008), processing (e.g., McNeice and Jones 2001; Garcia and Jones 2002; Jones 2011), modelling (e.g., Miensopust and Jones 2011) and multi-parameter interpretation (e.g., Jones, Plomerova et al. 2010). The group has access to a many modelling and inversion codes written by others, in 1D, anisotropic 1D, 2D, anisotropic 2D, and fully 3D, including the latest 3D inversion codes of Siripunvaraporn (Siripunvaraporn and Sarakorn 2011), Egbert (Egbert, Kelbert et al. 2010) and Avdeeva (Avdeev and Avdeeva 2009). In addition, group members have an established track record in developing novel approaches and new code for inversion of MT data, either on its own or jointly with other datasets (Moorkamp, Jones et al. 2007; Miensopust 2009; Moorkamp, Jones et al. 2010; Mandolesi and Jones 2011; Roux, Moorkamp et al. 2011; Schmoldt and Jones 2011).

7.2 Technical and Monitoring tools development

There is no point sequestering carbon dioxide in the ground without a comprehensive monitoring programme to assess whether the CO_2 is leaking and, over geological time scales, whether the carbon is precipitating out. The main research component to this project will be to develop new and novel surface and borehole EM tools for undertaking such monitoring, making full use of the increase in resistivity as saline waters are displaced by CO_2 during injection. Potential changes in resistivity due to mineral precipitation predicted by geochemists will also be investigated. Subsequent leaking of the CO_2 will result in an attendant lowering of the electrical resistivity as saline fluids are able to re-equilabrate within the matrix.

This development will be led by Jones throughout the whole four years of the project, and the PDF and the PhD student will both be involved. We will link with scientists from the University of Montpellier working at the Maguelone experimental site in southern France, which is not a candidate for CO_2 storage but is destined for testing novel geo-electric monitoring technologies (http://www.co2mustang.eu/SiteInFrance.aspx).

The technical developments will be:
1. Study of anthropogenic and geological (distortion) noise aiming to reduce their effects on the AMT/MT data.
2. Three-dimensional modelling at different scales from joint inversion of electromagnetic and other (e.g. gravity) data that allows geoelectrical characterization of the reservoir.
3. Numerical simulations of the observed physical and geochemical responses in different scenarios, and sensitivity and resolution analysis that will be used as the basis for the tracking, control and verification (monitoring) of the storage security of the reservoir.
4. Search for new petrophysical relationships from the correlation between models and effective properties, correlation between geophysical observations, specifically seismic velocities and electrical conductivity, and fuzzy logic models.
5. Development of appropriate surface and borehole EM monitoring tools.

8. Linkage to IRETHERM

The SFI-funded IRETHERM project (http://www.iretherm.ie/) is a four-and-a-half year, all-island, North-South, academic-government-industry collaborative project between DIAS, NUIG, UCD, UCC, GSI, GSNI, GT Energy, GeoServ Solutions and SLR Consulting to develop a strategic and holistic understanding of Ireland's geothermal energy potential through integrated modelling of new and existing geophysical and geological data. IRETHERM will acquire new data on key targets for this geothermal energy assessment, some of which are sedimentary basins. However, the planned IRETHERM AMT/MT coverage is insufficient for CCS assessment, as CCS is far more stringent in its resolution requirements (500 m site spacing, very high quality data - 2 nights AMT, 3-4 nights MT). The additional 200+ AMT/MT sites that will be acquired under IRECCSEM will also augment the IRETHERM project. Similarly, IRETHERM may yield new geological targets with CCS potential, warranting higher-resolution assessment under IRECCSEM.

9. Collaborators and Collaborations

IRECCSEM will involve active collaborations with the following collaborators:

Formal

- Dr. Mark Muller (DIAS): All aspects of IRECCSEM.
- Professor Juanjo Ledo, and Professors Pilar Queralt and Alex Marcuello: (UB): Synergy with Spanish Hontomin CCS project and collaboration with tool development.
- Dr. Brian McConnell (GSI): McConnell is the designated scientist for CCS within GSI, and will collaborate with IRECCSEM on advice, site location and data interpretation.

Informal

- Professor Pat Shannon and Dr. Peter Haughton (UCD): Access to new proprietary resistivity and lithology logs from drillholes in behind-outcrop coring of Clare Basin.

In addition, IRECCSEM will grow collaborations with other European groups, including:

- Maguelone experiment scientists (http://www.co2mustang.eu/SiteInFrance.aspx).
- MUSTANG Consortium (http://www.co2mustang.eu/)