Characterizing shallow intrasedimentary faults using magnetic depth estimation methods: Preliminary results of a high-resolution aeromagnetic survey at the San Luis Basin, south-central Colorado

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ABSTRACT

The San Luis Valley, the northernmost of the Rio Grande rift basins, is home to a large but poorly characterized network of shallow intrasedimentary faults. As known groundwater aquifers and hot springs are located within the basin fill, an improved understanding the subsurface structure of the basin has significant benefits for the inhabitants of the region. High-resolution aeromagnetic surveys can be used to delineate the horizontal extent of potential faults while the computer program PDEPTH can be used to estimate their depths. In 2008 an aeromagnetic survey of the Great Sand Dunes region of the San Luis Valley was flown and the resulting data was used to conduct a preliminary study of the subsurface geologic framework. The primary goal of this study was to interpret the horizontal locations and depths of potential faults. A secondary goal was to integrate user-friendly information about the proper use of the magnetic source location methods that PDEPTH relies on to make fault depth estimations.

Keywords: computer methods, geophysical surveys, high-resolution methods, hydrogeology, magnetic anomalies, Rio Grande Rift, San Luis Valley, sedimentary basins
INTRODUCTION

Recent studies suggest that shallow faults within sedimentary basin fill may be more extensive than previously thought. High-resolution aeromagnetic surveys are a useful tool for geophysicists interested in mapping these types of subtle linear features, but they can also be used to delineate the underlying structure of the basin on a more regional scale. The results of such surveys can aid in better characterizing the subsurface hydrogeologic framework of sedimentary basins, which has important implications for groundwater studies.

The horizontal extent of faults can be interpreted from linear anomalies that occur in high-resolution aeromagnetic data (sometimes abbreviated to just “aeromagnetic” data in this paper). These anomalies are produced by the magnetic contrast between adjacent layers of rock with differing magnetic susceptibility values. It is important to note that magnetic contrast can arise both in faulted and non-faulted rock. In order to locate “true” faults, aeromagnetic anomalies are typically examined in the context of other data (e.g. geologic surface mapping, ground magnetic data, time-domain electromagnetic data, magnetotelluric data, etc.). The depth to the top corner of the shallowest magnetic contrast layer can be approximated from aeromagnetic data using a number of different analytical methods. Given a magnetic profile taken across a potential fault, the computer program PDEPTH (Phillips, 1997) allows the user to superimpose the solutions from multiple methods onto one simulated cross-section.
Located in south-central Colorado, USA, the San Luis valley is a prime example of a sedimentary basin characterized by numerous shallow intrasedimentary faults. Furthermore, due to the unusually high magnetic susceptibilities of the basin fill units, this region offers a unique opportunity for the utilization of high-resolution aeromagnetic surveys in delineating shallow features. The primary goal of this study is to evaluate previous fault location interpretations made in this region for accuracy by analyzing them in context with the results of PDEPTH-generated fault depth estimations. In addition, due to the limited cohesion of fault detection methods that use high-resolution aeromagnetic data in the literature, this paper will also serve to synthesize information about modern analytical techniques that can be used as a resource for future studies.

**GEOLOGIC SETTING**

*Rio Grande Rift*

The Rio Grande rift is a major continental rift located within the western North American Cordillera. Regional crustal extension in what is now the western United States initiated during the late Oligocene as a result of lithospheric-plate interactions along and under the western margin of North American (Ingersoll et al., 1990). This extension was superimposed upon an already complex landscape that had been shaped by Mesozoic and Cenozoic tectonic activity (Baldridge et al., 1995; Grauch and Hudson, 2007; Ingersoll et al., 1990). Structures established by these tectonic events likely influenced basin geometry and extensional faulting in the rift (Grauch and Hudson, 2007). Rifting
has continued to evolve into the present by means of several lithospherically and/or aesthenospherically driven processes (Ingersoll et al., 1990). In comparison to similar rift systems, the Rio Grande rift exhibited markedly less magmatic and seismic activity (Baldridge et al., 1995; Ingersoll et al., 1990). For a more exhaustive examination of the tectonic and structural history of the rift, the interested reader is referred to Baldridge et al. (1995), Ingersoll et al. (1990), Keller and Baldridge (1999), and Keller and Cather (1994).

The modern topography of the Rio Grande rift is characterized by a series of interconnected basins that extend more than 1,000 km from Leadville, Colorado to Presidio, Texas (Fig. 1; Keller and Baldridge, 1999). The basins are narrow, asymmetrical, fault-bounded grabens and half-grabens (Keller and Baldridge, 1999; Ingersoll et al., 1990). The presence of a large amount of highly magnetized sedimentary fill, thicknesses of which can exceed 5 km, is a notable feature of these basins (Keller and Baldridge, 1999; Lozinsky, 1994).

**San Luis Basin**

The northernmost basin of the Rio Grande rift is the San Luis basin, an east-dipping half-graben located in south-central Colorado and north-central New Mexico. The basin forms a 200 km long, 30-70 km wide intermontane valley flanked by the Sangre de Cristo Mountains on the east and the San Juan Mountains on the west (Fig. 2; Grauch and Keller, 2004). Sediment thickness in the basin ranges from 1.7 to 4.0 km (McCalpin, 1996).

Prolonged tectonic instability along the Rio Grande rift has generated an intricate stratigraphic record in all the rift basins, including the San Luis.
Figure 1. Map showing the location of the San Luis basin relative to the other basins of the Rio Grande rift, Colorado and New Mexico, USA (modified from Madole et al., 2008).
Figure 2. Map showing the topography of the Rio Grande rift with features of the San Luis basin marked in white (courtesy of Jules Verne Voyager – Generic Mapping Tools, UNAVCO Boulder Facility, and Jules Map Server website).
Overlying the Precambrian-age igneous and metamorphic basement, the basin floor is composed of Paleozoic to Eocene pre-rift sedimentary and volcanic rocks (Grauch and Keller, 2004). Syn-rift Neogene-Quaternary sediments are separated from pre-rift rock by a distinctive layer of ash flow tuffs (Grauch and Keller, 2004; McCalpin, 1996).

Non-marine Neogene-Quaternary sedimentary basin fill forms a substantial component of the rift stratigraphy. The Santa Fe Group, where the faults of interest in this study are located, is composed of early Miocene to Pleistocene age clay to gravel sized clastic sediment (Grauch et al., 2001; Hudson et al., 2008). It is made up of the Zia and Arroyo Ojito Formations, both of which were sourced from regions north-northwest of the basin (Hudson et al., 2008). The underlying Zia Formation is ~600 m thick and is composed of mostly eolian sandstones, with the uppermost member being deposited in a mix of eolian and fluvial paleoenvironments (Hudson et al., 2008). The overlying Arroyo Ojito Formation (~300 m thick) was deposited in a dominantly fluvial paleoenvironment and is composed of poorly consolidated sands and gravels (Grauch et al., 2006; Hudson et al., 2008).

In modern times the valley floor appears relatively flat, but in reality exhibits a very low gradient, ranging from ~3.5 m/km near the apex at the western margin of the valley to ~1 m/km at the distal edge of the fan (Madole et al., 2008). Eolian reworking and transport of valley floor deposits has resulted in the preferential amassment of sand in a topographic low located within an embayment near the eastern margin of the valley (Madole et al., 2008). The
product of this amassment, the Great Sand Dunes National Park, is located along the easternmost edge of this topographic low (Fig. 3).

The structure of the San Luis basin is highly complex. Concealed intrasedimentary fault swarms that cut the Santa Fe Group may play a role in compartmentalizing basin aquifers and controlling groundwater-flow in the San Luis Valley (Grauch and Hudson, 2007; Huntley, 1979). The primary focus of this study is to investigate these types of faults.

AEROMAGNETIC EXPRESSION OF FAULTS

Before the acknowledgement of aeromagnetic methods, surface mapping was a well-established method used to delineate faults; however, when investigating rock units like the Santa Fe Group, this method is generally difficult considering the widespread cover and poor consolidation of strata in the region (Grauch, 2001). Drenth et al. (2009), Grauch et al. (2000), Grauch (2001), Grauch et al. (2001), Grauch et al. (2006), Grauch and Hudson (2007), and Phillips et al. (1998) have recently begun conducting high-resolution aeromagnetic surveys in an attempt to study shallow intrasedimentary faults through the magnetic anomalies that they produce.

In map view, linear anomalies present on aeromagnetic contour maps are important tools for subsurface mapping as they can aid in connecting and extending limited surface exposures of faults, verifying the existence of faults with unclear surface expression, and identifying regions to investigate for surface
Figure 3. Map showing the location of the Great Sand Dunes National Park and Great Sand Dunes National Preserve in the northern San Luis basin. The extent of the eolian sand surrounding the dunes is illustrated in tan, and the dunes themselves are depicted in yellow (modified from Madole, 2006).
evidence of faults (Grauch et al., 2001). When the anomaly is viewed in profile, the magnetic signature is useful for estimating the depth to the corresponding magnetic source. The presence of faults is indicated by a variety of different anomaly shapes which are produced by differences in the thickness, magnetic susceptibilities, dip, and depths of the sedimentary strata juxtaposed across the fault (Grauch et al., 2001; Grauch and Hudson, 2007).

**Modeling Fault Anomalies**

A large quantity of magnetic minerals does not ensure that a sedimentary rock will produce an anomaly; lateral contrast in total magnetization must also be present (Grauch and Hudson, 2007; Gunn, 1997; Hudson et al., 2008; Phillips et al., 1998). Lateral contrast can occur in two ways: (1) tectonic juxtaposition of sedimentary layers with differing magnetic properties, and (2) secondary magnetization due to the effects of geochemical processes along a fault zone (Grauch et al., 2006; Grauch and Hudson, 2007; Gunn, 1997; Hudson et al., 2008). Intrabasinal fault studies conducted in the Albuquerque basin conclude that the primary source of magnetic anomalies in the Rio Grande rift is the juxtaposition of magnetically differing sedimentary layers (Grauch et al., 2000; Grauch et al., 2006; Grauch and Hudson, 2007).

In geophysical models, the main variables that control variability in anomaly shape are lateral magnetic contrast; vertical extent, or the dip and the amount of distance covered by the contrast boundary; and the distance of the magnetometer from the contact, which is composed of the observation height and the depth to the contact from the ground surface (Grauch and Hudson, 2007).
Geophysical models are derived from hypothetical stratigraphic models that represent the actual characteristics present in the anomaly-producing rock. The theoretical magnetic-contrast layers in the resulting geophysical model produce the same magnetic anomaly as the geologic model.

Magnetized sedimentary layers are conceptually different from magnetic-contrast layers. A magnetized sedimentary layer has a certain magnetic susceptibility value that is a product of the amount of magnetic minerals contained in the layer. Additionally, it has a direct physical analogue in the geologic record, in the form of the sedimentary stratum from which the susceptibility values are obtained. On the other hand, a magnetic-contrast layer is derived by taking the positive difference in magnetic susceptibility of two magnetized sedimentary layers juxtaposed across a fault and assigning the resulting value to the stratum with the higher magnetic susceptibility (Grauch and Hudson, 2007).

Note that magnetic-contrast layers do not represent the actual value of magnetic susceptibility in the associated stratum, but rather the difference in magnetic susceptibility between two juxtaposed layers. When it is the case that juxtaposed strata share the same magnetic susceptibility value no magnetic-contrast layer (and thus, no magnetic anomaly) is produced. While it is clear that magnetic-contrast layers are a geophysical construct, it is crucial to note that they have a basis in geology as they are equivalent to the strata with higher magnetic susceptibility (Grauch and Hudson, 2007).
Grauch and Hudson (2007) constructed hypothetical geologic and geophysical models that help illustrate these concepts (Fig. 4). A stratigraphy-based model and its equivalent geophysical model are used in conjunction with one another in order to determine the relationship between the magnetic anomaly, the associated geology, and the relevant geophysical parameters that are required for further modeling.

**Types of Aeromagnetic Signatures**

There are four aeromagnetic signatures common to intrasedimentary faults in the Rio Grande rift basins (Fig. 5). As illustrated above, the shape of the fault-offset anomaly (also referred to as the aeromagnetic signature) is determined by the underlying geology. If multiple magnetic-contrast layers are stacked on top of one another, the resulting observed anomaly is a composite of the anomalies produced by the individual magnetic-contrast layers (Grauch and Hudson, 2007). Interpreting fault-offset anomalies can become quite complex when dealing with a large number of stacked magnetic layers, as a wide range of different geologic scenarios can produce the same type of aeromagnetic signature.

**AEROMAGNETIC DATA ANALYSIS**

Aeromagnetic surveys measure the total intensity of the Earth’s magnetic field and are performed using geophysical sensors aboard an aircraft following a regular pattern of flight lines. According to Gunn (1997), the implementation of close line-spacing (~400 m) and utilization of very sensitive instruments will highlight the low-amplitude anomalies produced by relatively weakly magnetized
Figure 4. Hypothetical fault-produced magnetic anomaly (A) geologic and (B) geophysical models. The geologic model was created using stratigraphic layers and the corresponding geophysical model was constructed using magnetic-contrast layers. Note that both layer types are truncated by the fault, but layers that lack magnetic contrast extend across the fault. A magnetic terrain effect is created by the juxtaposition of a magnetic topographic high with non-magnetic air. Magnetic susceptibility and magnetic contrast values are included below each model (modified from Grauch and Hudson, 2007).
Figure 5. Four simplified geophysical models depicting magnetic signatures common to Rio Grande rift basins. Magnetic susceptibility values ($m_i$) are displayed with each layer (SI units). The total-field anomaly curve (solid black line) is computed from the geophysical model. The horizontal-gradient magnitude of both the reduced-to-pole data (solid gray line) and of the pseudogravity data (dashed gray line) were derived from the total-field anomaly (modified from Grauch and Hudson, 2007).
shallow sources. Low flight-height also allows for better source detection, and will produce more coherent anomalies (Grauch and Hudson, 2007; Reid, 1980). Even after employing these techniques, data processing and enhancement must be performed in order to distinguish the subtle sediment-produced anomalies from the considerably more intense basement and volcanic features and strong regional gradients.

Raw aeromagnetic data cannot be easily or sensibly interpreted without first being mathematically enhanced. The data of interest must be isolated by removing the effects of the Earth’s field, then gridded in order to construct a framework with which to relate the field data to the appropriate causative geologic bodies, and finally draped a certain height above a digital model of the terrain. These processes provide only the most rudimentary enhancements of the features of interest; there are numerous supplementary transformations that can be applied to the data, either individually or in succession, that further delineate the shapes of and depths to magnetic sources.

There are a few data processing techniques that are applied to the raw data in all but the most unique cases; these are described in detail in the section below. Following the application of these techniques, magnetic depth estimation methods can be performed in order to more specifically describe the magnetic data in the context of the regional geology.

**Aeromagnetic Processing**

In order for depth estimates to be generated most effectively, mathematical enhancement of the raw data must be performed. These techniques
selectively enhance geologic anomalies of interest relative to other background anomalies. This is accomplished by performing linear transformations on the data through the manipulation of the following factors: direction of magnetization, direction of measurement, depth, source body shape, a scaling factor, and a factor distinguishing magnetic from gravity fields (Milligan and Gunn, 1997). In undergoing this transformation process the anomalies can be viewed as functions that form distinct peaks over isolated magnetic sources; the shape of such a function follows a common mathematical form with an associated equation that can be used to estimate the source depth from the value and curvature of the peak (Phillips et al., 2007). Contour maps of the transformed data are commonly used in the geophysical literature to aid in data interpretation.

*Upward and downward continuation.* One of the first transformations usually applied to aeromagnetic data is the upward and/or downward continuation. Upward continuation enhances the effects of deeper anomalies relative to shallower ones, while downward continuation sharpens anomalies by simulating a lower survey flight-height (Milligan and Gunn, 1997). A caveat of dealing with downward continuation is that it also enhances high-frequency noise, so it is inadvisable to continue the field very far from the actual flight-height (Milligan and Gunn, 1997).

*Reduction-to-pole.* The reduction-to-pole is one of the most commonly used transformations. In doing so it more accurately illustrates the structural framework or magnetic properties of the rocks of interest. The reduction-to-pole recalculates the observed magnetic field to what it would look like at a magnetic
pole, where the inclination of the inducing magnetic field is vertical. This can be done assuming that the rocks in the region of interest contain no remnant magnetization. In the case of the Rio Grande sedimentary basins, this assumption holds well. A second condition that must be met in order to most effectively employ this method is that the direction of total magnetization of the rocks must be within 25° of the Earth’s magnetic field (Grauch et al., 2009). This is generally the case for rocks in the San Luis basin (Drenth et al., 2009). Applying a reduction-to-pole transformation greatly simplifies data interpretation, as it converts asymmetric magnetic anomalies to ones that lie directly over their respective sources (Milligan and Gunn, 1997).

Vertical derivatives. Another useful transformation is the computation of vertical derivatives. Computing the first vertical derivative is an important step in the interpretation of magnetic data, particularly in studies dealing with narrow and shallow anomalies. It reduces the effect of long-wavelength regional anomalies (which are usually deeper) and enhances the higher frequency shallow anomalies (Grauch et al., 2009; Milligan and Gunn, 1997). In certain cases where the data quality is particularly high, the second vertical derivative can also be applied to the data, providing and even finer representation of the shallow anomalies (Milligan and Gunn, 1997).

Linear filtering. There are a wide variety of linear filtering methods with the objective of removing certain portions of magnetic anomalies that are deemed irrelevant to the study. For example, these procedures can be used to eliminate long-wavelength effects (i.e. deep and/or regional) from the data set and thus
visually enhance the shorter-wavelength (i.e. shallower) features of interest (Milligan and Gunn, 1997). This is the approach that was taken in this study. While this procedure is extremely useful for enhancing features of interest in the data by separating anomalies that arise from sources at different depths, it is important to note that it also distorts the results. Thus, it is necessary to compare the linear filtering solutions to the solutions from other methods during interpretation.

*Computation of pseudogravity.* In certain cases where gravity and magnetic data arise from the same sources, transforming magnetic fields into their equivalent pseudogravity field can be a useful tool in investigating the relationship between the two. This process has the effect of centering sources at their causative bodies as well as enhancing broad features of the data (Grauch et al., 2009).

*Magnetic Depth Estimation*

Magnetic anomalies can be described using certain mathematical expressions, referred to as special functions in the depth estimation literature, which form peaks and ridges over isolated causative sources (Phillips et al., 2007). These functions can be utilized to map the locations of steep lateral contrasts in rock properties, as these steep contrasts correlate with the steepest slope of the associated anomaly (Grauch et al., 2009). The point of steepest slope can be found through a method similar to finding the inflection points of the curve. The depth to the top corner of the shallowest magnetic contrast layer associated with a potential fault can be approximated using the computer program
PDEPTH, which employs several magnetic source location methods in order to generate depth estimates. Each method has its own unique advantages and drawbacks; when interpreting the data it is best to utilize a combination of methods in order to make the most realistic interpretation of the data.

The shape and depth below the ground surface of a causative body are revealed by the corresponding shape of the magnetic anomaly. In general, shallow sources have anomalies with steep gradients while deeper sources have anomalies with wider gradients. In situations where the subsurface geology is unknown, the shape of the causative body is approximated using a structural index variable (N), which is a measure of the rate of decay of the magnetic field with distance from the source. A caveat of relying on structural indices for the purpose of depth estimation is that as the value of N increases it produces progressively deeper solutions. Consequently, multiple source location methods should be used not only in conjunction with one another, but should also be viewed in context with other geologic information about the region.

PDEPTH can produce depth estimates from gridded magnetic data or from magnetic profiles taken across features of interest. In this study, the program was used solely on profiles taken across possible faults. If solutions from multiple methods cluster around the same point, the results are considered robust.

*Horizontal gradient filtering.* Horizontal gradient filtering is especially useful for approximating the horizontal location of magnetic edges and for estimating maximum and minimum source depths. Another advantage of using this method is that it produces relatively coherent results that are insensitive to
noise, which aids in interpreting the solutions (Phillips and Grauch, 2001). The horizontal gradient solutions may be offset from the solutions of other methods if the magnetic contacts are not precisely vertical (Phillips et al., 2007). If this is the case, the horizontal gradient solutions will be offset in the down-dip direction (Phillips et al., 2007).

Horizontal gradient filtering employs special functions that are calculated from the horizontal gradient magnitude (HGM), which is a function of the transformed potential field of the causative source. This method pinpoints the local maxima of the HGM curve of the transformed potential field data; in effect, this process finds the value of the slope at the inflection points of the HGM curve (Grauch et al., 2009). When used to locate vertical magnetic contacts, the potential field data should undergo a reduction-to-pole transformation before the HGM special functions are calculated (Phillips et al., 2007). It is often useful to display the HGM data in map view and look for linear ridges that may indicate the presence of subsurface faults.

One drawback of horizontal gradient filtering is that it can produce identical results for vertical magnetic contacts as for a number of other geologic features such as homoclines, high-relief topography, and igneous lithologic contacts (Grauch et al., 2009). Additionally, it is often difficult to effectively use horizontal gradient filtering if the data has not been filtered to remove long-wavelength components of the data, as their effect may distort the local features of interest (Grauch and Johnston, 2002).
Analytic signal filtering. When source geometry is relatively simple, analytic signal filtering produces exceptionally straightforward results. Instead of using the horizontal gradient to locate magnetic contacts, the analytic signal method uses the total gradient. An interesting feature of this method is that both source magnetization direction and the direction of the Earth’s magnetic field are independent of the computation of its solutions (Milligan and Gunn, 1997). Consequently, in situations where the magnetization direction of the rocks in the study area is difficult to transform, such as when remnant magnetization is prevalent, finding solutions using the analytic signal can aid in constraining the solutions of other methods.

Analytic signal filtering provides particularly robust results when investigating profile data (Phillips and Grauch, 2001). In two dimensions, this method can approximate horizontal locations regardless of dip and magnetization direction. In geologic situations where source geometry is clear-cut, peaks of the analytic signal will fall directly over the edges of wide bodies and directly over the centers of narrow bodies (Milligan and Gunn, 1997). Using this method in conjunction with the horizontal gradient method can aid in defining dip direction by comparing the two source depths produced by each method (Phillips and Grauch, 2001).

This method can be difficult to work with when source geometry is less than ideal; when this is the case the solutions should be viewed in the context of the results of other methods. Analytic signal filtering requires taking a vertical derivative of the magnetic data. This fact is important to keep in mind when
interpreting the solutions, because the results will be noisier and will over-enhance shallow sources. It is possible to reduce these effects by applying linear filtering to the data before using the analytic signal method.

*Local wavenumber filtering.* The most valuable aspect of this method is that it can be used to determine the most appropriate structural index for a particular causative body. Furthermore, like the analytic signal method, differences in edge location between this method and the horizontal gradient method can be used to identify dipping magnetic contacts.

One drawback to the local wavenumber method is that in order to reduce the effects of noise and over-emphasis on shallow sources it helps for the data to first undergo some type of linear filtering, which can be a time-consuming process (Phillips et al., 2007). Also, if the strike of the fault is not perpendicular to the profile the depth solutions will be overestimated (Grauch et al., 2009).

*Euler deconvolution.* Euler deconvolution is a type of magnetic inverse modeling that employs Euler’s homogeneity equation in order to estimate magnetic source depth. Euler’s equation establishes a relationship between the magnetic field and the location of the source, and the degree of homogeneity is conveyed as a structural index value (Yaghoobian et al., 1992). In this method, data is displayed on a grid and the Euler deconvolution is applied using the data from a square window that moves incrementally across the grid (Yaghoobian et al., 1992). The user can define certain parameters regarding which solutions to accept from each window. Solutions that form clusters or spirals indicate that an anomaly of interest is located at the point of the cluster or the source of the spiral.
One advantage of this method is that it is insensitive to magnetization direction and relatively unaffected by the presence of noise.

Euler deconvolution will produce inaccurate solutions when used on anomalies that arise from interfering sources (Grauch et al., 2009). Furthermore, this method is highly sensitive to the choice of input values, so it is best to use this method after obtaining a better sense of plausible values through application of other depth estimation methods.

Multi-source Werner deconvolution. Multiple-source Werner deconvolution is a depth-estimation method that can be used for two-dimensional bodies. Multi-source Werner deconvolution is similar to Euler deconvolution in that it requires the careful input of parameters in order to generate solutions. If the appropriate variables associated with the Earth’s magnetic field are also provided, it will also output estimations of the dip and magnetic contrast. Another benefit of this method is that it can be used in situations when the magnetic sources are close enough that their anomalies may interfere with one another. In addition, out of all of the aforementioned magnetic depth estimation methods it generally provides the best results for profile data. Some drawbacks of this method are that it cannot be used for three-dimensional sources, the strike of the fault must be perpendicular to the profile in order to avoid overestimating the depth, and deep sources are more difficult to identify (Grauch et al., 2009).
PREVIOUS WORK

Aeromagnetic surveys of the Great Sand Dunes region of the San Luis basin are beginning to be conducted only recently. In fact, the data for this study is some of the first of its kind in the geophysical literature. As a result, aeromagnetic data from the more southerly Rio Grande Rift basins are the closest analogues with which to provide some geologic context for this study. The details of aeromagnetic data collection, analysis, and interpretation have already been extensively discussed throughout this paper; interested readers are directed towards Grauch (2001), Grauch et al. (2001), Grauch et al. (2006), Grauch and Keller (2004), Grauch and Hudson (2007), Hudson et al. (2008), Phillips et al. (1998), Saltus et al. (2005), and Smith et al. (2002) for more specific examples of relevant research.

A group of geophysicists at the U.S. Geological Survey (USGS), the Crustal Imaging and Characterization Team, investigates the subsurface structure of the Rio Grande rift basins. A large volume of literature has been published by this group regarding geophysical research about the structure and magnetic properties of sedimentary basins associated with the Rio Grande rift, with a special emphasis on the use of potential field methods as well as on the hydrogeologic implications of the findings.

In conjunction with the USGS, ground magnetic data was collected in the Great Sand Dunes study area during the summer of 2009. Three profiles were taken across potential shallow intrasedimentary faults using a Geometrics mobile cesium magnetometer. When taken in the context of surface geology and
aeromagnetic data these profiles can help determine the horizontal location of possible magnetic contacts.

Because ground magnetic data can more easily overemphasize shallow features, the data may suggest the presence of faults when instead the anomaly is being produced due to variations in magnetic susceptibility. Thus, it is important to evaluate the results of these profiles in conjunction with other data types. While depth estimates cannot be generated from these data, an analysis of these profiles can help determine the horizontal location of possible magnetic contacts. The ground magnetic data is less sensitive to regional trends compared to aeromagnetic data; for this reason, the data may suggest the presence of “faults”, i.e. magnetic contacts, when instead the anomaly is being produced due to variations in magnetic susceptibility within the same unit.

APPLICATION TO THE GREAT SAND DUNES STUDY

The Great Sand Dunes study is a preliminary aeromagnetic survey of the northeastern portion of the San Luis basin. Due to widespread lack of exposure, surface geologic data is limited in this region. Aeromagnetic data was used in conjunction with previous work to estimate the depths of six potential faults in the western section of the study area.

Physical Properties

The sedimentary unit of interest in this study is the Santa Fe Group. Magnetic property data of Santa Fe Group sediments has not been collected within the San Luis Basin proper, but appropriate values can be inferred from
measurements made by Hudson et al. (2008) in the Albuquerque basin. This study found that magnetic susceptibilities in the Zia Formation range from 0.7–1.4 × 10^{-3} and in the Arroyo Ojito Formation range from 0.9–4.3 × 10^{-3}. The range from maximum to minimum magnetic susceptibility values is wide enough that tectonic juxtaposition within these units will potentially produce a measurable aeromagnetic anomaly (Hudson et al. 2008). Pre-rift sedimentary rocks have magnetic susceptibilities that are an order of magnitude less than the Santa Fe Group, ranging from 0.7–2.0 × 10^{-4} (Grauch et al. 2006).

**Aeromagnetic Data**

While a number of high-resolution aeromagnetic surveys have been flown in the San Luis basin, this study will utilize data from Drenth et al. (2009) which was collected in October 2008 (Fig. 6). The northern survey area includes a large portion of the Great Sand Dunes National Park and extends southward along the eastern mountain front to the foot of Blanca Peak. The southern margin of this survey borders previous high-resolution aeromagnetic surveys of the San Luis basin.

The Great Sand Dunes survey was flown by Upper Limit Aviation, Inc. for New Sense Geophysics, Ltd., on contract to the U.S. Geological Survey. A helicopter was outfitted with geophysical instrumentation and flown along lines oriented east-west, oblique with the predominant geologic strike in the region, and spaced 150 m apart (Fig. 7). To aid in data processing, tie lines were flown orthogonal (north-south) to the flight lines with spacing of 1,500 m. The average flight altitude for the survey was 100 m. The average sample interval was 3.19
Figure 6. Location map showing the location of the 2008 Great Sand Dunes Survey (bold red line) relative to the boundaries of other high-resolution aeromagnetic surveys (modified from Drenth et al., 2009).
Figure 7. Bell 206 B3 helicopter (N206BY) equipped with a fixed stinger containing one Cesium magnetometer. Flight carried out on behalf of Upper Limit Aviation, Inc. for the U.S. Geological Survey by New-Sense Geophysics Limited (modified from Drenth et al., 2009).
m/sample, which translates to one sample taken every 0.1 s. A total of 3,609.5 line-kilometers were flown for this survey.

In order to better isolate the region of interest the effects of the Earth’s field was removed and data collection errors were reduced. Next, the magnetic, radar, and laser data were interpolated onto a grid and the gridded radar and laser data were used to calculate a digital terrain model of the survey area. The digital terrain model provides the topographic foundation over which the magnetic data is superimposed.

Before fault depth estimations were made, the magnetic data underwent upward/downward continuation, linear, and reduction-to-pole transformations. First, the magnetic grid was continued to a common surface above the ground to simulate a terrain clearance of 100 m. During the continuation process, the data was also linearly transformed in order to implement a wavelength cutoff that is inversely proportional to continuation distance. This process had the effect of enhancing the appropriate ratio of wavelengths while accounting for changes in observation height. Finally, the reduction-to-pole transformation was made using the declination and inclination of the Earth’s magnetic field in the study area, which are 9.7° and 65.4°, respectively.

This version of the data was plotted as a contour map using the geophysical software OASIS Montaj™. The map view expression of a swarm of potential faults was overlain in the western portion of the contour map, the locations of the ground magnetic profiles were marked, and six profiles were drawn orthogonally across these faults (Fig. 8). Figure 9 depicts the same contour
Figure 8. Reduced-to-pole aeromagnetic data for the Great Sand Dunes region of the northern San Luis Valley, Colorado as produced by OASIS Montaj™. Interpreted parallel fault locations are depicted as linear north/northeast-trending features. Magnetic profile locations are marked roughly orthogonally to these faults. Along SPROF profiles, aeromagnetic data was evaluated using PDEPTH source location methods. Ground-based magnetic surveys were conducted along L profiles. The aeromagnetic data is displayed in nanoteslas (nT).
Figure 9. Reduced-to-pole aeromagnetic data for the Great Sand Dunes region of the northern San Luis Valley, Colorado as produced by OASIS Montaj™. Interpreted parallel fault locations are depicted as linear north/northeast-trending features. Magnetic profile locations are marked roughly orthogonally to these faults. Along SPROF profiles, aeromagnetic data was evaluated using PDEPTH source location methods. Ground-based magnetic surveys were conducted along L profiles. Interpreted potential fault locations are depicted as pink dots along the L profiles. The aeromagnetic data is displayed in nanoteslas (nT).
map supplemented by the potential fault locations interpreted from the ground magnetic results. The magnetic signatures produced by these profiles were then analyzed using PDEPTH with the purpose of generating depth estimates of the corresponding potential faults.

**Depth Estimation Results**

Using the analytical methods described above, magnetic contact depth estimates were made in PDEPTH for each of the profiles (Table 1). For four of the six profiles, SPROF8, SPROF9, SPROF10, and SPROF11, two depth estimates were generated because they each crossed two possible faults.

<table>
<thead>
<tr>
<th>Profile Name (N to S)</th>
<th>Source Depth(s) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPROF12 N</td>
<td>247</td>
</tr>
<tr>
<td>SPROF9 N</td>
<td>103 (W), 247 (E)</td>
</tr>
<tr>
<td>SPROF10 N</td>
<td>92 (W), 124 (E)</td>
</tr>
<tr>
<td>SPROF8 N</td>
<td>166 (W), 94 (E)</td>
</tr>
<tr>
<td>SPROF11 N</td>
<td>82 (W), 358 (E)</td>
</tr>
<tr>
<td>SPROF13 N</td>
<td>205</td>
</tr>
</tbody>
</table>

**Table 1.** Table depicting potential fault depth estimations for the profiles illustrated in Figs. 8 and 9. Profiles are organized north to south as they fall on the map.

In this study, the most reliable results were produced using the local wavenumber, Euler deconvolution, and multi-source Werner methods; however, both the horizontal gradient and analytic signal filtering methods were used to help constrain the results of the other three methods. When necessary, structural indices within the range of $0 < N < 1$ were used to solve for the three dimensional coordinates of magnetic source. Fault dip did not have a strong impact on the
results because the majority of faults in this region are steeply dipping (Grauch and Hudson, 2007).

**DISCUSSION**

The high-resolution aeromagnetic study of the Great Sand Dunes region of the San Luis basin further constrains the horizontal locations and depths of possible shallow intrasedimentary faults. While the ground magnetic data mainly confirms the horizontal fault locations that were previously interpreted, the L0 N profile suggests that a second fault may be located to the east of the mapped fault. Further studies should be conducted in order to gather more evidence regarding the possible presence of a second fault at this location. SPROF8 stands out amongst the aeromagnetic profiles with a deeper depth estimation value for the western fault and a shallower depth estimation value for the eastern fault that is inconsistent with the general trend exhibited by the other profiles. Because this profile is located over a magnetic low on the contour map, where magnetic contrast is not as marked as in other regions, the ability of PDEPTH to estimate the fault depth may be compromised to some degree. In order to determine whether or not this is a confounding variable in the depth estimation solution, more aeromagnetic filtering could be applied or ground magnetic surveys could be conducted closer to the profile in order to further enhance subtle magnetic anomalies. Aside from this potential outlier, the depth estimations follow a general pattern of being deeper on the eastern fault compared to the western fault. This is a reasonable trend to expect considering that this basin was formed by
crustal extension, so faulting should be more pronounced along the basin margin compared to the basin interior.

While more work in this area should be conducted to provide a larger picture of the lateral extent and depth of faults in the region, these preliminary results still have important implications for hydrogeologists interested in studying the San Luis basin. The groundwater-flow model of the basin will be the most realistic if a large volume of information regarding the subsurface structure of the basin is available; this study adds to this volume by better describing the horizontal locations and depths of a group of faults. This kind of knowledge can help community members make more informed decisions about how to allocate their groundwater resources, which is a major issue in the San Luis Valley since a large proportion of land is used for agricultural purposes.

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