geoconvention Virtual Event September 21-23 2020
CSPG · CSEG · CWLS · GAC · MAC · IAH

Machine generated curvilinear structures extracted from magnetic data in the Fort McMurray oil sand area using 2D structure tensor

Hassan H. Hassan
Multiphysics Imaging Technology

Summary

Curvilinear structures are among the most important geological features that are detected by geophysical data, because they are often linked to subsurface geological structures such as faults, fractures, lithological contacts, and to some extent paleo-channels. Thus, accurate detection and extraction of curvilinear structures from geophysical data is crucial for oil and gas, as well as mineral exploration. There is a wide-range of curvilinear structures present in geophysical images, either as straight lines or curved lines, and across which image magnitude changes rapidly. In magnetic images, curvilinear structures are usually associated with geological features that exhibit significant magnetic susceptibility contrasts. Traditionally, curvilinear structures are manually detected and extracted from magnetic data by skilled professionals, using derivative or gradient based filters. However, the traditional approach is tedious, slow, labor-intensive, subjective, and most important they do not perform well with big geophysical data. Recent advances in digital imaging and data analytic techniques in the fields of artificial intelligence, machine and deep learnings, helped to develop new methods to automatically enhance, detect, and extract curvilinear structures from images of small and big data. Among these newly developed techniques, we adopted one that is based on 2D Hessian structure tensor. Structure tensor is a relatively modern imaging technique, and it reveals length and orientation of curvilinear structures along the two principal directions of the image. It is based on the image eigenvalues (λ_1, λ_2) and their corresponding eigenvectors (e_1, e_2), respectively. The main goal of this study is to automatically enhance, detect, and extract curvilinear geological structures from magnetic images, using structure tensor technique. For this purpose, we downloaded a publicly available magnetic data, covering part of the Fort McMurray oil sand play of Alberta, from the Natural Resources Canada (NRC), and it was used as the input image, in this study. The Fort McMurray oil sand area is located in the Athabasca sub-basin, and its Lower Cretaceous McMurray Formation hosts the third largest oil reserves in the world, after Venezuela and Saudi Arabia. From the downloaded magnetic image, we extracted curvilinear structures, using the eigenvalues and eigenvectors that are derived from the Hessian matrix. The Hessian matrix used in this study is a 2x2 symmetric matrix of the second-order derivatives (I_{xx}, I_{xy}, *and* I_{yy}) of the magnetic image, computed with respect to the x- and y-coordinates. To reduce the level of noise in the second-order derivative images, and to control the widths of the extracted curvilinear structures, the second-order derivative images were convolved with Gaussian smoothing filters, at an appropriate standard deviation value (σ). A Gaussian filter with small standard deviation value, produces thin lines whereas a Gaussian filter with high standard deviation value produces thick lines. The obtained results are very interesting and they demonstrate that the proposed technique, in this study, is able to automatically enhance and extract high-quality, and coherent curvilinear structures, from the magnetic image of the Fort McMurray oil sand area. Most of the extracted curvilinear structures appear to be oriented in the NW-SE direction and, to a lesser extent in the NE-SW direction. The extracted curvilinear structures are most likely associated with faults and fractures within

the basement rocks and probably with those that are propagated into the overlying sedimentary rocks. The extracted curvilinear structures could be also linked to paleo-channels with significant deposits of magnetic minerals. Magnetic minerals such as magnetite or siderite may have been deposited along with the heavy minerals at the bottom of the paleo-channels. Significant amount of magnetic minerals such as magnetite, ilmenite and siderite were found in bedrocks, drill-holes, as well as in the oil sand tailings of the Fort McMurray area.

Introduction

Detection and extraction of curvilinear structures, is very important for a wide-range of applications including computer vision, medicine, remote-sensing and resource exploration. In resource exploration, curvilinear structures are often linked to faults, fractures, lithological contacts and to some extent paleo-channels. Curvilinear structures could also provide useful information and insight into the geology and tectonic framework of the study area. Traditionally, curvilinear structures in geophysical data are manually detected, analyzed, and extracted by human; a task that is proved to be tedious, time-consuming and subjective. Besides, traditional techniques are not well suited to analyze large volume or big geophysical data. Hence, there is a need to automate the process of the detection and extraction of curvilinear structures from geophysical images, for example, by using machine learning techniques. In this study, we are implementing a relatively new and promising technique that has recently gained popularity due to its potential applications in machine and deep learning based approaches. As plenty of testing and training data, become available, this technique can be modified into a supervised machine learning or a deep learning convolutional neural network (CNN) model that can be used for automatic detection and extraction of curvilinear structures from geophysical images. Unlike traditional techniques, where derivative or gradient based approaches are used, this new approach uses the structure tensor of the image to detect and extract curvilinear structures. In comparison to traditional techniques, the structure tensor is more accurate, because it is invariant to rotation and scale. Besides, it is fast, cost-effective and non-subjective. The structure tensor of the input image can be derived from the eigenvalues and eigenvectors of a 2D Hessian matrix. Eigenvalues and their corresponding eigenvectors, reveal information about the lengths and orientations of the curvilinear structures along the two orthogonal principal directions of the image.

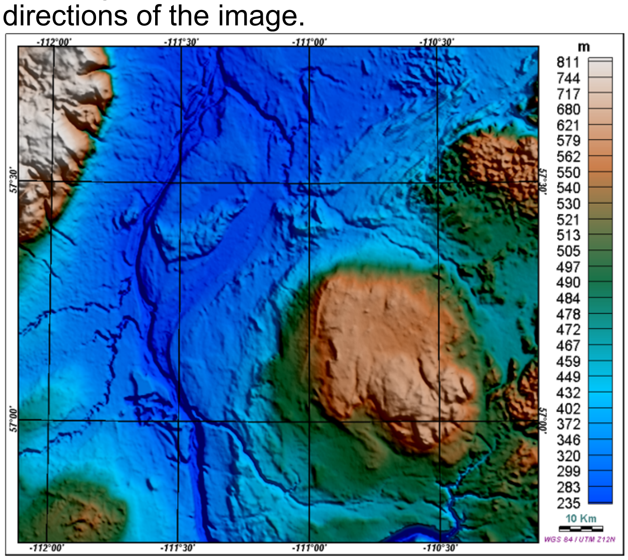

Figure 1. Topography of the study area

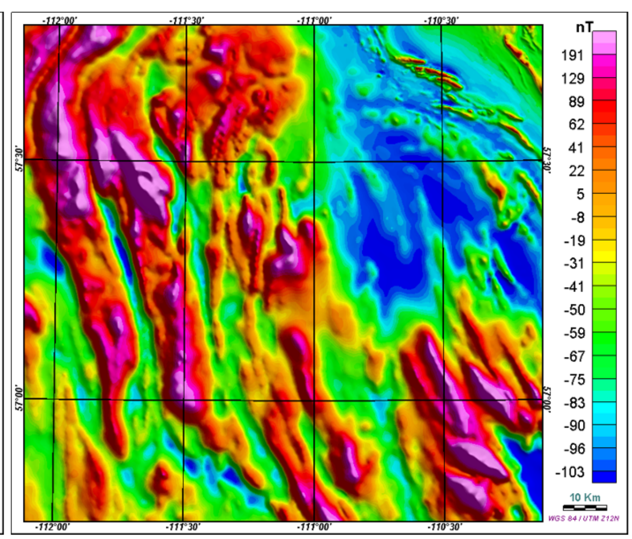

Figure 2. Total magnetic intensity of the study area

There are a number of existing techniques to detect and extract curvilinear structures from images (For example, Sato *et al*., 1997; Law and Chung, 2008; Moreno and Smedby, 2015).

However, in this study, we are using a technique that was initially introduced by Steger (1996; 1998) and further improved by others, including Raghupathy (2004), Rokicki *et al.* (2011), and Guan Xu *et al.* (2014), because it appears to work well with geophysical images. Steger developed an approach to extract curvilinear structures with sub-pixel accuracy and estimates their width. It was introduced as a method for identifying roads in aerial photographs. In this study, we applied the technique to detect and extract curvilinear structures from magnetic images. Accordingly, we used eigenvalues and their corresponding eigenvectors computed from second-order derivative of a 2D Hessian matrix to define locations, lengths, and orientations of curvilinear structures in a magnetic image. The magnetic image used for this purpose, is derived from a public magnetic database available at Natural Resources Canada (NRC), and it covers part of the Fort McMurray oil sand area of west-central Alberta. The topography and the total magnetic intensity images of the study area are shown in Figures 1 and 2, respectively. Fort McMurray oil sand area contains huge deposits of heavy oil within its Lower Cretaceous McMurray Formation (Fig. 3). The McMurray Formation, which mainly consists of clastic sedimentary rocks such as sandstone, siltstone and shale, lies on top of tilted Devonian carbonate rocks, and both are separated by an angular unconformity surface. Most of the heavy oil deposits lie above this unconformity surface, which is located at about 600m below the surface. The basement rocks beneath the study area are mostly granitic and mylonitic in composition (Wilson, 1986). The area is also reported to contain a significant amount of magnetic minerals such as magnetite, ilmenite, siderite, ironstone, garnet and spinel in the bedrocks as well as in the oil sand tailing materials (McLaws, 1980; Ellwood and Pemberton, 1984; Andriashek, 2003). Abundant amount of pyrite in the form of large nodules are found at the bottom of the McMurray Formation near its contact with the underlain unconformity surface. Pyrite is not a magnetic mineral but under diagenesis or other conditions such as heat and oxidation, it can be transformed into magnetic minerals such as magnetite.

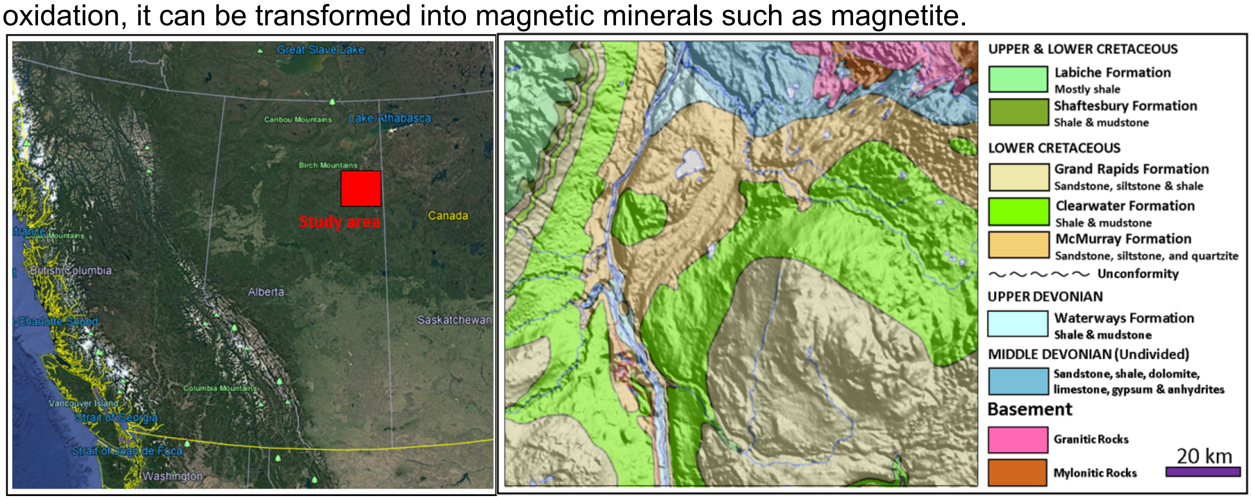

Figure 3. Index (left), and generalized geology (right), of the study area

Methodology

The workflow used, in this study, to extract curvilinear structures from a magnetic image, is illustrated in Figure 4. A curvilinear structure can be modeled as an elongated line whose length is characterized by the eigenvalues (λ_1, λ_2) and whose orientation is characterized by the eigenvectors (e_1, e_2). To extract the structure tensor of the magnetic image, we used a 2x2 Hessian matrix constructed from the second-order derivatives of the magnetic image as described below:

$$H(x,y,\sigma) = \begin{bmatrix} I_{xx}(\sigma) & I_{xy}(\sigma) \\ I_{xy}(\sigma) & I_{yy}(\sigma) \end{bmatrix} \qquad (1)$$

$I_{xx}(\sigma)$, $I_{yy}(\sigma)$, and $I_{xy}(\sigma)$ represent the results of convolving the second-order derivatives of the magnetic image by a Gaussian smoothing filter, at a selected standard deviation (σ) value. The advantage of using a Gaussian filter is to reduce the amount of noise associated with the second-order derivatives as well as to control the width of the extracted curvilinear structure. If we desire thin curvilinear structures we use Gaussian filter with small standard deviation, and vice versa. The eigenvalues and their corresponding eigenvectors along the two orthogonal principal directions of the magnetic image, can be calculated by the diagonalization of the Hessian matrix shown in Equation 1, as indicated below:

$$H = R.Q.R^{-1} = \begin{bmatrix} e_1 & e_2 \end{bmatrix} \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix} \begin{bmatrix} e_1 \\ e_2 \end{bmatrix} \qquad (2)$$

Q is a diagonal matrix, produced by rotating the Hessian matrix by the vector R and it contains the eigenvalues. R^{-1} is the transpose of vector R, and it contains the eigenvectors. After computing the structure tensor at each pixel of the magnetic image, we sort a pixel as being a curvilinear structure or not, on the basis of the lengths and orientations of the eigenvalues and eigenvectors, respectively. The eigenvector that is associated with the largest absolute eigenvalue (i.e., high curvature direction), represents the direction that is orthogonal to the direction of the curvilinear structure. The eigenvector that is associated with eigenvalue that has a small or close to zero magnitude (i.e., low curvature direction), represents the direction of the long axis of the curvilinear structure, at the pixel. To locate the center points along the axis of the extracted curvilinear structure, we use the zero-crossing of the second derivative in the direction perpendicular to the axis of the curvilinear structure as a guide. Afterward, a hysteresis (double) thresholding filter is applied to the image with the identified curvilinear structures, in order to remove weak and poorly connected curvilinear structures, and to keep only well-defined and connected curvilinear structures.

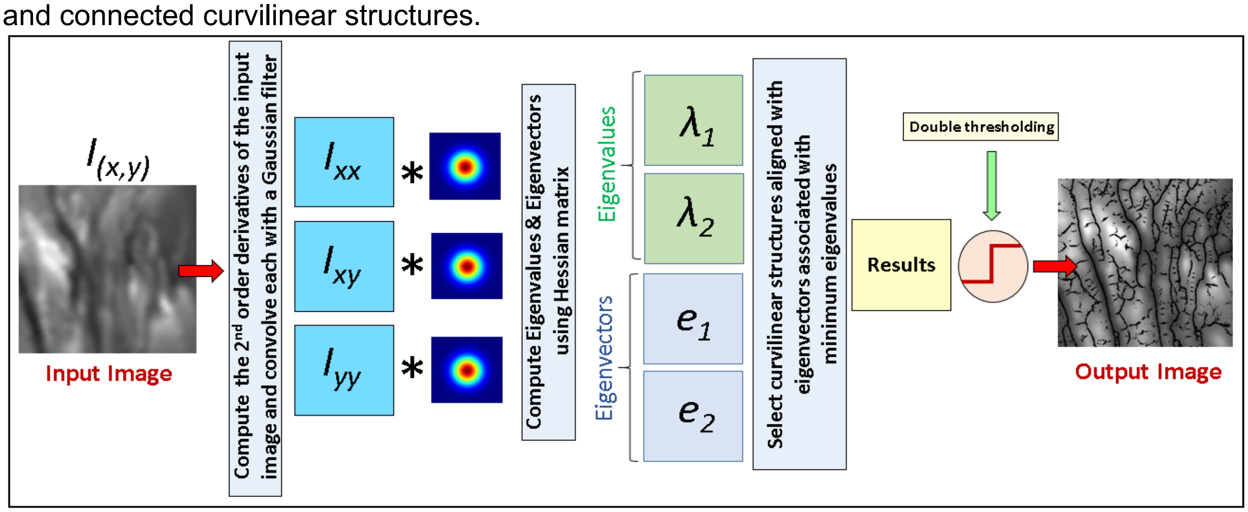

Figure 4. Workflow of the technique used in this study.

Results

The obtained results from applying structure tensor approach to an input magnetic image from the Fort McMurray oil sand area is shown in Figure 5. Figure 5a shows a color-coded NE-shaded relief image of the input magnetic data. The curvilinear structures detected in the magnetic image are displayed in Figure 5b. In comparison to the input image (Fig. 5a), the image in Figure 5b clearly shows well-defined and coherent curvilinear structures that are not apparent in the input magnetic image. These curvilinear structures were computed using a Gaussian filter with a standard deviation of one (σ=1), which was an appropriate choice for the input magnetic image used in this study. In addition of controlling the width of the lines, the Gaussian filter helped to reduce the amount of noise level in the data, and significantly enhanced the continuity and the coherency of the curvilinear structures.

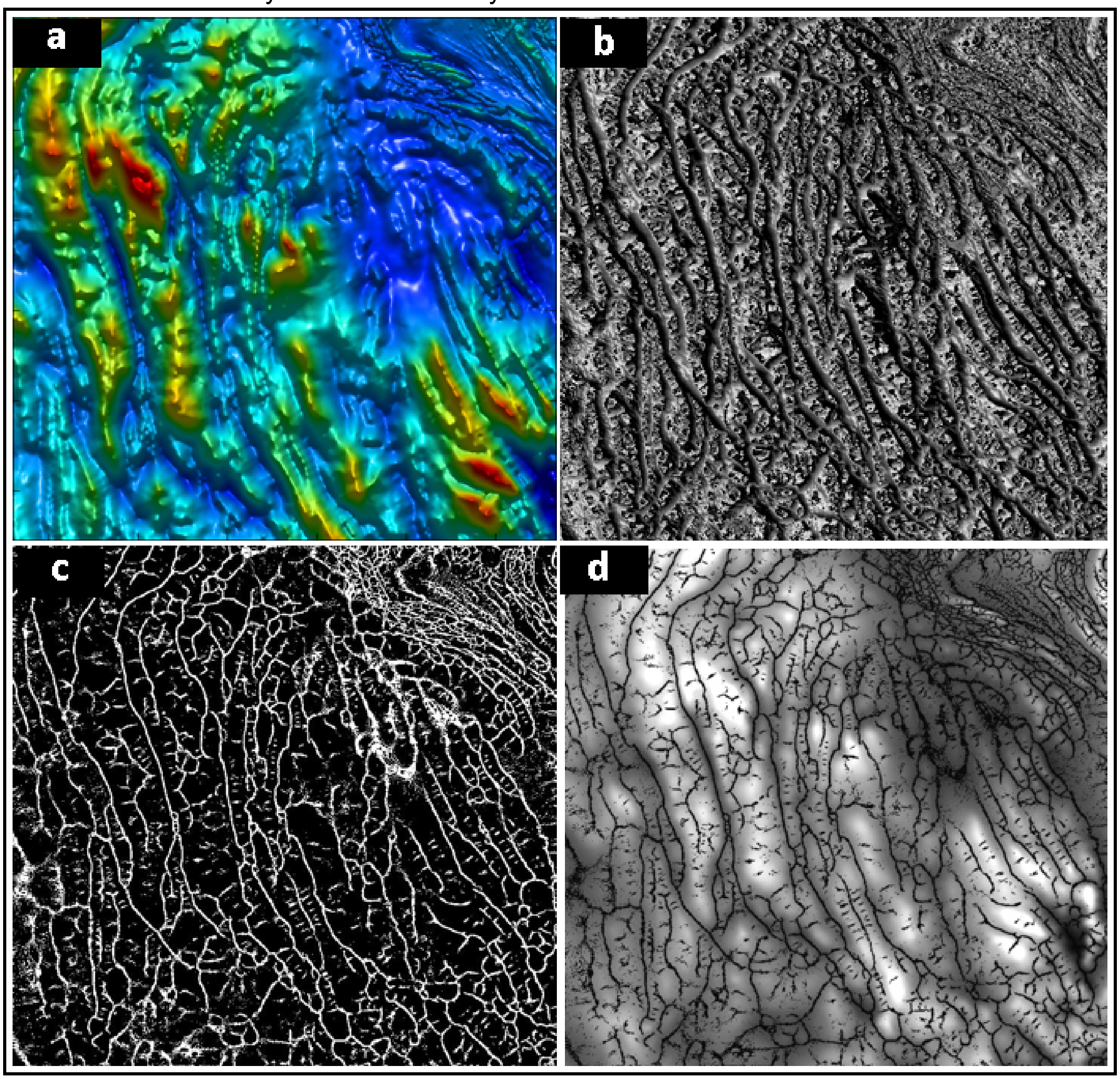

Figure 5. The input magnetic image, and the results obtained in this study; (a). The input magnetic image plotted in shaded relief; (b). Enhanced and delineated curvilinear structures obtained from the input magnetic image; (c). The extracted curvilinear structures; and (d). Extracted curvilinear structures draped on top of the input magnetic image

To extract the skeletons of the detected curvilinear structures, we applied a double threshold filter to the image shown in Figure 5b. The upper eigenvalue threshold was set at 0.60, whereas the lower eigenvalue threshold was set at 0.40. The outcome obtained after applying double thresholds to the image in Figure 5b, is shown in Figure 5c. The extracted curvilinear structures are shown as black color lines on white background. To visualize the extracted curvilinear structures with respect to the input magnetic image, we draped the curvilinear structures over the input magnetic image (Fig. 5d). Thus, a more focused curvilinear structures were obtained, and they appear to be oriented mostly in the NW-SE direction, and to a lesser extent in the NE-SW direction. These, curvilinear structures are most likely associated with faults and fractures originating within the basement rocks, and to some extent with those propagated into the overlying sedimentary rocks. It is also possible that some of the curvilinear structures may be related to the paleo-channels. Paleo-channels often contain magnetic minerals such as magnetite that could have been deposited along with heavy minerals at their bottoms.

Conclusions

In this abstract, we used structure tensor technique, derived from a 2D Hessian matrix to automatically detect and extract curvilinear structures from a magnetic image over the Fort McMurray oil sand area. The eigenvalues and eigenvectors, which reveal the length and orientation of a curvilinear structure, respectively were computed at each pixel of the magnetic image, using a Hessian matrix constructed from the second-order derivatives (I_{xx}, I_{xy}, and I_{yy}) of the image. The second-order derivative images of the Hessian matrix were convolved with Gaussian smoothing filters in order to reduce the amount of noise in the data, and to control the widths of the extracted curvilinear structures. Based on these information, we determined at each pixel of the magnetic image, if a curvilinear structure exists or not, and if exists we record its magnitude and orientation. Using a double threshold filter, we were able to extract well-defined and coherent curvilinear structures from the magnetic image. The obtained results are very interesting, and they show a set of curvilinear structures running mainly in the NW-SE direction, and to a lesser extent in the NE-SW direction. These, curvilinear structures are most likely associated with faults and fractures rooted deep in the basement rocks, and possibly with those propagated into the overlying sedimentary rocks. It is also possible that some of these curvilinear structures are linked to paleo-channels with significant concentration of magnetic minerals that could have been deposited along with heavy minerals at their bottom.

References

Andriashek, L.D., 2003, Quaternary geological setting of the Athabasca oil sands (in situ) area northeast Alberta: Alberta Energy and Utilities Board, EUB/AGS Earth Sciences Report 2002-03

Guan Xu, Sun, Lina, Li, Xiaotan, Su, Jian, Hao, Zhaobing, and Lu, Xue, 2014, Adaptable center detection of a laser line with a normalization approach using Hessian-matrix eigenvalues; Journal of the Optical Society of Korea, 18, no.4, 317-329

Law, M.W., and Chung, A.C., 2008, Three dimensional curvilinear structure detection using optimally oriented flux: in European Conference on Computer Vision (ECCV), Part IV, 368–382

Lindeberg, T., 1998, Edge detection and ridge detection with automatic scale selection: International Journal of Computer Vision, 30,117–156

McLaws, I.J., 1980, Silica sands in the Fort McMurray area, Alberta: Alberta Research Council, Economic Geology, Report 6

Moreno, R., and Smedby, O., 2015, Gradient-based enhancement of tubular structures in medical images: Medical Image Analysis, 26, no.1, 19–29

Pemberton, G.S., Mattison, B.W., Fox, A., and Ranger, M.J., 1980, Ichnology of the Lower Cretaceous McMurray Formation, Athabasca Oil Sands area: Canadian Society of Petroleum Geologists, Reserves 21

Raghupathy, K., and Parks, T., 2004, Improved curve tracing in images: IEEE International Conference on Acoustics, Speech, and Signal Processing, 2004, 3, 581-584

Rokicki, J, Matiukas, V., Usinskas, A., and Rimas, A., 2011, Extraction of centre line from curvilinear objects Opto-Electronics Review, 19, no. 1, 22-29

Sato, Y., Nakajima, S., Shiraga, N., Atsumi, H., Yoshida, S., Koller, T., Gerig, G., and Kikinis, R., 1998, 3D multi-scale line filter for segmentation and visualization of curvilinear structures in medical images: Medical Image Analysis, 2, no.2, 143–168

Steger, C., 1998, An unbiased detector of curvilinear structures: IEEE Transaction Pattern Analysis and Intelligence, 20, no.2, 113-125

Steger, C., 1996, Extracting curvilinear structures: A differential geometric approach: Fourth European Conference on Computer Vision, Springer-Verlag, 630–641

Wilson, J., 1986, Geology of the basement beneath the Athabasca Basin in Alberta: Alberta Research Council, Bulletin, no. 55, 66p.