

Expression of terrain and surface geology in high-resolution helicopter-borne gravity gradient (AGG) data: Examples from Great Sand Dunes National Park, Rio Grande Rift, Colorado

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Airborne gravity gradient (AGG) data are rapidly becoming standard components of geophysical mapping programs because of their advantages in cost, access, and resolution over measurements of the gravity field on the ground. Unlike conventional techniques that measure the gravity field, AGG methods measure derivatives of the gravity field. This means that effects of terrain and near-surface geology are amplified in AGG data, and that proper terrain corrections are critically important for AGG data processing. However, terrain corrections require reasonable estimates of density for the rocks and sediments that make up the terrain. A recommended philosophical approach is to use the terrain and surface geology, with their strong expression in AGG data, to the interpreter's advantage. An example of such an approach is presented here for an area with difficult ground access and little ground gravity data. Nettleton-style profiling is used with AGG data to estimate the densities of the sand dunefield and adjacent Precambrian rocks from the area of Great Sand Dunes National Park in southern Colorado. Processing of the AGG data using the density estimate for the dunefield allows buried structures, including a hypothesized buried basement bench, to be mapped beneath the sand dunes.

Geologic setting

The study area is largely coincident with Great Sand Dunes National Park and Preserve (GReat SAnd ...) in south central Colorado (Figure 1). GRSA sits along the eastern margin of the San Luis Basin, one of the northernmost major basins that make up the 30–25 Ma to present Rio Grande Rift (Hudson and Grauch, 2013, and references therein). There, a large dunefield is situated at the Sangre de Cristo Mountains western range front.

The Sangre de Cristo Mountains in the study area are made up mainly of Precambrian rocks, dominated volumetrically by intermediate-composition plutonic rocks. The Precambrian rocks are locally overlain by clastic sedimentary rocks of the Pennsylvanian Minturn Formation, emplaced by Laramide thrust faults. Broad areas of Minturn Formation outcrop include small outcrops of Precambrian rocks and Tertiary intrusions, too small to show at the scale of Figure 1. The structural boundary between these pre-rift rocks and the San Luis Basin is the Sangre de Cristo fault system (Ruleman and Machette, 2007), including several exposed faults (Figure 1) as well as many presumably buried faults near the range front that form complex structures elsewhere in the basin (Grauch et al., 2012).

Quaternary deposits at GRSA include fan alluvium near the range front, but are dominated by eolian deposits that

include sabkha and sand sheet deposits and culminate in a 78-km² dunefield (Valdez et al., 2007). Individual dunes reach several kilometers in length, and are tens to hundreds of meters high. The dunefield fully conceals underlying strata and structures from direct observation, making geophysical methods critical for imaging the underlying subsurface.

Airborne gravity gradient data

Gravity and gravity gradient anomalies reflect lateral variations of density. Positive anomalies, or highs, occur over areas of relatively high densities, and negative anomalies, or lows, occur over relatively low-density materials. Large density contrasts between low-density rift-filling sediments and older rocks make gravity and gravity gradient data useful for defining the configuration of basins within the Rio Grande Rift (e.g., Hudson and Grauch, 2013, and references therein). The magnitudes of both gravity field and gravity gradient anomalies are proportional to density contrasts that produce them, and are most sensitive to the nearest sources. Because gravity gradients are derivatives of the gravity field, gravity gradient anomalies more closely reflect near-surface density contrasts than gravity anomalies do. Further, the largest density contrast is normally that between the ground and the air, meaning that the effects of terrain are stronger in gravity gradient data.

Gravity field data, typically measured on the ground, require processing to separate geological signals from predictable signals related to elevation, latitude, and terrain (Blakeley, 1995). A density of 2670 kg/m³ is traditionally used as the initial standard upper-crustal density during processing (Hinze, 2003) in both Bouguer slab (accounts for the mass of rocks above a certain datum, normally sea level) and terrain corrections. Terrain corrections typically are recomputed during later project stages (including the interpretation stage) using densities more relevant to the surface and near-surface geology in the study area. Gravity gradient data measured from aircraft are referred to as airborne gravity gradient (AGG) data. Because of the gradient nature of AGG data, many of the processing steps required for conventional gravity field data do not apply. However, terrain corrections are still critical because of the strong effects of near-surface terrain and geology in AGG data.

Processing steps for gravity (and gravity gradient) data that require an estimate of density, including Bouguer slab (for gravity data) and terrain corrections, are often treated in introductory geophysical texts as necessary evils to remove the effects of terrain so that the geophysical data may be interpreted in terms of geological signals. A better philosophical approach is for interpreters to use terrain effects to their

advantage where possible, to more effectively interpret surface geology. The effectiveness of this approach is enhanced in AGG data because of the emphasis of near-surface features.

A high-resolution helicopter AGG survey was flown over the GRSA region during early 2012 (Drenth et al., 2013). The survey was split into two blocks, with each block having different survey specifications. AGG data from the northern block, flown with 100-m flight-line spacing at ~80 m above the ground, are used in this study (Figure 2). The southern block, not shown here, was flown with 50-m flight-line spacing at ~40 m above the ground. Prior to acquisition of these data, the gravity field over the dunefield was poorly mapped because of the difficulty of carrying surveying equipment on foot significant distances over the large dunes.

The AGG data were processed to remove types of noise inherent to gradiometer systems and measurements, as well

as noise common to all types of airborne geophysical data (Drenth et al., 2013). First, the residual effects of aircraft accelerations and self-gradients (measured gradient effects of the gradiometer and aircraft system) were modeled and removed. Second, terrain corrections were calculated from a digital terrain model, constructed from laser scanner data collected from the aircraft during the survey. Third, standard tie-line leveling and microleveling were applied. Finally, low-pass filtering was applied along each flight line to remove residual noise that clearly wasn't because of geology, with the wavelength cutoff chosen by inspection of the data. For this survey, the ideal cutoff wavelength was chosen to be 100 m for the northern block (shown here), and 50 m for the southern block (not shown here). These values are the same as the respective acquisition line spacing for each block. Residual high-frequency noise is still evident in the fully processed

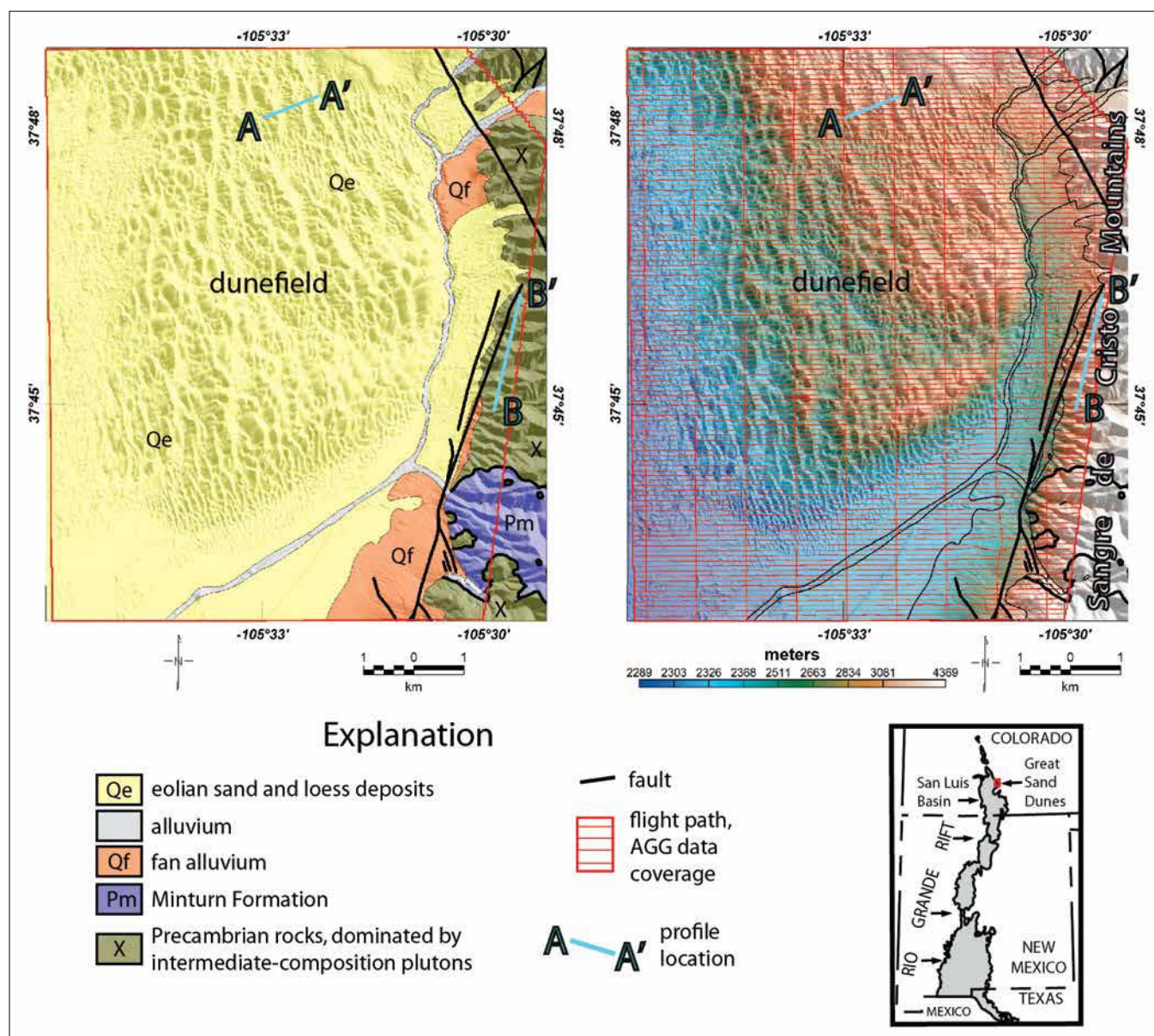


Figure 1. Geologic, elevation, and location maps of the study area. Geology simplified from Johnson et al. (1989), Bruce and Johnson (1991), and unpublished compilation mapping (T. Klein). Selected geologic linework included on elevation map for reference.

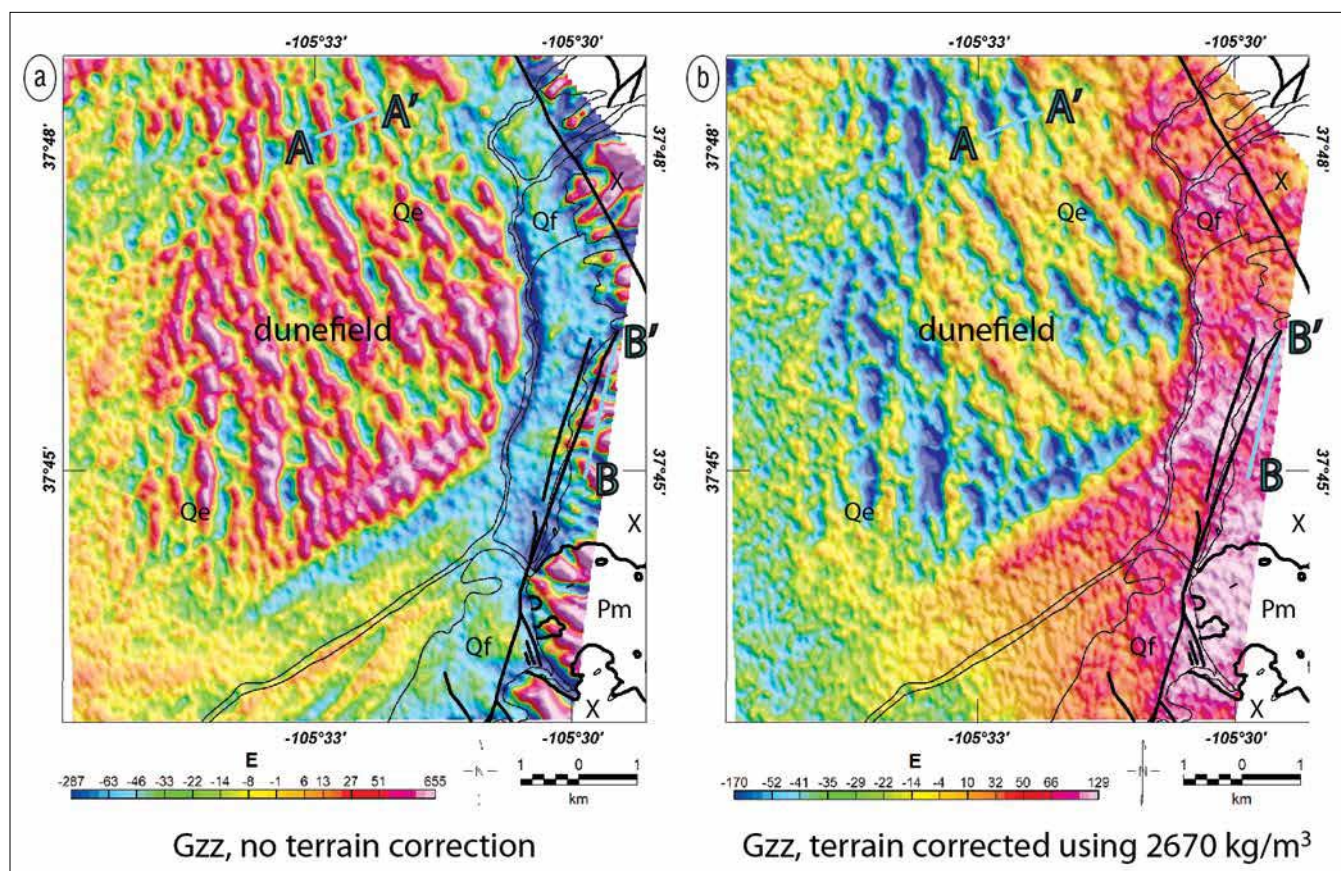


Figure 2. *Gzz* (vertical derivative of the vertical gravity field, Eotvos) without terrain corrections (a) and terrain corrected using a density of 2670 kg/m^3 (b). Selected geologic lines from Figure 1 included for reference.

data (Figure 2), but that noise is not easily separated from the shortest wavelength anomalies produced by shallow density contrasts. (A much closer look at the spatial resolution of this AGG data set is provided in a related article by M. Andy Kass, also in this issue of *TLE*.)

Effects of terrain corrections at different densities

Without terrain corrections, AGG data commonly show a strong correspondence with terrain in areas of high topographic relief, for the reasons discussed above. This effect is clearly demonstrated in the AGG data over the GRSA region (Figure 2a) where highs occur over locally high topography. Buried geologic features that we might wish to map are obviously concealed by the anomalies related to terrain. The general conclusion drawn from this example is that using too low of a terrain correction density, in this case effectively zero, results in data that have strong positive correlations with terrain and are unsuitable for mapping buried structure.

The opposite problem occurs if terrain corrections with too high a density are applied (Figure 2b). A terrain correction density using the standard 2670 kg/m^3 , suitable for many crystalline rocks, results in AGG lows over locally high topography of the sand dunes, which are composed of sediments with much lower densities. Again, the resulting AGG data are rendered unsuitable for mapping buried structure beneath the sand dunes.

Nettleton-style profiling for density determination

Knowledge of rock densities is clearly a requirement for appropriate processing of AGG (and gravity) data. Density is also the physical property that all types of gravity surveys aim to map and ultimately interpret. Density can be measured on samples from a study area, but the results often are not helpful, because (1) densities within individual geologic units often vary widely over outcrop areas and a large number of samples are needed to characterize that variability, (2) it is frequently difficult to obtain samples that aren't weathered, and (3) possible effects of compaction and water content may be unknown and/or not fully resolved (Nettleton, 1942; Parasnis, 1952).

A widely used solution to this problem, helpful in areas with significant topographic relief, was offered by Nettleton (1942) as a way to determine the ideal density for gravity data processing. In this method, a gravity field traverse is measured over a topographic feature such as a hill or valley, the data are processed using several different densities, and the results are compared to the shape of the topography in profile form. The true density of the topographic feature, and the ideal density for gravity data processing, is the one that yields the gravity profile with the minimum correlation to the shape of topography. The method assumes that the topographic feature is composed of rocks or sediments with uniform properties, or ideally a single geologic unit.

A similar approach can be taken with AGG data. The difference is that because of the gradient nature of AGG data compared to gravity field data, the effects of sources (i.e., terrain and geology) near the measurement location are amplified in AGG data. This makes Nettleton-style profiling more powerful. It is not difficult to imagine that the technique could be used in a more objective and quantitative manner, such as mathematically minimizing the correlation of AGG data with effects of terrain.

Here, the method is applied to estimate the densities of the eolian sand of the dunefield and the Precambrian rocks of the Sangre de Cristo Mountains range front (examples shown in Figure 3). Density estimation was not attempted for the Minturn Formation, because the topography it forms includes likely effects of underlying Precambrian rocks and small Tertiary plutons. For the dune sand, 39 estimates resulted in a minimum density of 1700 kg/m^3 , a maximum of 2000 kg/m^3 , and a mean of 1800 kg/m^3 . These estimates are expected to reflect mainly the density of dry sand, because the topographically high parts of the dunes are not thought to be saturated with water. For Precambrian rocks (Figure 1, unit X), 16 estimates resulted in a minimum density of 2400

kg/m^3 , a maximum of 2800 kg/m^3 , and a mean of 2700 kg/m^3 . These estimated densities are useful for proper processing and interpretation of the AGG data.

Looking beneath the sand dunes

The effects of structures beneath the sand dunes are best revealed by using the estimated density of the dune sand as the terrain correction density (Figure 4). A gravity gradient high is revealed over the dunefield, where only the signature of the dunes was apparent in nonterrain corrected data and data corrected using an inappropriate density (Figure 3). The anomaly signature is more apparent in data that have been upward continued 200 m, a filtering process that highlights the effects of relatively deep and/or broad features (Blakely, 1995). The simplest interpretation of the gravity gradient high is that it reflects buried high-density rocks under the sand dunes, likely in the form of fault-bound Precambrian rocks at an intermediate elevation between surface exposures in the Sangre de Cristo Mountains to the east and the deeper San Luis Basin to the west. Other features with similar gravity gradient expressions are present in the northern and southern parts of the study

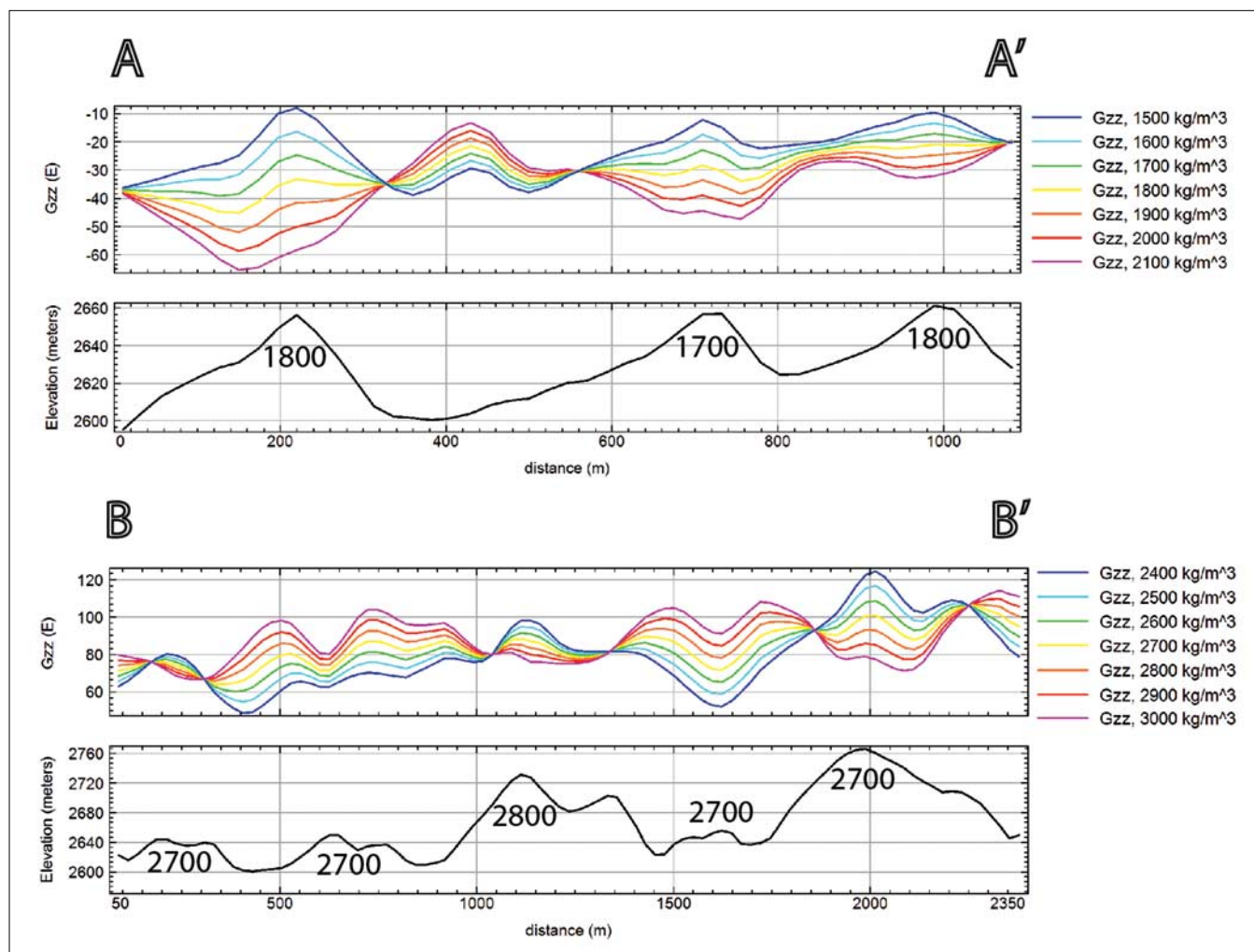


Figure 3. Nettleton-style profiling for density estimation. Profile A-A' is for the dunefield sand, and profile B-B' is for Precambrian rocks of the Sangre de Cristo Mountains range front. Individual density estimates are posted on selected topographic features.

area, and may reflect additional buried basement benches or structural highs.

If careful attention had not been paid to surface density, it is improbable that the hypothesized buried basement benches would be accurately mapped with other filtering methods. The anomalies caused by the dunes (Figure 2) are broad enough that neither upward continuation nor matched filtering of AGG data with inappropriate terrain corrections satisfactorily isolates the anomalies because of the buried structures. This also implies that surveying from a higher observation surface, as opposed to only 80 m above the ground, would also not be as effective as using properly chosen surface densities for terrain correction.

Conclusions

Airborne gravity gradient (AGG) data are especially well-suited to mapping the effects of near-surface terrain and geology. Processing of AGG data is similar to processing of gravity data in that the density effects of near-surface rocks and/or sediments must be properly identified and removed. Where significant terrain exists, the effects of the terrain can be exploited to interpret the densities of near-surface geology. An example of such an approach is Nettleton-style profiling to estimate terrain density, a method long used with gravity field data but even better suited for AGG data. Application of the method to high-resolution AGG data at GRSA, where ground-based gravity is impractical because of difficult access, yields an estimated density of dry dunefield sand of 1800 kg/m³, and an estimated density of 2700 kg/m³ for Precambrian rocks at the Sangre de Cristo Mountains range front. Further processing of the AGG data using the 1800 kg/m³ density of the dunefield allows mapping of structures beneath the dunefield. There, an AGG high reflects relatively dense rocks, with the simplest interpretation being a previously unknown buried bench of Precambrian rocks. From a philosophical standpoint, careful consideration of both terrain and density (i.e., geology) is viewed as the best approach to AGG data interpretation in areas of high relief. **TLE**

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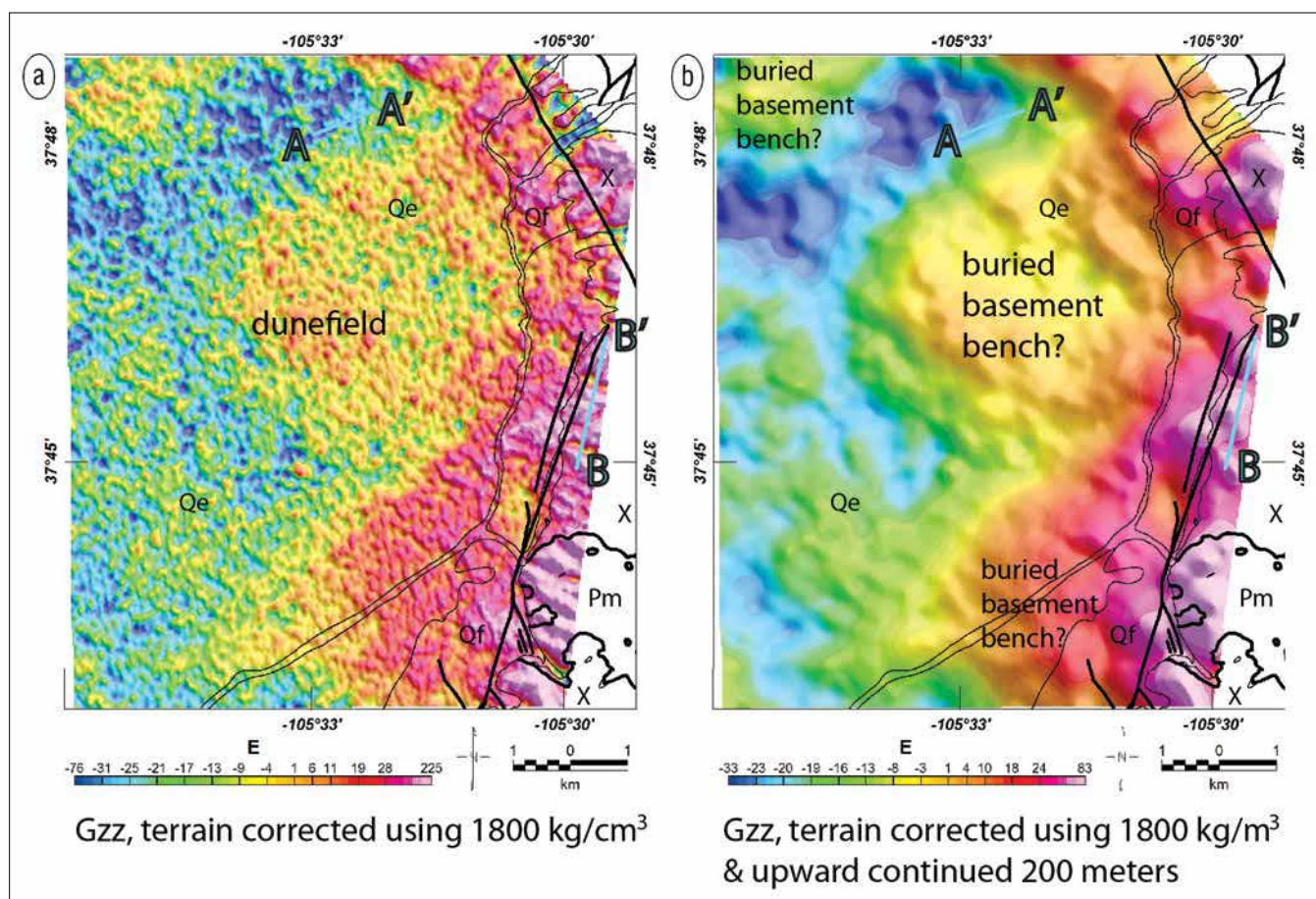


Figure 4. Gzz (vertical derivative of the vertical gravity field, Eotvos) terrain corrected using a density of 1800 kg/m³, the density estimated for dunefield sand (a), and upward continued 200 m to accentuate effects of buried features (b). Hypothesized buried basement benches labeled.

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Acknowledgments: Tien Grauch, Jeff Phillips, and Jeff Lucius provided helpful reviews. GRSA staff members, especially Andrew Valdez and Fred Bunch, provided critical assistance to U.S. Geological Survey research in the park and surrounding areas. This work was supported by the National Cooperative Geologic Mapping and Mineral Resource Programs of the U.S. Geological Survey. Any use of trade names is for descriptive purposes only and does not imply endorsement by the U.S. government.

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