Proterozoic rocks of the Caballo Mountains and Kingston mining district: U-Pb geochronology and correlations within the Mazatal province of southern New Mexico

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PROTEROZOIC ROCKS OF THE CABALLO MOUNTAINS AND KINGSTON MINING DISTRICT: U-PB GEOCHRONOLOGY AND CORRELATIONS WITHIN THE MAZATZAL PROVINCE OF SOUTHERN NEW MEXICO

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Abstract—Basement rocks of the Caballo Mountains and Kingston mining district of south-central New Mexico are Proterozoic in age based on their exposure beneath a nonconformity with overlying Cambro-Ordovician Bliss sandstone. We used SHRIMP (sensitive high-resolution ion microprobe dating) to obtain U-Pb dates on zircon from four samples of igneous or metaigneous basement. A sample of foliated gneissic biotite granite from the Caballo Mountains yielded a date of 1681 ± 12 Ma (all uncertainties are at 2σ). Two undeformed samples from the Caballo Mountains include the Longbottom pluton, dated at 1486 ± 16 Ma, and the Caballo granite with an age of 1487 ± 24 Ma. A granophyre from the Kingston district yielded a date of 1654 ± 15 Ma. The two samples older than 1650 Ma are similar in age to other Mazatzal province basement that forms the country rock for the >1.4 Ga granites that are widespread throughout New Mexico. The samples from the Caballo Mountains are among the oldest granites that are part of the continent-wide ~1.4 Ga granite-rhyolite province. These data demonstrate the similarity of lithology and age of the Proterozoic basement of the Caballo Mountains and Kingston Mining District to other exposures of Proterozoic rocks in southern New Mexico such as the Burro Mountains of southwest New Mexico.

INTRODUCTION

Proterozoic rocks of southern New Mexico are generally exposed as relatively small outcrops along the base of uplifted fault blocks along the Rio Grande Rift, in the central part of the state, or within the Basin and Range province in the southwest New Mexico (Fig. 1). As part of an ongoing effort to understand the Proterozoic evolution of the region, we sampled and obtained U-Pb ages from two areas near Truth or Consequences, New Mexico. The Caballo Mountains of south-central New Mexico are an east-tilted normal fault block within the Rio Grande rift that exposes Proterozoic rocks along its west flank. These rocks are overlain by a Paleozoic section with the Cambrian-Ordovician Bliss Sandstone at its base. The geology of this area was previously mapped by Darton (1922), Kelley and Silver (1952), and Seager and Mack (2003) whose comprehensive treatment of the geology of the range highlighted the lack of isotopic ages of the Proterozoic basement. The only preexisting date was an unreliable and imprecise whole-rock Rb-Sr isochron age of ~1300 Ma (Muehlberger et al., 1966). The Kingston mining district is located west of the Rio Grande rift in the Black Range, where Proterozoic rocks are also overlain by the Bliss Sandstone. No ages are known to have been published from the basement rocks of this range.

The goal of this paper is to provide new U-Pb dates on the Proterozoic basement and to compare them to the ages of other Proterozoic rocks in southern New Mexico from surrounding ranges, including the Burro Mountains and Little Hatchet Mountains of southwest New Mexico (Amato et al., 2008, 2011; Amato and Mack, in press).

For this study we used primarily U-Pb zircon dates obtained by SHRIMP (Sensitive High-Resolution Ion Microprobe). Despite relatively low precision, these dates provide a framework for interpreting the history of the basement rocks and correlating these magmatic episodes to other events known from more extensively studied ranges.

REGIONAL GEOLOGY

The Caballo Mountains and Kingston mining district areas are part of the Mazatzal province that consists of igneous basement

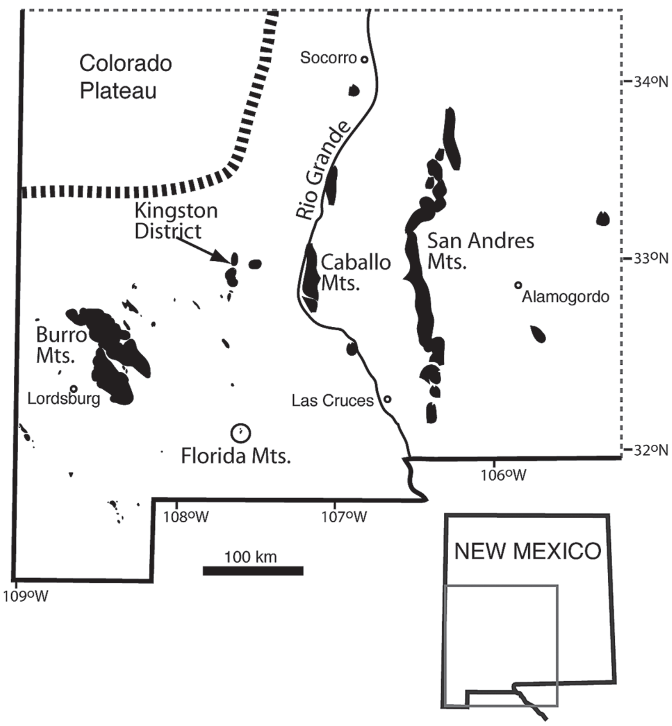

FIGURE 1. Map of southwestern New Mexico showing the distribution of Proterozoic rocks and the location of the study areas. Modified from Amato et al. (2008).

of likely arc origin that range in age from 1.7-1.6 Ga and have juvenile isotopic geochemical signatures (Karlstrom et al., 2004). The Mazatzal orogeny began around 1.65 Ga and records the accretion of the Mazatzal province to the Yavapai province along a NE-trending suture near the New Mexico-Colorado border (Karlstrom and Bowring, 1988; Amato et al., 2008). Rock types within the largest exposure of Mazatzal province crust in southern New Mexico, in the Burro Mountains, include amphibolite, gabbro, orthogneiss, metarhyolite, and metasedimentary rocks including schist and quartzite (Amato et al., 2008; 2011).

Granitic plutons and rhyolites ranging in age from 1490–1340 Ma are found in a wide belt across North America and have been referred to as "A-type" granites, but they are better described using the non-genetic term "ferroan" granites based on their FeO/(FeO+MgO) (Anderson, 1989; Frost et al., 2001; Anderson and Morrison, 2005; Amato et al., 2011). Many of these plutons are described as anorogenic, but in the southwest U.S., numerous plutons have fabrics indicating syntectonic intrusion, possibly related to an orogenic event at the nearby Laurentian margin to the south (Nyman et al., 1994; Duebendorfer and Christensen, 1995; Kirby et al., 1995; Amato et al., 2011). In the Burro Mountains, variably deformed granodiorite and granite plutons yielded 1470–1460 Ma ages (Amato et al., 2011).

Evidence for the Grenville orogeny to the south comes mainly from igneous events with ages around 1.2 Ga in the Van Horn, Texas, region (Bickford et al., 2000) and in the Burro Mountains (Rämö et al., 2003), and a 1080 Ma granite in the Little Hatchet Mountains (Amato and Mack, in press). Proterozoic diabase dikes inferred to be part of a 1.1 Ga dike swarm are exposed both west of the Caballo Mountains, in the Burro Mountains (e.g., Hedlund, 1980), and to the south, in the southern San Andres Mountains (Seager, 1981). Younger tectonic events relevant to interpreting the fabrics include the Grenville orogeny, the Laramide orogeny, and Paleogene magmatism and extension.

Proterozoic Rocks of the Caballo Mountains

Previous mapping in the Caballo Mountains has documented metamorphic rocks and four silicic plutons underlying the nonconformity with Paleozoic rocks (Bauer and Lozinsky, 1986; Seager and Mack, 2003). The metamorphic rocks include amphibolite-facies schists, amphibolite, and felsic orthogneiss. Amphibolite is interlayered with schists and is strongly deformed with a foliation, lineation, and boudinage (Bauer and Lozinsky, 1986; Seager and Mack, 2003). In the Burro Mountains, amphibolite was dated at ~1.68 Ga.

The Proterozoic rocks in the Caballo Mountains (Fig. 2) include the Longbottom granodiorite, the Caballo granite, a coarse-grained pink granite, and a gneissic granite, along with numerous granitic dikes (Bauer and Lozinsky, 1986; Mack et al., 1998; Seager and Mack, 2003, 2005). The Caballo granite is the largest of these plutons, with a map outcrop length of ~20 km (Seager and Mack, 2003). The Longbottom granodiorite of Bauer and Lozinsky (1986) has large K-feldspar crystals and xenoliths aligned as the result of magmatic flow (Seager and Mack, 2003).

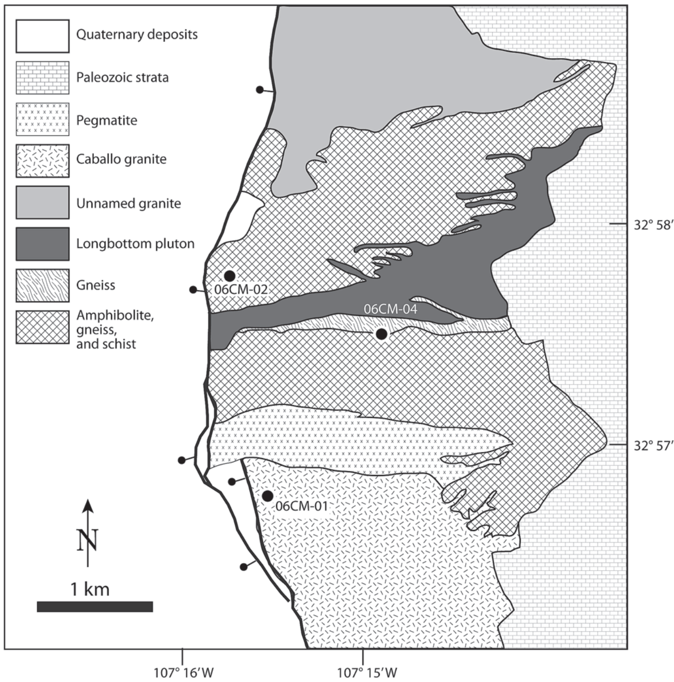

FIGURE 2. Simplified geologic map of the Proterozoic rocks and adjacent units in the Caballo Mountains. Small granite dikes and Quaternary deposits overlying Proterozoic exposures are not shown. Sample localities are shown. See Table 1 for geochronology data. Modified from Mack and Seager (1998).

The abundance of K-feldspar in some of the exposures indicates a granite composition based on the Quartz-Alkali Feldpar-Plagioclase diagram, so we prefer the term "Longbottom pluton" to reflect the compositional heterogeneity.

Proterozoic Rocks of the Kingston Mining District

The Kingston region of the Black Range of central New Mexico is located ~40 km due west of the Caballo Mountains, where Proterozoic rocks are exposed west of the Rio Grande rift. The area was mapped by Kuelmmer (1954), Lambert (1973), Hedlund (1977), and Seager (written communication, 2009). The Proterozoic rocks are overlain by Cambrian-Ordovician Bliss Sandstone and younger Paleozoic rocks. Granites are associated with metamorphic rocks that includes amphibolite, chlorite schist, and gneiss (Hedlund, 1977). A granophyre 4 km south of our study area yielded a U-Pb date (two-point concordia intercept age) of 1655 ± 15 Ma (Stacey and Hedlund, 1983).

METHODS

U-Pb geochronology was carried out using the SHRIMP-RG (sensitive high-resolution ion microprobe reverse geometry) at the Stanford–U.S. Geological Survey Ion Probe Facility. Beam diameter was 30 mm. All errors reported in the text are at 2σ. Details of the SHRIMP methods are in Amato et al. (2008). "Best age" refers to the most reliable age with the lowest uncertainty, and choosing which age as "best" depends on how discordant the analyses are for each sample. Individual analyses may not be included in the weighted mean calculations if they are likely related to Pb-loss or significant (>30%) discordance. Cathodoluminescence (CL) images were obtained from all samples.

SAMPLES DATED

Four samples were dated for this study; three from the Caballo Mountains and one from the Kingston mining district. The first sample is a gneissic granite (06CM-02). It has an igneous protolith based on texture and assemblage (Fig. 3A). Equant quartz and microcline grains are present in roughly equal proportions, and equant plagioclase grains are slightly less abundant. The strong foliation is made up of alternating wispy bands of biotite and Fe-Ti oxides alternating with quartz and feldspar. The color index is about 10-15. Accessory minerals visible in thin section include sphene, apatite, and abundant zircon.

The second sample is the coarse-grained Longbottom pluton (06CM-04). It has microcline crystals up to 2 cm in length with exsolution lamellae, plagioclase, and quartz (Fig. 3B). The abundance of K-feldspar likely makes it an alkali-feldspar granite, but modal analysis was not performed. Biotite is present in extremely low proportions (<5%), making the sample a leucogranite.

The third sample (06CM-01) analyzed is a medium- to fine-grained granite that is part of the Caballo granite pluton, with roughly equal proportions of K-feldspar with exsolution lamellae, plagioclase, and quartz (Fig. 3C). Biotite is the most abundant mafic mineral, with hornblende, sphene, Fe-Ti oxides, and epidote.

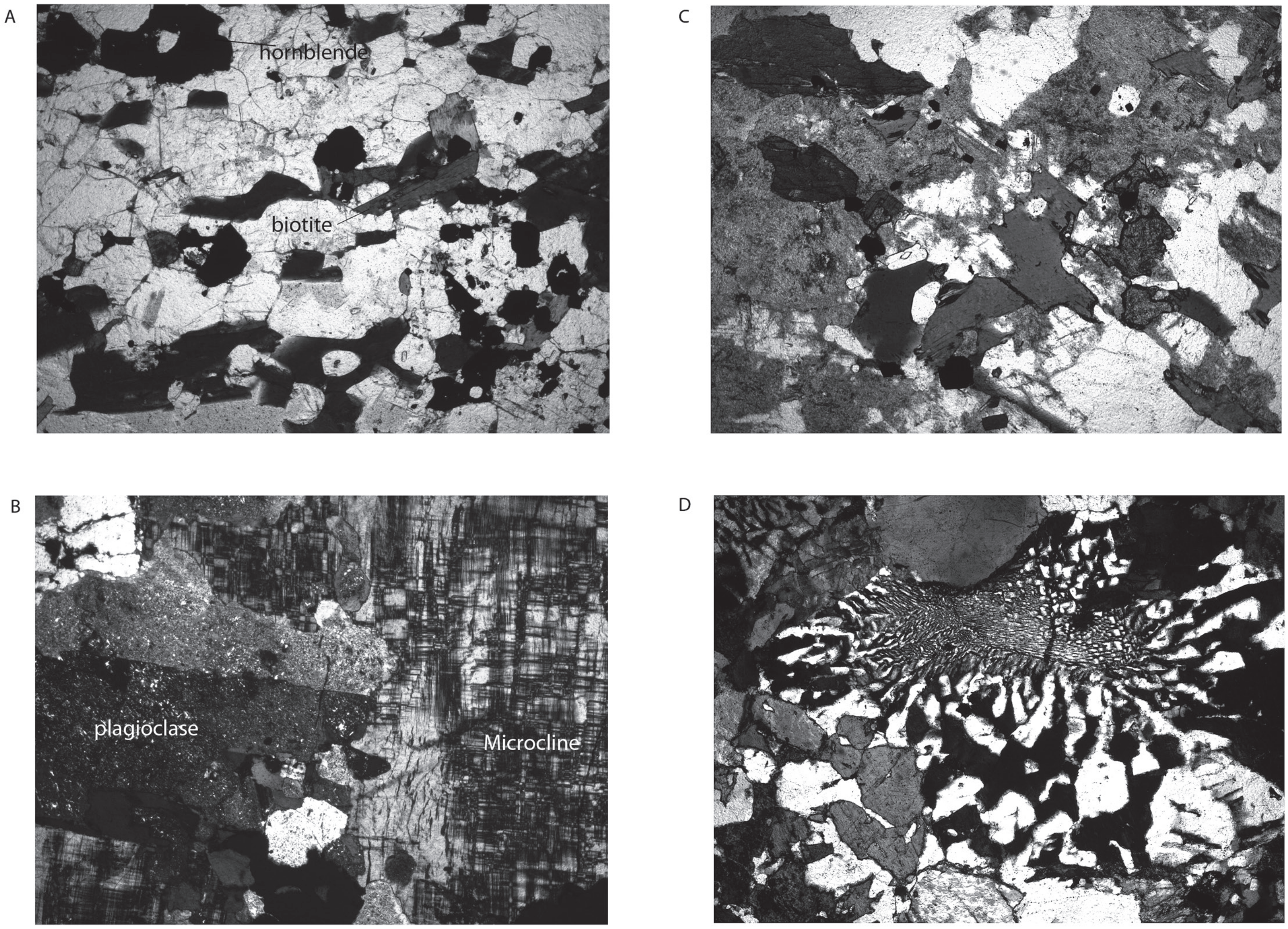

FIGURE 3. Photomicrographs from the dated samples; width of each image is approximately 1 mm. (A) Sample 06CM-02, gneiss from Caballo Mountains., plane light, dark minerals are biotite, light minerals quartz and feldspar; (B) Sample 06CM-04, Longbottom granite from Caballo Mountains., crossed polars, large mineral on the right is microcline with tartan twinning, mineral on center left is plagioclase, white minerals are quartz; (C) Sample 06CM-01, Caballo granite, plane light, biotite is the dark mineral in the center of the image, hornblende is the green mineral at upper left, and the cloudy minerals are altered plagioclase, clear colorless mineral is quartz; and (D) 06KD-02, granophyre from the Kingstone District, showing granophyric intergrowth of quartz (light) in K-feldspar (extinct in crossed polars).

The sample from the Kingston mining district was collected from a locality ~4 km due north of the town of Kingston. The rock is an alkali-feldspar granite with granophyric texture (i.e., granophyre) and it has extensive intergrowths of K-feldspar and quartz with exsolution lamellae in the K-feldspar (Fig. 3D). Also present is minor plagioclase, biotite altered to chlorite, and zircon.

GEOCHRONOLOGY RESULTS

Eight U-Pb dates from the gneissic granite (06CM-02) were obtained (Fig. 4, Table 1). Zircons are euhedral, 100–200 µm in length, have oscillatory zonation and no observed xenocrystic cores in CL images. The zircons had U concentrations ranging from ~150-500 ppm. One of the analyses was discordant with a low $^{238}U/^{206}Pb$ age relative to its $^{235}U/^{207}Pb$ age, so this was not used in the final age calculation. The weighted mean $^{207}Pb/^{206}Pb$ age of the remaining analyses is 1674 ± 16 Ma with a mean square weighted deviates (MSWD) of 1.8. The concordia upper intercept age, using all of the data, is 1681 ± 12 Ma (MSWD=1.3). The lower intercept age is 200 ± 77 Ma. We consider 1681 ± 12 Ma to be the best age.

The Longbottom pluton (sample 06CM-04) was analyzed for ten zircon ages (Table 1). Zircons have strongly metamict cores with oscillatory zonation in the rim areas. The cores do not appear to be xenocrystic, but instead have radiation damage related to high U concentrations as determined by dark areas on CL images. Several of these analyses had high common Pb, and all points were discordant with high uncertainties. U concentrations were ~500-2000 ppm. The weighted mean $^{207}Pb/^{206}Pb$ age of the best eight analyses is 1466 ± 21 Ma (MSWD=2.1). The concordia upper intercept age is 1486 ± 16 Ma (MSWD=1.1) and the lower intercept is 112 ± 39 Ma. We consider 1486 ± 16 Ma to be the best age.

The Caballo granite (06CM-01) has zircons that are euhedral, 100–200 µm in length, have oscillatory zonation, and have no observed xenocrystic cores in CL images. Fifteen zircons have U concentrations of 300-1000 ppm and all analyses are discordant (Table 1). Several of these analyses had high common Pb concentrations. The weighted mean $^{207}Pb/^{206}Pb$ age of the best 12 analyses is 1449 ± 13 Ma (MSWD=2.1). The concordia upper intercept age, using all analyses, is 1487 ± 24 Ma (MSWD=1.9). The lower intercept age is 161 ± 64 Ma. We consider 1487 ± 24 Ma to be the best age because of the discordance.

We dated eight zircons from the Kingston granite, sample 06KD-02 (Table 1). Zircons are euhedral, 50-150 µm long, have oscillatory zonation, and no obvious xenocrystic cores. They had low U concentrations (~75-300 ppm) and the analyses were all concordant except one that was slightly discordant. All had fairly large uncertainties. The weighted mean $^{207}Pb/^{206}Pb$ age is 1654 ± 15 (MSWD=0.55) and the concordia upper intercept age is 1659 ± 25 Ma (MSWD=0.58). We consider 1654 ± 15 Ma to be the best age for this sample.

DISCUSSION

The range of ages in this study is consistent with the ages of other previously dated Proterozoic rocks in southern New Mexico. The two oldest ages are gneisses. The sample from the Caballo Mountains at 1681 ± 12 Ma and the sample from Kingston at 1654 ± 15 Ma overlap within error. These are slightly older than metaigneous rocks from the Florida Mountains at 1623 ± 18 Ma and from the Burro Mountains, where gabbro and granite gneiss are both ~1630 Ma (Amato et al., 2011). In the San Andres Mountains, gneisses range in age from ~1675–1630 Ma (Amato et al., 2008). All of these rocks are part of the Mazatzal province basement. Because all of these samples are pervasively deformed, and because the ~1.4 Ga rocks intruding them are only locally deformed, the main phase of deformation probably occurred during the Mazatzal orogeny sometime after 1630 Ma but before the ~1.4 Ga granites. Regionally, the Mazatzal orogeny is thought to have ended by ~1600 Ma (Karlstrom et al., 2004; Luther et al., 2006)

The remaining samples are part of the ~1.4 Ga granite-rhyolite province. In the Caballo Mountains, the two samples are 1486 ± 16 Ma and 1487 ± 24 Ma. Despite large uncertainties, the data are consistent with both intrusions having been intruded during the same intrusive episode. A similar relationship was observed in the Burro Mountains, where plutonic rocks with different compositions and textures were intruded within ~7 m.y. of each other (Amato et al., in press).

Critical questions remain concerning the age (or ages) of metamorphism within Proterozoic metasedimentary rocks. In the Burro Mountains, the main episode of metamorphism was inferred to be coeval with 1.46 Ga magmatism (Amato et al., 2011). Evaluating the timing and age of any pre-1.4 Ga metamorphism is difficult given the widespread heating of the crust during 1.4 Ga magmatism. Nonetheless, areas with exposed Proterozoic metasedimentary rocks, regardless of their outcrop volume, should be evaluated carefully to determine the crustal conditions at the time of metamorphism.

CONCLUSIONS

The four samples from this study include two samples at 1.68-1.65 Ga and two samples at 1.48–1.45 Ga. The older samples are part of the Mazatzal province and the younger two are part of the ~1.4 granite-rhyolite province. These are the first radiometric ages from Proterozoic rocks in the Caballo Mountains and Kingston mining district and the data indicate that the basement in these areas in the Rio Grande Rift have a history similar to that of other Proterozoic rocks of southern New Mexico.

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The SHRIMP data were collected at the Stanford/U.S.G.S. facility at Stanford University and made possible by Joe Wooden.

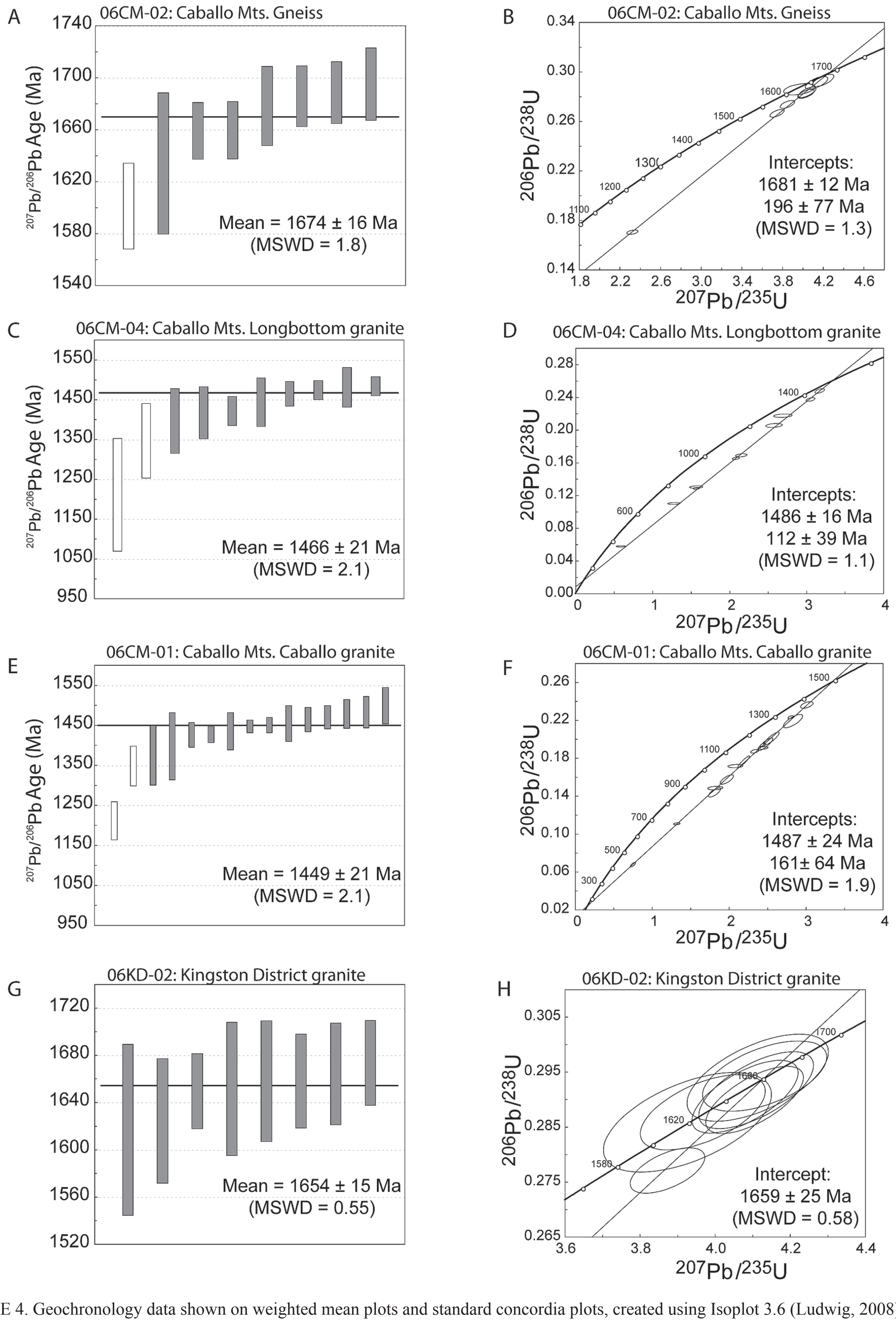

FIGURE 4. Geochronology data shown on weighted mean plots and standard concordia plots, created using Isoplot 3.6 (Ludwig, 2008).

TABLE 1. Complete U-Pb zircon data collected by SHRIMP.

Spot[a]	% comm ^{206}Pb[b]	U (ppm)	Th (ppm)	Th/U	$^{207}Pb^{c}/^{235}U$	% err	$^{206}Pb^{c}/^{238}U$	% err	err corr.[c]	$^{207}Pb^{d}/^{206}Pb$	% err	$^{206}Pb/^{238}U$ age (Ma)	± 1s (Ma)	$^{207}Pb/^{206}Pb$ age (Ma)[e]	± 1s (Ma)	%conc.[f]
06CM-02: Caballo Mountains gneiss (13, 288588, 3649171)																
7	0.52	491	254	0.52	2.32	1.0	0.1705	0.4	0.424	0.0988	0.9	987	4	1601	16	62
6	1.13	186	203	1.09	3.96	1.6	0.2860	0.6	0.407	0.1005	1.5	1620	10	1634	27	99
8	0.08	343	132	0.38	3.75	0.8	0.2666	0.5	0.633	0.1019	0.6	1512	7	1659	11	91
5	0.10	340	202	0.59	3.85	0.8	0.2738	0.5	0.622	0.1019	0.6	1551	7	1659	11	93
4	0.06	149	52	0.35	4.13	1.1	0.2913	0.7	0.661	0.1029	0.8	1645	12	1678	15	98
2	0.07	238	203	0.85	4.04	0.9	0.2835	0.6	0.699	0.1034	0.6	1602	10	1685	12	95
1	0.09	297	40	0.13	4.03	0.8	0.2823	0.5	0.628	0.1035	0.6	1595	8	1688	12	94
3	0.02	163	76	0.47	4.20	1.0	0.2932	0.7	0.678	0.1039	0.8	1653	11	1695	14	98
06CM-04: Caballo Mountains Longbottom granite (13, 289799, 3648809)																
9	4.46	2097	196	0.09	0.64	3.7	0.0580	0.6	0.155	0.0806	3.6	352	2	1211	71	29
5	4.37	1133	186	0.16	1.32	2.5	0.1106	0.4	0.152	0.0864	2.4	658	2	1348	47	49
10	3.49	692	102	0.15	1.60	2.2	0.1308	0.4	0.206	0.0887	2.1	772	3	1398	41	55
8	1.24	745	139	0.19	2.70	1.8	0.2183	0.4	0.217	0.0897	1.7	1264	5	1419	33	89
4	0.91	1023	121	0.12	1.60	1.0	0.1292	0.3	0.329	0.0899	1.0	762	2	1423	18	54
3	3.28	523	88	0.17	2.59	1.7	0.2063	0.5	0.284	0.0909	1.6	1195	5	1445	31	83
6	0.84	1076	199	0.19	2.10	0.9	0.1659	0.4	0.414	0.0919	0.8	968	3	1466	15	66
7	0.09	446	90	0.20	3.17	0.8	0.2486	0.5	0.581	0.0924	0.6	1428	6	1475	12	97
2	3.49	812	120	0.15	2.17	1.4	0.1697	0.5	0.326	0.0927	1.3	987	4	1483	25	67
1	0.79	722	82	0.11	3.05	0.7	0.2382	0.4	0.527	0.0929	0.6	1369	5	1485	12	92
06CM-01: Caballo Mountains Caballo granite (13, 288863, 3647322)																
9	3.39	933	804	0.86	0.75	1.8	0.0679	1.4	0.751	0.0806	1.2	410	5	1213	24	34
8	1.25	910	644	0.71	1.32	1.3	0.1109	0.4	0.307	0.0864	1.3	659	3	1348	25	49
7	4.72	1061	474	0.45	2.08	1.9	0.1718	0.4	0.184	0.0877	1.9	1005	3	1375	37	73
4	0.59	628	584	0.93	1.82	2.2	0.1486	0.5	0.216	0.0887	2.2	873	4	1397	42	63
6	0.53	671	492	0.73	2.33	0.9	0.1874	0.4	0.478	0.0900	0.8	1091	5	1425	15	77
11	2.07	710	463	0.65	2.19	1.4	0.1765	1.4	0.933	0.0900	0.5	1029	13	1426	10	72
14	3.76	1050	647	0.62	1.97	1.8	0.1576	1.3	0.745	0.0904	1.2	922	12	1434	23	64
1	0.03	865	678	0.78	2.80	0.5	0.2234	0.3	0.614	0.0910	0.4	1290	4	1447	8	89
5	0.14	956	759	0.79	2.44	0.6	0.1941	0.4	0.590	0.0911	0.5	1127	4	1449	10	78
13	3.76	752	551	0.73	1.81	1.8	0.1440	1.4	0.757	0.0913	1.2	843	11	1454	22	58
12	2.32	654	455	0.70	2.47	1.6	0.1948	1.4	0.865	0.0918	0.8	1129	15	1463	15	77
15	1.89	452	258	0.57	2.55	1.6	0.2008	1.4	0.878	0.0921	0.7	1163	15	1469	14	79
3	0.25	309	195	0.63	3.01	1.1	0.2363	0.6	0.549	0.0925	0.9	1359	8	1477	18	92
2	1.47	853	523	0.61	2.44	1.1	0.1909	0.3	0.298	0.0927	1.0	1107	3	1482	19	75
16	4.81	979	837	0.86	2.83	1.8	0.2193	1.3	0.748	0.0935	1.2	1263	16	1497	23	84
06KD-02: Kingston Mining District gneiss (13, 245990, 3648969)																
3	0.19	70	25	0.36	3.93	2.3	0.2859	1.3	0.555	0.0996	1.9	1621	21	1617	36	100
4	0.25	128	66	0.52	3.97	1.7	0.2877	1.0	0.567	0.1000	1.4	1631	15	1624	26	100
8	0.72	325	179	0.55	3.87	1.0	0.2771	0.6	0.580	0.1014	0.9	1570	9	1649	16	95
5	0.15	99	37	0.37	4.11	1.9	0.2940	1.1	0.588	0.1015	1.5	1662	18	1651	28	101
1	0.08	152	67	0.44	4.13	1.6	0.2943	0.9	0.542	0.1018	1.4	1663	14	1658	25	100
6	0.20	138	61	0.44	4.08	1.4	0.2905	0.9	0.657	0.1018	1.1	1643	15	1658	20	99
7	0.19	123	58	0.47	4.11	1.5	0.2917	1.0	0.646	0.1022	1.2	1649	16	1664	21	99
2	0.29	166	76	0.46	4.10	1.3	0.2899	0.9	0.666	0.1027	1.0	1638	14	1673	18	98

a) Analyses are listed in increasing age. All localities are in UTM coordinates using the NAD27 CONUS datum.

b) Common Pb component (%) of total ^{206}Pb, determined using measured ^{204}Pb

c) Error Correlation coefficient

d) Ratio was corrected for common Pb using measured ^{204}Pb

e) $^{207}Pb/^{206}Pb$ ages are not included for samples <300 Ma because of low precision

f) Concordance (%) = (^{206}Pb-^{238}U age)/(^{206}Pb-^{207}Pb age) *100

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REFERENCES

Amato, J.M., Boullion, A.O., Serna, A.M., Sanders, A.E., Farmer, G.L., Gehrels, G.E., and Wooden, J.L., 2008, The evolution of the Mazatzal province and the timing of the Mazatzal orogeny: Insights from U-Pb geochronology and geochemistry of igneous and metasedimentary rocks in southern New Mexico: Geological Society of America Bulletin, v. 120, p. 328-346.

Amato, J.M., Gaynor, S., Rioux, M., and Bowring, S.A., in press, Precise dating of the Burro Mountain granite and associated metamorphism, southern New Mexico: Syndeformational magmatism and rapid cooling of a gneiss dome (abstr.): Geological Society of America, Abstracts with Programs.

Amato, J.M., Heizler, M.T., Boullion, A.O., Sanders, A.E., Toro, J., McLemore, V.T., and Andronicos, C.L., 2011, Syntectonic 1.46 Ga magmatism and rapid cooling of a gneiss dome in the southern Mazatzal Province: Burro Mountains, New Mexico: Geological Society of America Bulletin, v. 123, p. 1720-1744.

Amato, J.M., and Mack, G.H., in press, Detrital zircon geochronology from the Cambrian-Ordovician Bliss Sandstone, New Mexico: Evidence for contrasting Grenville-age and Cambrian sources on opposite sides of the Transcontinental Arch (abstr.): Geological Society of America, Abstracts with Programs.

Anderson, J.L., 1989, Proterozoic anorogenic granites of the southwestern United States, *in* Jenney, J.P., and Reynolds, S.J., eds., Geologic Evolution of Arizona: Tucson, Arizona Geological Society Digest 17, p. 211-238.

Anderson, J.L., and Morrison, J., 2005, Ilmenite, magnetite, and peraluminous Mesoproterozoic anorogenic granites of Laurentia and Baltica: Lithos, v. 80, p. 45-60.

Bauer, P.W., and Lozinsky, R.P., 1986, Proterozoic geology of supracrustal and granitic rocks in the Caballo Mountains, southern New Mexico: N. M. Geological Society, 37th Field Conference Guidebook, p. 143-149.

Bickford, M.E., Soegaard, K., Nielsen, K.C., and McLelland, J.M., 2000, Geology and geochronology of Grenville-age rocks in the Van Horn and Franklin Mountains area, west Texas: Implications for the tectonic evolution of Laurentia during the Grenville: Geological Society of America Bulletin, v. 112, p. 1134-1148.

Darton, N.H., 1922, Geologic structure of parts of New Mexico: U.S. Geological Survey, Bulletin 726-E, p. 173-275.

Duebendorfer, E.M., and Christensen, C., 1995, Synkinematic(?) intrusion of the "anorogenic" 1425 Beer Bottle Pass pluton, southern Nevada: Tectonics, v. 14, p. 168-184.

Frost, B.R., Barnes, C.G., Collins, W.J., Arculus, R.J., Ellis, D.J., and Frost, C.D., 2001, A geochemical classification for granitic rocks: Journal of Petrology, v. 42, p. 2033-2048.

Hedlund, D.C., 1977, Geology of the Hillsboro and San Lorenzo Quadrangles, Sierra and Grant Counties, New Mexico: Reston, Virginia, U.S. Geological Survey, Miscellaneous Field Studies, Map MF-900A, scale 1:48,000.

Hedlund, D.C., 1980, Geologic map of the Redrock NE quadrangle, Grant County, New Mexico: Reston, Virginia, U.S. Geological Survey, Miscellaneous Field Studies Map MF-1264, scale 1:48,000.

Karlstrom, K.E., Amato, J.M., Williams, M.L., Heizler, M., Shaw, C.A., Read, A.S., and Bauer, P., 2004, Proterozoic tectonic evolution of the New Mexico region: A synthesis, *in* Mack, G.H., and Giles, K.A., eds., The Geology of New Mexico: A Geologic History:New Mexico Geological Society, Special Publication 11, p. 1-34.

Karlstrom, K.E., and Bowring, S.A., 1988, Early Proterozoic assembly of tectonostratigraphic terranes in southwestern North America: Journal of Geology, v. 96, p. 561-576.

Kelley, V.C., and Silver, C., 1952, Geology of the Caballo Mountains: Albuquerque, New Mexico, University of New Mexico Publications in Geology, no. 4, 286 p.

Kirby, E., Karlstrom, K.E., and Andronicos, C.L., 1995, Tectonic setting of the Sandia pluton: An orogenic 1.4 Ga granite in New Mexico: Tectonics, v. 14, p. 185-201.

Kuellmer, F.J., 1954, Geologic section of the Black Range at Kingston, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin, v. 33, p. 1-100.

Lambert, R.S., 1973, Geology of the country east of the Santa Rita mining district, Grant County, New Mexico–the San Lorenzo area [M.S. thesis]: Albuquerque, New Mexico, University of New Mexico.

Ludwig, K. R., 2003, Isoplot/Ex 3.00: A geochronological toolkit for Microsoft Excel: Berkeley, Berkeley Geochronology Center Special Publication 4, 70 p.

Luther, A.L., Jones, J.V., III, Shastri, L.L., Williams, M.L., Jercinovic, M., and Karlstrom, K.E., 2006, A new age of 1600 Ma for deposition of the Upper Manzano Group: Evidence for a progressive (1.66-1.60 Ga) Mazatzal orogeny, central New Mexico: New Mexico Geology, v. 28, p. 60.

Mack, G.H., Salyards, S.L., McIntosh, W.C., and Leeder, M.R., 1998, Reversal magnetostratigraphy and radioisotopic geochronology of the Plio-Pleistocene Camp Rice and Palomas Formations, southern Rio Grande rift:N. M. Geological Society, 49th Field Conference Guidebook, p. 229-336.

Muehlberger, W.R., Hedge, C.E., Denison, R.E., and Marvin, R.R., 1966, Geochronology of the mid-continent region, United States, part 3–southern areas: Journal of Geophysical Research, v. 71, p. 5409-5426.

Nyman, M.W., Karlstrom, K.E., Kirby, E., and Graubard, C.M., 1994, Mesoproterozoic contractional orogeny in western North America: Evidence from ca. 1.4 Ga plutons: Geology, v. 22, p. 901-904.

Rämö, O.T., McLemore, V.T., Hamilton, M.A., Kosunen, P.J., Heizler, M., and Haapala, I., 2003, Intermittent 1630-1220 Ma magmatism in central Mazatzal Province; new geochronologic piercing points and some tectonic implications: Geology, v. 31, p. 335-338.

Seager, W.R., 1981, Geology of Organ Mountains and southern San Andres Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 36, p. 97 p.

Seager, W.R., and Mack, G.H., 2003, Geology of the Caballo Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 49, p. 1-136.

Seager, W.R., and Mack, G.H., 2005, Geology of Caballo and Apache Gap quadrangles, Sierra County, New Mexico, New Mexico Bureau of Geology and Mineral Resources, Geologic Map 74, scale 1:24,000.

Stacey, J.S., and Hedlund, D.C., 1983, Lead-isotopic compositions of diverse igneous rocks and ore deposits from southwestern New Mexico and their implications for early Proterozoic crustal evolution in western United States: Geological Society of America Bulletin, v. 94, p. 43-57.

Bob Eveleth and Bob Osburn pose near a record (?) sized yucca, east side of Caballos. Time delay photograph by Bob Osburn.