How Basement Lithology Changes Affect Magnetic Interpretation

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Many people are intimidated by the magnetic method, but they are quite willing to attack gravity interpretation. This is usually a result of the inclination/declination issues with magnetics, and the fact that most people view a gravity map as a structural map. Magnetic maps are not structural maps; they are a contoured representation of magnetization changes in the geology. This is harder for people to "visualize" in terms of real rocks and structure. Gravity interpretation *seems* easier because a gravity high usually correlates with a structural high (except in the case of salt), but simple criteria such as that can cause problems if the interpreter is not careful.

On the other hand, some aspects of the magnetic method are quite straightforward. One is the direct mathematical relationship between anomaly wavelength and source depth. Another important relationship is that basement lithology changes typically have amplitudes of hundreds of nanotesla (nT), but structural changes usually cause anomalies of only tens of nT (see Gibson's magnetic susceptibility versus structure illustration later in this volume).

It is also important to note that, depending on magnetic inclination, a fault and a lithology change can have distinctly different magnetic signatures. One might cause a symmetrical anomaly while the other causes an asymmetrical anomaly. This underscores the importance of preliminary models prior to undertaking any gravity or magnetic interpretation.

There is a common misconception about magnetics: If there are rock-type changes in basement, then magnetics cannot tell anything about basement structures. *This statement is false.*

Magnetic anomalies are a result of two things:

1) a lateral contrast in rock structure or
2) a lateral contrast in rock composition

If there is no lateral contrast, the magnetic field is flat. Consider a very simple, straight-sided graben filled with nonmagnetic sediments (Figure 1). All of the basement rocks are the same susceptibility. You will get a magnetic anomaly at each edge of the basin. Since there is a direct, mathematical correlation between anomaly wavelength and depth, you can calculate the depth to the contrast. That would be to the *top* edge on either side of the basin.

This is not very satisfying to the explorationist, however, because he is interested primarily in the thickness of the sedimentary section or whether there is a structural trap within the basin. But if basement changed susceptibility (Figure 2), an anomaly would exist with a wavelength that is a function of the depth to the *top* of the contrast (top basement). Now the interpreter has three depth points, two at the edges and one on the basin floor. If these depths are contoured up with knowledge of the expected structural style (a rift, for example), the geologist gets a very simple picture of the basin. In fact, the basement rock change has helped rather than hindered the interpretation.

Visual inspection of maps must be accompanied by some visual and quantitative *analysis*! Linear trends or breaks in trends will correlate either with lithology changes or structure (faults). After a few correlations with known (and expected) geology, the interpreter can make depth calculations. Anomalies of similar wavelength in an area give depth information for that area. If there are strong anomalies, probably related to basement lithology changes, and their areal distribution shows changes in wavelength, then the basement is changing in depth. This is quick analysis rather than a quick glance.

Scenario

Well-intentioned explorationist (E): "But the magnetic map showed a low in our area of interest, so that means there's sedimentary section rather than basement, right? Why did we hit basement?"

Gravity/magnetics specialist (GMS): "It means that your area of interest is lower susceptibility than the surrounding area, not necessarily sedimentary. Does that linearity to the low make any sense with the regional tectonics?"

E: "Not really . . . but you know magnetics . . . it could be a basement rock change."

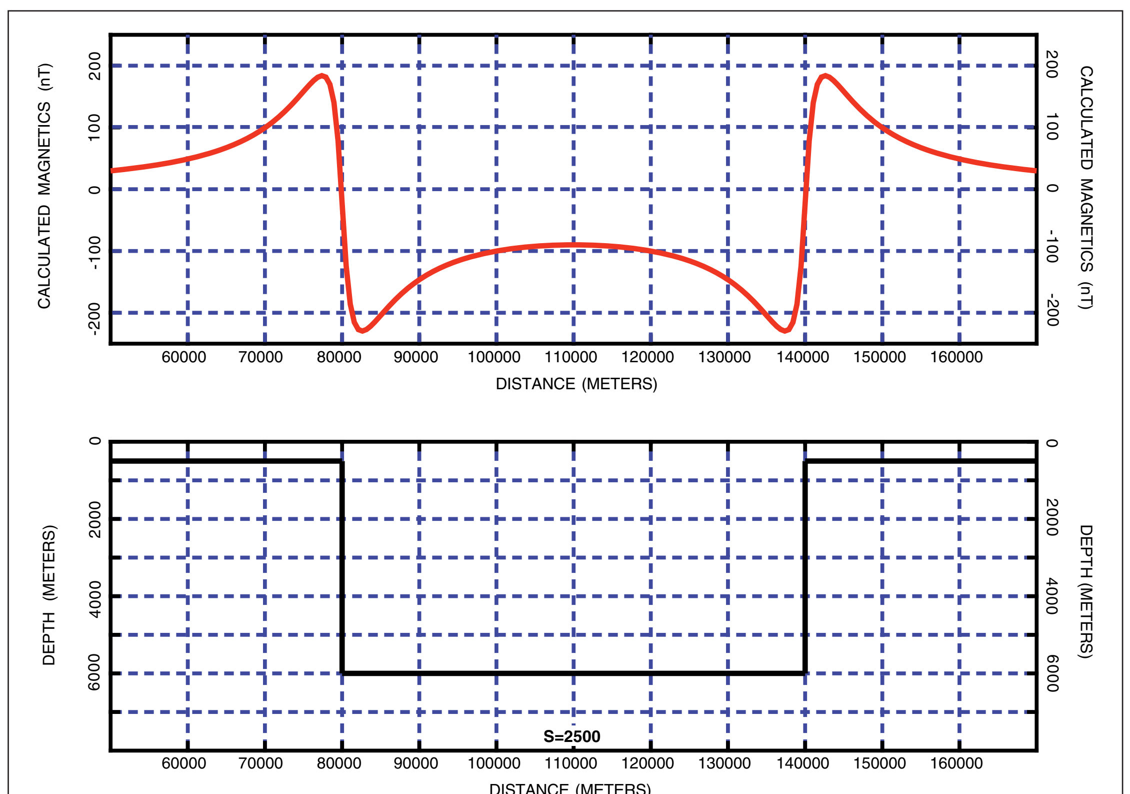

Figure 1. *A 2-D magnetic model of an extremely simplified, straight-sided graben filled with nonmagnetic sediments. The single basement polygon has a susceptibility of 2500 micro-cgs. Magnetic anomalies are caused by the "shoulders" of the basin. Depth estimates would give depth information at about 500 m ± 10% for the shoulders only.*

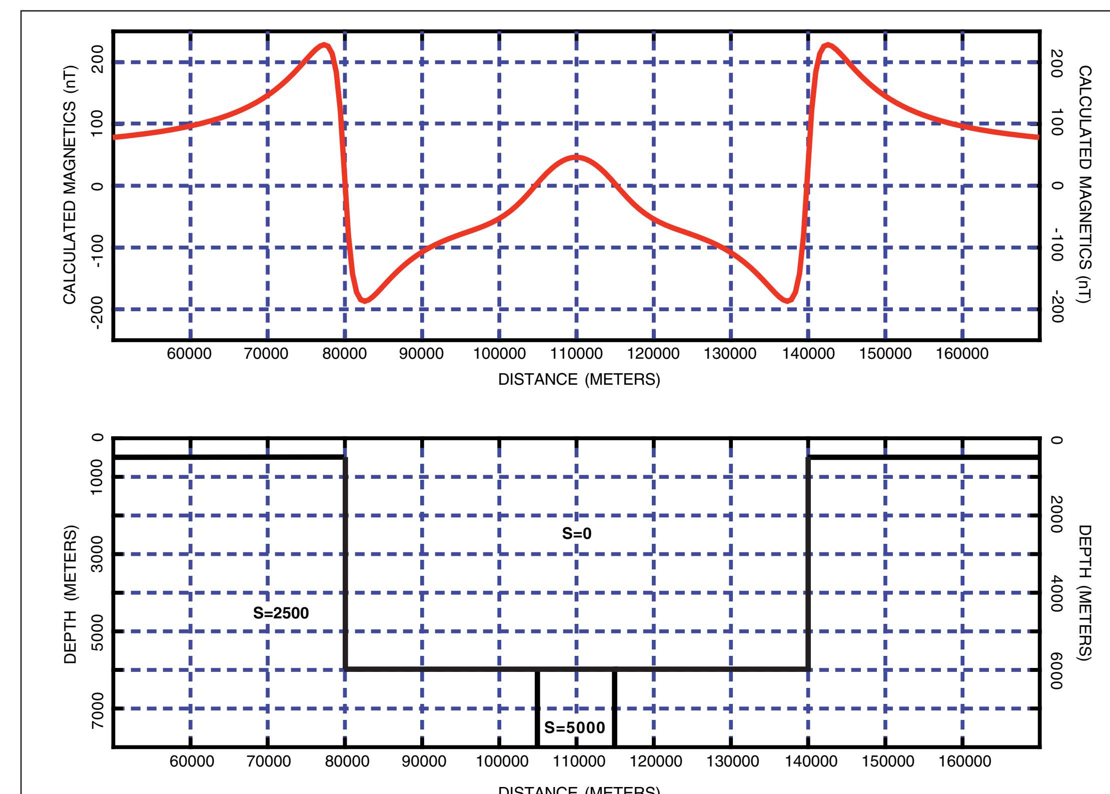

Figure 2. *The same simple model from Figure 1 with a basement susceptibility change of 5000 micro-cgs (2500 micro-cgs contrast) included in the center of the basin. A third magnetic anomaly (this time symmetrical) is created. Depth estimation would give depths for the shoulders as well as about 6000 m ± 10% in the center of the basin.*

GMS: "My point exactly. Did you do any depth work on the edges of the low?"

E: "Yes, an interpretation came with the data [digs it out of a file at the bottom of a pile of seismic sections]. It says 4000 ft."

GMS: "At what depth did the well penetrate granite?"

E: "3900 ft, but that's way over there. . . ."

GMS: "Magnetics are telling you that you have two edges at about 4000 ft within a few miles on either side of your prospect. You have a linear low-susceptibility zone . . . could be sedimentary, could be low-susceptibility igneous . . . at about 4000 feet . . . that doesn't make any sense with your seismic interpretation. Inspection of the magnetic map shows that all the anomalies are roughly the same wavelength across your area of interest . . . high versus low is immaterial; the magnetics were trying to tell us something. . . ."

Moral: Sometimes, just having the data is not enough, and just looking at it is not enough, either. You also must *analyze* the data. How much analysis depends on the geologic problem, the staffing levels, and the time available for interpretation.

The Concept of Continuation

Magnetic anomalies (on profiles or maps) become broader (longer wavelength) as the distance between the geologic source and the magnetometer increases. This concept of "continuation" is key to the interpretation of magnetic data. As L. L. Nettleton put it in his classic 1976 text:

. . . it is usually possible by simple inspection of a magnetic map over a broad area covering a wide range of depths to separate the map into areas of shallow, intermediate, and large basement depth by noting the areas of sharp, intermediate, and broad magnetic anomalies. . . . The whole process of basement-depth determination depends on devising quantitative measurements of this relationship of sharpness to depth.

Basement Rocks

From Nettleton (1976), 369–370:

. . . actual basement rocks may be compared with a mildly stirred-up matrix of components with varying magnetite content. The condition may be generally likened to an old-fashioned marble cake with dark and light batter lightly stirred together and covered with frosting. The two colors of batter correspond to basement materials with relatively high and low magnetite concentrations and the frosting to the overlying sediments.

Such concepts would seem to make numerical calculations from geometric models not very relevant. This is not true, however, apparently because at depths comparable with the horizontal dimensions of [the] units . . . effects from bodies with irregular boundaries are effectively simulated by models with simple geometric forms. Therefore calculated effects from simple models can be very useful in understanding the magnetic effects observed in nature.

Magnetic susceptibility is a measure of how susceptible the rock material is to being "magnetized" by the Earth's magnetic field (induced magnetization). This is also a measure of the amount of magnetite (or other minor magnetic minerals) in the rocks. Susceptibility is a dimensionless unit, expressed in SI or cgs units. Journals prefer the more formal SI units, while practitioners and most software vendors use micro-cgs (cgs × 10^{-6}) units for modeling. The following comments use micro-cgs units.

An "average" granite contains about 1% magnetite, which equates to about 2500 micro-cgs units. For comparison, the following table gives a simplistic rule of thumb for rock susceptibilities:

	(cgs × 10^{-6})
Sedimentary rocks	0–600
Acidic basement rocks	600–5000
Volcanics, mafic rocks	3000–10 000
Pure magnetite	30 000

On a few occasions in this author's twenty-two years of magnetic interpretation, real measurements from basement outcrop or cores were available for modeling purposes. It was impossible to use the actual measured susceptibilities to model geologic structure. This is probably because outcrops are weathered and magnetite oxidizes fairly easily, losing magnetization. Published accounts of basement from oil fields in the Gulf of Suez, for example, document wells encountering tens of meters of "fractured, weathered granite" over "fresh granite." The good news in this story is that the susceptibility values required for modeling varied within the range expected of the rock type, and the susceptibility *contrasts* between adjacent units were definitely comparable to the measured *contrasts.*

It is impossible to perfectly decipher the "marble cake" of basement susceptibilities. Try to think of the "simple geometric forms" in magnetic models as averaged zones of magnetite content. If shapes remain simple and comparable in a suite of models, then conclusions are possible. Keep the susceptibilities in the accepted range of rock materials; it is probably more nearly correct, and it will be easier to "sell" to management.

Basement Continuation Example

Figure 3 shows a geologic map of Quebec, over part of the Canadian Shield (latitude 55–60°N, longitude 70–75°W). There is no structural development here, only outcropping basement rocks. The map represents the area with a single pink color and describes "undifferentiated granitic basement." Another geologic map (Figure 4) shows more detail and describes "mostly granites, syenites, monzonites, diorites and their gneissic equivalents." Topographic relief is minimal, a few hundred meters, or essentially flat for the purpose of this discussion.

Figure 5 is a total-magnetic-intensity anomaly map from the public-domain compilation for the Decade of North American Geology (DNAG). The contour interval is 500 nT. The color interval on this and all the figures in this paper is the gravity/magnetic convention of purples, blues, and greens for the magnetic minima, and yellows, oranges, and reds for the magnetic maxima. The magnetic anomalies average about 1500 nT over this area. A visual comparison of Figures 4 and 5 shows a striking similarity in trends. Even some of the interpreted fault/fracture trends are clear in the magnetic map.

An upward continuation of 6000 m was applied to the total-intensity data (Figure 6), showing how the data would appear if the magnetometer was 6000 m above basement. The contour interval is 500 nT, the same as in Figure 5. The 6000-m (about 20 000-ft) continuation distance was chosen to simulate the depth of a sedimentary basin. Hence, if the granitic rocks of the Canadian Shield were buried under 6000 m of nonmagnetic sediment and there were no structures on the basin floor, then the magnetic map would look like Figure 6. The magnetic relief has diminished from 1500 nT to about 800 nT, the major lithologic trends are still visible, but the wavelengths have broadened (smoothed).

The same upward-continued map is displayed in Figure 7 with a 100-nT contour interval, to give a better representation of individual anomalies. The wavelengths across the map are roughly equivalent, and calculations would provide depths of about 6000 m for this hypothetical flat-bottomed basin.

If structural changes were imposed on this susceptibility regime, anomaly wavelengths would differ across the map, and depth estimation would provide varying depths that could be contoured as a map of structural (magnetic) basement. This is illustrated more easily in profile view (Figures 8 and 9).

Figure 8 is a cross-section model through the study area. Basement lithology changes have been "simulated by modeling simple geometric forms" (after Nettleton, 1976). Because this is to illustrate a point, the curve fitting between the observed and calculated fields is only approximate. In Figure 9, structure (a straight-sided, 6000-m-deep "basin") has been introduced to the same susceptibility scheme. Note the difference in anomaly wavelengths on the shoulders of the "rift" versus the deeper basin center.

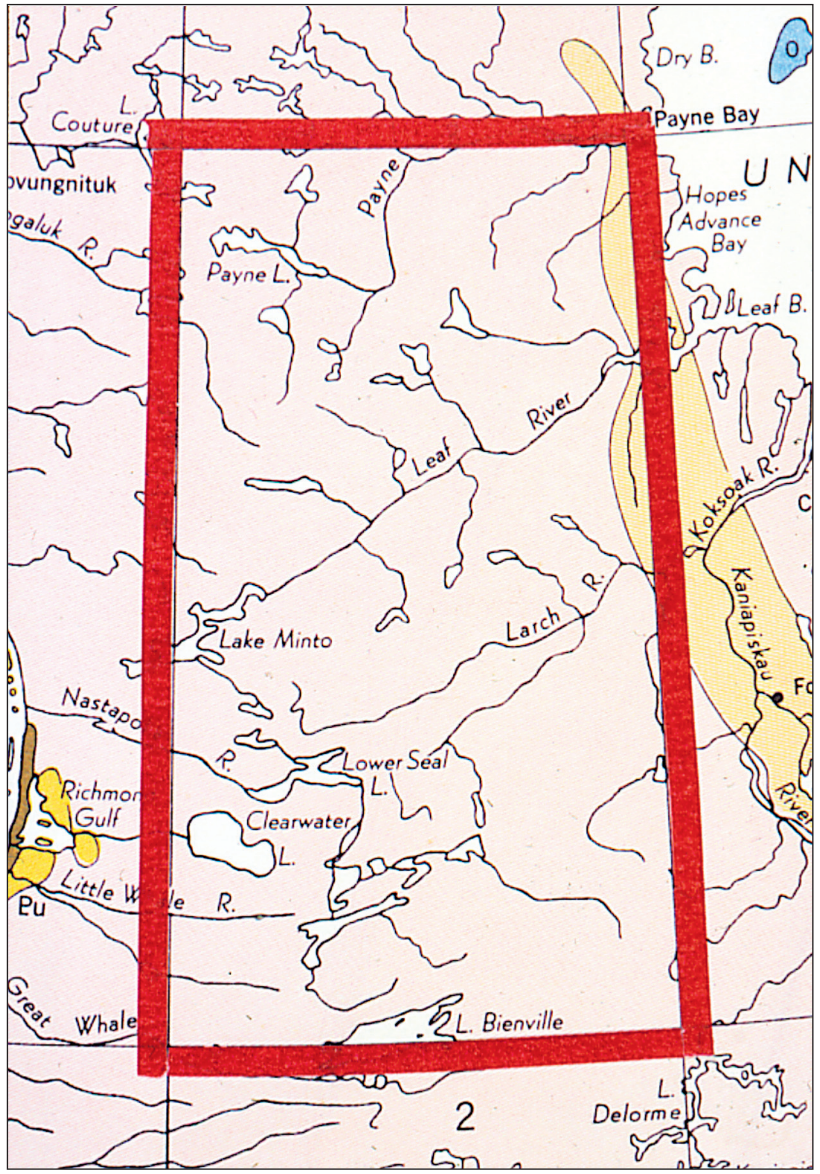

Figure 3. Geologic map of Quebec, Canada, over part of the Canadian Shield (latitude 55-60°N, longitude 70-75°W). The pink color is described as "undifferentiated granitic basement."

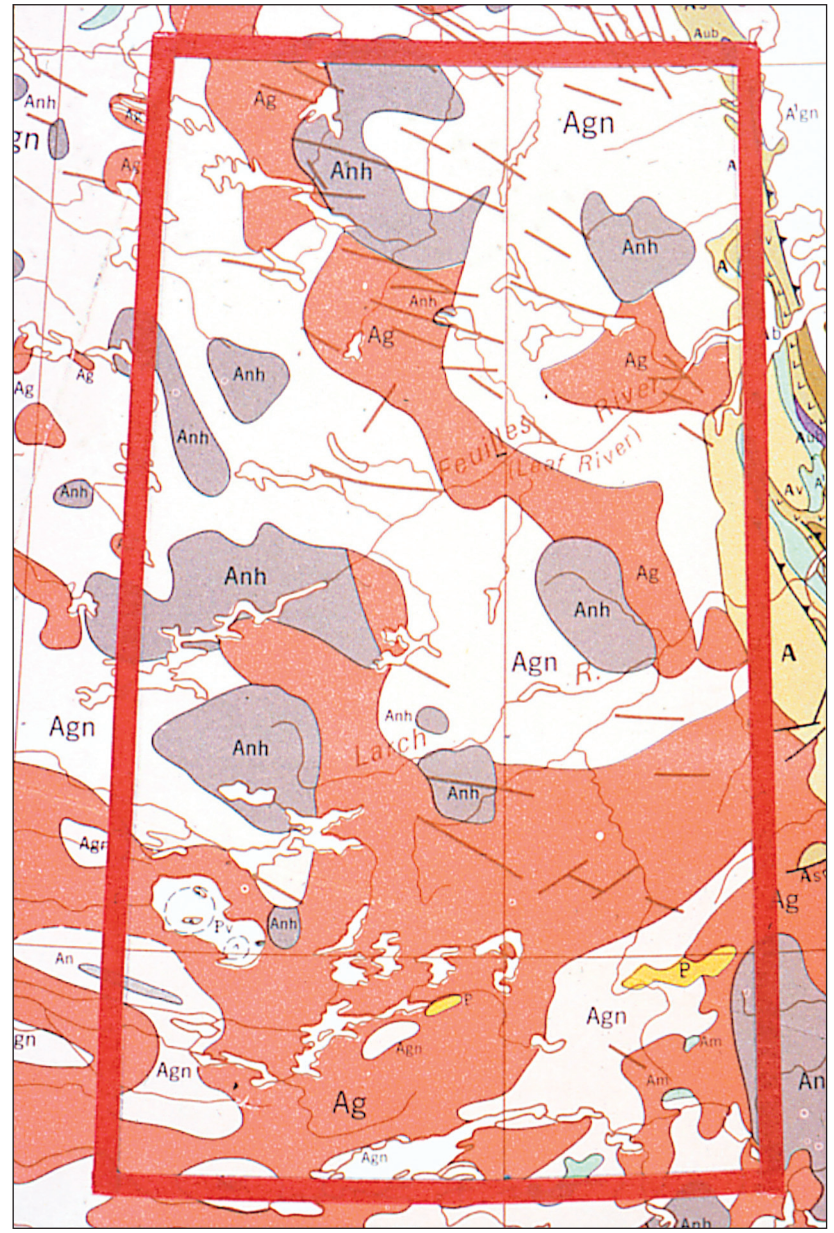

Figure 4. A more detailed geologic map of Quebec, Canada, over part of the Canadian Shield (latitude 55-60°N, longitude 70-75°W). The legend describes "mostly granites, syenites, monzonites, diorites and their gneissic equivalents."

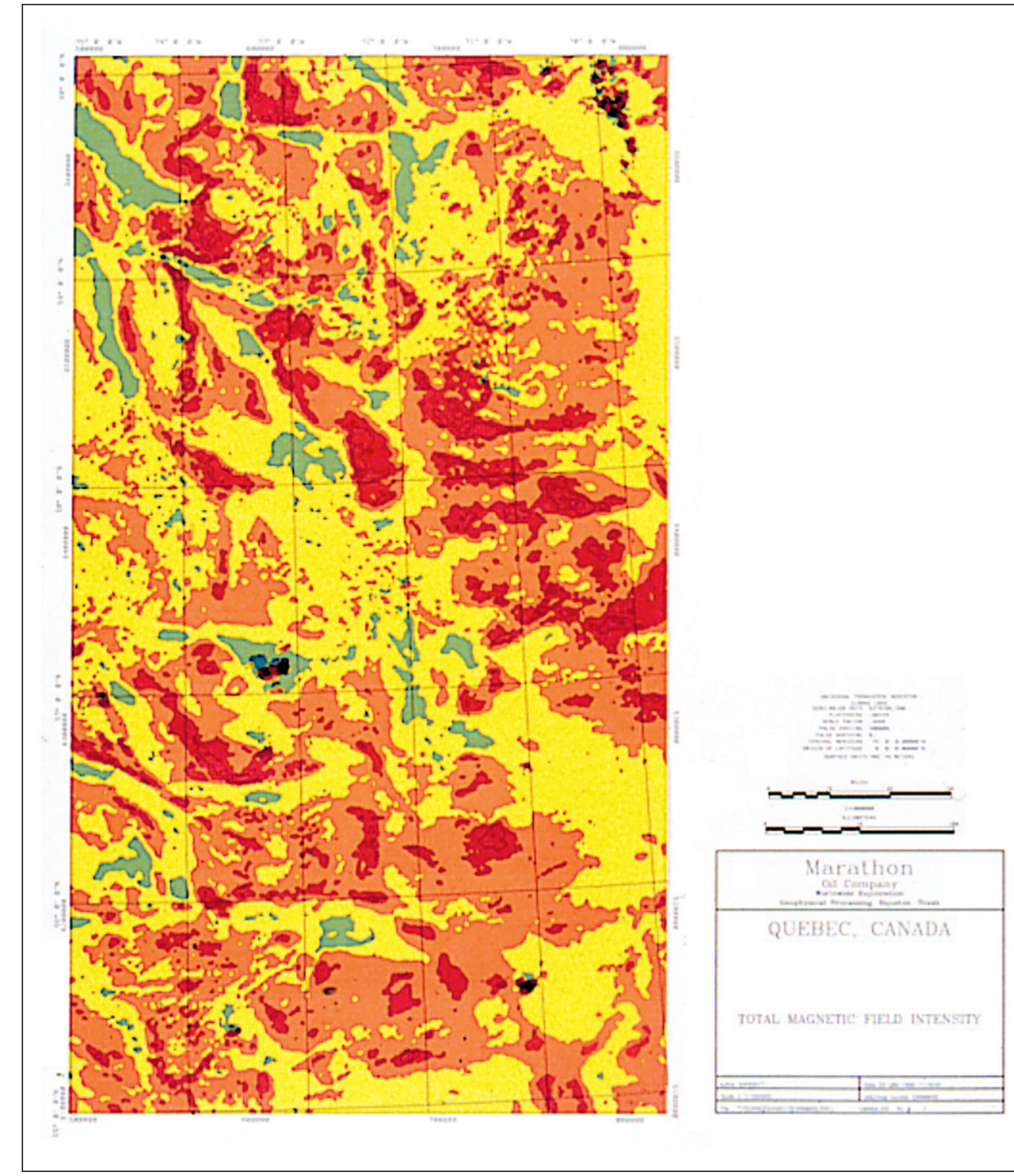

Figure 5. Total-magnetic-intensity anomaly map of Quebec, Canada, over part of the Canadian Shield (latitude 55-60°N, longitude 70-75°W), from the public-domain compilation for the Decade of North American Geology (DNAG). The contour interval is 500 nT. The colors represent purples, blues, and greens for the magnetic minima, and yellows, oranges, and reds for the magnetic maxima. The magnetic anomalies average about 1500 nT over this area. A visual comparison of Figures 4 and 5 shows a striking similarity in trends.

The goal of any magnetic interpretation is to gain information about the subsurface geology. Given planned and well-acquired aeromagnetic data over an area, an interpreter should be able to map tectonic (lithologic) provinces, if necessary. The interpreter also can calculate depth to magnetic basement and contour it. With high-resolution aeromagnetics, the interpreter also may be able to detail a potential trapping structure.

Whether an explorationist is involved in prospect analysis or in frontier basin evaluation, it may be important to know that the basement rocks represent the Kenoran orogeny, undergoing folding and granitic intrusion during the Late Archaean. This may impact source rock and reservoir quality, or thermal history. In short, knowledge of the regional geology and tectonics can be gained from magnetic data, along with a contoured depth map of the area being explored. Analysis of the data and an understanding of the geology (or proposed geologic model) are key to a successful interpretation. Analysis is required!

Reference

Nettleton, L. L., 1976, Gravity and magnetics in oil prospecting: McGraw-Hill Book Co.

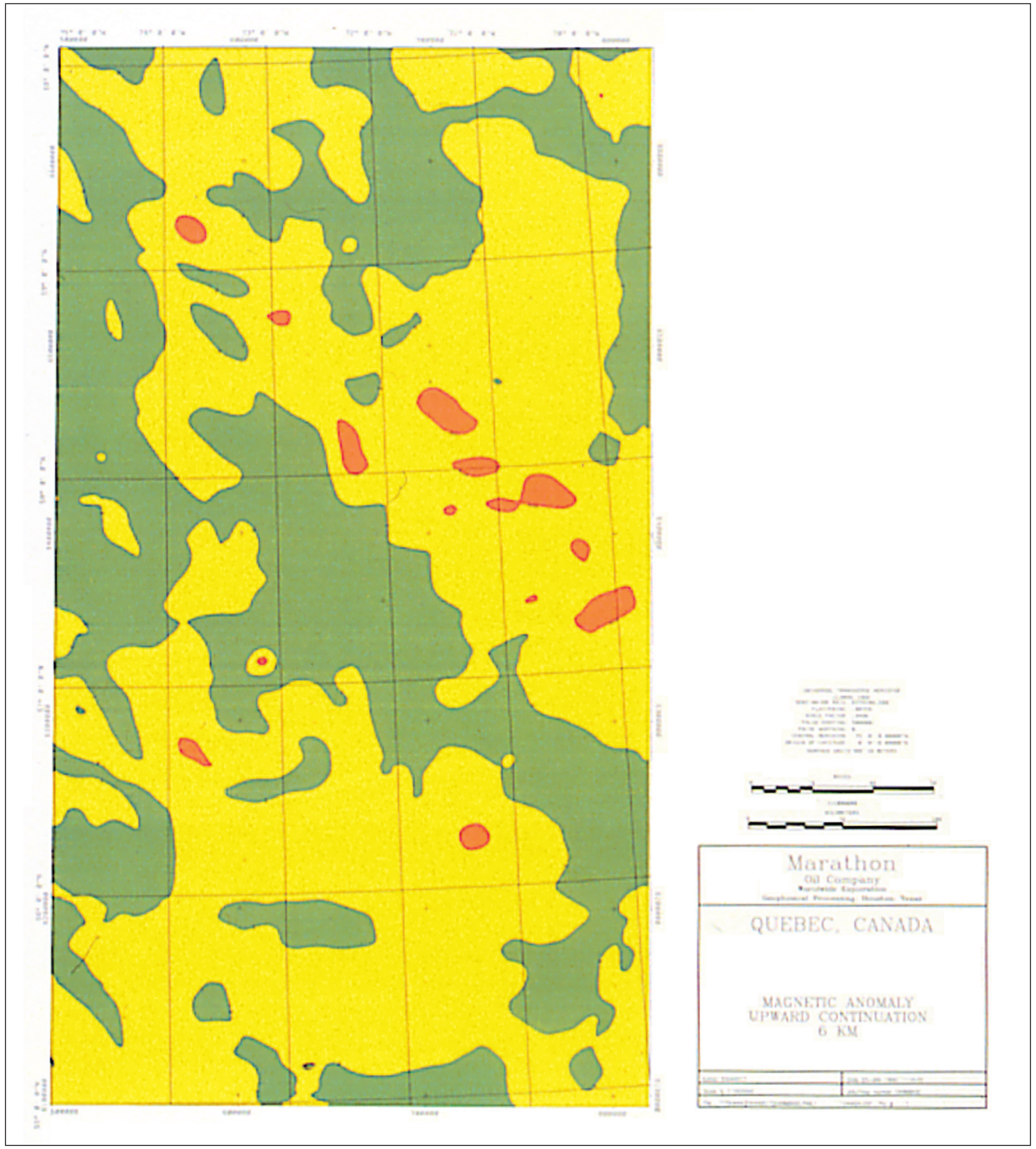

Figure 6. *Total-magnetic-intensity anomaly map of Quebec (same area as Figure 5). The contour interval is 500 nT. An upward continuation has been applied, showing how the data would appear if the magnetometer was 6000 m above basement. The continuation distance was chosen to simulate the depth of a sedimentary basin. Hence, if the granitic rocks of the Canadian Shield were buried under 6000 m of nonmagnetic sediment and there were no structures on the basin floor, then the magnetic map would look like this. The magnetic relief has diminished from 1500 nT to about 800 nT, the major lithologic trends are still visible, but the wavelengths have broadened.*

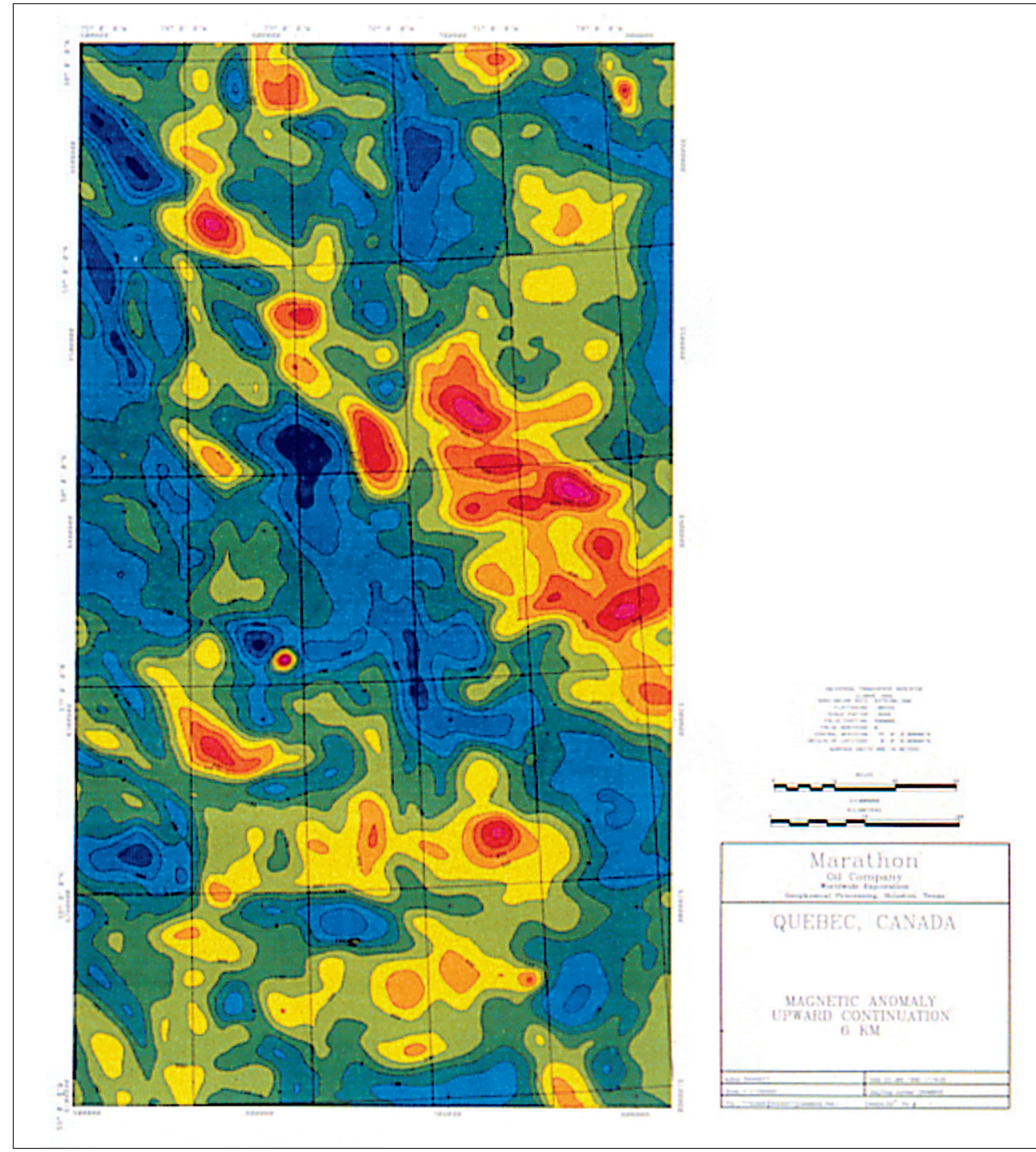

Figure 7. The same upward-continued total-intensity magnetic anomaly data as in Figure 6, but with a 100-nT contour interval to give a better representation of individual anomalies.

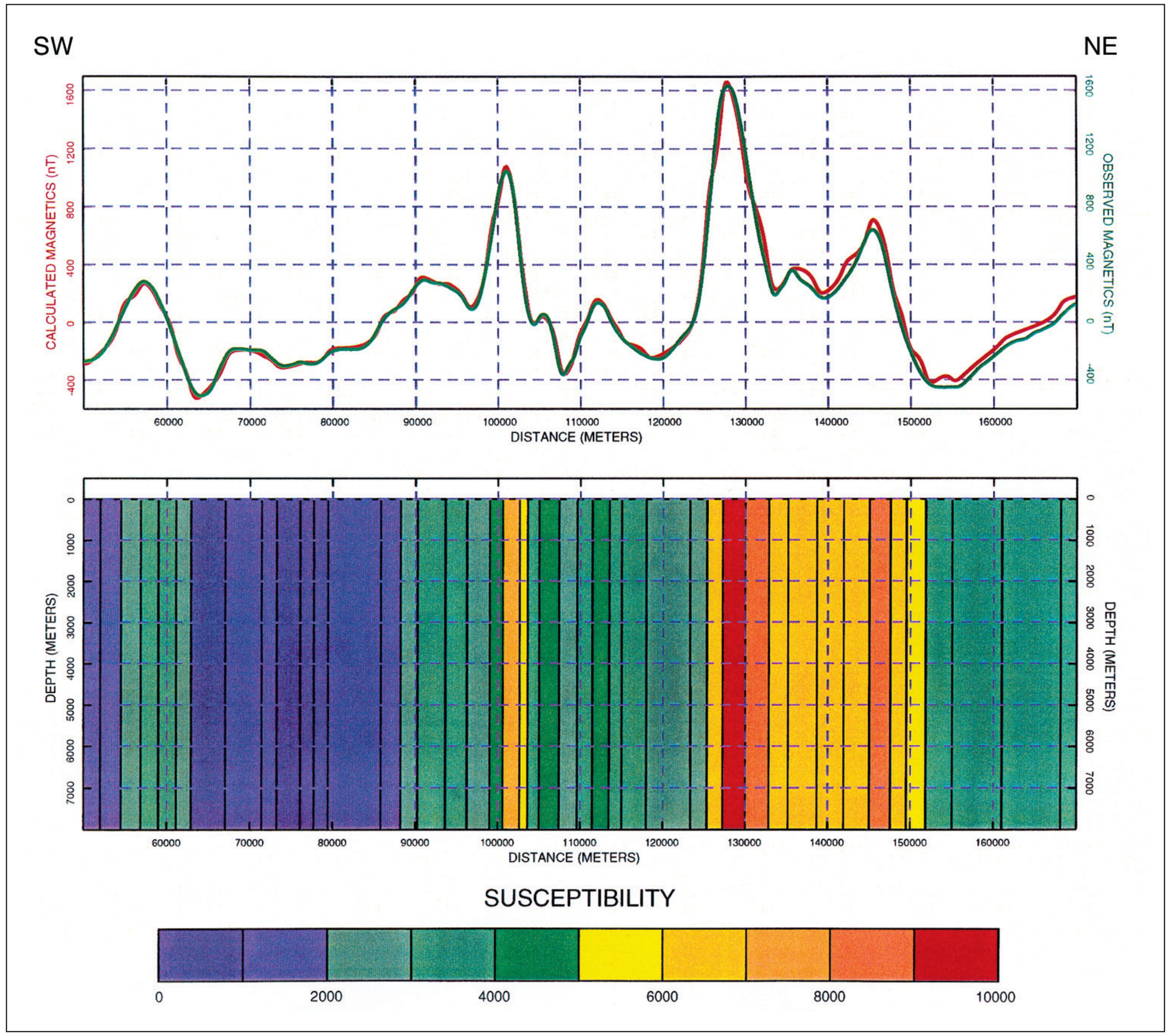

Figure 8. *A 2-D cross-section magnetic model through the study area from southwest to northeast across the center of the area. Basement susceptibility changes have been simulated by simple geometric forms. The observed (acquired) magnetic curve is green, while the magnetic curve calculated by the model is red. The attempt at curve fitting is only approximate, but seems to represent the actual data well.*

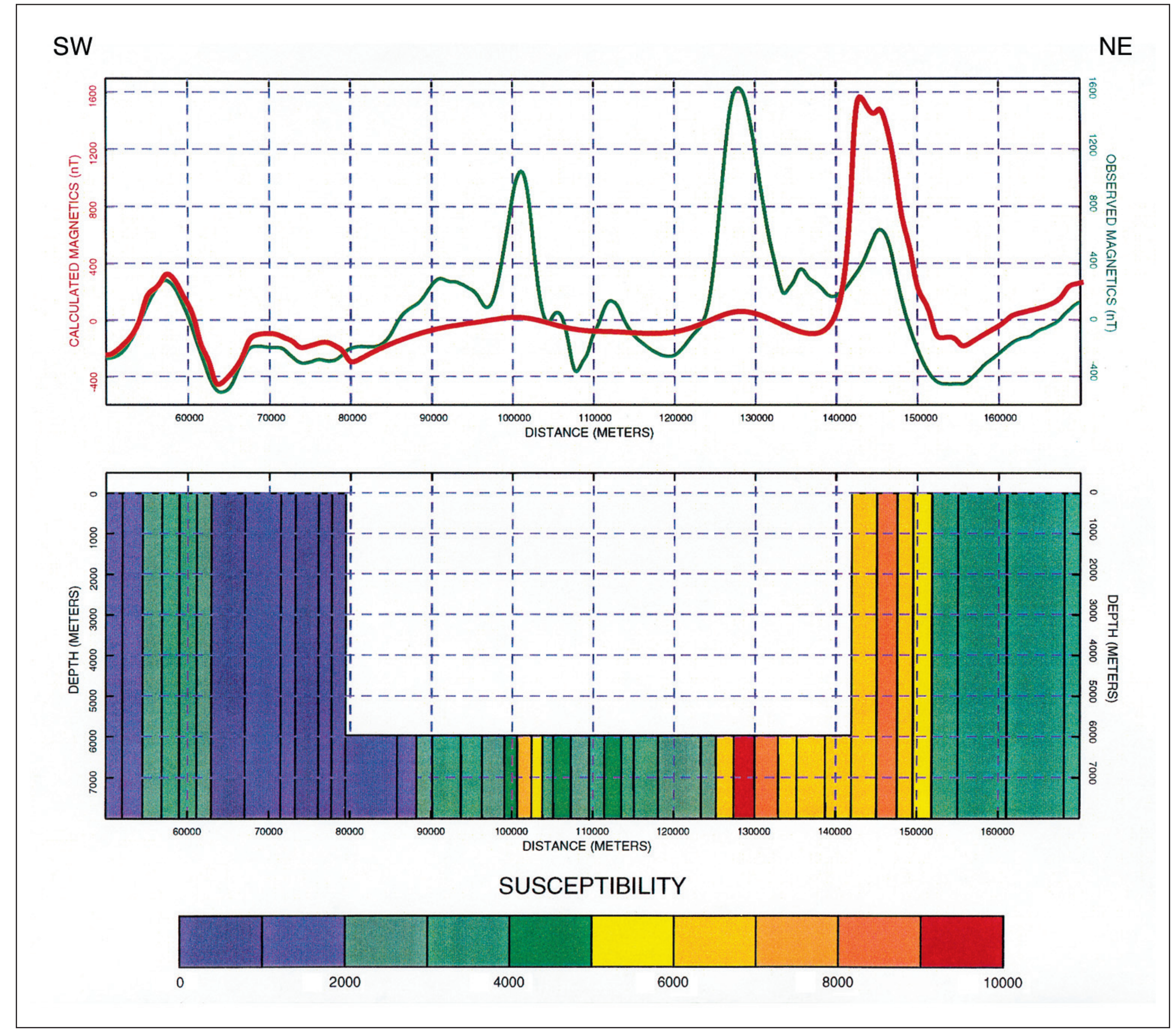

Figure 9. *A 2-D cross-section magnetic model (same as Figure 8) with the addition of a simple, straight-sided, 6000-m-deep "basin." It is the same susceptibility scheme as in Figure 8. Note that the anomaly wavelengths coming from the center of the basin are broader and lower amplitude than those on the shoulders of the "rift." At least two anomalies are distinct enough to provide depth information for the "basin floor."*

Millegan, P. S., and Bird, D. E., 1998, How basement lithology changes affect magnetic interpretation: in, Gibson, R. I., Millegan, P. S. (editors), Gravity and Magnetic Exploration Case Histories: American Association of Petroleum Geologists Studies in Geology, No. 43 and Society of Exploration Geophysicists Geophysical Reference Series, No. 8, pp. 40-44.