[AV]Seismic Velocity Model Building in an Area of Complex Geology, Southern Alberta, Canada*

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Abstract

We processed in time and depth two seismic lines from an area of extremely complex, overthrust geology at Turtle Mountain, Southern Alberta, Canada (Figure 1), where a disastrous debris slide, the Frank Slide, occurred in 1903. One of the contributing factors to the slide is the geology: steeply dipping, and sometimes overturned, folded and faulted carbonates overlying weaker clastic rocks creating an unstable situation.

Our objective was to improve the seismic imaging of the complex structures that form the mountain. Processing in the time domain was designed to attenuate noise and enhance signal in the data. The poststack and prestack time-migrated sections are not adequately focused and do not image correctly the structure deep in the section, which is expected to be relatively undeformed. Prestack depth migration provides better images. Our most effective velocity models for prestack depth processing are obtained by integrating all sources of geological and velocity information into the interpretation of seismic depth sections, which were created through iterative updates of the velocity models. Our choice of velocities for the depth migrations is guided by constant velocity migrated sections, near-surface velocity models from refraction statics analysis, averaged sonic interval velocities and limited migration velocity analysis in regions of coherent reflectivity. The locations of velocity pull-ups on the time-migrated sections act as guides to the extent of high-velocity carbonates carried in the hangingwall of a major thrust fault. We integrated the seismic velocity information with the mapped surface geology, geological cross-sections, and formation well depths.

The prestack depth migrated sections are better focused, making the sections easier to interpret than the time sections, and represent the expected structure of deep, relatively undeformed reflectors more reliably than the sections migrated in the time domain. Although the reprocessing has improved the quality of the processed seismic data, we are not able to image the details of the shallow, steeply dipping strata of Turtle Mountain. In particular, the overturned beds are not imaged by the seismic data. The detailed interpretation of Turtle Mountain relies strongly upon the geological model since the seismic data do not image adequately the structural complexities present here.

Time Processing

Before embarking on prestack depth migration (PSDM) we processed the data in time to attenuate noise, enhance signal, and obtain velocity estimates. The distribution of sub-weathering velocities from the refraction statics analysis corresponds well with the mapped surface exposure of high velocity Palaeozoic carbonates and lower velocity Cretaceous clastics. We integrated this near-surface velocity information into the velocity models for PSDM. Although time processing does not produce a properly focused image or accurate velocities in such complex geology, we processed the data in the time domain for images and preliminary velocity information to help us design velocity models for PSDM.

The post-stack time migrated sections are displayed in Figure 2. The surface geology and faults have been projected onto the sections. These time migrated lines show some very complex structures and faulting and are not easy to interpret. The deepest reflectors are expected to be fairly undeformed and the apparent structure observed on the west side of both lines is interpreted to be a seismic time artifact caused by velocity pull-up.

We know from the surface geology that the Livingstone Fault, a major thrust fault, carries high velocity Palaeozoic rocks to the surface. The location of these rocks correlates well with the velocity pull-up observed on the time section of line A (Figure 2). On line B the surface location of the Livingstone Fault is farther east than the observed velocity pull-up. We infer that the fault does not carry carbonates in its hangingwall beyond the location of the observed velocity pull-up, and we used this observation in our velocity models for line B.

Depth Processing

In areas of complex geology one cannot easily use a basic-layer-down approach to velocity model building as is often applied successfully in simpler geological settings. To design a velocity model for PSDM we integrated all the sources of geological and velocity information available: mapped surface geology, geological cross-sections, constant velocity migrations, the sub-weathering velocities, sonic log interval velocities, and the locations of observed pull-ups on the time sections. We iteratively interpreted the depth-migrated sections and modified the shapes of polygons in the velocity model, trying to focus the reflections and flatten the deepest horizons, which we do not believe to have significant structure, and to match the depths encountered in a few wells close to the lines. Constant velocity polygons were designed to represent packages of formations with similar interval velocities. We found that the shape of the polygons in the velocity model in the top 2000 m could have a profound effect on the alignment of the reflectors at 7000 m depth. The data were pre-stack-depth migrated from topography using a shot-based Kirchhoff migration developed in the Fold-Fault Research Project and a fairly simple, layer-based velocity model.

Interpretation

The interpretations of lines A and B on which the final velocity models were based are shown in Figures 3a and 3b, respectively. These sections are displayed at a 1:1 scale. They honour the surface geology, which is projected onto the top of the sections, the mapped dips, and well tops.

The significant well tops are annotated, as are the major thrust faults and the main velocity packages: Cardium (KC_a) and younger, Blackstone (KB_k), Lower Cretaceous–Jurassic (KC-J_F), and pre-Jurassic. The structural geology is certainly more complicated than interpreted here, with many more small faults, folded strata, and more detachment horizons present. In the centre of line B there is a large package of Crowsnest to Fernie strata (KC-J_F) that is anomalously thick and must contain repeated sections, as implied by the well picks of Well D. There must also be additional smaller thrust faults in the Cardium and younger section in the east parts of the lines. However, our goal was to interpret major packages of formations having similar interval velocities in order to obtain good migrated images, and we had more success with relatively simple velocity models than with complex models.

In the footwall of the Livingstone Thrust we interpret complex structures that are caused by thrust faulting and folding. A major regional detachment is present in the Jurassic Fernie shales and has been itself folded and faulted by further tectonic events. It is the fault immediately above the Carboniferous section between 3000 and 4000 m depth. Many of the faults are interpreted to sole out in this detachment. There are also major detachments in the Upper Cretaceous Blackstone Formation. We interpret two major faults that affect the Palaeozoic at depths below about 2000 m. The deeper, more easterly fault (the Burmis Thrust) is clear on both sections and is constrained by well data. It carries a carbonate thrust sheet in its hangingwall. The second thrust fault is much harder to interpret. It is interpreted as a splay off the Burmis Thrust on the west side of the lines and helps to account for the thickened carbonate section in the west part of the lines. How it relates to the faults in the Mesozoic section is hard to determine. Turtle Mountain is seen best on Line B as the topographic high on the west end of the line. A major influence on the structure in this area is the Livingstone Thrust, which carries Palaeozoic strata in its hangingwall, over Cretaceous rocks in the footwall. We used the fault's depth in wells, its mapped surface location, and the character of seismic reflections to estimate its subsurface trajectory.

Figure 4 shows more detailed interpretations of the Turtle Mountain structure and other structures in the hangingwall of the Livingstone Thrust. There is very complex faulting and folding above the Livingstone Thrust, and in some places the Jurassic Kootenay and Fernie formations are thickened and highly deformed. It is not possible to image such complex geology on the seismic data so the interpretation is based mainly on geological knowledge. What we do see, especially on Line B, are the highly reflective Kootenay coals that were mined locally.

We had difficulty interpreting Line B above the most easterly part of the Livingstone Thrust. If there are no carbonates here, as we interpret, then the Fernie must be greatly thickened by complex folding and multiple thrust faults, which we are unable to resolve with the seismic data. We are also unable to resolve clearly the structures in the footwall of the Turtle Mountain Thrust.

Discussion

We integrated all the geological and velocity information available into the velocity model building for prestack depth migration of two seismic lines acquired in complex mountainous terrain. Velocity information from constant-velocity-migrated sections, near-surface velocity models from refraction statics analysis, averaged sonic interval velocities, and migration velocity analysis was integrated with the mapped surface geology, geological cross-sections, and formation well depths.

The prestack depth migrated sections are better focused and represent the expected structure of deep, relatively undeformed reflectors more reliably than the sections migrated in the time domain. However, we were unable to image the details of the steeply dipping and complexly faulted rocks, particularly the overturned beds that form Turtle Mountain.

Acknowledgements
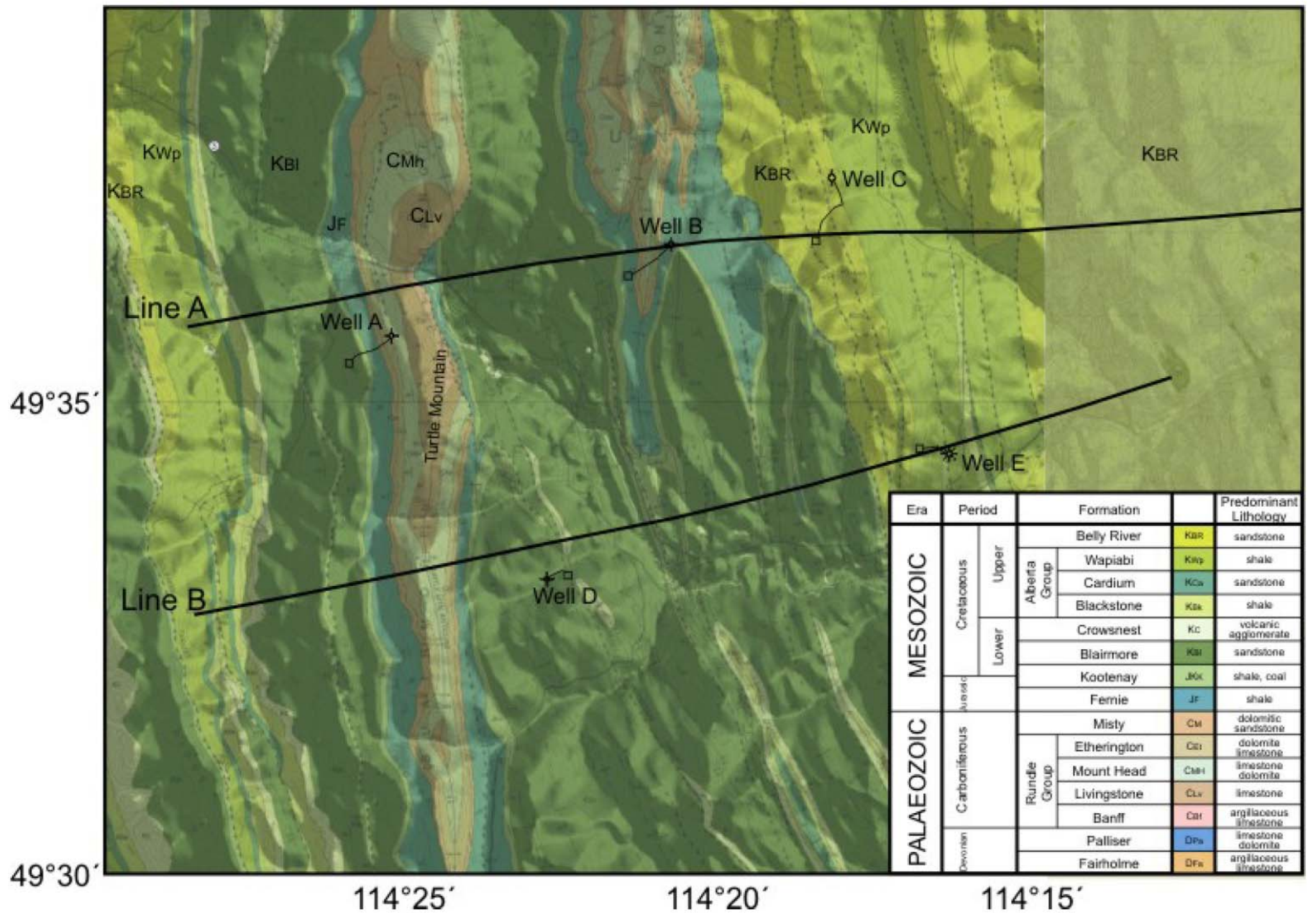
Figure 1. Geological map of the study area with digital elevations overlain and the stratigraphic chart (after Geological Survey of Canada).
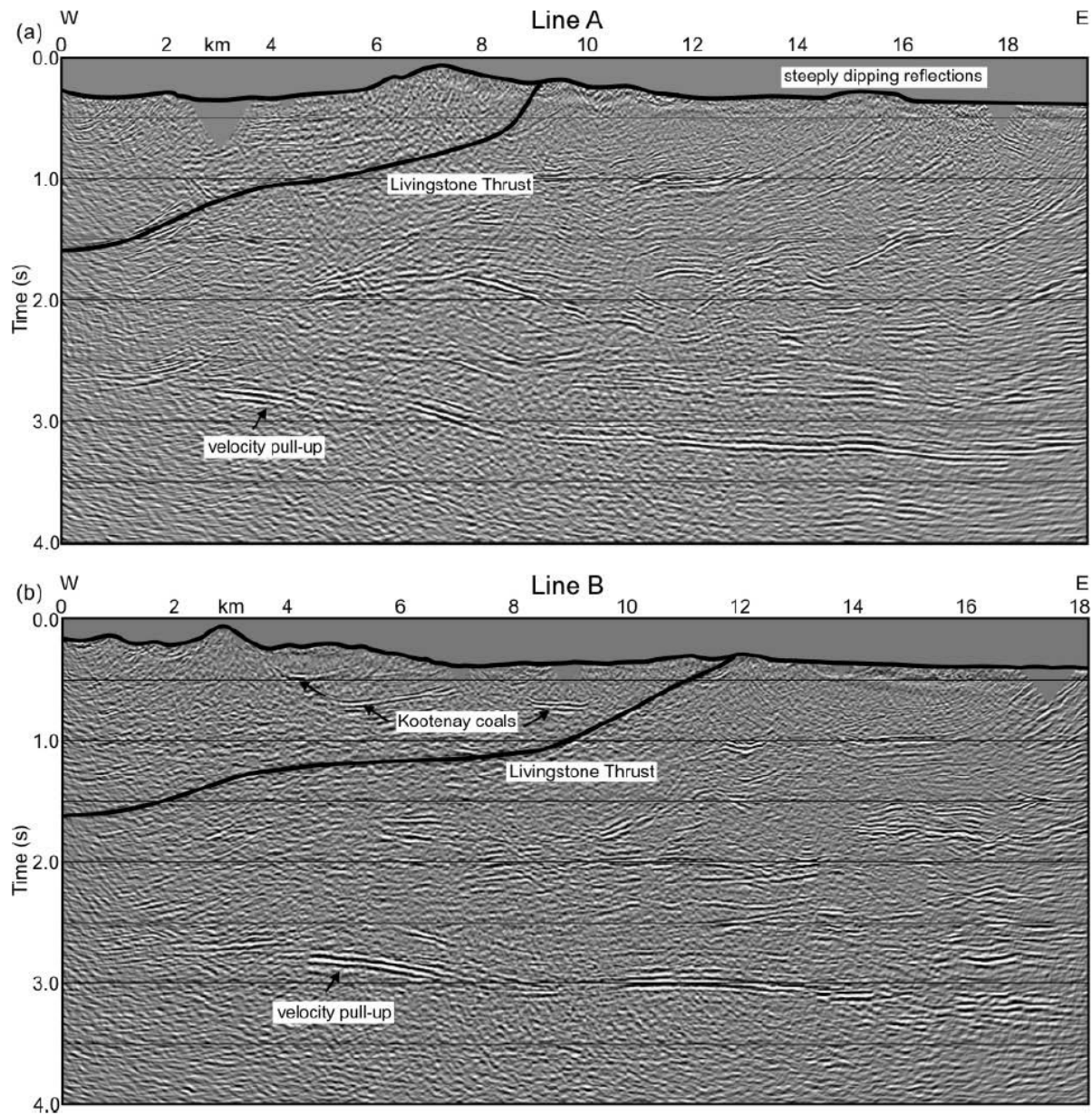
Figure 2. Post-stack time-migrated sections. The Livingstone Thrust carries some high velocity carbonates in its hangingwall, which contribute to a velocity pull-up of deeper reflections on the time sections. These carbonates are exposed at the surface on Line A.
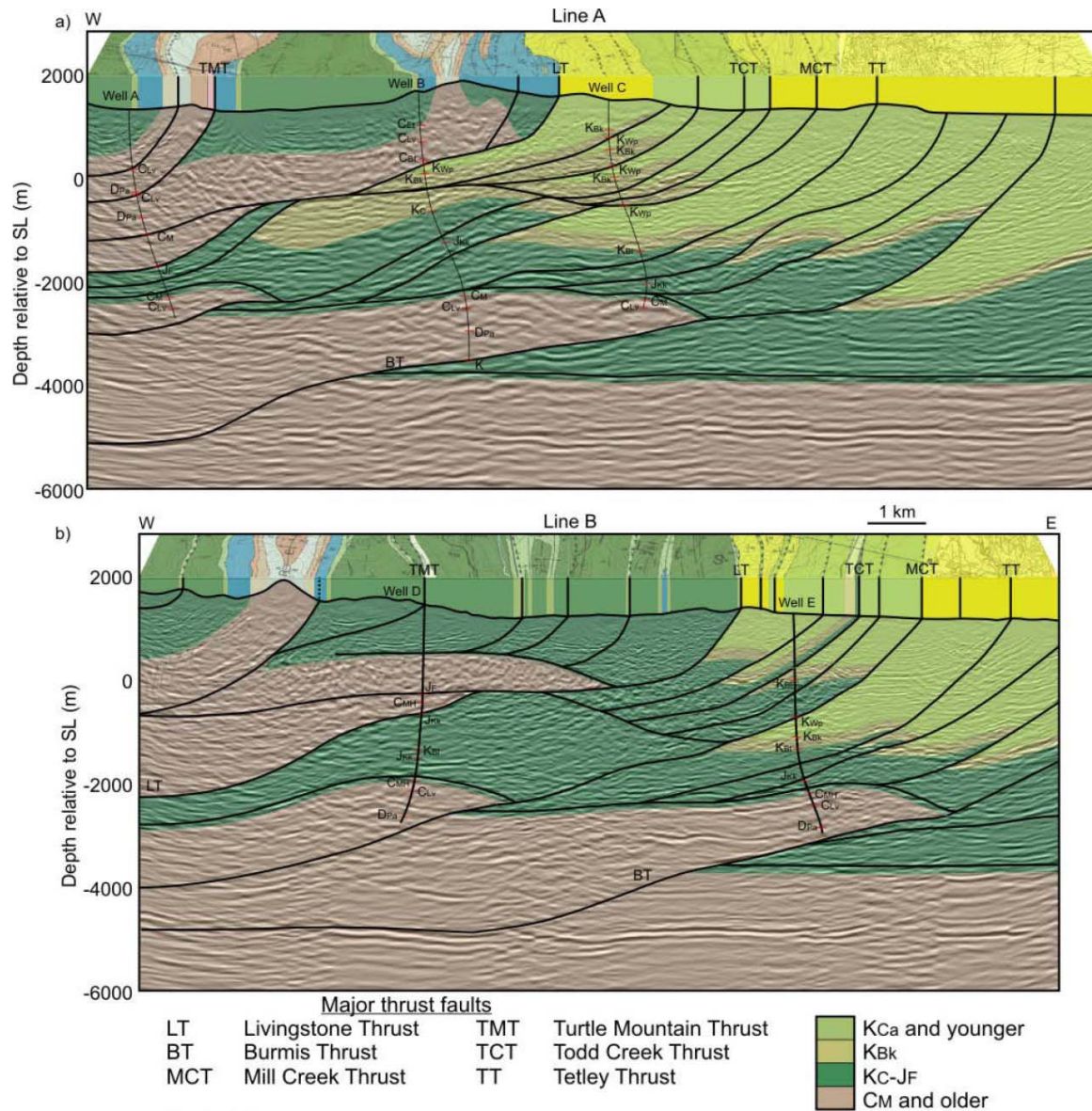
Figure 3. Pre-stack depth migrated sections with the simplified interpretation used for velocity models. The surface geology is projected along the top of the sections. The wells and the significant formation tops that were used to calibrate the interpretations are shown. Only the major faults are annotated.
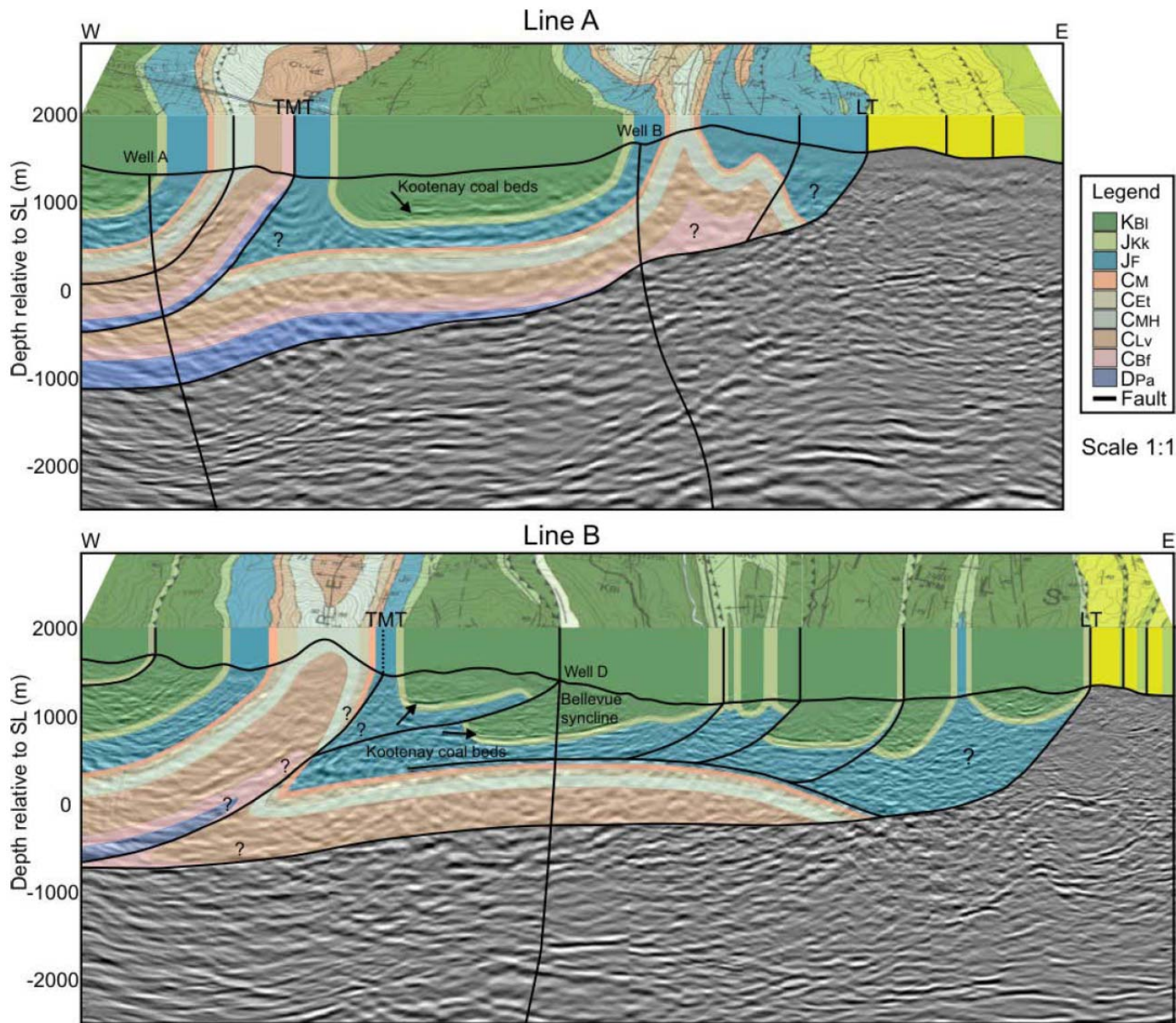
Figure 4. Detailed interpretations of the structures carried in the hanging wall of the Livingstone Thrust of Line A (a) and Line B (b). The interpretations are based on mapped surface geology, geological cross-sections, and seismic reflection characteristics.

Seismic velocity model building in an area of complex geology, Southern Alberta, Canada

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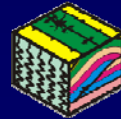
Note of Presenter: I would like to show you the procedure I went through to develop velocity models for prestack depth migration in an area of very complex geology.

Outline

- Introduction to study area
- Geology
- Time migrated seismic data
- Development of velocity models for prestack depth migration
- Interpreted depth sections
- Conclusions

Note of Presenter: After an introduction to the study area and its geology I will touch briefly on the results of processing the seismic data in the time domain. Then I will go into detail about how I developed the velocity models and show you the interpreted seismic data. I will finish by summarising what I learnt from this study.

Note of Presenter: Here we are right now in Denver. The study area is along strike up to the northwest in Southern Alberta, Canada.
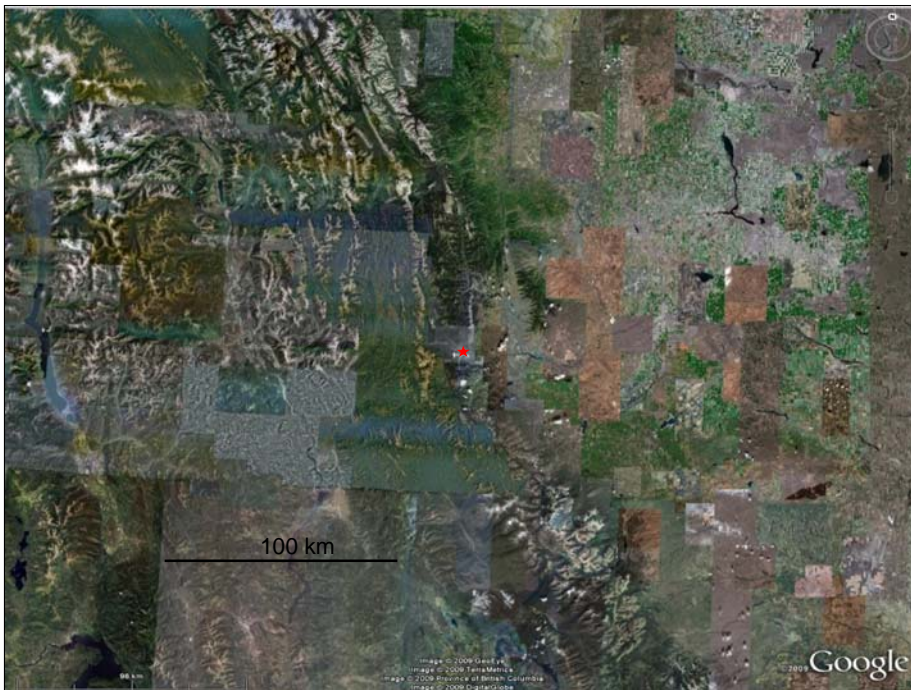
Note of Presenter: If we zoom in some more we can see that the study area (marked with the red star) is located close to the eastern edge of the deformed belt.
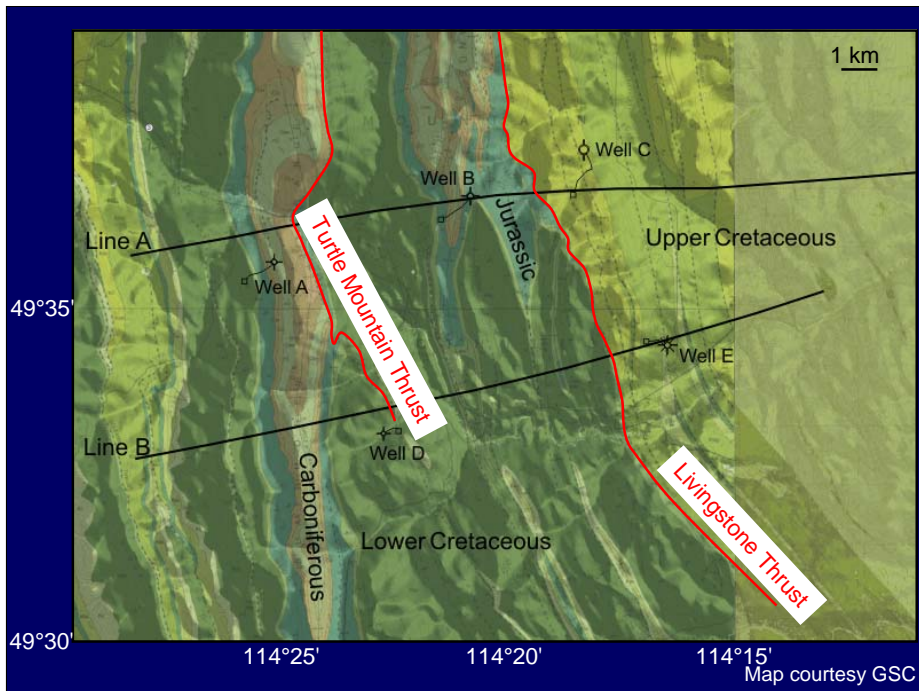
Note of Presenter: This map shows the surface geology overlain on the digital elevations. Pale greens represent Upper Cretaceous rocks; dark green is Lower Cretaceous; blue is Jurassic; and the pinks and pale colours are Carboniferous. Lines A and B are the seismic lines that I'm going to discuss and there are 5 wells that I used in this study. There are many thrust faults mapped here, but two of them are of particular importance. The Livingstone Thrust is the major fault carrying Lower Cretaceous and older rocks in its hangingwall over Upper Cretaceous in the footwall. The Turtle Mountain Thrust is also important to us because it controls much of the deformation of Turtle Mountain, this north-south linear feature in the west of the study area. Now, why are we so interested in Turtle Mountain?

The Frank Slide of 1903

Note of Presenter: In 1903 a huge section of the mountain detached and crashed down onto the small coal-mining town of Frank. This photograph of what is known as the Frank Slide was taken just a few years ago. One of the underlying causes of the disaster is the geology. Tightly folded, steeply dipping and sometimes overturned carbonates are thrust over weaker clastic rocks, to create instability. This situation has not changed and the possibility exists that another similar slide might occur. So the Alberta government has financed a monitoring program for Turtle Mountain.
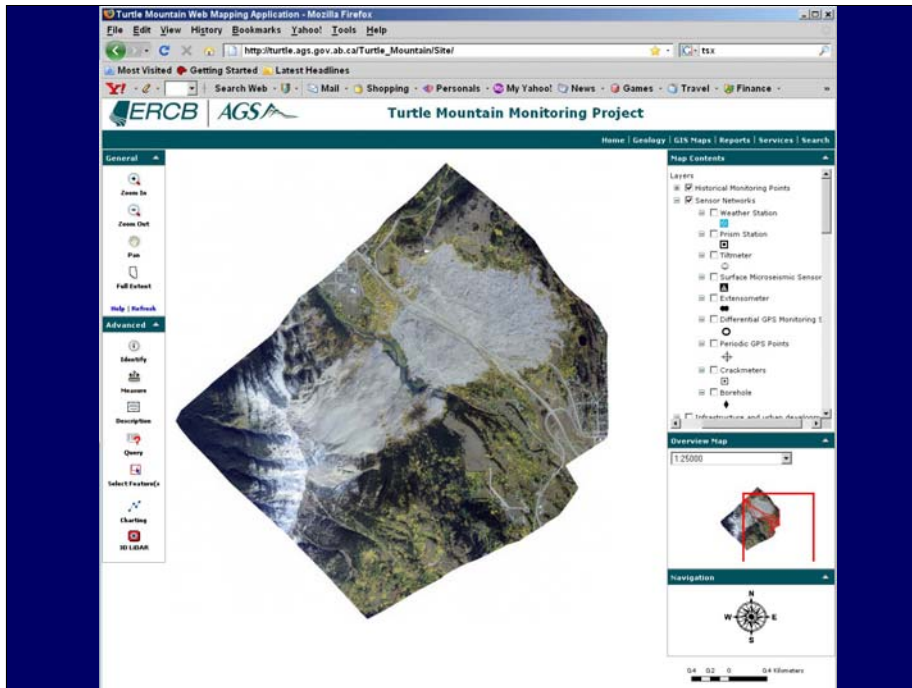
Note of Presenter: Coordination of the monitoring project is being done by the Alberta Geological Survey; and this is taken from their website--a magnificent satellite image of the Frank Slide. You can "play around" with displaying the locations of different sensors such as the tiltmeters, crackmeters and microseismic sensors.
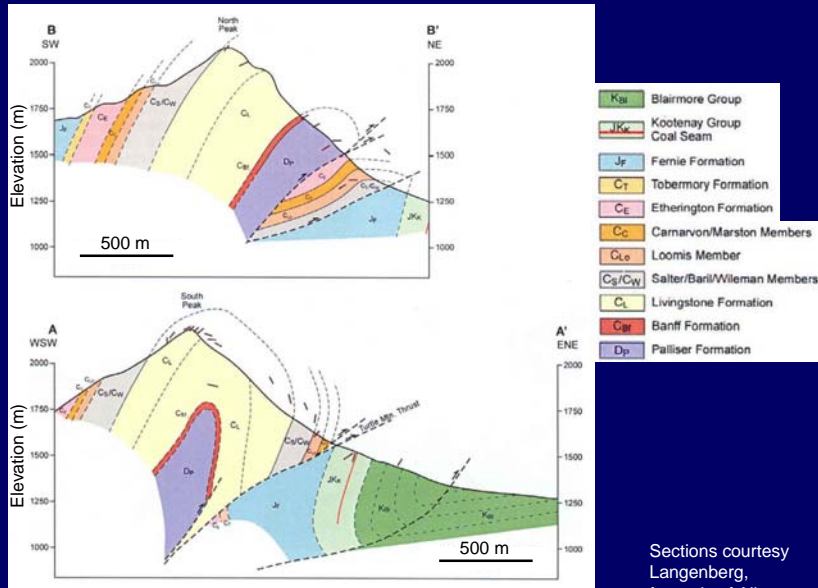
New geology map
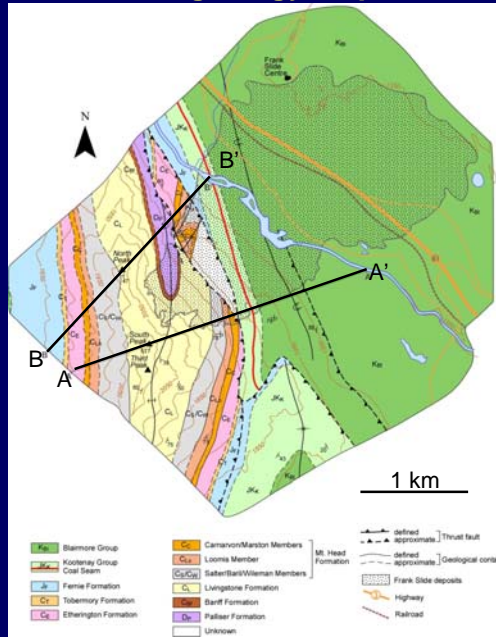
Map courtesy Langenberg, formerly of Alberta Geological Survey

Note of Presenter: As part of the monitoring program, new geological mapping was undertaken, and this is the latest map. You can clearly see the crest of the anticline. We also have two new cross-sections; locations shown here.

New geological cross-sections

Sections courtesy Langenberg, formerly of Alberta Geological Survey

Note of Presenter: These geological cross-sections incorporate the new surface mapping of Turtle Mountain and show how steeply dipping are the carbonates. It was hoped that reprocessing the two seismic lines might be able to provide details of the complex structure of Turtle Mountain. However, the seismic lines were acquired for deeper hydrocarbon targets; so the acquisition parameters were not ideal for imaging the shallow subsurface, and in any case it would be very hard to image the steeply dipping strata. However, I didn't let that deter me as this looked like a really interesting project to work on.

Geological cross-sections
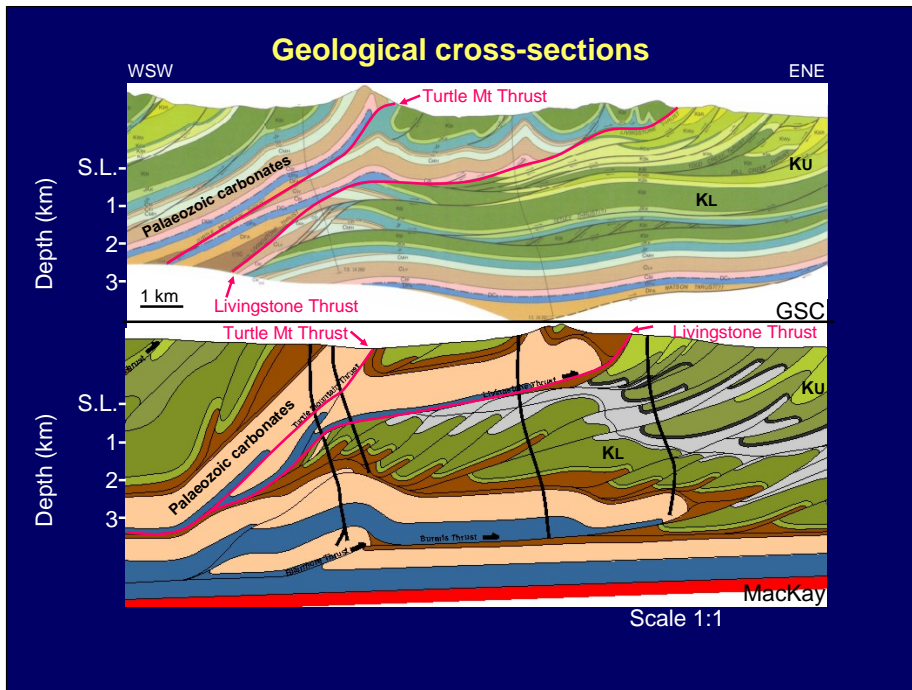
Note of Presenter: I also had two regional geological cross-sections across the study area. The top one is from the GSC, and the bottom one was kindly given to me by Paul MacKay. They both show the Livingstone Thrust carrying these Palaeozoic carbonates to the surface. Beneath the Livingstone Thrust they show a large amount of complex deformation although they do differ quite a lot in the style of deformation. There are many thrust faults and thickened sections in all formations from the Upper Cretaceous to the Devonian.

**Time domain seismic data processing**

- Refraction statics
- Spike and noise burst edits
- Air blast attenuation
- Surface wave noise attenuation
- Predictive deconvolution
- Residual statics
- Coherency filter
- Semblance velocity analysis
- Poststack and prestack time migration

Note of Presenter: Now, on to the seismic data processing. This slide shows the main processing procedures I applied in the time domain. These are pretty standard. Mostly my intention was to attenuate noise, enhance signal and apply static corrections.
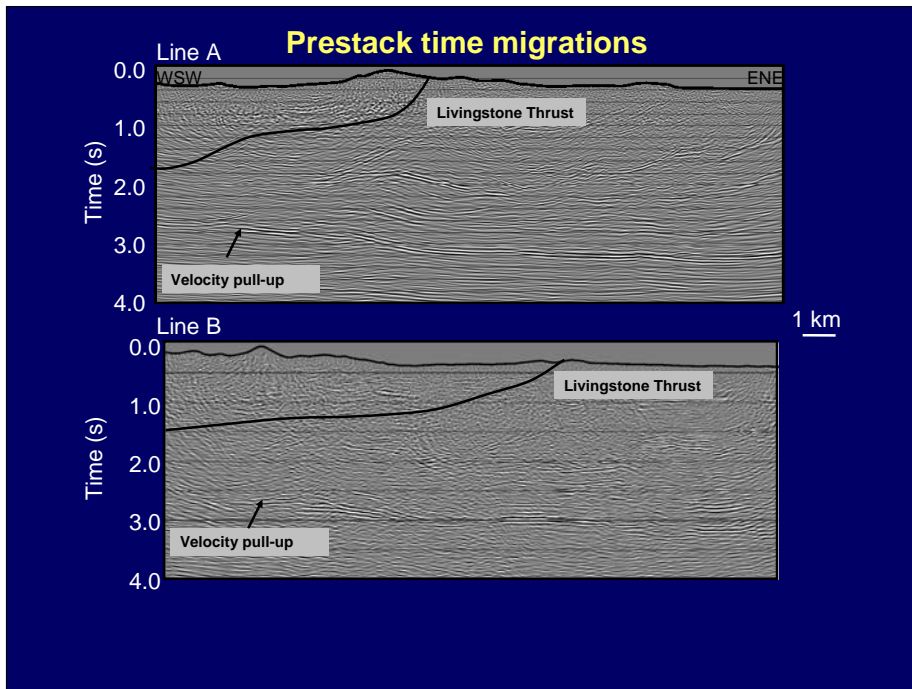
Note of Presenter: The prestack time migrations show some of the dipping, thrusted strata in the shallower section and relatively undeformed deeper reflections. You can see that the time migration hasn't adequately imaged the reflections – here are some cross-dipping events that haven't been migrated to their correct locations – and the focusing is poor. What I would like you to notice especially on these sections is the velocity pull-up in the western part of the lines. This is an artifact of the time processing caused by the high velocities shallow in the section. On Line A the location of the pull-up correlates well with the interpreted location of the Livingstone Thrust, which we know to be carrying high-velocity carbonates in its hangingwall. However, on Line B, the Livingstone Thrust extends farther to the east than does the velocity pull-up. I shall show you shortly how this observation was useful to me when I was creating the velocity model for prestack depth migration.

Time interval velocity (Line A)
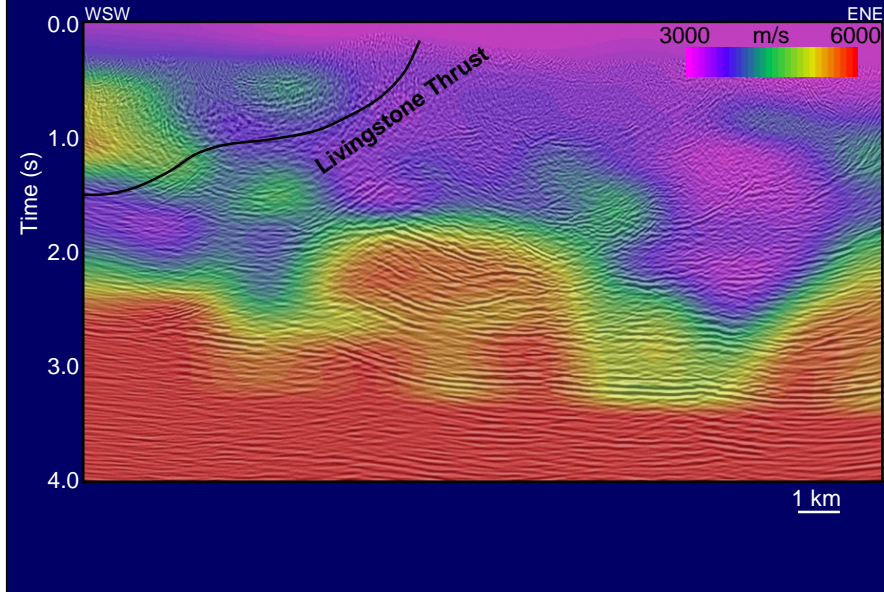
Note of Presenter: In this slide I show the time interval velocity field derived from velocity analysis of common reflection point gathers in the time domain. I know that there should be high velocities above the Livingstone Thrust and lower velocities below and we're not really seeing that. I also don't believe that these high velocities showing-up in the middle here. Thus, this velocity model will be inadequate for prestack depth migration, because for proper imaging in depth we need a velocity model that is a good representation of the true velocity field. How am I going to get this good velocity model?

Migration velocity analysis (MVA)

- Common image gather analysis in the depth domain is often used to determine imaging velocities for prestack depth migration

- The technique works well where there are continuous and strong reflectors across the section

- In areas of complex geology, we need more velocity information than can be gathered from MVA, especially in the top 1000 m, where source-receiver offsets are short

Note of Presenter: A common method for obtaining velocities for prestack depth migration is that of migration velocity analysis. This consists of finding those velocities that flatten common image gathers since we want all the data at a particular reflection point to migrate to the same depth, for all source-receiver offsets. This is a very powerful technique, and it can work very well, but it works best where there are continuous and strong reflectors right across the section so that you can do a layer-based approach. In this study area, the reflectors are intermittent, and in some areas they are very weak. So in areas of complex geology, such as the case we are dealing with here, more information is needed in addition to this type of analysis.

Geological and velocity information integrated into velocity model for prestack depth migration

- Surface geology maps – outcropping formations, surface faults and surface dips

- Geological cross-sections

- Formation tops from well logs

- Interval velocities from sonic logs

- Velocities from CIG migration velocity analysis

- Near-surface velocities from refraction statics analysis

- Constant velocity migrations

- Position of pull-ups on time sections

Note of Presenter: The best approach is to use all sources of information available. The geological information I used in this study includes the geology maps, with outcrops, faults and measured dips, which can be used to constrain the shallow section, geological cross-sections, which help me to interpret the preliminary prestack depth migrated sections, formation tops that must tie to the reflections, and interval velocities from sonic logs. On the geophysical side I have velocity models derived through migration velocity analysis, I can use the near-surface velocity models obtained by refraction statics analysis of the first breaks, I made some constant velocity migrations and also the position of the pull-ups on the time sections, which I showed you earlier.
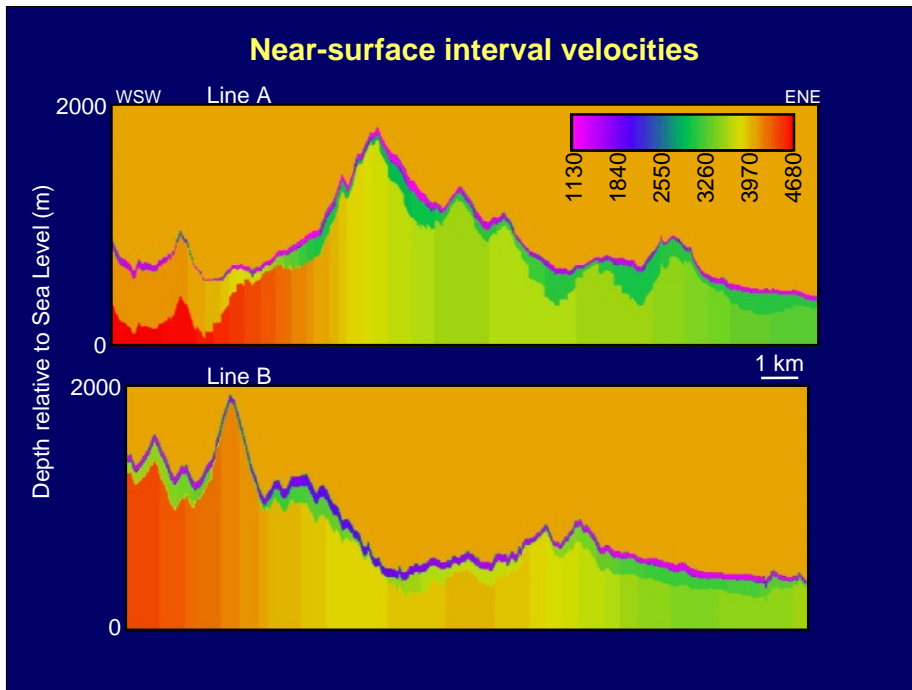
Note of Presenter: These are the near-surface velocity models I obtained using GLI3D. The general velocity distribution fits well with what I expect. The theory behind the program assumes that velocity increases with depth, which is not the case in the west where we have high velocity rocks exposed at the surface; so this part of the model is probably not very reliable, but it should be applicable towards the east ends of the lines. This analysis is useful for obtaining an estimate of the sub-weathering velocities and can also be used to make a detailed near-surface velocity model if desired.
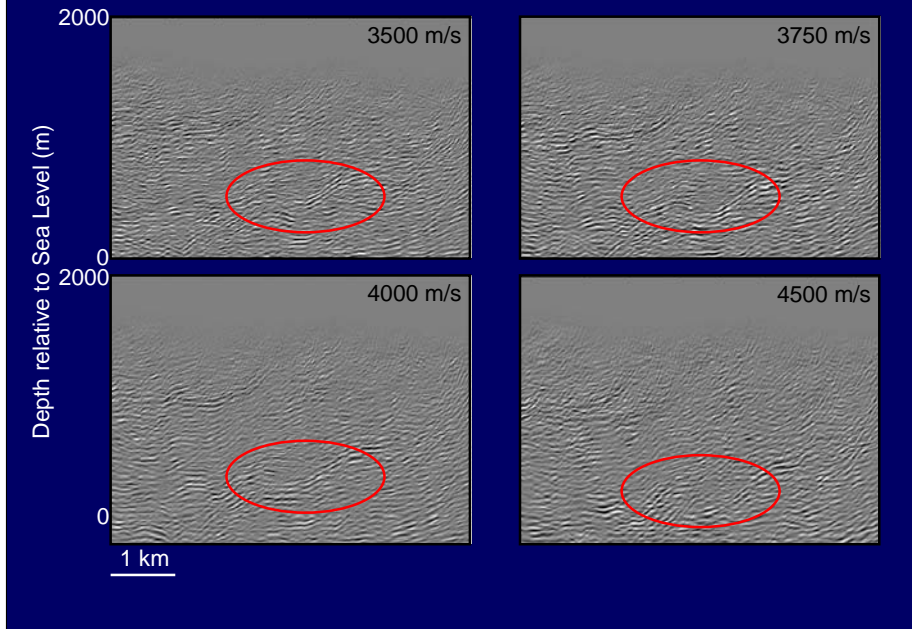
Note of Presenter: I did some constant velocity migrations to test the image capacities of different velocity functions for the shallow section. I have highlighted an area here in the red oval that images well at a velocity of 3750 m/s, but is poorer at the other velocities, and certainly at 4500 m/s is greatly over-migrated. I found this an easy and quick way to get a ballpark number for the imaging velocity in the top 2000 m.

**Migration velocity analysis**
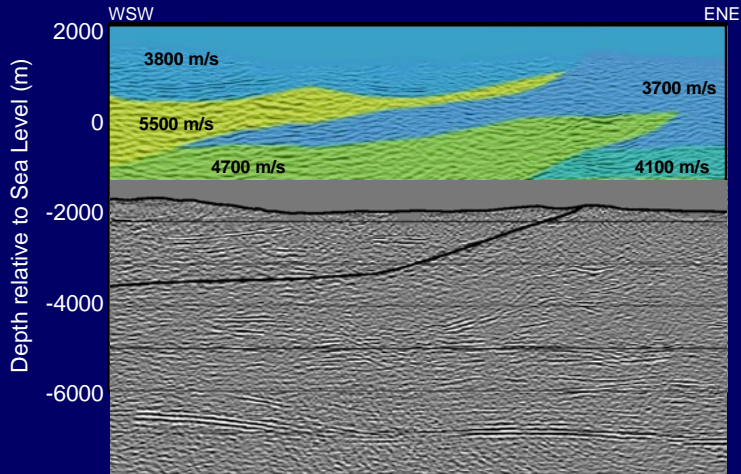
Note of Presenter: I did some migration velocity analysis on common image gathers because it was useful for the deep events, which are strong and continuous. The polygons show packages with a constant interval velocity and are based on an interpretation of the seismic section. Initially I put carbonates all the way across in the hangingwall of the Livingstone Thrust to match the geological cross-sections and got the depth migration you see here. But what I had seen on the time section was that the velocity pull-up did not extend far as the thrust fault; so I tried another model with less carbonate, which is represented by this yellowy colour.

Migration velocity analysis
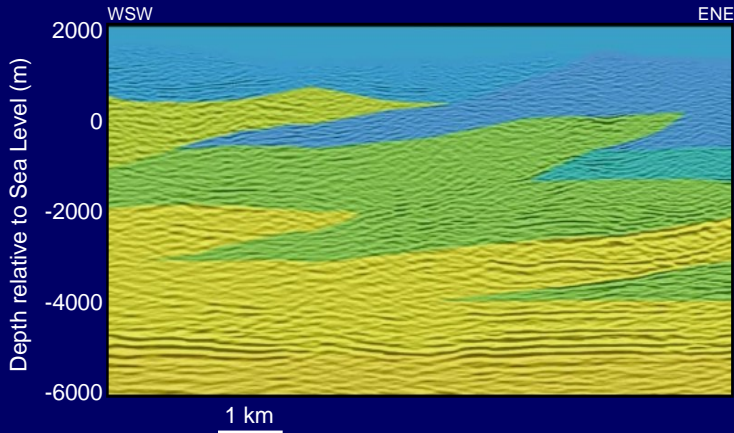
Note of Presenter: Here is the result. I'm going to toggle between the two models and I want you to notice the improvement in imaging, especially in the deeper reflectors for the model with less carbonate. There's a great improvement just from taking out this slither of high velocity.

Migration velocity analysis
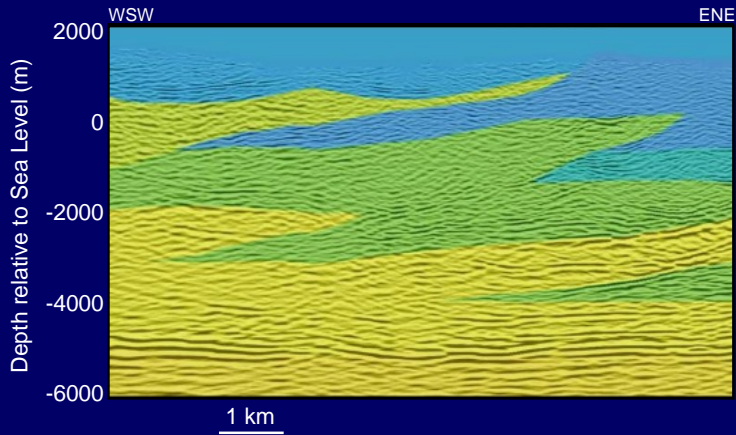
**Interpretations of depth migrated sections for velocity models**
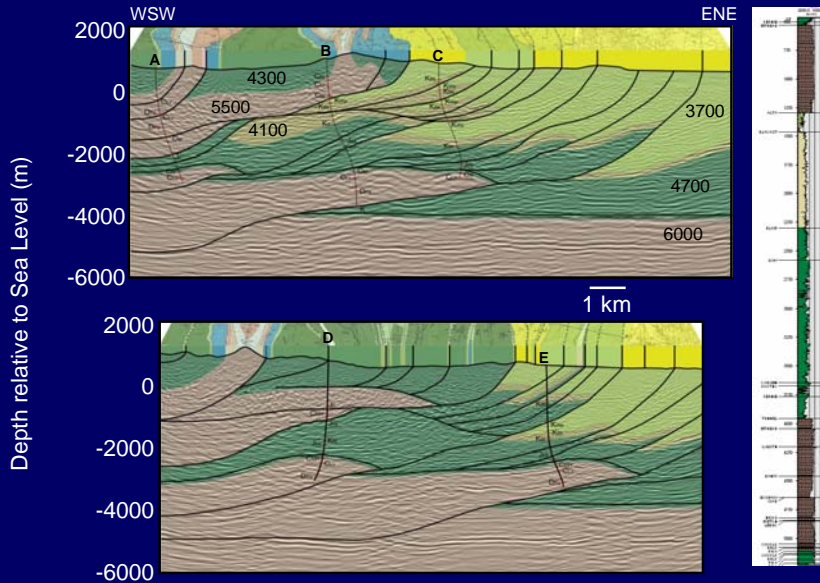
Note of Presenter: This slide shows the interpretations of velocity packages that I used for the prestack depth migrations. Projected along the top is the surface geology. Each block of colour represents a constant interval velocity and these velocity values were the best compromise of all the sources of velocity information that I integrated in this study. Here is the sonic log from well B, and it shows how I decided which formations to put in groups having constant velocities. It confirms that using constant interval velocities is valid; i.e., we don't see compaction effects.

Detailed interpretation of line A

Scale 1:1
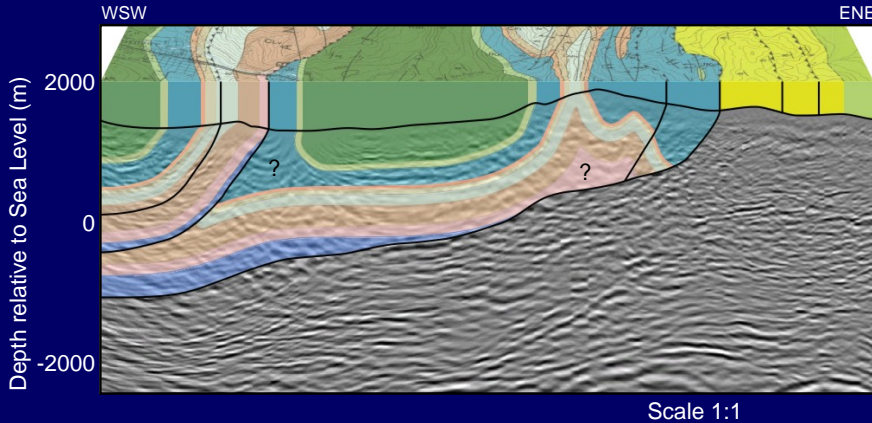
Note of Presenter: I want to finish by showing you the detailed interpretation of the Turtle Mountain structure. This interpretation honours the surface geology and mapped dips, the well tops and the seismic character where it is good enough to interpret. These high amplitude reflections in the syncline are from the coals which were mined in this area, and the depths correlate to the depths of the mined lodes.

Detailed interpretation of line B

WSW — ENE

Depth relative to Sea Level (m)

2000, 0, -2000

Scale 1:1
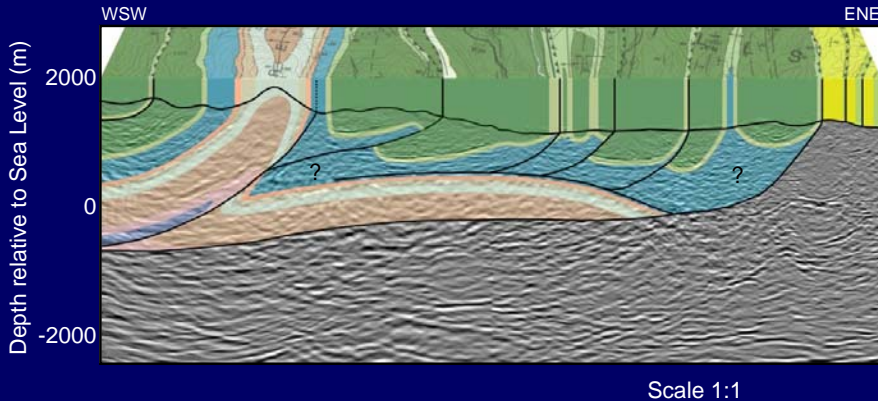
Note of Presenter: On line B here I have interpreted overturned beds at Turtle Mountain, but this comes from the geological cross-sections because the reflections are not seen on the seismic data. In some areas it is hard to know what is going on. Over here, for example, we have a greatly thickened package of Jurassic rocks; so there must be many more faults and more complex structure than we can image with the seismic data.

Grassy Mountain, Blairmore, Alberta

10 m

Note of Presenter: We know from outcrops that the coals can behave in a very ductile fashion. Here is a photo of a structure in a nearby mountain. It is about 40 m high and shows incredibly deformed coals.

Conclusions

- Time processing did not image the complex structures adequately

- Development of velocity model for prestack depth migration is not easy

- Integration of all available geological and velocity information resulted in the best velocity model:

    Geological maps, geological cross-sections, well formation tops
    Sonic interval velocities, near-surface velocities from refraction
    statics, constant velocity migrations, migration velocity analysis,
    location of pull-up on time sections

- The overturned rocks at the crest of Turtle Mountain were not imaged

Note of Presenter: What have we learnt from this exercise?
The message I want to leave with you is that if you are having a processor do a psdm for you in an area of complex geology, provide him or her with all the geological information you can. Don't leave him wallowing in common image gather never-never land because he won't have enough data to properly image the seismic data. I strongly believe that the integration of all forms of geological and geophysical data, including gravity and magnetic; if you have it, is the way to go.