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MAGMATISM AND METAMORPHISM AT 1.46 GA IN THE BURRO MOUNTAINS, SOUTHWESTERN NEW MEXICO

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Abstract — The Burro Mountain granite and biotite-hornblende granite in the Burro Mountains make up a large plutonic complex that cuts 1.65 Ga Mazatzal province metamorphic rocks. A foliation in the pluton consists of aligned biotite, is most prominent near the contact with the country rock, and is absent in the interior of the pluton. We interpret this fabric as being generated during magmatic emplacement. The Burro Mountain granite locally cuts the smaller volume biotite hornblende granite. U-Pb zircon dating of four samples of the Burro Mountain granite yielded ages ranging from 1463–1455 Ma. The weighted mean $^{207}Pb/^{206}Pb$ date from all of these samples is 1457 ± 4 Ma. The biotite hornblende granite was dated at 1459 ± 14 Ma. An amphibolite has a protolith interpreted to be coeval with 1.65 Ga metasedimentary rocks and a U-Pb zircon age of 1459 ± 9 Ma. This age reflects metamorphism of the amphibolite coeval with the intrusion of the granites. Timing of metamorphism of the metasedimentary rocks was investigated using electron microprobe dating of monazite. Most ages are around 1460 Ma with one sample yielding an age of 1411 Ma. The main episode of deformation in the Burro Mountains occurred between 1.65–1.63 Ga, and 1.46 Ga magmatism occurred in the apparent absence of regional tectonic activity. High-heat flow associated with the 1.46 Ga magmatic event reset both U-Pb monazite and $^{40}Ar/^{39}Ar$ thermochronologic systems and was apparently short-lived in the Burro Mountains on the basis of numerous dates within error of 1.46 Ga.

INTRODUCTION AND PREVIOUS WORK

A massive ~1.4 Ga igneous event in Laurentia is known from rocks ranging in age from 1.48–1.35 Ga that are exposed from Wisconsin to northern Sonora, Mexico (Fig. 1). This magmatism occurred up to at least 1000 km from the southern margin of Laurentia. Interpretations of the tectonic setting of this protracted episode of magmatism, summarized in Karlstrom et al. (2004), include anorogenic models invoking an extensional setting based on geochemical relationships (e.g., Anderson, 1983) and orogenic models that note many of these plutons in the southwest U. S. were emplaced during northwest crustal shortening (Nyman et al., 1994; Kirby et al., 1995). Geochemical relationships indicate that underplating of basaltic rocks induced melting of older crustal rocks (Frost and Frost, 1997).

The Burro Mountains of southwestern New Mexico (Fig. 2) contain the largest areal exposures of ~1.4 Ga igneous rocks in southern New Mexico. Magmatism of this age was the first major thermal event following the Mazatzal orogeny at 1.65 Ga (Anderson, 1983; Karlstrom et al., 2004; Amato et al., 2008). Controversies concerning this period of magmatism in the southwestern U. S. include the petrogenesis of the igneous rocks, the conditions of metamorphism, the duration of the event, and whether or not magmatism was accompanied by regional deformation. The goals of the current study were to determine the ages of magmatism and metamorphism and the P-T conditions of metamorphism in the Burro Mountains. We used U-Pb zircon geochronology and electron microprobe dating of monazite to determine the timing. A companion study focused on the pre-1.4 Ga rocks (Amato et al., 2008).

The area of the Burro Mountains was mapped at 1:24,000 scale in the late 1970s (Hedlund, 1978a, b, c, d, e, f, g, h, 1980a, b, c), and as part of that study Stacey and Hedlund (1983) determined an age of a granite in the Gold Hill quadrangle to be 1445 ± 15 Ma. Rämö et al. (2003) dated a rapakivi granite in the Redrock area at 1461 ± 24 Ma and a minette at 1465 ± 16 Ma. The earliest descriptions of the metamorphic rocks come from Hewitt (1959), who noted that the Redrock area had generally lower-grade igneous rocks and that the rest of the Burro Mountains exposed higher-grade rocks (up to upper amphibolite facies). Much of the present study relies on work conducted for two M.S. theses from New Mexico State University. Sanders (2003) mainly studied the distribution and ages of metamorphic rocks in the Bullard Peak area. Boullion (2006) mapped both deformed and undeformed igneous rocks, investigated the geochemistry of the igneous rocks, and dated six samples.

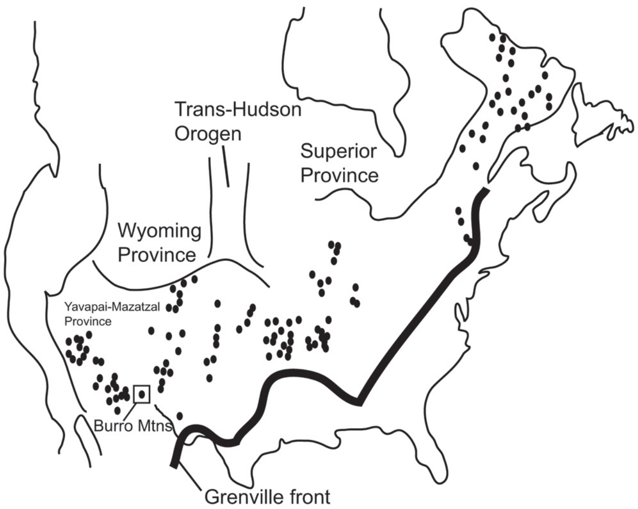

FIGURE 1. Locations of ~1.4 Ga granites in North America, modified after Anderson and Cullers (1999) and Windley (1993).

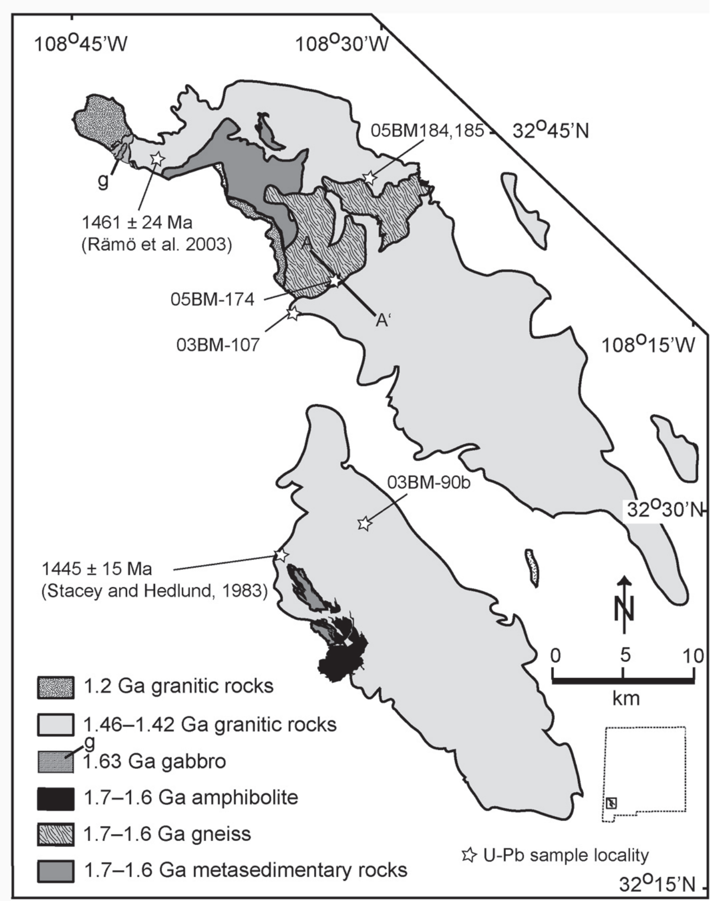

FIGURE 2. Simplified geologic map and sample localities, after Amato et al. (2008). The biotite-hornblende granite is too small to be shown at this scale. See Table 1 for ages. Cross-section line A-A' shown in Figure 6.

GEOLOGIC SETTING

There are two main uplifted fault blocks of the Burro Mountains. The northern block is referred to as the Big Burro Mountains and the southern block as the southern Burro Mountains. The main rock types include Paleoproterozoic igneous and metasedimentary rocks and a larger volume of ~1.4 Ga igneous rocks (Fig. 1). A few Laramide-age intrusions are present (see Amato and Boullion, this volume). A diabase dike swarm cuts all of the Proterozoic rocks, suggesting that these dikes are younger than 1.4 Ga and likely correlative to ~1.1 Ga diabase dikes that are abundant in the southwestern U. S. (Howard, 1991). Tertiary igneous rocks are abundant along the northern edge of the area (Finnell, 1987) and form a large intrusion in the central Big Burro Mountains.

Regionally, the oldest basement rocks in southern New Mexico are 1.68–1.65 Ga granitic rocks deformed at 1.65 Ga that make up the Mazatzal province (Amato et al., 2008). Deposition of siliciclastic and pelitic rocks occurred after 1.65 Ga based on detrital zircon geochronology, but before 1.63 Ga based on a cross-cutting gabbro intrusion in the Redrock area (Rämö et al., 2003). All of the pre-1.63 Ga rocks are metamorphosed and deformed with a strong foliation. The majority of the deformation must have occurred prior to 1.63 Ga, because contact metamorphism resulted in static porphyroblast growth in the metasedimentary rocks surrounding the gabbro of this age (Amato et al., 2008).

METHODS

U-Pb geochronology was carried out using a single-spot analytical instrument known as the SHRIMP-RG (sensitive high-resolution ion microprobe reverse geometry) at the Stanford–U.S. Geological Survey Ion Probe Facility. Zircons were extracted using standard crushing, gravimetric, and magnetic separation techniques. For SHRIMP analysis, a 30-μm diameter beam was used that analyzes to a depth of about 5 μm. Cathodoluminescence images were obtained for all zircons analyzed. U, Th, and Pb concentrations were standardized against RG-6 and VP-10 zircons that were analyzed after every four unknown analyses. Data was reduced using the SQUID program (Ludwig, 2001). Pb/U ratios were corrected for common Pb using the model Pb evolution curve of Stacey and Kramers (1975). Errors on spot ages of individual zircons grains are reported at 1σ, and weighted mean ages were calculated and reported in the text and figures at the 2σ level. The weighted mean of $^{207}Pb/^{206}Pb$ ages derived using the SQUID and Isoplot programs (Ludwig, 2003) incorporates uncertainties in the standards and decay constants into the reported errors.

Electron microprobe dating of monazite was conducted at New Mexico Tech using the techniques described in Williams et al. (1999). A scanning clectron microscope (SEM) was used to map thin sections for elements such as Ce, Y, and Th to determine the location of monazite grains. Monazites were then mapped and analyzed using an electron microprobe for Ce, Pb, Th, Y to determine any zonation or the presence of older cores. Five to seven grains per thin section were analyzed, and about six points per grain were analyzed for Pb, U, and Th concentrations.

SAMPLES STUDIED

The "Granite of Burro Mountain" of Hedlund (1980a), here referred to as the Burro Mountain granite, is the most widespread rock type in the Burro Mountains and crops out extensively in both the northern and southern parts of the range (Fig. 2). The Burro Mountain granite was mapped as a compositionally variable but coherent pluton that extends at least 25 km by 5 km in map area. It is light tan to brown, medium- to coarse-grained, and leucocratic. The unit is dominated by quartz (30-40%) and K-feldspar (50-60%) and has smaller amounts (5-15%) of plagioclase. Point counting indicates that the composition varies from granite to alkali-feldspar granite. Accessory minerals include biotite, muscovite, allanite, zircon, hornblende, and Fe-Ti oxides. Dikes of this composition are found to cut the biotite-hornblende granite (see below), and biotite-hornblende granite xenoliths are commonly found in the Burro Mountain granite, indicating at least locally that the Burro Mountain granite is younger.

A coarse-grained biotite-hornblende granite is generally present as small bodies in both the northern and southern Burro Mountains. This unit was referred to by Hedlund (1980a) as granodiorite, but point counting reveals that it is a plagioclase-rich granite. It consists of quartz (~25%), K-feldspar (~25%), plagioclase (~35%), hornblende (~10%), and biotite (5%). K-feldspar grains are as large as 2 cm in length. Xenoliths of calc-silicate metasedimentary rocks and amphibolite are common within the biotite hornblende granite.

Smaller outcrops of amphibolite are located throughout the Burro Mountains (Fig. 2). These rocks are fine-grained and consist of 60% hornblende, 40% plagioclase, and trace amounts of quartz (Hewitt, 1959). Metasedimentary xenoliths are commonly found in this unit. The relatively small size and sparse outcrops of this unit suggest that it intruded as dikes, though it is possible that some larger outcrops may have been lava flows coeval with deposition of the metasedimentary protoliths. This unit cuts and thus is younger than the 1.68–1.65 Ga metasedimentary and gneissic country rock. It has not been observed cutting any of the ~1.4 Ga units and is commonly present as xenoliths within the biotite hornblende granite.

ZIRCON GEOCHRONOLOGY RESULTS

Six samples were dated using U-Pb analysis of zircons (Table 1). These include one sample of amphibolite, one sample of biotite-hornblende granite, and four samples from the Burro Mountain granite. For each date we are reporting a 2σ analytical uncertainty based primarily on the weighted mean of $^{207}Pb/^{206}Pb$ dates, but in each case the intercepts on concordia diagrams yield ages within error of the weighted means (Fig. 3).

The amphibolite sample 05BM-174 is from the central part of the northern Burro Mountains, and is found within an elongate 2 km by 200 m outcrop of amphibolite within the 1.65 Ga gneiss (Fig. 2). The eight zircons are equant and have minimal internal zonation, suggesting a metamorphic origin. They do not have particularly low Th/U which is often, but not always, a hallmark of metamorphic zircon growth (Hoskin and Schaltegger, 2003). The weighted mean age for these dates is 1459 ± 9 Ma (Fig. 3).

One sample from the biotite hornblende granite yielded large zircons with magmatic oscillatory zonation. The weighted mean of the $^{207}Pb/^{206}Pb$ dates of these ten zircons is 1459 ± 14 Ma (Fig. 3). Four samples from the Burro Mountain granite were dated (Fig. 4). Three of these were from the northern Burro Mountains, and one was from the southern Burro Mountains. All samples yielded magmatic zircons with oscillatory zonation. At least nine zircons were dated from each sample. The weighted means of the dates from these four samples are 1463 ± 8 Ma, 1463 ± 13 Ma, 1456 ± 6 Ma, and 1455 ± 11 Ma. All of these dates are the same within error. If all of the Burro Mountains granite zircon ages are combined, the weighted mean date for the intrusion is 1457 ± 4 Ma with a mean square of weighted deviates (MSWD) of 1.5. This age is within error of both the metamorphic zircons in the amphibolite and the age of the biotite-hornblende granite.

MONAZITE GEOCHRONOLOGY RESULTS

The mineral monazite was used to determine the age of metamorphism of three metapelitic schists (01BM-19, 01BM-33, 01BM-37). The data are summarized in Figure 5; for complete data tables see Sanders (2003). All uncertainties are quoted at the 2σ level. The cores of the monazite grains contain the oldest ages ranging from 2400 Ma-1550 Ma and the highest 1σ uncertainties ranging from 75–200 Ma. These old ages have high uncertainties because the concentrations of U, Th, and Pb are all relatively low. When the Pb concentration is less than 0.1% by weight, the uncertainties are extremely high and increase as the Pb concentration decreases. For this reason, we consider these older dates to be suspect and only discuss the dates younger than 1600 Ma. Most of the rim ages range from 1500 Ma-1400 Ma with a few ages younger than 1400 Ma. The 1σ uncertainties range from 8–25 m.y. and this higher precision is the results of higher concentrations of U, Th, and Pb.

All three of the dated samples are garnet-biotite-sillimanite metapelitic schists. Sample 01BM-19a has one main peak on a histogram/relative probability diagram (Ludwig, 2003) that yielded a mean age of 1411 ± 4 Ma. The other peaks consist of only one date each and are not likely to be statistically significant. Sample 01BM-33 has a main peak with a mean age of 1476 ± 5 Ma. This sample was redated at the University of Massachusetts, and three grains yielded ages of 1460 ± 18 Ma, 1457 ± 25 Ma, and 1426 ± 24 Ma. Sample 01BM-37 yielded a peak age with a weighted mean of 1459 ± 7 Ma.

TABLE 1. U-Pb zircon ages for Burro Mountain rocks.

Sample	Rock type	Age ± 2σ (Ma)	UTM coordinates
05BM-174	Amphibolite	1459 ± 9	730854, 3615870
05BM-184	Biotite hornblende granite	1459 ± 14	733777, 3623055
03BM-107	Burro Mountain granite	1463 ± 8	728060, 3613538
04BM-148	Burro Mountain granite	1456 ± 6	727800, 3594225
03BM-90b	Burro Mountain granite	1463 ± 13	733676, 3597621
05BM-185	Burro Mountain granite	1455 ± 11	733777, 3623055

Notes: All ages are weighted mean of $^{207}Pb/^{206}Pb$ dates.

UTM zone 12S, datum is NAD27 CONUS.

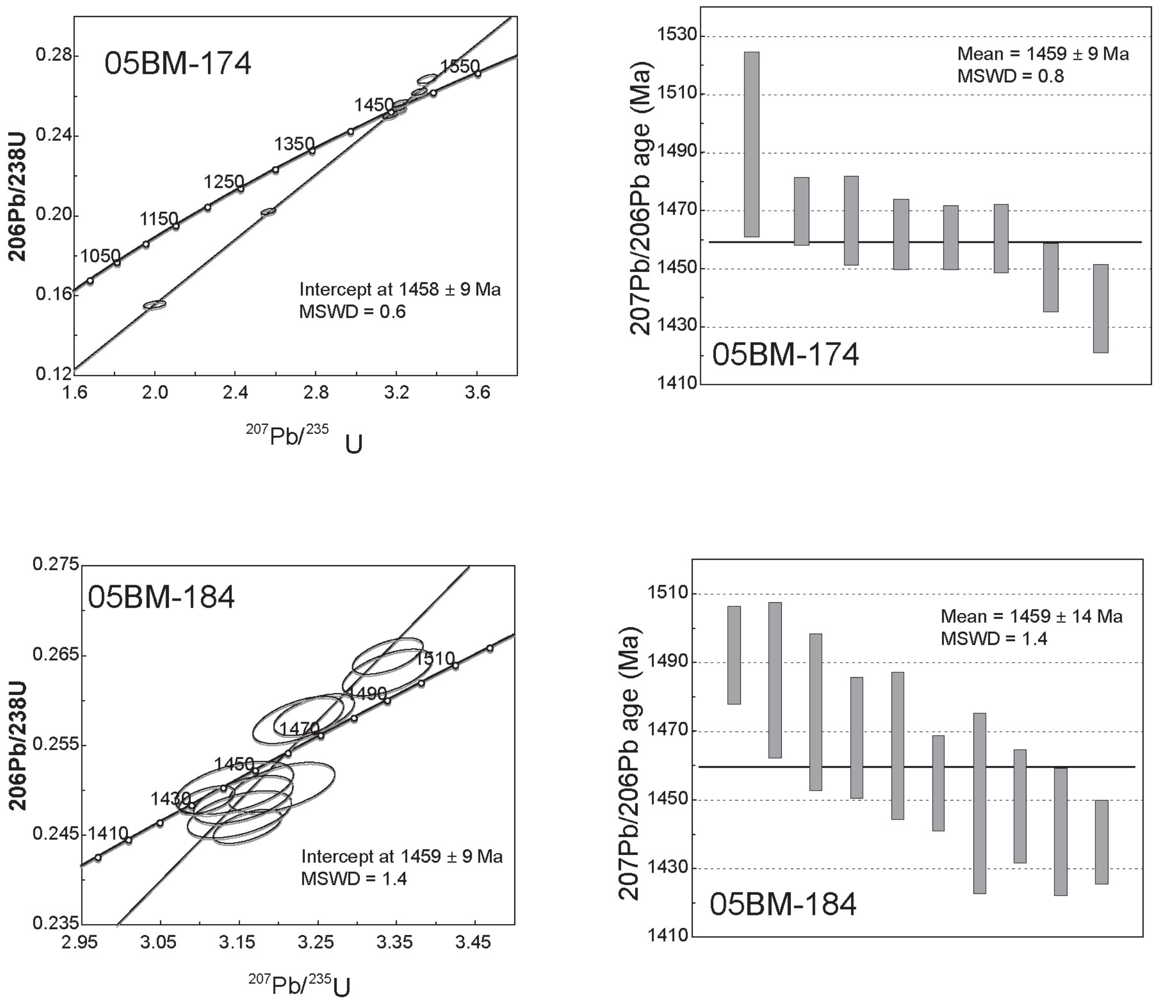

FIGURE 3. U-Pb concordia and weighted mean plots from amphibolite (05BM-174) and the biotite-hornblende granite (05BM-184).

FABRICS IN THE IGNEOUS ROCKS

The granite gneiss, amphibolite, and metasedimentary rocks (collectively referred to as the country rock) in the map area share a pervasive foliation that generally strikes northeast with highly variable dips. The Burro Mountain granite has a weak foliation that is similar in strike to the country rock near the margin of the intrusion. The outcrops of the Burro Mountain granite away from the country rock have foliations that are either weak, with highly variable orientations, or absent. A schematic cross section was constructed that shows a large anticline in the country rock that is cut by the Burro Mountain granite (Fig. 6). Dips in the foliation of the Burro Mountain granite are much steeper (> 65°) adjacent to the granite gneiss contact and those dips are maintained away from the contact and into the Burro Mountain granite. The biotite hornblende granite is locally foliated but generally contains no fabric. It should be noted that the strike of this foliation is generally the same as the foliation in the Burro Mountain granite when the two units are in direct contact.

DISCUSSION

Timing of magmatism and metamorphism

The Burro Mountain granite was mapped as a large coherent pluton, but it was unclear whether or not the entire intrusion was coeval. All three of the samples from the Burro Mountain granite yield the same age within error, with a combined date of 1457 ± 4 Ma. This is the same age as the rapakivi granite and minette from the Redrock area and suggests that the major phase of magmatism in the Burro Mountains occurred at approximately 1460 Ma. The age of the Burro Mountain granite was suspected to be around 1.45 Ga, based on a traditional thermal ionization zircon date (Stacey and Hedlund, 1983), but these ages can be suspect if the magmatic zircons contain older, inherited cores. We did find some evidence of older cores in the samples studied, but SHRIMP analysis allowed us to focus on the magmatic ages and exclude the older cores.

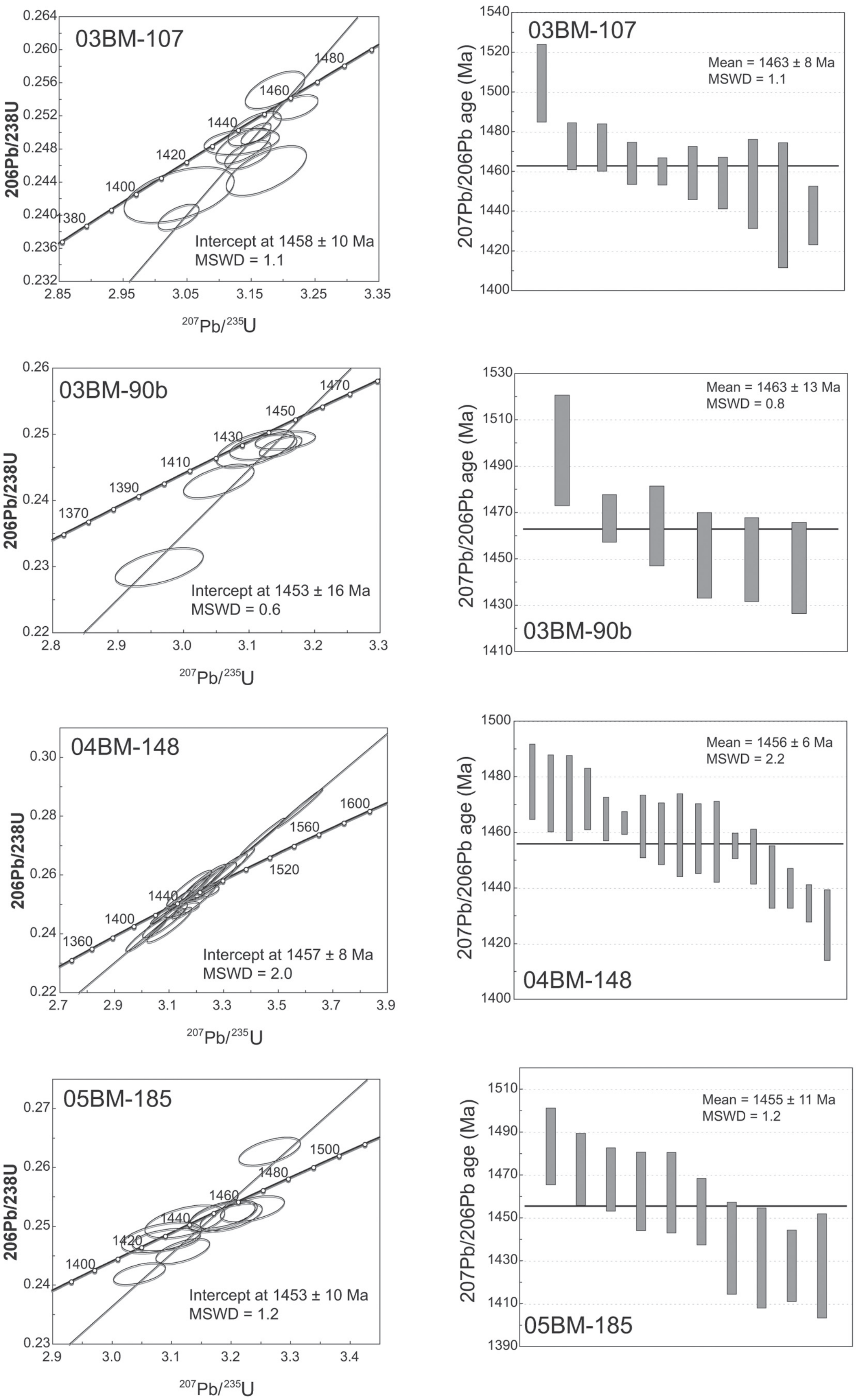

FIGURE 4. U-Pb concordia and weighted mean plots four samples of the Burro Mountain granite. The weighted mean of all of the combined data is 1457 ± 4 Ma (MSWD=1.5).

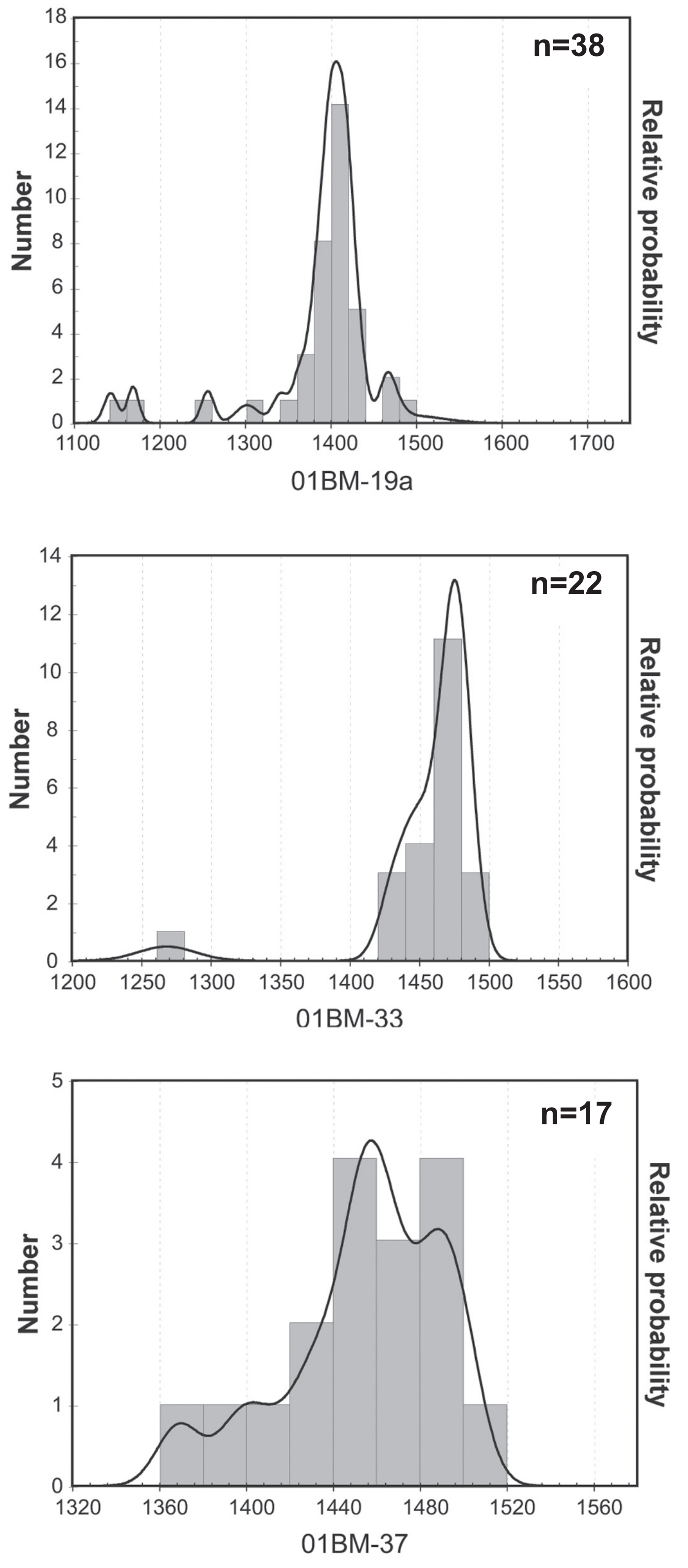

FIGURE 5. U-Pb weighted mean plots from electron microprobe dating of monazite from metasedimentary rocks. Each analysis represents a single spot on a monazite grain, and several grains were analyzed per sample.

The timing of metamorphism of the metasedimentary rocks associated with the 1.65 Ga thermal and deformational event was obscured by the high temperatures achieved during the large magmatic event at 1.46 Ga. It was known that $^{40}Ar/^{39}Ar$ dates were regionally and locally reset during ~1.4 Ga magmatism (Shaw et al., 2005; Amato et al., 2006), but our study of the U-Pb ages of metamorphic monazite indicates that monazite was also reset during this event. The closure temperature of monazite is controversial, but most studies suggest it is in excess of 600 °C and possibly as high as 725 °C (Parrish, 1990).

Origin of the foliation in 1.46 Ga intrusions

The identification of deformational versus flow fabrics in plutonic rocks is important to establish tectonic setting and timing of deformation in a region. Deformational fabrics in plutons are commonly associated with pre- or syn-tectonic plutons and show foliation patterns reflecting regional strain patterns. In the absence of regional strain, foliations reflect magma flow associated with intrusion (Paterson et al., 1989). The criteria applicable to observations made in the Burro Mountains include: (1) foliations developed from deformation of minerals versus foliations developed from preferential orientation of undeformed minerals; (2) differences in regional fabric intensity between deformational and flow fabric bearing units; and (3) differences in regional foliation strikes and dips, focusing on areas where units with different fabrics are in direct contact. The main criteria for identifying magmatic flow is the presence of a preferred orientation of primary igneous minerals, such as feldspar, biotite, and hornblende, that have no evidence of plastic deformation or recrystallization. General intensities for flow fabrics can range from strongly foliated with visually gneissic textures to extremely weakly foliated. Intensities are generally highly variable and inconsistent within a flow-fabric bearing pluton. The intensity of a magmatic foliation generally increases towards the external edge of the pluton margin (Frost and Mahood, 1987; Paterson et al., 1989). In contrast, deformational fabric intensities are more likely to be regionally consistent. Recrystallization following deformation can occur when post-tectonic heating affects a deformed pluton. However, in these cases strained minerals typically recrystallize to unstrained shapes, but foliations and gneissic fabrics are retained.

The ~1.6 Ga country rock has a pervasive deformational fabric that was generated before the 1.63 Ga gabbro intrusion. Both igneous and metasedimentary protoliths share this foliation. The 1.46 Ga igneous rocks, however, are not pervasively deformed, and the foliations are only locally present, particularly adjacent to contacts. In the Burro Mountain granite, biotite is aligned, but quartz and K-feldspar are randomly oriented and show no evidence of strain. Both the map-scale and microscopic observations point to the fabric in the 1.46 Ga igneous rocks being developed during intrusion, not during regional strain. Whether this fabric was created during ballooning or shearing during intrusion is unclear, but the decrease in fabric intensity away from the contact with the country rock argues strongly for a flow foliation interpretation.

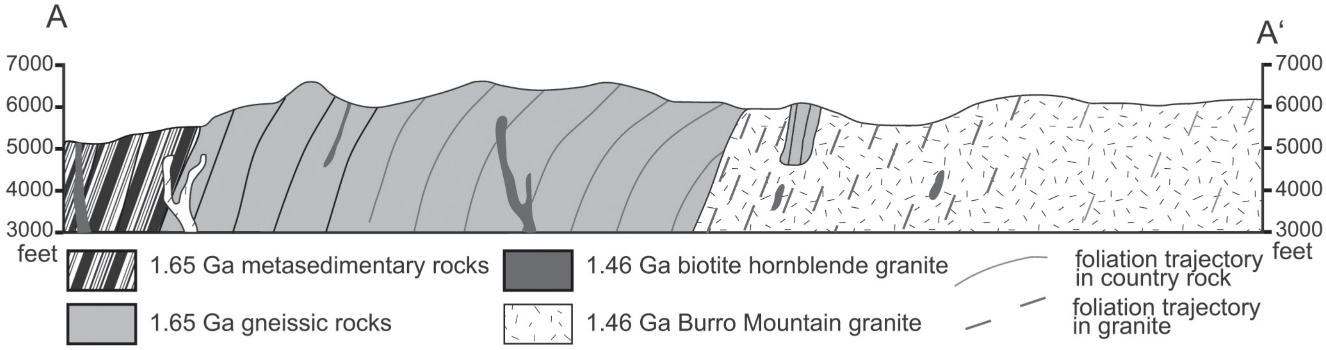

FIGURE 6. Schematic cross-section across the contact between the country rock and the Burro Mountain granite, showing foliation trends in each unit. No vertical exaggeration. After Boullion (2006). Line of section shown in Figure 2.

Several observations suggest that the fabric in the biotite hornblende granite is directly related to intrusion of the Burro Mountain granite and not regional strain: (1) the weak to moderate nature of the fabric; (2) preferential fabric development in the biotite hornblende granite at or near contact with the Burro Mountain granite; and (3) orientation of the older deformational foliations paralleling the flow fabric of the Burro Mountain granite. It is known from cross-cutting relationships that the intrusion of the biotite hornblende granite predates intrusion of the Burro Mountain granite. However, geochronology shows that these plutons are approximately coeval. Deformation in the biotite hornblende granite suggests that this intrusion was likely near its sub-solidus temperature and significantly hotter than the wall rocks. The biotite hornblende granite likely experienced solid-state deformation near contacts with the granite at elevated temperatures. The crystallized margins of some plutons can record regional strain while the cores do not, but in this case the foliated margins are adjacent to the younger pluton. Therefore we ascribe the foliation development to the subsequent intrusions.

REGIONAL TECTONIC IMPLICATIONS

The controversy over the tectonic setting of the ~1.4 Ga granites of North America is whether they were intruded during active tectonism (e.g., Kirby et al., 1995) or whether they were passively emplaced (e.g., Anderson, 1983). In New Mexico, plutons reported to be syntectonic lie north of a line around the city of Socorro, whereas ~1.4 Ga plutons south of this latitude were reported as undeformed (Fig. 7). The 1.46 Ga intrusions in the Burro Mountains do contain a fabric, but we ascribe this fabric to magmatic processes and not tectonism. Future work on this problem should concentrate on (1) whether the fabric in some of the granites reported as deformed could be magmatic; (2) whether the deformed ~1.4 Ga granites are located in specific areas; and (3) whether tectonism was limited to specific times within the long duration of the 1.48–1.34 Ga event.

The timing of ~1.4 Ga magmatism in southern New Mexico is now known to have occurred at 1.46 Ga and there is little evidence to suggest it was a protracted event, at least in the Burro Mountains area. The voluminous magmatism resulted in high heat flow that reset the U-Pb ages in metamorphic monazite in the metasedimentary rocks, as well as the $^{40}Ar/^{39}Ar$ ages of in minerals with closure temperatures as high as 550 °C, such as hornblende (Amato et al., 2006). Monazite U-Pb ages are very similar to the ages of igneous intrusion, indicating that magmatism was the heat source for high-temperature metamorphism.

Cross-cutting relationships and our new U-Pb date of 1460 Ma for the amphibolite from the Burro Mountains suggests that the amphibolite protolith either intruded or was erupted around 1.65 Ga and experienced zircon growth during the thermal event at 1.46 Ga. The textures in the zircons do not indicate that the amphibolite was generated as part of the 1.46 Ga magmatic event. We suggest that most, if not all, of the amphibolites in the southern Mazatzal province are also ~1.65 Ga in age. U-Pb dating of metamorphic zircon in mafic rocks can be a valuable tool for estimating the timing of high temperature metamorphism.

The interpretation of the fabrics in the igneous rocks as magmatically generated indicates that the main deformational event in the Burro Mountains occurred during the 1.65 Ga Mazatzal orogeny, and that locally the 1.46 Ga event was not associated with tectonically induced deformation. The implications of these observations are that 1.65 metamorphism was dynamic and regional, but that the 1.46 Ga metamorphism was static and resulted in mainly recrystallization of the existing metamorphic rocks. Ongoing studies of the P and T conditions of metamorphism in southern New Mexico will benefit from these observations.

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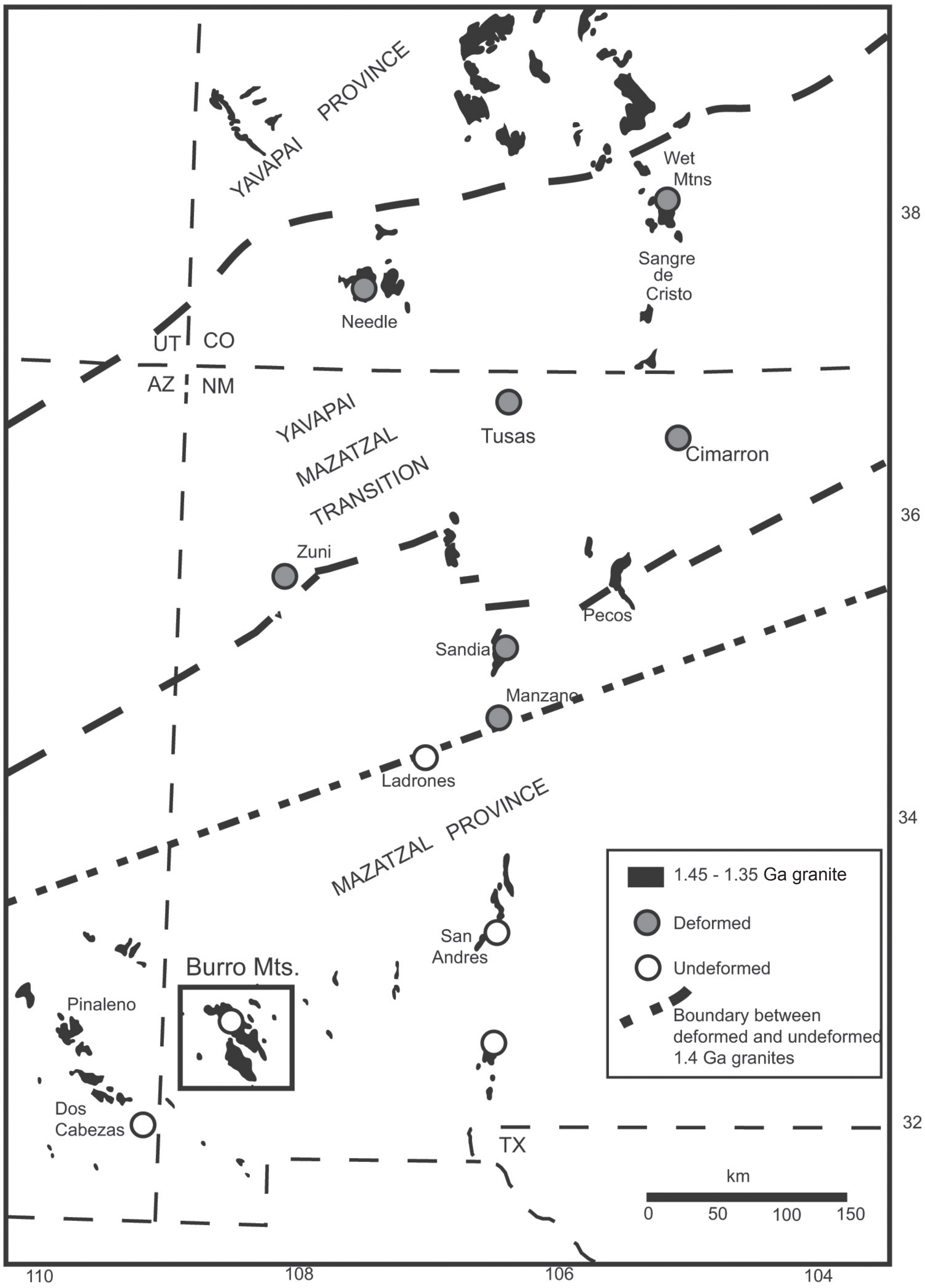

FIGURE 7. Distribution of deformed and undeformed 1.4 Ga granite plutons in Colorado, Arizona, and New Mexico. Dashed line delineates boundary between deformed and undeformed granites. Base map from Karlstrom et al. (2004).

Rancher, Tim Coates, generously provided access to his ranch in the Burro Mountains. Adam Read and Greg Mack provided thorough reviews.

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