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THE GALLINAS CANYON GNEISS: A WINDOW INTO THE NATURE AND TIMING OF PALEOPROTEROZOIC EVENTS IN NORTHERN NEW MEXICO

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ABSTRACT—The paucity of evidence of pre-1450 Ma tectonism in northern New Mexico limits the understanding of Paleoproterozoic magmatism, metamorphism, and deformation and correlating events regionally. Here, we report new field, petrographic, geochemical, and geochronological data from metamorphic rocks from the Gallinas Canyon area in the southern Sangre de Cristo Mountains of New Mexico that preserve evidence for 1.7 Ga tectonothermal metamorphism. Gallinas Canyon area metamorphic rocks include medium-grained quartzofeldspathic gneiss, amphibolitic gneiss, biotite schist, and granitic pegmatite. The units are in many places strongly layered and penetratively foliated with a dominant fabric dipping moderately to the southwest. Mafic units (amphibolite and biotite schist) show igneous differentiation trends and major and trace element characteristics of island arc tholeiites and ocean island arc basalts. All of these units were deformed and metamorphosed at upper-amphibolite facies (725°C, 550 MPa). Zircons from an amphibolite sample showed soccer ball morphologies and high (>10) elemental U/Th ratios indicative of metamorphic zircon. U-Pb isotopic analyses of this zircon population yielded an age of 1717 ±14 Ma, which we ascribe to amphibolite facies metamorphism during syntectonic emplacement of the ca. 1.7 Ga Hermit Peak granite. These data document Yavapai province arc-related magmatism, metamorphism, and deformation in northern New Mexico.

INTRODUCTION

The assembly of lithosphere in southern Laurentia has for more than 30 years been interpreted to have evolved by the formation, accretion and stabilization of juvenile outboard arcs throughout the Proterozoic (e.g. Condie, 1982; Karlstrom and Bowring, 1988; Karlstrom et al., 2001). This model has been disputed by Bickford and Hill (2007) and Bickford et al. (2008), who contend, based on rock type, chemistry, structure, and Lu-Hf depleted mantle model ages, that many of the 1.6–1.8 Ga magmatic rocks in the southwestern U.S. originated from the melting of older continental crust related to extensional tectonics. Other aspects of the model that are disputed include the amount of deformation and metamorphism attributable to province assembly—the ca. 1.70 Ga Yavapai orogeny; the ca. 1.65 Ga Mazatzal orogeny, and the ca. 1.45–1.35 Ga Picuris orogeny (Karlstrom and Williams, 1998; Williams et al., 1999; Karlstrom et al., 2001; Daniel et al., 2013). Some workers suggest a 1.71–1.69 Ga Yavapai orogenic peak, based predominantly on studies in the Grand Canyon region of Arizona and Gunnison Canyon region of southern Colorado, which involved pluton enhanced middle crustal metamorphism (Karlstrom et al., 2001). Others, however, suggest that all of the ductile deformation and metamorphism in northern New Mexico may be 1450–1350 Ma, citing the lack of strong evidence for earlier Paleoproterozoic tectonism (Daniel and Pyle, 2006; Aronoff et al., 2012; Hunter et al., 2012).

The southern Sangre de Cristo Mountains of northern New Mexico remain an important locality to continue to refine and test models of crustal growth throughout the Proterozoic. In particular, the Gallinas Canyon area (El Porvenir quadrangle) includes a continuous tract of Paleoproterozoic metamorphic rocks that host the ca. 1.7 Ga Hermit Peak granite (Lindline et al., 2014), a prominent 32 km^2 syntectonic granite (Cedillo, 2015). This study presents field observations, petrographic descriptions, geochemical analysis, geothermobarometric analysis, and U-Pb zircon geochronologic analysis of Gallinas Canyon metamorphic rocks to constrain the nature of the original rocks (juvenile versus older continental crust), timing of metamorphism (Yavapai, Mazatzal, or 1.45 Ga deformation), and geotectonic setting of formation (accretionary arc, extensional basin, other).

BACKGROUND GEOLOGY

The southwestern United States consists of a complex collage of crustal provinces that were accreted to the southern margin of the Archean Wyoming province between 1.8–1.45 Ga as part of a protracted period of Laurentian crustal growth (Condie, 1982; Karlstrom and Bowring, 1988; Hoffman, 1989; Bowring and Karlstrom, 1990; Reed, 1993; Daniel et al., 2013). Proterozoic provinces have been delineated based largely on geophysical lineaments, U-Pb ages and isotopic signatures (Bennett and DePaolo, 1987) and include the Mojave province (1.8–1.7 Ga arcs built on older crust), the Yavapai province (dominantly juvenile 1.8–1.7 Ga arc crust), and Mazatzal province (dominantly juvenile 1.7–1.6 Ga crust). The boundary between the Yavapai-Mazatzal provinces has been variably defined as a relatively discrete suture zone (Magnani et al., 2004; 2005; Karlstrom et al., 2005) and/or as part of a transitional zone of Yavapai-Mazatzal terrane imbrication—the Yavapai-Mazatzal transition zone—that extends north into southern Colorado (Karlstrom and Humphreys, 1998; Shaw and Karlstrom, 1999; Karlstrom et al., 2004).

The Mora-Rociada-Las Vegas Ranges comprise the eastern prong of the southern Sangre de Cristo Mountains and lie within the Yavapai-Mazatzal transition zone. This salient consists

Appendix data for this paper can be accessed at:
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of a series of west-tilted, north-trending Proterozoic basement blocks bounded on the east and west by high-angle, west-dipping Laramide-age reverse faults. The rocks are broadly divided into three main suites from northwest to southeast: a quartzite-schist terrane, the Pecos greenstone complex, and a quartzofeldspathic-amphibolitic gneiss terrane (Robertson and Moench, 1979; Moench et al., 1988) (Fig. 1). The quartzite-schist terrane includes well-stratified quartzite, feldspathic quartzite, and pelitic schist with conspicuous graded bedding and cross-bedding. The quartzite-schist units lie structurally over the metavolcanic rocks of the Pecos greenstone complex (Moench et al., 1988). The Pecos greenstone belt, from north to south, consists of metavolcanic rocks (basalts and rhyolites) that are in some places interlayered with pelitic and feldspathic metasedimentary rocks, extensive

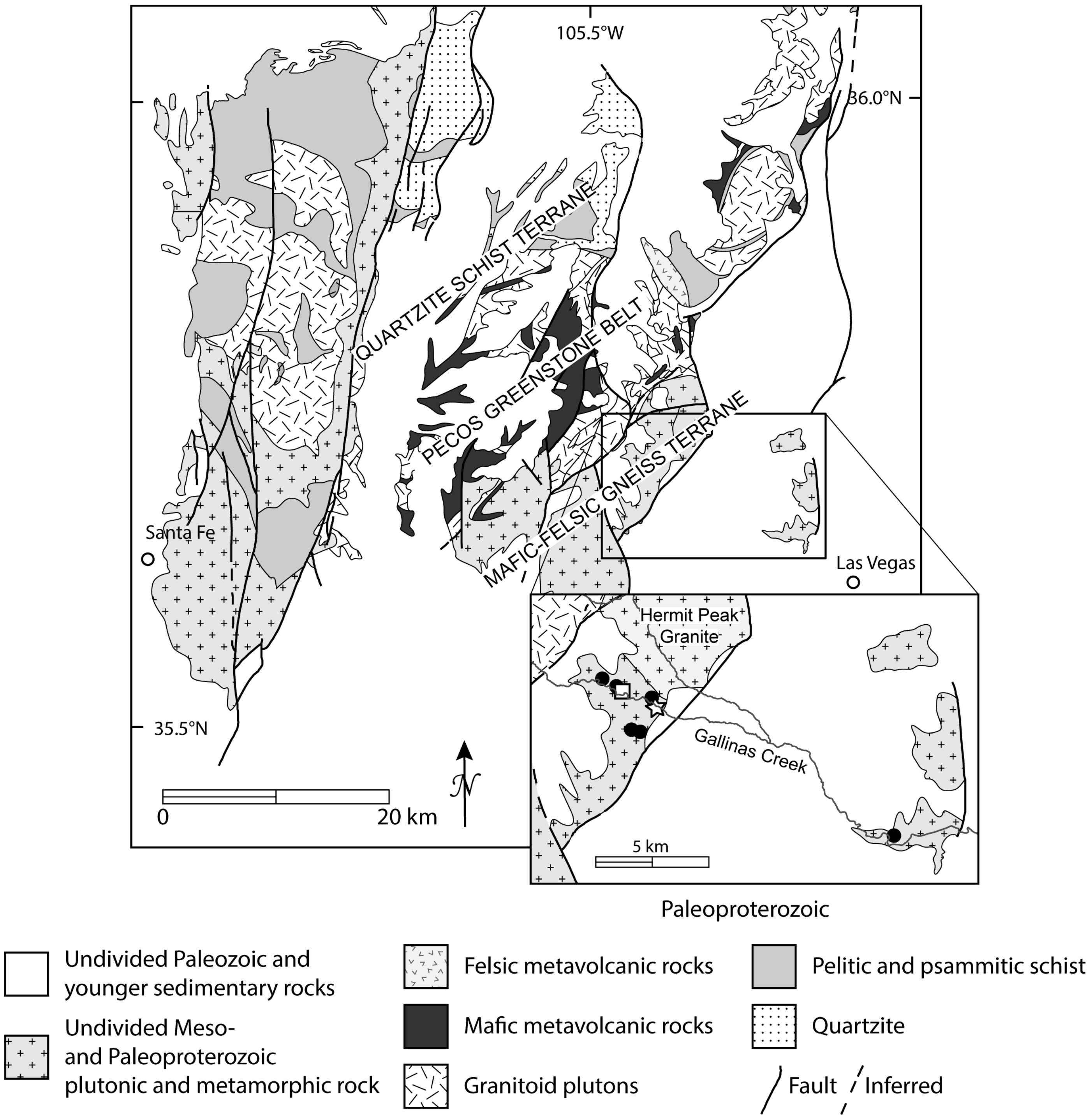

FIGURE 1. General geologic map of the southern Sangre de Cristo Mountains of New Mexico showing the distribution of major lithologies (New Mexico Bureau of Geology and Mineral Resources, 2003). The inset shows the Gallinas Canyon area and sample locations: star = Baker Flat picnic area; square = HP13_062 geochronology sample; and filled circles = mafic metamorphic rock samples.

FIGURE 2. Photograph looking west of the composition layering within the Baker Flat metamorphic suite.

basaltic amphibolite, and local ultramafic, tonalitic, and gabbroic metaplutonic rocks. The felsic-mafic gneiss terrane includes a broad array of quartzofelspathic and amphibolite gneisses that likely represent the oldest part of the Pecos greenstone complex volcanic pile or its subvolcanic equivalent (Moench et al., 1988). The felsic-mafic gneisses have been intruded by syn-tectonic (i.e., 1.7 Ga Hermit Peak granite) and post-tectonic (i.e., 1.4 Ga Evergreen Valley Plutonic Complex) intrusions (Lindline et al., 2013, 2014; Romero and Lindline, 2013).

Metamorphic or protolith ages of metamorphic rocks in the Gallinas Canyon area are largely unknown. U-Pb zircon dates from the Pecos greenstone belt consistently indicate a ca. 1.7 Ma age for volcanism, volcanogenic sulfide deposition, and subvolcanic intrusive activity. Stacey et al. (1976) report model lead ages of galena from the Pecos and Jones mines of 1710 Ma and 1720 Ma (no errors reported), respectively. Subvolcanic Pecos greenstone belt intrusions yielded U-Pb zircon ages of 1717 ±5 Ma (tonalite) and 1720 ±15 Ma (quartz porphyry) (Bowring and Condie, 1982).

FIELD INVESTIGATION

Data for this study come from metamorphic rocks in the upper canyon of Gallinas Creek, northwest of Las Vegas, between the Baker Flat picnic site and the Burro Basin trailhead (Fig. 1, inset map). A 132 m section of compositionally layered metamorphic rocks at Baker Flat was studied in detail and measured in profile (Figs. 2, 3). The Baker Flat suite is representative of the rock lithologies, compositional layering, and outcrop structures throughout the Gallinas Canyon area. The units are strongly layered and foliated with a dominant fabric dipping moderately to the southwest (average orientation: strike 10°SE, dip 47°SW). The section includes four compositionally distinct units: quartzo-feldspathic gneiss, amphibolitic gneiss, biotite schist, and granite pegmatite. The contact between each compositionally distinct unit is sharp and distinct. Multiple samples from

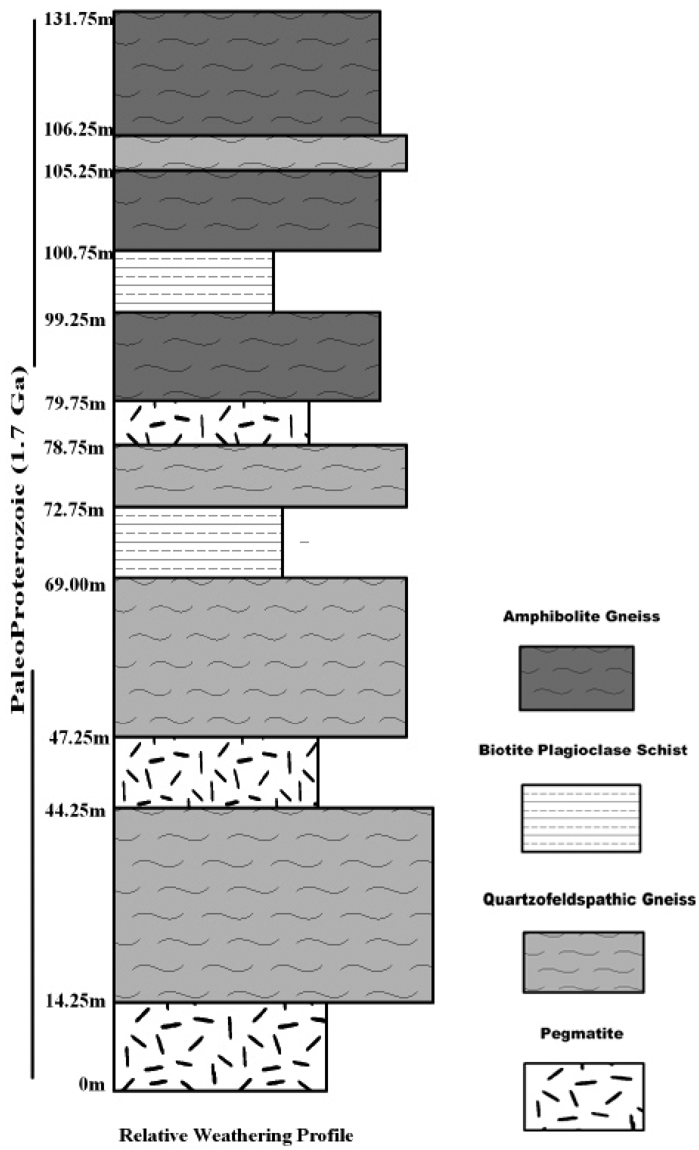

FIGURE 3. Measured section of compositionally layered metamorphic rocks at the Baker Flat picnic area, Upper Gallinas Canyon, NM-263.

each lithologic unit were collected for hand specimen and thin section study. Modal data were collected using visual estimation and crystal sizes were measured using a micrometer scale. The presence and relative abundance of accessory minerals such as Fe-Ti oxides, sulfides, apatite, and zircon were also noted as well as the amount and nature of alteration.

The quartzofeldspathic gneiss is pinkish-tan to orangish-tan colored and fine- to medium-grained with cm-scale banding defined by biotite segregations and layers dominated by quartz and feldspar. Within these layers quartz and feldspar display a shape preferred orientation defining a fabric which is parallel to gneissic banding. Microcline occurs in greater quantities than plagioclase feldspar, though the absolute amounts are variable. Magnetite is ubiquitous in the felsic gneiss, either as minor discrete grains, as porphyroblasts with distinct Fe-oxide halos, or as cm-thick seams. In thin section, quartz and feldspar show undulatory extinction, serrated grain boundaries and ribbon texture indicative of a temperatures >450°C at natural strain rates (Voll, 1976; Tullis, 1983).

The amphibolitic gneiss is dark-colored and fine- to medium-grained. It varies from non- to weakly banded with mm-scale quartz-plagioclase laminae making up <10% of any one outcrop. It consists of major blue-green and brown-green hornblende porphyroblasts (up to 40%), a colorless amphibole thought to be cummingtonite (5%), and intermediate plagioclase (up to 40%) with variable amounts of biotite (0 to 5%) and quartz (0 to 20%) and minor epidote, titanite, garnet, and magnetite. These units lack conspicuous pillow structures, amygdules, or flow breccias indicative of a volcanic protolith seen in the amphibolite bodies of the Pecos greenstone belt (Robertson and Moench, 1979). Recrystallization of the amphibolite is evident in thin section; most sections exhibit a moderately developed granoblastic-polygonal fabric with a weak to moderate foliation defined by the alignment of hornblende and biotite.

The granitic pegmatites occur predominantly as sills and consist of exceptionally large biotite crystal clusters (1–6 cm diameter books), large tabular potassium feldspar crystals (up to 4 cm length) and intergranular plagioclase and quartz. The pegmatites are pervasively weathered and easily broken into gruss. The pegmatites lack a macroscopic and microscopic foliation. In thin section, quartz crystals show a high degree of undulatory extinction and biotite crystals show a preferred alignment that parallels the outcrop-scale compositional layering.

The biotite schist consists of major (40%) plagioclase, (30%) biotite, (20%) quartz, minor microcline (6%) and muscovite (4%), and accessory garnet, hornblende, and Fe-oxides. The unit shows internal segregation of minerals with biotite-richer and biotite-poorer areas. The foliation is defined primarily by a biotite schistosity along with aligned plagioclase and microcline.

GEOCHEMISTRY

The principal control on the chemical composition of a metamorphic rock is the chemical composition of the pre-metamorphic protolith (Rollinson, 1993). Mafic metamorphic rocks, in particular, are useful for inferring protolith origins based on discrimination diagrams that employ minor and trace elements, specifically the high field strength elements that are relatively immobile during metamorphic processes. Ten mafic metamorphic rocks (amphibolite and biotite schist) from the Gallinas Canyon area were selected for whole rock geochemical analysis based on the freshness and homogeneity of the sample to assist in protolith determination. All analytical results are presented in Appendix Table DR-1. Seven samples (prefix TE03- in Appendix Table DR-1) were analyzed at the Analytical Geochemistry Research Laboratory at New Mexico State University via XRF while 3 samples (prefix $CT0_{4-}$ in Appendix Table DR-1) were analyzed at Activation Laboratories, Ltd. (Canada) via ICP-MS.

The Gallinas Canyon mafic metamorphic rocks range in SiO_2 values between 49.68–61.35 wt.% and MgO between 2.36 to 8.62 wt.%. The data set shows a decrease in CaO, MgO, and total Fe_2O_3

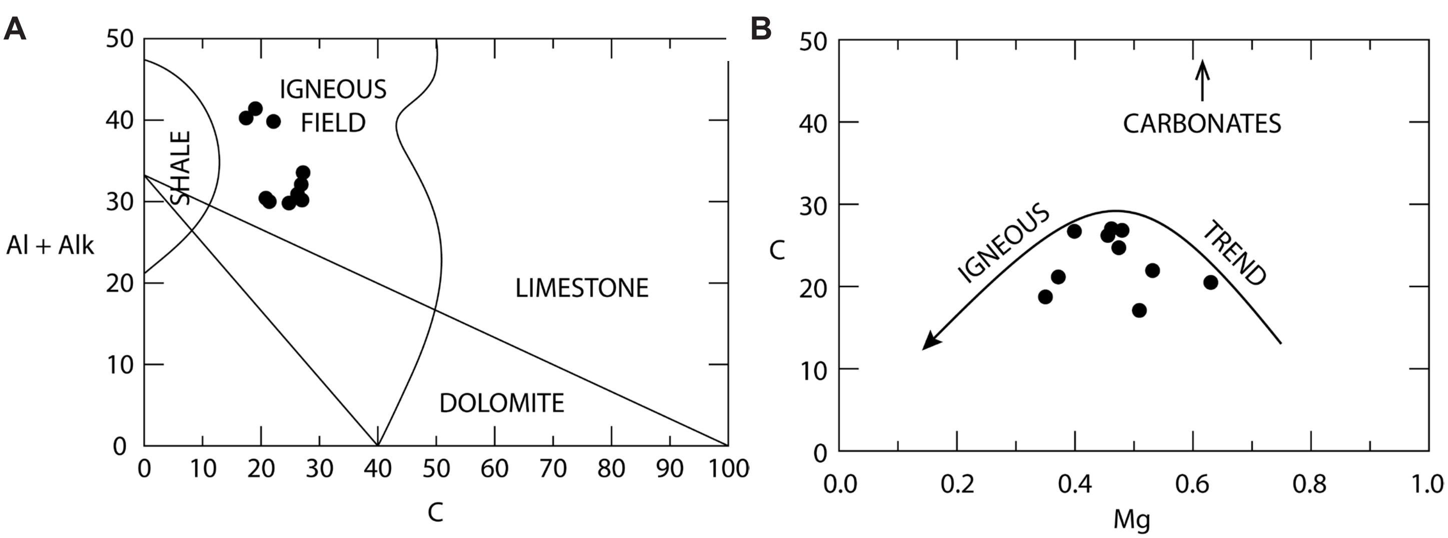

FIGURE 4. A. Niggli normative AL-ALK versus C for the Gallinas Canyon mafic metamorphic rocks with sedimentary and igneous rock fields defined. The Gallinas Canyon samples plot within the igneous rock field. B. Niggli C versus MG for the Gallinas Canyon mafic metamorphic rocks after Leake (1964) and Evans and Leake (1960). The samples follow the igneous trend (arrow) of variation for the Karoo dolerites.

and a general increase in Na_2O+K_2O with increasing SiO_2 wt.%. Trace elements Cr and Ni range from 483–3 ppm and 249–4 ppm, respectively. Mafic metamorphic rocks having Cr and Ni values as low as these can be either igneous or sedimentary in origin. Using chemical variation diagrams developed by Leake (1964) and van de Kamp (1969), which utilize normative values (Niggli, 1954) and data trends, the Gallinas Canyon samples show no correlation with the fields or trend lines for sedimentary rocks (Fig. 4). Rather, the samples plot within the igneous rock field (Fig. 4A) and follow the Karoo dolerite trend (Fig. 4B). If we presume that these rocks are metavolcanic assemblages, chemical analysis indicates that they are subalkaline and tholeiitic in composition. The rocks plot primarily as island arc tholeiites on the basalt tectonic discrimination diagram of Mullen (1983) (Fig. 5A). On a MORB-normalized trace element diagram (Fig. 5B), the samples show high Rb relative to the other large ion lithophile elements Sr and Ba, and decreasing amounts of Th, Nb and Ce all of which are characteristic of formation in an island arc setting.

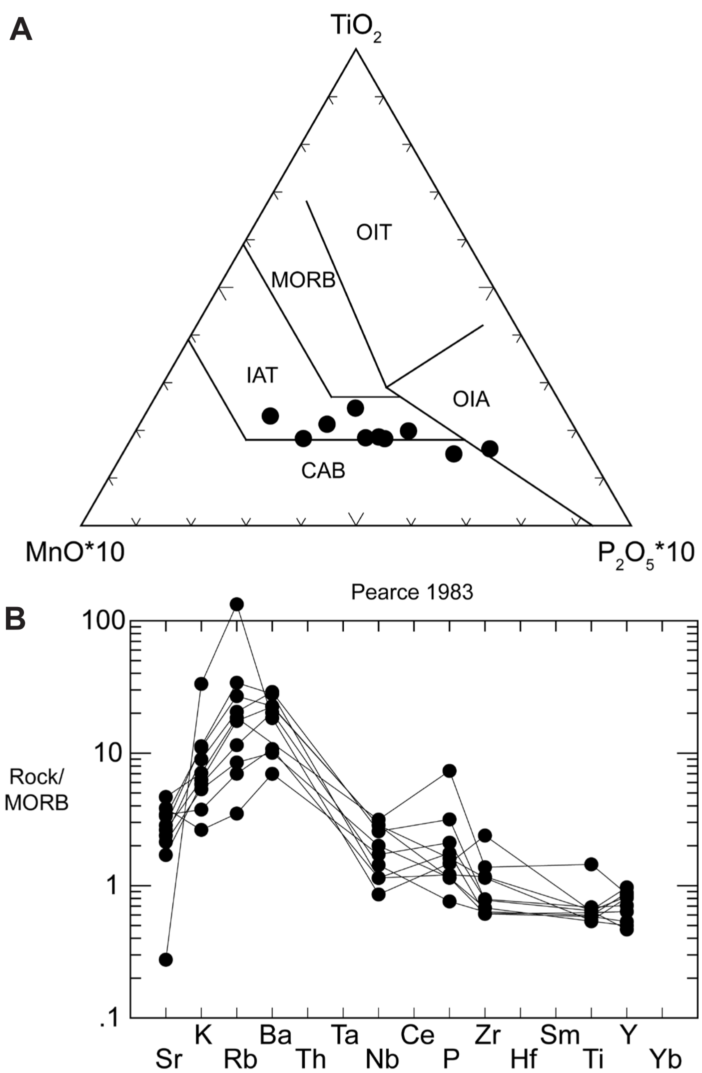

FIGURE 5. A. TiO_2-MnO-P_2O_5 tectonic discrimination diagram for mafic-ultramafic intrusions; CAB, continental basalt; MORB, midoceanic ridge basalt; IAT, island arc and volcanic arc tholeiite basalt; OIT, oceanic island tholeiite basalt; OIA, oceanic alkaline island. B. MORB-normalized trace element distributions for Gallinas Canyon mafic metamorphic rocks. Normalization values from Pearce (1983).

METAMORPHISM

The amphibolites at Baker Flat are among the few rocks in the area with an assemblage, garnet + hornblende + plagioclase, suitable for estimation of metamorphic temperature and pressure. Polished thin sections were analyzed on the FEI Quanta 400 scanning electron microscope housed in the Center for Microanalysis and Imaging Research and Training (CMIRT) at West Chester University of Pennsylvania. Mineral analyses were performed using the Oxford Instruments INCA energy dispersive spectrometer (EDS) and software. Petrographic analysis shows that garnet is zoned; poikiloblastic cores are surrounded by relatively inclusion free rims. Compositionally, Mg/Mg+Fe increases (0.15 to 0.21), while grossular (0.20 to 0.10) and spessartine (0.19 to 0.08) content decrease abruptly across the core-rim boundary (Appendix Table DR-2).

We report the results of pressure-temperature estimates obtained using the composition of the garnet rim together with nearby matrix plagioclase and hornblende. Calculations were performed with winTWQ (Berman, 1991) v. 2.3 (2007) using the Berman (1988) database and the geobarometer for garnet amphibolites of Kohn and Spear (1990). The positions of four independent reactions calculated using winTWQ are plotted in Fig. 6; steep curves are Fe-Mg exchange reactions between garnet and hornblende while the moderately sloping ones correspond to equilibria involving components of garnet, hornblende and plagioclase. The reactions intersect at approximately 725°C and 550 MPa, indicating that minerals of this composition achieved chemical equilibrium at these pressure-temperature conditions.

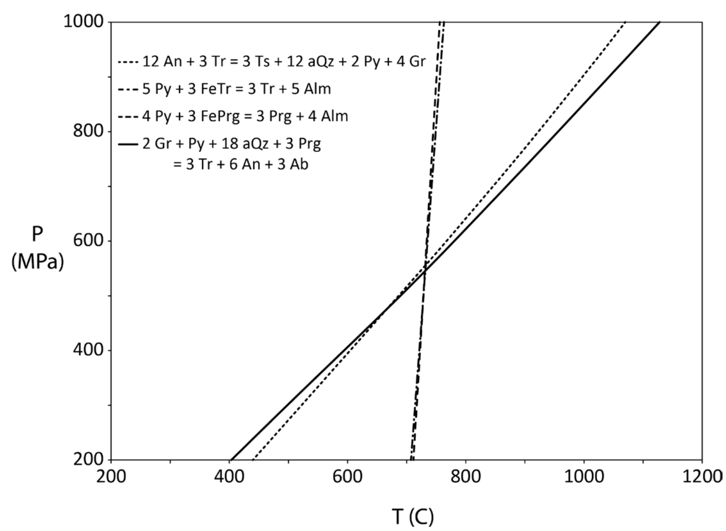

FIGURE 6. Pressure-temperature results calculated using winTWQ (Berman, 1991) v. 2.3 (2007), a software package for performing internally-consistent thermobarometric calculations, with the Berman (1988) database. Calculations used the composition of garnet overgrowth, matrix plagioclase and matrix hornblende. Mineral abbreviations after Whitney and Evans (2010); Alm = almandine, An = anorthite, Gr = grossular, Prg = pargasite, Py = pyrope, aQz = alpha quartz, Tr = tremolite, Ts = tschermakite.

These reactions are similar, but not identical, to those calibrated by Kohn and Spear (1990). Pressures calculated with the Kohn and Spear barometer are approximately 50 MPa lower.

U-PB GEOCHRONOLOGY

A ~10 kg sample of amphibolite from the upper Gallinas Canyon (sample HP13_062) was collected to constrain the age of the protolith and/or of metamorphism. Fresh, unweathered, fist-sized samples were shipped to and processed at the Arizona Laserchron Center (ALC) at the University of Arizona. Crystals were extracted from samples by traditional methods of crushing and grinding, followed by separation with a Wilfley table, heavy liquids, and a Frantz magnetic separator. A split of the zircon-laden heavy mineral fraction (generally 50–100 grains) was selected and incorporated into a 1” epoxy mount together with fragments of Sri Lanka standard zircon. The mount was sanded to a depth of ~20 microns, polished, CL-imaged, and cleaned prior to isotopic analysis.

U-Pb isotopic analyses was conducted at the ALC via a Nu Instruments high resolution laser ablation multicollector inductively coupled plasma mass spectrometer (HR-LA-MC-ICP-MS) coupled to a Photon Machines Analyte G2 excimer laser equipped with a HelEX low-volume cell (Gehrels et al., 2008). Ablated material was carried in He gas. All measurements were made in static mode, using Faraday detectors with $3x10^{11}$ ohm resistors for ^{238}U, ^{232}Th, $^{208-206}Pb$, and discrete dynode ion counters for ^{204}Pb and ^{202}Hg. Ion yields are ~0.8 mv per ppm. Each analysis consisted of one 15-second integration on peaks with the laser off (for backgrounds), 15 one-second integrations with the laser firing, and a 30 second delay to purge the previous sample and prepare for the next analysis. The ablation pit was ~15 μ deep. Common Pb corrections were made using measured ^{204}Pb concentrations and assuming an initial Pb composition from Stacey and Kramers (1975) with uncertainties of 1.0 for $^{206}Pb/^{204}Pb$ and 0.3 for $^{207}Pb/^{204}Pb$. For a full dialogue of the analytical techniques and data reduction procedures, see Gehrels et al. (2008). U-Pb analytical results are reported in Appendix Table DR-3.

Mineral separation produced a single zircon population having an average diameter of 60 μm and soccer ball morphology typical of high-grade metamorphic zircon (Schaltegger et al., 1999). Cathode luminescence imaging shows that the majority of crystals contained round <10 μm diameter xenocrystic cores overprinted by areas characterized by broad concentric or complex zoning. The zircon sample mount was analyzed using a Faraday cup and a 35 μm beam size. We analyzed one spot per crystal avoiding the relic cores and targeting the new growth areas. U/Th ratios for the crystal spot analyses range from 3.4–19.0, with 6 of the 35 analyses having values >10 indicating that zircon growth likely occurred in the presence of a fluid. Eleven analyses were omitted from the weighted mean age based on the high degree of discordance. The weighted mean plot for 24 accepted analyses shows a coherent population with a calculated weighted mean $^{207}Pb/^{206}Pb$ age of 1717.1 ±1.0 Ma with a mean square of weighted deviates (MSWD) of 1.0 (Fig. 7A). Inclusion of systematic errors yielded a final age of 1714 ±14 Ma. The concordia diagram shows the data plotting in an array that intersects concordia at 1720 Ma (Fig. 7B). While some of the analyses exhibit reverse discordance, the tightness of the array suggests that the crystal are cogenetic and that addition of common Pb or the subtraction of ^{206}Pb from the zircon crystal lattice affected the entire sample population.

DISCUSSION AND CONCLUSION

Metamorphic rocks of the Gallinas Canyon area lack clear indicators of the parent rock and geologic setting such as cross-beds and graded beds indicative of a sedimentary origin or

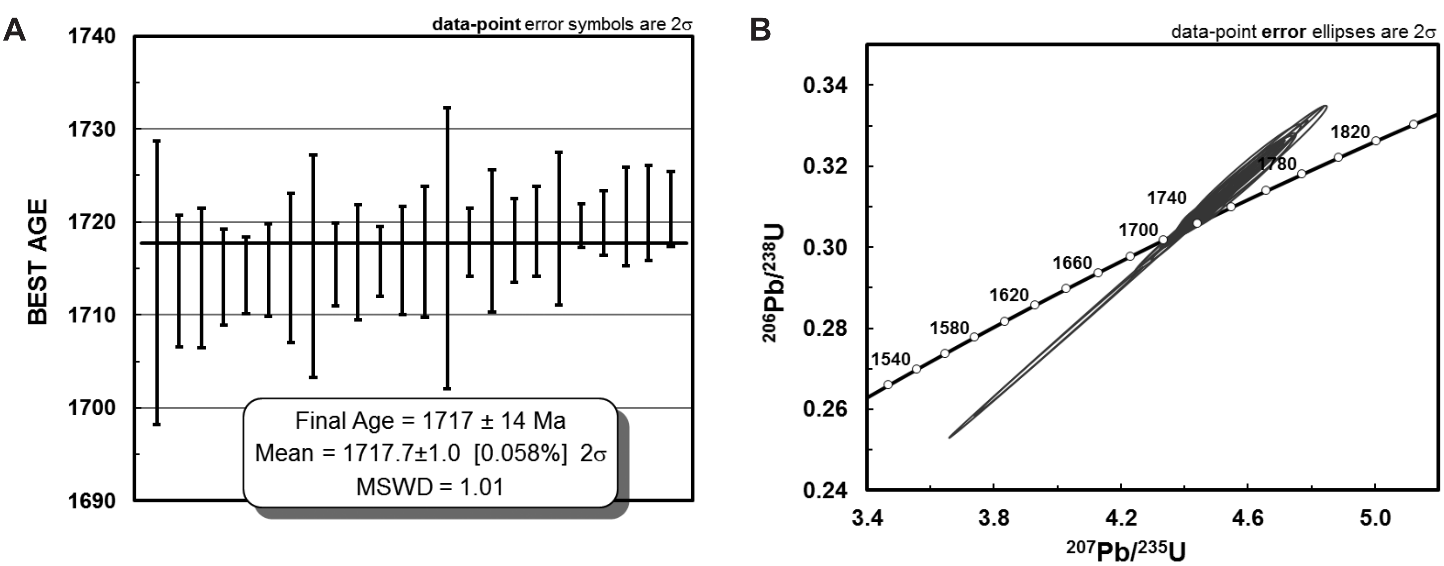

FIGURE 7. A. Weighted mean age plot for Gallinas Canyon amphibolite HP13_062 showing data points plotted at the 2-sigma level. Solid line shows weighted mean age of 1717 Ma. Final age includes both random and systematic error. B. Concordia diagram for the same data set, with data point error ellipses at the 2-sigma level. Upper intercept age is 1720 Ma, which is within error of the weighted mean.

pillow structures and amygdules indicative of a volcanic origin. This study, therefore, relied on field observations, petrographic features, and geochemical analysis to interpret protoliths and to surmise their tectonic setting.

The Gallinas Canyon amphibolitic and quartzofeldspathic gneisses display layering of various thickness and diverse composition, all of which fall within the range of normal igneous rocks (basalts and rhyolites). The sharp contacts between the units as well as the homogeneity of rock compositions, texture, and fabric within each discrete unit are features of metaigneous (volcanic or plutonic) rocks (Passhier et al., 1990). The lack of primary muscovite or other Al-bearing metamorphic minerals makes a sedimentary origin unlikely. An igneous origin is further supported by the interpreted volcanic arc basalt parentage of the amphibolite and biotite schist units based on whole rock geochemistry. The co-occurrence of metabasalt (amphibolite) and metarhyolite (quartzofeldspathic gneiss) throughout the area is characteristic of the bimodal associations that are found in modern oceanic arc systems (Hamilton, 1979) and that typify Proterozoic arc assemblages (Karlstrom et al., 2004). The magnetite-bearing quartzofeldspathic units that are closely associated with the amphibolites may represent Fe-rich metarhyolites or, as suggested by O'Neill (1990), a poorly developed oxide facies of iron-formation formed by exhalative submarine volcanic activity.

Amphibolite sample HP13_062 provides our best minimum age of the felsic-mafic gneiss terrane. The amphibolite yielded an age of 1717±14 Ma that we ascribe to zircon growth during amphibolite grade metamorphism concomitant with emplacement of the ca. 1.7 Ga Hermit Peak granite. The metamorphic pressure estimate of 550 MPa indicates pluton emplacement at a depth of slightly less than 20 km. The zircons lacked textural or U-Pb isotope data for a younger, post- 1.7 Ga metamorphic overprint and thus provide insight into the timing of older events that are missing in northern New Mexico.

The Gallinas Canyon quartzofeldspathic-amphibolitic gneiss terrane represents metamorphosed and deformed rocks of a juvenile (oceanic) island arc. The gneisses signify the basement to the Pecos greenstone complex as well as the syntectonic Hermit Peak granite. The Gallinas Canyon gneiss records magmatism, metamorphism, and deformation associated with the regionally established Yavapai orogeny.

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