An assessment of topographic effects on airborne and ground magnetic data

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Recent advances in magnetic surveying have focused on achieving higher levels of instrument sensitivity and better definition of the morphology of the magnetic field through the use of measured magnetic field gradients. Images derived from these high-resolution magnetic surveys are widely used as a direct proxy for geologic mapping, especially in areas of limited surface exposure. Commonly, this involves the application of skeletonization (e.g., multiscale edges, or "worms"), Euler, and/or wavelet-based processing routines to generate estimates of the location, and morphology of the edges of anomalous source bodies. The primary assumption for all of these image- (map-) based data processing routines is that the observed magnetic data set provides an unbiased representation of the magnetic mineral variation in the surface and subsurface geology. This assumption may be valid when the observed magnetic anomalies are greater than 5000 nT and the topography is relatively flat, but it is certainly not valid when the observed anomalies are less than 100 nT and topographic variations exceed 100 m. Indeed, in some situations, topographic variations of less than 20 m can lead to geologically erroneous conclusions derived from ground magnetic surveys.

Since the initial development of terrain corrections for gravity data in 1912 followed by the introduction of correction charts in 1939, numerous articles have been published suggesting new numerical algorithms and the use of new digital elevation models for computation and data reduction of gravity data. Unfortunately, while early researchers recognized that magnetic survey results could be affected by the same problem, the application of terrain corrections to magnetic data is quite rare. This problem is further exacerbated by the fact that many magnetic surveys are collected from an airborne platform. In this situation, the impact of topography on the observed magnetic signal introduces two complications: (1) the effect of not measuring on a planar surface, and (2) terrain clearance, the effect of varying source-sensor distance caused by the climb and descent limitations of the airborne platform. In this paper, we examine how failing to address these limitations can result in distorted geologic interpretations.

Large magnetization contrast at the air-ground contact. A magnetic anomaly is only produced when a rock unit has a magnetic contrast with a laterally adjacent rock unit. The cause of this magnetic contrast might be produced by a change in the magnetic susceptibility and/or magnetic remanence of the source bodies. By far the largest magnetic contrast is that between the Earth's surface and the air. The magnetic susceptibility of air is 0.0 SI, whereas any rock unit outcropping where magnetic data is being collected has magnetic susceptibilities of 0–200 000 × 10^{-6} SI (Hunt et al., 1995). Therefore, surface topographic variations will produce magnetic anomalies that are related to this air-surface magnetic contrast, and not to buried geology that is often the target of the survey.

Figure 1 shows a simple case of a north–south topographic valley, characterized by highland plateaus at both north and south, followed by a topographic depression with 45° slope towards the center, and a 1-km flat depression at the center. Maximum elevation change from middle of the depression to top of the highland is 250 m. The body representing the rock surface has a magnetic susceptibility of 0.01 SI. For simplicity, the induced magnetic field is vertical (I=90°; D=0°; F=70 000 nT). The generated total field magnetic anomaly ranges from 0 to +375 nT, with low peaks at the starting of the topographic slopes, positive peaks at the end of the slopes, and a major flat positive anomaly at the centre of the structure. Because of the small contribution of the bottom of magnetized bodies to the observed magnetic anomalies, reducing the thickness of the magnetic prism does not significantly change the intensity of the anomaly. The sharpness of the peaks is caused by the abrupt changes of topographic slope. For simplicity, the topography was simulated with a minimum number of points.

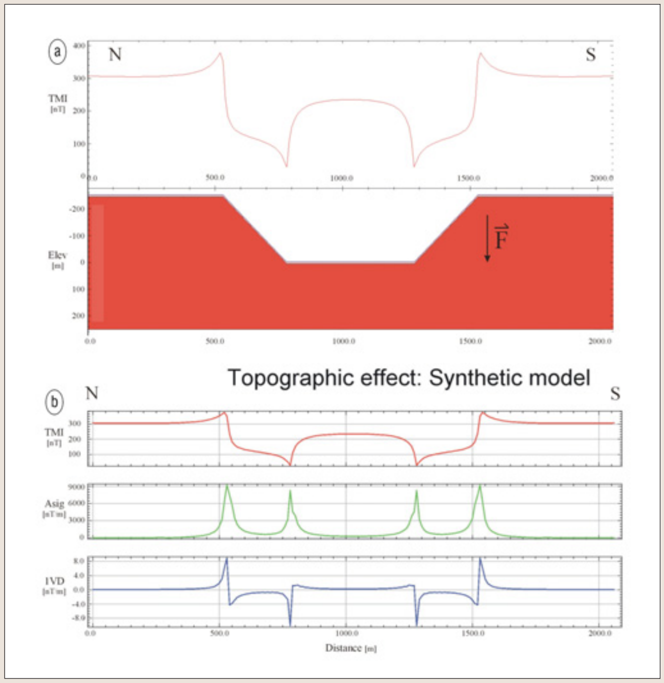

Figure 1. Synthethic model of a magnetized valley. The effective magnetic vector is vertical (I=90°; D=0°). Intensity of the field is 70 000 nT. The block has a uniform magnetic susceptibility of 0.01 SI. Observation level is 2 m above the ground to simulate a ground magnetic survey. (a) Observed magnetic field and cross-section of the valley; (b) observed TMI (top) and computed amplitude of the analytic signal (ASIG, middle) and first vertical derivative (1VD, bottom). Notice the peaks on both are caused by topographic changes.

In reality, a smoother topography would lead to smoother magnetic anomalies; however, the general shape of the observed magnetic field would remain the same. The interpretation of such an anomaly without consideration for topographic effects, or the superposition of the actual geological signal with this effect on a real geologic problem could lead to wrong conclusions. Figure 1b shows the synthetic total magnetic intensity (TMI; top), and computed amplitude of analytic signal (ASIG; middle), and first vertical derivative (1VD; bottom). The 1VD succeeds on mapping "structures," which in reality are changes in topographic slope. However, a plain analysis of the ASIG can be misleading. Peaks in the ASIG are supposed to be associated

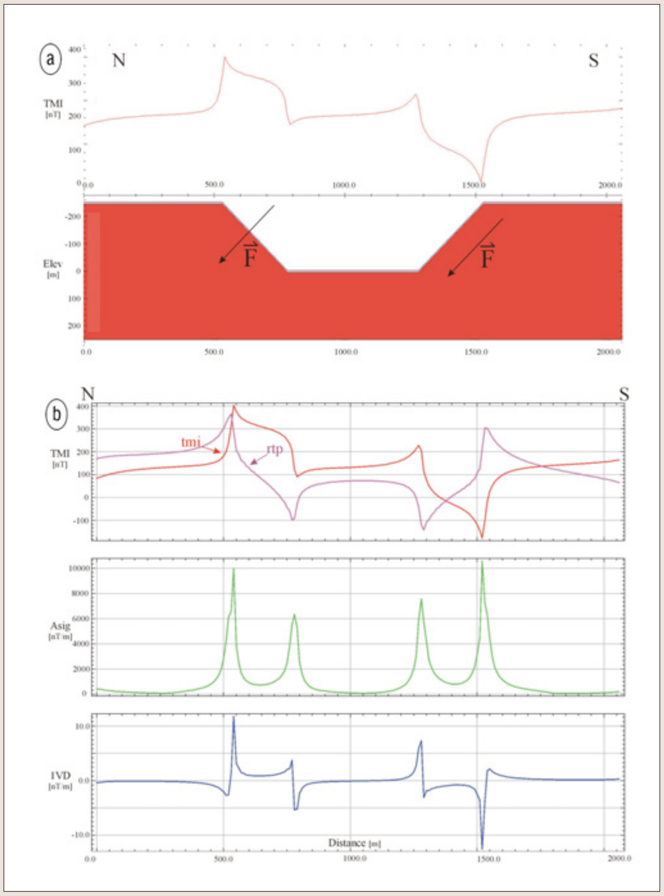

Figure 2. Synthetic model of a magnetized valley, but under an oblique effective magnetic vector. I=45°, D=0°, F=70 000 nT. The intensity of the inducing field, which should be smaller for this inclination, was kept constant for consistency with the previous example. The block has a uniform magnetic susceptibility of 0.01 SI. Observation level is 2 m above the ground to simulate a ground magnetic survey. (a) Observed magnetic field and cross-section of the valley; (b) top—observed TMI (red) and pole reduced TMI (purple); computed amplitude of the analytic signal (ASIG, middle); and first vertical derivative (1VD, bottom). ASIG and 1VD were computed on observed TMI to show the effect of the inclined field. Even after reducing the data to the pole the profiles show asymmetry due to the relative angle between the magnetic vector and the topographic slopes. Notice the change in amplitude of the center peaks of the ASIG as compared to Figure 1, which shows that the ASIG is indeed affected by the orientation of the magnetic field and/or remanence. Both ASIG and 1VD show topographic-related peaks, but this time their relative amplitudes vary depending on the angle of the magnetic field vs. the topographic slopes.

with edges of magnetized bodies, but in this case, that is not the true source of the observed magnetic anomalies. Moreover, the use of depth estimation methods like Euler deconvolution over this biased data set will lead to wrong depth estimations.

Variations in effective magnetic field direction versus topographic slopes. The previous example showed the effect of topography for a vertical inducing magnetic field. If we now change the inclination of the field, so that it is subparallel to the southern slope of the valley, there will be a coupling problem between the magnetic vector and the topographic surface. The northern slope will have a maximum field-slope coupling, whereas the southern slope being subparallel to the field, will have a minimum coupling. Figure 2a shows the magnetic signal of the same topographic valley as on Figure 1, but with an inclined effective magnetic vector (F=70 000 nT; I=45°; D=0°). Because of the change in inclination of the inducing magnetic field, this time the generated total field magnetic anomaly ranges from –260 to +375 nT. Note the negative anomaly on the southern slope of the valley, as compared to its northern counterpart. Any lithological mapping attempts based on total field data would lead to higher magnetization units in the northern rim of the valley. The pole-reduced data are able to overcome the asymmetry of the anomaly, but not completely, as the resultant pole reduced anomaly exhibits a north to south trend. Furthermore, reduction to the pole works well only when remanent magnetization is known, or the induced component is >10 times the remanent component. In any other cases, the obtained results will be unreliable and data should be analyzed carefully. The amplitude of the analytic signal (Figure 2b, middle) shows some important changes from the previous case (Figure 1b, middle). The two peaks in the center of the valley have smaller amplitudes than the two outer ones, and the northern anomalies have smaller amplitudes than the southern ones. This serves as synthetic proof that indeed the amplitude of the analytic signal is dependent on physical parameters such as remanent magnetization.

Changes in the observation level: Does draping really help? The advantage of conducting airborne magnetic surveys on a parallel to the ground planar surface instead of a barometric survey was recognized more than 30 years ago. As other authors have pointed out, the main advantage of a drape survey over a barometric one, or even a "loose drape" survey (that is, flying over a nonstrictly ground-parallel surface, but as parallel to the ground as the aircraft allows) lies in the higher frequency content achieved when flying closer to the ground. However, there are a couple of misconceptions that we want to address here:

1) Flying on a drape-surface will not have any topographic effect;
2) Any topographic effects on the data can be corrected by analytic continuation of the data to a surface parallel to the ground.

Figure 3 shows the same synthetic example of Figure 1 (magnetized valley, vertical-inducing field), but with different observation levels. The top panel shows the measured curves at different levels of surface clearance: ground level (at 2 m elevation, parallel to the ground); drape flight (at 250 m above the ground); loose drape (a low-passed version of the latter one, which turns onto a surface that is closer to the ground than the strictly drape survey on the ridges of the valley, but farther away on the middle of it); and barometric flight. The first observation from this analysis is the noticeable difference in amplitude and frequency content between the ground survey and all the other ones. As expected, the ground survey exhibits much larger amplitude, but also high-frequency anomalies not observed on any of the drape examples. The bottom panel shows the observed TMI, computed first vertical derivative (1VD) for only the airborne surveys, and one attempt to reconstitute the ground profile through downward continuation. The strict-drape (also called tight drape) survey shows more high-frequency content than both the loose-drape and the barometric survey.

However, it also has the greater topographic effect (observed as peaks on the 1VD due to the abrupt changes in topography at the edges of the valley). The gray profiles attempted to downward continue the data from the loose-drape to a tight-drape survey. However, this only enhances

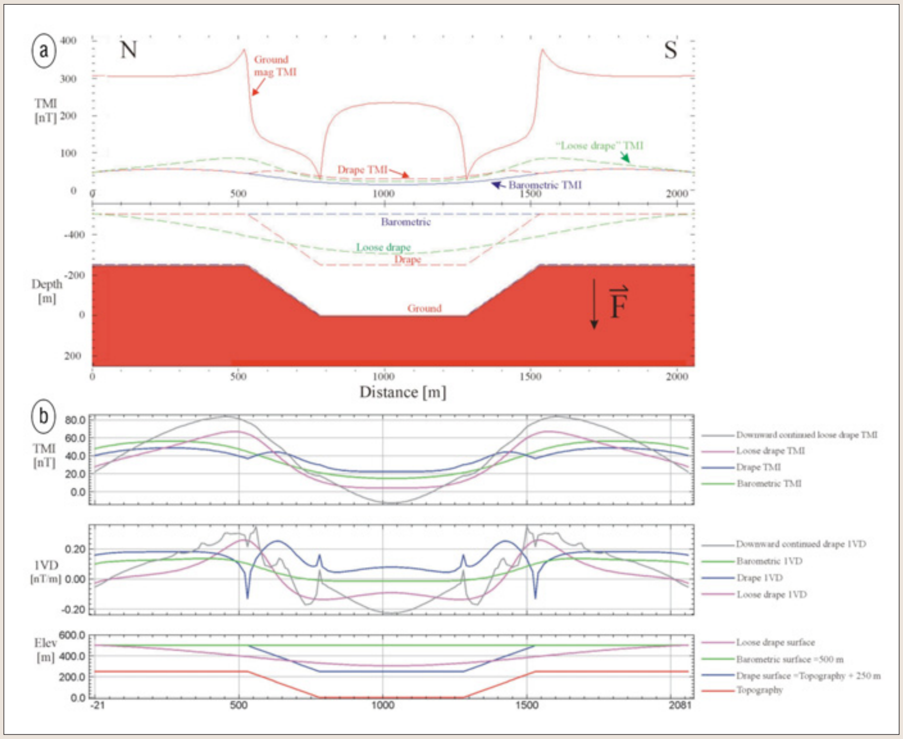

Figure 3. Synthetic model of a magnetized valley, with varying observation levels. For simplicity, the effective magnetic vector is vertical. I=90°, D=0°, F=70 000 nT. The block has a uniform magnetic susceptibility of 0.01 SI. (a) Different observation levels. Ground survey (red) computed at 2 m above the ground; drape survey (dashed red) computed at 250 m parallel to the ground; loose-drape (dashed green) surface is a low-passed version of the drape surface to simulate a real flight. Barometric surface (blue) is at 500 m above the sea level. Notice the immense amplitude contrast between the ground survey and the airborne ones; (b) TMI (top) and 1VD (middle) of the different observation surfaces (bottom). For scale purposes the ground survey is not shown. The loose drape survey (purple) was downward continued to the same level as the tight-drape surface (gray). The result is an increase in amplitude, but also an increase in the high-frequency noise levels, which can be observed on the 1VD curves.

the amplitude of the TMI anomalies, and also increases the noise levels of the later computed 1VD. The main conclusion of this exercise is that downward continuation, by any means (grid-based, profile-based, Taylor-series, chessboard or wavelets), will not be able to resample any high-frequency on the signal that was not measured. Therefore, the only way to improve sampling of shallow magnetic sources (i.e., high frequency) is to collect the data as close to the ground as possible. However, regardless of the observation surface, the data will not be exempt from terrain or topographic effect.

Some alternatives. As pointed out above, the large magnetization contrast between air and the surface rocks will create a magnetic anomaly that does not relate to the usual subsurface geologic targets. As well, an inclined magnetic field relative to the topographic slopes also creates an undesired element in the data. The only way to remove both is by computing a complete magnetic terrain correction for the data. As previously proposed, it must include a correction for source-sensor distance variations, and like gravity, it must also include a terrain effect that requires an assumption be made regarding the magnetic properties of the surface rocks. Secondly, the normal approximation of uniform magnetization has to be applied to compute the correction. Finally, in situations where there are significant elevation differences between adjacent flightlines, an individual line correction must be applied in advance of a more general grid based correction. The terrain corrected or residual magnetic data will be easier to interpret and show an enhanced view of the target anomalies.

Figure 4 shows an example of valley topography superimposed on two dipping dikes. As on the example in Figure 2, the magnetic field is inclined and parallel to the southern slope of the valley. The top panel shows the three curves: observed TMI, which includes the effect of both magnetized topography and dipping dikes; the computed terrain effect (uniformly magnetized block); and the residual (observed terrain). The bottom panel shows the effect of this terrain correction on both 1VD (middle) and ASIG (bottom). Notice the different scales between the "all" (that is, topography and dikes) and residual (observed-terrain) curves. The 1VD of the observed TMI shows strong peaks at the changes of elevation, so it is unable to map the dikes. The residual 1VD is able to see the top of both dikes. The signal on the northern dike is weaker because of its greater depth to top as compared to the southern one. The amplitude of the analytic signal shows the same effect. The one computed from the observed TMI only maps the changes in elevation, whereas the one computed from the terrain-corrected TMI maps both dikes.

Ideally this terrain correction should be computed based on measured magnetic susceptibilities and remanent magnetization intensities. However, missing the real magnetic susceptibility would only cause a constant (DC) shift in the computed data. As others have pointed out, missing the actual orientation of the effective magnetic field will cause a nonminor effect that can only be assessed through paleomagnetic sampling, or conducting 3D vector magnetic surveys.

As for the variations on the observation surface, there is no way around it: data have to be collected as close to the ground as possible. Higher observation surfaces (elevation) not only mean a reduction in topography, but a dramatic decrease in the observed high-frequency content of the data. Downward continuation algorithms are able to correct the amplitude of the anomalies to what they would be at a lower (closer to the ground) surface, but they can not recover any high frequency that is not in the data.

Conclusions. Vast amounts of airborne magnetic data are currently being collected by many contractors and mining companies. With the increased sensitivity level of magnetometers incorporated into the current generation of airborne systems and the move to more tightly draped survey procedures it is important to remember that terrain effects are going to be a common artifact in all magnetic data. None of this is new; actually some of it was published as early as 1971. Yet today many people are using semi-automatic geological inversion routines which assume there is no bias in the observed data. As demonstrated in this paper, computation of parameters such as analytical signal, Euler deconvolution, etc., using grids which are compromised by terrain effects may result in geologically erroneous interpretations.

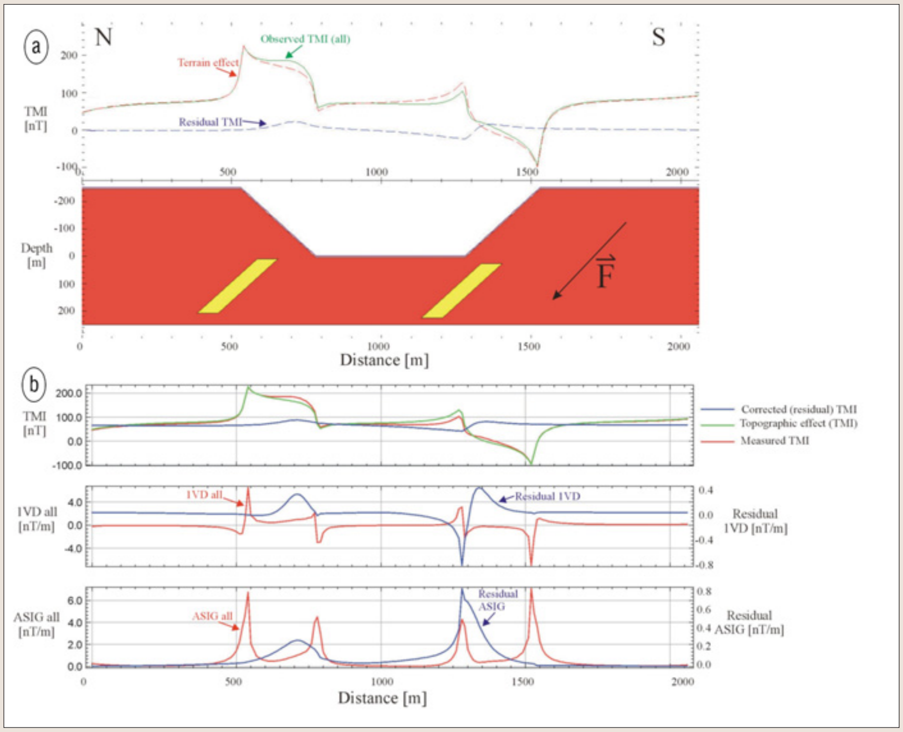

Figure 4. Synthetic model of a magnetized valley, with a couple of dipping dikes underneath. The effective magnetic vector is inclined. I=40°, D=0°, F=70 000 nT. The block has a uniform magnetic susceptibility of 0.01 SI and both dikes have a magnetic susceptibility of 0.013 SI. (a) Observed TMI (green), computed terrain effect (just the red block; red) and the residual field of observed—terrain (blue); (b) observed and corrected TMI (top), 1VD (middle) and ASIG (bottom). Scales of uncorrected and corrected 1VD and ASIG are different. Computing the 1VD and ASIG of uncorrected data only maps topography, whereas the ones computed from the terrain corrected data are able to map both dikes.

With current surveys it is an industry-wide standard practice to collect high precision GPS and radar altimeter simultaneously with the magnetic data. Combined, these location and elevation data provide a readily available digital elevation model that usually has a much higher precision than anything that has been commercially available. In turn, this resource presents an opportunity for determining if there is any significant terrain contamination in the observed magnetic signal as suggested by past researchers. Topographic effects can be readily accommodated in model inversion schemes by including the aircraft path in the inversion constraints. To achieve a similar level of accuracy in magnetic mapping requires that we begin to consider the effects of topography and terrain clearance.

Suggested reading. "Reduction of magnetic and gravity data on an arbitrary surface acquired in a region of high topographic relief" by Bhattacharyya et al. (Geophysics, 1977). "Drape-related problems in aeromagnetic surveys: the need for tight drape surveys" by Cowan et al. (*Exploration Geophysics*, 2003). "Aeromagnetic drape corrections applied to Turner valley Syncline, Hammersley Basin" by Flis and Cowan (*Exploration Geophysics*, 2000). "Does draping aeromagnetic data reduce terrain-induced effects?" by Grauch and Campbell (Geophysics, 1984). "Evaluation of terrain effects in ground magnetic surveys" by Gupta and Fitzpatrick (Geophysics, 1971). "Terrain corrections for gravimeter stations" by Hammer (Geophysics, 1939). "The effect of topography and isostatic compensation upon the intensity of gravity" by Hayford et al. (*USC and GS Special Publication 10*, 1912). *Magnetic Properties of Rocks and Minerals. Rock Physics and Phase relations: A Handbook of Physical Constants* by Hunt et al. (American Geophysical Union, 1995). "Euler deconvolution of the analytic signal and its application to magnetic interpretation" by Keating and Pilkington (*Geophysical Prospecting*, 2004). "Understanding 3D analytic signal amplitude" by Li (Geophysics, 2006). "3D Analytic signal in the interpretation of total magnetic field data at low magnetic latitudes" by MacLeod et al. (*Exploration Geophysics*, 1993). "Magnetic remanence constraints on magnetic inversion models" by Morris et al. (*TLE*, 2007). "The inversion of magnetic anomalies in the presence of topography" by Parker and Huestis (*Journal of Geophysical Research*, 1974). "Draping aeromagnetic data in areas of rugged topography" by Pilkington and Roest (*Journal of Applied Geophysics*, 1992). "Draping corrections for aeromagnetic data: line- versus grid-based approaches" by Pilkington and Thurston (*Exploration Geophysics*, 2001). "Drape corrections of aeromagnetic data using wavelets" by Ridsdill-Smith and Dentith (*Exploration Geophysics*, 2000). "Inversion of aeromagnetic data using digital terrain models" by Woodward (Geophysics, 1993). "The iteration method of downward continuation of a potential field from a horizontal plane" by Xu et al. (*Geophysical Prospecting*, 2007). TLE

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