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1995, pp. 219-225. https://doi.org/10.56577/FFC-46.219

in:

Geology of the Santa Fe Region, Bauer, P. W.; Kues, B. S.; Dunbar, N. W.; Karlstrom, K. E.; Harrison, B.; [eds.], New Mexico Geological Society 46 th Annual Fall Field Conference Guidebook, 338 p. https://doi.org/10.56577/FFC-46

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STRUCTURAL AND THERMAL SETTING DURING EMPLACEMENT OF THE SANDIA PLUTON

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Abstract—Structural and metamorphic studies of the 1.42 Ga Sandia pluton and its aureole document significant deformation and metamorphism synchronous with pluton emplacement. The pluton has a minimum areal extent of ~500 km² and a 1–2 km wide aureole preserved at its NW and SE margins. Field and microstructural observations indicate that syn-emplacement deformation occurred along a bounding shear zone, within the main body of the pluton, and in the NW and SE aureoles. Kinematic elements of the pluton and aureole all record consistent subhorizontal shortening (ESE) and extension (N–S) directions interpreted to be part of a regional deformation event at ca. 1.4 Ga. Pluton-enhanced low-pressure, high-temperature metamorphism facilitated growth of sillimanite and andalusite in the NW aureole and generated a well-developed metamorphic field gradient. Assemblage data and thermobarometry indicate that temperatures increased toward a maximum of ~750°C at the pluton margin at a pressure of ~0.35 GPa. Similar field gradients occur along the SE margin of the pluton in the Monte Largo Hills and in Tijeras canyon, suggesting that the aureole can be traced across the Phanerozoic Tijeras fault. The Vincent Moore thrust truncates the southern margin of the Sandia aureole, and juxtaposes greenschist grade rocks with the amphibolite grade aureole. Field, microstructural, mineral assemblage and geochronologic data suggest that latest movement along the thrust occurred during or after cooling of the Sandia aureole at ~1.423 Ga, and thus reinforce evidence for regional contractional deformation.

INTRODUCTION

Tectonism in southwestern North America ca 1.4 Ga involved emplacement of voluminous, dominantly granitic plutons into the middle crust. Although this plutonism has previously been termed "anorogenic" (Anderson, 1983), there is increasing evidence that appreciable deformation and metamorphism accompanied pluton emplacement (e.g., Nyman et al., 1994). The anorogenic model, in one of its most recent forms (Hoffman, 1989 and references therein; Windley, 1993), envisions a Laurentian supercontinent that insulated its mantle, inducing convective mantle upwelling, magmatic crustal underplating, and the generation of silicic crustal melts. This model considers 1.4 Ga granitoids as products of supercontinent breakup and implicitly predicts that each pluton should produce independent local kinematic and thermal regimes during emplacement, or they should all record subhorizontal extension (and subvertical shortening) as a consequence of lithospheric thinning. In contrast, Nyman et al. (1994) presented an "orogenic" model where 1.4 Ga granitoids across the Southwest record subhorizontal contractional strains during emplacement. They attribute these strains to regional deformation inboard of an active continental margin during thermal softening associated with pluton emplacement. The 1.42 Ga Sandia pluton provides a key case study in support of this model (Kirby et al., 1995), and the first goal of this paper is to summarize the structural and thermal setting of the Sandia pluton and its aureole.

The second goal is to address the tectonic significance of contractional deformation along the Vincent Moore thrust (VMT), a greenschist grade ductile shear zone that truncates the aureole of the Sandia pluton (Grambling et al., 1992). We describe deformational and metamorphic features associated with the VMT that suggest that some component of movement on the shear zone postdates cooling of the Sandia pluton and its aureole through ~350°C at 1423 Ma.

The third goal of this paper is to make some observations on the Tijeras fault system using constraints from Precambrian rocks on opposite sides of the fault. The Tijeras fault is a NE-striking, subvertical network of brittle faults with a complex movement history (Woodward, 1982), including proposed movements from the Precambrian to the Quaternary (Lisenbee et al., 1979). However, kinematic interpretations are hindered by a lack of exposure (but see Abbott and Goodwin, this volume), by ambiguous kinematic indicators, by poor timing constraints on movements, and by an absence of piercing lines. Our data indicate that the aureole of the Sandia pluton occurs on both sides of the Tijeras fault system and thus suggests limited finite offset (probably <10(s) km), a potentially useful constraint on the net slip. Furthermore, structural data offer new insights on the relationship of the fault to Precambrian structures.

BACKGROUND

The Sandia pluton is continuously exposed in an area 30 km long by 5 km wide on the western escarpment of the Sandia Mountains. Isolated outcrops to the east suggest a minimum areal extent of ~500 km² (Kelley and Northrop, 1975, pl. 5). The pluton is truncated on the west by Tertiary faults related to the Rio Grande rift and unconformably overlain to the east by 10–15° east-tilted Paleozoic strata. Contacts of the pluton with Paleoproterozoic country rock are well exposed in the northwest and southeast portions of the range and in isolated outcrops on the east side of the Sandia Mountains (Fig. 1). The northwest margin of the pluton is intrusive with Proterozoic country rock, whereas the southeast margin is a 1–2 km wide, N-dipping ductile shear zone (Fig. 1), first discussed by Vernon (1986) and Mawer et al. (1989).

The Tijeras fault truncates the ductile shear zone and juxtaposes the Sandia pluton with a domain of moderate to steeply S-dipping fabric that extends south for ~50 km (Fig. 1). Structurally lowest in this southern package and immediately south of the Tijeras fault is a lithologically heterogeneous package of metavolcanic, volcaniclastic, and metasedimentary units collectively termed the Tijeras greenstone (Connolly, 1982). The greenstone lies structurally below a ductile thrust (Vincent Moore thrust—VMT) that placed an isoclinally folded, overturned package of quartzite and schists above the greenstone (Cavin et al., 1982).

The Sandia pluton consists of two main compositional units: a K-feldspar megacrystic biotite monzogranite to granodiorite (Sandia granite) and a leucocratic two-mica granite near the deformed southern margin (Cibola granite). The Sandia granite contains megacrysts of K-feldspar 3–5 cm long typically aligned in a coarse matrix of quartz, plagioclase, and biotite (± hornblende) (Brookins and Majumdar, 1989). Microgranitoid enclaves (10–20 cm long) occur throughout much of the Sandia granite, often in layers. Enclaves show mingling relationships such as lobate and diffuse margins, local pillowing, and isolated microcline megacrysts that appear to be texturally and compositionally out of equilibrium with the matrix and are interpreted to have floated in from the host granite (Kirby et al., 1995). Pegmatite and aplite dikes occur throughout much of the pluton, but are relatively scarce in the southern 4–5 km of the pluton (Fig. 1).

The Cibola granite is generally fine- to coarse-grained (often mylonitic) and is composed almost entirely of quartz, plagioclase, and K-feldspar with minor muscovite and biotite. Previous workers have interpreted the Cibola granite as an older paragneiss intruded by the Sandia granite (Kelley and Northrop, 1975; Condie and Budding, 1979; Connolly, 1982; Brookins and Majumdar, 1989). However, field relationships show that Cibola granite locally cross-cuts deformed phases of the Sandia granite and fills small-scale shear bands (Kirby et al., 1995, fig. 3), suggesting that the Cibola is relatively younger, but still part of the larger Sandia

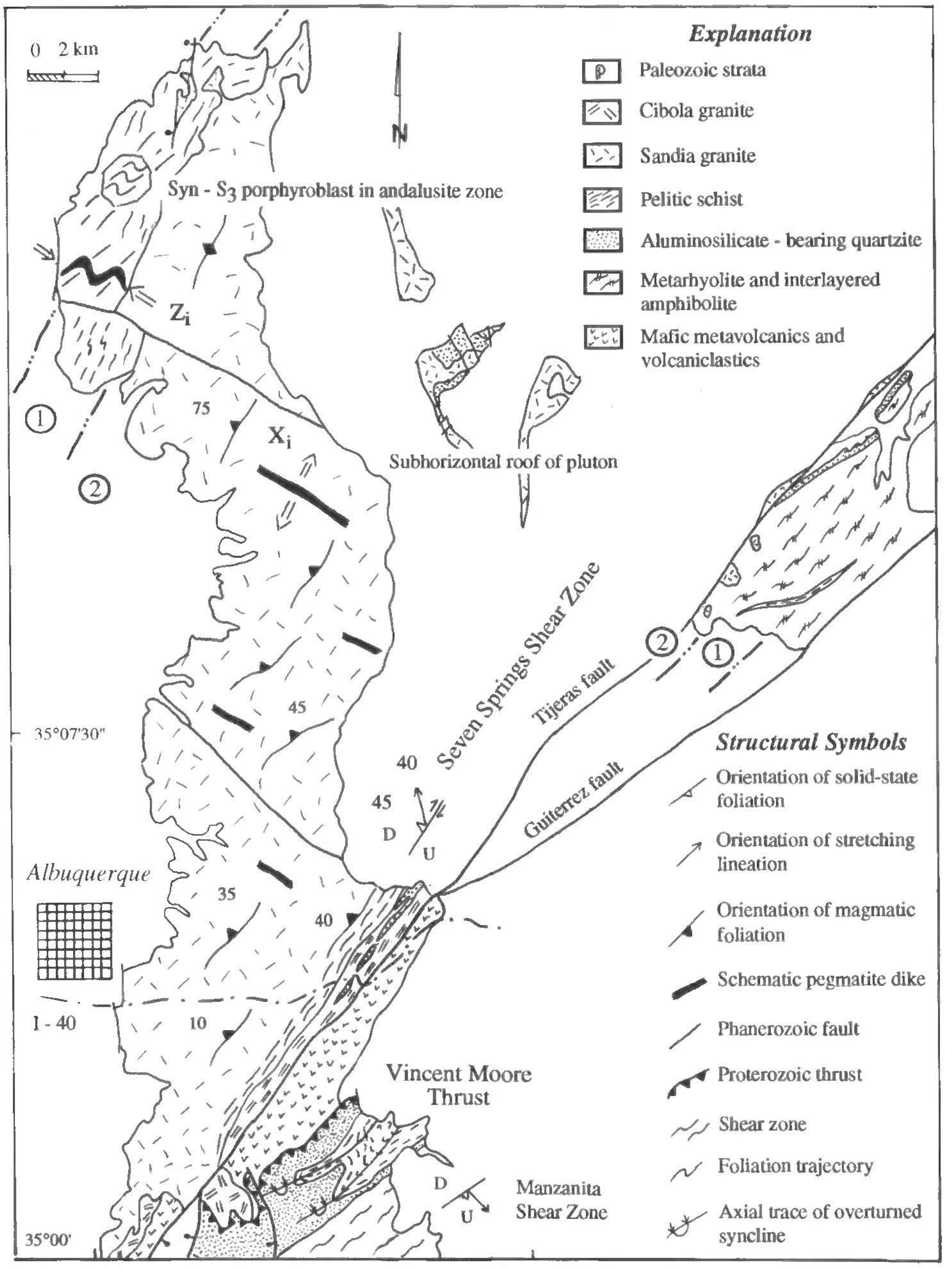


FIGURE 1. Schematic geologic map of the Sandia pluton and its aureole. Sketches in NW aureole represent syn-pluton shortening in dikes and porphyroblast-matrix relationships. Z_i = incremental shortening direction inferred from folded dikes. X_i = incremental extension direction inferred from dike orientations in pluton. Heavy dash-dot lines show approximate locations of isograds discussed in text. 1 = andalusite zone assemblages; 2 = sillimanite zone assemblages.

pluton. Limited geochemical data from both granitoids generally display linear trends in major and trace elements (Fig. 2), consistent with a cogenetic relationship between the Cibola and Sandia granites.

Geochronologic and thermochronologic data from the Sandia pluton and its aureole are summarized by Kirby et al. (1995). $^{40}Ar/^{39}Ar$ incremental release heating methods on hornblende and muscovite from the southern margin of the pluton give identical ages of 1423 Ma. Combined with existing U-Pb zircon and titanite (sphene) mineral ages, these data suggest that the Sandia pluton was emplaced at ~1423 Ma and cooled rapidly (<10^6 yrs) through the contrasting closure temperatures for retention of radiogenic daughter products in zircon, titanite (sphene), hornblende and muscovite from >700°C to ~350°C.

STRUCTURAL SETTING OF THE SANDIA PLUTON

The following section summarizes observations and interpretations presented fully in Kirby et al. (1995) that suggest that emplacement of the Sandia pluton records the interaction of extension and contraction directions during regional (at a scale larger than the pluton) deformation.

The Sandia pluton is bordered on the southeast by the Seven Springs shear zone (SSSZ), a 1-to-2-km wide extensional ductile shear zone that was active during pluton emplacement and crystallization. The zone deforms the Sandia granite, Cibola granite, and several country rock screens (quartzite and partially assimilated schists). It dips ~45°NW under the pluton, and is thus inferred to be a deformed lower side of the pluton. The northwest margin is subvertical for 5 km along strike, whereupon it rolls over to a shallowly NW-dipping roof region. This northwest boundary is also cut by Tertiary faults that produce repetitions of the margin and contact aureole. Roof pendants with irregular but subhorizontal contacts between granite (below) and vertically-foliated country rock (above) are exposed in erosional windows beneath Paleozoic strata east of the range crest (Fig. 1). The margin geometries suggest that the Sandia pluton is a 45–50°N-dipping tabular sheet some 5–7 km thick (measured

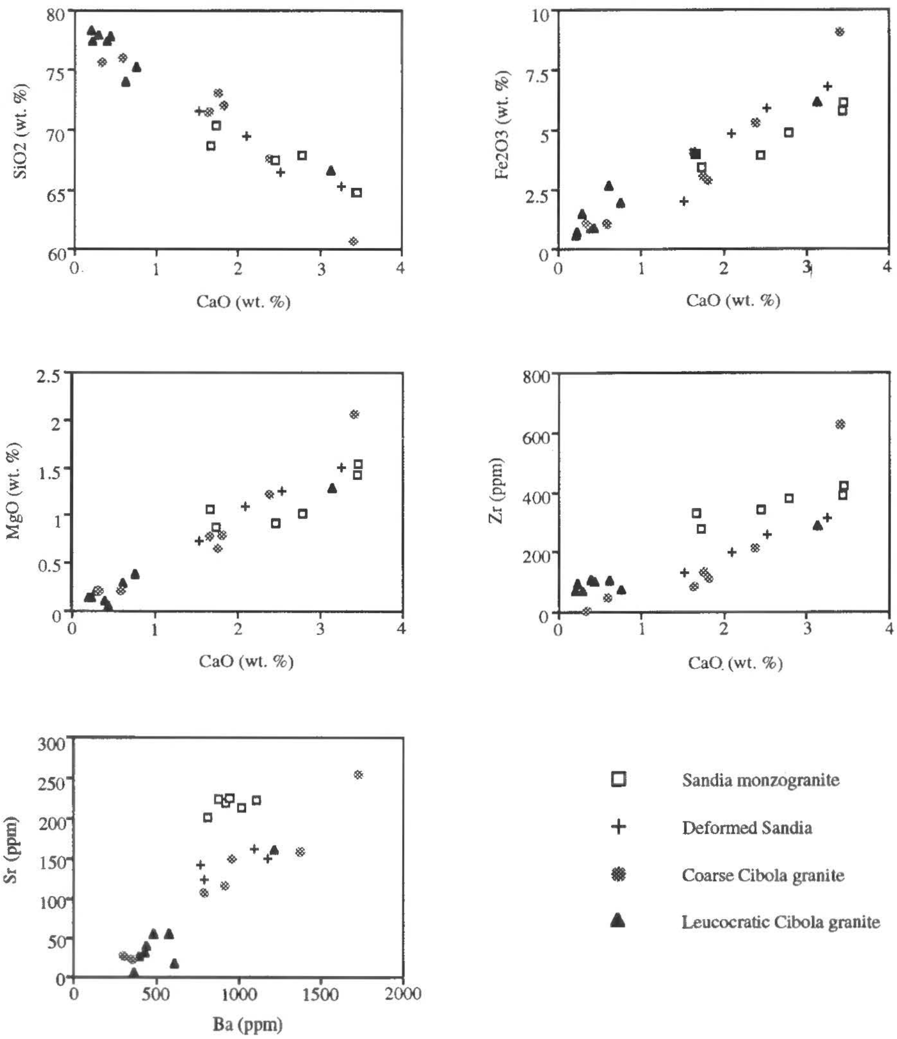


FIGURE 2. Selected geochemical data from the Sandia pluton. Linear trends are consistent with co-genetic relationship between Cibola and Sandia granitoids.

perpendicular to the SSSZ and magmatic layering) and at least 2 km thick vertically.

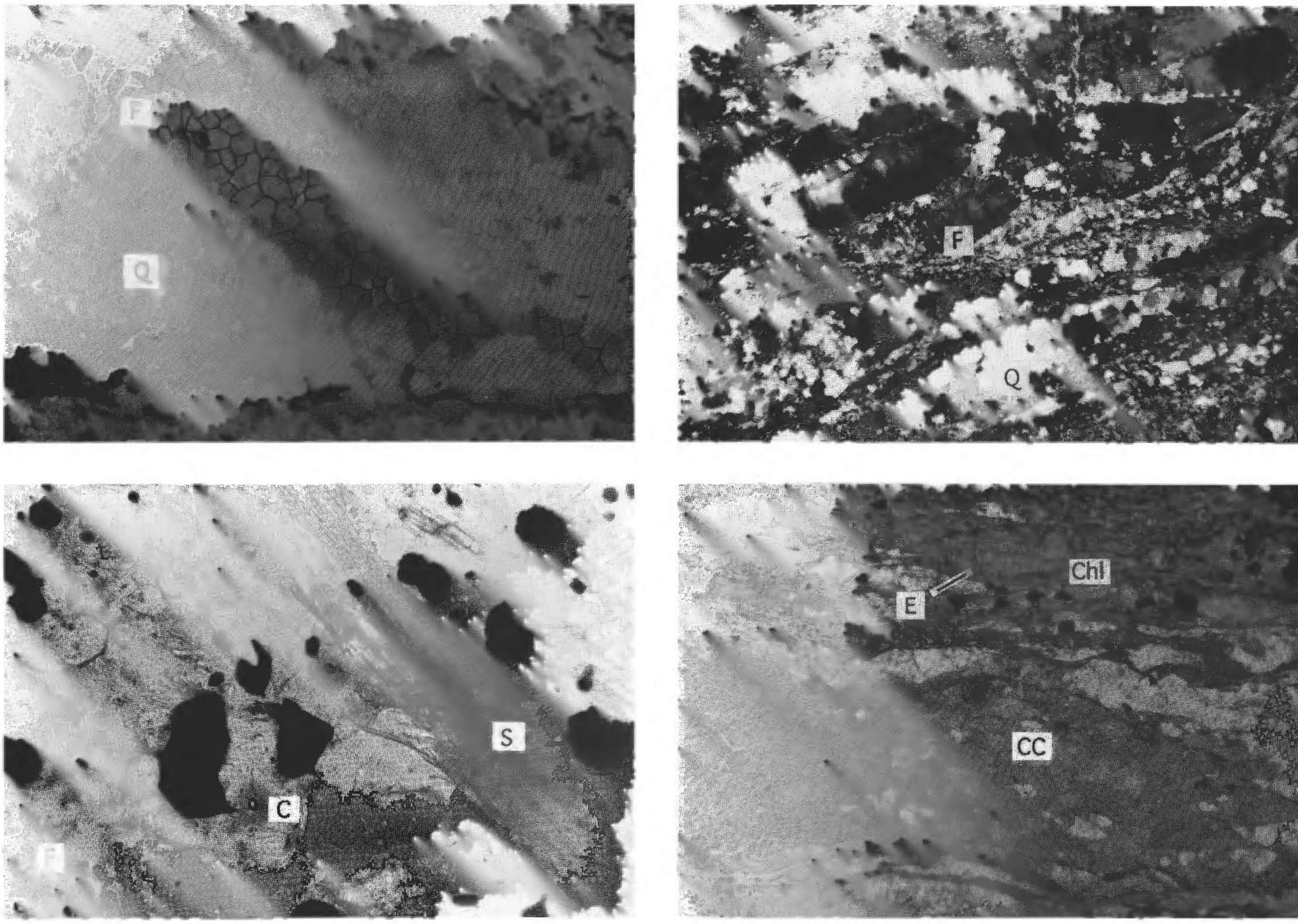
Field observations suggest that the SSSZ was active during pluton emplacement and crystallization. Evidence includes (1) fine-grained granitic melt injections along S, C and C' planes; (2) high-temperature dynamic recrystallization of asymmetric (s-type) microcline porphyroclasts (Fig. 3A); and (3) late-stage undeformed to weakly deformed pegmatite and aplite dikes that cross-cut mylonitic fabrics. These observations suggest that deformation occurred at elevated temperatures in the presence of granitic melt and had ceased locally by emplacement and crystallization of latest liquids. We interpret the Cibola granite to represent evolved melts segregated from the crystallizing Sandia pluton and drawn down pressure gradients into the active shear zone.

Foliations in the SSSZ are mylonitic in character and defined by recrystallized quartz and feldspar ribbons and aligned biotite. Foliation development varies appreciably across the zone and reflects partitioning of solid-state strain and/or temporal variations in the relative timing of local deformation and magma crystallization. Kinematic indicators abound in the zone and include S–C fabrics, asymmetric s-type feldspar porphyroclasts (Fig. 3A), and synthetic and antithetic shear bands. Sense of shear is consistently top to the northwest (normal sense) with inferred movement parallel to an average finite stretching lineation that plunges 45° and trends 340° (Fig. 4).

Solid-state fabrics in the shear zone grade northward into subparallel magmatic fabrics in the Sandia pluton, suggesting emplacement synchronous with shear zone movement (Paterson et al., 1989). Magmatic fabrics are defined by the alignment of feldspar megacrysts, biotite, and microgranitoid enclaves (foliations) and by mineralogical variations (layering). Enclave-rich layers parallel to magmatic layering are interpreted to represent injection and disaggregation of coeval, mingled magmas. Inferred movement sense from mesoscopic and macroscopic geometries of foliations suggests that over large regions of the pluton, magmatic flow mimicked solid-state flow in the SSSZ both with top to the northwest movement sense (Fig. 5).

Pegmatite and aplite dike orientations in the pluton are used to infer local incremental extension directions. We infer that most dikes opened as tensile fractures perpendicular to local incremental extension (X_i) because they occur within isotropic Sandia granite in parallel swarms or suborthogonal sets. In addition, where observed, markers (e.g., enclaves) are offset perpendicular to dike walls. Dikes within the pluton suggest a nearly uniaxial strain field with suborthogonal extension directions (X_i and Y_i) trending NE and subhorizontal and plunging steeply WNW, respectively (Fig. 4). Dikes also occur locally in suborthogonal networks with no cross-cutting relationships (continuous granite infilled the fracture network). Networks consistently have one thick and one thin limb that allow inference of the local incremental strain field during dike emplacement (X_i normal to thick limb, Y_i normal to thin limb, and Z_i parallel to intersection). These directions are consistent with those from dikes throughout the pluton and together record N–S extension and E–W shortening (or least extension) during final crystallization of the Sandia pluton.

Syn-emplacement deformation in the northwest aureole records the same kinematic framework as that of the rest of the pluton. ESE shortening is documented by development of a new crenulation cleavage (S_3)



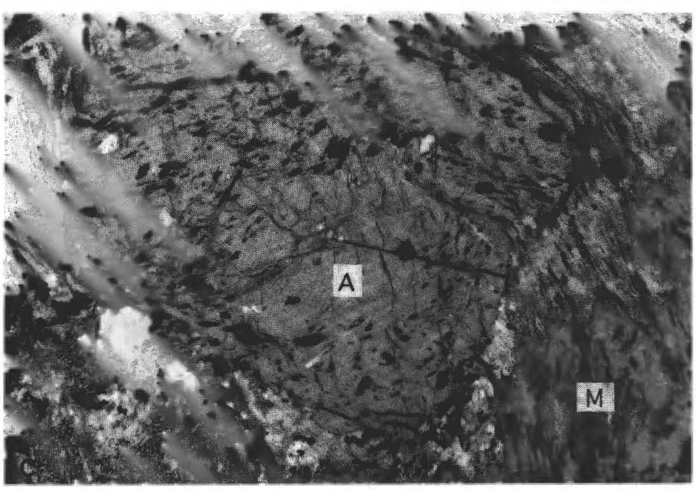


FIGURE 3. Photomicrographs from the Sandia pluton and its aureole. Mineral abbreviations are as follows: F - potassium feldspar, Q - quartz, A - andalusite, S - sillimanite, M - muscovite, C - cordierite, Chl - chlorite, E - epidote, and CC - calcite. A, Sigmoidal feldspar megacryst from Seven Springs shear zone; grain boundaries highlighted to emphasize recovered texture. B, Sillimanite + K-feldspar + cordierite assemblage adjacent to Sandia pluton. C, Syntectonic andalusite porphyroblast from medium-grade rocks in the northwest aureole. D, Greenschist facies mylonite from Vincent Moore thrust. E, Greenschist facies mineral assemblage from Vincent Moore thrust (epidote / calcite / chlorite).

synchronous with contact metamorphic aluminosilicate growth (Figs. 3B, C), associated open to tight F_3 folds of pegmatite dikes, and tabular dike swarm orientations that are subparallel to those of the pluton interior (Fig. 4). N–S extension is documented by shallowly north-dipping extensional melt-filled shear bands, amphibolite boudins, and dike orientations. Thus syn-emplacement deformation in the northwest aureole was similar to that in the pluton and in the SSSZ.

Rapid cooling of the pluton (inferred from $^{40}Ar/^{39}Ar$ data) implies that we can interpret syn-emplacement features as recording a geologic snapshot of local kinematic regimes. The consistency of kinematic elements from the base of the pluton (SSSZ), the interior, and the northwest aureole suggests that all were responding to a regional strain field, larger than the pluton, that involved the interaction of subhorizontal N–S extension and ESE shortening directions. In contrast to extensional tectonic regimes dominated by subvertical shortening due to collapse or thinning of continental lithosphere (e.g., Dewey, 1988), the strain field around the Sandia pluton involved subhorizontal shortening. Thus we infer that the bulk crust around the pluton was extended (and dilated) N–S and shortened E–W during pluton emplacement.

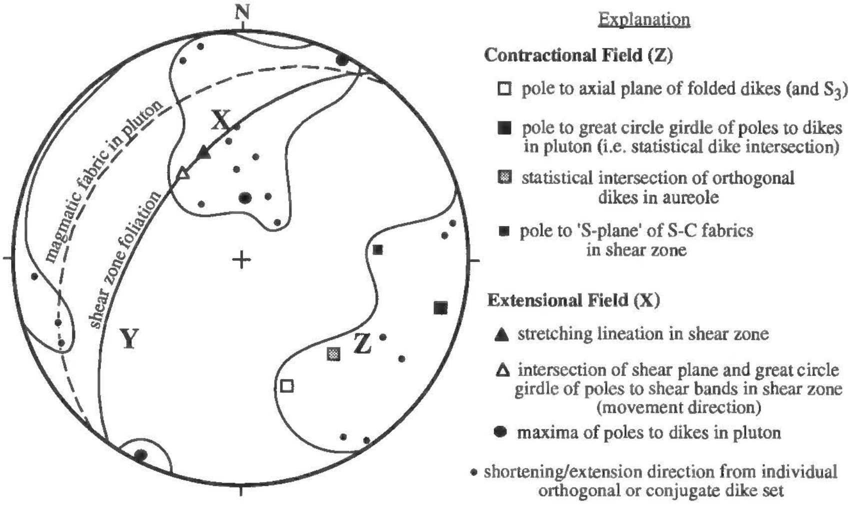


FIGURE 4. Synoptic equal-area, lower hemisphere projection of kinematic elements from Sandia pluton and aureole showing fields of shortening and extension during pluton emplacement.

THERMAL SETTING OF THE SANDIA PLUTON

The following section summarizes the distribution of mineral assemblages defining the northwest contact aureole of the Sandia pluton and its thermobarometric evolution, presented more fully in Andronicos et al. (in prep). These observations indicate that metamorphic rocks exposed around the Sandia pluton underwent pluton-enhanced low-pressure, high-temperature metamorphism during pluton emplacement. Furthermore, the distribution of pluton-related mineral assemblages along the southeast margin of the pluton (in Tijeras canyon, in the Monte Largo Hills, and on the Four Hills of Manzano Base) suggest that the thermal aureole of the Sandia pluton can be recognized across and south of the Tijeras fault (Fig. 1).

The Sandia pluton has a well-developed contact aureole defined by two isograds subparallel to the northwest margin of the pluton (Fig. 1). Phyllites 2 km from the pluton contain the assemblage muscovite + chlorite + quartz ± biotite ± chloritoid and are interpreted to reflect the regional metamorphic grade (greenschist) of country rocks prior to intrusion of the pluton (Berkley and Callendar, 1979; Andronicos et al., in prep.). Approximately 1.5 km from the pluton, andalusite appears and biotite increases in abundance. Mineral textures suggest that the reaction muscovite + chlorite = andalusite + biotite + H_2O may be used to define the first isograd (Fig. 1). Within approximately 500 m of the pluton, andalusite is replaced by coarse sillimanite allowing the definition of a second isograd, the andalusite = sillimanite polymorphic phase transition. Kyanite occurs as relict inclusions within andalusite porphyroblasts and is also interpreted to represent metamorphic grade prior to emplacement of the Sandia pluton (Paleoproterozoic?). Within the sillimanite zone peak, metamorphic conditions reached sillimanite + K-feldspar + cordierite grade (> 700°C) (Fig. 3B) with variable development of anatectic migmatites.

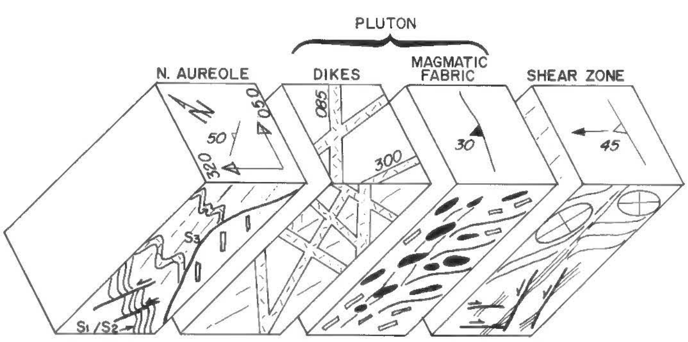


FIGURE 5. Schematic block diagram of same elements in Figure 4 (from Kirby et al., 1995).

Phase equilibria and quantitative thermobarometry suggest that the Sandia pluton was emplaced near 0.3 GPa (3 kb) and that temperatures varied as a function of distance from the pluton. Within the aureole, the transition from andalusite to sillimanite occurs near the maximum stability of muscovite + quartz = Al_2SiO_5 + K-feldspar + H_2O. The intersection of these two curves in P–T space define a unique point, assuming a fixed activity of H_2O and mineral composition. Assuming end-member mineral compositions and allowing H_2O activity to vary from 0.5 to 1 gives pressure values between 0.3 and 0.37 GPa and a temperature estimate between 590 and 645°C at the sillimanite isograd (Kerrick, 1971; Pattison, 1992). Quantitative estimates from pelitic system thermobarometers and from igneous hornblende barometry also suggest that pluton-enhanced metamorphism involved nearly isobaric heating and cooling at approximately 0.3 GPa. Maximum temperatures at the pluton margin were as high as 750°C.

Metamorphic mineral assemblages in country rock along the southeast margin of the pluton suggest that a similar thermal aureole is preserved despite Phanerozoic faulting. In the Monte Largo Hills, a horst block between the Tijeras and Gutierrez faults, small pods of Sandia and Cibola granite, some of which are mylonitic, intrude a felsic metarhyolite package just south of the Tijeras fault (Timmons et al., this volume), suggesting that the pluton margin and the SSSZ extend for at least 10 km to the northeast. Pelitic layers from quartzite lenses adjacent to the granite contain sillimanite + K-feldspar. Sillimanite is commonly aligned in the foliation and is occasionally folded, suggesting that deformation and mineral growth were synchronous. Andalusite occurs as syntectonic porphyroblasts at ~1–2 km from the pluton. 3–4 km southeast of the margin, however, phyllites contain muscovite + chlorite + quartz ± kyanite, similar to phyllites from the Placitas aureole (Timmons et al., this volume).

Similar assemblages occur in Tijeras Canyon. North of the Tijeras fault, pelitic selvages within quartzite screens surrounded by Cibola granite contain coexisting andalusite and sillimanite, whereas sillimanite + K-feldspar + cordierite assemblages occur in pelitic gneisses immediately adjacent to the pluton on Manzano Base (Fig. 1). South of the Tijeras fault, metamorphic grade decreases toward the south, away from the inferred margin. Pelitic metasedimentary lenses in the northwest portion of the Tijeras greenstone, nearest the inferred margin, contain abundant andalusite porphyroblasts (Connolly, 1982). Assemblages of andalusite + staurolite + chlorite + quartz, and of garnet + biotite + chlorite + muscovite + quartz occur in metapelites and suggest that metamorphic conditions were similar to those in medium-grade rocks (andalusite zone) in the northwest aureole.

A similar decrease in metamorphic grade with increasing distance from the pluton occurs within the mafic rocks of the Tijeras greenstone. In the northwest, mafic assemblages are dominated by blue-green hornblende, whereas in the southeast, actinolite is the only amphibole. Intermediate assemblages contain amphiboles with actinolite cores and hornblende rims, suggesting a spatial relationship between metamorphic grade and the pluton margin. All assemblages are consistent with amphibolite facies metamorphism (Connolly, 1982) related to the emplacement of the Sandia pluton.

We infer from these observations that amphibolite-facies metamorphism and aluminosilicate porphyroblast growth were spatially and temporally related to emplacement of the Sandia pluton. Connolly (1982) interpreted the presence of two aluminosilicates to represent two temporally distinct metamorphic events (sillimanite related to Sandia emplacement). However, the presence of greenschist-grade mineral assemblages (including kyanite) at greater distances from the pluton (Timmons et. al, this volume) suggests that both andalusite and sillimanite grew on a prograde heating path below the aluminosilicate triple point (~3.7 kb, Holdaway and Mukhopadhyay, 1993) during granite emplacement. Similar mineral assemblages and distributions occur in the northwest aureole (Placitas–Juan Tabo area) and along the southeast margin in Tijeras Canyon and the Monte Largo Hills. Pluton-enhanced metamorphism was apparently associated with high-temperature deformation in the Seven Springs shear zone and in the northwest aureole, attesting to the mutual interaction of plutonism, metamorphism, and deformation during tectonism in the middle crust.

VINCENT MOORE THRUST

The Vincent Moore thrust (VMT) is a narrow, (1–10 m wide) shallowly S-dipping ductile shear zone that emplaced greenschist-grade, kyanite-bearing quartzites and schists above amphibolite-grade Tijeras greenstone. Local retrogression of footwall rocks (both greenstone and granite) accompanied thrusting, suggesting that thrusting took place after the peak of pluton-enhanced metamorphism. Grambling et al. (1992) cited this as evidence that greenschist-grade metamorphism and associated thrusting throughout the Manzano/Manzanita range occurred post 1.4 Ga plutonism. Our investigations suggest that country rocks in the Sandia region were at greenschist grade prior to pluton emplacement, and we are faced with the continuing problem of sorting out multiple, superimposed metamorphic/deformational events at ~1650 Ma (Bauer and Williams, 1994), ~1420 Ma, and perhaps post-1400 Ma (Bauer et al., 1993). The following section describes deformational and metamorphic features associated with the VMT.

The VMT ranges in thickness from a discrete ductile shear zone approximately 1 m wide to a ~10-m-wide network of anastomosing high strain zones. The thrust occurs along the upright limb of a km-scale overturned synclinorium (Fig. 1) and has been interpreted as a bedding plane fault (Cavin et al., 1982). Mylonitic foliations consistently dip to the south; strike is variable because of undulations of the fault trace. Stretching lineations plunge shallowly to moderately SE, suggesting an oblique, sinistral component to thrusting. Kinematic indicators include: S–C fabrics, asymmetric s-type quartz porphyroclasts, grain shape, preferred orientation of quartz grains, and "domino-style" rotation of fractured feldspars. All give top to the NW movement sense. A notable abundance of asymmetric tails and pressure shadows occur on the long axes of quartz and feldspar grains, respectively, suggesting that there may have been a significant component of coaxial thinning across the zone (Simpson and DePaor, 1993).

In marked contrast to the Seven Springs shear zone, microstructures in the VMT zone suggest that mylonitization took place at lower temperatures and/or higher strain rates. Quartz occurs typically as aggregates of very fine grains or as polycrystalline ribbons (Fig. 3D). Ribbons display variable grain shape, preferred orientation and subgrain development; some have monocrystalline portions with slightly serrated grain boundaries. These textures suggest that recovery mechanisms were suppressed, and deformation mechanisms such as dislocation glide dominated. Large relict quartz grains have variably developed core and mantle textures, often with asymmetric tails and may indicate that strain rate, temperature, and/or fluid pressure varied along the zone. A few samples contain foliation-parallel microfaults in quartz ribbons, suggesting that the above conditions may have also varied temporally. Overall, quartz microstructures suggest that the latest deformation took place under greenschist conditions, probably < 350–400°C. Feldspars are ubiquitously fractured and altered to sericite (Fig. 3D), consistent with greenschist grade conditions during mylonitization (Simpson and DePaor, 1993).

Thrusting was accompanied by significant retrogression and alteration of metamorphic minerals in both the footwall and hanging wall (cf. Grambling et al., 1992). Amphibolites from the shear zone contain quartz + epidote + chlorite + calcite + muscovite + sericite ± tourmaline greenschist facies assemblages in marked contrast to amphibolite facies just outside the zone (Fig. 3E). Feldspars from granites within and below the shear zone have been altered to sericite and white micas whereas biotite and igneous hornblende are replaced by Fe-rich chlorite and epidote. Retrograde minerals are aligned in the mylonitic foliation. The presence of hydrous assemblages suggests that the VMT acted as a conduit for fluid migration during thrusting, and supports the microstructural interpretation of greenschist grade mylonitization.

Mineral assemblages in the hanging wall are also of greenschist grade. Pelitic layers in quartzite contain chlorite + albite + epidote ± calcite, and rare samples contain kyanite. Metamorphic grade is indistinguishable, using only assemblage information, from retrograde conditions near the VMT. Kyanite in samples 1–2 m above the shear zone, however, occurs as relict grains aligned and boudinaged in the stretching lineation and retrograded to clay minerals. This suggests that the fluid event associated with movement along the VMT may have been locally superimposed on pre-pluton greenschist grade assemblages.

Incremental heating, $^{40}Ar/^{39}Ar$ whole-rock release spectra from a sheared, phyllonitic granite within the VMT gives a plateau age of 1423 ± 2 Ma (Karlstrom and Dallmeyer, in prep.), identical to that of the Sandia pluton. Feldspar in the sample is entirely retrograded to white mica, and coarse muscovite is aligned in the mylonitic foliation. Metamorphic mineral assemblages nearby (Fig. 3E) and microstructures suggest that deformation along the VMT took place near or slightly above the closure temperature for muscovite. Therefore the 1423 Ma age probably reflects the time of fabric formation and associated thrusting, although a younger age cannot be ruled out. Apparent ages from low-volume release fractions decrease to ages as young as 1.1 Ga, which may reflect partial resetting during later tectonism (Heizler et al., in prep).

Microstructures, mineral assemblages, field relationships, and thermochronology all suggest that latest movement along the VMT occurred during or after cooling of the Sandia pluton and its aureole. However, the VMT is parallel to large-scale folding and regional greenschist-grade fabrics in the Manzano Mountains. These fabrics are truncated by the 1427 Ma Priest pluton in the southern portion of the range (Thompson et al., in prep) and by the Sandia pluton near its roof (Fig. 1) and in the Monte Largo Hills (Timmons et al., this volume). This problem of the relative contributions of pre-, syn-, and post-1.4 Ga movements on fabrics in the southern aureole remains unsolved, although present data suggest that the main, steeply S-dipping fabrics and folds predate the pluton, that low-temperature shearing along the VMT occurred late syn- to post-emplacement, and that the thrust may have moved as recently as 1.1 Ga.

DISCUSSION AND CONCLUSIONS

Implications for 1.4 Ga tectonism

The emplacement of the 1.4 Ga Sandia pluton was associated with significant deformation and metamorphism. Our kinematic data suggest that the pluton accumulated in a regional strain field involving subhorizontal extension and contraction directions. Pluton emplacement was associated with a rapid thermal pulse that produced a well-developed metamorphic aureole along both the northwest and southeast margins of the pluton, from which we infer that the subsurface extent of the pluton is much greater (batholith size) than its present exposure.

Recent detailed work is showing that an increasing number of 1.4 Ga plutons in the Southwest contain well-developed syn- and post-emplacement contractional deformational fabrics and have sizable metamorphic aureoles (Graubard, 1991; Nyman et al., 1994; Duebendorfer and Christensen, 1995). Also, a regional disturbance of K-Ar (and Ar/Ar) and Rb-Sr isotopic systems in the Southwest at ca. 1.4 Ga suggests regional reheating and/or cooling through mineral blocking temperatures of 300–500°C at this time (Karlstrom and Bowring, 1993). These data indicate that the 1.4 Ga event has many of the hallmarks of orogeny, compatible with recent models for long-lived convergent tectonism along the southern Laurentian margin (Gower et al., 1991; Nyman et al., 1994).

Greenschist-grade movement along the Vincent Moore thrust apparently post-dates cooling of the Sandia pluton and its aureole. The combination of retrogression of amphibolite facies assemblages in the Tijeras greenstone and an $^{40}Ar/^{39}Ar$ age of 1423 Ma from a mylonitized granite argues strongly for syn-pluton deformation. Thus, the VMT is interpreted to reflect a continuum of contractional deformation during cooling of the Sandia pluton and bolsters evidence for the interaction of contraction and extension during 1.4 Ga tectonism. In contrast to Grambling et al. (1992), however, we feel that movement along the VMT cannot necessarily be correlated with the main deformational fabric and associated greenschist facies metamorphism throughout the Manzano Mountains. Instead, we argue that we are seeing the superposition of multiple deformational events at or near the same metamorphic grade, 1.65 Ga thrusting to form the main regional fabric (Bauer and Williams, 1993), renewed 1.42 Ga movements during Sandia emplacement, and possibly 1.1 Ga movements during the Grenville orogeny (Heizler et al., in prep.).

Implications for Phanerozoic Tijeras fault

The Tijeras fault system has long been an enigmatic structure whose role in deformational events ranging from the Precambrian through the Cenozoic is not well understood (Lisenbee et al., 1979). In Tijeras Canyon, the fault is a vertical zone 1–10 m wide that truncates NW-dipping mylonites on its northwest side. Proposed Precambrian left-slip coincident with Sandia pluton emplacement was based on reported en echelon pegmatite arrays in the Tijeras greenstone (Lisenbee et al., 1979; Connolly, 1982). However, this is opposite to the dextral component seen in the mylonites of the SSSZ. In addition, syn-pluton deformation occurred at markedly higher temperatures and in the presence of melt (Kirby et al., 1995). Thus, we see no evidence for Precambrian movement on an ancestral Tijeras fault nor for direct reactivation of Precambrian structures (i.e. Seven Springs shear zone). Indeed, the presence of the Sandia aureole on both sides of the fault implies limited finite displacement (probably <10 km?). However, several features suggest that the location of the Tijeras fault may crudely reflect a Proterozoic crustal boundary or anisotropy. The fault is located at (1) the southern edge of a large batholith and associated shear zone; (2) the northern edge of S-dipping thrusts of the Manzano Mountains; and (3) the southern edge of magnetic anomalies associated with the Jemez lineament (Karlstrom and Daniel, 1993; Daniel et al., this volume). Thus, the Tijeras fault may have been localized along a strong anisotropy that reflects Proterozoic lithospheric structure, with recurring movements in the Laramide, Tertiary, and Recent (Abbott and Goodwin, this volume).

ACKNOWLEDGMENTS

Reviews by Matt Nyman and Steve Ralser helped us clarify parts of the manuscript. Amy Thompson and Calvin Barnes kindly lent a portion of the geochemical data. Thanks.

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