CREWES 5-year research plan: Towards broadband multicomponent seismology and practical iterated inversion

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SUMMARY

Seismic images provide the best possible views of the earth below its surface; but, despite an 80 year history, they are still far from optimal. Today, the computer methods used to create such images are transitioning from a standard methodology (SM), which incorporates an evolved blend of physical theory and practical experience, to the very modern full-waveform inversion (FWI) that is much more firmly rooted in mathematical physics. However, this transition is hindered by insufficient low-frequency content in seismic data, by the inherently unknown seismic source waveform, by incompletely understood physics, and by the extreme computational effort required. As a consequence, SM is the dominant approach while FWI is rarely attempted outside of dedicated research labs. SM uses a sophisticated data processing sequence to create a reflectivity image of the subsurface. Then, incorporating well information, an inversion process converts the reflectivity image to earth properties such as impedance. FWI is a fundamentally iterative process that converges on an impedance model by minimizing the difference between real and predicted seismic data. FWI never creates a reflectivity image and does not use well control; while SM does not predict synthetic data and is not iterated. We will create a new class of seismic inversion methods that combines the most robust features of SM with most promising concepts from FWI. From SM, we will retain most of the data processing steps, the creation of a reflectivity image, and the matching to well control. In particular, matching to well control facilitates the source waveform estimation and provides the needed low frequency information. From FWI, we will incorporate the concepts of iteration, prediction of synthetic seismic data, and imaging of the data residual. The proposed approach, which we call IMMI (Iterated Modelling, Migration, and Inversion), will produce estimates of subsurface properties that both match measurements in wells and also predict most features in the recorded seismic data. Such estimates should be much more reliable than those presently achieved by SM. This will have significant benefits to resource exploration and to subsurface environmental studies.

DETAILED PROPOSAL

1.0 Introduction

We propose to create a new class of seismic inversion methods that combine new theoretical developments with the rich history of practical seismic methods, recast and applied in novel ways. We are well poised to accomplish this because we are a large, diversely-skilled, group of researchers with a 25 year record of achievement in exploration seismology research. Our new inversion methods will be a significant advance in the ability of geophysicists to determine earth properties in the subsurface and will be sufficiently practical to be used routinely in resource exploration and environmental studies.

Figure 1: The Standard Methodology (SM)

We will refer to SM, or Standard Methodology, to mean the current state-of-the-art seismic processing. SM uses a complex "flow" of processes to create a *reflectivity image* which is a detailed multi-dimensional map of reflection coefficients in the subsurface (Yilmaz, 2008). The reflectivity image is then input to a variety of processes known as *inversions* (e.g. Russell, 1988; Yilmaz, 2008) in which earth properties such as impedance, density, porosity, fluid saturation, fluid flow, and more are inferred (e.g. Lindseth, 1979; Oldenburg, 1983; Lines and Treitel, 1984; Larsen, 1999; Mahmoudian, 2006). SM is further characterized by its extensive use of supplementary information from wells to validate the reflectivity image prior to inversion (e.g. White and Simm, 2003; Lloyd, 2013). We will refer to this use of well information as *well validation*, in the sense that that the earth properties estimate has been validated by comparison with known values in wells.

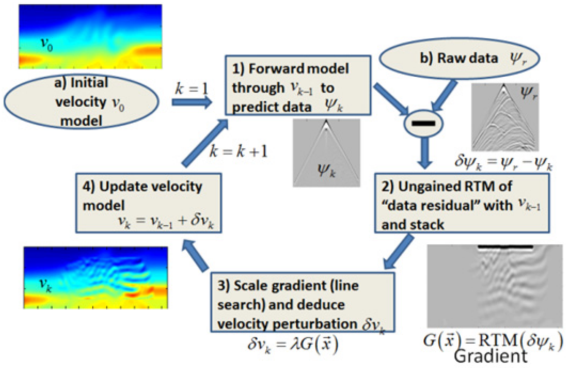

Figure 2: Full Waveform Inversion (FWI)

Recent theoretical developments have solidified into the process known as FWI, or Full-Waveform Inversion (Lailly, 1983; Tarantola, 1984; Virieux and Operto, 2009). FWI is a fundamentally iterative process designed to build an earth model that minimizes an *objective function* defined as the sum-squared error between predicted and observed seismic data. Thus FWI places a strong emphasis on the seismic modelling problem and seeks an earth properties estimate that is validated by its ability to produce synthetic data that matches the real data, which we will call *data validation*. At each step of the iteration, FWI calculates a multidimensional gradient, which gives a direction for change at each position in the earth model but not the magnitude of that change. Deducing the latter is called finding the *step length* and this is normally done with an algorithm called a *line search* (e.g. Pratt, 1999). In comparison with SM, FWI does not produce a reflectivity image and does not incorporate well validation. Conversely, SM is not typically iterative and does not incorporate data validation. At present, FWI is not yet practical and it is rarely attempted outside of dedicated research labs. It faces a number of severe obstacles that are detailed elsewhere in this document. We observe that many of these obstacles have possible solutions within SM that are not yet part of FWI. Incorporating these solutions within the FWI concept will lead to the new class of inversion methods proposed.

Within the set of technical issues occupying the forefront of current FWI research internationally, we identify five key items: (1) the solution of the inverse problem for multiple elastic (or other) parameters, including the quantitative incorporation of data variations with reflection- or scattering-angle (Prieux et al., 2013); (2) the quantitative, physical understanding of the role of the Hessian and its approximations in altering the direction and size of the step length (Virieux and Operto, 2009; Margrave et al., 2012c); (3) the theoretical and practical inclusion of viscous effects (Q) in inversion (Ribodetti and Virieux, 1998; Innanen and Weglein, 2007; Innanen and Lira, 2010; Hak and Mulder, 2011; Vasheghani and Lines, 2012; Kamei and Pratt, 2013); (4) determination and mobilization of all means of increasing the conditioning and convergence of iterated inversion available to seismic exploration and monitoring problems while enhancing the signal-to-noise; and (5) missing low frequencies and unknown source waveform (see 1.1.3 and 1.1.4 below). We will carry out research whose results will directly address these technical FWI items. We will in particular tackle the problems associated with FWI as applied to reflection seismic data.

We will conduct research designed to culminate in a new class of inversion methods that combine the best features of both SM and FWI. Called IMMI, or Iterative Modelling, Migration, and Inversion, we essentially intend to evolve SM to the point that it becomes routinely iterative and incorporates both well validation and data validation. Moreover, we will retain SM's focus on the creation of a reflectivity image as a primary product. We expect that the incorporation of elements of SM like depth migration and well validation will greatly speed the conditioning and convergence of the FWI iteration (item 4 above). We prefer the new acronym IMMI over the conventional FWI as we intend to greatly modify this theoretical approach.

As we progress the development of IMMI, we will simultaneously work to progress the theory and practice of the more standard FWI, maintaining a particular focus on issues (1) and (2) above. It is generally accepted that Newton and quasi-Newton methods have improved convergence properties over gradient-based methods in part because the inverse Hessian includes a form of illumination compensation (Virieux and Operto, 2009)—at, however, the expense of the significant increase in computational burden the Hessian brings. In SM, illumination compensation can be incorporated through the choice of an imaging condition, generally without a commensurate increase in computational burden. We will work to understand to what extent the use of various sophisticated imaging conditions are consistent with the incorporation of an approximate Hessian; to the extent that they are consistent, a great deal of the computation involved in taking Newton and/or quasi-Newton steps might be eliminated.

When more than one elastic (or other) parameters vary in the Earth, reflection FWI becomes responsible for separating out their combined influence on reflection seismic amplitudes. Much of the information relevant to this problem is contained in the amplitude-variation-with-offset (AVO) or amplitude-variation-with-angle (AVA) signatures in the data. In SM, AVO analysis is a mature technology, and the question of how robustly density (say) can be independently estimated from a reflection with a given maximum angle can be meaningfully answered linearly (e.g., Castagna and Backus, 1993; Foster et al., 2010) and to some extent considering nonlinearity (Innanen, 2013). That AVO information drives more complete full wave equation seismic inversion frameworks has been clear for decades (Clayton and Stolt, 1981; Raz, 1981), and its relation to elastic inverse scattering is also now also evident (Zhang and Weglein, 2009;

Stolt and Weglein, 2012). However, the sometimes highly numerical character of FWI algorithms has left the question of the influence of AVO/AVA on convergence, step direction, and exact or approximate Hessian computation largely unanswered—or at any rate, answered only empirically with reference to numerical studies (Prieux et al., 2013). Through a combination of analysis and numerics we will develop the role of AVO in FWI Newton step lengths and directions. When this is clear, we will seek to incorporate the extensive AVO knowledge and capability in SM either exactly or approximately in FWI, with the aim of improving convergence, it is hoped without drastically increasing computational burden. With the role of elastic AVO in FWI elucidated, the AVO-FWI problem for complex physical models, based e.g., on poroelasticity (Russell et al., 2011; Kim and Innanen, 2012a,b), can then be considered.

Whether to treat viscous aspects of wave propagation as a pre-processing problem (wherein, through Q compensation, an effectively elastic or acoustic data set is estimated from anelastic or anacoustic input, and thereafter elastic/acoustic inversion methods are applied), or as part of the modelling internal to inversion, is a longstanding question. It was explicitly raised at least as early as 1991 by Hargreaves and Calvert (1991), and has been recently discussed further in light of FWI and other types of inversion (Innanen and Lira, 2010; Innanen, 2011; Zhang et al., 2013). Anelastic scattering potentials have been derived (Innanen, 2012); we will use these to form anelastic sensitivities, which in turn become anelastic FWI gradients. When the FWI quantities are in hand, the question of gradient and inverse Hessian influence on the gradient can be treated quantitatively for the problem of Q. If the anelastic inverse Hessian includes a component of Q_P and/or Q_S compensation, which is part of the SM toolbox, we may again have a way of speeding the convergence of FWI using relatively fast and robust SM technology.

While targeting the creation of IMMI, we expect to improve nearly all aspects of the seismic method. We are a large and highly experienced research group and we are deeply committed to advancing exploration seismology from the acquisition stage through data processing to imaging and onto the final inversion. We will also continue our study of FWI in its purest sense. We will do this with the oversight required to direct the entire effort towards the goals of IMMI. We anticipate that many incremental goals (milestones) will be met over the lifetime of this project that will deliver significant value to our industrial partners and to Canada.

1.1 Why seismic inversion is difficult

The inversion of seismic data for earth properties, such as the impedance of P (pressure) and S (shear) waves plus density, is an old but still vigorous topic of research. The subsequent inference of lithology (rock type) and pore-fluid identification is obviously of enormous economic significance. While the economic impact of such research is easy to grasp, less so are the reasons that the problem still remains unsolved and very challenging. Here we mention five essential difficulties that are fundamental to the seismic problem: (1) incompletely understood and highly complex physics, (2) immense computational burden, (3) the inherently unknown seismic source, (4) the lack of low frequency information in seismic data, and (5) the unavoidable presence of contaminating noise. These problems impact all inversion approaches and their remediation will be addressed elsewhere in this document.

1.1.1 Complex physics:

The fundamental physics of seismic waves is very complex and our understanding of seismic waves is still incomplete. We know seismic waves are vector-valued displacement waves that show many of the properties expected of elastic waves (e.g. Aki and Richards 2002). However, there is also obvious viscous loss, manifesting as frequency-dependent attenuation and associated dispersion, and whose physical mechanism is only approximately known (e.g. Carcione, 2007). Reflection amplitudes themselves are influenced by contrasts in seismic-Q (Lines et al., 2013). Furthermore, the propagation medium (i.e. the earth) is highly heterogeneous and anisotropic and most of this detailed structure is unknown. A seismic wave simulation with the medium described at the sub-millimeter scale of the smallest variations found in rocks is impossible. The most viable theories of seismic waves rely heavily upon the concept of a macroscopic *equivalent medium* (e.g. Backus, 1962; Burridge et al., 1993) that is intended to give the same wavefield as the sub-millimeter simulation. Such theories are approximate and incomplete and draw upon the diverse and semi-empirical fields of rock physics and poro-elasticity. Thus, while seismic simulation is routinely accomplished, such simulations are always based on approximate physics and the ultimate consequences of this are unknown.

1.1.2 Computational burden:

Inherent in a successful seismic inversion is the forward modelling problem, in which synthetic seismic data are predicted. When the correct earth model is used, synthetic seismic data should match seismic signals acquired in the field. Unfortunately, the forward calculation of anisotropic, heterogeneous, visco-elastic, displacement wavefields is a huge computational challenge, not currently feasible in a routine iterative inversion. When this is coupled with the terabyte to petabyte size of modern seismic datasets and the corresponding earth volumes of many cubic kilometers, the computational load becomes impractical especially for industrial applications. Thus, as mentioned previously, the physics model must be simplified and this implies that there will be features in real data that cannot be modelled. Therefore, in an iterative inversion, data processing is required to address, in some approximation, the removal of effects that are outside the physics model. Although early studies have been carried out concerning the incorporation of anelasticity in inversion algorithms (Innanen and Weglein, 2007; Innanen, 2011; Kamei and Pratt, 2013), a key example of practical pre-processing concerns such viscous loss. This loss is commonly addressed by one of several classes of algorithms known as *deconvolutions* (e.g. Robinson, 1967; Margrave et al., 2011a) and/or *Q compensations* (Hargreaves and Calvert, 1991; Innanen and Lira, 2010) and then lossless physics is assumed in subsequent inversions. A further costly computation is the multidimensional gradient function that must be estimated in each step of an iterative inversion (e.g. Pratt, 1999). If we are solving for N earth properties (e.g., N=3 for an elastic problem involving V_P, V_S, and ρ), this gradient has independent dimensions for each point in the earth model, and there can be billions of such points. This gradient function is computed with an algorithm known as a *migration* and is almost as costly as forward simulation.

1.1.3 Unknown source waveform:

Another difficulty is the inherently unknown nature of the seismic source. For exploration on land, the two most common seismic sources are dynamite and vibroseis (referring to a large heavy vehicle designed to shake the earth with a prescribed signal). While a dynamite explosion is appreciably complex, it might seem that a vibroseis source, with its designed signal, can be considered to emit a known waveform. However, the earth immediately beneath the vehicle modifies the emitted signal in ways that are both extremely complex and that change rapidly with the position of the vehicle. For dynamite, it might seem that empirical studies could calibrate such sources, but again, local effects will always modify the emitted signal. The result is that the actual source waveform must be assumed unknown, requiring that it be estimated from the data itself. Here again, deconvolution algorithms supply a partial answer, but the comparison of reflectivity images to well control also is essential.

1.1.4 Missing low frequencies:

A key and frustrating obstacle is the lack of low frequency content in seismic data. This is a consequence of the fact that only very large and powerful sources (e.g. earthquakes or atomic weapons) can emit significant power at very low frequencies. Also, while it is possible to build very low frequency receivers, they are usually too large, complex, and fragile to be used in an industrial setting. This missing information means that inversions from seismic data alone are indeterminate to within a large smooth function or “trend”. That is, there will exist an infinity of such trends which can be added to any inversion result for which predictions will fit observations equally well. An example of a trend is the general increase of velocity with depth due to gravitational compaction. An inversion without a trend can only predict relative property fluctuations and not their absolute values. Of the possible solutions to this problem, we mention the acquisition research targeted at pushing data to lower frequencies (e.g. Margrave et al., 2012a and 2012b) and the incorporation of well information into inversions (e.g. Lloyd, 2013; Lloyd and Margrave, 2013; Gavotti et al., 2013).

1.1.5 Unavoidable noise:

A final issue is the presence of noise, both random and coherent, that has no bearing on the proposed inversion. Mechanical seismic sources such as vibroseis radiate bandlimited signals by design, but all seismic sources are effectively bandlimited by the earth’s attenuation processes. For example, a dynamite source is known to radiate very high frequencies but these are subject to strong exponential attenuation and rapidly drop below the instrument recording floor. On a typical recording day, wind, traffic, ocean waves, and other phenomena cause a broadband background noise that is effectively random and which fills the recorded spectrum at levels usually well above the instrument recording floor. At frequencies where the seismic source signal drops below this background noise, inversion becomes very problematic. Thus all inversions must be considered to be of limited frequency band and hence limited resolution (unless an artificial condition such as sparsity is imposed) and such band limits are generally time and space variant.

A second type of noise, coherent noise, poses a different problem. An example of coherent noise is the repetitive signal radiated by a pump jack in a producing oil field. Unlike random noise which becomes a problem outside a definable signal band, coherent noise is likely to fall in the middle of the seismic signal band. Failure to address coherent noise usually results in a biased inversion.

2.0 Acquisition research

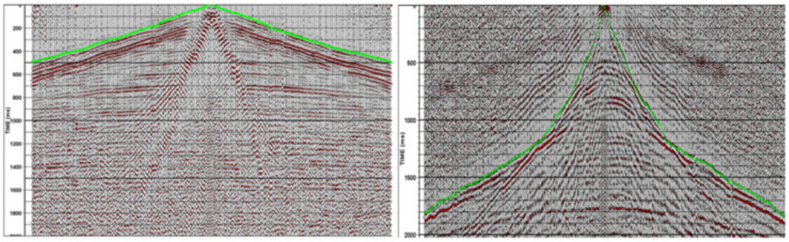

Figure 3: PP (left) and SH-SH shot gathers from the same location.

We are fortunate in having an industry-standard, comprehensive seismic acquisition system comprised of a 600-channel ARAM recording system and a 9000 kg vertical-force Envirovibe seismic source. We also have a small trailer-mounted accelerated weight drop P-wave source and a 120-channel Geode system for near-surface studies. Importantly, CREWES has qualified technical staff to operate this complex equipment. Over the past 7 years, we have used this equipment to conduct many unique geophysical field experiments and will continue to do so. Datasets obtained in our field experimentation are used for student thesis projects, staff research, and are also made available to sponsors.

A key research goal in this application is to understand better shallow S-wave velocities and attenuation. For multicomponent seismic data, rapid to extreme lateral variations in S-wave weathering static corrections are probably the most challenging aspect of data processing and ultimately, inversion robustness and image quality. If the travel-times of shear head-waves are pickable, then standard static methods (inversion or tomography) can be employed to calculate the receiver static correction. Figure 3 shows an example of first arrival traveltimes picked on a vertical component gather with a vertical source (left) and a transverse component gather with and SH source (right), illustrating the significant difference in near-surface P-wave and S-wave velocity structure (Zuleta and Lawton, 2012). Figure 4 shows the resultant P-wave and S-wave receiver statics, showing very significant differences.

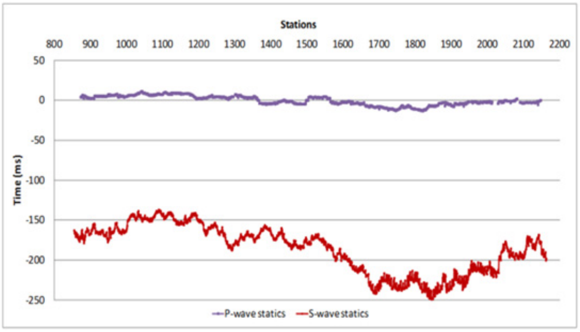

Figure 4: Example receiver statics. P-wave (top) and S-wave (bottom)

However, shear head-waves are not easy to pick on most P-wave datasets. Some advances in surface-wave analysis have been made recently, with promise for evaluating long-wavelength shear statics. Most standard processing approaches use the P-wave structure stack and radial-component common receiver stacks to extract the "optimum" receiver static solution. However, this method can be slow and tedious and output sections are not structurally independent from the P-wave data. Often, the S-wave receiver statics can be an order of magnitude larger than the P-wave statics (Figure 4) and there may be no relationship in trend between them. Sometimes a bulk shift is applied to the S-wave static to avoid PS data being shifted to negative times.

If PS statics are data-limiting in the survey area, then recording an SH refraction survey along receiver lines is recommended. Depending on line access, these can be done quite quickly and SH first arrivals can be used to calculate receiver S-wave static corrections. However, there is no guarantee that S-wave statics corrections will be azimuthally isotropic. In order to advance this research, CREWES has recently built an S-wave seismic source. This is an accelerated weight drop (driven by compressed nitrogen) that has a tiltable mast (through $\pm 45^{o}$) which enables paired records to be subtracted, enhancing the SH mode and cancelling the P mode data (Lawton, 1990).

A project is also presently underway to drill four shallow boreholes (each 150 m deep) to be used for testing geophysical instrumentation and for improving our understanding of P- and S-wave propagation and attenuation in the shallow subsurface. Located on University of Calgary land at the Priddis Geophysical Observatory west of Calgary, these boreholes will facilitate experiments planned in support of the goals of this proposal. One of these boreholes will have a 40-level 3C geophone array permanently installed in it while the other wells are intended for temporary deployment of tools. A range of walkaway and 3D vertical seismic profile (VSP) experiments will be recorded into this array using the Envirovibe and the new S-wave source. The 40-level tool will be used to record the radiation pattern of dynamite, and the surface sources. This will enable a detailed description of the main P and S radiation lobes and therefore document the effectiveness of each source. We will study the influence of the borehole and the variation of charge size for dynamite. For vibroseis, we seek a characterization of the distortion of the vibroseis signal by the earth immediately beneath the source. In addition, a downhole piezoelectric source will be deployed in one well in order to record cross-well surveys into the permanent geophone array. The 40-level tool will also be used to study the evolution of the upcoming P and S wavefields through the near surface. We will estimate Q values and document the effectiveness of the constant Q model to describe this evolution. Measurements from active seismic surveys will be complemented by borehole logging methods, including gamma ray, full waveform sonic and neutron density tools which are available to CREWES.

We will also conduct comparative studies of seismic receivers. Currently of interest are new optical sensor arrays. We have recently purchased a 6-node USSI 3C fibre-optic accelerometer array along with the interrogator unit. The node spacing is 10 m with a 500 m lead-in. In the same borehole as our 40-level tool, we will keep the center annulus open to deploy the USSI array and record multi-azimuth walkaway VSPs into both the conventional geophone array and the optical sensors, for direct comparison between optical receivers and geophones. We wish to test if the optical accelerometers record broader bandwidth data than achieved with conventional geophones, particularly low frequencies down to less than 1 Hz, where geophone sensitivity decreases and phase distortion occurs. Recording broadband data, particularly low frequencies are a key goal for the inversion goals of this proposal. We also plan to run some standard optical fibre in one of the wells to evaluate distributed acoustic sensors (DAS) technology, although at this time we do not have the DAS interrogator or recording box. Our present understanding is that the DAS systems lack the sensitivity of accelerometers (or geophones) and separation of modes and mode sensitivity is still a concern, but these tests are all goals of this proposal.

Having seismic equipment and instrumented wells allows us to give our students field experience and training in surface and borehole seismic methods. This is an extremely valuable component of HQP training. We have found that students with field experience find it much easier to grasp the realities of the seismic method than those whom have not been involved in data acquisition.

Time-lapse seismic studies are becoming increasingly important as we seek more optimal exploitation of reservoirs and detailed knowledge of injected fluids associated with enhanced oil recovery operations and the geological storage of CO_2. At our Priddis Geophysical Observatory we will conduct time-lapse seismic studies to detect the possible seasonal changes of shallow features such as the water table. In the course of such studies we will also characterize the degree of repeatability in the seismic method, using metrics discussed, for example, by Gagliardi and Lawton (2012).

3.0 Multicomponent data processing and preparation for inversion

The purpose of data processing within SM is the estimation of reflectivity which is a function whose values are typically between -1 and 1 quantifying the reflective ability of a subsurface point. The penultimate goal of data processing is to convert raw seismic records, whose samples represent voltage in a geophone, into time series (traces) of bandlimited reflectivity. Given a large number of such time series for many different source-receiver positions, and a model of the subsurface velocities, the ultimate data processing step converts reflectivity traces into a reflectivity image in depth by a final data processing step called migration (or imaging).

Reflectivity is a property of the subsurface but raw seismic data are dominated by waves that are confined to the surface (Rayleigh waves) or near surface (first break refractions). There may also be waves from nearby infrastructure such as highways and pumpjacks. Waves traveling up from subsurface reflectors carry the desired information but are much weaker than surface waves. Furthermore, the reflection signals are not themselves reflectivity as they show amplitude loss and phase rotations from wavefront spreading and anelastic attenuation. Moreover, the strength and waveform of the source and the receiver-to-ground coupling must be taken into account. Thus reflectivity estimation requires the intelligent extraction of a relatively weak signal, and then correcting that signal for various physical effects unrelated to reflectivity. This requires a variety of processes such as gain recovery, coherent noise reduction, deconvolution, near-surface traveltime compensation (statics), random noise reduction, and velocity analysis. Multicomponent data make possible the estimation of distinct reflectivity types such as a reflectivity for P-P (P-waves reflecting as P-waves), P-S (P-waves reflecting as S-waves), S-S, and possibly others. Isolating these reflectivities requires use of all three components of ground motion to separate wave modes and careful mode-dependent traveltime analysis (e.g. Harrison, 1992; Stewart et al., 2002 and 2003; Bale, 2006). Additional care can be required to compensate for the reduced bandwidth of P-S events.

Specific topics of focus for our project are the detection and removal of surface related waves (Henley 2003), surface related multiples (Verschuur et al., 1992; Weglein et al., 1997; Kaplan and Innanen, 2008), and interbed multiples (Weglein et al., 2003; Hernandez and Innanen, 2012a and b), recovery of low-frequency reflectivity (Isaac et al., 2012; Lloyd and Margrave, 2013; Lloyd, 2013), inversion of surface waves for near surface properties (Askari and Ferguson, 2012), the estimation of near surface traveltime delays for P and S waves (Henley, 2012a and 2012b; Henley and Daley, 2008), the creation of velocity models for imaging of both wave types (Guirigay and Bancroft, 2012), interferometric construction of P-P and P-S reflectivity images (Henley, 2012a and 2012b), surface consistent analysis of multicomponent data, imaging (migration) of P-P and P-S reflectivities, analysis of the same both in elastic (Innanen, 2013) and poroelastic frameworks (Kim and Innanen, 2013a, b), estimation and removal of residual amplitude and phase errors in reflectivity images (Lloyd and Margrave, 2012), and perhaps more. Our attention to data processing will concentrate on those topics that are most relevant to inversion.

4.0 Multicomponent bandwidth expansion

In 1.1.3 and 1.1.4 it was observed that seismic data are always of limited bandwidth because of source and receiver limitations, noise, and the earth's natural attenuation. The typical seismic bandwidth over the last decade has been roughly 10-100 Hz, although there are numerous instances of greater bandwidth, especially on the high end. Examples of extension of the seismic band towards low frequencies are less numerous but becoming increasingly important with the growing focus on inversion. An inversion of data lacking low frequencies will only be able to estimate property deviations from an unknown trend. Low frequencies are essential if the true magnitudes of subsurface properties are to be estimated (Figure 5). An inversion of data lacking high frequencies may show the correct magnitudes but will lack resolution (i.e. will be blurred). In the best circumstances, a reflectivity image will always have some sort of band limits at both high and low frequencies but we seek to make this usable frequency band as broad as possible. Within this signal band, the reflectivity image should have a spectrum with the same spectral shape as observed in well-log estimates of reflectivity.

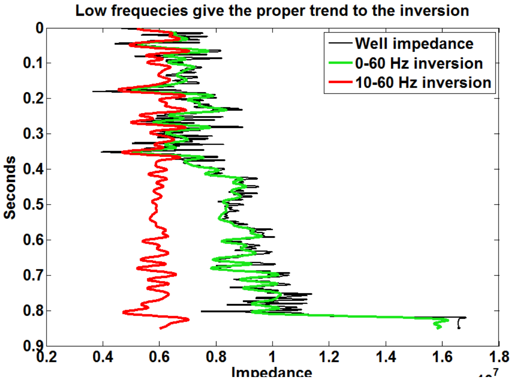

Figure 5: Inversion with and without low frequencies

Seismic acquisition plays a key role in bandwidth expansion. Linear methods cannot expand the bandwidth of a reflectivity image beyond that of the seismic source. For example, a vibrator emitting a 10-100 Hz sweep is inherently limited to this bandwidth unless sweep harmonics can be used as signal. On the other hand dynamite emits a much broader spectrum that is shaped by many uncertain effects such as charge size, hole depth, and local ground conditions. We will study the design of the geometry of acquisition, and the source and receiver characteristics, to maximize the final bandwidth. We are presently emplacing a permanent recording system in a 150m borehole at our

Priddis test site. We plan to use this facility to study the radiation patterns of our common sources. (See section 2.0)

Expansion of the seismic band to higher frequencies, where the source strength exceeds background noise, can be done with data processing. As a seismic wave propagates, it suffers exponential decay with increasing frequency and this is accompanied by phase distortions. Theory suggests that these phase distortions are predictable from the amplitude decay (e.g. Futterman, 1962) so that it suffices to predict the latter and compute the former using a formula known as the *minimum phase relation* (e.g. Claerbout, 1976; Gibson and Lamoureux, 2012). In SM, there is a large class of algorithms known as *deconvolutions* that address this issue. Most deconvolutions are *stationary* (e.g. Robinson, 1967) meaning that they design a single convolutional operator to address a time variant (nonstationary) phenomenon. Such algorithms are useful but the best they can do is to produce an optimal result in a single zone of interest, leaving time variant residuals above and below this zone. We have been successful in estimating and removing attenuation using a novel nonstationary deconvolution (Gabor deconvolution, Margrave et al., 2011a). This promising approach results in a very high resolution reflectivity image, but it is difficult to avoid slowly time variant amplitude errors. We will work to improve this process for incorporation into IMMI.

The estimation of reflectivity images at very low frequencies brings two unique problems. One is that the coherent source-generated noise, which is always present in seismic data, is very strong at low frequencies. We have found that removal of this noise using common algorithms in SM usually removes low-frequency reflection signal too (Isaac et al, 2012). In fact, the separation of signal and coherent noise at very low frequencies is almost unexplored terrain. We have several lines of investigation open on this problem. The other issue is to determine the correct spectral shape of the reflectivity estimate. In SM, deconvolution is primarily responsible for this spectral shaping and most methods assume a white (flat) spectrum. This assumption is reasonable above 10 Hz but low-frequency reflectivity computed from wells shows a strong power roll-off towards low frequencies. This *coloured reflectivity* is observed worldwide and is caused by the cyclic nature of certain geological patterns such as marine transgressions and regressions. We have developed methods to impose this spectral colour and are still investigating its significance (Cheng, 2013; Cheng and Margrave, 2010).

We have championed the use of multicomponent seismic data for the estimation of two dominant reflectivity types: P-P and P-S (Stewart et al., 2002, 2003). We have looked for other possibilities (e.g. S-S and S-P) and found them to be much weaker. In general, P-S data shows 50% of the bandwidth of P-P data. We attribute this reduced bandwidth to the strong attenuation of S-waves in the upper 100 meters of the earth. It is not clear how this circumstance can be improved but we have several lines of investigation. We will use instrumented shallow boreholes to study the evolution of the wavefield in the upper 150 m with the hope that better recovery algorithms can be developed. We will also investigate the possible use of instrumented shallow boreholes to record entire multicomponent surveys. In a third investigation, we will continue to improve our ability to estimate statics and velocities required for P-S reflectivity images.

5.0 Classical impedance and AVO Inversion and their logical extensions

A number of non-iterative procedures for estimation of earth properties are regularly used as the final step of SM. These are called *inversions* and typically require one or more reflectivity images as input. For example, P-P reflectivity theoretically allows estimation of both Lamé parameters and density but using both P-P and P-S images is a stronger constraint and gives better results (Larson, 1999; Zhang, 2003; Downton, 2005; Mahmoudian, 2006). Reflectivity may be either be averaged over all available incidence angles or be sectored into incidence angle bins. In the former case, we say the image is "stacked" while in the latter case we say it is an "angle image" or sometimes simply "unstacked". Stacked reflectivity images are either 2D or 3D while a corresponding angle image has one or two additional dimensions depending upon how many angles are being tracked. While these images are constructed at great computational expense with very sophisticated algorithms, they are generally deficient in at least two ways: (1) there is always an unknown residual wavelet convolved with the reflectivity, and (2) the reflectivity image lacks low frequencies. These deficits must be addressed in the inversion step.

A reflectivity image shows large amplitudes at layer boundaries and is often called an interface image. *Impedance inversion* (e.g. Lindseth, 1979; Oldenburg et al., 1983; Lloyd, 2013) converts reflectivity image(s) into estimates of layer impedance which are often preferred for geological mapping and reservoir characterization. During this process, the problems of source waveform estimation and missing low frequencies are directly confronted. The key strategy is the incorporation of well control information, in the form of appropriate well logs, into the inversion process. Comparing the reflectivity image to reflectivity calculated directly from well logs allows an estimate of the residual source waveform. Further, the low-frequency information missing from the reflectivity image can also be estimated from the same well information (e.g. Lloyd, 2013).

The details of how AVO information permits elastic seismic inversion to proceed has been studied in the case of direct inverse scattering methods (Zhang and Weglein, 2009), and simplified single-interface environments (Innanen, 2011, 2013). However, current understanding of the role of AVO in the convergence of iterative methods like IMMI and FWI is shallow at best. We will investigate this theoretically and numerically, and improve the process of incorporating AVO and well information into both IMMI and FWI. Present techniques for residual wavelet estimation using well control are inherently ambiguous and often prefer empirical manipulations over scientific rigour. We will develop methods to incorporate more physical constraints, such as independently derived overburden and attenuation models, into this process. We will also study the estimation of the residual wavelet in depth rather than in time. As we move to IMMI and FWI, it will be necessary to develop new techniques that can be applied in a progressive iteration from low to high frequency. In such an iteration, impedance inversion incorporating well control will be investigated as a replacement for the line search currently used to estimate the iteration step length.

Impedance inversion can be applied to either stacked or unstacked reflectivity images, with the latter giving much stronger constraints on P and S impedance and especially density. We have made considerable progress here especially with simultaneous inversion of P-P and P-S data (Larson, 1999; Zhang, 2003; Downton, 2005; Mahmoudian, 2006). However, there are a number of outstanding problems including: event registration (alignment of P-P and P-S images), compensation for the differing bandwidths of P-P and P-S, sectoring into azimuthal gathers for anisotropic inversion (Mahmoudian, 2013; Mahmoudian and Margrave, 2013), and using frequency dependence of reflectivity to estimate Q attenuation (Innanen and Bird, 2011; Innanen, 2011; Bird, 2012).

6.0 Numerical and physical modeling of seismic wave propagation

Modelling of seismic data, meaning the prediction of synthetic seismic data given a geological structure, plays an essential role in our research strategy. We use modelled data to understand the response of geological structures, to test data processing and imaging algorithms, to explore the capabilities of inversion concepts, and most recently as an essential step in both FWI and IMMI. We will continue to emphasize both numerical and physical approaches to modelling as both have their advantages. Numerical methods are more flexible in that any structure which can be described numerically can be modelled, although the underlying physics of the simulation may be limited. In physical modelling, a scale model of a geological structure must first be constructed from physical materials such as plexiglas, phenolic, or water, and then ultrasonic transducers are used to send and receive P and S waves through the structure. The main advantage of physical modelling is that the physics is real not simulated.

A focus of recent modelling efforts has been the simulation of seismic waves through anisotropic media (Mahmoudian, 2013; Mahmoudian and Margrave, 2013). This will likely remain a priority as the specific anisotropy induced by fractures, either natural or artificial, is highly indicative of unconventional reservoirs. We have successfully modelled such media both numerically and physically and have used these data to verify approximate theoretical expressions for the reflection coefficients of a fractured layer.

We have recently developed a series of codes that are a finite-difference variant of the well-known “reflectivity” method to simulate seismic waves in highly anisotropic and absorptive media. A reflectivity code (e.g. Fuchs and Müller, 1971; Müller, 1985) is a specific numerical method appropriate only for strictly horizontal interfaces, but with very accurate physical response over a broad frequency band. Simpler reflectivity codes have been used for decades to generate synthetic seismograms at wells to aid in “tying” seismic data to well control. Our method (Daley, 2010; 2011) replaces the propagator matrices of the standard reflectivity method with finite-differences as suggested by Mikhailenko (1985) and Mikhailenko and Korneev (1984). A simplified acoustic variant of these methods (e.g Waters, 1992 sec 4.8) has been used for many years to create normal incidence acoustic seismograms for tying seismic lines to wells. We intend to use these new reflectivity codes in the “well validation” step in our proposed IMMI iteration.

We are also investigating elastic pseudo-spectral methods, and discontinuous Galerkin methods as alternatives to finite differencing. These mathematically sophisticated approaches yield higher spectral fidelity although typically at a cost of increased run time (McDonald et al., 2011a, 2011b, 2012).

We maintain a rather large library of other numerical modelling codes; some were developed by us and some are commercial. This two-pronged strategy is useful because it keeps us actively involved in modelling research while allowing us access to commercial solutions. We have created a software package for modelling directly from well logs and we will continue to evolve this for use in IMMI. We have also created elastic-wave finite difference software (e.g. Wong et al., 2012) which we will continue to evolve.

The question of the value of FWI or IMMI using incomplete physics will also be investigated as a modelling study. For example, an elastic synthetic dataset can be created and inverted using acoustic physics. This will like result in systematic distortions in parameter estimates that may be quantifiable.

7.0 Iterative modelling migration and inversion (IMMI)

In addition to studying FWI in its purest sense, we will address the serious limitations of FWI to develop a similar, but more practical, method (IMMI) that borrows strength from SM while retaining the essential FWI virtues of forward modelling, imaging of the data residual, and iteration (e.g. Margrave et al., 2010, 2012c, 2012d). While it is common to hear of FWI studies requiring thousands of iterations, we anticipate that just a few iterations of IMMI will produce a large improvement over SM. IMMI will depart from FWI in 3 significant ways: (1) we will incorporate data processing to condition the data for an approximate physics model, (2) we will incorporate well control for source waveform estimation and to calibrate the gradient step length, (3) we will use conventional depth migrations with deconvolution imaging conditions to approximate the application of an inverse Hessian. IMMI will differ from SM by having a prescribed iteration path, by including simulation of the recorded data, and by migration of the data residual.

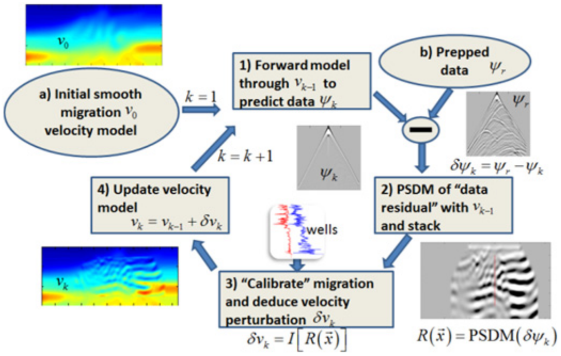

Figure 6: IMMI or Iterated Modelling, Migration, and Inversion.

We observe that modern seismic processing, described here by SM, is an approximate implementation of ¾ of a first cycle of a FWI iteration. However, SM is almost never iterated in the sense proposed by FWI. The missing component of the iteration is forward modelling and this is highly problematic. In theory, the modelling engine needs to use the full physics of seismic waves and this means a poro-visco-elastic simulation done in fully heterogeneous and anisotropic media. While such modelling is technically possible, the computational burden is immense (sections 1.1.1-2) and it is not feasible to use in a practical iteration. Moreover, the imaging step in FWI should be accomplished with the adjoint process of the same physics description, thus doubling the computational load. We will seek an approximate implementation that uses an approximate physical model and compensates for this approximation in other ways.

That an implementation with approximate physics should be possible is indicated by several successful elements of SM. Viscous loss is a complex physical phenomenon that is not only difficult to model, but there is also no generally agreed upon physical mechanism. However, it is known that, if the mechanism is linear and causal, the result is a continuously evolving wavelet whose evolution operator is minimum phase (Futterman, 1962). In SM, this effect is treated by deconvolution algorithms which use robust statistical arguments to estimate either the wavelet at the target (stationary case) or the entire evolving waveform (nonstationary case). The result is a modified dataset that can be modelled with simpler, lossless, physics. A second example is the broad class of seismic imaging algorithms known as depth migrations. The overwhelming majority of these algorithms are based on the acoustic wave equation, yet the resulting reflectivity images are routinely used in elastic impedance inversion algorithms. This succeeds because the acoustic wave equation, when used with the correct velocities for the wavetype (P or S) under consideration, accurately describes the dominant effects of physical positioning and wavefront spreading. Current technology even allows the wavetype to change (e.g. P to S) upon reflection. There are advantages to imaging with an elastic wave equation but these seem small in comparison to the computational effort required.

A further strength of SM that helps correct for the effects of approximate physics is the incorporation of well control. At a well with a full logging suite (P and S sonic logs plus a density log), the reflectivity of interest can be estimated with great accuracy. Given a reflectivity image with unknown but systematic errors in wavelet and amplitude, corrective methods can be derived that estimate and remove apparent distortions. For example, for an elastic medium the average P-S reflectivity varies proportionally to the sine of the incidence angle, but after data processing traces for all angles tend to be similar in amplitude due to the essential use of algorithms that equalize energy levels on all traces. However, using well control, the correct average behavior can be imposed on the P-S image to condition it for elastic inversion.

Thus, for a given physical effect, we have suggested 3 options: estimate and remove the effect in data processing, correct for it using well control, or incorporate it in the imaging and modelling algorithms. In FWI, only the third option is considered. Our experience has also shown that a fourth option is viable, and that is using more sophisticated physics in the modelling step than in the imaging step. Thus we depart from strictly using adjoint operators in the iteration. We have found that, in an acoustic iteration, imaging can be done with one-way propagators (i.e. neglecting multiples) while modelling uses the full two-way acoustic wave equation (e.g. Margrave et al., 2010). All of these strategies will be the subject of intense study.

Once a modelling method has been chosen, there are many possible strategies to iterate SM. A common practice that makes iteration very difficult is to conduct the first imaging step with an overly detailed velocity model. It is quite likely that detail such as precise fault and interface locations will be incorrect (or inconsistent) and should not be prescribed until determined by the data itself. Experience with FWI suggests that an iteration beginning with only the lowest frequencies in the data and then moving up through the frequency band is effective. Such a frequency dependent iteration also gives a rational criterion for velocity model smoothness. For a frequency, *f*, the model spectrum should not contain wavenumbers higher than af/v where v is the average velocity of the model and a is a constant likely between 1 and 2.

Data processing steps such as deconvolution, surface-consistent amplitude adjustment, noise reduction, and statics (all types), will likely remain in IMMI as necessary preconditioners. Deconvolution will be necessary to estimate the source waveform and to move the data towards a state where lossless physics suffices. Surface-consistent amplitude adjustment is the best technique available to equalize source strengths and receiver coupling. Statics, especially surface-consistent residual statics, are unequaled in their ability to resolve near-surface traveltime anomalies. It seems likely that tomographic velocity analysis will also remain as a model building tool. Precisely how such methods will be applied and where in the iteration will be a major research topic.

Forming the data residual in each iteration is not a matter of simple subtraction of modelled data from real data. There will always be at least a scale factor to be estimated and perhaps even small time shifts. Such methods are in common practice in the removal of surface-related multiples where they are called least-squares subtraction.

The imaging algorithm used in FWI to compute the gradient estimate is almost always a variant of reverse-time migration (RTM) with a correlation imaging condition. In comparison to a standard migration in SM, the FWI gradient is very poorly scaled and is not a reflectivity estimate. The common approach of choosing a single constant to scale the gradient into an impedance update leads to very slow convergence. Theoretically, the better approach is to calculate and apply the *inverse Hessian* operator but this is known to be computationally prohibitive for a problem as large as seismic inversion. Alternatively, a standard (non-RTM) *prestack depth migration* (PSDM) from SM, computed using either a deconvolution imaging condition or with gained data, produces a much better scaled alternative to the FWI gradient. Also, because standard PSDM operators have analytic representations, we believe that it is possible for us to develop approximate inverse Hessians by analytic or numerical means that result in non-prohibitive computation (Margrave et al., 2011b; Zubov et al., 2013). Moreover, the conversion of the result from PSDM into an impedance update is essentially the standard impedance inversion of SM. Therefore, we will investigate the use of all common migration algorithms in IMMI and retain the concept of estimating a reflectivity image that is subsequently converted to impedance.

8.0 Time-lapse inversion

Our research into the analysis of time-lapse multicomponent seismic data has included a project in an in-situ oil-sands production area where we developed an innovative approach to matching the datasets so that seismic anomalies could be interpreted directly in terms of changes in the steam chamber (Kelly and Lawton, 2012). In other studies, we have mapped time-lapse changes in anisotropy due to fractures in a potash mining region (Nicol and Lawton, 2012). However, time-lapse seismic analysis is challenging and improved methods are needed for detecting the time-lapse signal.

In addition to time-lapse seismic surveys at the Geophysical Observatory at Priddis (described in section 2.0), we will be partnering with Carbon Management Canada and the University of Calgary on another site in Alberta known as the Geoscience Field Research Station (GFRS). This site (location confirmed but not yet publicly disclosed) will have a focus on monitoring of small volumes of injected CO_2 into subsurface formations in order to evaluate and improve subsurface monitoring systems and to determine the detection threshold of CO_2 at relatively shallow depths where it will be in gas phase and also at greater depths where it will be close to the critical point on the CO_2 phase diagram.

We have demonstrated that the time-lapse signal for monitoring fluid changes in reservoirs in Alberta is very small (Sodagar and Lawton, 2013) and that simple differencing of monitor and baseline seismic data sets using the SM is inadequate to resolve these signals reliably. Thus, a key application of IMMI will be to improve resolvability in time-lapse seismic surveys for fluid detection and monitoring. Recently, we have successfully demonstrated the application of surface-consistent matching filters to precondition time-lapse data to give a more meaningful difference (Almutlaq and Margrave, 2013). CREWES will have access to the GFRS site for the development of improved time-lapse seismic surveys and analysis and will contribute significantly to all aspects of surface and well-based seismic monitoring programs at the GFRS.

The time-lapse seismic problem dovetails with FWI and IMMI. In addition to the more mature theories for analysis of time-lapse seismic amplitudes (Landro, 2001), in recent years sensitivities specifically designed to treat time-lapse inversion have been presented and are currently the topic of intensive study (Denli and Huang, 2010; Shabelansky et al., 2013). We have begun the process of characterizing the time-lapse reflection seismic problem from scattering theory (Innanen et al., 2013). Here we have shown that a full accounting of difference data involves a nonlinear combination of both time-lapse changes in earth properties and the baseline elastic structural variations. This has been derived in scalar and acoustic settings, and extended to elastic settings, wherein the time-lapse AVO problem has been analyzed and validated with physical modeling data (Jabbari and Innanen, 2013a, b). We will further extend these results to multicomponent amplitudes, and move the theoretical results towards application to field data.

9.0 Team Expertise (From here on is a direct copy from last CRD)

CREWES is led by five geophysics professors, one mathematics professor, and one adjunct professor (geophysics). These individuals bring a broad spectrum of expertise to the project and are key to enable us to address the seismic imaging problem both broadly and deeply.

- Professor Gary Margrave has 15 years of industry experience and has been at the University of Calgary since 1995. His expertise includes seismic data processing and imaging, seismic exploration, well log analysis, numerical analysis, nonstationary spectral analysis, and computation. He is the Director of CREWES.

- Professor Don Lawton came to the University of Calgary in 1979 and was previously Department Head. He has recently been appointed as Director of the Containment and Monitoring Institute, a joint program between Carbon Management Canada and the University of Calgary. His strengths are seismic acquisition, multicomponent seismic exploration, seismic imaging, anisotropy, and interpretation. Most recently, Don has led our efforts in time lapse seismology and seismic monitoring of injected gases.

- Professor Kris Innanen joined the faculty at the University of Calgary in 2009, coming from the Department of Physics at the University Houston where he was an assistant professor. His strengths are in theory of wave propagation in acoustic, elastic and anelastic media, and the application of perturbation and scattering methods to problems of seismic data processing and direct as well as iterative inversion. His interests in applied geophysics include seismic inversion, seismic Q estimation and compensation, multiple prediction, and AVO modeling and inversion for nonstandard rock models (e.g., poroelastic and anelastic solids).

- Professor Larry Lines came to the University of Calgary in 1997 from the NSERC/Petro-Canada Chair position at Memorial University to take the CSEG Chair in Exploration Geophysics and subsequently served as Department Head (2002-2007). Dr. Lines was President of the SEG in 2008-2009, a position with worldwide responsibility that serves to broaden our industrial contacts. Dr. Lines is very strong technically at all aspects of exploration seismology but especially imaging, inversion, and interpretation.

- Professor Michael Lamoureux has been at the University of Calgary since 1992 and is presently Head of the Department of Mathematics and Statistics. His expertise includes functional analysis, mathematical inverse theory, numerical methods, and applications to seismic and medical imaging. He leads the POTSI Research Group (Pseudodifferential Operator Theory and Seismic Imaging).

- Dr. John Bancroft has been with the CREWES project since 1994 and is an Adjunct Professor in the Department of Geoscience. Dr. Bancroft is an acknowledged authority on seismic migration. He leads research in areas of static analysis, velocity estimation, and seismic migration.

In addition to the expertise possessed by the applicants of this proposal, CREWES technical staff has a collective depth of experience and expertise that is a tremendous strength. Many of our staff have extensive industry backgrounds, five have Ph.D.'s, and two have M.Sc.'s. Their expertise is essential in our field experiments, in our data processing, and in the day to day research activities.

On average, there are about 20-30 graduate students working with us. Often our students have industry experience before entering the project and then gain more through summer jobs or internships during their degree programs. Our senior students are often in mentorship roles with respect to the junior students.

CREWES has had a number of PDF's (post doctoral fellows) in the past; but the wide gap between industry and PDF salaries makes such positions difficult to fill. Recently, we have been successful in finding Ph.D. mathematicians who are eager to learn geophysics and accept a PDF position to do so.

10.0 Research Management

CREWES manages the conduct of research through a formal management structure plus an Industrial Advisory Board. Furthermore, CREWES disseminates research results first through a large, internal-report to our sponsors, and then to the wider community through peer-reviewed journal publications and scientific conferences.

Management Structure: The CREWES executive consists of a Director, Associate Directors (presently two), an administrative manager, and a support staff manager. This group meets monthly to review progress towards research goals, set new goals, discuss planned expenditures, plan group meetings, and many other items. The entire CREWES project, faculty, staff, and students, meets on a weekly basis during the academic year (September-April) to discuss CREWES business and participate in technical presentations. Usually, the speakers are students as this is an excellent opportunity for them to practice presenting their work.

Management of Industry Partnerships: Industry guidance is a vital part of the CREWES structure and this is provided in several ways:

- We have an Industrial Advisory Board (IAB) whose membership consists of the CREWES Executive and about eight to twelve representatives from sponsor companies. The IAB meets at least twice yearly and reviews the research progress, budget, and plans for the project. The industrial representatives are encouraged to influence our research direction and do so regularly.

- Each year, in late November or early December, CREWES holds its annual Sponsors Meeting where our research results are presented to our industrial sponsors over a 2-day period. Industry attendance is usually between 30 and 50 delegates, with typically between one and two people attending from each sponsoring company. There is always a great deal of interaction at this event and the industrial interaction is detailed and intense. At the end of the meeting the industrial representatives vote on their top choices from a detailed list of research topics. This list then assists us in the coming year.

- During the year there are often informal interactions between CREWES and industry. These can consist of visits by CREWES personnel to an industry office or the reverse. We often have industry people at our weekly CREWES meeting to hear the technical talk.

Dissemination of Research Results: A very important aspect of CREWES management is the dissemination of research results of faculty, staff, and students to the geophysical communities of Canada and the World. While our annual research report to sponsors must remain confidential for two years, we are free to publish papers derived from this research as we please. This helps to ensure that our research is widely disseminated and has global impact. Our website (www.crewes.org) gives unrestricted access to all CREWES research reports that are more than two years old. Our journal publications appear in the major geophysics journals and occasionally in applied mathematics, wave propagation theory, and signal processing. Further, CREWES personnel present research papers at the annual technical meetings and workshops of the major relevant professional societies.

11.0 Training of Highly Qualified Personnel (HQP)

The training of HQP is one of the core activities of CREWES and is viewed by our industrial sponsors as one of our most important contributions. Most obvious in this regard is our training of graduate students. During the 5-year term of this proposed NSERC grant, we anticipate graduating 30 M.Sc and 10 Ph.D. students. Over the past twenty year span of the project, 70 M.Sc. students and 22 Ph.D. students have successfully completed their programs with us. CREWES provides an exceptional training and learning environment, with a comprehensive suite of software and hardware tools to undertake leading edge research in all aspects of applied seismology. The quality of our graduate students and research environment was demonstrated at the 2008 Annual International Meeting of the Society of Exploration Geophysicists where two CREWES graduate students won the SEG’s Challenge Bowl, a international competition about geoscience knowledge, open to University teams from around the world. All past CREWES graduates are presently employed, the majority in industry, but some have chosen the academic path. It is difficult to visit a geophysical company in Calgary and not encounter a CREWES graduate. The highly technical nature of seismic exploration is not easily learned and our M.Sc. graduates are highly sought for their expertise. Our Ph.D. graduates often become independent researchers or research team leaders.

A less obvious HQP training mechanism is that experienced by our technical staff. While we do not encourage their departure, industry dynamics have caused this on a number of occasions. We have seen staff members with M.Sc. or Ph.D. degrees, often in fields other than Geophysics, become highly valued in industry after having spent a term with CREWES.

There is also a reverse mechanism to that mentioned in the previous paragraph. CREWES often hires senior, or even retired, scientists from industry who wish a change of focus. Usually, these people become involved with all CREWES activities including the mentoring of students, and this is an extremely valuable feedback loop from senior industry scientists directly to young graduate students. Through this mechanism, knowledge and experience that might otherwise be lost re-enters the system.

12.0 Benefits to Canada

This work will make extensive and important contributions to Canada’s ability to find and manage its hydrocarbon reserves and to safely sequester greenhouse gases in subsurface reservoirs. A sustainable energy plan will require hydrocarbon resources for the foreseeable future as alternative energy sources are developed. Furthermore, the sequestration of greenhouse gasses in depleted oil and gas reservoirs or deep saline aquifers must be accompanied by a monitoring component to verify the entrapment.

Seismic imaging offers the potential to discriminate between various lithologies and pore fluids, and to track the motion of the latter as a result of injection or production processes. However, the realization of this potential will require extensive research and investment of the requisite time and resources as detailed here. This research will move seismic imaging science towards greater fidelity, meaning image amplitudes will reliably predict reservoir properties, and towards greater resolution, meaning smaller features than those presently detectable will be imaged).

The long term benefits to Canada are (i) a greater system of hydrocarbon reserves with the means to image the internal fluids as they are drained thus allowing optimal exploitation, and (ii) the ability to monitor gas sequestration projects thereby enhancing the projects' safety and reliability. Shorter range benefits include a steady stream of highly-trained imaging scientists and, through their skills and technology, better success at hydrocarbon exploration. The technologies developed here can be used directly in environmental studies of soil and water, as well as contaminant tracking. CREWES also interacts with other imaging groups, especially medical imaging, and there are likely crossover benefits to other fields.

In geographically specific terms, the exploitation of the Alberta oil sands often requires high resolution seismic images and their inversion. This area is especially interesting because the reservoirs are shallow and the data is very high quality. Improved inversions will mean a more optimally produced resource. Also, the increasing importance of unconventional reserves such as shale oil and gas released through induced fractures is very important to large areas of British Columbia, Alberta, and Saskatchewan. Improved inversions will allow induced fractures to be better predicted and tracked, thus improving reservoir drainage.

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