Chapter 1

Introduction

An accurate velocity model of the subsurface is a crucial component of successful seismic imaging projects. Unfortunately, producing such a model is also one of the most time-consuming and difficult aspects of the imaging workflow. For several reasons, this is especially true in areas characterized by large subsurface salt bodies. First, salt is relatively fluid or ductile compared to the sedimentary formations within which salt is normally encountered. This creates a wide variety of shapes and formations as the salt moves and deforms throughout the subsurface. For example, salt structures often feature extremely steep dips along their flanks, making them difficult to image (and subsequently model) using standard seismic migration techniques. A second reason salt modeling can be so time-consuming is the extreme care necessary to ensure that salt interpretation is as accurate as possible. Seismic waves travel at a much greater velocity (often over twice as fast) through salt than they do through the sedimentary rocks that typically surround salt bodies. The sharp velocity contrast leads to a large reflection coefficient, and the resulting scattering of seismic energy, along the interface between salt and sediments. Even a slight error in the interpreted location of this interface can have a disproportionate impact on calculations of wave propagation beneath the interface, and lead to significant degradation of the resulting image. To combat this, salt modeling is often carried out in an iterative fashion, with interpretations of the top and base of salt bodies being performed on one or more
images created using sediment- or salt-flood velocity models, respectively (Mosher et al., 2007). The iterative nature of the process, combined with the challenges interpreters face when salt bodies are not clearly imaged, leads to salt modeling workflows that can stretch for weeks or even months for the enormous 3D seismic surveys that are standard in today’s exploration environment. Thus, salt modeling represents a tremendous bottleneck in the backbone workflow of a multi-billion dollar industry.

At the same time, exploration for oil and gas is becoming increasingly focused in areas of the world dominated by salt bodies, and in reservoirs existing below those salt bodies. Notable examples include offshore Brazil and West Africa, the North Sea, and the Gulf of Mexico, which is the origin of all the field data used in this thesis. Increased exploration in these salt-dominated areas is not a coincidence; in much of the world, the “easy oil” in reservoirs above salt has been located and produced, leaving the more challenging reservoirs below salt as prime targets for imaging and exploration. Furthermore, the presence of salt itself can sometimes be an indicator of possible resource deposits. As it moves through and deforms the subsurface, salt helps create structural traps for oil and gas, and in addition acts as an impermeable seal for those reservoirs (Hudec and Jackson, 2007). An indication of the extent to which salt tectonics can dominate the geology of a region can be found in the bathymetry of the transition zone between the continental shelf and deepwater in the Gulf of Mexico. As Pilcher et al. (2011) demonstrate, the extreme bathymetric variations found there are a result of subsurface salt movements – as salt bodies flow and retreat, they deform the overlying sediments to such an extent that their surface expression is clearly visible. These irregularly shaped salt bodies, like the one shown in Figure 1.1, are difficult to interpret even when well-imaged, and contribute to the model-building bottleneck described above.

The goal of my thesis is to alleviate this bottleneck by introducing two model building tools. The first of these tools is interpreter-guided seismic image segmentation, which is a semi-automatic method of delineating salt bodies like the one in Figure 1.1. The method is designed to incorporate valuable interpreter insight from 2D sections into an automatic 3D segmentation, thus combining humans’ pattern
Figure 1.1: Slices through a 3D seismic image cube featuring a salt body in the Gulf of Mexico. Even though the salt body is relatively well-imaged, portions of the boundary and subsalt reflectors are missing or discontinuous.
recognition strengths in 2D with ever-increasing computational capabilities in 3D. The second tool is a method for quickly and efficiently evaluating the relative accuracy of two or more potential velocity models. Such a method is useful if, for example, an ambiguous base salt interpretation leads to several possible salt “scenarios”. The efficient model evaluation scheme can evaluate these models for a tiny fraction of the expense required for a full migration of the data for each model. In the following sections and chapters, I will describe the background and theory behind both of these tools, and provide examples using both synthetic and field seismic data, in 2D and 3D. Finally, in Chapter 4, I will demonstrate how these tools can work together to create and test alternate velocity models for a 3D dataset from the Gulf of Mexico, and identify a model that leads to an improved subsalt image.

**IMAGE SEGMENTATION**

One way to streamline salt interpretation is to automate some of its processes. Automating some aspects of seismic interpretation is not a new idea; automatic horizon trackers are ubiquitous in seismic processing and interpretation software packages, and are often effective for relatively flat and/or highly continuous reflectors. However, “flat” and “continuous” are words rarely used to describe the imaged boundaries of salt bodies, and automatic pickers can struggle if they encounter local discontinuities along a reflector. Figure 1.2 provides one such example. Even though the salt boundary in this image is relatively prominent, the automatic picker fails to accurately track the entire boundary even when multiple seed points (in red) are supplied by an interpreter. It follows that salt interpretation would benefit from algorithms that take a more global approach to the problem, rather than relying solely on local attributes along a reflector. *Image segmentation* algorithms fit this description.

The term “image segmentation” refers to the process of automatically detecting non-overlapping regions within an image based on certain characteristics. These characteristics vary depending on the type of image in question. For example, color attributes are popular for algorithms aimed at segmenting photographs (Cheng et al.,
Figure 1.2: An automatic horizon-tracker attempting to follow the salt boundary on a seismic image from the Gulf of Mexico, using (a) two, (b) three, and (c) four manually-placed seed points indicated in red on each figure. Even using four seed points on this relatively prominent boundary, the algorithm struggles to accurately track the boundary.
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Image segmentation algorithms can be grouped into families based on the methods employed, and several families of methods have been applied to seismic images. These include pixel-based schemes (Valet et al., 2001; Berthelot et al., 2012) and fast-marching methods based on level sets (Osher and Sethian, 1988). The latter method has attracted interest based on its utility both for standard salt segmentation (Haukas et al., 2013), and in conjunction with velocity estimation using the Full Waveform Inversion (FWI) objective function (Lewis et al., 2012; Dahlke et al., 2014). However, the class of algorithms which has proven most popular for seismic image segmentation, and to which the method presented in this thesis belongs, is called graph-based image segmentation. In these methods, pixels in the image are treated as nodes of a graph, which are connected via various edges. The graph (and thus the image) is partitioned by making one or more optimal cuts through the graph’s edges. Early efforts using these methods focused on atomic meshing of seismic images (Hale and Emanuel, 2003, 2002), while later work adapted the Normalized Cuts Image Segmentation (NCIS) algorithm (Shi and Malik, 2000) for tracking 3D salt boundaries (Lomask, 2007; Lomask et al., 2007). This approach was effective, but faced computational hurdles because of the need to calculate eigenvectors from large, 3D images. In contrast, the method presented here, adapted from the Pairwise Region Comparison (PRC) scheme of Felzenszwalb and Huttenlocher (2004), is designed to be extremely computationally efficient. This allows us to obtain results like the one in Figure 1.3, in which the salt body has been automatically identified much more accurately than in the horizon-tracking results in Figure 1.2, at negligible computational expense. In the next chapter, I will describe how to modify the original PRC algorithm to account for the unique nature of seismic images, and how to incorporate interpreter guidance.
into the process when necessary.

Figure 1.3: The same image used in Figure 1.2, with the salt body automatically delineated using a modified version of the Pairwise Region Comparison (PRC) scheme from Felzenszwalb and Huttenlocher (2004). This result was obtained with negligible computational expense and with less human interaction than was required for even the inaccurate results in Figure 1.2.

EFFICIENT MODEL EVALUATION

Velocity model building is rarely a straightforward exercise, especially when salt is involved. For example, Figure 1.4(a) shows a velocity model provided with the underlying image (from the same 3D image cube seen in Figure 1.1). Much of the salt interpretation is unambiguous, especially along the top salt reflector. However, a couple aspects of the model suggest room for improvement. First, a highly noticeable inclusion within the salt body has not been modeled with lower, sediment-like velocity. And second, the base salt reflector is much more ambiguous than the top salt in several locations, allowing for a range of possible interpretations. Either or both of these issues could be affecting the quality of the image subsalt, leading to the fading
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or discontinuous reflectors beneath the salt body. To investigate, an interpreter could create an alternate model like the one seen in Figure 1.4(b), either manually or, in this case, with the aid of tools such as image segmentation. The question becomes, what is the best way to determine which of these models is more accurate?

The simplest way to gauge the accuracy of a velocity model is to obtain an image by migrating the data using that model. However, this approach quickly becomes infeasible for very large datasets and/or multiple models. For example, the images shown here are from a wide-azimuth survey from the Gulf of Mexico, provided by Schlumberger Multiclient. Wide-azimuth surveys are beneficial because the increased azimuthal coverage allows for better illumination and (ideally) higher-quality images beneath salt bodies. These advantages come at the expense of more manageable dataset sizes, however. This particular dataset is almost 8 terabytes in size, with over 700 million data traces. The goal of this thesis is to alleviate model building bottlenecks, but the ability to quickly create velocity models using image segmentation does little to achieve this goal if testing these models requires repeated migrations of such large data volumes.

In Chapter 3 of this thesis, I propose the idea of using wavefields synthesized from an initial image to more efficiently test velocity models. The goal of this procedure is similar to others (Gao et al., 2006; Wang et al., 2008) which rely on a fast variant of Gaussian beam migration (Hill, 1990, 2001). However, using wavefield propagation methods allows for a more physically realistic solution, while avoiding frequency assumptions inherent to beam imaging. Wavefield synthesis via Born modeling (Stolt and Benson, 1986) has been used previously to successfully address imaging problems in a target-oriented fashion (Tang, 2011; Tang and Biondi, 2011), which is similar to the strategy presented here. In addition, this method takes advantage of the prestack exploding reflector concept (Biondi, 2006; Guerra, 2010; Guerra and Biondi, 2011) to incorporate prestack velocity information from an initial image into an areal source function used to synthesize new receiver wavefields. This creates the opportunity to identify and correct errors in the initial velocity model. Most importantly, this method is highly efficient; by targeting specific locations along a single reflector, it
Figure 1.4: Slices through the same image as in Figure 1.1, with two different velocity models overlaid: (a) the original model provided with the data and image; and (b) an alternate model obtained via image segmentation techniques. The alternate model features a modeled inclusion within the salt body, and a different base salt interpretation. [ER] chap1/. vmod0,vmod1
can produce both qualitative and quantitative indications of a model’s accuracy in a fraction of the time needed for a full migration of the original dataset.

THESIS OVERVIEW AND CONTRIBUTIONS

Interpreter-guided seismic image segmentation: In Chapter 2, I introduce the concept of image segmentation and review some of its past applications to geophysical images. I then describe the Pairwise Region Comparison (PRC) graph-partitioning algorithm of Felzenszwalb and Huttenlocher (2004), and explain its potential for use in automatic salt body segmentation. Because seismic images are quite distinct from the more conventional images for which the PRC algorithm was originally designed, I detail the adaptations and changes necessary to make the algorithm more suitable for seismic image segmentation. These changes include pre-processing of images via edge-preserving smoothing, transformation of the input data, and modifications to the way graph edges are constructed and weighted prior to partitioning. Finally, I explain the motivation and strategy for incorporating interpreter input into the segmentation process. This involves having interpreters provide limited 2D salt boundary picks, and using those picks to guide an automatic 3D segmentation. Throughout the chapter, I use 2D synthetic data from the Sigsbee 2a model, as well as 2D and 3D field data images from the Gulf of Mexico, to demonstrate these concepts.

Efficient velocity model evaluation: In Chapter 3, I introduce a target-oriented wavefield synthesis method for quickly and efficiently evaluating velocity models. After providing the motivation and background for such a procedure, I detail each of the required steps. These include generating an areal source function from an initial image with prestack velocity information; using the new source function to synthesize a receiver wavefield via Born modeling, again using the initial image as a reflectivity model; and imaging the synthesized wavefields to produce a new image of locations along a target reflector. As long as the first two steps are carried out using an identical, initial velocity model, the final step
may use any other model to produce the final image. This is what allows for the fair and efficient comparison of multiple models. Next, I explain that one limitation of this approach is the potential for crosstalk artifacts to contaminate the results, and propose a strategy for mitigating these artifacts. This strategy requires imaging only sparsely-spaced locations along a reflector of interest, preventing overlapping events in the subsurface offset domain from contaminating the model evaluation experiment. Even when following this approach, a clearer picture of the reflector can be obtained by synthesizing several wavefields using appropriately-spaced locations, and summing the resulting images into a final image. Finally, I introduce an image-focusing measure that can provide a quantitative measure of the relative accuracy of velocity models being tested. After demonstrating the basic procedure using single-reflector synthetics, I show its applicability to the more complicated Sigsbee 2a model, and 2D and 3D datasets from the Gulf of Mexico. Importantly, I show that even when an incorrect velocity model is used to generate the initial image, this method can be used to identify a more accurate model.

**Integrated model building tools:** In Chapter 4, I show how the two tools I introduce in this thesis, interpreter-guided image segmentation and efficient velocity model evaluation, can be used in an integrated fashion to produce an improved velocity model and image. After presenting an image obtained from a wide-azimuth 3D survey in the Gulf of Mexico provided by Schlumberger Multiclient, I introduce the velocity model used to obtain that image, and discuss areas of potential improvement. Specifically, the initial model does not incorporate a sedimentary inclusion within the salt body that is clearly visible on the image, and features an ambiguous base salt interpretation. I then demonstrate how automatic image segmentation can be used to isolate the salt body inclusion, and generate two additional interpretations of the base salt reflector. Alternate velocity models are easily created from the initial model by replacing salt velocities with appropriate sedimentary velocities according to the segmentation
results. Next, I use the efficient model evaluation scheme to judge the relative accuracy of the three potential models. By summing the results of multiple wavefield synthesis and imaging experiments, I am able to quickly produce partial images of the base salt reflector for each model. Qualitative examination of subsurface offset panels, as well as quantitative calculations based on the image focusing measure introduced in the previous chapter, suggest that an alternate model with a conservative removal of salt compared to the originally interpreted salt body is the most accurate model. Finally, I validate these results by showing that a full migration of the original data with this model results in an improved image, most notably characterized by improved continuity of subsalt reflectors.