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$^{40}Ar/^{39}Ar$ Geochronlogy of the Jones Camp Dike, central New Mexico: an eastward projection of the Magdalena Radial Dike Swarm from under the Oligocene Socorro-Magdalena Caldera Cluster

Richard M. Chamberlin, William C. McIntosh, and Lisa Peters
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$^{40}Ar/^{39}Ar$ GEOCHRONOLOGY OF THE JONES CAMP DIKE, CENTRAL NEW MEXICO: AN EASTWARD PROJECTION OF THE MAGDALENA RADIAL DIKE SWARM FROM UNDER THE OLIGOCENE SOCORRO-MAGDALENA CALDERA CLUSTER

RICHARD M. CHAMBERLIN, WILLIAM C. McINTOSH, AND LISA PETERS

New Mexico Bureau of Geology and Mineral Resources, Socorro NM 87801, richard@gis.nmt.edu

ABSTRACT—A new $^{40}Ar/^{39}Ar$ age determination of 28.88 ± 0.22 Ma for the ESE-trending, 16-km long Jones Camp dike confirms it is part of the large diameter Magdalena radial dike swarm (MRDS), which is broadly focused on the large volume (5,000 km^3) Socorro-Magdalena caldera cluster (SMCC; 32.3-24.5 Ma) of the early Rio Grande rift. Precise $^{40}Ar/^{39}Ar$ ages and near horizontal flow lineations indicate that long basaltic andesite dikes of the MRDS were driven outwards and upwards from an inferred lower crustal basaltic sill complex that presumably fueled the SMCC. Long dikes at Pie Town, Jones Camp and Elephant Butte, were driven outwards—to the north, east, and south— presumably during periods of high magma pressure prior to eruption of the large volume (1250 km^3) La Jencia Tuff from the Sawmill Canyon caldera. A rhyolite lava dome immediately under the La Jencia Tuff provides a precise age of pre-caldera tumescence at 28.91 ± 0.11 Ma, which is equivalent to the age of Jones Camp dike.

Locally exposed primary flow folds on the chilled margin of Jones Camp dike indicate the initial pulse of aphyric basaltic andesite magma was driven eastward at a shallow upward angle of about 25-30º, presumably along a deep penetrating Paleozoic shear zone of the Capitan lineament. From near Socorro, the east propagating subsurface trajectory of Jones Camp dike was about 50 km long and required about 5-10 km^3 of basaltic magma to fill a 10 m-wide dike (typical width of La Jencia-age dikes). We hypothesize that the inferred long trajectory of Jones Camp dike intersected a somewhat older and mostly crystalline hornblende-diorite pluton at depth in the Proterozoic basement under Chupadera Mesa. Minor volumes of the older hornblende diorite contaminated the initial pulse of basaltic andesite magma, now apparent in the form of small hornblende-diorite xenoliths in the margins of the dike and adjacent mafic sills. Shortly thereafter (ca. 10^1-10^3 years) a second and more forceful pulse of hybrid andesite magma mush carried abundant small to large xenoliths of coarse-grained hornblende diorite upward and re-inflated the still hot mafic core of the initial dike injection. A near horizontal paleomagnetic direction in a north dipping sill on the north flank of Jones Camp dike (determined in a previous thesis study) becomes coincident with the reverse paleomagnetic direction of the coeval La Jencia Tuff when 40º of northward tilt are removed from the sill. The mafic sill must have cooled quickly after the initial basaltic andesite dike injection that presumably fed the sill. The second pulse of hybrid andesitic magma injection then apparently domed the adjacent strata and pushed the sill up and away from the inflating core of the dike. The unusual width of Jones Camp dike (180 m) is attributed to its emplacement within incompetent evaporite beds of the Yeso Formation, which probably arrested the initial rise of the laterally propagating dike and later allowed it to mushroom outwards at the present level of exposure, about 1 km below the Oligocene land surface.

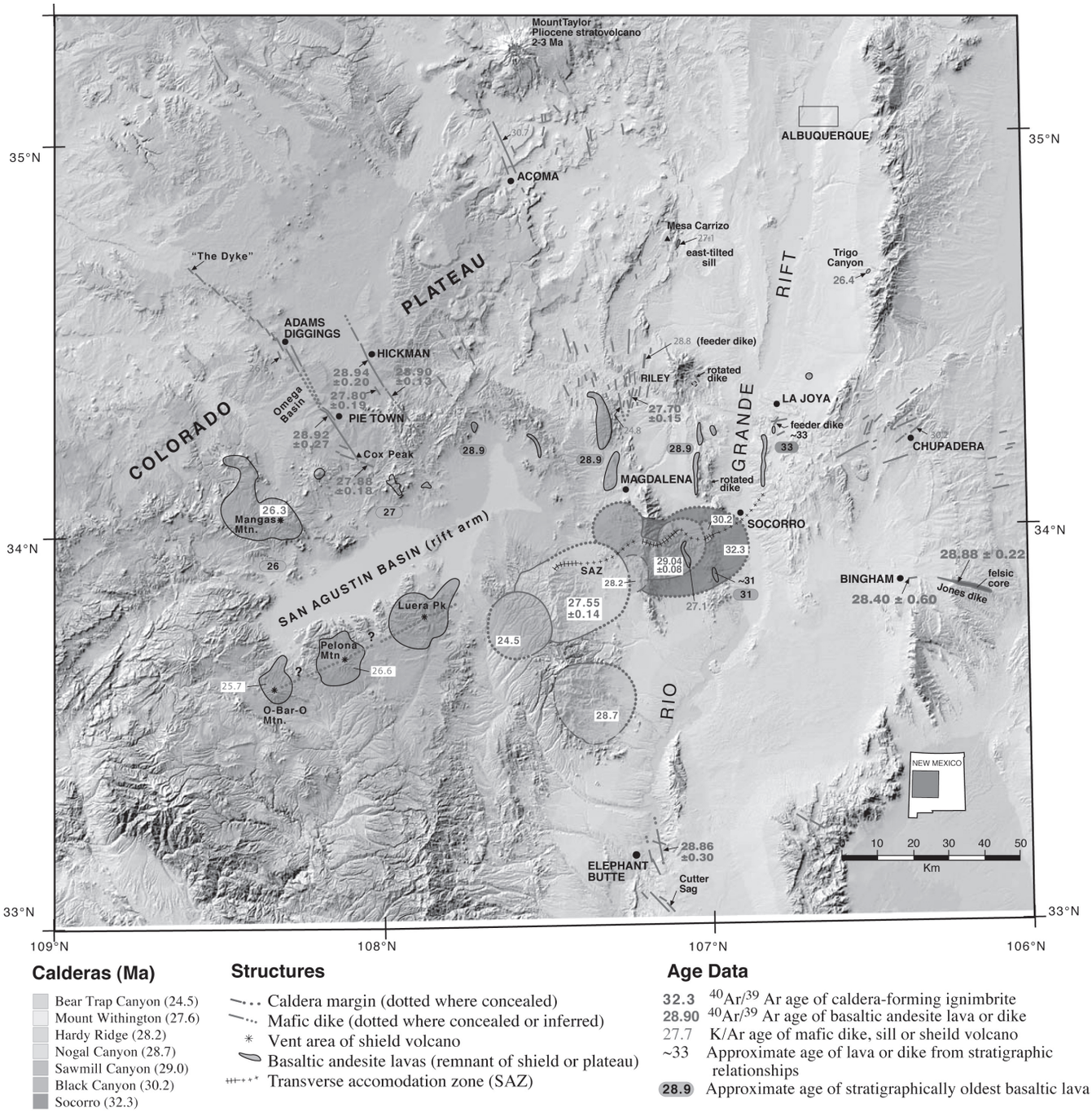
The ENE-trending pyroxene-hornblende diorite dike at Bingham yields a less precise $^{40}Ar/^{39}Ar$ age of 28.4 ± 0.6 Ma. Field observations and significant differences in concentrations of immobile trace elements suggest the Bingham dike is probably not the offset lateral equivalent of the Jones Camp dike.

INTRODUCTION

This paper presents new results of an ongoing geochronologic and geologic study of a large radial array of Oligocene mafic dikes (Fig.1; Plate 5), which is broadly focused towards Magdalena and widely exposed across central New Mexico (Chamberlin et al., 2002, 2003, 2007; Dimeo, 2008; and Chapin et al., 2004). A radial pattern of Cenozoic dikes surrounding the Mogollon-Datil volcanic field in southwestern New Mexico was first recognized by Elston et al. (1976, fig.18) . They state (Elston et al., 1976, p.25) "A plot of Tertiary dikes of all ages shows them to be roughly radial to a focus southwest of Magdalena." Aldrich et al. (1986) published numerous K-Ar dates of Cenozoic dikes in New Mexico; their moderately precise age data indicate that dikes on the southern and southeastern flank of the Mogollon-Datil field are mostly of Eocene age and predate the MRDS. Progress toward unraveling the complex relationships of Cenozoic magmatism, volcanism, tectonism, and dike emplacement in central New Mexico has been made possible through precise $^{40}Ar/^{39}Ar$ dating of regional ignimbrites (McIntosh et al., 1991) and relatively precise dating of mafic dikes (Chamberlin et al., 2007).

As defined here, the Magdalena radial dike swarm (MRDS) of Oligocene age (ca. 33-24 Ma) is about 250 km in diameter and spans 220º of arc from Pie Town to Acoma, Chupadera, Bingham and Elephant Butte. The MRDS is broadly focused on the westward younging Oligocene Socorro-Magdalena caldera cluster (SMCC), which was active from 32.3 to 24.5 Ma (Fig.1; Plate 5). Longer dikes of the MRDS (10-70 km) are moderately alkaline, aphyric, basaltic andesites (53-56 wt. % SiO_2) with aphanitic textures at the chilled margins. Dikes at Pie Town, Hickman and Elephant Butte are 7-10 meters wide and grade inward to fine-grained (diabasic) pyroxene diorite at the core of the dike. When plotted on an IUGS total alkali vs. silica diagram the moderately alkaline dikes plot as basaltic trachyandesites (Le Bas et al., 1986). For the sake of brevity, they are simply referred to here as "basaltic andesites". Compared to the 28.9-Ma basaltic andesite dikes at Pie Town, Hickman and Elephant Butte (Fig.1; Plate 5), the 28.9-Ma dike at Jones Camp is unusually wide, intensely altered and mineralized, plus more variable in composition and igneous textures.

The four primary objectives of this paper are to present: 1) a new precise $^{40}Ar/^{39}Ar$ age determination for the Jones Camp dike and a less precise age for the Bingham dike; 2) new whole-rock geochemical data for major and trace element concentrations in the Jones and Bingham dikes; 3) a reinterpretation of paleomagnetic data for the Jones Camp dike-sill complex that is based on a previous thesis study (Jochems, 1987); and 4) a petrogenetic model for the structural and magmatic evolution of the Jones Camp dike. As described elsewhere in this guidebook, primary flow folds on the northern chilled margin of the Jones Camp dike provide tangible evidence for initial eastward dike propagation and eastward flow of aphyric basaltic andesite magma at a shallow upward angle of about 25-30º (Chamberlin, minipaper Day 1 Road Log).



Calderas (Ma)

- Bear Trap Canyon (24.5)
- Mount Withington (27.6)
- Hardy Ridge (28.2)
- Nogal Canyon (28.7)
- Sawmill Canyon (29.0)
- Black Canyon (30.2)
- Socorro (32.3)

Structures

- Caldera margin (dotted where concealed)
- Mafic dike (dotted where concealed or inferred)
- Vent area of shield volcano
- Basaltic andesite lavas (remnant of shield or plateau)
- Transverse accomodation zone (SAZ)

Age Data

- **32.3** $^{40}Ar/^{39}$ Ar age of caldera-forming ignimbrite
- **28.90** $^{40}Ar/^{39}$ Ar age of basaltic andesite lava or dike
- 27.7 K/Ar age of mafic dike, sill or sheild volcano
- ~33 Approximate age of lava or dike from stratigraphic relationships
- **28.9** Approximate age of stratigraphically oldest basaltic lava

FIGURE 1. Oligocene calderas, mafic lavas and radiating mafic dikes of the Socorro-Magdalena magmatic system are shown on a shaded DEM of central New Mexico. Westward younging Oligocene calderas and a coeval satellitic caldera are referred to as the Socorro-Magdalena caldera cluster (SMCC). Radiating mafic dikes of Oligocene age comprise the Magdalena radial dike swarm (MRDS). Note that long dikes at Pie Town, Hickman, Jones Camp and Elephant Butte are analytically equivalent in age to the La Jencia Tuff, which was erupted from the Sawmill Canyon caldera at 29.04 ± 0.08 Ma. 40Ar/39Ar age data are from McIntosh et al., 1991, McIntosh and Chamberlin, 1994; Chamberlin et al., 2004; Chamberlin et al., 2007; and this report. Map is modified after Chapin et al., 2004 and Chamberlin et al., 2007. "SAZ" is the Socorro accomodation zone.

Previous Work

The first detailed geologic map of the Jones Camp iron deposits and the adjacent dike was published by Kelley (1949, fig.44). With our explanatory notes in brackets, Kelley (1949, p. 216-217) states *"Three igneous types make up the dike and associated sills. The central part of the dike is a medium-grained hornblende monzonite…the central dike averages about 225 feet wide. On both sides of the central dike there are marginal facies or perhaps separate dikes that average 125 feet wide. This rock is a light- or pale green [where hydrothermally altered], fine-grained [augite] monzonite which is highly banded parallel to the nearly vertical contacts. ...The third type of igneous rock is diabase. It extends in tongue like sills for several hundred to perhaps as much as a thousand feet from the margins of the dike into the sedimentary rocks. The magma which gave rise to this rock ascended through the banded dike or along the outer contact… It [diabase] was intruded after the hornblende monzonite inasmuch as inclusions of the latter are found locally in the diabase."* However, on the accompanying geologic map (Kelley, 1949, fig.44) Kelley abandons the uncertainty expressed in his text and maps the "marginal facies" as "marginal dikes" delineated by dashed contacts adjacent to the "central dike".

Five later thesis studies under the direction of Professor Clay Smith at New Mexico Tech (Nogueira, 1971; Bickford, 1980; Gibbons, 1981, Jenkins, 1985 and Jochems, 1987) followed the same path of uncertainty as Kelley (1949) and suggested or concluded that the Jones Camp dike represents: 1) a mafic to felsic dioritic intrusion formed by in-situ differentiation with gradational boundaries between the facies (Nogueira, 1971); or 2) a composite intrusion consisting of at least two, and as many as six (Jochems, 1987), compositionally distinct intrusive phases or pulses. Gibbons (1981) tested three hypotheses for observed compositional variations in the Jones camp dike: 1) in-situ differentiation, 2) zonation caused by hydrothermal alteration and 3) a composite intrusion. Gibbons rejected the first two hypotheses and also noted that the lack of internal chilled margins does not support a composite origin; however, he astutely suggested that near coeval intrusions would lack chilled margins. A detailed discussion of conflicting results of these thesis studies and Kelley's original mapping is beyond the scope of this report. If one reads "between the lines" in these controversial reports the following generalities emerge.

The Jones Camp dike is about 16 km long, as much as 180 m wide and compositionally variable. It generally exhibits fine-grained mafic margins of pyroxene-plagioclase rock and a central felsic core of medium- to coarse-grained hornblende-plagioclase rock. Potash feldspar is a minor to sparse component (< 15%) and quartz is typically absent (Gibbons, 1981), so the phaneritic rocks are best described as diorite with variable proportions of pyroxene and hornblende as mineral modifiers in the name. Pyroxene diorites tend to be dominant at the margins (Gibbons, 1981, fig.6) and pure hornblende diorites locally occur near the core. Rocks in between are either pyroxene-hornblende diorites (pyroxene dominant) or hornblende-pyroxene diorites (hornblende dominant).

Wide zones along the margins of the dike are almost everywhere hydrothermally altered and contain secondary scapolite, tremolite-actinolite, calcite, dolomite, chlorite, sphene, hematite and magnetite (Jenkins, 1985). Hydrothermally altered zones are typically depleted in total iron content, non-magnetic, and formed during a period of reverse magnetic polarity (Jochems, 1987).
Fine-grained mafic rocks at the margin of the 180 m wide dike are locally well exposed and occasionally contain xenoliths of coarser-grained hornblende diorite (Gibbons, 1981, pl.12). All investigators apparently assumed these hornblende diorite xenoliths to have been derived from the adjacent solid (cold) core of "the Jones Camp dike" near the present level of exposure. Xenolith-bearing exposures at the margin of the 180 m wide dike were presumed to represent younger diabase dikes (i.e. not part of " the Jones Camp dike"), but none of the investigators located or described a chilled margin between these putative younger dikes and the central core of the dike, leaving their existence in doubt. All investigators reported the presence of xenoliths, "pseudo-xenoliths" or inclusions of hornblende diorite within the dike-sill complex at Jones Camp. Banded contacts within the wide dike at Jones Camp were interpreted to represent intrusive contacts between different phases (e.g. Kelley, 1949).

Several small exposures of Permian sandstones were mapped along the top of the dike towards its western end (Jenkins, 1885) and recognized as remnants (roof pendants) of the original intrusive crest of the dike. Jenkins (1985) projected the Mesozoic and Cenozoic stratigraphic column from the Sierra Blanca Basin westward to Chupadera Mesa and estimated the depth of dike emplacement at Jones Camp to be about 1.5 km below the Oligocene land surface. However, Jones Camp is on the west margin of the basin where the Cenozoic section was probably thinner; thus the depth to the top of Jones Camp dike at the time of emplacement could have been as little as 1 km.

The multiple dike interpretation of Kelley (1949; fig44), and adopted by most other investigators, appears to fail near the west end of Jones dike. Here the coarse-grained felsic core of the dike terminates westward (Fig.2) and the north and south fine-grained border zones (putative north and south dikes of Kelley, 1949) merge into one single map unit (Jochems, 1987, pl.7). The western end of Jones Camp dike is a key area that warrants additional mapping and analysis.

The plethora of igneous rock names applied to the Jones Camp dike and associated sills (e.g. Jochems, 1987) is most likely linked to widespread hydrothermal alteration, the inherent difficulty in field identification of feldspar phases, and unrecognized synonyms (e.g. monzonite and syenodiorite). The aphanitic chilled margins of the dike and adjacent mafic sills are best described as hypabyssal intrusions and given volcanic rock names, such as basaltic andesite or andesite.

Jochems (1987) reported results of a detailed paleomagnetic study of the Jones Camp dike-sill complex. Unfortunately Jochems erroneously assumed the Jones Camp dike to be of normal magnetic polarity based on an imprecise K-Ar date of 27.9 ± 1.1 Ma published by Aldrich et al.(1986). Jochems also assumed the sills were emplaced at a high angle to the horizon, within Permian beds that were tilted prior to sill emplacement. Structure sections of Jenkins (1985) illustrate that the mafic sills

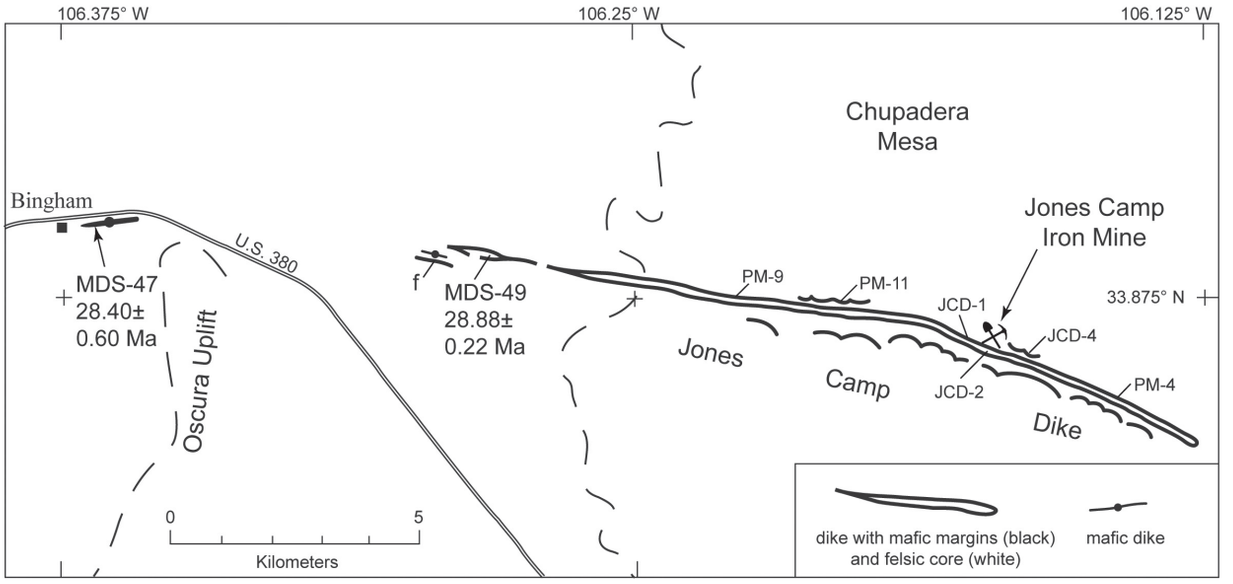


Figure 2. Index map of the Jones Camp and Bingham dikes showing location of $^{40}Ar/^{39}Ar$ dating samples and whole-rock geochemistry samples (Tables 1 and 2). Cuspate black lines illustrate north and south dipping mafic sills on the flanks of Jones Camp dike. PM-4, PM-9 and PM-11 are paleomagnetic sites of Jochems, 1987. An en echelon felsic dike at the west end of Jones Camp dike (f) apparently lacks a mafic margin (Jochems, 1987). Dashed lines delineate the west-facing escarpments of the Oscura uplift and the west flank of Chupadera Mesa.

are uniformly tilted away from the dike axis near Jones Camp and range in thickness from about 10-20 m.

Kelley and Thompson (1964) and later Chapin et al., 1978, recognized the Jones Camp dike as part of the east-southeast trending Capitan lineament. Kelley and Thompson (1964) also recognized that the Capitan lineament parallels a south-facing Paleozoic hinge line and is a continuation of the late Paleozoic Matador arch as recognized in west Texas (Ewing, 1990). For a different perspective on the Capitan lineament, see Cather, this guidebook. In their review of the geochemical and isotopic characteristics of the Lincoln County porphyry belt, Allen and Foord (1991) emphasize that the older north-trending calc-alkaline porphyry belt (38.2-36.5 Ma) must have a different magma source than the younger east-trending Capitan belt (30-26.5 Ma) and the two cannot be related by fractional crystallization or differences in partial melting. Allen and Foord (1991, p. 104) also briefly note that "the Jones Camp dike contains both alkali and silica oversaturated rocks."

The poorly exposed mafic dike at Bingham was first mapped by Wilpolt and Wanek, 1951. Jochems (1987, p.142) described minor iron mineralization and hydrothermal alteration associated with the dike at Bingham. He considered the coarse-grained, hornblende-bearing core of the diorite dike at Bingham to be equivalent to the core of the Jones Camp dike and interpreted it as a western extension of the Jones Camp dike.

Angular unconformities between Oligocene ignimbrites in the Socorro region (Chamberlin, 1983) and a shallow half-graben basin in the Joyita Hills that predates the 32.3 Ma Hells Mesa Tuff (De Moor et al., 2005) indicate that the SMCC formed during early opening of the Rio Grande rift, perhaps in a regime of back-arc spreading. Relatively abundant and closely spaced mafic dikes that trend NNW to NNE in the Riley area are attributed to a local coaxial relationship between early rift tectonic stress (westward opening) and magmatically induced regional stress (Chamberlin et al., 2007; Dimeo and Chamberlin, 2006; Dimeo, 2008).

^{40} Ar/^{39}Ar METHODS AND RESULTS

Samples of the Jones and Bingham dikes, collected for $^{40}Ar/^{39}Ar$ dating, were preferentially taken from dense (hard) crystalline zones near the centers of the dikes, particularly where crystalline potassic phases could be identified in hand specimen. Zones of hydrothermal alteration were avoided where apparent. Weathered rinds visible on the dense samples were removed in the field. Prior to dating, splits of the hand samples were thin sectioned in order to confirm the identity and freshness of dateable potassic phases. Results of the 2 age determinations using the $^{40}Ar/^{39}Ar$ method are listed in Table 1. Both samples were prepared and analyzed at the New Mexico Geochronology Research Laboratory at New Mexico Tech in Socorro. Fish Canyon Tuff sanidine, with an assigned age of 28.02 Ma, was used as a monitor for reducing the analytical data (Renne et al., 1998). All $^{40}Ar/^{39}Ar$ age data cited in this report have been reduced or recalculated using the 28.02 Ma age of the Fish Canyon Tuff monitor. Table 1 lists additional details of analysis. Complete analytical data, including age spectrum diagrams, will be made available on line at a later date.

GEOCHEMISTRY METHODS AND RESULTS

Four samples representative of the Jones Camp dike-sill complex and one sample of the Bingham dike were analyzed for 10 major rock-forming oxides and 19 trace elements using standard X-ray fluorescence techniques at the Washington State University Geo Analytical Lab in Pullman, Washington. Total volatile contents of each sample were also determined by loss on ignition

Table 1. Summary of 40Ar/39Ar age determinations for the Jones Camp dike and Bingham dike, east-central New Mexico

Field No.	Dike Name	Lab No.	Material Dated	Method	n	Age (Ma)	± 2 σ	MSWD	K/Ca	± 2 σ	UTM-E	UTM-N
MDS-49	Jones Camp	58720-01	hornblende	RHIF	2	28.88	0.22	0.59	0.062	nc	0381185	3749732
MDS-47	Bingham	58719-01	hornblende	RHIF	1	28.40	0.60	nc	0.068	nc	0373207	3750330

NOTES: Method is resistance furnace incremental heating (RFIH); n is number of heating steps used to calculate weighted mean age (RFIH). K/Ca is molar ratio calculated from K-derived 39Ar and Ca-derived 37Ar. Some variance cannot be calculated (nc).
Methods: Sample preparation: hornblende –crushing, LMT heavy liquid, Franz, HF; Irradiation: NM-221, 7.07 hours, D-3 position, Nuclear Science Center, College Station, TX. Neutron flux monitor Fish Canyon Tuff sanidine (FC-2) Assigned age = 28.02 Ma (Renne et al., 1998); samples and monitors irradiated in alternating holes in machined Al disks.
Laboratory: New Mexico Geochronology Research Laboratory, Socorro NM.
Instrumentation: Mass Analyzer Products 215-50 mass spectrometer on line with automated all-metal extraction system.
Heating:RFIH – 17.77 mg and 2.62 mg aliquots in resistance furnace. Reactive gas cleanup: SAES GP-50 getters operated at 20º C and ~450º C; RHIF– 6 minutes. Error calculation: all errors reported at ±2 sigma, mean ages calculated using inverse variance weighting of Samson and Alexander (1987); decay constant and isotopic abundances: Steiger and Jaeger (1977).
Analytical parameters: electron multiplier sensitivity = 8.34 x 10-17 moles/pA; typical system blanks were 2440, 14.7 , 1.1 , 9.4, 31.5 x 10-18 moles (furnace) at masses 40, 39, 38, 37, 36 respectively.
J-factors determined by CO2 laser-fusion of 6 single crystals from each of 10 radial positions around the irradiation tray; correction factors for interfering nuclear reactions, determined using K-glass and CaF2, (40Ar/39Ar) K = 0.0000±0.0003; (36Ar/37Ar) Ca = 0.00028±0.00002; and (39Ar/37Ar) Ca = 0.00068±0.00005.
Samples: Samples collected by R. M. Chamberlin and V. W. Lueth. UTM sample locations are based on 1927 NAD.

(LOI). The normalized results of these analyses (recalculated to 100% on volatile free basis) are summarized in Table 2. Samples for geochemical analysis (and dating) were taken from dense outcrops that did not exhibit the telltale signs of hydrothermal alteration, such as greenish colors, nodular textures or mineral veinlets; all are moderately magnetic under a hand magnet. Three samples were collected in the Jones Camp Mine area, in order to geochemically characterize 1) the flow-folded chilled margin of the 180 m-wide dike (JCD1), 2) the coarse-grained hornblende diorite core of the wide dike (JCD2), and 3) a nearby north-dipping mafic sill (JCD-4). The other two geochemical samples are splits from the dating samples for the Jones and Bingham dikes (MDS-49 and MDS-47).

GEOLOGY, GEOCHRONOLOGY AND GEOCHEMISTRY OF OLIGOCENE DIKES

Results of our geochronology based study (Table 1) indicate that the compositionally variable Jones Camp dike and the mafic dike at Bingham are part of the Magdalena radial dike swarm of Oligocene age (Fig.1; Plate 5). Some important geologic relationships to be addressed here include: 1) age relationships of rock types in the compositionally variable Jones dike; 2) potential correlation of the flow-folded mafic chilled margin of the dike and mafic sills near the Jones Camp mine; 3) cooling history of the Jones Camp dike, which is pertinent to the age determination; 4) character and origin of widely observed xenoliths in the Jones Camp dike; and 5) possible correlation of the Bingham dike with the Jones Camp dike. A reinterpretation of paleomagnetic data from a study by Jochems (1987) provides important constraints on the structural evolution of the Jones Camp dike and the relative age of adjacent mafic sills that are now tilted away from the axis of the dike (Fig.2).

Jones Camp dike

The Jones Camp dike is exposed along strike for a distance of about 16 km; it trends ESE and generally exhibits a mafic margin and felsic core (Fig.2). Surrounding Permian strata of the Yeso, Glorieta and San Andres formations are strongly upturned away from the dike axis and contain several mafic sills generally conformable with the outward dipping strata (Fig.2). Numerous small magnetite lenses occur in the Yeso Formation adjacent to the 180m wide dike in the Jones Camp mine area; they are most likely of contact metasomatic origin (Jenkins, 1985). Intensely altered margins of the dike are generally depleted in iron and thus considered to be the source rock for the iron mineralization (cf. review section by Jochems, 1987, p. 17-40).

Near the west end of the exposure, the Jones Camp dike tapers westward, from about 180 m wide to about 50 m wide. The dike distinctly narrows westward where the coarse-grained felsic core of the dike terminates, and the north and south mafic borders merge into a single map unit (Jochems, 1987, pl. 7). Traverses to collect dating samples in this area indicate the 50 m wide mafic dike is a simple cooling unit with no internal chilled margins. A sample of medium gray, fine-grained diabase (MDS-48) from the crest of the dike, about 300 m east of the Hale Well road, was found to contain abundant tremolite-actinolite masses replacing fine interstitial clinopyroxene. This sample was rejected as being too altered for dating purposes or geochemical analysis.

A section-line road (west of the Hale Well road) follows the crest of the dike to where it widens westward to about 100 m (Fig.2), and again contains a core of light gray, medium- to coarse-grained hornblende diorite with moderately abundant (5-10%) black needles of hornblende as much as 8 mm long. A sample of this hornblende diorite (MDS-49), collected about 10 m south of the section-line road, yields a precise $^{40}Ar/^{39}Ar$ age of 28.88 ± 0.22 Ma (Table 1). In thin section, the dated sample is composed of medium-grained sericitic plagioclase (80-85 %); fresh, brown pleochroic hornblende (5-7%); relatively coarse (1-2 mm) euhedral magnetite (2-3%) and traces of biotite crystals (<1%) as long as 5 mm. Interstitial areas between plagioclase crystals form about 5% of the rock. About half of these interstices are filled by equal amounts of fine-grained sanidine crystals (2Vx ~ 20º) and plagioclase; the other half of the interstitial areas are occupied by washed out holes in the thin section. The discovery of sanidine in this coarse-grained portion of the dike was unexpected; it is

Table 2. Summary of whole-rock geochemical data for the Jones Camp dike and Bingham dike, east-central New Mexico.

Field No.	MDS-49	JCD-2	JCD-1	JCD-4	MDS-47
Location/zone	felsic core-west end JCD	felsic core at mine	mafic margin at mine	mafic sill at mine	mafic core at Bingham
Rock type	hornblende diorite	hornblende diorite	basaltic trachy-andesite	diabasic pyroxene diorite	pyroxene-hornblende diorite
7.5' Quad.	Wrye Pk.	Pink Pk.	Pink Pk.	Pink Pk.	Wrye Pk.
UTM-E	0381185	0391493	0391099	0391499	0373207
UTM-N	3749732	3747670	3747894	3747712	3750330
Major Elements (weight percent)					
SiO2	57.74	59.72	53.63	54.15	53.20
TiO2	1.522	1.398	1.653	1.719	1.618
Al2O3	17.44	17.43	16.44	16.89	17.10
FeO*	6.43	5.38	9.79	7.25	9.79
MnO	0.094	0.068	0.144	0.091	0.124
MgO	2.86	2.42	4.55	4.82	4.86
CaO	3.44	3.87	4.49	7.89	5.97
Na2O	6.68	7.82	5.67	5.58	6.75
K2O	3.17	1.37	2.95	0.98	0.12
P2O5	0.618	0.539	0.689	0.638	0.473
Total	100.00	100.00	100.00	100.00	100.00
LOI (%)	0.74	0.59	3.39	2.00	2.83
Trace Elements (parts per million)					
Ni	0	0	35	23	6
Cr	2	1	64	60	3
Sc	15	14	19	21	25
V	118	106	205	229	237
Ba	1018	1051	1039	1083	39
Rb	49	19	60	33	3
Sr	760	910	526	788	220
Zr	315	322	261	265	230
Y	46	47	33	36	35
Nb	19.3	19.0	13.4	14.1	12.5
Ga	21	22	20	21	21
Cu	25	5	81	4	33
Zn	53	21	56	47	121
Pb	3	1	0	6	27
La	57	39	42	39	42
Ce	114	86	88	79	88
Th	5	6	5	4	4
Nd	53	47	46	45	44
U	1	2	3	3	1
Immobile Element Ratios					
Zr/TiO2(ppm)	0.21	0.23	0.16	0.15	0.14
Nb/Y	0.42	0.40	0.41	0.39	0.36
Ga/Sc	1.40	1.57	1.05	1.00	0.84

Notes: XRF analyses by Washington State University GeoAnalytical Lab. See WSU Geolab website for analytical details.
Major elements normalized to volatile free. Total iron reported as FeO
JCD means Jones Camp dike; "mine" refers to Jones Camp iron mine
UTM sample locations are based on 1927 NAD.
Samples collected by R.M. Chamberlin and V.W. Lueth

an anomalous occurrence for such a coarse grained rock. Nevertheless, the presence of homogeneous sanidine demonstrates that this core zone of the Jones Camp dike — presumably near the intrusive crest of the dike (cf. Jenkins, 1985) — was cooled quite rapidly. Near the dating locality, the coarse hornblende diorite is in contact with a fine grained mafic border facies exposed on the north side of the dike (Jochems, 1987, pl.7), but the authors have not observed the contact relationships here.

Traverses in the Jones Camp mine area by the senior author have crossed several exposures of coarse-grained hornblende diorite that are compositionally and texturally very similar to the dated sample (MDS-49), both as large lenticular masses lacking chilled margins (Table 2, JC-2) and as small rounded xenoliths in a fine-grained, hybridized matrix of dioritic (andesitic) composition (Fig.3). Thus the 28.88 ± 0.22 Ma age reported here (Table 1, MDS-49) is interpreted to represent the cooling age of the entire Jones Camp dike, including the well exposed mafic chilled margin of the dike at the iron mine (Fig.2, JCD-1).

A contrasting and corroborating example of relatively uniform cooling within Jones Camp dike is found at a water fall exposure near the southeast end of the strip mine area (UTM: 0392151E, 3747382N). Here a fine-grained hornblende diorite dikelet cuts a wide exposure of slightly coarser grained pyroxene diorite. The dikelet is 2-3 cm thick and dips at 70º to the NE (035). The absence of a chilled margin on the dikelet implies the slightly younger (i.e. "rapid fire") pulse of hornblende-rich magma injection occurred prior to complete cooling of the initial emplacement of basaltic andesite magma.

Inspection of Table 2 shows that the mafic chilled margin of the dike (JCD-1) and a nearby mafic sill (JCD-4) at the Jones Camp mine (Fig.2) are chemically quite similar, especially with regard to immobile trace elements (Zr, Nb, Y, Ga, Sc, Ni, and Cr) and immobile titanium dioxide (TiO_2). Likewise the core-zone sample at the mine (JCD-2) and the dated sample collected at the west end of Jones Dike (MDS-49) are also quite similar with respect to immobile elements and their ratios. In contrast, the same 4 samples show considerable variation in Na_2O and K_2O content, which implies some of the samples (most likely JCD-1 and JCD-2) and have undergone some degree of alkali metasomatism. Thus it seems unwarranted to chemically classify these

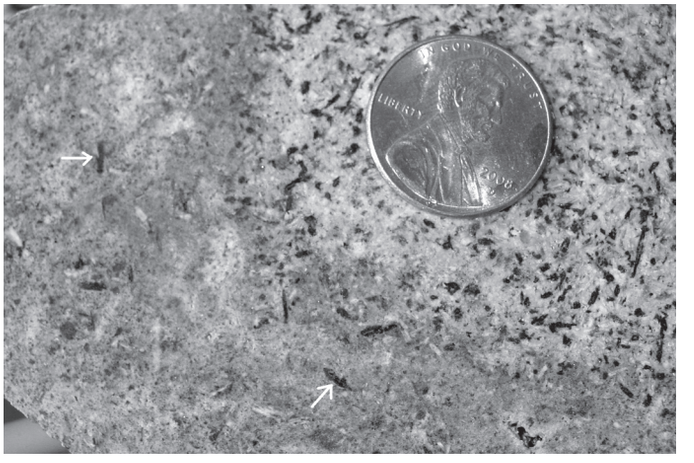


FIGURE 3. Slabbed hand specimen from a road-cut exposure in the core zone of Jones Camp dike, near the Jones Camp iron mine (UTM: 0390866E, 3747916N). Slab shows a rounded xenolith of light gray, medium-grained hornblende diorite within a matrix of medium gray, fine-grained pyroxene-hornblende diorite "porphyry". Note the diffuse interface between the phaneritic hornblende diorite and the darker matrix of pyroxene-hornblende diorite. Textural patterns suggest that the phaneritic hornblende-diorite xenolith was partially melted and disaggregated into the initial aphyric (liquidus temperature) basaltic andesite magma at depth (perhaps 5-10 km) shortly before its ascent to the present level of exposure in the upper crust, where it must have cooled rapidly. White arrows mark long black hornblende crystals in the fine-grained dioritic matrix that are readily interpreted as xenocrysts. Diameter of coin is 1.8 cm.

intrusive rocks using the total alkali-silica scheme of Le Bas et al, 1986. Following the method of Winchester and Floyd (1977), a binary plot of the immobile element ratios, Nb/Y versus Zr/TiO_2 (TiO_2 in ppm) shows that the mafic sill and dike margin samples (JCD-4 and JCD-1) lie on the field boundary between basalt and andesite (i.e. basaltic andesite) and the medium- to coarse-grained hornblende diorite samples from the core of the dike (JCD-2 and MDS-49) lie well within the andesite field.

Reinterpretation of Paleomagnetic Data from Jones Camp Dike-Sill Complex

Jochems (1987, p. 40-65) presents paleomagnetic data for 12 different sites that he sampled within the Jones Camp dike-sill complex. Based on a relatively imprecise K-Ar age of 27.9 ± 1.1 Ma (Aldrich et al., 1986; p.6201, stress indicator 312), Jochems unfortunately presumed the Jones Camp dike was emplaced during a period of normal magnetic polarity. Jochems (1987, p. 40) stated "The data suggests several possible models but is not conclusive". Jochems (1987, p.52-53) attributed the wide scatter in observed magnetic directions to "complex remanence acquisition" and to multiple pulses of intrusion. Some of the same paleomagnetic data can now be confidently re-interpreted knowing that the 28.9 Ma age of the Jones Camp dike requires that it was intruded and cooled during a period of reverse magnetic polarity, as defined by numerous paleomagnetic directions measured in the coeval La Jencia Tuff (McIntosh et al., 1991).

Figure 4 summarizes Jochems paleomagnetic directions at three different sites. Jochems found the paleomagnetic directions at two sites in the intensely altered margins (PM-4 and PM-9) to be held by secondary hematite and clearly of reverse polarity. Jochems suggested the episode of alteration must have been short lived and that the hematite formed during the waning stages of hydrothermal activity. The inclination of reverse polarity in the altered zones closely matches that of the coeval La Jencia Tuff (Fig.4). The small difference in declination (~ 20º) can be attributed to a vertical axis rotation in Neogene time that is of uncertain tectonic significance.

Paleomagnetic cores at site PM-11 (Fig.4.) were collected within a north dipping sill on the north flank of Jones Camp dike about 3 km west of the iron mine area (Fig.2). It is commonly recognized that dikes transport magma and sills store magma. Likewise dikes also feed sills. However, the geometry of dikes and sills requires a paradoxical flip in the orientation of the least principal stress, from horizontal to vertical, at the level of sill injection (Parsons, et al., 1992). The most reasonable mechanism for this enigmatic flip in stress fields is the presence of a rheologically ductile (incompetent) layer that cannot store deviatoric tensile stress for a tectonically significant period of time (Parsons et al., 1992). Mafic dikes in the northwestern Chupadera Mesa area commonly appear to terminate upwards where mafic sills are preferentially intruded at the base of the Glorieta Sandstone, which is also the horizon of incompetent evaporite beds in the upper Yeso Formation (Bates et al., 1947). Bates et al. (1947. p.40) attribute doming of the Glorieta and San Andres beds near the dikes to inflation of linear laccolith-type bodies where the

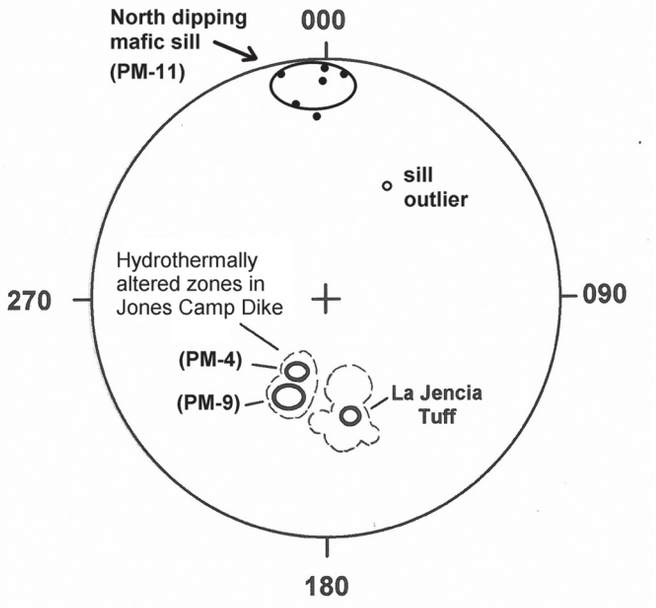


FIGURE 4. Lower hemisphere stereographic projection shows paleomagnetic directions for hydrothermally altered zones in the 28.9 Ma Jones Camp dike and an adjacent north dipping mafic sill. Paleomagnetic data are from Jochems (1987; PM-4, PM-9, PM-11). The mean paleomagnetic direction for the 29.0 Ma La Jencia Tuff (ellipse shown with heavy line) is from McIntosh et al. (1991). Dashed lines indicate outer limits of the greater majority of observed paleomagnetic directions for the different rock units.

dikes intersected the Yeso evaporite beds. However, at short distances away from the dikes (~ 200 m) the mafic sills and enclosing beds are essentially horizontal (Bates et al. 1947; fig.4). Thus it seems likely that mafic sills adjacent to the Jones Camp dike were also essentially horizontal at their time of emplacement.

Jochems (1987, p.63) described the outcrop at sample site PM-11 (Fig. 4) as follows. "At the outcrop, stringers of porphyritic pyroxene syenodiorite two to three inches wide intrude an earlier igneous rock. Only the porphyritic rock was sampled." Jochems goes on the state "They [pyroxene syenodiorite] appear to have intruded as a large, northward dipping sill." Jochems did not state the strike and dip of the "northward dipping sill" at sample site PM-11. However, the geologic map of Jenkins (1985, pl.1) shows that Permian strata of the Yeso Formation, along strike with the PM-11 sample site of Jochems (Fig.2), dip from about 25-50º to the north and range from 6 - 30 m in thickness. Jochems apparently assumed the "syenodiorite" sill was originally intruded at a high angle to the horizon, within beds of the Yeso Formation that had been previously tilted to the north. Excluding one outlier determination (Fig.4), Jochems assumed the north dipping sill at PM-11 was originally of normal polarity and the remaining well grouped but unusually flat paleomagnetic directions could be attributed to gypsum dissolution and slumping of the sill toward the central dike. As described below, Jochems did not consider the possibility the sill was intruded into horizontal strata during a period of reverse magnetic polarity.

When 40º of northward structural dip is removed from the sill (PM-11) the near horizontal paleomagnetic directions become

coaxial with the reverse paleomagnetic direction of the La Jencia Tuff (Fig.4), which is now known to be coeval with intrusion and cooling of the Jones Camp dike (Fig.1; Plate 5). This relationship supports the interpretation that the surrounding Yeso beds were near horizontal at the time of sill injection. The mafic sill (including porphyritic stringers) must have cooled quickly after the initial injection of the basaltic andesite magma (pyroxene diorite) that presumably fed the sill. Thus the steeply dipping sill implies a second, more forceful, pulse of magma injection occurred after the initial basaltic andesite intrusion that formed the mafic margins of Jones Camp dike and presumably fed the adjacent mafic sills. As mapped near the west end of the dike (Fig.2), the felsic core of Jones Camp dike has apparently inflated the mafic margins of the dike and more than tripled its width. We suggest that a second forceful pulse of hybrid andesitic magma injection (c.f. Fig.3) pushed the sill up and away from the inflating core of the dike shortly after the sill cooled and acquired a reverse magnetic polarity. We attribute the unusually large width of the Jones Camp dike (180 m) to its emplacement in the incompetent evaporite beds of the Yeso Formation, which probably arrested the initial rise of the laterally propagating dike and then allowed it to mushroom outwards at the present level of exposure, approximately 1-1.5 km below the Oligocene land surface (Jenkins, 1985).

Bingham Dike

A poorly exposed mafic dike on the south side of U.S. 380 and just east of Bingham is here referred to as the "Bingham dike". The kilometer long outcrop of the diorite dike trends ENE (080) and is about 40-60 m wide along most of its length. The east and west ends of the dike outcrop disappear under alluvium. Coarsely crystalline gypsum and limestone beds of the host Yeso Formation stand slightly higher than the dike on its south margin. Minor iron mineralization locally occurs near the poorly exposed intrusive contacts. Scattered blocky outcrops toward the center of the dike consist of medium gray, fine- to medium-grained pyroxene-hornblende diorite. Three traverses across the Bingham dike did not reveal any coarse-grained hornblende diorite xenoliths or a light colored central zone similar to the felsic core of the Jones Camp dike (cf. Jochems, 1987, p. 142).

In thin section, the dated sample (Table 1, MDS-47) shows abundant fine-grained plagioclase, which is clouded by secondary sericite and some chlorite, plus about 15-20 % clinopyroxene that is partly replaced by patches of hornblende. A minor amount of biotite and magnetite are also present. The observed alteration is probably deuteric.

A relatively imprecise $^{40}Ar/^{39}Ar$ age determination of 28.40 ± 0.60 Ma from hornblende in the Bingham dike (Table 1, MDS-47) would permit, but does not require it, to be coeval with the Jones Camp dike. Except for higher soda and depleted potash, major element concentrations in the Bingham dike are similar to the mafic margin of the Jones Camp dike and a nearby mafic sill (Table 2). These differences in alkali content probably reflect late-stage alkali metasomatism (or deuteric alteration) and not the primary composition of the Bingham dike. Immobile trace elements provide a more reliable comparison. Compared to mafic rocks at Jones Camp (Table 2; JCD-1 and JCD-4), the Bingham dike (Table 2, MDS-47) is significantly depleted in Ni, Cr, and Zr and enriched in Sc. Overall, the available data suggest that the Bingham dike is probably not a lateral equivalent of the Jones Camp dike (cf. Jochems, 1987, p. 142).

A PETROGENTIC MODEL FOR JONES CAMP DIKE

A new $^{40}Ar/^{39}Ar$ age determination of 28.88 ± 0.22 Ma for the Jones Camp dike confirms it is part of the large diameter Magdalena radial dike swarm, which is broadly focused on the large volume (5,000 km^3) Socorro-Magdalena caldera cluster of Oligocene age (Fig.1; Plate 5; Chamberlin et al., 2002, 2003, 2007; Chapin et al., 2004). The growing data base of precise $^{40}Ar/^{39}Ar$ ages (Fig.1, Plate 5) implies that long basaltic andesite dikes of the Magdalena radial dike swarm were driven outwards and upwards from an inferred lower crustal mafic sill complex that presumably fueled the Socorro-Magdalena caldera cluster (Chamberlin et al., 2007). Long mafic dikes at Pie Town, Jones Camp and Elephant Butte, were driven outwards—to the north, east, and south— presumably during periods of high magma pressure prior to eruption of the large volume (1250 km^3) La Jencia Tuff from the Sawmill Canyon caldera (McIntosh et al. 1991; Chapin et al., 2004; Fig.1; Plate 5). The bulk sanidine age of the La Jencia Tuff, 29.04 ± 0.08 Ma (Fig.1: Plate 5), may be slightly old due to the presence of xenocrysts (McIntosh and Chamberlin, 1994). Individually dated sanidine crystals (n = 45) from a rhyolite lava dome immediately under the La Jencia Tuff provide a precise age of pre-caldera tumescence at 28.91 ± 0.11 Ma (Chamberlin et al., 2004, p. 256, no.12), which is analytically equivalent to the age of Jones Camp dike (Table1).

As a working hypothesis, we suggest that the extreme pressures necessary to drive the basaltic magmas outward in fractures (pre-existing or not), for as much as 100 km, were developed within the pre-La Jencia rhyolitic magma body at depths of less than about 8 kilometers. Melt inclusion studies of Wallace et al., 1995, have found that CO_2 can begin to exsolve from rhyolitic magma at depths less than 8 km. We infer that formation of a CO_2 rich gas cap above the pre-caldera La Jencia magma body could have forced some rhyolitic magma downwards and in turn forced mafic magma outwards from the deep roots of the hydraulically connected magma system. Although explained by a different scenario, the downward flow of rhyolitic (granitic) magma in the crust is not unrecognized in the geologic record (Bolle et al., 2002).

Primary flow folds on the chilled margin of Jones Camp dike (Chamberlin, Day 1 Road Log) indicate the initial pulse of aphyric basaltic andesite magma was driven eastward at a shallow upward angle of about 25-30º, presumably along a deeply penetrating late Paleozoic shear zone of the Capitan lineament. From near Socorro (Fig.1; Plate5), the east propagating subsurface trajectory of Jones Camp dike would be about 50 km long (total length at least 66 km), which would require about 5-10 km^3 of basaltic andesite magma to fill a 10 m-wide dike (a typical width of other La Jencia-age dikes).

Again as a working hypothesis, we suggest the inferred long trajectory of Jones Camp dike intersected a somewhat older and

mostly crystalline hornblende diorite pluton at a moderate depth in the crystalline basement under Chupadera Mesa. Minor volumes of the intersected hornblende diorite apparently contaminated the initial pulse of basaltic andesite and its coarser-grained equivalent, pyroxene diorite, which are now visible in the form of small xenoliths in the chilled margins of the dike and hornblende-rich fluidal inclusions in the adjacent mafic sills (UTM: 0392262E, 3747592N). Shortly thereafter (perhaps within 10^1-10^3 years) a second, more forceful, pulse of hybrid andesitic magma mush carried abundant small to large xenoliths of older coarse-grained hornblende diorite upward and re-inflated the upper portion of the still hot mafic core of the initial dike injection. A near horizontal paleomagnetic direction in a north dipping sill on the north flank of Jones Camp dike (Jochems, 1987, PM-11) becomes coincident with the reverse paleomagnetic direction of the coeval La Jencia Tuff when 40º of northward tilt are removed from the sill (Fig.4). The mafic sill must have cooled quickly after the initial basaltic andesite dike injection that presumably fed the sill. The second pulse of hybrid andesitic magma injection then apparently domed the adjacent strata and pushed the sill up and away from the inflating core of the dike. The unusually large width of the Jones Camp dike (180 m) is attributed to its emplacement in the incompetent evaporite beds of the Yeso Formation, which probably arrested the initial shallow rise of the laterally propagating dike and then allowed it to mushroom outwards at the present level of exposure (approximately 1 km below the Oligocene land surface). For a discussion of the influence of Yeso evaporite beds on hydrothermal alteration at the Jones Camp iron mine see the paper by Lueth (2009)

CONCLUSIONS

1. A new and precise $^{40}Ar/^{39}Ar$ age determination of 28.88 ± 0.22 Ma for the ESE-trending Jones Camp dike confirms that it is an eastward projection of the large diameter Magdalena radial dike swarm, which is broadly focused on the coeval Socorro-Magdalena caldera cluster (32.3-24.5 Ma) of the early Rio Grande rift.

2. Precise $^{40}Ar/^{39}Ar$ ages and near horizontal flow lineations indicate that long basaltic andesite dikes of the Magdalena radial swarm were forced outwards as much as 100 km and upwards as much as 30 km from an inferred lower crustal basaltic sill complex that presumably fueled the Socorro-Magdalena caldera cluster.

3. Long dikes at Pie Town, Jones Camp and Elephant Butte, were driven outwards—to the north, east and south— presumably during periods of high magma pressure shortly before eruption of the large volume (1250 km^3) La Jencia Tuff from the Sawmill Canyon caldera.

4. Primary flow folds on the chilled margin of Jones Camp dike (described elsewhere) show that the initial pulse of aphyric basaltic andesite magma was driven eastward from about 25-30º below the horizon, presumably along a deep penetrating Paleozoic shear zone of the Capitan lineament.

5. The inferred long subsurface trajectory of the Jones Camp basaltic andesite dike presumably intersected a somewhat older and mostly crystalline (near solidus?) hornblende-diorite pluton at depth in the Proterozoic basement under Chupadera Mesa. Minor volumes of remobilized hornblende diorite contaminated the initial pulse of basaltic andesite magma, now apparent in the form of small hornblende-diorite xenoliths in the margins of the dike and adjacent mafic sills.

6. A second, relatively “rapid fire”, pulse of hybrid andesitic magma mush then carried abundant xenoliths of the older coarse-grained hornblende diorite upwards and re-inflated the still hot core of the initial mafic dike injection at Jones Camp.

7. A north dipping mafic sill on the north margin of the Jones Camp dike has an anomalous (near horizontal) paleomagnetic direction of apparent normal polarity (Jochems, 1987). Removing 40º of northward tilt from this mafic sill makes the magnetic direction of the sill coincident with the reverse magnetic direction of the coeval 29.0-Ma La Jencia Tuff.

8. Immobile element concentrations in the chilled margin of the dike and a nearby mafic sill at Jones Camp are quite similar, which implies that the initial basaltic andesite magma injection along the Jones Camp dike also fed the adjacent mafic sills. Paleomagnetic data also indicate that the mafic sills were initially horizontal.

9. The thin mafic sills (10-20 m thick) cooled quickly and acquired a reverse magnetic polarity prior to injection of a second forceful pulse of hybrid andesite magma mush, which apparently domed the adjacent strata and pushed the sills up and away from the inflating core of the Jones Camp dike.

10. The unusually large width of Jones Camp dike (180 m) is attributed to its emplacement within incompetent evaporite beds of the Yeso Formation, which probably arrested the initial rise of the laterally propagating dike and then later allowed it to mushroom outwards at the present level of exposure, about 1 km below the Oligocene land surface.

11. The ENE-trending diorite dike at Bingham yields a less precise $^{40}Ar/^{39}Ar$ age of 28.4 ± 0.6 Ma from hornblende, which would permit it to be correlative with the Jones Camp dike. However, significant differences in concentrations of immobile trace elements and the absence of a felsic core suggest that the Bingham dike is probably not the lateral equivalent of the Jones Camp dike.

12. We suggest that exsolution of CO_2 from the pre-caldera La Jencia Tuff magma body, at a depth of less than 8 km, produced the extreme pressures necessary to drive underlying basaltic-andesite magmas outward in fractures (as much as 100 km) to Pie Town, Jones Camp and Elephant Butte

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