Preliminary Geologic Map of the Sandia Park Quadrangle, Bernalillo and Sandoval Counties, New Mexico

By

Charles A. Ferguson, J. Michael Timmons, Frank J. Pazzaglia, Karl E. Karlstrom, Glenn R. Osburn, and Paul W. Bauer

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New Mexico Bureau of Geology and Mineral Resources
Open-file Digital Geologic Map OF-GM 1

Scale 1:24,000

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New Mexico Bureau of Geology and Mineral Resources
801 Leroy Place, Socorro, New Mexico, 87801-4796

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by Charles A. Ferguson[1], J. Michael Timmons[2], Frank J. Pazzaglia[2], Karl E. Karlstrom[2], Glenn R. Osburn[3], and Paul W. Bauer[4]

[1]*Arizona Geological Survey, Tucson, Arizona 85705*
[2]*Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131*
[3]*Department of Earth & Planetary Sciences, Washington University, St. Louis, Missouri 63130*
[4]*New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico 87801*

INTRODUCTION

The geologic map of the Sandia Park 7fi-min quadrangle should be of use to many, not just geoscientists. Most of the text, however, was written for stratigraphers and structural geologists. Engineers, laypersons, landowners, and those interested chiefly in the mechanical properties and general configuration of the rocks should read the structural multilayer section in the structural geology section. With the aid of a basic glossary of geologic terms, it should be comprehensible to most nongeoscientists.

The new detailed mapping of this area has helped to refine interpretation of the structure of the area and to resolve some stratigraphic problems; however, the overall map pattern has not changed significantly, and the structural interpretation of the area as a Laramide contractional belt (Kelley and Northrop, 1975) has not changed.

Principal contributions and improvements on the work of Kelley and Northrop (1975) include: 1) definition of the San Antonito fault zone as an east-vergent reverse fault system and recognition of a pervasive set of associated north–northwest-striking short-wavelength folds; 2) recognition of a pervasive set of synthetic riedel shears along Tijeras fault and parts of the Gutierrez fault indicating probable mid-Tertiary and younger sinistral slip along the fault system; 3) discovery of a sliver of Proterozoic granite along the Tijeras fault that helps to set a lower limit of sinistral offset (about 1 km); and 4) discovery of important upper Turonian guide fossils in the poorly exposed Mancos Shale of the Tijeras synclinorium.

We found it difficult to define the Abo–Yeso contact precisely in this area, and this problem was dealt with by mapping the two units together. A small intrusive complex in the lower San Pedro Creek area was found to be more extensive than previously mapped. Hornblende $^{40}Ar/^{39}Ar$ ages of 34.5±0.2 Ma and 35.02±0.13 Ma were obtained from the main dike and a plug, respectively, in this area.

Detailed mapping of the Monte Largo area showed that the roof of the Sandia pluton is just below the surface and that the structure and overall composition of the Proterozoic basement does not change significantly across the Tijeras synclinorium. The orientation of the intrusive contact seems to have influenced the location and west-vergent sense of displacement of the Tijeras–Gutierrez fault system during the Laramide.

This quadrangle map has been open filed to make it available as soon as possible. The map has not been reviewed according to New Mexico Bureau of Mines and Mineral Resources (NMBMMR) standards. Because of the ongoing nature of work in the area, revision of this map is likely. As such, dates of revision will be listed in the upper right corner of the map and on the accompanying report. The contents of the report and map should not be considered final and complete until it is published by the NMBMMR.

ACKNOWLEDGMENTS—Mapping of this quadrangle was funded by a matching-funds grant from the 1995 STATEMAP program of the National Geologic Mapping Act coordinated by the U.S. Geological Survey and the New Mexico Bureau of Mines and Mineral Resources (Charles E. Chapin, Director). We would like to thank Orin Anderson and John Bloch for their assistance with Mesozoic lithostratigraphic and biostratigraphic correlations. Thanks also to Gary Smith for discussions regarding Pennsylvanian stratigraphy. Ferguson would like to thank the Bloch family, Christopher McKee, and Kentlin J. Keebler for logistical assistance.

NEOGENE–QUATERNARY SURFICIAL GEOLOGY

Physiography and geomorphic setting

The Sandia Park quadrangle encompasses a region of moderate topographic relief between the uplifted rift-flank shoulder (Sandia Mountains) of the Rio Grande rift in the west and the relatively undeformed High Plains in the east. Elevations range from 7,934 ft on the Sandia Mountains to 6,100 ft in the San Pedro Creek valley where it flows out of

the quadrangle in the north. The Monte Largo Hills rise in the east-central part of the quadrangle with as much as 800 ft of relief. Elsewhere, the landscape is much more gentle, exhibiting on average approximately 200 ft of local relief between stream valleys and adjacent interfluves.

The quadrangle could be broadly subdivided into three geomorphic terranes based on the primary surficial deposits and local topography. Surficial deposits of significant thickness and continuity are rare on the steep dip slope of the Sandia Mountains and along a northeast-trending band of relatively high relief represented by the Monte Largo Hills and the uplands west of Gutierrez Canyon. The lower-standing topography in the southern three-fourths of the quadrangle is relatively unincised and mantled with thin, predominantly fine-grained alluvial and colluvial deposits. In contrast, the northern one-quarter of the quadrangle is more deeply incised and preserves rather coarse-grained alluvial-fan and pediment-gravel deposits on broad, low-gradient interfluves.

Drainages

The Sandia Park quadrangle is drained primarily by the north-flowing San Pedro Creek and its major tributaries, Frost Arroyo and Arroyo Armijo. A small area of the southwestern part of the quadrangle forms the headwaters of the south-flowing Tijeras Arroyo.

San Pedro Creek is an ephemeral and/or intermittent stream from its headwaters to San Pedro Spring. Downstream (north) of San Pedro Spring, San Pedro Creek assumes a more perennial character except during the late summer and early fall. Alluvium in the active channel is rarely more than 2 m thick, and bedrock is everywhere near the channel bed. Locally, such as at San Pedro Spring and in the northern quarter of the quadrangle, the stream flows on a bedrock channel. San Pedro Creek is a major tributary to Arroyo Tonque, the master drainage and regional base-level control in the Hagan Basin to the north. A longitudinal profile (Fig. 1) of San Pedro Creek through the Sandia Park quadrangle shows that it has a straight profile with several small knickpoints and one major convexity/knickpoint approximately 2 km south of where the stream flows out of the quadrangle to the north. Knickpoints in the San Pedro Creek valley correspond well to changes in rock type in the bed of the stream; steeper channel segments are developed across the more resistant rock types

Well-stratified fluvial terrace deposits are preserved along the San Pedro Creek valley and locally along the valleys of its larger tributary streams. These terraces represent former locations of the stream channel, and when mapped and correlated they can be used to reconstruct paleo-longitudinal profiles (Fig. 1). Comparison of the paleo-longitudinal profiles to the modern stream profile demonstrates the degree of stream incision since terrace deposition.

Previous work and regional considerations

Surficial deposits were mapped in and around the Sandia Park quadrangle by Bryan (1938), Stearns (1953), Kelley (1977), and Kelley and Northrop (1975). The Ortiz Mountains lie immediately north of the Sandia Park quadrangle. A spectacular regional geomorphic surface named the Ortiz surface (Ogilvie, 1905) extends like an apron around the base of the Ortiz Mountains. The base of the Ortiz surface is a classic fluvial pediment of low relief cut across the intrusive rocks of the Ortiz Mountains and steeply dipping sedimentary rocks of variable resistance westward into the Hagan Basin. The pediment is buried by several meters (locally as many as 10 m) of coarse-grained, subrounded gravel of Ortiz Mountain provenance named the Tuerto gravels (Stearns, 1953) for exposures along Tuerto Arroyo. An important characteristic of these gravels is that they are locally indurated and hold a steep vertical face along incised valley sides. This induration is in part a reflection of a very well developed weathering profile characterized by a large accumulation of pedogenic calcium carbonate.

The age of the Ortiz pediment and Tuerto gravels is not well known. Projection of the pediment west into the Rio Grande rift suggests that the basalt-capped mesas west of the Rio Grande may be axial stream equivalent surfaces. Correlation of surfaces based strictly on elevation, especially when the surfaces are projected across major rift-bounding faults, cannot be used as reliable age control. Nevertheless, these correlations have been proposed, and they suggest a Pliocene age for the Ortiz pediment based on the age of the basalts capping the mesas in the rift.

Kelley (1977) was the first to consider regional correlations of geomorphic surfaces in his compilation of the Albuquerque Basin map. Kelley (1977) and Kelley and Northrop (1975) mapped several high-level gravel deposits in the Sandia Park quadrangle and suggested that some of these deposits might be southern equivalents of the Ortiz pediment gravels (Tuerto gravels) farther north. High-level surficial deposits in the Sandia Park quadrangle, that is those gravels that lie more than 100–200 ft above local grade, have a similar elevation to the Tuerto gravels. In composition and weathering characteristics, Sandia Park high-level deposits are highly variable. Nowhere are the very well developed weathering profiles of the Tuerto gravels observed. It is this author's opinion that most high-level deposits in the Sandia Park quadrangle are either inset below the Ortiz pediment or are younger Quaternary-age deposits that have reworked and/or prograded across the southern equivalent of the Ortiz pediment. These Quaternary units include the extensive older alluvial-fan and pediment/fan deposits preserved in the northern quarter of the quadrangle at elevations between 6,800 ft and 6,400 ft. At two locations, on the ridge east of La Madera and along the southern flank of the Monte Largo Hills, high-level stratified deposits (*QTug*) have been mapped. These deposits, which lie at or above 7,100 ft in elevation, may be true equivalents to the Tuerto gravels.

Landscape evolution

Long-term landscape evolution in the Sandia Park quadrangle has been affected by changes in the rate of regional baselevel fall, Pleistocene climatic changes, and the local effects of tectonic deformation.

Effects of regional base level

The Ortiz pediment indicates that base level in the Hagan Basin must have been relatively stable for a protracted period of time during the late Tertiary. Deposition of the Tuerto gravels in the Pliocene(?) probably signified an up-basin change in hydrology and sediment supply or a down-basin rise in base level such that the streams that were formerly transporting detritus and cutting the pediment aggraded, burying the pediment surface. Since that aggradational event, all local streams have experienced protracted base-level fall and have incised at variable rates. The regional base-level fall may be related to the incision of the rift axial

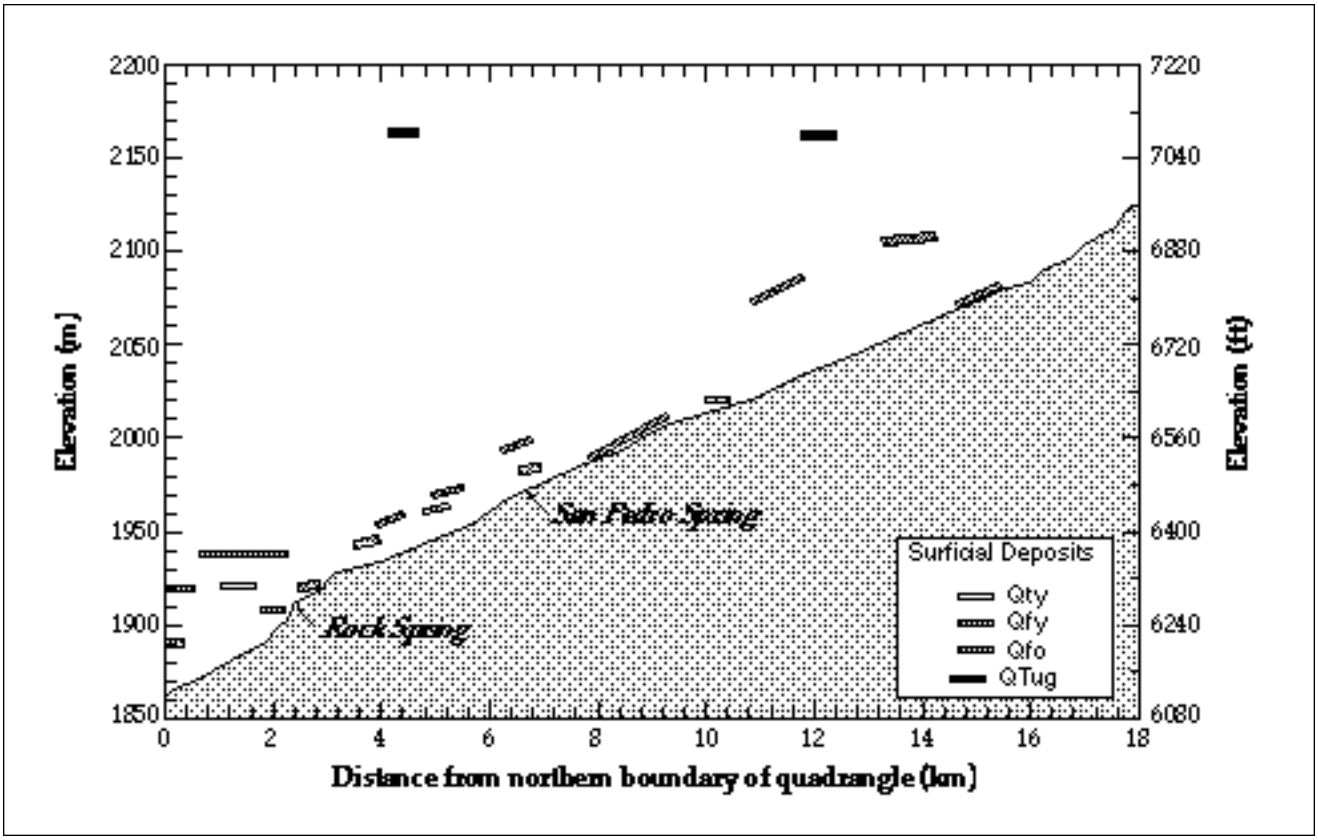

FIGURE 1—Plot of the valley longitudinal profile and bases of associated surficial deposits along San Pedro Creek in the Sandia Park quadrangle. All elevation data is projected to an imaginary vertical plane constructed as straight segments along the San Pedro Valley. Profile begins where the steam flows out of the quadrangle to the north.

stream, the Rio Grande, the timing of which is loosely constrained between 1 and 2 Ma. Streams closer to the Rio Grande, such as Arroyo Tonque, have incised the most, resulting in a rapidly exhumed Hagan Basin. Geomorphic surfaces are relatively unstable in the Hagan Basin proper; except for wind-derived deposits, well-developed soils in alluvium are rare, and soils in bedrock-derived regolith are virtually nonexistent. Farther up basin, away from the Rio Grande, such as along San Pedro Creek in the Sandia Park quadrangle, the downstream effects of base-level fall have been more complicated. Combined with up-basin changes in hydrology and sediment yield, rates of incision in the San Pedro quadrangle have varied such that there have been periods of relative base-level stability characterized by aggradation of fan, pediment, and terrace deposits, as well as periods of base-level fall characterized by stream incision.

A plot of the paleo-longitudinal profiles of San Pedro Creek constructed by projection of terrace, fan, and pediment deposits to an imaginary vertical plane constructed down the axis of the San Pedro Valley (Fig. 1) illustrates the competing effects of downstream base-level fall, changes in upstream hydrology, and upstream tectonic(?) uplift. The knickpoint at Rock Spring separates San Pedro Creek into a downstream portion that has felt the effect of base-level lowering in the Hagan Basin and has responded by incising. Mapped surficial deposits in this region have both a lower gradient than the modern channel and project in elevation to near the top of the knickpoint. Both of these observations are consistent with increased rates of post-*Qfo* stream incision. Upstream of Rock Spring, the younger terrace and fan deposits have gradients very similar to the modern channel suggesting rather uniform channel incision, albeit at variable rates. In contrast, the *Qfo* deposits have long profiles steeper than the modern channel. It is important to point out that the detailed petrographic, sedimentologic, and numeric age dating necessary to positively correlate the *Qfo* deposits has not been done. The *Qfo* map unit probably contains several deposits of middle Pleistocene age. Nevertheless, if the mapped *Qfo* deposits are all roughly the same age, the upstream divergence from the modern channel argues for uplift in the San Pedro Creek headwaters after *Qfo* time, but before *Qfy / Qty* time. Pleistocene uplift of the region is not inconsistent with the rugged topography and lack of appreciable surficial deposits characteristic of the Monte Largo Hills.

Effects of Pleistocene climatic changes

The Sandia Park quadrangle lies just 40 km northwest of the best-studied Quaternary paleoclimatic system in New Mexico—pluvial Lake Estancia (Allen, 1993; Allen and Anderson, 1993). The paleoclimatic studies definitively demonstrate that there have been major changes in hydrology and sediment yield during global climate fluctuations of the late Pleistocene and Holocene. Pleistocene climates for central New Mexico were on average cooler and wetter than the present. Under these conditions, hillslopes in the Sandia

Park quadrangle might be expected to produce more weathering products from enhanced chemical and physical processes. Mobilization of those hillslope deposits into the fluvial system provides one explanation for the periodic slowing of incision rates and aggradation of fans, terraces, and pediment gravels. The ages of fan, terrace, and pediment deposits are poorly known, but the relative weathering profiles and elevation above local grade argue for multiple episodes of aggradation and renewed incision in the Pleistocene.

Locally, the effects of an intense, cold Pleistocene climate are recorded in the coarse colluvial deposits and talus best preserved on the dip slope of the Sandia Mountains. Certain rock types, such as the sandstones of the Madera Formation, are particularly susceptible to frost shattering under these climatic conditions.

Effects of local tectonic deformation

The effects of tectonic deformation recorded in the landscape and surficial deposits of the Sandia Park quadrangle are limited to the few well-mapped faults, namely the Tijeras–Gutierrez fault system. Several low-order tributaries of Tijeras Arroyo, Gutierrez Arroyo, and San Pedro Creek in the southwestern part of the quadrangle are oriented parallel to the northeast strike of these faults. Late Pleistocene and Holocene left-lateral deformation along the Tijeras fault is supported by offset surficial deposits in the northeastern part of the quadrangle (Abbott and Goodwin, 1995). If the above-mentioned regional stream incision is driven in part by tectonic deformation, uplift in the Sandia Park quadrangle must be of a regional, epeirogenic nature, rather than driven by local deformation associated with mapped faults.

Implications for ground-water resources

Surficial deposits in the Sandia Park quadrangle are generally thin and not suitable for shallow alluvial aquifers, although locally, the deposits may be thick enough to support a shallow aquifer for a single domestic household. Likely locations for shallow alluvial aquifers include the alluvium/colluvium undivided deposits (*Qacuf, Qacu*) of the west-central and southern parts of the quadrangle. Engineers' reports for housing developments in these areas show that the alluvial/colluvial deposits can be as thick as 10 m.

The springs along San Pedro Creek and its tributaries are related to bedrock aquifers and not to the alluvium of the valley bottom. Flow in San Pedro Creek is too low and unreliable to use for domestic water supply, although it can and is being used as a water source for cattle.

More important than consideration of potential alluvial aquifers in the surficial deposits is the role that they play in determining deep aquifer recharge and in protecting the deep bedrock aquifer from contamination. All surficial deposits, particularly the coarser-grained ones, do not generate as much runoff as exposed bedrock. Younger surficial deposits are better as potential recharge zones than the older deposits because the older deposits contain well-developed calcic soils that impede infiltration.

Housing development on surficial deposits is preferable to development on bedrock from the standpoint of construction considerations in moving unconsolidated material vs. indurated bedrock. If domestic housing is not to be part of a regional sewer system, most mapped surficial deposits will

MESOZOIC AND PALEOZOIC STRATIGRAPHIC NOMENCLATURE AND BIOSTRATIGRAPHY

Cretaceous

The Mancos Shale is mostly concealed by alluvial deposits in the broad valleys that flank the Tijeras syncline. The unit's stratigraphy is known from rare exposures in deeply incised gullies, many of which may not have been present when this area was mapped by Kelley and Northrop (1975). Molluscan fossils in the Mancos Shale were identified by comparison with the plates in Cobban and Hook (1989).

The most continuous exposure of Mancos Shale is near the head of Arroyo San Antonio, along the eastern half of the boundary between secs. 25 and 36 T11N R5E. In this gully, the oldest exposed rock is a dark-gray shale with a 20–60-cm-thick, black micrite bed containing the bivalve *Mytiloides mytiloides*. This limestone is overlain by at least 100 m of black, noncalcareous shale containing abundant septarian nodules as much as 1 m in diameter. Above the septarian-nodule shale is a shale sequence with several thin- to medium-bedded calcareous sandstone beds. These sandstone beds, which also are preserved in the next gully to the north, contain abundant bivalve fragments and the ammonite *Prionocyclus novimexicanus* (sample F-95-54).

The Mancos Shale is also exposed along the headwaters of Gutierrez Canyon in the east limb of the Tijeras syncline. Incomplete exposures here suggest a similar stratigraphic sequence to that along Arroyo San Antonio. A *Mytiloides mytiloides*-bearing black micrite (sample F-95-49) is present just above the uppermost Dakota Formation exposure. Farther downstream a medium-bedded calcareous sandstone contains fragments of the ammonites *Prionocyclus novimexicanus* and *Scaphites whitfieldi* and the bivalve *Inoceramus rotundatus* (sample F-95-52). The *Scaphites whitfieldi* indicates a late Turonian biostratigraphic age for this interval, and, based on precise laser-fusion radiometric ages from sanidine phenocrysts in bentonites elsewhere in the western interior basin, an absolute age of between 90.21±0.72 Ma and 88.34±0.60 Ma (Obradovich, 1993) is presumed. Kauffman et al. (1993) reported an age of 89.4 Ma for the *Scaphites whitfieldi* (T12) biozone.

Discovery of the ammonites *Prionocyclus novimexicanus* and *Scaphites whitfieldi* in the Mancos Shale on both limbs of the Tijeras syncline has improved our understanding of the correlation of this outlier with the Cretaceous rocks in other parts of New Mexico. Correlation of the overlying mixed terrestrial and marine sandstone-rich sequence in the core of the Tijeras syncline with other Upper Cretaceous sequences is not clear. This sequence was divided into lithostratigraphic units based on the presence of evidence of marine conditions. At least three "terrestrial" sequences were recognized, each overlying marine sandstones or shales. How these tongues correlate with the numerous possible regressive sandstones that have been described elsewhere in the western interior basin is still not known, because definitive biostratigraphic control is lacking. Areas where molluscan shell debris was found are indicated on the map, and these might help direct the search for guide fossils in this sequence.

Jurassic

Recent revision of the Jurassic stratigraphic nomenclature of the Hagan Basin (Lucas et al., 1995) consists of formal subdivisions of the Todilto Formation and recognition of the Summerville Formation as distinct from the Morrison Formation.

The Todilto Formation consists of a lower, thin-bedded, algal-laminated limestone (Luciano Mesa Member) that is overlain by the thicker Tonque Arroyo Member, which consists of massive or bedded gypsum (Lucas et al., 1995). In the past, these units were referred to as the limestone and gypsum members (e.g. Pigman and Lucas, 1989). In the Sandia Park area, both members are present. The upper Tonque Arroyo Member is exposedonly in a quarry at the south end of a prominent ridge that terminates near the Cedar Crest Post Office in the southwest corner of the map area. Elsewhere, the only exposed part of the Todilto Formation is the Luciano Mesa Member (basal limestone). Because these exposures are separated from the overlying Summerville Formation, Bluff Sandstone, or Morrison Formation by a colluvium-covered recessive interval, the presence of the younger Tonque Arroyo Member is implied, and areas where only the Luciano Mesa Member is exposed were mapped as Todilto Formation, undifferentiated. A sink hole in the NE/ sec. 30 T11N R6E is considered evidence for the presence of the Tonque Arroyo Member in this area.

A thin, recessive unit of red and green shale and thin sandstone and siltstone between the Todilto and Bluff Formations is correlated with the Summerville Formation of the Hagan Basin (Lucas et al., 1995). Because of its lithologic similarity to the finer-grained parts of the Morrison Formation, the Summerville Formation probably would not be mappable in the study area, except that it is separated from the Morrison Formation by the Bluff Sandstone, a prominent ledge-forming, light-colored sandstone unit.

Triassic

Three map units of probable Triassic age were recognized in the map area. The basal unit is a recessive-weathering, dark-red sandstone and siltstone that was mapped as Moenkopi Formation. The Moenkopi Formation is overlain by the Chinle Group (Lucas, 1993), which is divided into two map units. The basal unit is a clean, light-colored, resistant feldspathic arenite to quartz arenite that Kelley and Northrop (1975) mapped as Santa Rosa Formation. However, based on arguments presented by Lucas and Hunt (1989), we have changed the name to the Agua Zarca Formation, which is the lower unit of the Chinle Group in the Hagan Basin, less than 50 km to the north of the map area. We made this revision because in the Sandia Park area the unit does not include the medial shale Los Esteros Member of the Santa Rosa Formation. In some areas a medial, finer-grained interval is suggested by the geomorphic expression of the unit as a hogback with a minor trough or recessive ledge developed on its updip side. The exposure of this recessive trough is very poor, but it should be noted that a prominent medial shale is present at the easternmost exposure of the Agua Zarca Formation at the east end of Frost Arroyo monocline. The remainder of the Chinle Group in the Sandia Park area was not divided because of poor exposure and difficult access to private lands. In some areas, laterally extensive limestone-pebble conglomerates crop out as resistant ledges and micro-hogbacks. Some of these in the Cañoncito area in the southwest corner of the quadrangle are depicted by dotted lines.

Permian

Mappable rocks of Permian age consist of four formations in central New Mexico, but they could be divided consistently into only two map units in the Sandia Park area: the upper or San Andres–Glorieta (Ps–g) and the lower or Abo–Yeso (Pa–y). Each map unit is a pair of lithotypes that interfinger and are facies of each other, and the lithotype at the base of each map unit appears to be a facies of the formation or lithotype that it directly overlies. The lithotypes correspond closely to the formations for which they are named. They are herein referred to informally by dropping the word "Formation." This is because of the highly subjective nature of picking the contacts. Locally, each lithotype was mappable, but only the basal Glorieta contact and the top of the San Andres (a sharp unconformity with Triassic red beds) are distinctive throughout the study area.

Abo–Yeso map unit

The lower map unit is an upward-fining, fluvial/marine siliciclastic facies association. The Abo lithotype consists of arkose and dark-red, feldspathic sandstone, siltstone, and shale displaying dominantly fluvial sedimentary structures. The Abo changes gradually upward into the Yeso lithotype, which consists of lighter-colored, generally finer grained feldspathic to quartzose sandstones, siltstones, shales, and interbedded micritic limestone near the top. The unit is overlain sharply by a blanketlike sheet of Glorieta quartz arenite. Its lower contact is gradational with the Pennsylvanian Madera Formation.

Limestones in the Abo lithotype are rare, thin, and restricted to its lower part. They are similar in appearance to those of the upper Madera Formation, but Abo macrofossils are dominated by robust bivalves as opposed to the more diverse and delicate-appearing shelly fossils common to Madera Formation limestones. It is not clear how closely the lithologic transition from Madera Formation to the overlying Abo–Yeso map unit corresponds to the Pennsylvanian–Permian boundary. The lithologic transition, well exposed along the west side of San Pedro Creek, appears conformable through a sequence of limestones and varicolored arkoses, sandstones, and shale. The contact was placed at the abrupt change in the skeletal faunas preserved in the limestones. Whether this change represents an evolutionary transition or merely reflects changing environmental conditions was not discernable during this study.

The identification of a sharp contact between the Abo and Yeso lithotypes is very difficult to make because of the poor exposure in the Sandia Park area. Farther south, in the Abo Pass and Socorro areas, where they are well exposed and formally defined, it is easy to distinguish these units, based on the first appearance of the salt-hopper impressions that define the base of the Yeso Formation. Unfortunately, this change is rather difficult to find consistently in the Sandia Park area primarily due to the small size and poorly preserved nature of Yeso float material. For this reason, much of the Abo–Yeso siliciclastic sequence was lumped together, and a map symbol for salt-hopper casts was created to assist workers who would endeavor to define this contact more accurately.

The contact between the Abo and Yeso Formations as depicted by Kelley and Northrop (1975) may be an unconformity in the lower San Pedro Creek area. This is indicated by the apparent erosional truncation of a hornblende-porphyritic dike along a bed-parallel surface that is nearly coincident with the location of Kelley and Northrop's (1975) con-

tact. The dike, mapped as a Tertiary monzonitic body by Kelley and Northrop (1975) and petrographically similar to other Tertiary intrusive rocks in the area, may be actually late Paleozoic in age. Hornblende phenocrysts from the dike and related rocks farther to the west are being dated at New Mexico Tech's Ar/Ar lab in Socorro.

San Andres–Glorieta map unit

The upper map unit of Permian age is a marine siliciclastic/carbonate facies association. The Glorieta lithotype, an exceptionally clean (nonargillaceous) quartz arenite, is interbedded with the San Andres lithotype, a light-gray, micritic limestone.

Limestones of the Yeso and San Andres lithotypes are virtually indistinguishable, except that those of the Yeso are less likely to contain macrofossils and more likely to be algal or cryptalgal laminated and to preserve fenestral fabrics. The Yeso limestones were probably deposited in a more restricted, lagoonal or sabkha environment than those of the San Andres.

Pennsylvanian

None of the Pennsylvanian units are bounded by sharp contacts except for the base of the Sandia Formation, which is a nonconformity with crystalline basement. The contacts are gradational and fairly subjective. In the lower San Pedro Creek area, the contact between Madera Formation and the Abo lithotype was picked at a sharp change in lithology and skeletal faunas in the limestones, but this criteria may not apply to all areas.

PROTEROZOIC GEOLOGY

New Mexico Geological Society graciously gave permission to reprint the following description of the Proterozoic geology of the Monte Largo Hills modified from Timmons et al. (1995).

Previous work

Previous work in the Monte Largo Hills area provided some lithologic mapping, but only a limited discussion of the regional context for deformation and metamorphism. Herrick (1898) initially described the Proterozoic metamorphic rocks in the Monte Largo Hills area. Darton (1928) briefly discussed the metamorphic structure of the Golden–San Pedro area. Lambert (1961) completed a petrographic analysis of the metamorphic rocks on the west side of the Monte Largo Hills. Huzarski (1971) discussed the petrology and structure of the eastern Monte Largo Hills. Kelley and Northrop (1975) identified Sandia and Cibola granites in the Monte Largo Hills and published a 1:48,000-scale map of the Sandia Mountains and vicinity.

Early Proterozoic country rock

Metavolcanic and metasedimentary rocks of the Monte Largo Hills include metarhyolite (~60% of exposed rock), amphibolite (25%), quartzite (10%), and pelitic schist (5%). The bimodal metavolcanic rocks consist of intimately interlayered metarhyolite and amphibolite with variable thicknesses and lensoidal shapes in map view. Amphibolites commonly have calc-silicate pods and relict lensoidal clasts, supporting the interpretation that these rocks were originally extrusions. These rocks are similar to rocks dated at 1.66 Ga in the Los Pinos Mountains to the south (Shastri, 1993). Metarhyolite predominates in the northwest, whereas amphibolite predominates in the southeast.

Metarhyolite is commonly orange–pink and fine grained and contains quartz (as great as 5 mm in diameter) and K-feldspar phenocrysts. Quartz grains are lineated and flattened and, along with aligned muscovite or biotite grains, define the foliation. Average modal composition is quartz, 43%; plagioclase, 34% (An_6 to An_{13}); microcline, 13%; muscovite, 6%; biotite, 2%; and opaque minerals, 2%. Plagioclase exhibits albite twinning (Lambert, 1961). Foliation intensity varies depending on intensity of strain and mica content.

Amphibolite layers vary in thickness from 30 cm to tens of meters. Amphibolites are dark gray to black, fine grained, and foliated. Average mineral composition is hornblende, 40%; plagioclase, 37% (An_{37} to An_{45}); quartz, 13%; and magnetite, 8%. Trace amounts of biotite, muscovite, epidote, apatite, sphene, and garnet are present. Plagioclase grains are anhedral to subhedral and are generally untwinned, although albite and pericline twinning are present locally. Hornblende varies from anhedral equant grains to subhedral prisms. Hornblende crystals are aligned crudely in the foliation plane but are commonly radiating, suggesting that hornblende grew late during formation of the steeply dipping regional foliation.

Metasedimentary rocks in the study area include quartzite, muscovite schist, and sillimanite schist. Quartzite is typically gray to dark red in outcrop and locally preserves oxide layering that defines original bedding. Quartz grains are recrystallized and strongly elongate, having length-to-width ratios as high as 9 to 1. Pelitic units are gradational with the quartzites and are rich in sillimanite (30%), quartz (>50%), and muscovite (20%). Associated muscovite schists are fine grained and are generally gray to brown.

Sandia granite and related rocks

Granitic rocks in the Monte Largo Hills include: (1) megacrystic granite that is strongly deformed and correlated with the 1650 Ma Manzanita granite, (2) medium-grained leucogranite that is correlated with the 1630 Ma Cibola granite, (3) megacrystic granite that is undeformed and correlated with the 1.44 Ga Sandia granite, and (4) pegmatite and aplite dikes that probably are related to the Sandia granite. The megacrystic granite has centimeter-scale K-feldspar phenocrysts and elliptical mafic enclaves that are typically aligned in a magmatic-flow foliation. The granite generally lacks strongly developed solid-state fabric. The medium-grained leucocratic granite is more strongly deformed and crops out in fault-bound slivers in the northern part of the map area. Pegmatite dikes are present as subvertical sheets that were emplaced parallel to the dominant northeast-striking country-rock foliation. Other dikes crosscut the foliation of the leucocratic granite in the northeast part of the map area. Pegmatite and aplite dikes generally are undeformed but locally are sheared parallel to their margins.

Intrusive contacts can be observed between the megacrystic granite and the metavolcanic rocks in the west-central part of the uplift. Granite crops out in topographic lows, suggesting that the contact of the roof of the pluton in this area is shallowly dipping and near the present surface. The inferred low-angle contact truncates the high-angle metavolcanic foliation and, in outcrop scale, undeformed megacrystic granite intrudes into foliation planes. Contacts tend to be sharp and undeformed.

The megacrystic granite and leucocratic granite were correlated by Kelley and Northrop (1975) with the Sandia granite and Cibola gneiss respectively. These correlations seem appropriate in view of the similarities in lithologies and

structural fabrics. Here, we refer to the leucocratic granite as the Cibola granite and interpret it to be genetically and temporally related to a similar unit mapped near the south end of the Sandia pluton. The latter has been dated recently by U–Pb methods as 1653±21 Ma (D. Unruh, unpubl. data 1997).

Deformational fabrics in country rocks

Deformation of the 1.66-Ga country rock required the development of at least two generations of fabrics. The dominant fabric is a penetrative, northeast-striking, subvertical foliation (S_1) that is axial planar to isoclinal folds (F_1) of compositional layering. Foliation orientation varies from a strike of 000 to 085, averaging near 040. F_1 fold axes trend generally to the south and have a steep plunge.

L_1 stretching lineations plunge steeply south within S_1. These lineations are characteristic of the southeastern part of the Monte Largo Hills, the area at greatest distance from the Sandia pluton contact. For this reason and because similar downdip lineations are found in areas of the northern Manzano Mountains, they are interpreted to predate the pluton. Kinematic indicators associated with this steep lineation include sigma porphyroclasts and shear bands. The latter show southeast-side-up slip on steeply southeast dipping shear bands.

Deformational fabrics in granitoids

Deformational fabrics associated with the intrusion of the pluton are seen in both granite and country rock. Megacrystic granite is generally unfoliated in outcrops southeast of the Tijeras fault but is strongly foliated in a sliver preserved between strands of the Tijeras fault in the north-central part of the area. In these outcrops, feldspar megacrysts as well as quartz pods are dynamically recrystallized into augen and ribbons. Solid-state ductile deformation of feldspar takes place only above 500° C, indicating that this deformation occurred after the granite crystallized and before it cooled back to regional greenschist facies conditions, close to the time of emplacement of the granite. Stretching lineations in the deformed granite plunge moderately northeast, and feldspars form sigma-type porphyroclasts that indicate dextral oblique shearing during this high-temperature deformation.

The Cibola granite outcrops are mylonitized also and contain dynamically recrystallized feldspar. Here, stretching lineations defined by microcline ribbons are subhorizontal, and kinematic indicators such as sigma porphyroclasts also suggest dextral strike slip. As mentioned earlier, pegmatite and aplite dikes crosscut the mylonitic layering, which suggests that deformation ended before final crystallization of highly evolved melts from the pluton. These features are similar to the synemplacement deformational features observed in the Seven Springs shear zone that crops out in Tijeras Canyon to the southwest (Kirby et al., 1995), and we interpret the fault-bounded outcrops of deformed Sandia in the Monte Largo Hills to represent parts of this same shear zone.

Some of the deformation in aureole rocks adjacent to the pluton is also interpreted to be related to emplacement of the pluton, as foliations and lineations are defined by contact-metamorphic sillimanite. In contrast to downdip lineations observed in areas far from the pluton, stretching lineations defined by contact-metamorphic sillimanite plunge shallowly northeast, parallel to the stretching lineations observed in the deformed granite. These lineations get steeper away from the intrusion, suggesting that early steep lineations were rotated to shallower orientations during strike slip associated with pluton emplacement.

Metamorphism

The Monte Largo Hills area preserves an increase in metamorphic grade to the northwest with sillimanite schist found in areas nearest to the granite. Isograds are defined crudely by sparse aluminum-silicate index minerals. The sillimanite zone in the Monte Largo Hills extends laterally for about 1–1.5 km south of the granite contact. This is wider than the ca. 0.5-km-wide sillimanite zone in the other areas of the aureole (Berkley and Callender, 1979) and is compatible with the inferred shallow pluton margin. Sillimanite is present with abundant muscovite (no K-feldspar was observed) as both fibrolite and as prismatic grains. This suggests temperatures of 500–600° C, below the second sillimanite isograd but above the aluminum-silicate triple point. Sillimanite can be seen overgrowing andalusite porphyroblasts, suggesting the polymorphic phase transition of andalusite to sillimanite. This transition, together with the second sillimanite isograd, constrains peak pressures from 0.2 to .35 GPa (2–3.5 kbars). Euhedral garnet is found in the sillimanite-bearing units within the quartzite. Sillimanite grains are strongly aligned in the fabric, are folded, and record dextral strike slip, all indications that deformation accompanied peak metamorphism during pluton emplacement.

The andalusite zone is about 0.5 km wide and is marked by the presence of andalusite in pelitic rocks. Andalusite is commonly rich in aligned inclusions that are interpreted to be the prepluton S_1 foliation. Rotation of matrix relative to andalusite porphyroblasts is interpreted to be related to the reactivation of the S_1 fabric during pluton emplacement. Chloritoid, biotite, and muscovite assemblages in the pelitic units and hornblende in amphibolites are found at map distances as great as about 2 km from the pluton. These minerals are also interpreted to be in the andalusite zone.

The zone farthest from the pluton contains kyanite according to work by Huzarski (1971). At map distances greater than 2 km from the contact, amphibolites contain actinolite rather than hornblende. Together, these minerals indicate upper greenschist metamorphic facies in the southern Monte Largo Hills.

Based on assemblage data, as discussed above, we infer peak conditions of about 600° C and 3 kbar adjacent to the pluton. This is similar to conditions in other parts of the aureole (Berkley and Callender, 1979; Kirby et al., 1995).

Discussion

The Sandia pluton is an important locality for studying the processes of magma intrusion at middle crustal depths far from convergent plate boundaries. Recent studies in the Monte Largo Hills area document the eastern aureole of the ~1.4-Ga Sandia pluton and suggest a complex history for Proterozoic tectonism and magmatism in New Mexico.

The Monte Largo Hills preserve the part of the southeastern aureole of the Sandia pluton that is used to infer some aspects of the character of tectonic events before and during pluton emplacement. Exposures of megacrystic granite in the study area are interpreted to be the shallowly southeast dipping roof of the Sandia pluton. This contact truncates the northeast-striking, steeply southeast dipping S_1 foliation. Thus, the regional foliation and associated tight to isoclinal folds predate emplacement of the 1.42-Ga plu-

ton. Stretching lineations in areas far from the pluton are steeply plunging, and shear-sense indicators suggest reverse slip. These, plus the folds, suggest that the regional country-rock fabric formed during northwest–southeast shortening, probably about 1.65 Ga, based on comparison to nearby areas (Bauer and Williams, 1994). Metamorphic conditions during the early fabric-forming event were probably greenschist grade, as this is the background metamorphism in areas farthest from the pluton.

Tectonic features associated in time and space with the pluton include a contact-metamorphic aureole and synpluton deformational features. The contact aureole is defined by a 1.5-km-wide sillimanite zone, a 0.5-km-wide andalusite zone, and a kyanite zone at greatest distance from the pluton. Assemblages suggest peak temperatures of about 550–600° C and peak pressures of 2–3 kbars. Textures of sillimanite and andalusite porphyroblasts indicate that deformation accompanied peak metamorphism.

Deformational features around the pluton include variable but locally intense solid-state deformation of the granite. Deformation took place at high temperatures (>500° C), as shown by dynamically recrystallized K-feldspar. Lineations are shallowly plunging, and kinematic indicators show dextral shear. Pegmatite and aplite dikes locally cross-cut mylonitic granite, indicating that this deformation took place during pluton emplacement.

Reactivation of country-rock foliation also took place during pluton emplacement. Country-rock stretching lineations are defined by contact-metamorphic sillimanite and are shallowly plunging in areas near the granite. At greater distances, lineations get progressively steeper. This suggests that older downdip lineations were rotated to progressively shallower orientations in areas that were thermally softened by the pluton. Overall, the Monte Largo Hills area is similar to other parts of the Sandia pluton in recording the dynamic interaction of pluton emplacement, deformation, and

STRUCTURAL GEOLOGY

Structural multilayer

A stratigraphic sequence that is viewed purely in terms of each layer's mechanical properties and thickness and how the layers are arranged and contrast with each other is called a structural multilayer. The structural multilayer of the Sandia Park area consists of over 3 km of layered sedimentary rocks. These strata overlie a crystalline basement composed of Sandia granite in the northwest and metavolcanic and metasedimentary rocks in the southeast. The contact between the granite and metamorphic rocks is intrusive, meaning that the granite was emplaced as molten rock at great depth (at least 5–10 km). At the relatively shallow depths where these basement rocks are currently overlain by the layered sedimentary rocks, the granite represents a homogeneous massif of unlayered rock that resists deformation by folding or other ductile processes. The metamorphic rocks are layered in a way similar to the overlying sedimentary rocks, but the layers are highly discontinuous and the internal, microscopic layering or foliation (also called fabric) of the rocks is variably developed and apt to change orientation significantly over short distances.

Before the Laramide-age (approximately 70–50 million years ago) orogeny, which accounts for most of the area's present-day structural complexity, the structural multilayer consisted of three components, listed in order of increasing mechanical strength and resistance to deformation: (1) the 3-km-thick sequence of horizontally layered sedimentary strata, (2) the metamorphic rocks, and (3) the granite. The contacts between these three rock types represent zones of weakness along which translation or shearing can occur with relative ease when the entire package is subjected to tectonic forces in the course of mountain building.

Basement

The structural configuration of the basement in the Sandia Park area strongly influenced the location and orientation of structures during the Laramide orogeny. By late Paleozoic time (approximately 300 million years ago), several kilometers of rocks had been eroded from the area, exposing the granite and the metamorphic rock it intrudes. The intrusive contact is currently northeast striking and gently southeast dipping. The foliation and compositional layering in the metamorphic rocks dips steeply and is also northeast striking. Where it is intruded by the underlying granite, the steeply dipping regional fabric of the metamorphic rocks is overprinted by a gently dipping structural fabric produced by emplacement of the granite. The Tijeras–Gutierrez fault zone and the large-scale fold structure of the area is northeast striking, and we believe this was inherited from the similar orientation of the preexisting foliation and intrusive contact in the basement in a general way, although we found no specific basement structure that was reactivated.

Sedimentary rocks

The sedimentary sequence consists of interlayered beds of highly contrasting mechanical strengths, porosities, and permeabilities. Three types of strata are the most abundant: limestone, sandstone, and shale or mudstone. Compared to the shales and mudstones, the limestone and sandstone beds are competent, but they are rarely very thick. The multilayer contains abundant incompetent beds, mostly shale and mudstone, and they are scattered throughout the sequence. Apart from the shales, there are also bedded gypsum layers in the Jurassic Todilto Formation and at least two coal seams in the Upper Cretaceous Mesaverde Group that are extremely incompetent. The only thick sequence of homogeneous strata is the 500-m-thick Mancos Shale. No massive, competent units greater than 100 m thick are present, and there are very few that are thicker than 20 m. These competent units and maximum thicknesses are: (1) parts of the Morrison Formation (30–50 m), (2) parts of the Dakota Formation (50 m), (3) parts of the Agua Zarca Formation (75 m), and (4) the basal Madera Formation 75–100 m).

The presence of abundant shales and other incompetent unit throughout the multilayer is important because this allows the entire multilayer to fold easily. Even the relatively competent Madera Formation at the base of the multilayer contains thin shale layers throughout, and the relative proportions of these ductile units to the limestone beds makes this package of strata highly susceptible to the formation of fold trains where competent layers form concentric folds, shales accommodate space problems, and deformation is facilitated by slip on bedding planes (c.f. Dahlstrom, 1970). An important train of these folds, previously unrecognized, occurs in the La Madera area.

Paleozoic (pre-Laramide) deformation

Little evidence of ancestral Rocky Mountains-age deformation exists in the study area. There are no significant regional changes in thickness or lithology of the Pennsylvanian units that might reflect such activity. However, two minor structures of possible Pennsylvanian age were noted. One is a west–southwest-striking normal fault with about 50 m of north-side-down displacement that cuts the Proterozoic basement and the Sandia Formation but is apparently overlapped by the basal Madera Formation near La Madera. The fault is interpreted as an Early Pennsylvanian structure across which the Sandia Formation thickens abruptly from less than 2 m to over 40 m.

Another possible late Paleozoic fault occurs along strike and parallel to the previously described fault about 4 mi to the east in the lower San Pedro Creek area. It only has a few meters of north-side-down offset, but it is important because a hornblende-latite dike of unknown age intrudes it. The structure is mentioned as a possible late Paleozoic feature only because nearby, the dike appears to be truncated along the Pennsylvanian–Permian unconformity.

Contractional (Laramide) deformation

Two distinct styles of contractional deformation were recognized in the Sandia Park area. Because they involve Upper Cretaceous rocks, they are presumed to be Laramide in age. The styles are divided on the basis offold wavelength and amplitude: greater than or less than 100 m. The two sets will be referred to simply as small or large amplitude from here on. Both styles are closely associated with oppositely verging, high-angle reverse faults. The map pattern of the Sandia Park quadrangle and adjoining areas is dominated by the larger-amplitude folds, which, with the exception of some moderately plunging drape folds in the Frost Arroyo area, are consistently northeast striking and west vergent. The smaller-amplitude set of folds strike north–northwest. They apparently are restricted to areas west of the Tijeras fault. They may be deformed by the large-amplitude foldsin the northern part of the San Pedro synclinorium. To the south the distinction between the two sets of folds, if any, is not clear. A schematic cross-sectional diagram shows the overall geometry of folds and their relationship to the Tijeras–Gutierrez fault system and to the structure of the crystalline basement.

Large-amplitude folds and west-vergent reverse faults

Deformation associated with the large-amplitude fold set is concentrated along the Tijeras–Gutierrez fault zone. Although both faults were reactivated as Tertiary strike-slip faults, strike-slip motion alone can not account for the abruptly changing, apparent dip-slip offset along each fault and for the large-scale folds with which both faults are associated.

Several hundred meters of west-side-down offset is concentrated along different segments of each fault in the Tijeras–Gutierrez fault system. The segments are linked by a south-dipping monoclinal warp and associated drape folds that parallel Frost Arroyo. We refer to it as the Frost Arroyo transfer zone or Frost Arroyo monocline. To the south, the Gutierrez fault cuts through the anticline of a major west-vergent, anticline–syncline pair, preserving in its footwall the Tijeras synclinorium. Likewise, north of Frost Arroyo the Tijeras fault cuts through the anticline of a major west-vergent, anticline–syncline pair, preserving the San Pedro synclinorium in its footwall. The dip-slip component of offset along each fault decreases abruptly (and in some areas actually changes sense) as each fault crosses the Frost Arroyo monocline zone; the decrease is northerly for the Gutierrez fault and southerly for the Tijeras fault.

The Frost Arroyo monocline appears to have acted as a transfer zone for east-side uplift of areas to the east. Uplift was most likely contractional, because the faults parallel the axial planes of major, west-vergent fold pairs. Reverse motion along the faults may have been facilitated by the favorable orientation of the Sandia pluton's southeast-dipping intrusive contact and by the reoriented metamorphic fabrics within its contact aureole.

East of the Tijeras–Gutierrez fault system, a single, broad, northeast-striking, northwest-vergent anticlinal arch in the lower San Pedro Creek area appears to merge in the La Madera area with the Barro fault, an important north–south-striking, west-side-down structure that forms the big hogback directly east of Doc Long Campground. Although no attitudes were obtained on the Barro fault, its map pattern directly south of Doc Long Campground suggests that it is vertical or steeply east dipping, and it is interpreted as a west-vergent reverse fault. Unfortunately, continuation of this fault to the south lies along the eastern edge of the adjacent map area (Sandia Crest), which has not been mapped yet in sufficient detail. Preliminary work in the area shows that a probable continuation of the Barro fault cuts through a series of upright, open-to-close, north-striking folds that are along strike with a series of folds that were recognized farther to the south (Flatiron area) and interpreted as contractional by Kelley and Northrop (1975).

Small-amplitude folds, monoclinal warps, and associated faults

The small-amplitude folds are less important in terms of total tectonic shortening. They are associated with more penetrative fabrics such as incipient axial-planar cleavage and a-c joints. They are also associated with high-angle, east-side-down, north-striking reverse faults and monoclinal warps that represent the only important east-vergent Laramide structures (akin to the Montosa fault of the Manzano Mountains to the south) in the area. The folds are disharmonic, open to close, and locally tight and have 5–100-m wavelengths and consistent north- to north–northwest-striking, steeply dipping axial planes. Some of them resemble the concentric fold trains of Dahlstrom (1970).

The small-amplitude folds are common and well developed in the northern half of the study area. They are found where the structural multilayer is composed of repeating, between 2-m-thick and 10-m-thick, rigid layers of limestone or sandstone interbedded with shaley units, which is typical of the upper Paleozoic section. These folds are difficult to show on a map because of their small wavelengths and amplitudes and disharmonic nature. Even at 1:12,000 scale they produce subtle map patterns. Many of the orthogonal faults depicted by Kelley and Northrop (1975) in the La Madera area do not exist. Instead, a belt of close-to-open folds in this area is cut by three zones of east-side-down high-angle reverse faults. Collectively, these faults are referred to as the San Antonito fault zone.

Associated with the small-wavelength fold set in the La Madera area are extensive bed-parallel slickened surfaces near the base of the Sandia Formation. Slickenlines trend east–northeast, normal to the axes of the small-wavelength folds. Because this type of slickensurface development is not expressed throughout the layered sequence, a flexural-slip origin is doubted. These slickened surfaces are tentatively

interpreted as resulting from minor, east-directed detachment along the basement contact, and this motion may have contributed to the minor amount of shortening that produced the small-wavelength folds.

Interaction of the two sets

We do not know whether formation of structures indicative of the two styles of deformation was synchronous or, if not, which structures are older. Based on equivocal relationships in the north-central part of the study area, the small-amplitude folds appear to be older. A pair of short-wavelength close folds in the Madera Formation along the steep eastern limb of the San Pedro synclinorium are steeply north–northwest plunging, as if they were tilted during formation of the large-amplitude fold. A tight zone of small-wavelength folds (crossing the county line in the north-central part of the quadrangle) appears to be folded by the broad, northeast-striking, large-amplitude fold that originates in the lower San Pedro Creek area.

The distinction between the two fold sets is fairly clear in the north, because of their divergent strikes, their markedly different amplitude and wavelengths, and their association with oppositely verging reverse faults. To the south, all contractional structures west of Tijeras fault are north to northwest striking, and the wavelengths of folds are intermediate (in the 50–300-m range). Classification of these structures, based on the criteria established farther north, is not possible. These faults and associated folds appear to represent the northward continuation of a north-striking fold belt that is truncated at its south end by the Tijeras fault near the head of Tijeras Canyon.

Tijeras–Gutierrez faults as strike-slip structures

Only two known exposures of the Tijeras fault exist in the Sandia Park quadrangle. One of these was described in the northeast corner by Abbott and Goodwin (1995). Abbott and Goodwin (1995) identified both sinistral and dextral motions along the exposure in the northeast. The significance, however, is uncertain because the exposure is in a tectonic melange adjacent to the fault. Many of the blocks, because they had to have been translated into position, could also have been rotated significantly. The other exposure is in the southwest, just behind the Cedar Crest Post Office. Rocks within 100 m of the fault are highly fractured and cut by a myriad of high-angle faults that have dominantly low-angle slickenlines.

Evidence of sinistral motion

The best evidence of strike-slip motion along the Tijeras–Gutierrez fault system comes from detailed, regional mapping of structures associated with the faults and from discovery of an isolated sliver of Proterozoic Sandia granite along Tijeras fault in the Frost Arroyo area. Throughout the study area competent units adjacent to the Tijeras and Gutierrez faults are highly fractured. The concentration of faults along the west side of the Tijeras fault and along the Gutierrez fault north of Frost Arroyo defines a consistent map pattern. The pattern consists of closely spaced, north- to northwest-striking, high-angle faults with sinistral separations. The faults are interpreted as strike slip because both southeast- and northwest-dipping contacts are sinistrally offset, and horizontal slickenlines were found along some of the faults. Another set of east–west-striking, high-angle, apparently dextral faults also are present but are less common.

The steeply dipping sinistral and dextral faults described in the previous paragraph are in the proper orientation for the two sets, synthetic (mostly) and antithetic (less common), of riedel shears that would be created by sinistral motion along the fault. Sinistral motion is also supported by the apparent 1.5-km offset of two markers in the Frost Arroyo area: 1) offset of Jurassic and Cretaceous marker beds and 2) a sliver of Sandia granite along the fault just to the east of the confluence of Arroyo Armijo and San Pedro Creek. The sliver must have been translated from the north a minimum of 1 km (nearest along-strike distance to the Monte Largo and exposures of Proterozoic rocks). The sliver is also important because its juxtaposition between Permian and Pennsylvanian strata virtually precludes any dip-slip-only motion along the Tijeras fault.

The sinistral faults adjacent to Tijeras fault are oriented parallel to preexisting, upright, penetrative fabrics that are recognized locally throughout much of the area west of Tijeras fault. The fabrics consist of a-c joints and incipient axial-planar cleavage that is probably related to the north–northwest-striking set of small-amplitude folds. It is possible that this fabric facilitated development of the synthetic sinistral shears. One of the faults of the San Antonito zone near La Madera appears to have accommodated some sinistral motion. This is based on a larger than expected apparent sinistral separation of the Abo–Madera contact in the area and on the near-horizontal slickenlines along the fault just north of La Madera road.

Evidence of dextral motion

Abbott and Goodwin (1995) report direct kinematic evidence of dextral motion along Tijeras fault to the northeast and southwest of the Sandia Park quadrangle. The best dextral kinematic indicator in the map area is the geometry of major structures on the map. The structures of particular interest are the San Pedro and Tijeras synclinoriums, which are really continuations of the same major fold structure, the Tijeras and Gutierrez faults, and the Frost Arroyo monocline. The system is a west-vergent fold and reverse fault belt, and the prominent left-step at Frost Arroyo monocline represents the restraining bend indicating dextral transpression (see also Karlstrom and Ferguson, 1996). We found no evidence to support the dextral transtensional interpretation of Abbott (1995) and Abbott and Goodwin (1995).

Abbott (1995) suggested that Laramide deformation along the Tijeras–Gutierrez fault system was transtensional, supporting Cather's (1992) tectonic model for the New Mexico area in general. Abbott's (1995) three main lines of evidence are questionable: 1) The mid-Tertiary Gallisteo Basin is interpreted as extensional in origin (Abbott, 1995), based on its shape and sediment-dispersal patterns. These features, however, are not by themselves supportive of extensional or contractional tectonic subsidence histories. No quantitative tectonic subsidence analysis has been done on this basin; 2) Minor dextral strike-slip faults used by Abbott and Goodwin (1995) to support Laramide dextral transtension are in a tectonic melange adjacent to Tijeras fault in blocks that may have rotated significantly; some of the faults cut probable mid-Tertiary intrusive rock; and 3) Near its southern intersection with the Tijeras fault, the Gutierrez fault, which has about 2 km of north-side-down stratigraphic separation, was interpreted as a normal fault based on the measurement of equal numbers of north- and south-dipping minor faults at least a hundred meters south of the main structure. The minor faults are interpreted as

antithetic and synthetic, but there is no indication of how it is known that the south-dipping set is antithetic and the north-dipping set is synthetic (Abbott, 1995, p. 95, fig. 3-11).

Summary

The present map pattern of the Tijeras–Gutierrez fault system was produced by the interaction of a Laramide contractional event with a preexisting, regional, northeast-striking fabric in Proterozoic rocks. During the Laramide, the Tijeras–Gutierrez faults were the principal structures of a pair of left-stepping, northeast-striking, west-vergent basement uplifts. The left step, which has been interpreted as a restraining bend formed during dextral transpression (Karlstrom and Ferguson, 1996), occurs along Frost Arroyo in the form of a south-dipping monoclinal warp.

Tijeras–Gutierrez fault system was later reactivated as a Tertiary sinistral strike-slip zone that accommodated at least 1.5 km of slip, based on offset of two markers along Tijeras fault and on the association along both faults with a pervasive set of sinistral riedel shears. A pervasive set of small-amplitude, north–northwest-striking folds to the west of Tijeras fault (in the San Pedro synclinorium) may be interpreted as manifestations of a dextral transpressional shear along the Tijeras fault. This is not required, however, as it is possible that these folds reflect an earlier episode of pure east-directed contraction.

Laramide tectonic shortening in the Sandia Mountains differs from areas to the north and south chiefly in that the major structures involve a complex interaction of strike slip, west-vergent reverse faults, and east-vergent folds and reverse faults. This may explain why there is such a poor expression of east-vergent (akin to the Montosa fault) deformation in the area. We interpret the zone, however, to record a northward continuation of the Montosa system of the

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Manzano Mountains. This contractional system marks the east side of a major Laramide uplift of the Rocky Mountain front. These structures were reactivated during Tertiary extension and formation of the Rio Grande rift, but the major structures of the Sandia Park quadrangle reflect Laramide deformation.

pass a septic perc-test if the tile lines are to be laid beneath well-developed soil calcic horizons.