Geological Sciences Research (GEOL490.3)

School year: 2006/2007, Term 1

Topic: **Numerical modeling of Amplitude Variations with Offset (AVO) in deep crustal reflections**

Problem

A nearly 160-km long Wollaston Lake Reflector (WLR) represents one of the most spectacular and well-recorded features imaged within the crystalline crust. It was recorded in seismic reflection profile S2b of the 1994 Lithoprobe Trans-Hudson Orogen transect (THOT) in northern Saskatchewan. Initial analysis of this line targeted structural and geological interpretation and left aside the subtler properties of reflection amplitudes. Based on modeling its normal-incidence reflectivity, the reflector was originally interpreted as a series of subhorizontal, tabular diabase intrusions. However, the unusual horizontal extent, nearly constant depth, compactness, brightness, and continuity of this intrusion still remain enigmatic and suggest a contribution of low-viscosity fluids in its formation.

To study the properties of WLR, and also to elucidate the deep crustal reflectors and rock properties along the Trans-Hudson Orogen transect, Ma and Morozov (in press) reprocessed line S2b with an emphasis on the Amplitude Variations with Offset (AVO) analysis. While recognizing the difficulty of establishing the reflection polarity of crustal reflections, they considered both positive- and negative-polarity interpretations. The measurements indicate high and positive AVO gradients and suggest two possible interpretations: 1) the reflector is caused by a massive mafic intrusion as suggested earlier (Mandller and Clowes, 1997, 1998), in which case the intruded rocks should have anomalous Poisson's ratios of $\sigma \geq 0.33$, and 2) the WLR represents a silicified shear zone, with only moderate (~ 5%) alteration of the host rock.

To further corroborate and develop these conclusions, numerical modeling of reflectivity from the WLR will be conducted in this study. We will examine both models for a range of parameters of the reflecting zones as well as of the surrounding host rock, measure their AVO responses, and correlate them with observations.

In addition to the AVO analysis, we will use the same synthetics modeling to test the efficiency of the parallel code used for simulations. For a selected model, we will conduct a series of runs using different cluster node configurations, and measure the speedup achieved by parallelization.

Method

The project will use numerical simulations of seismic wavefields using the 1-D modeling program *reflectivity*. The program computes wavefields in complex layered (up to ~2000 layers) models. The program has been parallelized and integrated in I. Morozov's seismic data analysis package SIA. The work will include the following key steps:

1) Build several models (SIA jobs) corresponding to the high- or low-velocity WLR intrusion, and optionally stochastic layering above it (particularly in the near surface) and near the Moho (base of the crust) boundary;
2) For each reservoir model, the reflection amplitudes will be picked (for example, using ProMAX) and compared to those predicted by plane-wave AVO. To calculate plane-wave reflection amplitudes and also for further data analysis and plotting, Matlab or Octave software could be used.
3) Repeat computing synthetics in one model using different numbers of processes (1 through ~90). Plot the resulting computation wall clock time versus the number of processes and evaluate the efficiency of the parallel code.

The work will be conducted using the Linux and Windows computers in Geology Room 111. One or both of our Linux clusters (*geomaster* and *frontend*) could be utilized in numerical simulations. Therefore, the project will rely on a part of the IT support normally provided to the Geophysics group.

Expected results

A research paper and presentation summarizing the results will be prepared. The results of this research should contribute to two papers in preparation: on the properties of WLR (to be submitted to the *Geophysical Journal International* or *Tectonophysics*) and on the parallel *reflectivity* code (for *Computers and Geosciences*). They should also lead to further studies, in particular to 2D and 3D finite-difference simulations of the WLR and deep crust along the Trans-Hudson and other Lithoprobe transects.

Evaluation

Recommended examining committee

1) Zoltan Hajnal
2) Jim Merriam
3) Igor Morozov

Grading:

Paper:	50%
Oral presentation:	30%
Computer scripts, plots, and test examples in electronic formats:	20%

Recommended reading

Aki, K., and P. G. Richards, 2002. Quantitative Seismology, Second Edition, University Science Books, Sausalito, CA

In this text, note in particular:

Chapter 5: plane-wave reflection coefficients;

Section 9.2: the reflectivity method (this is what you will be using for modeling); see also the paper by Fuchs and Muller below.

Castagna, J., Swan, H., and Foster, D., 1998. Framework for AVO gradient and intercept interpretation, Geophysics, 63, 948-956.

This paper explains (and many other you can easily find) the idea of AVO interpretation in industry seismics.

Christensen, N. I. and W. D. Mooney, Seismic velocity structure and composition of the continental crust: A global view, J. Geophys. Res., 100, 9761-9788, 1995.

Standard paper on seismic structure and composition of continental crust. We need it to the set the "likely" crustal velocity profile.

Ma, J. and Morozov, I. (in press) Structure of the Wollaston Lake Reflector (Trans-Hudson Orogen, Canada) from reflection AVO analysis: fluids, massive fractured diabase intrusion or silicified shear zone?

Here, we critically reconsider a previous interpretation by Mandller and Clowes (below) by carefully looking at AVO data.

Mandler, H. A. F. and Clowes, R. M. (1997). Evidence for extensive tabular intrusions in the Precambrian shield of western Canada: A 160-km-long sequence of bright reflections. Geology, 25: 271-274.

Mandler, H. A., F., and Clowes, R. M., (1998). The HSI bright reflector: further evidence for extensive magmatism in the Precambrian in western Canada, Tectonophysics, 288: p. 71-81.

Fuchs, K., and G. Müller, (1971), Computation of synthetic seismograms with the reflectivity method and comparison with observations, J. R. Astronom. Soc., 23, 417-433.

Classical paper on 1D synthetic modeling approach found in many academic and industry programs.

Telford, W.M., L. P. Geldart, R. E. Sheriff. Applied Geophysics, Cambridge University Press.

Work plan

(Note that this is also roughly an outline of your expected report).

Work will be conducted using Linux computers in Rm. 111. Octave can replace Matlab very well under Linux.

1) Study the recommended and other literature and compile information for the report. Look for answers to the following questions:

   a. What is AVO? What is its role and use in seismic interpretation? Has it been used much in deep crustal studies?

   b. What is the geology and tectonics of the study area? Compile some background information on the THOT project (you may need to follow some references in the recommended texts).

   c. What is the Wollaston Lake Reflector? Why is it so important?

   d. What is the key problem/uncertainty in the previous interpretation being addressed?

   e. What is the average crustal seismic velocity vs. depth function in this area (from Christensen and Mooney)?

   f. What are the methods for synthetic waveform modeling (Aki and Richards, Chapter 9)

2) Set up models and perform 1D modeling of the WLR reflector using SIA version of *reflectivity* program. Modify and execute the provided SIA script. It may take several tries to get the frequencies, etc., right. We want to model frequencies of about 30 Hz.

   a. Use the two models (low- and high-velocity intrusions) from Ma and Morozov's paper.

   b. Note the program execution times. They are likely to be significant on a single Linux PC. Execute the same job on the cluster.

   c. Pick the travel times of the reflections from the reflector (can you tell its top from the bottom?)

   d. Pick the reflected amplitudes. See if you can differentiate the reflection from the top of the WLR intrusion from the one from the bottom (I don't think you will). Investigate whether you can use the positive or negative polarities. I expect that for consistent interpretation, you would have to use the absolute (Root-Mean-Square) amplitudes.

   e. Plot the resulting amplitudes using GMT (preferably) or Matlab. Compare them to the data shown in Ma and Morozov's paper. Does any of the two model s make sense?

3) For a selected model, makes a series of runs on the cluster using different numbers of UNIX processes (list `nodes` in SIA jobs). Make a plot of *t*(1)/*t*(n) as a function of the number of processes *n*, where *t*(n) is the execution time. Does it appear linear?

4) Discuss the results:

a. Can the polarity of reflection indeed be established (can you tell the reflection from the top of the intrusion from the one from the bottom)?

b. Which of the two models discussed by Ma and Morozov is in beret agreement with the modeling?

c. Speculate on how 2D or 3D modeling could alter the results and conclusions.

d. How successful is our code parallelization in speeding up the computations? For what number of processes the system appears saturated?