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## Introduction

The Canadian Rocky Mountains expose one of the world's classic fold and thrust belts. Much of the classic mapping in the southern Canadian Rockies was carried out by Raymond Price, Eric Mountjoy and colleagues as part of the "Operation Bow-Athabasca" of the Canadian Geological Survey in the 1960s. The maps from this effort are widely regarded as some of the finest published anywhere. We will use Price and Mountjoy's Siffleur River (East Half) 1:50,000 geological quadrangle map (1465A) which is freely available from the GSC. The purpose of this exercise is to extract quantitative information from a geologic map which we can subsequently use to interpret the structural geology of part of the Canadian Rocky Mountains. You can think of this lab as a type of capstone exercise that pulls together several individual techniques that we have learned by doing the exercises in Modern Structural Practice (MSP).

## Materials

For this exercise, the student will need:

- The computer program ***GeolMapDataExtractor (GMDE)*** that can be downloaded for Mac, Windows, or Linux at <http://www.geo.cornell.edu/geology/faculty/RWA/programs/strikedipthickness.html>. The program is free.
- A jpeg copy of the Siffleur River (East half) map
- (optional) A copy of the georeferencing text file that ***GMDE*** creates automatically for the map. This is optional but if unavailable, the student will have to do their own georeferencing and determination of coordinate system offset.
- (optional) An internet connection to access elevations of clicked points automatically. If unavailable, the student will have to enter their own elevations by reading the contour lines.
- Microsoft Excel or some similarly powerful computing environment.
- The computer program ***EigenCalc*** that can be downloaded for Mac or Windows computers from <http://www.geo.cornell.edu/geology/faculty/RWA/programs/utility-programs/eigen-calc.html>

## Methods

The methods to be used, along with their location in MSP are:

- Calculation of direction cosines from trend and plunge and vice versa (MSP, p. 36-39)
- Three point problems to calculate orientations of faults and bedding (MSP, p. 50-54)

- Coordinate transformation to calculate stratigraphic thickness (MSP, p. 73-75)
- Calculation of the orientation tensor to get the fold axis (MSP, p. 94-97)
- Calculation of fault slip from offset piercing points (MSP, p. 108-111)
- Construction of a geological cross section (MSP, Chapter 10)
- Interpretation of the relative geological history of the region

## **A Note about *GMDE***

All of the calculations described here can be done completely within ***GMDE***. Indeed, if you only have a week and want your students to focus solely on the thrust belt geology documented in this beautiful map, that may be an acceptable solution. In that case, however, ***GMDE*** becomes a black box which is non-ideal from a pedagogical point of view. I prefer that my students use ***GMDE*** to get XYZ coordinates of the position vectors but then calculate their answers in Excel (which they can check in ***GMDE***). This can be done over the course of several weeks, culminating in the interpretation of the thrust belt structure and history. This guide is written for people who prefer this second approach.

## **Exercise**

Open the Siffleur River quadrangle map in ***GMDE***. If you have been provided the related georeferencing file, then the program should be ready to go. Otherwise, you will have to georeference the map, yourself, following the instructions in the ***GMDE*** Users Manual and Quick Start guide. Note that the text box in the bottom left corner of the map shows the longitude and latitude beneath the cursor as well as the east and north positions in local map coordinates (from the bottom left corner of the raster image). If you click and drag in the map, a red line will appear between your starting point and the current position of the cursor and the text box will show the length and the angle of that line. The zoom control in the lower right corner of the map pane will allow you to see more or less of the map, depending on what you are trying to do.

Find the part of the map that is shown in the graphic at the beginning of this document. All of the activities described below come from this part of the map.

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### Three Point Problem

This map has almost no strike and dip symbols on it. In the section of the map shown at the beginning of this exercise, there are just five strikes and dips, all located along measured stratigraphic sections. Fortunately, this is the Canadian Rockies so there is plenty of topography to enable us to use the "V's" of the contacts across topography to calculate three-point problems and get a usable suite of orientations. Let's check out the agreement between strike and dip as

measured in the field and determined from a three point problem.

One of the five measured orientations occurs at the contact between Dpa and Mbf in the Sulphur Mountain thrust plate south of the Clearwater River valley (Fig. 1). Use the prominent "V" where that contact crosses the ridge immediately north of the orientation to determine the strike and dip using a three point problem. Click on three points, one near the Clearwater Valley, one near the ridge crest, and one in the valley north of the measured section. **GMDE** will, of course, show you the answer but, as a scientist, you will want to calculate it for yourself! After you have clicked on the three points, go to File>Copy Special>All Coordinates. Switch over to Excel where you can paste in the matrix of the nine values, three for each of the three position vectors.

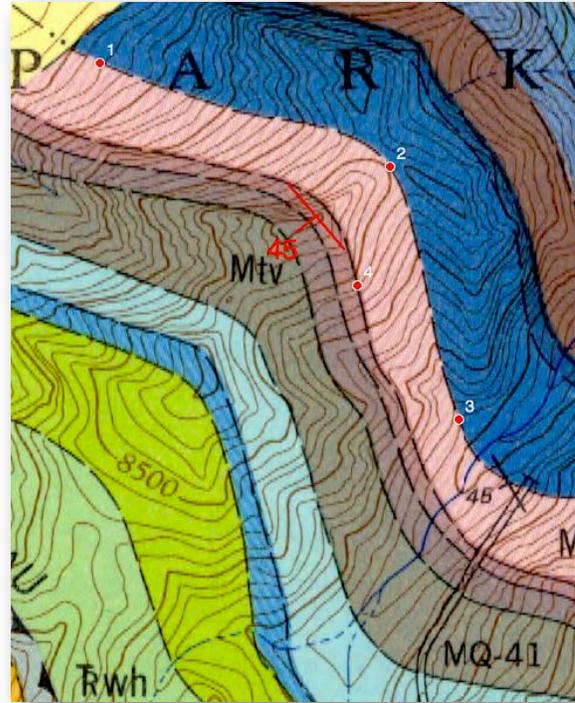


FIGURE 1

Note that the vectors you just copied are in an East-North-Up coordinate system. By following the instructions in MSP, p. 50-54, calculate the strike and dip of the Dpa-Mbf contact using the cross product of the two vectors in the plane. How does your measurement compare to that shown one the map?

*Note that **GMDE** can propagate errors because the uncertainty is based on the errors in location of the three points. The student can see these errors by entering the horizontal and vertical uncertainties in the Set Errors group box. These errors can be further propagated to the stratigraphic thickness calculation in the next section.*

*Although the match in this case is quite close, on many maps you will see significant disagreement between the orientation from a three-point problem and local geologist measured strike and dip. In that case, it is useful to ask you students to list all of the possible reasons for the difference. It is even possible that both are correct but just represent orientations at different scales. The **GMDE** Details window (which will only show already recorded data) will show the position of the orientation on a Google satellite image, which will allow the student to assess whether exposure plays a big role. If you check the above example, you'll see that the exposure is excellent.*

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## Stratigraphic Thickness

The measured section gives the thickness of the unit Mbf as 842 ft. How does this compare to the map thickness? By using a coordinate transformation into a bedding plane coordinate system, we do not need to measure thickness exactly in the dip direction. To calculate map thickness, proceed as follows:

With the three points already selected on the base of formation Mbf used in the previous problem, select a point on the top contact of Mbf, show where between 1 and 3 (e.g., point 4 in Fig. 1). Select File>Copy Special>All Coordinates to copy all four position vectors to the clipboard. Switch to Excel and select the upper left cell where you want to paste the matrix of position vectors and choose Edit>Paste from the menu. The four position vectors are now ready for you to calculate the thickness of Mbf as described in MSP, p. 73-75.

*You can follow up with the enterprising student by asking them to use **GMDE** to calculate thickness at several different points along the Mfb-Mpk contact. They will see that the thickness varies, typically by 10-20% or more of the mean value. Ask them to list the possible sources of uncertainty evident in their calculation. See Allmendinger and Judge (2013) for a discussion.*

### Fold Axis

By choosing your points carefully, you should be able to measure about 12-15 orientations of bedding within the Bourgeau thrust plate, from Mount Malloch on the north to the quadrangle boundary on the south (see Fig. 2). You can, of course use your spreadsheet to calculate the points by simply cutting and pasting each new matrix of orientation vectors. However, for the purposes of this exercise, you can let **GMDE** do the additional work. Each time you have a bedding orientation that you like, click the Record S & D button and a list of strikes and dips will appear in the listbox in the lower right corner of the window.

In this listbox, select all of the rows with the strikes and dips and choose Edit>Copy (not copy all coordinates!). Switch to Excel, select the upper left cell where you want the list to appear, choose Edit>Paste. You may want to erase the columns with the errors as we will not use them in

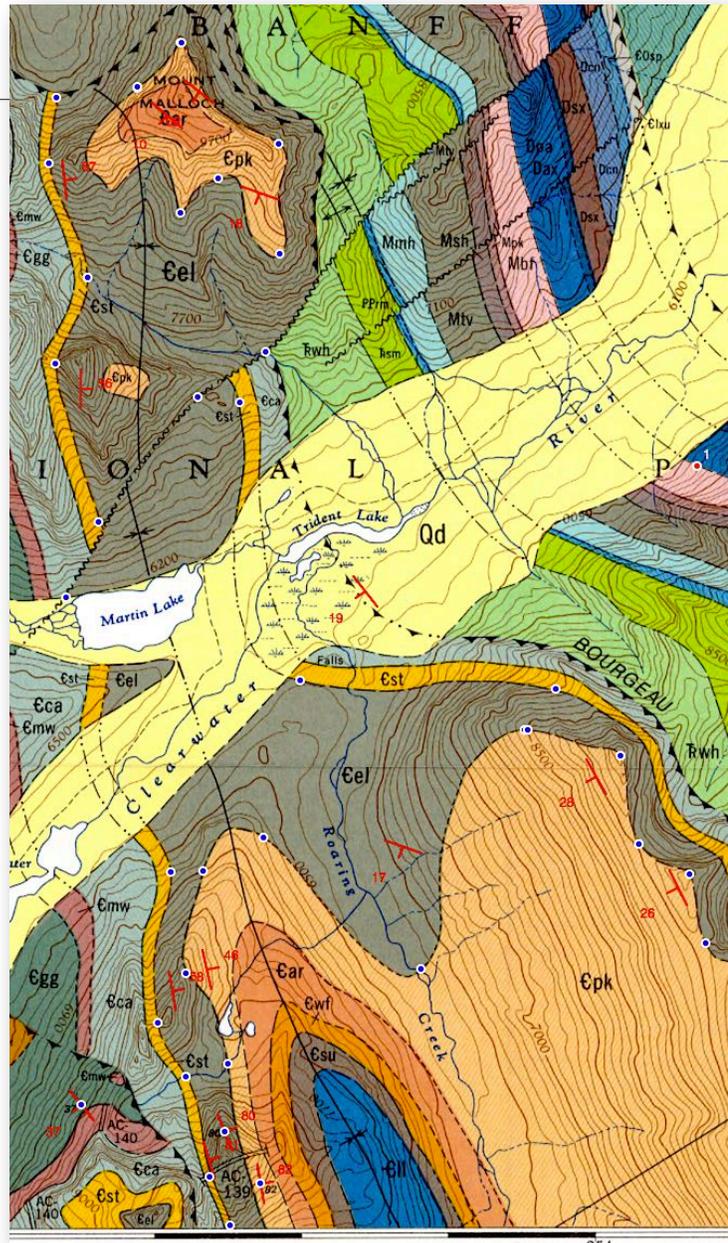


FIGURE 2

this case. Calculate the pole to each plane and then calculate the direction cosines for each pole (MSP, p. 36-38). Now, you can construct the orientation tensor as described in MSP, p. 94-97.

After you have calculated the orientation tensor, you can use the program EigenCalc to derive the principal axes of the orientation tensor. By default, EigenCalc will give you the orientations of the three principal axes as direction cosines so you will have to convert those back to trend and plunge following the directions in MSP, p. 38-39. The third axis corresponds to the fold axis. Note that you can have **GMDE** calculate the fold axis for you to check your answer (Operations>Calculate Cylindrical Fold Axis).

*To calculate an accurate fold axis for the next section, use only orientations within the Bourgeau thrust plate. You can use the Lasso and Toggle Off functions in the Edit Menu to select subsets of observations.*

*In EigenCalc, if you hold down the option/alt key while clicking the Calculate button, the program will also calculate and display the trend and plunge of the three principal axes. It is up to you whether you want to tell your students about this shortcut or not!*

*Note that only a synclinal fold axial trace is shown on the map but the shape of the Cpk-Cel contact hints that there might be a plunging anticline along Roaring Creek and maybe even another syncline farther east. This would be a good time to ask the students about these map patterns. When they draw their section, below, is when they will see what is really going on.*

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## Fault Slip from Offset Piercing Points

Recall that the only way to determine true slip on a fault surface is by calculating piercing points of a once continuous linear feature that has been offset by the fault. The Siffleur River map has just such a feature.

Note the synclinal fold axial surface trace just to the west of Roaring Creek. We will use the corresponding fold axis at the base of formation Cpk to determine the slip of the northeast-striking fault just north of Martin Lake (Fig. 3). This fold axis at this stratigraphic horizon is visible both north and south of the fault. Before proceeding with the calculation, see if you can determine using rule of V's and offset geology what type of fault this may be.

To do a piercing point problem, you will need: (1) one point on the surface trace of the fault plane and the strike and dip of the plane; (2) one point where the line of interest intersects the surface in the hanging wall with known trend and plunge; and (3) one point where the same line intersects the surface in the footwall and the trend and plunge at that point. For this exercise, we will use the trend and plunge of the fold axis as determined in the previous section and assume that it has the same trend and plunge both north and south of the fault (i.e., there has not been any rotation produced by the fault).

First, use a three point problem to calculate the strike and dip of the fault plane. You can do this in the "Orient. & thick..." tab of **GMDE** by clicking on or near points 1, 2, and 3 depicted in Figure 3. Now click on the Piercing Pts. tab, click the "Click" button in the Plane Intersected group box and in the map click on any point along the trace of the fault. After you enter the strike and dip (in right-hand rule), the program will show a cyan colored line with shorter dip tick with arrow head to indicate the point on the fault. In the example in Figure 3, I clicked on point 2 from the three point problem but there is no reason why you have to choose that point.

Now use the click button in the Line 1 group box to click on the map where the fold axis coincides with the base of -Cpk in the hanging wall and then enter the trend and plunge of the fold axis. **GMDE** will put a cyan triangle at the clicked point and will immediately calculate the intersection of the line with hanging wall of the fault, showing its map position with a cyan target symbol with and elevation in which next to it. Repeat this procedure for the point in the footwall as shown in Figure 3.

Now, calculate the offset for yourself in Excel as described on p. 108-111 of MSP. You can transfer all of your piercing point data from the Piercing Pts. tab by selecting Edit>Copy Special>All Coordinates and then paste them into an Excel sheet to start your calculations.

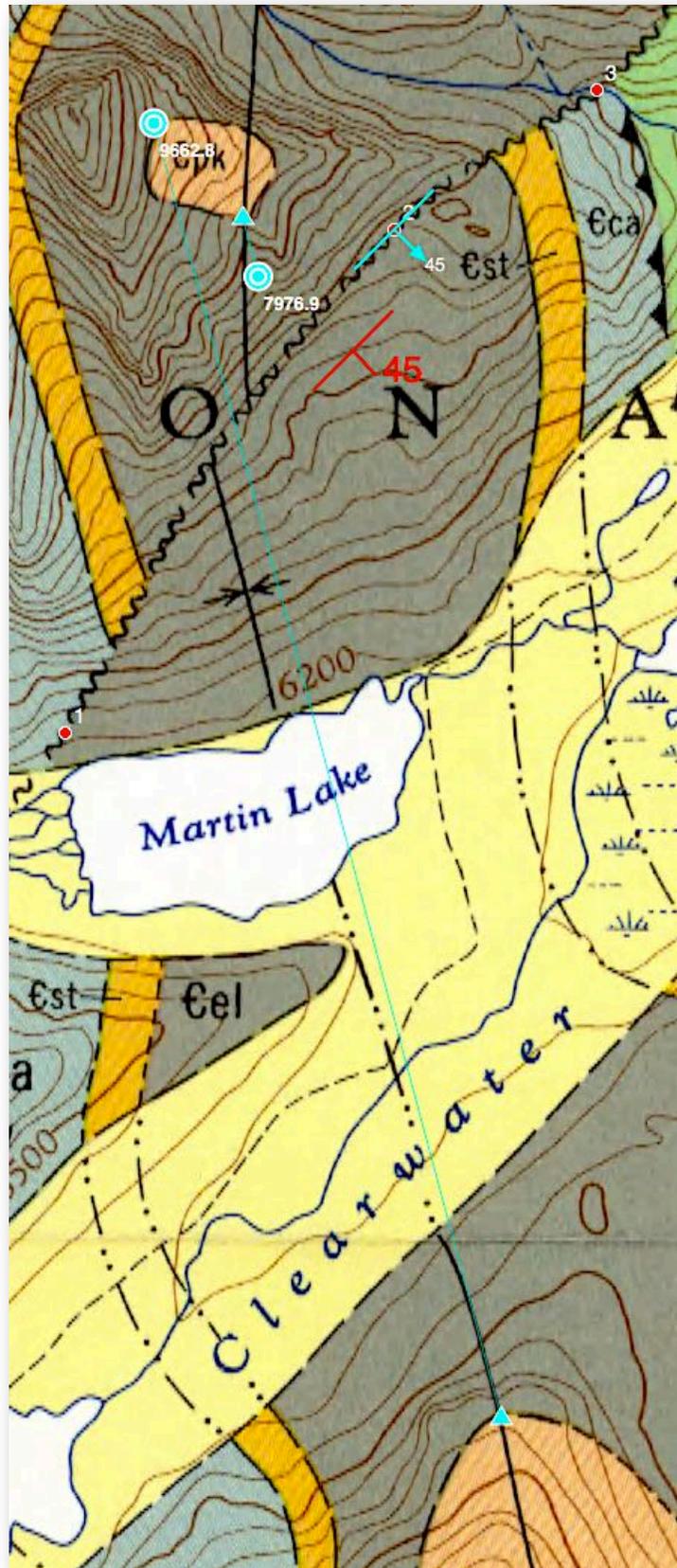


FIGURE 3

*In Figure 3, because of the south plunge and steep topo, both piercing points are in the air above the surface. The student can explore the uncertainty of this calculation back in **GMDE** by varying the input parameters. For example, if they choose the fold axis on the base of -Cpk just south of Mount Malloch, the slip will be quite different than in the case shown in Figure 3. Likewise, they can change the location of the point along the fault plane and the values will also change, albeit less dramatically. Finally, there is, of course, uncertainty in the fold axis orientation and they can play around with those values as well.*

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## Thrust Geometries

A critical relationship in thrust belts is the angle between the thrust fault and bedding; this is what determines whether fault has a ramp or flat relationship with the stratigraphy. You can use the Siffleur River East quad to explore this by comparing orientations from three point problems on thrust faults and adjacent bedding. It is particularly useful for them to compare the bedding orientations in the Sulphur Mountain thrust plate with the attitudes of the Sulphur Mountain Thrust and the overlying Bourgeau thrust and then comment on the ramp and flat relationships. Then, have them look at the Sawback thrust farther west, which presents quite a different picture for both hanging wall and footwall.

*The student should conclude that the Bourgeau and Sulphur Mountain thrusts parallel bedding in their hanging wall and footwalls. and thus are in a position of hanging wall flat on footwall flat. In contrast, the Sawback thrust is a ramp on ramp structure because it cuts across bedding in both hanging wall and footwall.*

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## Interpret Structural Geometry and History

This part of the Siffleur River map preserves an excellent relative structural chronology from which one can draw the following leading questions:

- What are the stratigraphic constraints, preserved in map view, on the maximum age of thrusting?
- What is the relative age of the NE-striking fault studied in the piercing point problem with respect to the Sulphur Mountain, Bourgeau, and Sawback thrust faults and how do you know?
- How do the three thrust plates differ in terms of their stratigraphic packages?
- What is the age of the Sawback thrust relative to the Bourgeau and Sulphur Mountain thrusts and what does this tell you about the sequence of thrust formation?
- What is the age of the syncline relative to the age of the Sawback thrust?

*The last question is tricky enough that you might want to wait until after drawing the section in order to answer it. The other questions are best considered before starting to draw the cross section. Basically, the Sawback thrust is an*



*out-of-sequence thrust that formed after the two thrusts farther east. Price and Mountjoy's interpretation, which I agree with, is that the Sawback is a splay off the upper corner of a footwall ramp (a classic out-of-sequence geometry) at the stratigraphic level of the Triassic section. Thus it would dismember the pre-existing hanging-wall anticline, though it could have produced a superposed fault-propagation fold as it made its way up-section.*

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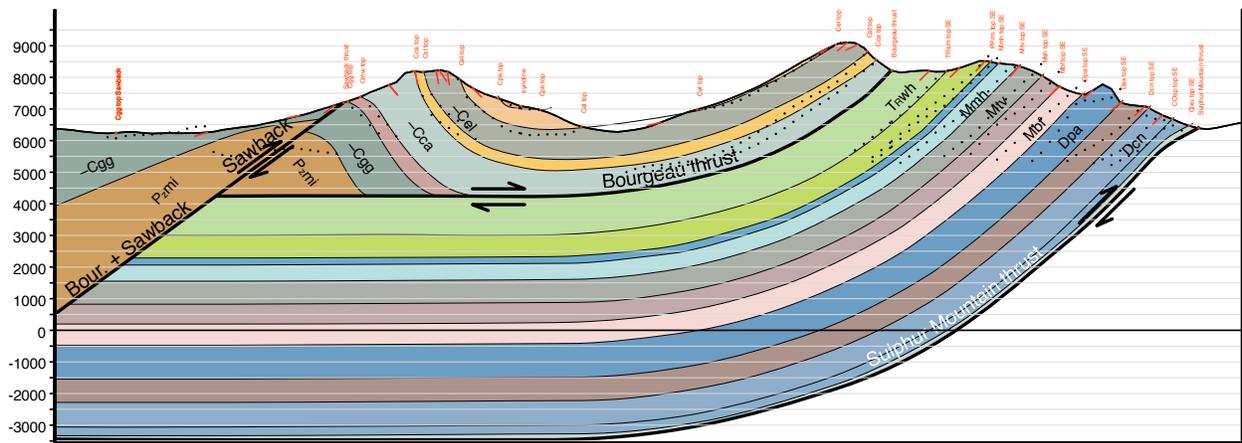
## Draw a Structural Cross-section

**GMDE** has some useful tools to take the tedium out of drawing geologic (and topographic) cross sections but does not do the hardest part: getting the geology right. To draw a topographic cross section, select Operations>Define Topo Profile. The actual number of points you click will depend on whether you wish to add additional information along the line of section. Each time you click the mouse along the line of section the notes field will automatically be selected so you can label the point. For example, in Figure 4, I clicked the starting point, the Sawback thrust, syncline, Bourgeau thrust, and Sulphur Mountain thrust because I wanted those labeled on my section. The stratigraphic labels are captured automatically from my digitized contacts. **GMDE** will also project and calculate apparent dips for all orientations within whatever distance you specify from the section. Recall that you project the dips parallel to the trend of the fold axis and not parallel to the strike of the dip but the apparent dip is calculated with respect to the angle between strike and line of section. Therefore, it is important to calculate the fold axis carefully.

*As shown in Figure 4, **GMDE** can plot your section right on the line of section on the map itself and furthermore, can use a cylindrical fold model to project your digitized contacts onto the line of section. This latter attribute you probably do not want to point out to your students! For actually drawing sections, it is better to open the section in a separate window by selecting Window>Topo Cross Section and leave the "plot depth to folded surfaces" unchecked as shown in Figure 5. This window has additional functionality including setting the vertical exaggeration, ability to measure distances and angles in the section, and importantly, the ability to save the section file as an .svg file for use in a vector drawing program. Also increasing the vertical dimension of the window will yield a deeper section with more room to work.*

After **GMDE** has taken care of the details for setting up the template for the section, you can now export the section from the Topo Cross-section Window as an SVG (scaleable vector graphics) file, a format that most modern vector graphics programs can read. **GMDE** is not an environment for drawing geologic cross sections and that is best done in a vector graphics program.

*My solution to the cross section is shown in Figure 6. Note that I used the dots of contacts projected onto the section using a cylindrical fold model only as general guideline and not to be followed religiously. The down dip structure of the Sulphur Mountain thrust plate is uncertain.*



vertical:horizontal = 1:1

Note that, at the surface, the Sulphur Mountain plate does not exposed the Cambrian section seen in the Bourgeau plate. Thus, at some point beneath this section, the Sulphur Mountain thrust must ramp down into the Cambrian. Alternatively, the Bourgeau thrust could also be an out of sequence thrust that ramped up from a deeper level across the pre-existing Sulphur Mountain plate.

**FIGURE 6**

## References

- Allmendinger, R.W., and Judge, P.A., 2013, Stratigraphic uncertainty and errors in shortening from balanced sections in the North American Cordillera: Geological Society of America Bulletin, v. 125, p. 1569–1579, doi:10.1130/B30871.1.
- Allmendinger, R.W., 2015, Modern structural practice: A structural geology laboratory manual for the 21st Century: <http://www.geo.cornell.edu/geology/faculty/RWA/structure-lab-manual/downloads.html>
- Price, R.A., and Mountjoy, E.W., 1978, Geology, Siffleur River (east half), Alberta: Geological Survey of Canada Map 1465A, scale 1:50,000.