The biggest steps forward in Earth imaging are coming from the border of mathematics and geoscience. To address the problems of energy and the environment that face our population today, efforts on this front must focus on our ability to understand the location and behavior of subsurface fluids. My research is an interdisciplinary blend of geophysics and mathematics and I am most interested in how we can use seismic data, often in non-traditional ways, to understand where fluids and fractures are in the subsurface and what fluids are present without the need to directly sample those fluids. My work extends from the lab scale to the field scale, with a focus on understanding the fundamental mathematics and physics, and developing tools with long-term practical applications. To this end, I am working on three separate but interrelated fronts: Seismic imaging, microseismic location and interpretation, and nonlinear elasticity.

Seismic Imaging

Seismic data give the best resolution of any available data to see inside the Earth and so are the workhorse of both locating and monitoring reservoirs. Standard techniques ignore much of the recorded wavefield, however, because it does not satisfy the assumptions of simplified methods. I have worked to mitigate this by incorporating smaller signals, that are often more difficult to identify and process but still contain valuable information about the subsurface. Examples of this work reach back to my Ph.D. work (Malcolm & de Hoop 2005, Malcolm et al, 2007, Malcolm et al 2011) in which I adapted conventional imaging techniques that use singly reflected data to incorporate waves that reflect multiple times. This work has continued in one publication (Richardson and Malcolm, 2016) as well as three Extended Abstracts (Richardson and Malcolm, SEG, 2013, 2014, 2015), and a PhD thesis (Richardson, 2015), and continues at MUN where Dr. Polina Zheglova, a postdoc in my group, is working on adapting these and similar techniques to give more detailed subsurface information than just a standard seismic image, as well as adapting them to the microseismic location problem.

One of the key areas of reservoir monitoring that require detailed analysis of seismic data is the processing and interpretation of time-lapse or 4D seismic data sets. These data are simply repeated experiments over the same location as the reservoir is produced; they are collected to look for and characterize changes in subsurface fluid properties and locations. I am interested in these data for two reasons. First, they are repeats of the same experiments allowing us to better examine the errors (Yang et al, EAGE, 2014, Willemsen & Malcolm, SEG, 2015), giving us an ideal situation in which to test and develop more robust error analysis techniques as in Poliannikov & Malcolm, (2016). Second, because such data are typically collected over actively producing reservoirs, the surrounding geology is well-known and the results of interest are focussed on a relatively small region. This has allowed us to develop focussed modeling and imaging techniques (Shabelansky et al 2013, Willemsen et al, 2016), which allow us to form an image of only part of the subsurface. In addition, we have developed imaging strategies specifically for 4D, exploiting the fact that we have multiple images. This has resulted in five papers as well as a Ph.D. thesis (Yang et al 2014-2015). Moving forward, Ph.D. student Maria Kotsi is studying how best to incorporate formalized understanding of uncertainty (e.g. Poliannikov & Malcolm, 2016) to improve our understanding of the location and properties of subsurface fluids, building on Yang et al (EAGE 2014). This work will also build upon work done by undergraduates Colin Ash and David Cray on the 4D prospects for offshore Newfoundland and Labrador (NL). We have a submitted paper to the professional magazine “The Leading Edge” on this topic (Malcolm and Willemsen, 2016). This work is of interest to local companies, helping with funding, and also attracting students who hope to work in the local oil industry.

Building upon our work in 4D imaging, M.Sc. student Mostafa Akrami is working on how best to image with a new type of data beginning to be collected that incorporate not just the seismic wavefield but also its direction; these data are called vector data. This improves the prospects of targetted imaging on at least two fronts. First, it allows one to select directions in the data, thus more easily focussing the imaging on a specific target or location. Second, it incorporates additional data improving the resolution and, we hope, our ability to determine subsurface properties of both fractures and fluids. This is again of local interest as such data have been collected offshore NL. Mostafa has now completed the research part of his thesis; I expect him to graduate by the end of the Fall Semester. Incoming PhD student Ligia Osorio will continue this work, incorporating the detectibility of shear waves with this type of data.

Related to this, we have performed several studies on how best to image with waves converted phases (Shabelansky et al SEG 2012-2015, Shabelansky et al GJI 2015, submitted). These are waves that change the direction of particle motion, as well as propagation, when interacting with an interface. In most imaging it is assumed that only the direction of propagation changes during such interactions. This work is targetted at microseismic data, but moving forward we hope to examine vector data to ascertain whether or not such phases have been recorded; this may also form part of Ligia Osorio’s work. Once we see such data, we will be able to adapt the methodologies developed to exploit these phases to give valuable additional information about the subsurface.

Microseismic Location and Interpretation

For both conventional reservoir and unconventional reservoirs, the monitoring of induced seismicity is becoming increasingly important. This seismicity is generally very small (less than magnitude 1), but contains a wealth of information. The location of events can be used to monitor a fluid front, estimate fluid pressure, and estimate such parameters as fracture length and spacing. On this topic, I have worked extensively on both event location (Poliannikov et al 2011-2015; Melo et al 2011, 2013) as well as on imaging (Shabelansky et al SEG 2012-2015, Shabelansky et al GJI 2015, submitted). My work has focussed on the converted phase imaging mentioned above as well as on the characterization of uncertainty in event location, particularly when using relative event location algorithms.

Over the past year, I have worked with postdoc Dr. Frédérick Massin at MUN to take the uncertainty estimation in location and expand it to include an estimate of uncertainty in picking the traveltimes and on moment tensors. For traveltime picking, through the use of an automated pick that combines a variety of existing methods we have developed a robust measure of the probability of an arrival in a given time window (Massin & Malcolm, SEG, 2016). On the topic of moment tensors, which describe the rupture shape of an Earthquake, we have developed a source-scanning algorithm that scans a grid of possible moment tensors and computes the most likely moment tensor given the input polarizations. This is the subject of a publication we hope to submit by the end of September 2016 (Massin & Malcolm, BSSA, 2016). Related to this, M.Sc. student Jayne

Simmons has been working on the effects of velocity uncertainty on an existing method for locating microseismic events that uses the methods of migration rather than traditional microseismic traveltime-based techniques.

Moving forward, together with the Computational and Applied Geophysics Group (CAGG) that consists of myself, Dr. C. Farquharson in Earth Sciences, and Dr. A. Bihlo, Dr. R. Haynes, and Dr. S. MacLachlan in Mathematics and Statistics, we are working on a comprehensive project on this topic. In this project, we aim to do two things. First, we aim to explore the best ways (i.e. the ways that minimize uncertainty) of locating microseismic events with the well geometries that are common in offshore NL. This geometry consists of relatively few surface drill points each with many horizontal or nearly horizontal wells extending from a single vertical hole, and is not that typically used in microseismic monitoring. This work will involve the adaptation of existing techniques, including those developed by myself with Drs Poliannikov and Massin, as well as the exploration of new techniques.

The second aspect of this project will build upon the work in Poliannikov et al (2015), as well the expertise of Dr. MacLachlan to look at how microseismicity can be used to constrain fluid flow models. This will involve the understanding of how to couple microseismic event locations, and the moment tensors with their associated uncertainties from Massin & Malcolm (2016), with key flow parameters like permeability and fracture width and orientation. It will build on current knowledge in that we will aim to both characterize uncertainty and use that uncertainty to better characterize the space of flow models that fit the observed data.

The third aspect of this project will exploit the optimization expertise of Dr. Haynes to utilize the detailed error analysis in our event locations to optimize well placement, and injection rates for best production. Taking these three aspects together will improve our understanding of the information content of microseismic data as well as help our industrial sponsors to better understand what they can expect to gain by collecting microseismic data for reservoir monitoring. I am the only faculty member on this project who has a key role in all three aspects of the project.

Nonlinear Elasticity

In Earth imaging, seismic data generally give the highest resolution images of the features of interest. Contrasts, particularly between different fluids, in density and elastic moduli tend to be relatively small however, leading to the question of whether to use a high-resolution method (seismic) and accept low-contrast images or use a high-contrast method (EM) and accept low-resolution images. This is similar to the situation in medical imaging. In that field, however, a great deal of work has gone into the development of so-called hybrid imaging techniques that aim to combine the resolution of one method with the contrast of another. This opens up an important opportunity to attempt to adapt techniques developed for medical imaging and apply them to imaging the Earth.

My contributions to this field began when I was a postdoc in 2006, and worked on modelling a medical imaging modality that combined waves of different frequencies (Malcolm et al 2006). Building upon this work with a postdoc I supervised (Dr. T. Gallot), we began to explore how best to adapt similar techniques to imaging of rocks. We began by developing a simple lab experiment that looked at the interference of two elastic waves (Gallot et al, 2014, 2015). The advantage of our approach over other techniques is in its simplicity. This experiment has now been repeated by four researchers in three labs, including myself in my lab here at MUN, with consistent results. We have found that the method lends itself well to the characterization of fracture orientation (TenCate et al, 2016).

Moving forward, my group is going to focus on extending and improving our understanding of the impact of fractures and their orientations on these signals. I have already begun this work, generating a data set that is included in TenCate et al (2016). Over the next five years, we will work to better characterize this preliminary result focussing on the following three aspects. (i) Simplify the sample to completely isolate the effects of fractures; we have begun this working with Dr. Kris Poduska from physics to create our own rocks from both cement and powdered limestone. This work has been done largely by MUN undergraduate student Lauren Hayes. (ii) Develop a numerical model that will allow us to get a better handle on the underlying physics, hopefully verifying our suppositions as to what processes are causing the two waves to interfere. An incoming postdoc will begin this process as soon as he is able to move to St John's; this work will incorporate at least one M.Sc. project as well as part of a Ph.D. project. (iii) Refine the experimental technique to reduce the dependence on the coupling of contacting transducers to the rock sample. This will be the first project of incoming Ph.D. student Kamal Moravej.

Ultimately I hope that this work will allow us to develop an imaging modality with the resolution of seismic methods and straightforward sensitivity to fractures and fluids of a similar strength to EM or other techniques.