Guides to understanding the aeromagnetic expression of faults in sedimentary basins: Lessons learned from the central Rio Grande rift, New Mexico

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ABSTRACT

High-resolution aeromagnetic data acquired over several basins in the central Rio Grande rift, north-central New Mexico, prominently display low-amplitude (5–15 nT) linear anomalies associated with faults that offset basin-fill sediments. The linear anomalies give an unparalleled view of concealed faults within the basins that has significant implications for future basin studies. These implications provide the impetus for understanding the aeromagnetic expression of faults in greater detail. Lessons learned from the central Rio Grande rift help to understand the utility of aeromagnetic data for examining concealed faults in sedimentary basins in general. For example, linear anomalies in the rift can be explained entirely by the tectonic juxtaposition of magnetically differing strata rather than the product of chemical processes acting at the fault zone. Differences in layer thickness, depth to the layer(s), and magnetic susceptibility govern the variability of the anomaly shape. Further investigations of these variables using simple models provide graphical, mathematical, and conceptual guides for understanding the aeromagnetic expression of faults, including the criteria for aeromagnetic expression of faults, how to locate fault traces from aeromagnetic anomalies, the effect of fault dip, and how to assess the role of topography. The horizontal gradient method applied to reduced-to-pole aeromagnetic data is particularly effective in mapping fault locations, especially at regional scales. With our new understanding of the aeromagnetic expression of faults, we updated interpretations of faults from the aeromagnetic data for the central Rio Grande rift. These interpretations, along with the guides, should provide direction and fuel for future work in a wide variety of multidisciplinary basin-related topics.

Keywords: aeromagnetic surveys, faults, faulting, sedimentary basins, rifts.

INTRODUCTION

High-resolution aeromagnetic data acquired over the central Rio Grande rift (Fig. 1) reveal numerous subtle, northerly trending, linear anomalies that are widespread across the basin areas. The anomalies are best delineated in shaded-relief images, as demonstrated in an area over Rio Rancho, northwest of Albuquerque, New Mexico (Fig. 2). Linear anomalies are interpreted as faults that offset basin-fill sediments based on their consistent correspondence to isolated exposures of mapped faults, follow-up investigations at individual sites, and geophysical modeling (Grauch, 2001; Grauch et al., 2001, 2006).

As in many sedimentary basins, mapping faults in the central Rio Grande rift is difficult because of the extensive alluvial cover. As a consequence, geologists have used the linear aeromagnetic anomalies to delineate partially concealed faults and denote possible locations of totally buried faults on geologic maps (e.g., Connell, 2006) and in fault compilations (Machette et al., 1998; Personius et al., 1999). The benefit of using aeromagnetic data to locate faults in conjunction with geologic mapping is exemplified in the Hubbell Spring area, south of Albuquerque (Fig. 3). The aeromagnetic data reveal a comprehensive view of the fault patterns and provide evidence for a significant, previously unknown fault system located under cover east of the Hubbell Spring fault (“buried faults” on Fig. 3B).

As demonstrated by the Rio Rancho and Hubbell Spring examples, the aeromagnetic data imply that faults are much more numerous than previously suspected throughout the basins in the central Rio Grande rift. This inference has significant implications for a variety of structural topics, such as the evolution of structural styles involved in rifting, the amount of basin extension, the linkage between intrabasin and basement faults, and relations between fault trace length and fault throw. The numerous linear anomalies have already led hydrologists to consider the important role that faults may play in compartmentalizing basin aquifers and controlling ground-water flow in the central Rio Grande rift (Bartolino and Cole, 2002; Heywood et al., 2002).

Although subtle linear anomalies are associated with faults in other sedimentary basins (Gunn, 1997; papers in Peirce et al., 1998; Smith et al., 2002), the ones in the central Rio Grande rift are prominent and generally isolated from interfering anomalies, providing excellent illustrative examples for study. For example, a significant conclusion from earlier studies is that the source of the anomalies is the tectonic juxtaposition of magnetically differing strata rather than the product of chemical processes acting at the fault zone (Grauch et al., 2001, 2006; Hudson et al., 2008). This conclusion suggests that chemical processes are not required to explain fault-related anomalies. In fact, no definitive case study showing that the effects of chemical processes at fault zones are significant

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Figure 1. Regional geology and topography of the central Rio Grande rift, showing the locations of the Albuquerque, Santo Domingo, and southern Española basins. Generalized geology (New Mexico Bureau of Geology and Mineral Resources, 2003; Machette et al., 1998) is overlain on a shaded digital elevation model (U.S. Geological Survey National 30 m digital elevation data). ABQ—Albuquerque. Inset map locates the map area with respect to basins of the Rio Grande rift in Colorado and New Mexico.
Figure 2. Color shaded-relief image of reduced-to-pole (RTP) aeromagnetic data for the Rio Rancho area (Sweeney et al., 2002). The colors primarily reflect the broad variations in the data, whereas the illumination (from the west) emphasizes detailed variations, especially linear features associated with faults. Geologic contacts from New Mexico Bureau of Geology and Mineral Resources (2003). QTS—Quaternary and Tertiary sediments (Santa Fe Group and alluvial cover). QTb—Quaternary and Tertiary basaltic and andesitic rocks, undifferentiated. Mz—Mesozoic sedimentary rocks. Asterisks indicate volcanic vents. See inset for location. Labeled profiles are shown in Figures 6 and 11. Dashed white boxes show areas of Figures 11 and 12.
Aeromagnetic expression of faults in sedimentary basins

enough to produce anomalies detected by aeromagnetic surveys is known in the literature (Nabighian et al., 2005; Mushayandebvu and Davies, 2006). These considerations suggest that tectonic juxtaposition of faulted strata may be a common cause of linear anomalies in sedimentary basins.

Given the likelihood that tectonic juxtaposition explains many fault-related aeromagnetic anomalies in sedimentary basins, the next step is to investigate the relation in greater detail. In particular, we seek to answer the following questions:

- What is required for a fault to produce an aeromagnetic anomaly?
- How does one locate a concealed fault trace from an anomaly?
- Can fault displacement and geometry be determined from an anomaly? and
- How much of the anomaly is due to topography?

We use lessons learned from studies of the sources of linear anomalies in the central Rio Grande rift to develop guides for answering these questions. The guides rely on understanding the relations of juxtaposed strata, fault geometry, and magnetic properties to the variations in the aeromagnetic signatures. Based on the understanding gained at individual faults, we then develop a systematic procedure for mapping faults from aeromagnetic data at scales more regional than 1:24,000. Examples of the utility and limitations of this procedure provide guides to using linear anomalies for mapping concealed faults.

The guides in this report can be used in the central Rio Grande rift or in other sedimentary basins to examine the concealed portions of individual faults, judge the utility and limitations of aeromagnetic interpretations of faults at local or regional scales, and assess the feasibility of collecting new aeromagnetic data for fault studies. A byproduct of developing these guides is a digital compilation of aeromagnetically inferred faults for the central Rio Grande rift. We hope this compilation, used in conjunction with the guides, will benefit a myriad of future investigations concerning the central Rio Grande rift or the structural aspects of sedimentary basins in general.
The magnetic properties important to assess for aeromagnetic interpretation include magnetic susceptibility, which is primarily a function of the quantity of magnetic minerals, and remanent magnetization, which represents the vector sum of permanent magnetizations held by the magnetic minerals. Magnetic susceptibility multiplied by a vector representing Earth's present-day magnetic field gives the induced magnetization. The vector sum of the induced and remanent magnetizations gives the total magnetization, a value required to compute the magnetic fields of models. Traditionally, magnetic susceptibility (a dimensionless number in the SI system) is reported rather than its associated vector quantity, induced magnetization. In contrast, remanent magnetization is commonly reported as intensity in A/m (SI) with a given orientation (declination and inclination).

Generally, both magnetic susceptibility and remanent magnetization are much lower in magnitude for sedimentary rocks and sediments than for igneous and metamorphic rock types (Reynolds et al., 1990). Detailed magnetic-property studies in two areas of the Albuquerque basin show that total magnetizations of the Santa Fe Group fall toward the high end of the range for sedimentary rock types and are dominantly a function of magnetic susceptibility (Hudson et al., 1999a; 2008). The remanent component likely accounts for less than 25% of the magnitude of the total magnetization (Köningsburger or Q ratios less than 0.25) and causes negligible deviation in the direction of the total magnetization from one that is parallel to Earth’s magnetic field (Hudson et al., 1999a; 2008). For these reasons, and given most geologists’ greater familiarity with magnetic susceptibility rather than magnetization, we simplify all following discussions by referring only to magnetic susceptibility.

Results from one of the detailed magnetic-property studies of the Santa Fe Group has been particularly useful for examining not only the magnetic properties, but how the properties are distributed into magnetic sources that produce the aeromagnetic expression of the fault (Hudson et al., 2008). In this study, magnetic susceptibility measurements from 310 sites were measured on both sides of the San Ysidro fault (Fig. 2) and were used to characterize the magnetic properties of stratigraphic units in terms of geometric mean and typical ranges of value (Fig. 4). Members of the Arroyo Ojito Formation, representing the fluvial dominated upper Santa Fe Group, show variable magnetic susceptibilities, with a typical range (determined by the 25th and 75th percentiles of the populations) of 0.9–4.3 $10^{-3}$ (SI). The higher susceptibility values of the Arroyo Ojito Formation generally correspond to coarser sediment grain size, with coarse sands and gravels of the youngest member exhibiting the highest values (Fig. 4). Members of the Zia Formation, representing eolian-dominated sands of the lower part of the Santa Fe Group, show less variation in magnetic susceptibility and less correlation with grain size compared to those of the Arroyo Ojito Formation. Susceptibility values for the Zia Formation have a typical range of 0.7–1.4 $10^{-3}$ (SI). Pre-rift sedimentary rocks, primarily shales and sandstones, display magnetic susceptibilities that are generally an order of magnitude less than the syn-rift units, typically 0.7–2.0 $10^{-4}$ (SI). Although faults are commonly cemented throughout the basin (Minor and Hudson, 2006), the cemented zones are too narrow and their variations in magnetic properties too small to be significant for aeromagnetic studies (Grauch et al., 2001; Hudson et al., 2008).

Magnetic susceptibilities measured for core samples of the Arroyo Ojito Formation from the west-central part of the Albuquerque basin (Hudson et al., 1999a) give similar results as the San Ysidro fault study. Reconnaissance measurements of magnetic susceptibility of Santa Fe Group sediments from other parts of the central Rio Grande rift confirm that values are on the order of 1 $10^{-3}$ (SI) for the dominant sand fraction. Exceptional magnetic susceptibilities on the order of 1 $10^{-2}$ (SI) have been measured for eolian sands that form a thin cover over some areas and sandstones containing high amounts of volcanic ash that are locally present along the
Aeromagnetic expression of faults in sedimentary basins

Aeromagnetic data are standardly collected from aircraft following a regular pattern of flight lines over an area. The collected data are processed to remove noise and the effects of Earth’s primary magnetic field to isolate the subtle variations related to geology. The processed data are gridded at an interval commensurate with the flight-line spacing before they are displayed as aeromagnetic anomaly maps. High-resolution surveys are flown closer to the ground and with narrower line spacing than conventional aeromagnetic surveys. The low flight height allows better detection of weak magnetic sources near the surface. The narrow line spacing increases sampling of the magnetic field and thus provides better definition of sources with limited lateral extent and improves the overall resolution of details in map view. Surveys designed with a line spacing that is similar to the flight height provide optimal resolution for interpretation of data in map view (Reid, 1980; Nabighian et al., 2005).

Aeromagnetic data for the central Rio Grande rift were assembled from seven individual surveys, flown mainly during 1996–1998 (Fig. 5; Sweeney et al., 2002). One was flown more recently to fill in coverage east of Santa Fe (area A on Fig. 5; Bankey et al., 2006). The surveys avoided the Albuquerque city center because of the large concentration of iron-bearing anthropogenic structures that mask the effects of geologic features. All but two of the surveys were flown for optimal map resolution, using east-west lines spaced 100–150 m apart and a magnetometer height nominally 100–150 m above ground. To save on cost, the Santa Fe East survey (area A on Fig. 5) was flown with 200-m line spacing at nominal 150 m above ground. The Cochiti survey (area C on Fig. 5) was flown with 400-m line spacing at nominal 73 m above ground as part of an electromagnetic survey that required a different survey design (Sweeney et al., 2002; Deszcz-Pan et al., 2000).

Before interpretation, the aeromagnetic data from the seven surveys were analytically continued from the variable observation surfaces to a common surface draped 100 m above ground, digitally merged into a 50-m-interval grid, then transformed to reduced-to-pole (RTP) data, as described in Sweeney et al. (2002). The RTP transformation, a standard geophysical technique for areas of high latitude (Blakely, 1995), corrects for shifts of anomalies from the centers of their magnetic sources. These shifts occur because of the oblique orientation of the measured magnetic field with respect to Earth’s surface (the field is vertical at the magnetic poles). A related technique, called the pseudogravity transformation (or computation of the magnetic potential) also minimizes these shifts, while enhancing the broad features of the data. The RTP and pseudogravity transformations are best utilized in areas where the total magnetizations of sources are generally collinear (within 25°) of Earth’s main field (Bath, 1968). General collinearity is a reasonable approximation for most of the study area because of the Neogene age of basin units and lack of significant tectonic rotation over most of the area. The RTP aeromagnetic data for the central Rio Grande rift assume Earth’s field has declination = 11° and inclination = 63°. Plate 1 shows these data, annotated for selected geologic and geographic features at a map scale of 1:250,000.

THE AEROMAGNETIC EXPRESSION OF FAULTS

Linear anomalies associated with faults in sedimentary basins are generally very subtle, especially compared to the anomalies produced by shallow volcanic rocks or underlying basement. In the central Rio Grande rift, they have typical amplitudes of 5–15 nT, much less than the amplitudes of several hundred nT associated with the broad anomalies caused by underlying basement and the intense anomalies caused by neighboring volcanic rocks (Fig. 2). Linear anomalies of similar character and amplitude are also evident from high-resolution aeromagnetic data flown over Dixie Valley, in the Basin and Range Province of Nevada. The linear anomalies coincide with shallow faults that offset basin sediments and are superposed on large-magnitude anomalies related to volcanic and igneous rocks that comprise the basin floor (Smith et al., 2002). Lack of similar linear anomalies in high-resolution aeromagnetic data over the Tucson basin, Arizona, is explained by a thick cover of young sediments that were not cut by earlier extensional faulting (Rystrom, 2003).

The expression of faults as linear aeromagnetic anomalies contrasts with fault expression in high-resolution aeromagnetic data from other rift basins, where uplifting involved a higher degree of magmatism. In these cases, magnetic anomalies primarily reflect the magnetic igneous rocks, and faults are indicated indirectly by breaks in the anomaly patterns (Modisi et al., 2000; Cannon et al., 2001).

The Underlying Cause

Faults produce linear anomalies in sedimentary basins owing either to tectonic juxtaposition of strata with differing magnetic properties or to alteration of magnetic properties along the fault plane (Gunn, 1997). Lack of exposure commonly prevents distinction between these two origins (Mushayandebvu and Davies, 2006). In contrast, serendipitous exposures in the central Rio Grande rift have provided opportunities to establish that...
Figure 5. Index map showing the locations, names, and acquisition years of aeromagnetic surveys from which data were obtained for this report (Sweeney et al., 2002; Bankey et al., 2006). Geologic and topographic base from Figure 1.
Plate 1. Color shaded-relief image of reduced-to-pole (RTP) aeromagnetic data for the central Rio Grande rift, compiled from Sweeney et al. (2002) and Bankey et al. (2006). The colors primarily reflect the broad variations in the data, whereas the illumination (from the west) emphasizes detailed variations, especially linear features associated with faults. Selected geographic, geologic, and interpretative features are labeled. Map projection is NAD27, UTM zone 13, in units of meters. Inset shows locations and names of aeromagnetic survey areas. Map scale 1:250,000. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00128.S1 or the full-text article on www gsajournals.org to access the full-size file of Plate 1.
the fault-related anomalies are principally explained by tectonic juxtaposition (Grauch et al., 2001; Hudson et al., 2008; Grauch et al., 2006).

In profile form, the linear anomalies in the central Rio Grande rift demonstrate a range in shape, from a single curving ramp to multiple ramps and peaks associated with one apparent anomaly in map view (Fig. 6). The range of anomaly shapes can be explained by differences in the relations between the thicknesses and magnetic properties of strata juxtaposed at faults (Grauch et al., 2001). These differences can even explain the presence of aeromagnetic lows over a fault zone, a counterintuitive situation that may previously have been mistaken as the expression of alteration along the fault zone.

Juxtaposition of strata can also produce multiple, vertically stacked magnetic sources at a single fault. A detailed study of the San Ysidro fault (Grauch et al., 2006), located in the northwest part of the Rio Rancho image (Fig. 2), demonstrated that several magnetic contrasts were distributed at depth along the fault plane, caused by multiple strata juxtaposed at the fault. The aeromagnetic expression differed along strike of the fault between the southern area, where the entire stack of juxtaposed strata was preserved, and the northern area, where erosion had removed the overlying strata, bringing the underlying juxtaposed strata closer to the surface.

The primary factors driving the aeromagnetic expression of faulted strata involve differences in how the strata are juxtaposed at the fault, the magnitudes of the magnetic-property contrasts, and the depths where the contrasts occur (Grauch et al., 2001; Grauch et al., 2006). The effect of fault dip becomes increasingly important with greater depth of the magnetic contrast. In the central Rio Grande rift and perhaps in sedimentary basins in general, this effect is less important than the other factors because faults are commonly steeply dipping and magnetic contrasts are generally shallow, as discussed below. In the following sections, we examine these factors in terms of the main geophysical parameters that drive anomaly variability, and then discuss the geologic and magnetic-property criteria for expression of faults in aeromagnetic data.

**Geophysical Parameters**

To understand the primary geophysical parameters that drive anomaly variability at faults, we first translate a model of juxtaposed strata into a geophysical model that isolates the main variables. Sedimentary strata can be reasonably represented in geophysical models as uniformly magnetized layers with finite thickness extending laterally to infinity. Based on geophysical principles, if such a layer is horizontal, it will not produce an anomaly, no matter what its magnetic susceptibility (Blakely, 1995). If two such layers of differing magnetic susceptibilities are truncated and juxtaposed against each other at a fault, then the lateral magnetic contrast at the juxtaposition boundary will produce a magnetic anomaly. The resulting observed anomaly is a function of the difference between the magnetic susceptibilities of the layers (lateral magnetic contrast), the extent and dip of the juxtaposed boundary (vertical extent), and the distance of the magnetometer away from the boundary (observation height plus depth below ground).

The concept of lateral magnetic contrast can be counterintuitive, because it implies that high magnetic susceptibility is not a sufficient condition to produce an anomaly. The concept also may be difficult to visualize at faults where multiple strata are juxtaposed. For this reason, we develop models of equivalent magnetic-contrast layers, which are constructed from a stratigraphic model by inspecting the lateral magnetic contrast only. A magnetic-contrast layer is assigned a magnetic susceptibility that is the positive difference between the magnetic susceptibilities of two strata across a fault and is placed on the side with the higher magnetic susceptibility. It is given a thickness that represents the vertical extent of the juxtaposition between the two layers. Where two layers with the same magnetic susceptibilities are juxtaposed, no magnetic-contrast layer is constructed. Figure 7 illustrates these concepts. Strata in a hypothetical fault model were assigned values of arbitrary magnetic...
susceptibility and juxtaposed along a fault with 400 m of throw (Fig. 7A). The equivalent magnetic-contrast model (Fig. 7B) translates all the juxtapositions of strata into layers with positive magnetic contrast, which occur on both sides of the fault. Computation of the magnetic effects of the stratigraphy-based and equivalent magnetic-contrast models shows that both models produce identical anomalies (Fig. 7). Importantly, the layers of magnetic contrast in the geophysical model are not equivalent to the strata in the geologic model; they merely represent the aggregate contrast in magnetic properties across the fault.

Given a known observation height, the primary geophysical variables governing the anomaly produced by a magnetic-contrast layer are the magnitude of the magnetic contrast, depth to the top of the layer, and layer

Figure 7. Magnetic-contrast layers derived from a geologic model. (A) Hypothetical geologic model of an intrasedimentary fault with 400 m of vertical throw. (B) Its equivalent geophysical model to demonstrate the concept of lateral magnetic contrast. The matching computed curves for both models (observed at 100 m above ground) demonstrate the equivalency of the models. Magnetic-contrast layers are constructed by inspecting only the lateral contrast in magnetic susceptibility between juxtaposed strata in (A). Where two juxtaposed strata have different susceptibilities, the magnetic-contrast layer is assigned to the side of the fault having greater susceptibility in (B). Its thickness is determined by the vertical extent of the juxtaposition between the two strata. Note the contribution of magnetic terrain effects from the hill composed of strata B, which has a magnetic susceptibility contrasting with adjacent nonmagnetic air.
Criteria for Aeromagnetic Expression

In this section, we examine the values of the geophysical parameters required for juxtaposed strata to produce an aeromagnetic anomaly for the study area. Using a simple truncated-layer, magnetic-contrast model (Fig. 8A), we can examine the values and relations required for magnetic contrast, thickness, and depth of the layer utilizing relations developed extensively in the geophysical literature (e.g., Reford and Sumner, 1964; Grant and West, 1965; Grant and Martin, 1966; Stanley, 1977; Rao and Babu, 1983; Rao et al., 1987; Telford et al., 1990; Murthy et al., 2001). For simplicity, we consider the truncated-layer model with vertical dip and vertical Earth’s field inclination (equivalent to RTP data). Using the notation of Figure 10 and considering anomaly magnitude as the difference between the maximum and minimum values of the anomaly profile, we can obtain an expression for magnetic susceptibility contrast \( \Delta m \) as a function of anomaly magnitude \( T_{\text{anom}} \), thickness of the layer \( t \), depth to the layer \( d \), and observation height \( h \), as

\[
\Delta m = \frac{\pi T_{\text{anom}}}{F_0} \left[ \tan^{-1} \left( \frac{d + h + t}{d + h} \right) - \cot^{-1} \left( \frac{d + h + t}{d + h} \right) \right] \tag{1}
\]

where \( F_0 \) is the strength of Earth’s magnetic field (considering a reduced-to-pole aeromagnetic map), and the arctangent arguments are in radians.

The gallery of simple stratigraphic models (Fig. 9) illustrates how various geologic scenarios can produce the four typical aeromagnetic signatures. The relations of Equation (1) are best visualized in graphical form. To demonstrate, we use typical and known values for the aeromagnetic data for the central Rio Grande rift: Earth’s field \( F_0 = 51,715 \text{nT} \), observation height \( h = 100 \text{m} \). In addition, depths estimated from anomalies range from 0 to 100 m for the most prominent ones and 200–500 m for the more subtle ones (Grauch et al., 2001). Thus, magnetic-susceptibility contrast \( \Delta m \) is plotted versus magnetic-contrast layer thickness \( t \) for two typical depths, \( d = 0 \) and 100 m, using two choices for the assumed minimum required to be observable in the data set, \( T_{\text{anom}} = 2 \text{nT} \) or 5 nT (Fig. 10). This thickness-contrast graph provides a rough guide to the geophysical criteria for aeromagnetic expression of faults in the study area. The graph is similar to one developed earlier to show the relation between anomaly amplitude and layer thickness represented as a percentage of depth (Reford and Sumner, 1964). To easily modify the use of the \( T_{\text{anom}} = 2 \text{nT} \) curves for different values of \( T_{\text{anom}} \), multiply the values on the magnetic-contrast scale (y-axis) by the ratio of the new \( T_{\text{anom}} \) divided by 2. The division by 2 represents the ratio with the 2-nT threshold currently shown in Figure 10.

Although layer thickness \( t \) of a single truncated-layer model is not always equivalent to fault throw, the thickness-contrast graph can still provide general guides on the amount of throw and magnetic contrast required for a fault to have aeromagnetic expression. For the parameters that we chose for the central Rio Grande rift, the following generalizations can be used as guides.
Figure 8. Simple magnetic-contrast layer models representing four main types of aeromagnetic signatures associated with intrasedimentary faults in the study area. Shown for each model are computed total-field anomaly curves (bold solid lines) and the derived horizontal gradient magnitude of reduced-to-pole data (HGM of RTP—solid gray lines) and of pseudogravity data (HGM of pseudogravity—dashed gray lines). (A) The truncated-layer model involves only one layer, truncated at the fault. (B) The offset-layer model represents two offset layers with equal thickness and magnetic susceptibility. (C) The contrasting-layers model represents two offset layers with equal thickness but contrasting magnetic susceptibilities. (D) The thin-thick layers model represents two offset layers with the same magnetic susceptibilities but with a much thicker lower than upper layer. The anomaly curves were computed from polygonal models using Earth’s field, inclination, and declination of 51,715 nT, 63°, and 11°, respectively. The HGM curves involve a transformation to Earth’s field inclination of 90° and 0°, respectively, before taking the horizontal gradient magnitude. Magnetic susceptibilities are in SI units.
Figure 9. Gallery of hypothetical stratigraphy-based models (colors) that are equivalent to the four types of simple magnetic-contrast models (patterns) of Figure 8. Magnetic susceptibility values (SI units) are assigned to each hypothetical stratigraphic unit and give rise to equivalent contrasts for the magnetic-contrast layers. Fault throw is indicated for each geologic model. Truncated-layer geophysical models arise from hypothetical geologic models of (A) an eroded normal fault, (B) an eroded normal fault or a growth fault, (C) an eroded normal fault or a growth fault with magnetic colluvium on the hanging wall. Offset-layers geophysical models arise from hypothetical geologic models of (D) a normal fault with alternating weakly and moderately magnetic units, and (E) a normal fault with the opposite alternation of strata. A contrasting-layers geophysical model arises from a hypothetical geologic model of (F) a normal fault offsetting a magnetic unit, with moderately magnetic colluvium on the hanging wall. Thin-thick layers geophysical models arise from hypothetical geologic models of (G) an eroded normal fault, and (H) an eroded normal fault or a growth fault with moderately magnetic colluvium on the hanging wall.
A magnetic-susceptibility contrast less than \( 0.2 \times 10^{-3} \) (SI) likely will not produce an observable anomaly, even for faults with >500 m of throw.

A fault with throw less than 10 m likely will not produce an observable anomaly even for a magnetic-susceptibility contrast as high as \( 3.0 \times 10^{-3} \) (SI).

More specific guides can be added, if we assume that typical magnetic-susceptibility contrasts are on the order of \( 1.0 \times 10^{-3} \) (SI), as is applicable to the central Rio Grande rift.

Faults projecting to the surface will generally require at least 30 m of throw to produce observable aeromagnetic anomalies.

Where the top to the first magnetic-contrast layer occurs at depths of 100–300 m, faults generally require more than 50–100 m of throw to produce observable aeromagnetic anomalies.

Considering that intrabasin faults exposed in the central Rio Grande rift commonly meet the criteria of the latter two generalizations, it is not surprising that so many of them are expressed in the aeromagnetic data. On the other hand, aeromagnetic data for the northeastern part of the study area show little to no expression of multiple faults mapped there (latitudes 35°52'30″ to 36° and longitudes −105°52'30″ to −106° on Plate 1). Faults in this area have displacements as much as 100 m and accommodate homoclines and horsts (Koning et al., 2002). Although reconnaissance measurements show magnetic susceptibilities on the order of \( 1 \times 10^{-3} \) (SI) for Santa Fe Group sediments, a contrast in magnetic properties must be lacking at depth.

Three important caveats apply to the use of the thickness-contrast graph (Fig. 10). First, layer thickness should not be equated to fault throw without adequate knowledge of magnetic susceptibility values and stratigraphy for

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**Figure 10.** Thickness-contrast graph illustrating the minimum parameters required to produce an observable anomaly in the reduced-to-pole aeromagnetic data (given for both 2 nT and 5 nT). Inset describes the parameters, notation, and Equation (1) used to produce the graphs from a simple truncated layer model with vertical face. Curves represent the layer thickness \( t \) (meters) and magnetic contrast \( \Delta m \) (SI susceptibility) required to produce the specified \( T_{\text{anom}} \) for depths \( d \) of 0 (at the surface) and 100. \( \Delta m \) assumed to be SI magnetic susceptibility.

See text on the uses and limitations of this graph. Earth's magnetic field \( F_0 = 51715 \) nT, declination = 0°, inclination = 90°. To use the \( T_{\text{anom}} = 2 \) nT curves for different anomaly amplitudes, the magnetic-contrast scale can simply be multiplied by the ratio of the new amplitude over an amplitude of 2 nT, as detailed in Equation (2).
that fault. For faults that can be represented as a single truncated-layer model, layer thickness is indeed a good representation of fault throw. However, this approximation fails for faults that are best represented by multiple magnetic-contrast layers. Magnetic-contrast layers on opposing sides of the fault (e.g., Figs. 9D–9H) can be viewed as two truncated-layer models with interfering anomaly lows and highs, resulting in a reduction of the overall amplitude of the anomaly. For these situations, the thickness-contrast graph gives the minimum parameters required to produce a given anomaly. The presence of opposing magnetic-contrast layers could be recognized by comparing observed profiles to the signatures of the simple models with opposing layers (Figs. 8B–8D and 9D–9H). For faults that are equivalent to two truncated layers on the same side of the fault (e.g., Fig. 8C), the two layers both contribute to the amplitude of the anomaly high, resulting in an overestimation of fault throw using the thickness-contrast graph.

Second, the graph should not be used to estimate depths to the magnetic contrast for a given anomaly. Instead, hypothetical depths should be fixed and the other parameters derived from those. Although depth is a factor in determining the magnitude of an anomaly produced by a particular magnetic contrast, standard geophysical techniques rely on the shape of the anomaly to determine depth rather than its magnitude. Deep magnetic contrasts produce broad anomalies, whereas shallow ones produce narrow or sharp anomalies, apart from the particular anomaly amplitudes. The hypothetical depths to use with the thickness-contrast graph could be estimated beforehand through geophysical analysis of a particular anomaly, qualitative comparison with anomalies where the fault parameters are known, or geologic considerations.

Finally, deposits that locally occur next to paleo-fault scarps can enhance magnetic contrasts in addition to those caused by tectonic juxtaposition. These deposits include fault colluvium, calcic soils, or coarse-grained stream sediments. Estimates of magnetic contrast using field measurements should account for local deposits as well as those from the stratigraphic layers juxtaposed at the fault.

**LOCATING FAULT TRACES FROM ANOMALIES**

Fault traces can be approximately located from anomalies by locating the surface projection of the top edge of the shallowest magnetic contrast layer (Fig. 8). We seek a method to locate this edge without knowledge of the underlying configuration of magnetic-contrast layers. Common approaches to locating edges from aeromagnetic data utilize mathematical derivatives, based on the behavior of the magnetic field over an ideal, near-vertical layer of finite or infinite thickness (Nabighian et al., 2005). These approaches are desirable because they can provide quick and objective analyses of the aeromagnetic data, especially over large areas. The choice of method to apply is a matter of preference, and is commonly dependent on the particular data set at hand. A method that works well for aeromagnetic data of the central Rio Grande rift is the horizontal gradient method, which uses the local maxima of the horizontal gradient magnitude (HGM) of RTP magnetic or pseudogravity data to find steepest gradients associated with near-vertical boundaries (Cordell and Grauch, 1985). Advantages of the horizontal-gradient method over other derivative based methods are its stability in the presence of noise (Phillips, 2000) and its simple application to grids, without requiring adjustment of extra parameters. On the other hand, application of the horizontal gradient method to anomalies where the sources are strata cut by dipping faults requires some adjustment in approach. In the following sections, we discuss how the application of the method can be adjusted to account for the variability of anomaly shape and the presence of dipping faults.

**Using Horizontal Gradient Magnitude (HGM)**

Traditional application of the horizontal-gradient method for delineating faults is demonstrated by the HGM curves computed for the truncated-layer and offset-layers geophysical models (Figs. 8A and 8B), where the HGM curves peak over the top edges of the truncated magnetic-contrast layers. The trace of the fault can be approximately located by mapping the HGM peak. The multiple HGM peaks in the other two models (Figs. 8C and 8D) result from the unique geometry and relation between the magnetic-contrast layers. These situations require a different approach. Contrary to geophysical intuition, transformation to pseudogravity before computing the HGM does not always eliminate the multiple peaks (Fig. 8; Grauch et al., 2001).

Note that despite the variability of aeromagnetic signatures and the multiple peaks of the HGM curves, there is always a peak of the HGM of RTP curve that is located directly over the top edge of the shallowest magnetic-contrast-layer in the geophysical models (Fig. 8). The HGM of pseudogravity fails to locate this edge in the important case of the thin-thick model (Fig. 8D). It is notable that the same problem occurs for the analytic signal, an operation that forms the basis of many popular geophysical methods to locate and estimate depths to faults (Nabighian et al., 2005). Where the HGM of RTP has multiple peaks, the peak over the top edge can be recognized as the narrowest one (Figs. 8C and 8D). The width of the HGM peak is related to depth of the causative edge (Roest and Pilkington, 1993); the narrowest peak is related to the shallow depth of the edge. These results suggest that the horizontal gradient method applied to RTP data can be used to map the near-surface traces of faults, as long as multiple peaks are identified properly.

Figure 11 demonstrates the interpretation of fault locations for an area in the central Rio Grande rift that includes anomalies with a wide range of shapes in profile form (from Fig. 6). The RTP anomalies (Fig. 11A), the HGM of the RTP data (Figs. 11B and 11C), and a digital elevation model (Fig. 11D) are shown in map view. For ease of comparison, interpreted fault locations (yellow lines) are overlain on one of the HGM of RTP images (Fig. 11C) and are absent on the other (Fig. 11B). In Figure 11E, curves are plotted for the same selected profiles as in Figure 6. In cases with a single HGM peak, such as the anomalies associated with profiles A and B, fault locations are interpreted to coincide with the greatest peak of the HGM. The map view for these fault interpretations shows how they are inferred across areas that have varying magnitudes of the HGM (compare Figs. 11B and 11C). For the anomalies associated with profiles C and D, which have multiple HGM peaks (Fig. 11E), the narrowest HGM peaks were used to map the fault locations. Note that the fault inferred for the anomaly associated with profile D has multiple HGM peaks near the profile location, but appears as one HGM peak farther north (Figs. 11B and 11C). For comparison, Figure 11D shows a digital elevation model for the area with fault locations interpreted from the aeromagnetic data (yellow lines) compared to those inferred independently from geologic mapping (white lines). Note the good correspondence over most of the area.

In practice, application of the horizontal gradient method to RTP data must also address the problem of superposed regional magnetic gradients that alter the shape of the local aeromagnetic signature. The problem can be minimized by applying a filter or other technique to remove the regional anomalies from the data before computing the HGM. Regional-residual separation is standard practice in magnetic interpretation and is most successful when designed specifically for the data at hand (Nabighian et al., 2005). For the central Rio Grande rift, we used a modification of the horizontal-gradient method (gradient window technique) that removes a regional trend from a moving window of the data before computing the HGM (Grauch and Johnston, 2002). Grauch and Johnston...
Figure 11. Demonstration of the interpretation of fault locations for an area in the central Rio Grande rift, located on Figure 2. Profile locations are the same as in Figure 6. All map data are illuminated from the west. (A) The RTP magnetic map using a color display stretched to enhance anomalies for this particular area. The HGM of RTP data are shown without (B) and with (C) interpreted fault locations (yellow lines). (D) Digital elevation model with aeromagnetically interpreted fault locations (yellow lines) and geologically mapped faults (white lines, dashed where uncertain). Mapped faults are from Cather et al. (1997) and Personius et al. (1999, 2000). (E) Curves of RTP data, HGM of RTP, and digital elevation for the same profiles as in Figure 6 to demonstrate how faults are interpreted from the HGM peaks for a range of anomaly shapes.
Grauch and Hudson

(2002) discuss the advantages of this approach in greater detail for an area over the Sand Hill fault, on the northwestern side of the Albuquerque basin (similar to the area of Fig. 12). Using the residual HGM removes the interfering effects of the broad regional gradient due to underlying basement structure (Fig. 2). Similar results can be obtained by computing the HGM of the first vertical derivative of the RTP data, except that interference from anomalies due to anthropogenic sources is more problematic. Although we actually used multiple derivative maps for interpretation of fault locations for the central Rio Grande rift, we found the most useful version to be the residual HGM map. It is available for download in conjunction with this report (see Appendix Table 1) and shown in Plate 2.

Figure 12. Residual HGM maps for the Sand Hill fault area (located on Fig. 2), comparing the observed gradients to those produced by a model of magnetic terrain. All maps are illuminated from the west. (A) The well-exposed Sand Hill fault (solid lines) and partially exposed Calabacillas fault (mainly dashed lines) mapped on an image of topography (fault locations from Machette et al., 1998). (B) Residual HGM of magnetic terrain effects computed from the effects of a topographic model assigned a uniform magnetic susceptibility of $1.0 \times 10^{-3}$ (SI). (C) Residual HGM of RTP aeromagnetic data. Observed gradients due to magnetic terrain effects (MT) in (C) are determined by comparison to (B). It is unclear whether the linear ridge in the HGM of RTP data between the two mapped faults on the south is due to an unrecognized fault, to magnetic sand dunes concentrated along the topographic rim, or both. Data for both residual HGM maps, shown with identical display parameters, were determined by removing a regional trend from a moving 1-km x 1-km window (21 grid points) before computing the horizontal gradient magnitude (Grauch and Johnston, 2002).
Plate 2. Fault locations (white lines) interpreted from aeromagnetic data, overlain on image of horizontal gradient magnitude (HGM) of reduced-to-pole (RTP) aeromagnetic data, illuminated from the west. Interpretation procedure and caveats are described in text. Fault interpretation as of July 2007. Map projection is NAD27, UTM zone 13, in units of meters. Inset shows locations and names of aeromagnetic survey areas. Map scale 1:250,000. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00128.S2 or the full-text article on www.gsaforums.org to access the full-size file of Plate 2.
Lateral Offsets and Effect of Fault Dip

Intuitively, offsets between the locations of HGM peaks and fault traces are expected over dipping faults, caused by the dip geometry and the behavior of the magnetic field over a non-vertical boundary. The dip geometry dictates that points located at depth along a dipping fault plane will have surface projections that are laterally offset from the fault trace. Offsets related to magnetic-field behavior are related to the shape of the magnetic source, analogous to the effects expected for gravity data (Grauch and Cordell, 1987). To examine the significance of both these effects for the study area, we derive an equation for the offset of the HGM peak for a truncated-layer model with large (mathematically infinite) thickness (Appendix 2). Using a model with such a large thickness is a limiting case for all layers with finite thickness, and thus estimates the maximum offset possible. As detailed in Appendix 2, the two combined effects give a total lateral offset $\ell_{\text{offset}}$ of the HGM peak from the fault trace for a fault with dip $\alpha$, depth $d$ to the top of the magnetic-contrast layer, and observation height $h$, as

$$
\ell_{\text{offset}} = 0 \quad \text{for} \quad \alpha = 90^\circ \quad (3a)
$$

and

$$
\ell_{\text{offset}} = d(\cos \alpha + f_\alpha h) \quad \text{for} \quad 0^\circ < \alpha < 90^\circ \quad (3b)
$$

where

$$
f_\alpha = \frac{1 - \sin \alpha}{\cos \alpha}.
$$

For vertical dip ($\alpha = 90^\circ$), there is no lateral offset of the HGM peak from the surface fault trace, no matter what the depth $d$ or height $h$. For dips less than vertical and fixed observation height $h$, lateral offsets increase with increasing depth $d$ and with shallowing dip $\alpha$.

Using an observation height $h$ of 100 m and typical fault dips of 60° to 70° for the study area, we can use Equation (3b) to develop some general rules regarding the maximum lateral offsets to be expected. Depths to the topmost magnetic contrast estimated for most anomalies in the study area, recognized by their prominent aeromagnetic expression, are mainly less than 100 m (Grauch et al., 2001). At these shallow depths, lateral offsets will generally be less than 112 m for dip $\alpha = 60^\circ$, and less than 72 m for dip $\alpha = 70^\circ$. These offsets may be difficult to resolve compared to the aeromagnetic grid interval of 50 m. Depths estimated for subtler anomalies generally range from 200 to 500 m (Grauch et al., 2001). At these depths, offsets may be more significant (maximum offset ~200–450 m for $\alpha = 60^\circ$). Magnetic contrasts deeper than 500 m along intrasedimentary faults are not evident from the aeromagnetic data (Grauch et al., 2001). However, basement faults that juxtapose Precambrian rock with high magnetic susceptibility against basin sediments at >1-km depth could produce offsets of greater than 500–900 m.

The cause of a large apparent offset observed between the HGM peak and the trace of a steeply dipping mapped fault can be qualitatively evaluated by observing the shape of the HGM curve, because the curves widen with increasing depth to the source (Roest and Pilkington, 1993). A broad HGM curve can qualitatively confirm that depth $d$ is indeed great enough to explain a large offset $\ell_{\text{offset}}$. A narrow HGM curve suggests the presence of an additional fault or other geologic complexities under cover.

Figure 13. Aeromagnetic, topographic and HGM images from Cat Mesa (see inset for location). Maps are illuminated from the west. Pink lines indicate the generalized mapped contact between Quaternary eolian deposits and basalt, both of which overlie the Santa Fe Group, exposed below the mesa. Geologically mapped faults are shown as white lines, dashed where uncertain. Geology is generalized from Maldonado and Atencio (1998a, 1998b). (A) Color shaded-relief aeromagnetic image. The variable short-wavelength pattern indicates the presence of basalt. (B) Color shaded-relief topographic image from a 30-m digital elevation model (U.S. Geological Survey U.S. GeoData). Magnetic sands concentrated along the top edge of the mesa may augment the aeromagnetic expression of the escarpment in the aeromagnetic image. Note the broad topographic expression of most faults on top of the mesa (Fig. 13B) compared to their sharp aeromagnetic expressions (Fig. 13A). (C) Horizontal gradient magnitude (HGM) map of the RTP aeromagnetic data. Note the strong values over the volcanic rocks compared to those over the sediments and the weak HGM ridges over the escarpment compared to those over the faults.
THE ROLE OF TOPOGRAPHY

Irregular topography can produce aeromagnetic anomalies that are caused by lateral contrasts between magnetic materials underlying the topographic surface and nonmagnetic air. The shapes of these anomalies, called magnetic terrain effects, correlate strongly with topography, especially evident in crystalline terrain (Blakely and Grauch, 1983; Grauch, 1987). In aeromagnetic maps for the central Rio Grande rift, linear anomalies commonly follow the top edges of mesas or arroyo banks, producing anomalies that can look “fault-like” in the aeromagnetic map but are not related to faults. For example, a prominent semi-linear anomaly follows a 50–60-m-high escarpment located northwest of Cat Mesa volcanic field, similar in signature to the fault-related anomalies that cross it (Figs. 13A and 13B). In contrast, the 50-m-deep, generally east-west oriented Hell Canyon (northern part of Fig. 3B) is barely recognizable in the aeromagnetic map. The prominent (~10-nT), northerly trending linear anomalies crossing Hell Canyon correspond to faults with scarps only ~5–10 m high (Love et al., 1996).

In some places, linear anomalies follow topographic scarps that may result from faulting. In these places, the contributions of magnetic terrain effects are difficult to distinguish from those of tectonic juxtaposition. This distinction can be important, if it is unclear from surface exposures whether a fault is present or not. In these cases, the scarp can be viewed as a truncated-layer model where the thickness is the scarp height, the depth is zero, and the magnetic contrast is determined by the magnetic susceptibility of the material composing the scarp (such as the case of the hill composed of strata B in Fig. 7). Given a range of magnetic susceptibilities for sediments at the scarp or estimates of scarp height, one could determine whether the corresponding aeromagnetic anomaly can be explained solely by magnetic terrain effects using the thickness-contrast graph (Fig. 10). For example, an estimated or measured average magnetic susceptibility of $1 \times 10^{-3}$ (SI) for sediments can produce a 2-nT anomaly with 27 m of topographic relief (Fig. 10). If the relief of the scarp in question is much less, an underlying source is required. Conversely, a 5-m topographic scarp would require an average magnetic susceptibility of $25 \times 10^{-3}$ (SI) to produce an observed 10-nT anomaly. Because this magnetic susceptibility is unreasonable high for Santa Fe Group sediments, an underlying fault is likely present.

Local deposits of transported sediments, such as sand bars or sand dunes, can enhance the apparent effect of magnetic terrain effects. Sand dunes following the top edge of Cat Mesa may contribute to its aeromagnetic expression (Fig. 13). The wind-blown sand, with magnetic susceptibilities on the order of $10 \times 10^{-3}$ (SI), adds an additional magnitude to the magnetic contrasts associated with the escarpment.

To assess the potential role of topography for large areas, hypothetical magnetic fields can be computed from digital elevation models (DEMs) and a uniform magnetic susceptibility that is assumed to be typical of the surficial materials in the area. The computed results simulate the magnetic field that is produced solely by topography (magnetic terrain effects), which are directly comparable in magnitude and shape to the observed aeromagnetic data (Grauch, 1987). For example, we used a 30-m DEM (Fig. 1; U.S. Geological Survey National Elevation Database) and chose a uniform susceptibility of $1 \times 10^{-3}$ (SI) as a representative value for the Santa Fe Group. Using the same Earth’s field parameters and observation surface as for the RTP aeromagnetic data (Plate 1), we calculated the magnetic terrain effects using a computer program that determines the sum of all magnetic fields due to each 50 x 50-m grid cell within the DEM (unpublished computer program by J. Phillips, 2002, based on the prism routine given by Blakely, 1995).

For investigating faults, it is most useful to compare the horizontal gradient magnitudes of the magnetic terrain effects to those of the RTP data, especially if the residual HGM of the magnetic terrain effects are computed in the same way as for the RTP data. For example, the residual HGM maps for these data are compared for the Sand Hill and related faults using identical color and shading schemes (Fig. 12). The comparison gives a feel for how the observed RTP gradients compare to those that would be produced by topography composed of material with a magnetic susceptibility of $1 \times 10^{-3}$ (SI). From this comparison, magnetic terrain effects appear to account for moderately strong observed gradients related to steep slopes within the badlands topography (marked MT on Fig. 12C) and along an embayed rim of the main escarpment. In contrast, strong HGM values closely follow the Sand Hill fault where it is mapped west of the escarpment (Fig. 12C), suggesting that tectonic juxtaposition accounts for most of the aeromagnetic expression of the fault. South of the embayed rim in between the two main mapped faults, values of the HGM of RTP along the topographic escarpment are much higher compared to the HGM ridges of the hypothetical magnetic terrain effects (Fig. 12B), suggesting that topography may only have a partial contribution to the observed anomaly. The same is implied from the results of Equation (1), which gives a magnetic susceptibility of $7.3 \times 10^{-3}$ (SI) to account for the 17-nT amplitude anomaly that is observed over the 40-m scarp. This susceptibility is fairly high for large thicknesses of the Santa Fe Group (Fig. 4). However, the result warrants further analysis because sand dunes concentrated along the rim can have susceptibilities averaging $10 \times 10^{-3}$ (SI).

INTERPRETING FAULT LOCATIONS AT REGIONAL SCALE

A pragmatic approach to mapping faults over large regions is to interpret and digitize their locations based on inspection and cross-reference between interpretative maps. The images that are most useful are the RTP aeromagnetic data, the HGM of the RTP and pseudogravity data, the HGM of the magnetic terrain effects, digital elevation data, and thematic maps (for determination of anthropogenic features). The locations of inferred faults are determined by tracing ridges in the residual HGM of the RTP or pseudogravity data, which can be guided by spot locations of maxima determined automatically (Blakely and Simpson, 1986). The guides developed earlier regarding multiple HGM peaks and the role of topography are applied on a case-by-case basis. The effect of fault dip can be ignored at regional scales (more regional than 1:24,000), if the magnetic contrasts at faults are fairly shallow, as is the case for the central Rio Grande rift. Mapping the fault locations in this manner should provide a fairly good view of fault patterns and concealed faults at scales more regional than 1:24,000.

Difficulties in interpreting the location of inferred faults from HGM maps are related to masking from overlying anthropogenic sources, multiple peaks over faults that have attributes of the thin-thick model (Fig. 8D), inadequate resolution of complicated fault or linear topographic patterns, and linear anomalies caused by linear geologic features that are not fault related. In addition, following HGM ridges can be difficult in the limited areas of strongly magnetic volcanic rocks, where small variations in topographic relief or magnetic properties can cause large effects. Typically, all these problems must be addressed on a case-by-case basis through subjective decisions based on geologic or geophysical experience.

The most serious difficulty is the masking effect of highly magnetic anthropogenic structures. Widespread, spatially limited anomalies with well-defined edges in the aeromagnetic image are produced by structures such as commercial buildings, land fills, community water tanks, utility stations, and communication towers (e.g., Fig. 2). Where these structures are clustered in urban areas, their anomalies coalesce into a
“bumpy-looking” pattern, which can completely mask the expression of underlying faults and produce interfering patterns on the HGM of RTP map. Strong linear anomalies and corresponding HGM patterns are commonly associated with pipelines, arising from the magnetic fields produced by electric currents used for cathodic protection (Figs. 2 and 3; Gay, 1986).

High-amplitude anomalies over volcanic rocks can produce enormous values in the HGM of RTP map, as exemplified in the Cat Mesa area (Fig. 13C). In these areas, only moderate variations in petrology, stratigraphic thickness, or topographic relief can cause large horizontal gradients in the RTP data, and faults are difficult to distinguish from other sources of linear anomalies without comparison to geologic maps. For example, the large magnetizations typical of volcanic rocks, arising from both induced and remanent components, can produce anomalies with >2-nT amplitudes with much less than 5 m of topographic relief (assume a magnetic susceptibility contrast $>5 \times 10^{-3}$ (SI) on Fig. 10). Thus, linear anomalies due to faults can be difficult to distinguish from the erosional edges of slightly tilted flows or from the edges of paleovalleys filled with magnetically contrasting volcanic rocks without the help of geologic mapping. Moreover, the aeromagnetic expressions of faults may be masked by the magnetic effects of underlying complexities, such as multiple interfingering volcanic layers of locally varying thickness.

Where multiple faults occur in swarms or are arranged in complicated, crossing patterns, a regional-scale view of fault patterns must be kept in mind. In these areas, the aeromagnetic expressions of the individual faults are not resolved. One large anomaly will commonly reflect the general strike of the fault swarm rather than any one fault trace in particular. This scenario is evident in an area northwest of Santa Fe, where numerous faults are close together (Koning and Maldonado, 2001). The HGM ridges follow only portions of some of the individual faults, yet still provide a general view of the trends of fault zones in the area (Fig. 14).

Linear anomalies produced by geologic features unrelated to faulting must be assessed with geologic or other independent information. Examples are the edges of dipping beds that do not have topographic expression or dendritic patterns reflecting buried paleodrainages (e.g., Gay, 2004). The patterns by themselves are not necessarily definitive. For example, faults interpreted for a dendritic pattern of linear anomalies near the Hubbell Spring fault (northeastern corners of Figs. 3B and 3C) are supported by geologic mapping (Love et al., 1996). Interfingering or gradational stratigraphic contacts are unlikely to produce the types of linear anomalies observed in the central Rio Grande rift aeromagnetic data because the boundaries of magnetic contrast are not abrupt.

A compilation of aeromagnetically inferred faults for the central Rio Grande rift is shown at page size in Figure 15 and overlain on the HGM of RTP data at 1:250,000 scale in Plate 2. The compilation and map images can be downloaded in geo-registered formats (see Appendix Table 1). In addition, a digital page-size illustration is available that allows the user to toggle layers showing the HGM of RTP and fault interpretation on and off (see Appendix Table 1). The new interpreted fault compilation improves on previous versions of aeromagnetically inferred faults for regions of the central Rio Grande rift, such as those presented in Hudson et al. (1999b), Maldonado et al. (1999), Grauch and Bankey (2003), and Minor (2006). Because ambiguities and subjective decision making are inherent in the process of mapping the fault locations, this compilation is likely to change somewhat as more time is available for study of individual cases. In the interim, images used for the interpretation are available for others to judge the strengths or weaknesses of the interpretations.

SUMMARY AND CONCLUSIONS

High-resolution aeromagnetic data acquired over several basins in the central Rio Grande rift, north-central New Mexico, display prominent linear anomalies associated with faults that offset basin-fill sediments. Their abundance, especially in areas of cover, implies that faults throughout the basins are much more numerous than previously suspected. This inference has significant implications for a variety of basin studies and provides impetus for understanding the aeromagnetic expression of these faults in greater detail. Lessons learned will help to understand the

Figure 14. Mapped faults (white lines) in the Española basin compared to the residual HGM map of RTP aeromagnetic data, illuminated from the west. Faults are from Koning and Maldonado (2001). The HGM ridges do not resolve individual faults where they are close together in the central part of the area. A few prominent HGM ridges in the western part of the area suggest additional concealed faults, whereas an inferred mapped fault in the south-central part of the area does not have aeromagnetic expression. Circular rings in the HGM map correspond to buildings, which coalesce and mask geologic signal near the city of Santa Fe on the south.
Figure 15. Aeromagnetically interpreted faults for the central Rio Grande rift overlain on regional geology and topography of Figure 1.
Utility of Aeromagnetic Data for Examining Concealed Faults in Sedimentary Basins in General

In plan view, linear anomalies in the central Rio Grande rift are commonly sinuous, extensive, and display anastomosing and en echelon configurations, evocative of fault patterns. The aeromagnetic expression primarily originates from the tectonic juxtaposition of strata at the fault that produces lateral magnetic contrasts. In profile form, the anomaly shapes show wide variation, which can be explained by differences in layer thickness, depth to the layer(s), magnetic susceptibility, and fault dip. Using a concept of equivalent magnetic-contrast layers, which are geophysical representations of simple stratigraphic models, we can isolate the influences of these variables and develop guides that answer several questions regarding how and why the faults are expressed in aeromagnetic data.

Criteria for Aeromagnetic Expression

Assuming a vertical-sided, truncated-layer model and fixing depth and anomaly amplitude, we graphed the relations between magnetic-susceptibility contrast and layer thickness. The resulting thickness-contrast graph (Fig. 10) aids in estimating the minimum criteria for aeromagnetic expression of faults.

Assuming that an observable aeromagnetic anomaly for the study area has an amplitude of at least 2 nT, minimum fault throw for a given magnetic contrast and required magnetic contrast for a given fault throw can be determined. Because these variables are interdependent, we can only generalize criteria to test for the lack of aeromagnetic expression, as follows.

- Faults with magnetic-susceptibility contrasts less than 0.2 × 10^{−3} (SI) will not produce observable anomalies, even for fault throws >500 m.
- Fault throws less than 10 m will not produce observable anomalies, even for a magnetic-susceptibility contrast as high as 3.0 × 10^{−3} (SI).

For the central Rio Grande rift in particular, where a magnetic-susceptibility contrast of 1.0 × 10^{−3} (SI) is common, we expect that faults should have at least 30 m of throw to produce observable aeromagnetic anomalies when the magnetic contrast is at the surface, and 50–100 m of throw to produce observable aeromagnetic anomalies where the contrast is at 100–300 m depth. Of course, faults without magnetic contrast will not produce any anomalies, no matter what the displacement.

Complicating the thickness-contrast guide is the likely possibility that multiple magnetic contrasts occur at depth along a fault plane. For these cases, the fault throw estimated from the thickness-contrast graph will be too small, if the fault is best represented by opposing magnetic-contrast layers and too large, if it is best represented by magnetic-contrast layers stacked on one side of the fault.

Determining Fault Locations

An effective technique for mapping surface or near-surface traces of faults locates peaks in the horizontal gradient magnitude (HGM) of the RTP aeromagnetic or pseudogravity data. Faults that can be represented by a thin-thick, magnetic-contrast model (a thin shallow layer opposing a thick deeper layer across the fault) produce multiple HGM peaks for both RTP and pseudogravity data. Where these types of faults are common in the study area, such as the central Rio Grande rift, the narrowest HGM peak of the RTP data best represents the location of the near-surface fault trace. At regional scales, the HGM maps show linear ridges that enhance the visualization of fault patterns. Guided by understandings of the effect of fault dip and the role of topography, the ridges can be digitized to form a digital layer of inferred fault locations.

The Effect of Fault Dip

Anomalies over dipping faults have associated HGM peaks or ridges that are offset laterally from their associated faults, dependent primarily on the depth to the topmost magnetic contrast along the fault. This effect is greatest for large depths and shallow dips. From an equation derived to estimate maximum offset, we develop the following guides for faults with dips between 60° and 70°, typical of the central Rio Grande rift and extensional basins in general.

- For shallow depths (<100 m), the offsets are likely less than ~100 m, which is insignificant at scales more regional than 1:24,000.
- For greater depths (200–500 m), maximum offsets are likely in the range 200–450 m. These depths are uncommon for anomalies associated with intrabasin faults in the central Rio Grande rift.
- Basement faults that juxtapose magnetic crystalline rock against basin sediments at >1-km depth could produce anomalies that are associated with HGM peak offsets of greater than 500–900 m.

Sense of Displacement and Fault Throw

Because anomaly shapes can be explained by multiple scenarios of juxtaposed strata, sense of displacement and amount of fault throw are both difficult to determine from aeromagnetic anomalies without additional information about the strata and magnetic properties. On the other hand, general assumptions about relative magnetic properties and stratigraphy may be enough to estimate the sense of displacement from anomalies. For example, the general correlation between sediment grain size and magnetic susceptibility in the central Rio Grande rift can lead to reasonable assumptions about the source of certain anomaly highs with general knowledge of the stratigraphy. However, accurately estimating fault throw requires greater knowledge of how strata are juxtaposed and may benefit from geophysical modeling.

Assessing the Role of Topography

Magnetic sediments and rock that comprise irregular topographic forms are an important source of aeromagnetic anomalies. Because topography can appear linear, distinguishing the contribution of topography to anomalies from those of faults requires some care. A useful technique compares the aeromagnetic data to a hypothetical magnetic field computed from a digital elevation model using a uniform magnetic susceptibility. The computed results simulate the magnetic field produced solely by topography (magnetic terrain effects). Where the simulated magnetic terrain effects correspond to observed linear anomalies, topography is the likely source of the anomaly.

Where a topographic scarp is the result of faulting, the contributions caused by terrain are difficult to distinguish from those caused by tectonic juxtaposition. In these cases, the thickness-contrast graph can be used to generally assess whether topography is the primary contributor by estimating the magnetic-susceptibility contrast that is required for a topographic scarp to produce the amplitude of the anomaly observed. Where this estimated magnetic contrast is too high, an underlying source must be considered. In ambiguous cases, geophysical analysis or modeling may be required.

Implications for Future Studies

Faults interpreted from aeromagnetic data over sedimentary basins can reveal new views of concealed fault patterns within the basin fill. Examples shown here for the central Rio Grande rift, New Mexico, and reported
elsewhere for Dixie Valley, in the Basin and Range Province of Nevada, suggest that high-resolution aeromagnetic data may be a useful tool for examining intrabasin fault patterns in many other sediment-filled rift basins. Combined with geologic mapping and other geophysical methods, the results can be interpreted to address a wide range of topics. These topics might include assessing seismic hazards, explaining where subsidence occurs in response to ground-water withdrawal, establishing links between intrabasin and basement faults, investigating relations between fault trace length and fault throw, and understanding the structural styles involved in rifting.

In the course of this study, we developed an updated compilation of aeromagnetically inferred faults for the central Rio Grande rift. We hope this compilation, used in conjunction with the guides, benefits a myriad of future investigations concerning the central Rio Grande rift or the structural aspects of sedimentary basins in general.

**APPENDIX 2. DERIVATION OF EQUATIONS FOR A TRUNCATED-LAYER MODEL**

The truncated-layer geophysical model can be used for examining fault parameters and their effects on fault-related magnetic anomalies, e.g., equations (1) and (3) of this report. Notations for derivations related to the model are shown in Figure A-1. In this notation, the origin of the $x$-axis is located over the ground-surface projection of the top edge of the magnetic layer. To simplify the derivations, an inducing field with 90° inclination and 0° declination is assumed, which can be satisfied in practice by reducing observed magnetic field data to the north pole. This assumption permits the use of an equation previously derived for the vertical field component due to two semi-infinite slabs with contrasting susceptibilities (Telford et al., 1990, equation 3.64a). After modifying the notation to be consistent with Figure A-1 and converting to SI units, the equation for the anomaly produced by the truncated one-layer model becomes

$$T = \frac{\Delta m F_0 \sin \theta}{2\pi} \left( \cos \theta \log \left( \frac{x^2 + D_1^2}{y^2 + D_2^2} \right) + \sin \theta \left( \cot^{-1} \frac{x}{D_2} - \cot^{-1} \frac{x}{D_1} \right) \right)$$  \hspace{1cm} (A-1),

where

- $\Delta m =$ magnetic susceptibility contrast (or apparent magnetic susceptibility that incorporates a remanent contribution) in SI units,
- $F_0 =$ strength of Earth’s magnetic field (for inclination $= 90^\circ$, declination $= 0^\circ$) in nT,
- $\theta =$ angle of the truncated face of the layer in the range $0^\circ$ to $180^\circ$,
- $D_1 = D + h$, where $d$ is the depth to the layer and $h$ is observation height (assumed constant) in meters, and
- $D_2 = D + t$, where $t$ is the thickness of the layer in meters.

Note that geologic dip $\alpha = \theta$ when $0^\circ \leq \theta \leq 90^\circ$, and $\alpha = 180^\circ - \theta$ when $90^\circ \leq \theta \leq 180^\circ$.

Given a specific magnetic anomaly under investigation, the unknowns of Equation (A-1) are $\Delta m$, $\alpha$, $d$, and $t$. Recognizing that $\theta = 90^\circ$ gives the greatest value of $T$ when all other parameters are held constant, we can reduce the number of variables by using the limiting case of a vertical fault. This restriction simplifies Equation (A-1) as
Setting the derivative to zero gives:

\[ x^2 = \frac{D_1 D_2}{D_1 + D_2} \]

Solving for \( x \) gives the two solutions corresponding to \( T_{\text{max}} \) and \( T_{\text{min}} \):

\[ x = \pm \sqrt{\frac{D_1 D_2}{D_1 + D_2}}. \]

Figure A-1. Notation used for a single truncated-layer model to derive equations. Note that geologic dip \( \alpha = \theta \) when \( 0^\circ \leq \theta < 90^\circ \), and \( \alpha = 180^\circ - \theta \) when \( 90^\circ \leq \theta \leq 180^\circ \).

Relation of Anomaly Amplitude to \( \Delta m \), \( d \), and \( t \)

The magnitude of the anomaly \( T \), \( |T_{\text{anom}}| \), which is produced by the horizontal layer with vertical face, is defined as the difference between the maximum and minimum values of \( T \). To compute the maximum and minimum values, we must first find for which \( x \) the maximum and minimum occur. For this step, we use the simplifying assumptions that gave Equation (A-2) (this will give the maximum anomaly amplitude), and use a standard minimization technique. In other words, we take the derivative of \( T \) with respect to \( x \) and solve for \( x \) when the derivative is zero. The first derivative from Equation (A-2) is:

\[ T' = \frac{\Delta m F_0}{2\pi} \left( \cot^{-1} \frac{x}{D_2} - \cot^{-1} \frac{x}{D_1} \right) \]  

(A-2).

Substituting the two solutions for \( x \) into (A-2) and taking the difference gives:

\[ T_{\text{anom}} = T_{\text{max}} - T_{\text{min}} = \frac{\Delta m F_0}{2\pi} \left[ \cot^{-1} \frac{\sqrt{D_1 D_2}}{D_1} - \cot^{-1} \frac{\sqrt{D_1 D_2}}{D_2} \right]. \]

Utilizing trigonometric properties allows combination of terms, as

\[ T_{\text{anom}} = \frac{\Delta m F_0}{\pi} \left[ \tan^{-1} \frac{D_2}{D_1} - \cot^{-1} \frac{D_1}{D_2} \right]. \]

Rearranging the equation to solve for \( \Delta m \) gives

\[ \Delta m = \frac{\pi T_{\text{anom}}}{F_0} \left[ \tan^{-1} \frac{D_2}{D_1} - \cot^{-1} \frac{D_1}{D_2} \right]. \]

Substituting for \( D_1 \) and \( D_2 \) in terms of \( d \), \( t \), and \( h \), gives

\[ \Delta m = \frac{\pi T_{\text{anom}}}{F_0} \left[ \tan^{-1} \frac{d + h + t}{d + h} - \cot^{-1} \frac{d + h + t}{d + h} \right], \]

which is given as Equation (1) in the text of this report.

We know that \( h = 100 \) m and \( F_0 = 51715 \) nT for the study area. Thus, setting specific values for \( T_{\text{anom}} \) and depth \( d \) allows us to use Equation (A-3) to graph the variations of magnetic susceptibility contrast \( \Delta m \) versus magnetic-contrast layer thickness \( t \) (Fig. 10). Curves corresponding to other anomaly amplitudes can be computed using Equation (A-3), or simply replotted from the 2-nT curves by replacing the magnetic susceptibility values with ones that are multiplied by the ratio between the new amplitude and 2 nT.

Offset of HGM Peaks over Dipping Faults

Mismatches between peaks of the horizontal gradient magnitude (HGM) curve and the traces of dipping faults are caused by the combination of geometric effects and the behavior of the magnetic field over a dipping boundary (Fig. A-2). Both effects result in an offset of the HGM peak from the surface fault trace in the downdip direction, with greater offset corresponding to shallower dips.

The lateral offset \( \ell \) of the top edge of the magnetic-contrast layer at \( x = 0 \) from the fault trace at the ground surface is determined by geometry as

\[ \ell = d \left| \cot \theta \right| = d \cot \alpha, \]

where \( d \) is the depth to the layer, \( \theta \) is the dip of its truncated face determined as in Figure A-2, and \( \alpha \) is geologic dip measured from horizontal (\( \alpha \leq 90^\circ \)).

The lateral offset \( \ell \), due to magnetic field behavior can be estimated by examining the horizontal gradient of the magnetic anomaly of a truncated layer with arbitrary dip, as in Equation (A-1). (The assumption of \( 90^\circ \) inclination and \( 0^\circ \) declination for the inducing field is retained.) Because the model is two-dimensional, the horizontal gradient is just the first
derivative in the x direction. Therefore, to compute the offset of the HGM
peak, we need to find the x for which \( \frac{dT}{dx} \) is maximum. We do this by
taking the second derivative of T with respect to x, setting the result to
zero, and solving for x. The approach is analogous to one used previously
to examine the HGM of the gravity field over a dipping contact (Grauch
and Cordell, 1987). Taking the first derivative from Equation (A-1) gives

\[
\frac{dT}{dx} = \frac{\Delta m F_x}{2\pi} \left( \frac{D_x \sin \theta - x \cos \theta}{D_x^2 + x^2} - \frac{D_x \sin \theta - x \cos \theta}{D_x^2 + x^2} \right).
\]

To reduce the number of variables, we assume that the layer is infinitely
thick; that is, we take the limit as \( \ell \to \infty \) gives

\[
\frac{dT}{dx} \bigg|_{\ell \to \infty} = \frac{\Delta m F_x}{2\pi} \left( \frac{D_x \sin \theta - x \cos \theta}{D_x^2 + x^2} \right).
\]

Taking the second derivative with respect to x gives

\[
\frac{d^2T}{dx^2} = \frac{\Delta m F_x}{2\pi} \left( x^2 \cos \theta - 2D_x \sin \theta - D_x \cos \theta \right) \left( D_x^2 + x^2 \right)^{-1}.
\]

Setting to zero, solving for x, and considering geologic dip \( \alpha \) instead of
angle \( \theta \), gives

\[
\ell_m = 0 \quad \text{for} \quad \alpha = 90^\circ
\]

and

\[
\ell_m = \left( h + d \right) \cos \alpha \quad \text{for} \quad 0^\circ < \alpha < 90^\circ
\]

In this equation \( h + d \) (observation height plus depth to the layer) has
been substituted for \( D_x \). Because only positive values of the distance \( \ell_m \)
are considered, geologic dip \( \alpha \) can be used in place of \( \theta \). Note that \( \ell_m \)
is a measure of the offset of the HGM peak from \( x = 0 \), which is defined as
the vertical projection of the top edge of the layer. Equation (A-4) gives
a maximum estimate of offset due the magnetic behavior over a dipping
boundary; magnetic-contrast layers with finite thickness will exhibit less
offset, depending on their thickness.

A maximum estimate of the total offset of the HGM peak from the fault
trace is then

\[
\ell_{\text{offset}} = \ell_g + \ell_m,
\]

and

\[
\ell_{\text{offset}} = 0 \quad \text{for} \quad \alpha = 90^\circ
\]

(A-5a),

and

\[
\ell_{\text{offset}} = d(\cot \alpha + f_a) + hf_{\alpha^*} \quad \text{for} \quad 0^\circ < \alpha < 90^\circ
\]

(A-5b),

where

\[
f_a = \frac{\sin \alpha - 1}{\cos \alpha}
\]

Equation (A-5) is given as Equation (3) in the text of this report.

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Aeromagnetic expression of faults in sedimentary basins


