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# PRINCIPAL FEATURES OF HIGH-RESOLUTION AEROMAGNETIC DATA COLLECTED NEAR ALBUQUERQUE, NEW MEXICO

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**Abstract**—High-resolution aeromagnetic surveys flown in the middle Rio Grande basin north and south of Albuquerque show expressions of exposed and buried bedrock blocks on the edges of the Rio Grande rift, intrabasinal faults, shallowly buried igneous rocks, topographic effects, and several different types of cultural features. The aeromagnetic maps are especially useful for mapping intrabasinal faults in areas covered by thin, but widespread surficial cover. Expressions of faults on the aeromagnetic map are prominent and numerous, showing curvilinear patterns with many splays. The magnetic expressions can be generally explained by offsets between units having different magnetic properties. The aeromagnetic map also shows expressions of probable buried volcanoes or intrusive centers southwest of the Albuquerque Volcanoes and extensive buried basalt and intrusive centers in the southern part of the study area beneath the Rio Grande flood plain.

## INTRODUCTION

Aeromagnetic methods are used to infer subsurface geologic features by observing variations in the Earth's magnetic field arising from contrasts in total magnetization of the crust. These studies have traditionally focused on mapping igneous and metamorphic rocks and structures related to them, because these rocks commonly have high total magnetizations compared to other rock types (Nettleton, 1971; Reynolds et al., 1990). In contrast, magnetizations of poorly consolidated sediments were considered negligible for aeromagnetic stiudies (Nettleton, 1971).

With advances in technology and shifts in objectives, aeromagnetic surveys are now designed to detect more subtle magnetization contrasts than had previously been targeted (Grauch and Millegan, 1998). These high-resolution surveys are flown closer to the ground and with narrower line spacing than conventional aeromagnetic surveys. The difference in survey design allows better detection of weakly magnetic sources, better definition of sources with limited lateral extent, and overall better resolution of details in plan view. The high resolution facilitates interpretation of aeromagnetic maps by allowing easier discrimination between different patterns and shapes according to their corresponding geologic origin.

As part of a study to understand better the hydrogeology of the Middle Rio Grande basin (Slate, 1998), two high-resolution aeromagnetic surveys were flown north and west of Albuquerque in 1996 (A and B, Fig. 1). The purpose was to test the use of high-resolution aeromagnetic surveys for mapping faults and shallowly buried volcanic rocks within the basin fill. The surveys were flown at flight-line spacings and terrain clearances of 100–150 m, covering areas mapped as Tertiary and Quaternary Santa Fe Group rift-filling sediments, Tertiary and Quaternary volcanic rocks, and Quaternary surficial deposits (Fig. 1; Kelley, 1977). The experiment was unique, due to the alluvial environment of the study area and the tight line spacing, which was narrower than commonly used in hydrocarbon and mineral exploration.

The resulting maps provide remarkable resolution of faults and igneous rocks within the basin fill, as described below. The results are especially useful in areas where geologic mapping is hindered by widespread surficial cover and where subsurface information is sparse. The success of the experiment led to further acquisition of high-resolution aeromagnetic data in other parts of the basin, which is still in progress (see http://rmmcweb.cr.usgs.gov/public/mrgb/airborne.html).

The data from three high-resolution surveys collected in 1996 and 1997 near Albuquerque (Fig. 1) were enhanced analytically and merged to simulate data observed on a surface 100 m above ground (Plate B; editor's note: pages 134–135). The purpose of this report is to explain briefly the principal features expressed on this map, from those of low interest to hydrogeologic studies (basement-related and "cultural" or anthropogenic features) to those of high interest (faults and igneous rocks within the basin fill). Generally less prominent topographic expressions are also described in order to contrast them with fault expressions.

## BACKGROUND

Total magnetization of rocks is determined by the quantity, composition, and grain size of magnetic minerals and by the processes that produce the remanent magnetization carried by these minerals. For a given composition, the quantity of magnetic minerals is reflected in magnetic susceptibility, which is multiplied by the Earth's present-day magnetic field vector to give induced magnetization. Remanent magnetization, which is relatively permanent, is measured using paleomagnetic methods. Total magnetization is the vector sum of the induced and remanent magnetizations, and is manifested as variations in field intensity on aeromagnetic anomaly maps.

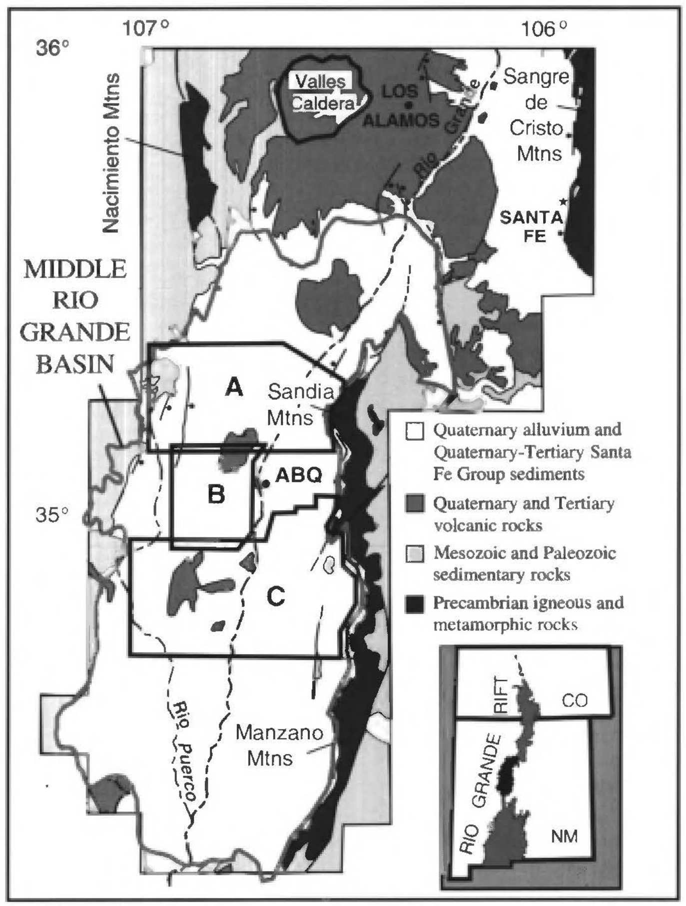


FIGURE 1. Index map showing general geology and location of the middle Rio Grande basin and boundaries of aeromagnetic survey areas flown in 1996 and 1997. ABQ, Albuquerque. A and B, Rio Rancho and Albuquerque West high-resolution surveys, respectively (U.S. Geological Survey and SIAL, 1997). C, Isleta-Kirtland high-resolution survey (U.S. Geological Survey and Sander Geophysics, 1998). Survey A was flown at nominal 100-m spacing at 100-m height above ground. Spacing and height for surveys B and C were 150 m. Inset map shows location of the middle Rio Grande basin (black) within the Rio Grande rift.

Total magnetizations of volcanic rocks are commonly dominated by the remanent component, with values that range from less than 1 to greater than 5 amperes/meter (Bath, 1968). Volcanic rocks that have large remanent components and were formed during a period of an Earth's field reversal give rise to negative-inclination total magnetizations. These rocks produce distinctive, high-amplitude negative aeromagnetic anomalies (Grauch, 1987a) that, in conjunction with age data, can be useful in distinguishing units of different ages.

Total magnetizations of poorly consolidated sediments have not been well studied. Magnetic properties of Santa Fe Group sediments have been recently evaluated in a core hole drilled west of Albuquerque (Hudson et al., 1998). These workers estimated positive-inclination total magnetizations as high as 0.84 amperes/meter (A/m) and negative-inclination total magnetizations as high as 0.13 A/m, with the strongest magnetizations carried by coarse-grained sediments. The range of values provide enough contrast to produce weak to moderate aeromagnetic anomalies, especially if coarse-grained material is juxtaposed against fine-grained material at faults.

## BASEMENT-RELATED FEATURES

The steep flanks of large, positive anomalies appear mostly as shaded red areas along the east-central edges of the survey area in Plate B (labeled "shallow basement"). On regional aeromagnetic maps (Cordell, 1984) these anomalies are associated with Precambrian granite, exposed in the Sandia Mountains to the east (Kelley and Northrop, 1975; Plate B). The extension of these anomalies at high amplitudes (>500 nanoTeslas (nT)) west of exposed granite indicates the presence of granite at shallow depths. The linear western extension of the magnetic anomaly along the Tijeras fault (east-central part of Plate B) corroborates geologic evidence elsewhere of about 2.4 km of left-lateral offset along the fault (Kelley and Northrop, 1975). Similarly, the high-amplitude, negative anomalies along the northeastern edge of the survey area (deep blue colors on Plate B) correspond to mapped Precambrian metamorphic rocks at the surface and indicate shallow basement where the anomalies extend farther westward than the exposed rocks. The high-amplitude negative anomalies indicate the rocks have strong reverse-polarity remanent magnetization.

The broad positive anomaly in the northwestern part of the survey area (yellow- to orange-colored on Plate B) is also apparent on regional aeromagnetic maps (Cordell, 1984). Drill-hole information, seismic-reflection data (Russell and Snelson, 1994), and gravity modelling (Cordell, 1976; Birch, 1982) indicate that crystalline rocks are at about 2 km depth in this area. The strong magnetic expression suggests the rocks are similar to those on the eastern side of the basin in the Sandia Mountains, or to those exposed in the Nacimiento Mountains (Fig. 1) that also correspond to high-amplitude magnetic anomalies on regional aeromagnetic maps (Cordell, 1976). The increased depth of the crystalline rocks explains the broader and lower amplitude character of the anomaly in comparison to the anomalies associated with exposed Precambrian rocks. Likewise, the broad, higher magnetic-field values across the southern half of Plate B may indicate shallower crystalline basement in this area compared to other parts of the basin.

## CULTURAL FEATURES

"Cultural" or anthropogenic features are widespread on the aeromagnetic map and are characterized by spatially limited anomalies with well-defined edges (Plate B). Because of the high resolution of the aeromagnetic survey, the cultural features are easy to distinguish from geologic features in most places. Notable exceptions are in areas of concentrated urban development around Albuquerque (Plate B), where dense cultural features interfere with recognition of geologic features. Aeromagnetic data were not acquired over most of Albuquerque due to this expected interference.

The prominent linear feature that trends northwest-southeast across the northwestern part of Plate B is actually a high-low pair of narrow anomalies with amplitudes of about 5–10 nT each. This expression is due to a buried natural-gas pipeline with rectified current applied for cathodic protection. The current, rather than the pipe itself, produces the magnetic field. A switch in the polarity of the high-low pair in the northwestern part of the study area corresponds to a change in current direction along the pipeline (J. Jojola, Public Service Company of New Mexico, personal commun., 1997). Other pipelines are expressed similarly in the south-central and southwestern parts of the study area (Plate B).

Clusters of circular anomalies that are prominent in urban areas and along Interstate 25 (Plate B) primarily correspond to commercial buildings that were constructed with a substantial amount of steel. Except for the anomaly associated with the industrial complex in the southeastern part of Rio Rancho (Plate B), the largest of the circular to oblong cultural anomalies correspond to active landfills (Plate B). Smaller, isolated, circular anomalies are generally related to large metal structures such as community water storage tanks, compressor stations, electrical substations, and microwave radar towers (Plate B). Magnetic expressions of metal power poles are partially evident in the northeastern part of Plate B; they are more evident in enlarged views of the data (Grauch and Millegan, 1998).

## INTRABASINAL FAULTS

The magnetic expressions of faults were assessed by comparing aeromagnetic features associated with known faults located from on-going surface mapping (by those listed in the Acknowledgments) and drill-hole information (Hawley and Haase, 1992). These fault expressions could then be recognized elsewhere to identify previously unknown faults. In general, semi-linear, sinuous, generally northerly-striking features on the aeromagnetic map, which commonly have little relation to topography, are primarily caused by faults. Recognition of intrabasinal faults that juxtapose units of the Santa Fe Group is especially noteworthy because their detection has been commonly neglected in previous aeromagnetic studies.

Aeromagnetic data for the Loma Machete 7½-min quadrangle illustrate the magnetic expression of intrabasinal faults (Fig. 2). Faults identified by geologic mapping (Personius et al., 1999) are well exposed in the northern part of the quadrangle, evident only in isolated exposures in the southern part, and covered by widespread surficial deposits throughout the central part, including alluvium-colluvium and eolian sand. Semi-linear aeromagnetic features coincide or align with many of these mapped faults, arguing for a causal relation. Therefore, extensions of these semi-linear anomalies and similar ones elsewhere permit mapping of faults beneath cover. On the other hand, some mapped faults have no aeromagnetic expression (Fig. 2). This can be explained by: (1) lack of magnetic contrast in the juxtaposed materials; (2) limited fault offset; or (3) interference from nearby metal structures. Limited fault offset and interference from a building complex explain the lack of magnetic expression of the faults mapped south of the landfill near Loma Colorado (LC, Fig. 2).

Magnetic expressions of intrabasinal faults typically consist of paired high and low anomalies. Each anomaly in the pair ranges from 2–5 nT in amplitude in the northern and central part of the study area and from 5–20 nT in the southeastern part. Examination of profiles across the faults show that pairs typically are either similar in magnitude and shape (symmetric) or that the low is greater in magnitude and narrower than the high (asymmetric). A fault-offset model can generally explain the paired signature, where materials of differing magnetic properties are juxtaposed. However, the asymmetric signatures probably indicate a somewhat more complicated geometry or chemical history that requires further examination.

The high anomaly in the fault-expression pair, which corresponds to the more magnetic material across the fault, can be on the down-thrown or up-thrown side. The Cat Mesa fault illustrates both situations in the south-central part of the study area (Plate B). On the mesa south of the escarpment, the high anomaly is located west of the fault, which appears white in the illuminated image (Plate B). In the valley north of the escarpment, the high anomaly is east of the fault, which puts the fault in shadow. The switch in polarity of the fault-expression pair can

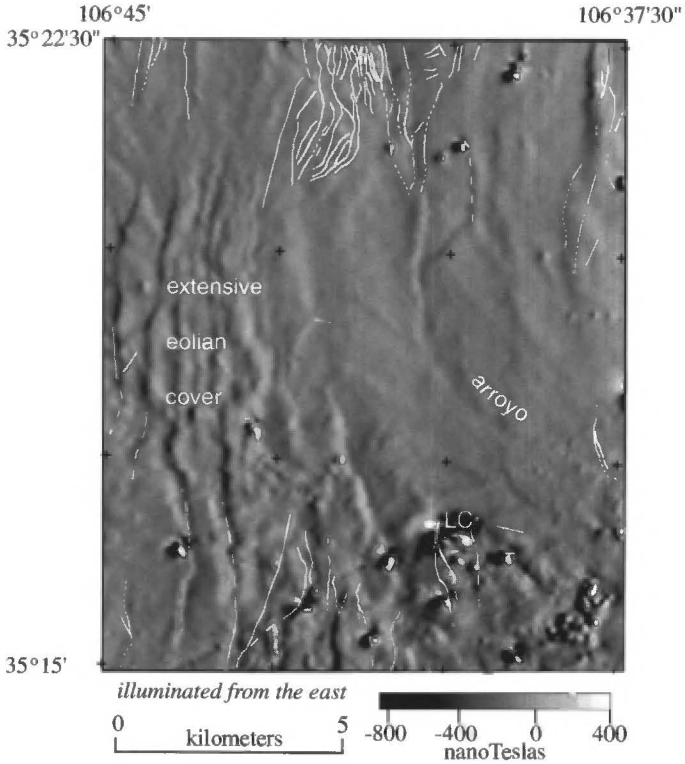


FIGURE 2. Mapped faults (white lines) and gray-scale, shaded-relief image of aeromagnetic data for the Loma Machete 7½' quadrangle. The coincidence or alignment of many of the faults with linear magnetic features argues for their genetic relationship. Faults trending south of the landfill near Loma Colorado (LC) have little offset. Geology from Personius et al. (1999).

be explained by a magnetic unit west of the fault on the mesa that has been eroded north of the escarpment. In the valley, the fault juxtaposes different units, the more magnetic of which is on the east.

Mapping of fault traces from the aeromagnetic map has revealed connections between known faults that were unexpected from geologic mapping. The hydrologically important Hubbell Springs fault (southeastern part of Plate B) appears as the central splay in a series of parallel, generally north-striking, fault systems that extend from about longitude 106° 37' 30", east to the Manzano Mountains. The Tijeras fault appears to curve into to the western splay of this system rather than to the Hubbell Springs fault. The eastern, en echelon portion of this splay system corresponds to the most pronounced expression of faults on the entire map (Plate B). These faults are only tenuously evident in isolated surface exposures (J. Slate, oral commun., 1998).

In the northeastern part of the map area, a linear magnetic anomaly that parallels the Rio Grande valley may be related to a buried river terrace (marked "river terrace?" on Plate B). The anomaly trends from northwest to southeast along the river then dog-legs to the southwest, mimicking the dog-leg in the river. Along the southwest-trending dog-leg, the anomaly follows the inner-valley scarps, which are composed of ancient river deposits (Connell, 1997) and may be the source of the anomalies. The linearity of the northwest-trending dog-leg suggests a structural control.

## MAGNETIC FEATURES RELATED TO TOPOGRAPHY

Some aeromagnetic anomalies correlate with topographic surfaces and commonly have lower amplitudes (1–2 nT) than fault expressions. Aeromagnetic anomaly patterns that correspond to topographic patterns are expected in areas of undulating topography composed of magnetic material (Grauch, 1987b). Magnetic expressions of drainages are generally broader, lower in amplitude, and more limited in extent than fault expressions. Examples on Plate B are west- and northwest-trending arroyos in the northwest and north-central parts of the map area, Tijeras Arroyo in the east-central map area, and the arroyo in the east-central part of the Loma Machete quadrangle (Fig. 2). In particular, the subtle, broad expression of the 50-m-deep drainage associated with the western part of Hell Canyon (southeastern part of Plate B) contrasts well with the prominent magnetic expressions associated with fault scarps that cross or terminate at the canyon and are only about 5–10 m high (Plate B; Love et al., 1996).

In several places, the magnetic expression of escarpments has higher amplitude (2–5 nT) than most other anomalies related to topography. The increase in amplitude is produced by magnetic material that is concentrated along the top of the escarpment. For example, the northwest-facing escarpment along the Rio Puerco floodplain (southwestern map area, Plate B) corresponds well to a magnetic gradient. The gradient is produced by the termination of sand dunes that formed along the cliff edge (Maldonado and Atencio, 1997). The anomalies along the mesa side of the gradient have shapes that correspond well in detail to the shape of the dunes. Magnetic gradients along portions of the Sand Hill and nearby faults also correspond to topography (northwestern map area, Plate B). The magnetic expressions are a combination of terrain effects and fault offset of different lithologies (Cather et al., 1997; Hawley and Haase, 1992).

## VOLCANIC ROCKS AND INTRUSIVE CENTERS

Exposures of basalts and andesites in the study area are generally associated with high-amplitude, highly variable anomaly patterns (Plate B). These patterns reflect the great variability of magnetization and/or thickness of the volcanic units. The broad, circular, high-amplitude (either positive or negative) anomalies within the volcanic fields likely represent major intrusive centers, such as those near Isleta and Los Lunas volcanoes (Plate B). An elongated negative anomaly is associated with the Albuquerque volcanoes (Plate B), suggestive of a vent. Negative anomalies associated with intrusive centers reflect the dominance of reverse-polarity remanence in the total magnetization. Reverse-polarity remanent magnetization has been documented for flows related to the volcano at El Cerro de Los Lunas (Southern et al., 1995); shallow-inclination reverse-polarity remanent magnetization has been measured for the Albuquerque volcanoes (Geissman et al., 1990). Relatively low amplitudes of aeromagnetic anomalies associated with basalt flows exposed east of Albuquerque volcanoes may reflect thin basalt in this area (less than 100 m thick; Kelley and Kudo, 1978).

The aeromagnetic anomaly patterns characterizing flows and intrusive centers can be used to infer the presence of shallow igneous rocks in the subsurface. Subsurface igneous rocks are inferred from the high-amplitude, highly variable anomaly pattern suggestive of buried basalt just west of the Cat Mesa fault (south-central part of Plate B). Numerous faults offset flows at the northern end of the Wind Mesa volcanic field and continue to the north. Broader, more circular negative anomalies indicate intrusive centers southwest of El Cerro de Los Lunas and southwest of El Cerro Tome. The large area of high-amplitude anomalies south of Isleta volcano, extending almost to Cerro de Tome, contains expression of both buried intrusive centers and flows, some of which are buried under the Rio Grande floodplain. An inferred buried intrusive center is located just west of the Rio Grande, about 6 km north-northeast of Los Lunas (Plate B). Several shallow (<65 m) water wells drilled on the opposite (east) side of the river encountered volcanic units at depth (Wilson and Associates, unpubl. report for the Village of Los Lunas, 1994). These wells corroborate the aeromagnetic evidence for extensive, past volcanic activity in this area.

None of the circular, high-amplitude positive anomalies in the west-central part of the study area can be explained by surface rocks ("buried volcanoes?" on Plate B). Jiracek et al. (1982) first recognized some of these anomalies from ground magnetic data. They inferred thin-sheet sources, such as laterally limited sills. Instead, I counter that their circular shapes and diffuse edges more closely resemble the anomalies related to intrusive centers or volcanoes elsewhere on the map (such as Isleta volcano). Basin-fill sediments subsequently buried these intrusive centers or volcanoes. This hypothesis is corroborated by a recent exploration well drilled just north of the isolated anomaly crossed by Interstate 40 (Plate B). The well penetrated rocks related to a shallow intrusive center within the top 1500 m (J. Hawley, oral commun., 1998).

## CONCLUSION

High-resolution aeromagnetic surveys flown in the Middle Rio Grande basin north and south of Albuquerque are useful for mapping faults and igneous rocks within the basin fill, especially in areas of thin, widespread deposits of eolian sand. Integrated with geologic mapping and drill hole information, the maps define the subsurface margins of igneous rock, fault-contacts of Santa Fe Group units, and the general locations of shallow basement. This information can be used to understand better the hydrogeology of the basin.

The clarity of expression of intrabasinal faults that juxtapose units of the Santa Fe Group is the most significant contribution of the high-resolution aeromagnetic surveys. Faults are expressed as linear features that can be generally explained by offsets between units having different magnetic properties. Because faults are generally poorly exposed in the basin, the aeromagnetic maps are an efficient, cost-effective way to trace fault patterns over a large area.

## ACKNOWLEDGMENTS

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## REFERENCES CITED

Bath, G. D., 1968, Aeromagnetic anomalies related to remanent magnetism in volcanic rock, Nevada Test Site: Geological Society of America, Memoir 110, p. 135–146.

Birch, F. S., 1982, Gravity models of the Albuquerque basin, Rio Grande rift, New Mexico: Geophysics, v. 47, p. 1185–1197.

Cather, S. M., Connell, S. D., Heynekamp, M. R. and Goodwin, L. B., 1997, Geology of the Sky Village SE (Arroyo de Las Calabacillas) 7.5' quadrangle, Sandoval County, New Mexico, New Mexico Bureau of Mines and Mineral Resources, Open-file Digital Geologic Map OF-DGM 9, scale 1:24,000.

Connell, S. D., 1997, Geology of the Alameda 7.5' quadrangle, Bernalillo County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Digital Geologic Map OF-DM 10, scale 1:24,000.

Cordell, Lindrith, 1976, Aeromagnetic and gravity studies of the Rio Grande graben in New Mexico between Belen and Pilar: New Mexico Geological Society, Special Publication 6, p. 62–70.

Cordell, Lindrith, 1984, Composite residual total intensity aeromagnetic map of New Mexico: National Oceanic and AtmosphericAdministration, National Geophysical Data Center, scale 1:500,000.

Geissman, J. W., Brown, L., Turrin, B. D., McFadden, L. D. and Harlan, S. S., 1990, Brunhes chron excursion/polarity episode recorded during the late Pleistocene, Albuquerque Volcanoes, New Mexico, USA: Geophysical Journal International, v. 102, p. 73–88.

Grauch, V. J. S., 1987a, The importance of total magnetization in aeromagnetic interpretation of volcanic areas; An illustration from the San Juan Mountains, Colorado: Expanded abstracts with biographies, 57th Annual International Society of Exploration Geophysicists meeting, Oct. 11–15, 1987, p. 109–110.

Grauch, V. J. S., 1987b, A new variable-magnetization terrain correction method for aeromagnetic data: Geophysics, v. 52, p. 94–107.

Grauch, V. J. S. and Millegan, P. S., 1998, Mapping intrabasinal faults from high-resolution aeromagnetic data: The Leading Edge, v. 17, no. 1, p 53–55.

Green, G. N. and Jones, G. E., 1997, The digital geologic map of New Mexico in ARC/INFO format: U.S. Geological Survey, Open-file Report 97-52, digital files available from anonymous ftp at http://greenwood.cr.usgs.gov.

Hawley, J. W. and Haase, C. S., 1992, Hydrogeologic framework of the northern Albuquerque basin: New Mexico Bureau of Mines and Mineral Resources Open-file Report 387, variously paged.

Hudson, M. R., Mikolas, M., Geissman, J. W. and Allen, B. D., 1998, Magnetic properties of Santa Fe Group sediments in the 98th Street core hole, Albuquerque, New Mexico: U.S. Geological Survey, Open-file Report 98-592, 71 p.

Jiracek, G. R., Gustafson, E. P. and Parker, M. D., 1982, Geophysical exploration for geothermal prospects west of Albuquerque, New Mexico: New Mexico Geological Society, Guidebook 33, p. 333–342.

Kelley, V. C., 1977, Geology of Albuquerque basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 33, 59 p.

Kelley, V. C., and Northrop, S. A., 1975, Geology of Sandia Mountains and vicinity, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 29, 136 p.

Kelley, V. C. and Kudo, A. M., 1978, Volcanoes and related basalts of Albuquerque basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 156, 30 p.

Love, D. W., Hitchcock, C., Thomas, E., Kelson, K., Van Hart, D., Cather, S., Chamberlin, R., Anderson, O., Hawley, J., Gillentine, J., White, W., Noler, J., Sawyer, T., Nyman, M. and Harrison, B., 1996, Geology of the Hubbell Spring 7.5-min quadrangle, Bernalillo and Valencia Counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Digital Geologic Map 5, scale 1:12,000.

Maldonado, F. and Atencio, A., 1997, Preliminary geologic map of the Dalies NW quadrangle, Bernalillo County, New Mexico: U.S. Geological Survey, Open-file Report 97-741, 7 p., 1:24,000 scale.

Nettleton, L. L., 1971, Elementary gravity and magnetics for geologists and seismologists: Society of Exploration Geophysicists, Monograph series, no. 1, 121 p.

Personius, S. F., Machette, M. N. and Stone, B. D., *in press*, Preliminary geologic map of the Loma Machete quadrangle, Sandoval County, New Mexico: U.S. Geological Survey, Open-file Report, 21 p., scale 1:24,000.

Reynolds, R. L., Rosenbaum, J. G., Hudson, M. R. and Fishman, N. S., 1990, Rock magnetism, the distribution of magnetic minerals in the Earth's crust, and aeromagnetic anomalies: U.S. Geological Survey, Bulletin 1924, p. 24–45.

Russell, L. R. and Snelson, S., 1994, Structure and tectonics of the Albuquerque basin segment of the Rio Grande Rift: Insights from reflection seismic data: Geological Society of America, Special Paper 291, p. 83–112.

Slate, J. L. 1998, ed., U.S. Geological Survey Middle Rio Grande basin Study—Proceedings of the Second Annual Workshop, Albuquerque, New Mexico, February 9–12, 1998: U.S. Geological Survey, 91 p.

Southern, H. D., Rowe, H. D., Kudo, A. M. and Geissman, J. W., 1995, Geochemistry and petrogenetic modeling of Cerro de Los Lunas andesites, New Mexico: EOS, Transactions, American Geophysical Union, v. 76, no. 46, p. 656.

U.S. Geological Survey and SIAL, Ltd., 1997, Description of digital aeromagnetic data collected north and west of Albuquerque, New Mexico: U.S. Geological Survey, Open-file Report 97-286, 45 p., digital data on anonymous ftp.

U.S. Geological Survey and Sander Geophysics, Ltd., 1998, Digital data from the Isleta-Kirtland aeromagnetic survey, collected south of Albuquerque, New Mexico: U.S. Geological Survey, Open-file Report 98-341, 1 compact disk.