Detection of subtle basement faults with gravity and magnetic data in the Alberta Basin, Canada: A data-use tutorial

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Exploration for a wide range of mineral deposits is critically dependent on knowledge of the location and age of fractures and faults. Oil and gas fields in many sedimentary basins are distributed along fault-controlled linear trends, and fault identification is often used effectively for target-area selection in hydrocarbon exploration. Similarly, mineral deposits in various geologic settings are commonly associated with fluid-conducting faults. In the platformal, Phanerozoic Alberta sedimentary basin in western Canada (Figure 1), two fundamentally different types of crystalline-basement structure, formed in different tectonic conditions, are recognized (Lyatsky et al., 1999):

1) Archean and Early Proterozoic (Hudsonian and older) ductile orogenic structures, and
2) Middle Proterozoic to Recent cratonic ones.

The influence of ancient ductile structures on the Alberta Basin seems largely confined to the control on Early Paleozoic depositional and drape patterns by the Precambrian erosional basement relief, which may to some extent be related to the basement lithology distribution controlled by ductile ancient structures. These structures were mostly healed and innactive during the Phanerozoic development and evolution of the Alberta Basin, and thus of limited significance to fluid migration. Their geophysical expression typically consists of large magnetic and gravity anomalies, which often obscure the potential-field signatures of the desirable brittle faults.

The steep, brittle basement faults in the western Canadian platforms and Cordilleran foreland, although much more subtle than their spectacular counterparts in western United States, exerted considerable syn- and postdepositional influence on the Phanerozoic sedimentary cover.

Occasionally, brittle faults and fractures follow the older orogenic basement structures, but commonly cut across them. Even when subresolution seismically, many brittle faults appear to have controlled basin sedimentation and diagenesis. The control was partial, episodic, variable, and sometimes even passive and indirect, such as where zero-offset fractures affected fluid flow, salt dissolution and carbonate alteration. Steep, straight faults in the Alberta Basin are commonly expressed as subtle potential-field lineaments, which can be gradient zones, alignments of separate local anomalies of various types and shapes, aligned breaks or discontinuities in the anomaly pattern, and so on. These are the desirable faults in exploration.

To refine the techniques of detecting basement faults and to assist exploration, the Alberta Energy & Utilities Board/Alberta Geological Survey, and Lyatsky Geoscience Research & Consuting have created a gravity and magnetic atlas of northern Alberta, with the data processed to highlight subtle lineaments (Lyatsky and Pana, 2003). Building on the format and experience of the Canadian Geophysical Atlas (Geological Survey of Canada, 1990) and on previous interpretation work in northeastern Alberta (Sprenke et al., 1986), our new atlas is intended for a broad spectrum of geologists, geophysicists, interpreters, processors, instructors and students. It contains 34 text-annotated gravity and magnetic maps, a regional geologic map, and an interpretive note. Written as a tutorial, from first principles and in accessible terms, the atlas explains the data-processing steps taken to highlight geophysical anomalies, in particular those that may be related to brittle faults.

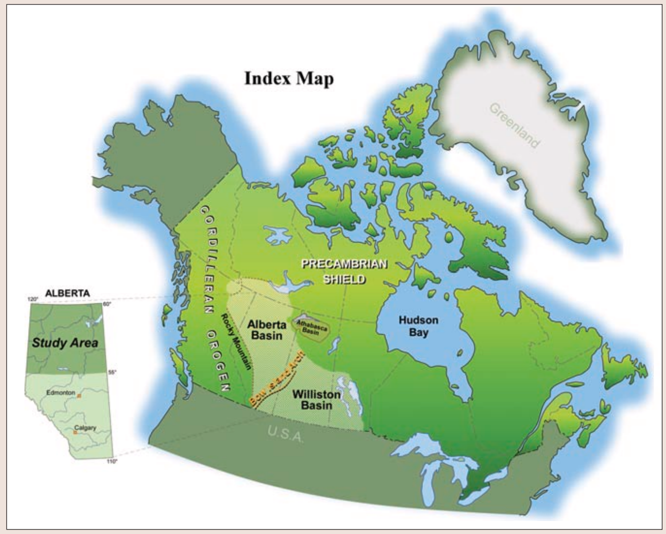

Figure 1. Location of the northern Alberta study area in relation to main regional geologic features.

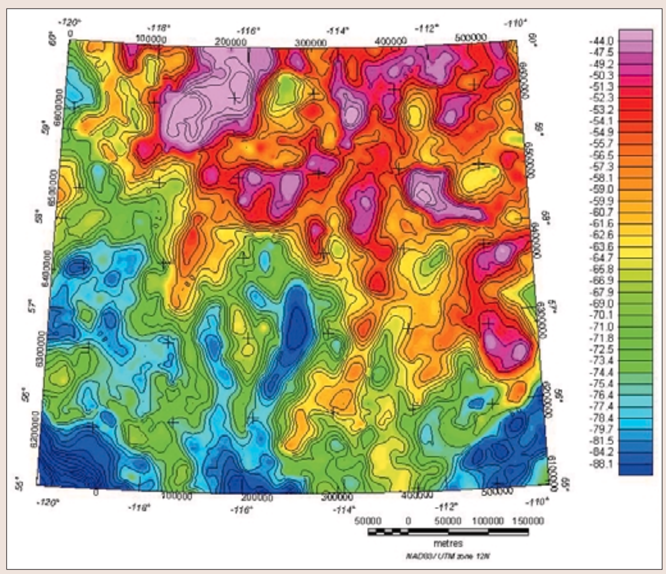

Figure 2. Bouguer gravity anomaly map of northern Alberta, in mGals. Contours, in addition to colors, sharpen the visual definition of anomaly shapes.

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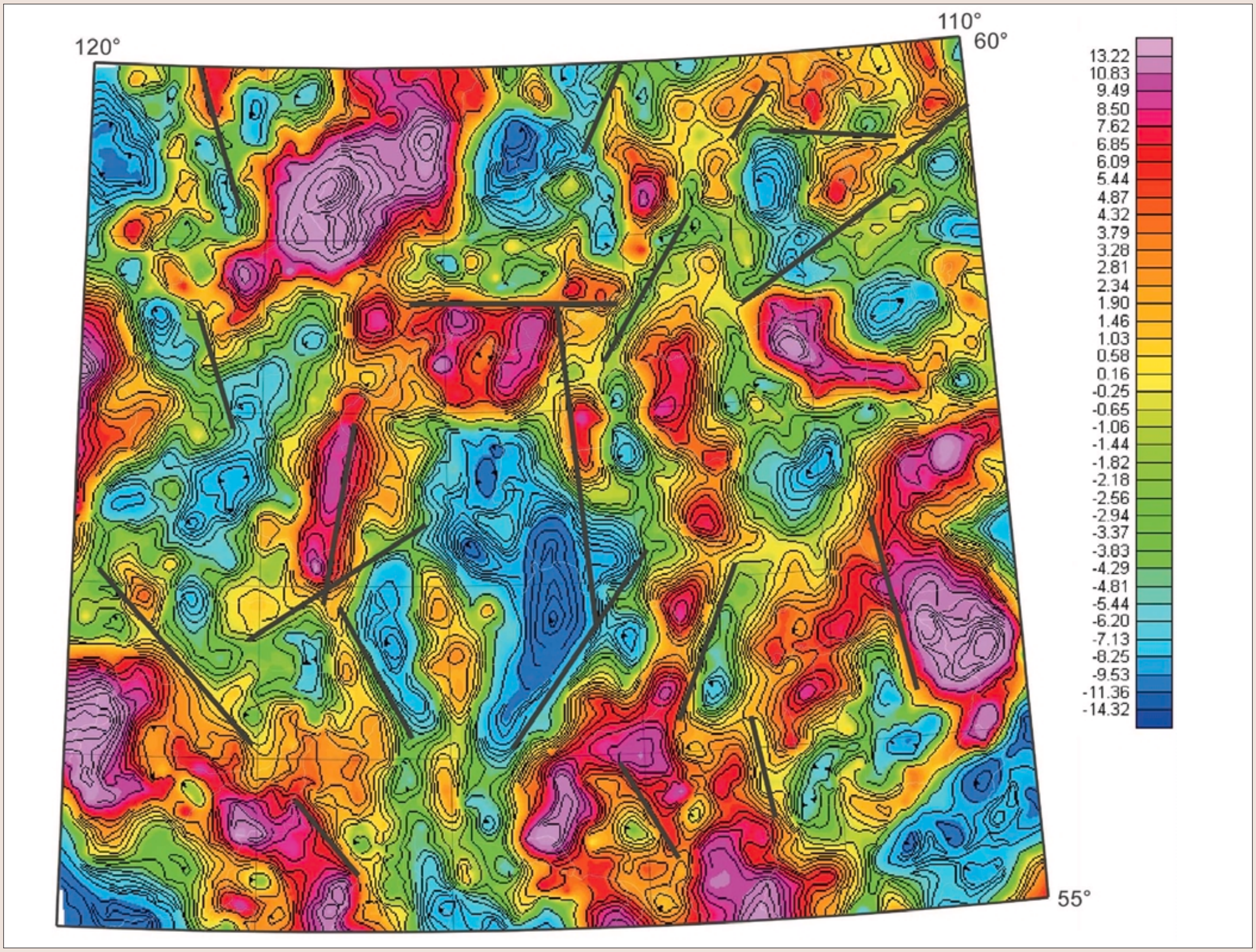

Figure 3. Bouguer gravity anomaly map of northern Alberta with regional component (third-order trend) removed, in mGals. Dark lines are regional lineaments interpreted from this map.

Objectives of data processing. Subtle potential-field signatures of brittle faults and fractures necessitate detailed data processing, using a wide variety of anomaly-enhancement techniques and display parameters. Which methods will produce the most geologically meaningful results is often hard to know in advance. The final choice of processing and display options depends on which types and aspects of anomalies one aims to enhance, as well as on extensive experimentation.

Neither a panacea nor a self-purpose, data processing is a necessary evil. Because the signal and noise anomaly characteristics commonly overlap, complete separation between them may be impossible. Noise artifacts may actually be introduced. Unexpected consequences and processing side effects are normal. As well, it may be hard to predict in advance which of the many anomalies are desirable.

Best processing is guided by the specific objective to enhance anomalies of a particular sort, related to the geologic targets of interest. The processed and enhanced anomalies should ideally be easy to relate back to the original anomaly shapes. We kept the processing to a minimum, avoided ill-described "black-box" techniques and complicated mathematics, and instead relied on simple and intuitive procedures. The Geosoft processing software was used.

Low-cost database. For all the popularity of costly "high-resolution" surveys, many basement features in Alberta are detectable with extremely low-cost gravity and magnetic data already in the public domain. As well, while aeromagnetic data are deservedly popular in the oil industry, gravity data are often underappreciated but nonetheless very useful for fault detection.

The public-domain Bouguer gravity data (Figures 2-6) were supplied by the Geological Survey of Canada (GSC). From exploration experience, gravity data in the Alberta and Williston basins are sensitive to local vertical offsets across high-angle faults, where rocks with different densities are juxtaposed. Yet, high densities in some Paleozoic sedimentary rocks just above the basement may smear out the subtle gravity signatures of basement faults, and so can the sparse data coverage. Notably, in the Peace River Arch in northwestern Alberta, where vertical basement-fault offsets reach tens and hundreds of meters, the associated gravity anomalies are not strong.

The total-field magnetic data (Figures 7-13) were also supplied by the GSC, with the International Geomagnetic Reference Field removed. The sedimentary cover in Alberta is generally considered almost nonmagnetic, and the anomalies are sourced overwhelmingly in the crystalline basement. Local intrasedimentary anomaly sources may be related to depositional concentrations of magnetic minerals in some clastic rocks, or to secondary magnetization of sedimentary rocks by circulating brines. At the surface, glacial erratics, river valleys and man-made infrastructure may also cause anomalies.

Gravity and magnetic data in northern Alberta were compiled by the GSC from surveys recorded at different

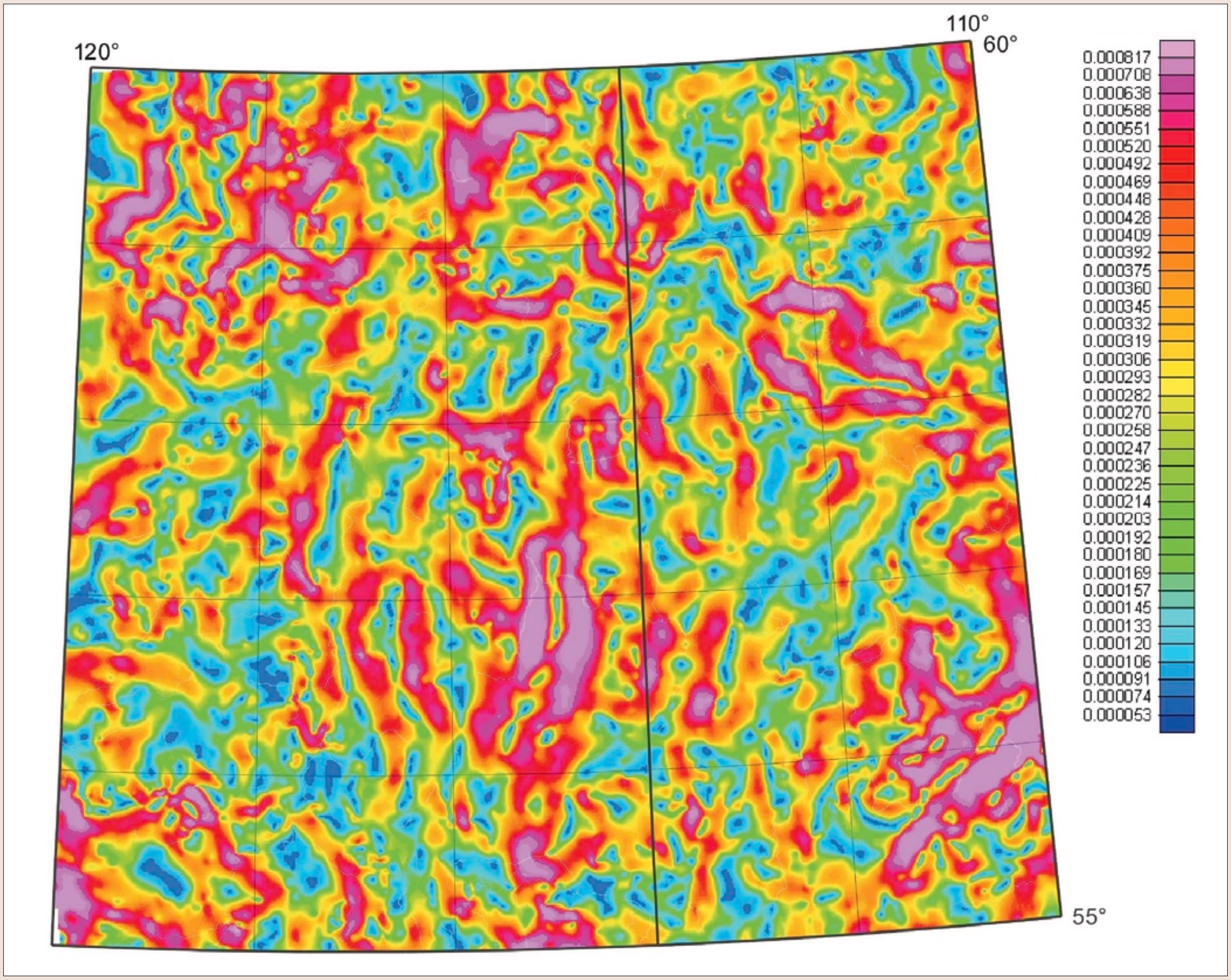

Figure 4. *Horizontal-gradient Bouguer gravity anomaly map of northern Alberta, in mGals/m.*

times, sometimes with different parameters, technologies and specifications. The GSC gravity-data standard of one station per 10 km is usually not maintained in remote areas of northern Alberta, but even in sparse data, long lineaments are detectable with careful anomaly enhancement. Detailed, good-quality regional aeromagnetic data are available from the GSC in northeastern Alberta, with flight-line spacing generally in the hundreds of meters.

Bouguer gravity values decline gradually to the southwest as the Alberta Basin deepens. Because the depth to magnetic sources increases with basement depth, the shortest-wavelength magnetic anomalies are found in northeastern Alberta, where the basement is at shallow or zero depth.

Data preparation. Gridding of the data had to be tight enough to capture the anomaly details where the data were recorded at a close spacing, without needlessly creating enormous data files. For the gravity data, optimal grid-cell size was chosen to be 1000 m; it was 400 m for the magnetic data.

Short-wavelength noise in the data, such as gridding artifacts, cultural noise, undersampled anomalies or flight-line corrugation, may interfere with geologically meaningful lineaments, and it is boosted when the subtle and short-wavelength anomalies are enhanced. This noise should be suppressed before processing, albeit at a price of sacrificing some useful anomaly information. Band-pass wavelength filtering requires assuming the cut-off wavelengths, can smear the anomaly separation due to nonvertical filter roll-off, and can contaminate the data by Gibbs ringing. Noise suppression can also be achieved by slightly upward continuing the data, or with smoothing convolution filters. By experimentation, small upward continuation (usually by one cell size) was found to be the most effective for the gravity data in the study area, and two passes of the Hanning convolution filter for the magnetic data.

Utility of processing steps. Horizontal-gradient maps (Figure 4) are vivid, simple and very intuitive derivative products to reveal the anomaly texture and to highlight anomaly-pattern discontinuities. These maps contour the steepness of the anomaly relief's slope. Horizontal-gradient maxima occur over the steepest parts of potential-field anomalies, and minima over the flattest parts. Short-wavelength anomalies are enhanced.

Vertical-derivative (vertical-gradient) maps (Figure 9) accentuate short-wavelength components of the anomaly field, while de-emphasizing long-wavelength components. The vertical gradient can be thought of as the rate of change of anomaly values as the potential-field data are upward continued (indeed, vertical derivative used to be simulated by some users by taking the difference between existing and slightly upward-continued data). Such maps are not intu-

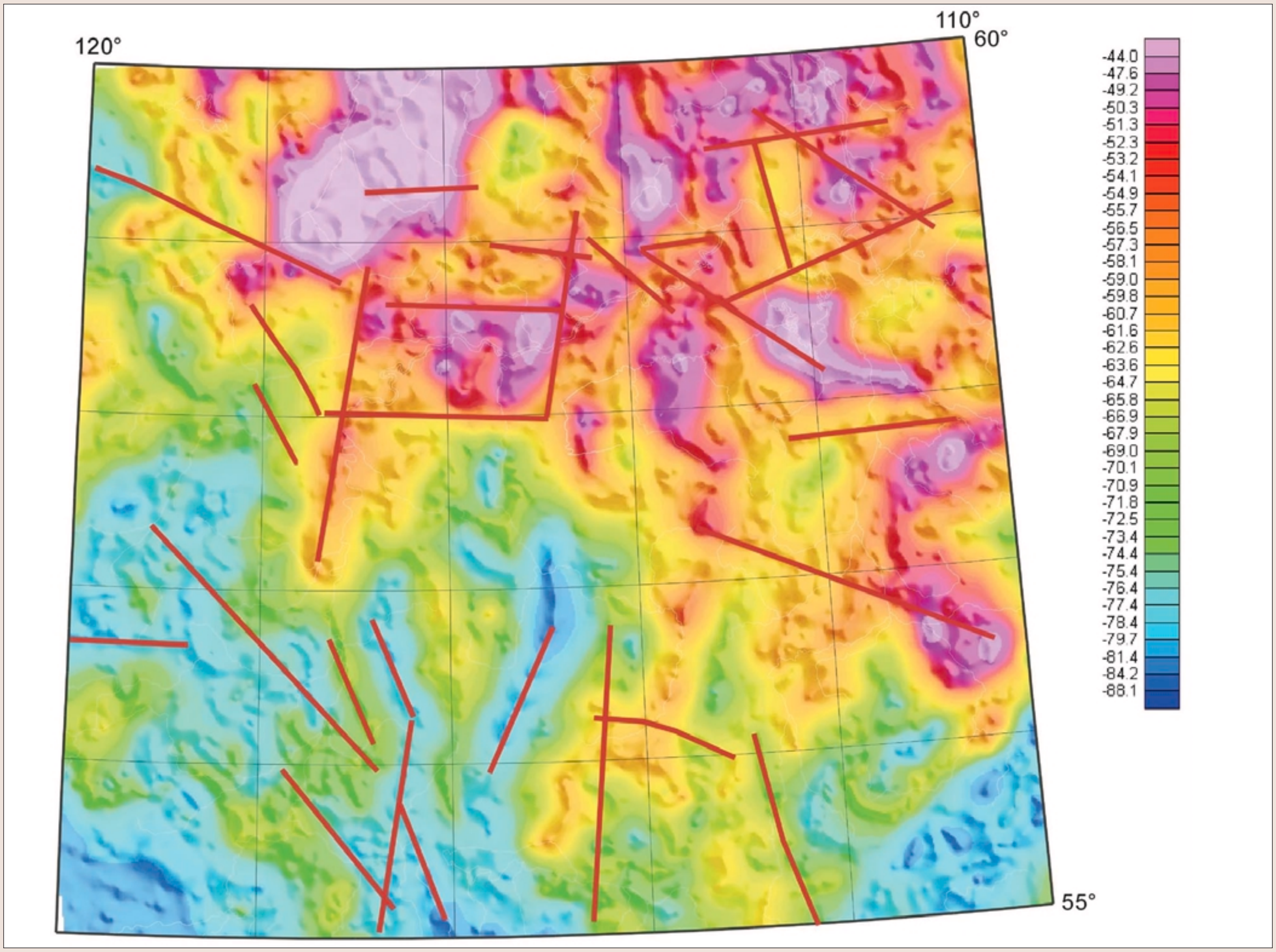

Figure 5. *Bouguer gravity anomaly map of northern Alberta in mGals, with superimposed vertical-illumination shaded-relief map. Red lines are regional lineaments interpreted from this map.*

itive, and they may be harder than horizontal-gradient maps to relate to the original anomaly shapes. Still, vertical-gradient maps help highlight the details, discontinuities and breaks in the anomaly texture. The vertical-gradient procedure was found to be effective in northern Alberta for enhancement of magnetic anomalies. The gravity data, however, were too sparse to greatly benefit from such processing, which boosted gridding artifacts.

Total-gradient (or analytic-signal) maps (Figure 10) help to reveal the anomaly texture and highlight discontinuities. Short-wavelength anomalies are enhanced. Total-gradient maps are mathematically analogous to horizontal-gradient ones, but less intuitive because they incorporate the vertical derivative. Yet, analytic-signal maps are often effective at highlighting geologically meaningful subtle and local anomalies.

To highlight the local anomaly details, automatic gain control (AGC) boosts amplitudes in areas with smooth anomalies (Figure 8), without sacrificing the long-wavelength information. Gain is estimated with a sliding square filter window, centered on each grid node in turn. Experimentation determines the optimal window size for each data set. A maximum gain correction is specified to prevent the procedure from blowing up in the areas of low signal. Local (as opposed to regional) AGC was found experimentally to be effective for the magnetic data in the study area, but the gravity data were too sparse and lacking short-wavelength components. Inside the filter window centered at each position, the best-fit plane is calculated, which minimizes the rms (root-mean-square) misfit with the data. The average rms difference between the data and plane values within the window is the local signal gain. Signal at the grid node in the center of the window is the difference between the data value and the plane value at that position. The first pass over the grid determines the signal and gain for each position, and records the largest (maximum) gain encountered. In the second pass, the signal at each position is multiplied by the ratio of maximum to local gain, not exceeding the specified maximum correction. The gained signal is then added to the original background value to obtain the final signal value.

To highlight local anomalies, the regional component of the gravity or magnetic anomaly field is commonly subtracted from the data, generating a residual map. The definition of regional versus local anomalies is subjective. Regional-local separation can be achieved by band-pass wavelength filtering, but that procedure suffers from limitations noted above. More intuitive is to compute from the gridded data the best-fit smooth surface, of an optimal low order, and then remove that smooth surface as the regional component. Good results in the Alberta and Williston basins are obtained by subtracting from the data a third-order best-fit surface. Gravity-anomaly definition was helped by this procedure (Figure 3), but no significant improvement resulted for the already "crowded" magnetic maps.

Shadowgrams (Figures 5-6 and 11-13) reveal variations in the dominant anomaly texture, wavelengths and trends between regions. This simple procedure treats a potential-

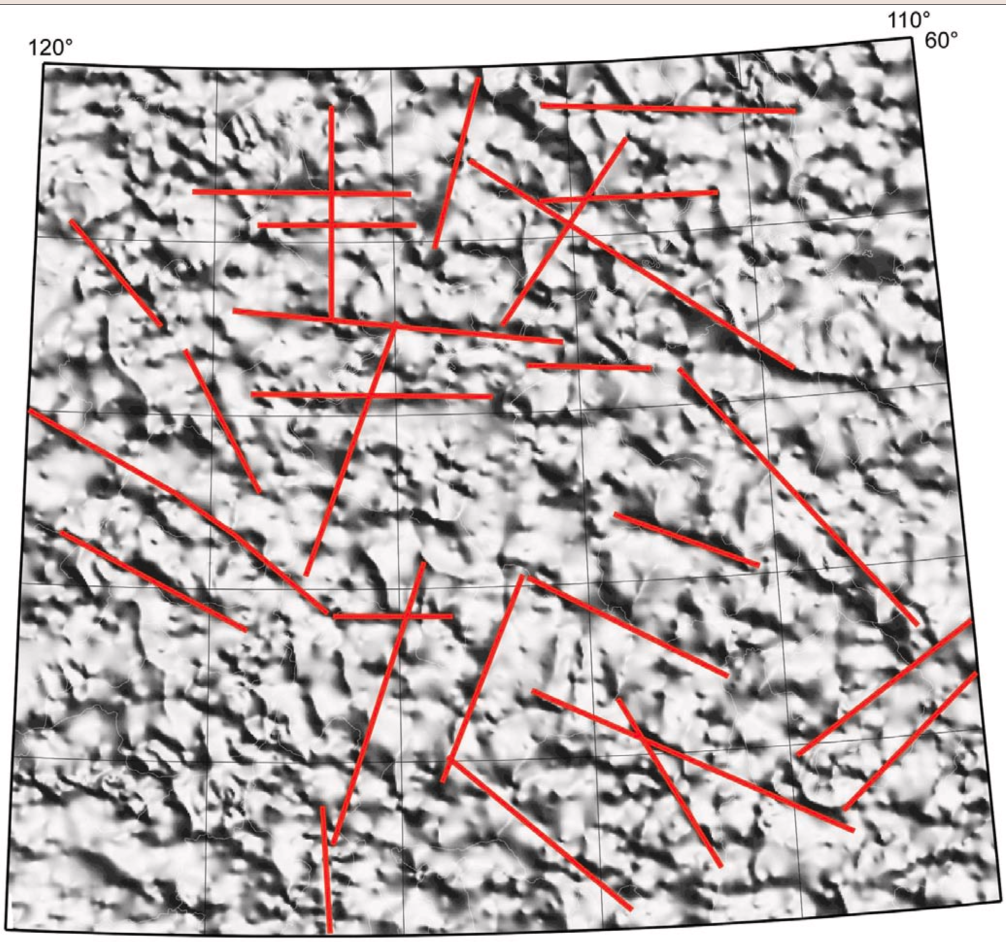

Figure 6. Shaded-relief Bouguer gravity anomaly map of northern Alberta, illuminated from the north. Red lines are regional lineaments interpreted from this map.

field map as a relief, and computes the shadow pattern that would be created if this relief were illuminated by the sun from a user-specified angle. Subtle, local and short-wavelength anomalies are emphasized. Sidelighting (nonvertical illumination) acts as a directional filter, but directional bias is avoided in shadowgrams computed with a vertical sun angle, where the resulting vertical shadowgrams simulate horizontal-gradient maps.

Vertical shadowgrams and horizontal-gradient maps are comparable and complementary, but not identical. These computational procedures are dissimilar in their nature, treatment of the data, and map display, and the differences in results are greatest with sparse data.

Sidelighting enhances anomalies non-parallel to the "sun" azimuth, and many shadowgrams with various sun angles were needed to reveal variously oriented anomalies. The optimal "sun" inclination for the gravity data was found experimentally to be 45° from the horizon, and 30° for the magnetic data. Sweeps of shadowgrams were generated for the gravity and magnetic data, with the "sun" illumination from the north, northeast, east, southeast, south, southwest, west, and northwest.

The large-scale regional anomaly pattern is revealed by upward continuation. This procedure uses wavelength filtering to simulate the appearance of potential-field maps if the data were recorded at a higher altitude. Short-wavelength anomalies are suppressed preferentially. Upward continuation is intuitive, as it is easy to understand while avoiding the band-pass filtering pitfalls. The bulk structure of the continental upper crust (where the brittle faults reside, above the brittle-ductile transition) is often revealed by upward continuing potential-field data to around 20 km. Because the gravity data in northern Alberta are sparse and have a diminished short-

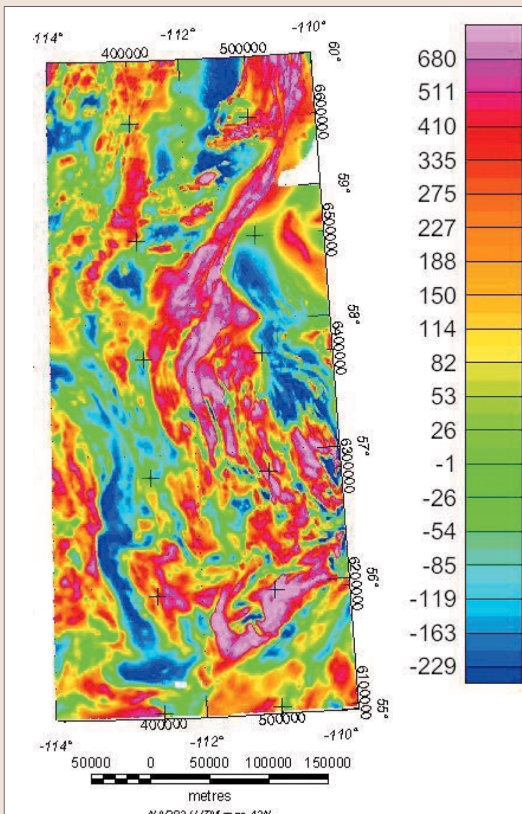

Figure 7. Total-field aeromagnetic anomaly map of northeastern Alberta, in nT. The magnetic map area covers the eastern part of the gravity map area.

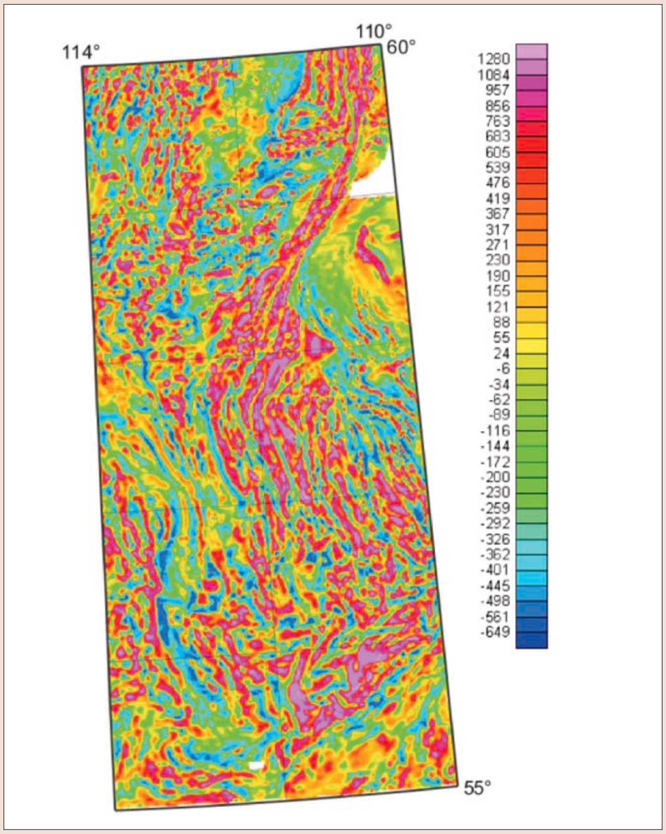

Figure 8. *Total-field aeromagnetic map of northeastern Alberta with automatic gain control, in nT.*

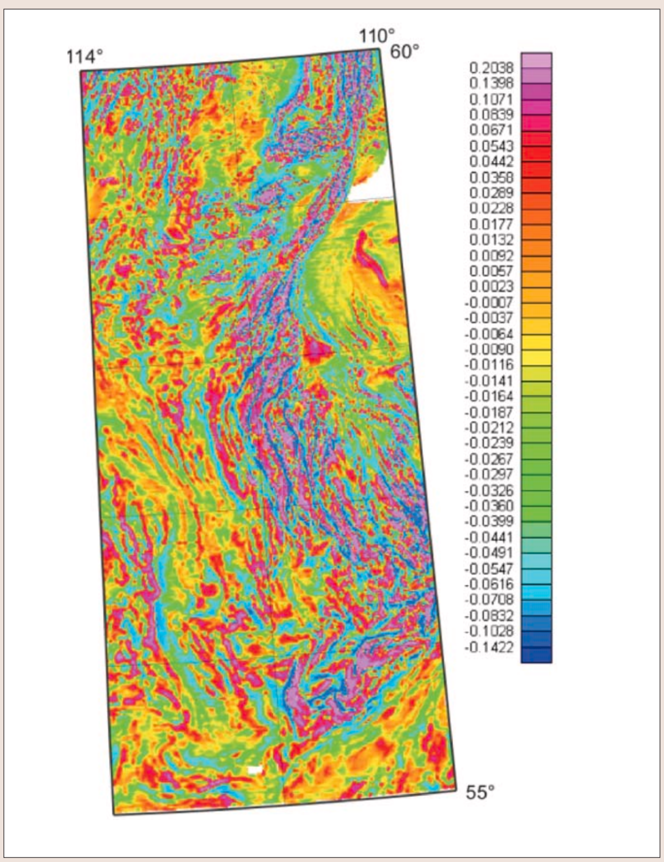

Figure 9. *Vertical-gradient aeromagnetic anomaly map of northeastern Alberta, in nT/m.*

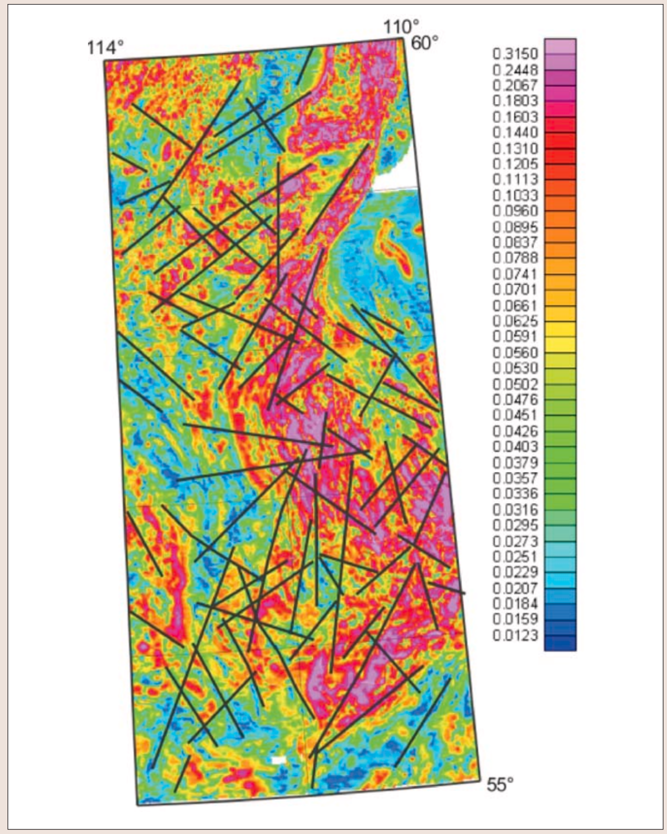

Figure 10. *Total-gradient (analytic-signal) aeromagnetic anomaly map of northeastern Alberta, in nT/m. Dark lines are regional lineaments interpreted from this map.*

Figure 11. *Vertical-illumination shaded-relief aeromagnetic anomaly map of northeastern Alberta. Red lines are regional lineaments interpreted from this map.*

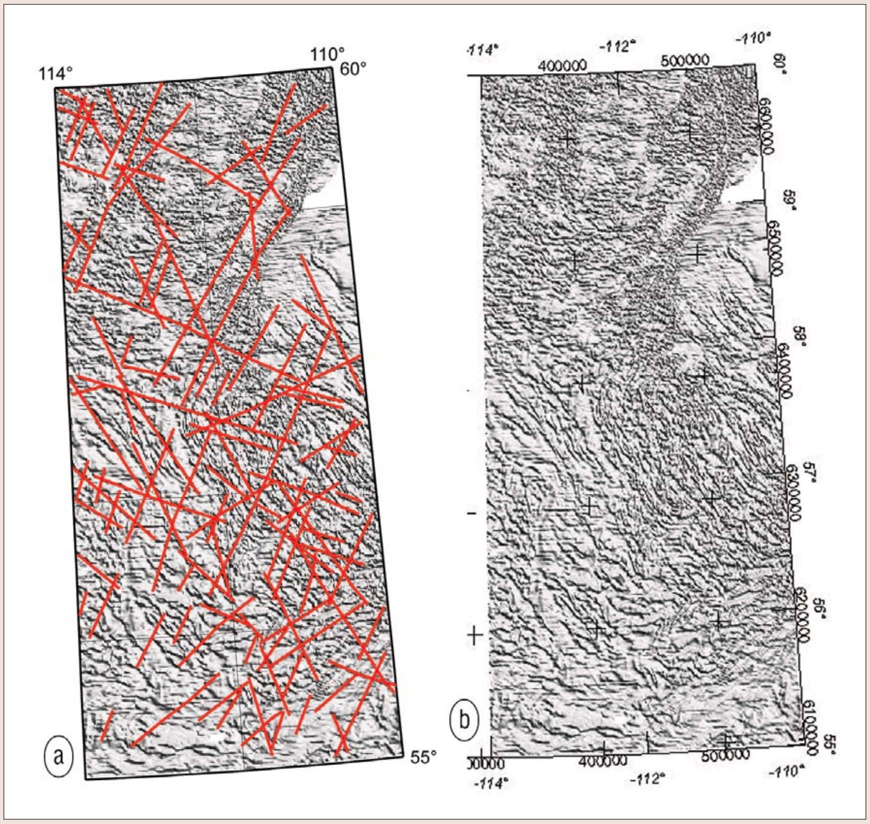

Figure 12. (a) and (b) Shaded-relief aeromagnetic anomaly map of northeastern Alberta, illuminated from the north. Red lines in (a) are regional lineaments interpreted from this map.

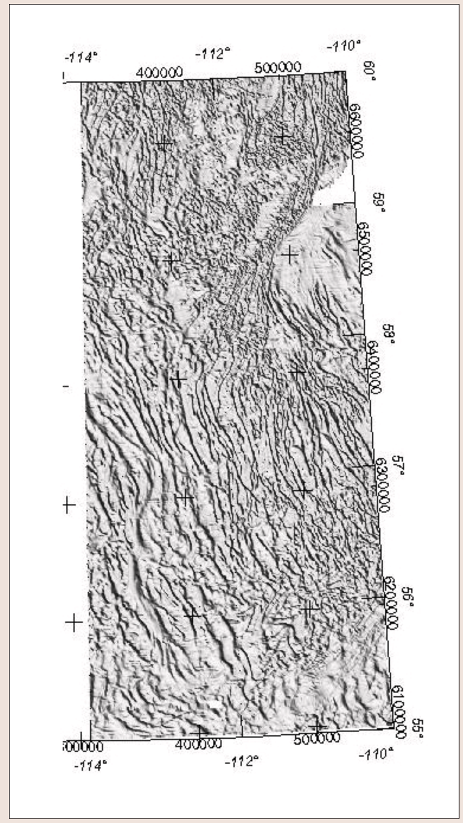

Figure 13. Shaded-relief aeromagnetic anomaly map of northeastern Alberta, illuminated from the west.

wavelength component to begin with, best results were obtained with upward continuation to only 15 km. A 20-km nominal altitude was found to be effective with the magnetic data.

Comparing upward-continued and raw data shows which of the anomalies survive the filtering, and thus can be inferred to probably have big rock sources. Principal orientation of geologic features in the crust is revealed by the orientation of potential-field anomalies in upward-continued maps.

Lineament detection. Visual identification of lineaments is the most reliable when done by an experienced interpreter familiar with both the geologic targets and the local specifics of the anomaly field. Automatic anomaly-identification techniques rely on advance parameterization of desirable anomalies that may be too rigid and assumption-based to generate the most geologically meaningful anomaly picks.

A good visual method to identify subtle lineaments is to view maps at a low angle on a table. Rotating the map on the table, to change the interpreter's viewing direction, reveals features with various orientations. Viewing a map from above helps to see the distribution of anomaly patterns and domains. Particularly interesting are aligned slight disruptions of an otherwise consistent anomaly field. Because brittle faults commonly cut through the ancient ductile basement structures without causing significant offsets, such razor-sharp but extremely subtle disruptions of the anomaly pattern are a prime target for interpretation.

More vivid discontinuities, across which the overall anomaly pattern noticeably changes, may be related to the ancient ductile structures, but sometimes younger brittle structures are aligned with old ductile ones. Linear potential-field features that run for hundreds of kilometers commonly represent major crustal shear zones and faults. The potential-field manifestation of a fault may vary along its trend, depending on the local geology, so alignments of discontinuous, multiple local anomalies are of interest.

Geologic significance of potential-field lineaments is confirmed by comparisons with the known geology of the ground surface, the basement and the sedimentary cover, as well as with topographic lineaments.

Suggested reading. *Canadian Geophysical Atlas* (Geological Survey of Canada, 1990). *Principles of Practical Tectonic Analysis of Cratonic Regions* by Lyatsky et al. (Springer-Verlag, 1999). *Catalogue of Selected Regional Gravity and Magnetic Maps of Northern Alberta* by Lyatsky and Pana (Alberta Energy & Utilities Board/Alberta Geological Survey, Special Report 56, 2003). *Geophysical Expression of the Canadian Shield in Northeastern Alberta* by Sprenke et al. (Alberta Geological Survey, Bulletin 52, 1986). TLE

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