 # Reviewer 3

The authors of the manuscript titled "Seismic imaging across fault systems in the Abitibi greenstone belt – An analysis of pre- and post-stack migration approaches in the Chibougamau area, Quebec, Canada" presents a processing strategy to image strong dipping reflections from a crooked-line acquisition. The manuscript is well written and the methodology is well described. Although, the geological interpretation is not really developed. The manuscript should be a significant and valuable work, and it fits the scope of Solid Earth's special issue "State of the art in mineral exploration". However, some suggestions and technical comments are as follow:

Reply to comment:

We would like to appreciate the reviewer for their positive opinion about our research. We have explained in the introduction of our paper which the main goal of our research is to address optimizing application of the DMO and PSTM in crystalline rock environment where majority of the seismic profiles are crooked. The inclusive interpretation including Kinematic of faults or structural studies are not our main goal. However, we provide more details about the interpretation of the seismic profiles in the revised version in section 4 data processing and results, and section 6 discussion. We have cited publications from some of the co-authors of our paper in Chibougamau are with focused view on geological interpretation:

Mathieu, L., Snyder, D.B., Bedeaux, P., Cheraghi, S., Lafrance, B., Thurston, P., and Sherlock, R.: Deep into the Chibougamau area, Abitibi Subprovince: structure of a Neoarchean crust revealed by seismic reflection profiling, Tectonics, 38, 1–25, 2020.

Bedeaux, P., Brochu, A., Mathieu, L., Gaboury, D., Daigneault, R.: Structural analysis and metamorphism of the Barlow Fault Zone, Chibougamau area, Neoarchean Abitibi Subprovince: Implications for gold mineralization, Canadian Journal of earth Sciences, accepted, 2020.

1) It is not clear why the different offset ranges of 0-3, 3-6, and 6-9 km are selected, even considering that, the seismic profile is 10 km. In addition, during the text, these ranges are changing from 0-3, 3-6, and 6-9 km to 0-3, 0-6 and 0-9 km. Which is the correct one?

Reply to comment:

In "section 3.1 Offset distribution for Kirchhoff PSTM and DMO corrections, paragraph 4" we explain that: We designed offset planes ranging 0-3 km, 0-6 km, and 0-9 km in order to study the survey geometry (Fig. 4). These offset ranges are chosen based on analysis shown in Fig. 2 and Fig.3 and testing the seismic images of variety of offset ranges when they contribute to the process of post-stacked DMO and PSTM images (see Table 2 for the processing details). The offsets greater than 9 km did not increased the image quality and deemed unnecessary to present their images.

All seismic images in Figure 5 and 6 are generated in offset range of 0-3 km, 0-6 km, and 0-9 km and it has been mentioned in text. In Figure 4 instead of overprinting of CMP distribution for offset range of 0-3 km, 0-6 km, and 0-9 km, we show CMPs of offset range of 0-3 km, 3-6 km, and 6-9 km, to present their distribution along the survey line where offset is increasing.

2) In the interpretation, some of the reflections are associated with different geological structures. However, the geological map does not provide any strike and dip information. Also, the profile, to

the south, does not cross the Doda fault while in the interpretation one of the reflections is associated with the fault. In the conclusions, it is mentioned that this fault is only imaged in the first 2 km, while the chs4 (associated with the fault) is observed around 2–3 km depth. Are you sure that chs4 is the fault? In the text, it is not clear the origin of the diffractions. Is it the fault or a potential ore body?

Reply to comment:

Figure 1 has been changed to show major axis of the folds (anticline/syncline) in the Chibougamau area. Also, the strike of the Doda fault has been edited in Figure 1 based on recent finding of one of the co-authors in our paper (P. Bedeaux). In "section 6.2.2 Seismic interpretation along the south profile, paragraph 5" we interpret chs4 and its possible association with the Doda fault. In section 6.2.2 we explain that the Doda fault is measures subvertical in the field and chs4 may image this fault at depths greater than 2 km. This is consistent with what we say in the conclusion.

The diffractions are interpreted potentially as orebodies (section 6.2.1 Seismic interpretation along the north profile, paragraphs, 5-9)

3) It is possible to provide a geological model of the final interpretation? Which are the relationship between chn1 and chs1?

Reply to comment:

The distance between the areas associated to chs1 and chn1 is ~ 50 km on the map (Figure 1). Providing a regional model/interpretation is beyond the scope of our study. The interpretation of the regional seismic profile in Chibougamau area including the geological sections and regional model are published somewhere else by some of the co-authors of our paper:

Mathieu, L., Snyder, D.B., Bedeaux, P., Cheraghi, S., Lafrance, B., Thurston, P., and Sherlock, R.: Deep into the Chibougamau area, Abitibi Subprovince: structure of a Neoarchean crust revealed by seismic reflection profiling, Tectonics, 38, 1–25, 2020.

4) Can you provide the orientation of the seismic profiles in Figures 5–12? In Figure 7, why is represented 12 km, if only there are interpreted the first 6 km, why chn4-chn6 are not to interpreted in this figure? Also, in Figure 10, the chn_diff seems not agree on the shot gather and the stacked section.

Reply to comment:

Now, the orientation of the profiles is shown in figures. Entire depth of the section i.e., 4 s (12 km) is shown in Figure 7 first to show the effect of CDMO on both shallow and deeper part and observe if CDMO can enhance the coherency of the reflections in deeper part and second to be consistent with other sections shown in text. They all present depths between 0-4 s (0-12 km).

Reflection sets chn4, chn5, and chn6 are better imaged in the second segment of the profile shown in Figure 8. The interpretation is provided based on imaging properties in Figure 8 (6.2 Seismic interpretation in Chibougamau area)

Figures 7-11 are update to show time for depth variations of the CDMO stacked sections. Table 3 shows that the velocity of 6000 m/s is considered for time-to-depth conversion after migration shown in Figures

5-6. Figure 10a and Figure 8c is referring to the shallow diffraction (~ 2.5 km/0.75 s) imaged in reflection package chn3 marked with dashed ellipse in Figure 8.c. Figure 10 b show the location of this diffraction at ~ 0.75 s which is not at the same depth/location diffraction chn_diff is imaged. Diffraction chn_diff is shown in Figure 8b-c (at depth of ~ 4 km/1.5 s). Figure 11 shows its location in a shot gather at ~ 1.5 s.

5) In the text is mentioned that for DMO it is used a range velocity of 5000–6500 m/s, while for the CDMO is used a constant velocity of 5500 m/s. Why this decision was made, can you explain it further? In addition, in my understanding, a range of velocities, such as 5000–6500 m/s, will not be considered a constant velocity.

Reply to comment:

Cross dip moveout is applied to DMO corrected sections with constant velocity of 5500 m/s. Velocities between 5000-6500 m/s are utilized for stacking after CDMO (section 5. Cross-dip analysis, paragraph 2).

6) Some references are missing.

It has been checked. Now all the references are properly cited and listed.

Minor comments:

L.15 Canada,

Text has been (Abstract)

L.17-18 with a known metal endowment in the area

Text has been edited (Abstract)

L.24 key geological structures // sets

Text has been edited (Abstract)

Introduction, paragraph 1

L.35-36 (Juhlin, 1995a; Juhlin et al., 1995 and 2010; Bellefleur et al., 1998 and 2015; Perron and Calvert, 1998; Ahmadi et al., 2013)

Text has been edited (section 1. Introduction, paragraph 1)

L. 36 add comma after “however”

Text has been edited (section 1. Introduction, paragraph 1)

L. 67 Mercier-Langevin et al., 2014

Text has been edited (section 1. Introduction, paragraph 1)

L.33 crystalline rock

Text has been edited (section 1. Introduction, paragraph 1)

L. 35-36 Juhlin, 1995a; Juhlin et al., 1995, 2010; Bellefleur et al., 1998, 2015 … // remove ; // . However, all …

Text has been edited (section 1. Introduction, paragraph 1)

L.37 than a coherent

Text has been edited (section 1. Introduction, paragraph 1)

L. 38 Petrophysical measurements, where available, complemented with reflectivity/velocity models of the shallow crust, …

Text has been edited (section 1. Introduction, paragraph 1)

L. 39 permit a more

Text has been edited (section 1. Introduction, paragraph 1)

L.42 limited the application

Text has been edited (section 1. Introduction, paragraph 1)

L.45-46 confusing sentence. Can you rephrase it?

Text has been edited (section 1. Introduction, paragraph 1)

L.47 change "which" for "that"

Text has been edited (section 1. Introduction, paragraph 1)

L.59 Bedides

Text has been edited. Beside is replaced with besides (section 1. Introduction, paragraph 2)

L.61-63 confusing sentence. Can you rephrase it?

Text has been edited (1. Introduction, paragraph 2)

L.78 Are the offset ranges between 0-10 km or 0-9 km? In the abstract is mentioned 0-9 km, while here is between 0 and 10 km. It is somewhat confusing.

Section 1. Introduction, paragraph 3: it has been edit to show 0-9 km.

L.90felsic lava flows

Text has been edited (Section 2. Geological setting, paragraph 1)

L. 92 Mueller et al., 1989; Leclerc et al., 2017

Text has been edited (Section 2. Geological setting, paragraph 1)

L.92-93 …, observed along the southern profile, …

Text has been edited (Section 2. Geological setting, paragraph 1)

L.102 , and

Text has been edited (section 2. Geological setting, paragraph 2)

L. 103 Dimroth et al., 1995

Text has been edited (section 2. Geological setting, paragraph 2)

L.106 change “to” for “with”

Text has been edited (section 2. Geological setting, paragraph3)

L. 108-109 Leclerc et al., 2012 and 2017 // schistosity

Text has been edited (section 2. Geological setting, paragraph3)

L.114 at the surface

Text has been edited (section 2. Geological setting, paragraph3)

L. 117 Dimroth, 1985; Mueller et al., 1989

Text has been edited (section 2. Geological setting, paragraph3)

L.120-121 confusing sentence. Can you rephrase it?

Text has been edited (Section 3. Seismic data section, paragraph 1)

L. 148 low-velocity

we did not see this in text to edit.

L.142 DMO or PSTM,

Text has been edited (section 3.1. Offset distribution for Kirchhoff PSTM and DMO corrections, paragraph 1)

L.152 artifacts

Text has been edited (section 3.1. Offset distribution for Kirchhoff PSTM and DMO corrections, paragraph 2)

L.158 . for example,

Text has been edited (section 3.1. Offset distribution for Kirchhoff PSTM and DMO corrections, paragraph 3)

L.161 , for example, // , however,

Text has been edited (section 3.1. Offset distribution for Kirchhoff PSTM and DMO corrections, paragraph 3)

L.162 , for example,

Text has been edited (section 3.1. Offset distribution for Kirchhoff PSTM and DMO corrections, paragraph 3)

L. 166 add space between two paragraphs (the space is added)

Text has been edited (section 3.1. Offset distribution for Kirchhoff PSTM and DMO corrections, paragraph 3)

L.167 am irregular (we assume the reviewer wants to say an irregular)

Text has been edited (section 3.1. Offset distribution for Kirchhoff PSTM and DMO corrections, paragraph 4)

L.169-170 In Figure 4 the ranges are: 0-3 km, 3-6 km and 6-9 km, while in the text is 0-3 km, 0-6km and 0-9 km. Which is correct? Why did you choose those ranges? If the profile is 10 km, why only 9 km were considered for the CMPs? This needs to be clarified.

Reply to comment:

In "section 3.1 Offset distribution for Kirchhoff PSTM and DMO corrections, paragraph 4" we explain that: We designed offset planes ranging 0-3 km, 0-6 km, and 0-9 km in order to study the survey geometry (Fig. 4). These offset ranges are chosen based on analysis shown in Fig. 2 and Fig.3 and testing the seismic images of variety of offset ranges when they contribute to the process of post-stacked DMO and PSTM images (see Table 2 for the processing details). The offsets greater than 9 km did not increased the image quality and deemed unnecessary to present their images.

All seismic images in Figure 5 and 6 are generated in offset range of 0-3 km, 0-6 km, and 0-9 km and it has been mentioned in text. Only in Figure 4 we show offset range of 0-3 km, 3-6 km, and 6-9 km, to present CMP distribution along the survey line where offset is increasing.

L.173 remove "than"

Text has been edited (section 3.1. Offset distribution for Kirchhoff PSTM and DMO corrections, paragraph 4)

L.171 , whereas many …

Text has been edited (section 3.1. Offset distribution for Kirchhoff PSTM and DMO corrections, paragraph 4)

L.172 lies

Text has been edited (section 3.1. Offset distribution for Kirchhoff PSTM and DMO corrections, paragraph 4)

Table 1 change "1000 m" for "10 km" // the offset ranges do not agree with Figure 4

Reply to comment:

Table 1 does not present offsets. Table 2 shows the offset range. Text is edited to show 10 km. Please see above our reply about Figure 4 and the offsets ranges utilized in our processing.

L. 240 , as well as …

Text has been edited (section 4. Data processing and results, paragraph 1)

L. 244 … refraction, and …//… filter, and …

Text has been edited (section 4. Data processing and results, paragraph 1)

L.247 again, the offset range do not match with figure 4

Reply to comment:

Please see our reply about Figure 4 above mentioned

L. 251 .. was derived // Is this a range of constant velocities that you have use, or is the final velocity? 5000 – 6500 m/s I will not consider a constant velocity. // … a step range

Text has been edited (Section 4. Data processing and results, paragraph 2): "This chosen velocity derived from several tests using various constant velocities between, 5000-6500 m/s, with step range of 100 m/s".

L.258 New paragraph, then add space between paragraphs

Text has been edited (section 4. Data processing and results, paragraph 3)

L.262-263 unclear sentence

Text has been edited (section 4. Data processing and results, paragraph 3)

L. 268 Labeled

Text has been edited (section 4. Data processing and results, paragraph 3)

L.276 New paragraph, then add space between paragraphs

Text has been edited regarding this comment (Text has been edited (section 4. Data processing and results, paragraph 5).

L.283 summarizes

Text has been edited (section 4. Data processing and results, paragraph 5)

L.289-292 unclear sentence

Text has been edited (section 5. Cross-dip analysis, paragraph 1)

L. 294 remove ";"

Text has been edited (section 5. Cross-dip analysis, paragraph 1)

L.299 why did you use a constant velocity of 5500 m/s for the CDMO, while a range of velocities was used for the DMO and PTSM? This needs to be clarified

Reply to comment:

DMO corrected section with constant velocity of 5500 m/s is considered for CDMO. Then, time delays of CDMO is calculated and applied. Finally, we stacked DMO-CDMO corrected traces using a velocity model designed from the one applied after DMO corrections during standard processing (Table 2). This is mentioned in section 5. Cross-dip analysis, paragraph 2

L.300 to the west to 40º to the east with …

Text has been edited (section 5. Cross-dip analysis, paragraph 2)

L.307 ... of the seismic …

Text has been edited (section 5. Cross-dip analysis, paragraph 3)

L310 in the deeper

Text has been edited (section 5. Cross-dip analysis, paragraph 3)

L.313 remove "the" before "diffraction"

Text has been edited (section 5. Cross-dip analysis, paragraph 3)

L.321 to the west

Text has been edited (section 5. Cross-dip analysis, paragraph 4)

L. 325 Fig. 9a-c

Text has been edited (section 5. Cross-dip analysis, paragraph 4)

L.326 …, and its coherency decreases (Fig. 9c-f).

Text has been edited (section 5. Cross-dip analysis, paragraph 4)

Figure 5. Can you add the orientation of the profile? Also, the offset ranges are not the same as Figure 4

Reply to comment:

The orientation of the line is added now to this figure. Please see our comment about Figure 4 mentioned above

L.356357 to address the challenges of the applications of the method in a crystalline rock environment.

Text has been edited (section 6. Discussion, paragraph 1)

L.368 In this study,

Text has been edited (section 6.1 The effect of survey geometry on seismic imaging, paragraph 1)

Figure 6 same as Figure 5

The labels have ben added to show the orientation of the profile.

Figure 7 add the orientation. Also, why are represented 12 km, while only the first 6 km are interpreted. Why chn4-chn6 are not interpreted in this figure?

Reply to comment:

Figure 7 is updated to show time for depth variations. Entire depth of the section i.e., 12 km (4s) is shown in Figure 7 first to show the effect of CDMO on both shallow and deeper part and observe if CDMO can enhance the coherency of the reflections in deeper part and second to be consistent with other sections shown in text. They all present depths between 0-4 s (0-12 km).

Reflection sets chn4, chn5, and chn6 are better imaged in the second segment of the profile shown in Figure 8. The interpretation is provided based on imaging properties in Figure 8 (6.2 Seismic interpretation in Chibougamau area)

Figure 8 I cannot see chn4 on Figure 8d-f, neither chn5 in e-f. Am I supposed to see them?. What is chn2 pointing out?

Reply to comment:

Figure 8 is updated to show time for depth variations. Figure 8 present the application of the CDMO. The section without CDMO is shown in Figure 8c and all the reflections marked and interpreted in Figure 5 are shown here. Then, after application of CDMO to the west or to the east some of the reflections show more coherency some less. The location of the all reflections are shown for better comparison/evaluation. Interpretation of reflection chn2 is shown in section 6.2.1 Seismic interpretation along the north profile, paragraph 2: “Similar to reflection chn1, Reflection chn2 (Fig. 5, Table 3) correlates with local structure, i.e., small fault or mafic/ultramafic lithology in outcrops of Opémisca Group rocks”.

Figure 9, aren’t chs3 and chs4 pointing the same reflection? What is chs1 point out?

Reflection sets chs3 and chs4 are two separate packages. See section 6.2.2. Seismic interpretation along the south profile, paragraph 4-5 for interpretation.

For interpretation of reflection chs1 see section 6.2.2. Seismic interpretation along the south profile, paragraph 2.

L.403 remove “the” borfee “regularity#

Text has been edited (section 6.1. The effect of survey geometry on seismic imaging, paragraph 2)

L.407 with an offset

Text has been edited (section 6.1. The effect of survey geometry on seismic imaging, paragraph 2)

L.406 Artifacts

Text has been edited (section 6.1. The effect of survey geometry on seismic imaging, paragraph 2)

L. 407 artifacts

Text has been edited (section 6.1. The effect of survey geometry on seismic imaging, paragraph 2)

L.412 … of CMPs, especially for longer offsets.

Text has been edited (section 6.1. The effect of survey geometry on seismic imaging, paragraph 2)

L.413, for example,

Text has been edited (section 6.1. The effect of survey geometry on seismic imaging, paragraph 2)

L.416 near-surface

Text has been edited (section 6.2. Seismic interpretation in Chibougamau area)

L.424 south-dipping

Text has been edited (section 6.2.1. Seismic interpretation along the north profile, paragraph 1)

L.439 at the surface

Text has been edited (section 6.2.1. Seismic interpretation along the north profile, paragraph 3)

L.444 CDMO towards the west

Text has been edited (section 6.2.1. Seismic interpretation along the north profile, paragraph 3)

L.446 structure of

Text has been edited (section 6.2.1. Seismic interpretation along the north profile, paragraph 3):

“originates within a complex structure, off the plane of the north profile”.

L.449 Unless the north profile was …

Text has been edited (section 6.2.1. Seismic interpretation along the north profile, paragraph 4):

L.453 cross-dip elemts

Text has been edited (section 6.2.1. Seismic interpretation along the north profile, paragraph 4)

L.470 remove ";"

Text has been edited (section 6.2.1. Seismic interpretation along the north profile, the last paragraph)

L.476-480 I do not think this fits in the interpretation section, as it is more like an observation of the results. Can you explain what is related to the diffractions?

Reply to comment:

Diffraction are interesting objects in exploration seismology as they could refer to small lenses which in mineral exploration could be an orebody. Diffraction imaging is always a challenging fact in seismology and the observed diffraction needs to be supported in stacked sections (depth converted) as well as the shot gathers (time domain). In section 5 Cross-dip analysis we just comment about diffraction imaging. In section 6.2.1. Seismic interpretation along the north profile, paragraphs 5-9 we inclusively addressing the diffraction imaging/validity of imaging, its potential for mineral exploration and also justify our results when we show the diffractions in shot gathers. There are two diffractions along the north profile (See Figure 8). In section 6.2.1. Seismic interpretation along the north profile, we discuss that CDMO can be applied for better observation of the diffractions.

L.493 ... towards the east or the west.

Text has been edited (section 6.2.2. Seismic interpretation along the south profile, paragraph 2).

Figure 10. The diffraction on the shot gather is observed at 0.5 s, while on the stack section is observed at 2.5 km. Can you explain how is diffraction observed so dip, should not be seen around 1.5 – 2 km? Why do you not compare the shot gather with an unmigrated stacked section (in the time domain)?

Reply to comment:

We explained in "section 5. Cross-dip analysis" that CDMO stacked sections are considered. Now, Figures 7-11 are updated to show time for depth variations. Table 3 shows that velocity of 6000 m/s is considered for time-to-depth conversion after migration shown in Figures 5-6. The diffraction in Figure 10b is imaged in at ~ 0.75 s which will be ~ 2.5 km.

L.522 ~8000 ms-1

Text has been edited (section 6.2.2 Seismic interpretation along the south profile, paragraph 3)

L.525 of

The sentence is correct and it has not been changed regarding this comment (section 6.2.2 Seismic interpretation along the south profile, paragraph 3): "This uncertainty would suggest greater complexity of the Guercheville fault off the plane of the south profile".

L. 544 remove point before (Mathieu et al., 2020b)

Text has been edited (section 6.2.2 Seismic interpretation along the south profile, paragraph 6)

Figure 12. Why the CDP dash line is so short? What does it means? Also, the change on chs2 is observed more towards the right of the dash line. Is it well located?

Reply to comment:

The CDP location is marked based on its coordinate. The dashed line is only presenting the location of CDP without any indication of length or width of the CDP. The projection of Reflection chs2 in shot gather differs compare with its projection and in stacked/migrated sections is different. The shot gather shows the reflections based on the signal gathered in receiver locations. Only after application of NMO corrections, DMO corrections, stacking, and migration process reflections will appear in their true geometrical location.

Section 6.3 can you provided a geological sketch that correlated the north and south interpretations?

Reply to comment:

In above we mentioned that the distance between south and north profile is about 50 km. Providing such regional model/interpretation to cover the area from south profile to north profile is beyond the scope of our study. However, interpretation of the regional seismic profile in Chibougamau area including the geological sections or regional models are published somewhere else by some of the co-authors of our paper:

Mathieu, L., Snyder, D.B., Bedeaux, P., Cheraghi, S., Lafrance, B., Thurston, P., and Sherlock, R.: Deep into the Chibougamau area, Abitibi Subprovince: structure of a Neoarchean crust revealed by seismic reflection profiling, Tectonics, 38, 1–25, 2020.

L.586 missing spaces "… processing work flow applied in this study ..."

Text has been edited (section 7. Conclusions, paragraph 2)

L. 596 (Vermeer, 1990, 1998 and 2010)

Text has been edited (Appendix A, paragraph 1)

References

The following citations are missing in the reference list

Cheraghi et al. (2011); Bellefleur et al. (2018); David et al. (2011); Daigneault and Allard (1990); Bedeaux et al. (2020); Vermeer (1994); Dimroth et al., 1995

Reply to comment:

Bedeaux et al. (2020) has ben added to the reference list.

Bellefleur et al. (2018): The correct reference is Bellefleur et al. (2019) which is already in the reference list. Bellefleur et al. (2018) has been changed to Bellefleur et al. (2019) in section 1. Introduction, paragraph 2.

Cheraghi et al. (2011): This reference has been added to the reference list.

Daigneault and Allard (1990): The proper reference is Daigneault et al. (1990) which is already in the reference list and text has been changed to properly cite this reference in section 2. Geological setting, paragraph, 3.

Dimroth et al., 1995: The proper reference is Dimroth et al. (1985) which is already in the reference list. Dimroth et al. (1985) is cited in section 2. Geological setting, paragraph, 3.

David et al. (2011) has been added to the reference list.

Vermeer (1994): This reference has been added to the reference list.

The following reference is not cited in the text

Juhlin, C.: Finite difference elastic wave propagation in 2D heterogeneous transversely isotropic media, Geophysical Prospecting, 43, no.6, 843–858, 1995b

This reference has been removed from the reference list.