New insight into the timing and history of diatreme-dike complexes of the northeastern Navajo volcanic fiedl, southwestern Colorado

D. A. Gonzales, B. E. Turner, R. T. Burgess, C. C. Holnback, and M. R. Critchley

2010, pp. 163-172. https://doi.org/10.56577/FFC-61.163

in:

Geology of the Four Corners Country, Fassett, James E.; Zeigler, Kate E.; Lueth, Virgil W., [eds.], New Mexico Geological Society 61 st Annual Fall Field Conference Guidebook, 246 p. https://doi.org/10.56577/FFC-61

This page is intentionally left blank to maintain order of facing pages.

NEW INSIGHT INTO THE TIMING AND HISTORY OF DIATREME-DIKE COMPLEXES OF THE NORTHEASTERN NAVAJO VOLCANIC FIELD, SOUTHWESTERN COLORADO

GONZALES, D.A.[1], TURNER, B.E.[2], BURGESS, R. T.[3], HOLNBACK, C.C.[1], AND CRITCHLEY, M.R.[1]

[1]Department of Geosciences, Fort Lewis College, 1000 Rim Drive, Durango, CO 81301

[2]School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287

[3]Newmont Mining Corporation, 1655 Mountain City Highway, Elko, NV 89801-2800

Abstract—The northern extent of the Navajo volcanic field (NVF) is defined by several diatreme complexes that evolved from swarms of north-northeast-trending mafic dikes exposed near Mesa Verde National Park (MVNP). Field evidence indicates that the eruptive phases were generated by multi-stage degassing and fluidization of mantle magmas. This produced diatreme buds that developed along dikes, lateral eruptions that scoured and were injected into adjacent sedimentary strata, and the formation of dome-shaped blind diatremes.

New $^{40}Ar/^{39}Ar$ age constraints on mafic dikes exposed near MVNP indicate a time of emplacement of ~24 Ma, within the accepted age range of magmatism for the NVF. Swarms of mafic dikes with similar composition to NVF rocks are exposed as far north as Placerville, approximately 75 kilometers north of MVNP. Mafic dikes exposed near Mt. Wilson yield a $^{40}Ar/^{39}Ar$ age of ~7 Ma. The younger dikes are either part of NVF magmatism or another distinct period of potassic magmatism in the region.

Oligocene to Miocene mafic dikes exposed from MVNP to Placerville are potassic to ultrapotassic alkaline basalts to basaltic andesites with mineral associations that are similar to those found in minette dikes in other parts of the Navajo volcanic field. All of these rocks have chemical affinities that are consistent with partial melting of metasomatized lithospheric mantle with possible minor contributions from other mantle sources.

The protracted period of Oligocene to Miocene potassic magmatism in southwestern Colorado makes up part of mantle magmatism that led to the emplacement of mafic-dike swarms across the northern margin of the San Juan basin after 30 Ma. The dominant north-to-northeast trends of these dike swarms lend evidence for incipient west to northwest rifting in southwestern Colorado that is aligned with a regional zone of crustal anisotropy (Colorado Mineral belt), and high heat flow related partial melting in the mantle (the Aspen anomaly). Regional extension and influx of mantle magmas into the crust in southwestern Colorado in the Middle to Late Tertiary were a probable catalyst to crustal melting in the adjacent San Juan volcanic field, and potassic mantle magmas in particular may have made an important contribution to the production of these crustal magmas.

INTRODUCTION

The Navajo volcanic field (NVF) contains ~100 eroded Oligocene to Miocene (28 Ma to 19 Ma; Naeser, 1971; Roden et al., 1979; Laughlin et al., 1986; Nowell, 1993) diatreme pipes with related dikes and plugs that are exposed in a crescent-shaped array over ~30,000 square kilometers on the northeastern Colorado Plateau (Gregory, 1917; Williams, 1936; Akers et al., 1971) (Fig. 1). Most of the NVF formed at about the same time as eruptions in the adjacent Oligocene San Juan volcanic field (Fig. 1).

Dissected dikes and diatreme necks are the most numerous and prominent features in the NVF, but several less-eroded parts of the field preserve lava flows, sills, and maar craters (e.g., Beautiful Mountain, Sonsela Buttes, Narbona Pass) that represent near-surface parts of these diatreme systems (Appledorn and Wright, 1957; Ehrenberg, 1978; Akers et al., 1971). These features are some of most distinctive and iconic landforms in the Southwest, particularly the 500-meter-tall Ship Rock or *Tsé bit'a'í* ("Navajo for rock with wings").

Numerous studies have been conducted on the diatreme-dike centers of the NVF in the past fifty years in attempts to gain insight into their origins and evolution (refer to Nowell, 1993). Although considerable work has been done on much of the NVF, the northeastern extent of the field in southwestern Colorado has been poorly documented. Wanek (1954) compiled the first geologic mapping showing the NVF diatreme-dike complexes in southwestern Colorado. Condon (1991) re-compiled this early mapping on a more regional-scale geologic map. More detailed field studies combined with new geochronological and geochemical data have been conducted by the author and students at Fort Lewis College over the past five years. The intent of this paper is to discuss these new data and the interpretations that have developed from this research.

OVERVIEW OF THE DIATREME-DIKE COMPLEXES IN SOUTHWESTERN COLORADO

Dikes and diatremes of the NVF in southwestern Colorado are exposed along the southern and eastern margins of Mesa Verde National Park (MVNP) (Fig. 2). In this area there are a series of minette dikes with an average trend ~24º (Fig. 2) (Gonzales, 2009). The trends of these dikes are similar to those of NVF diatreme-dike complexes in northwestern New Mexico and northeastern Arizona which are focused on north- to northeast-trending Laramide monoclines related to faults and fractures at depth. Swarms of mafic dikes are also exposed up to 75 kilometers north of MVNP (Fig. 2). These rocks have not previously been connected with the NVF but they have strong petrochemical similarities to minette dikes in the NVF.

The prominent north to northeast trends of mafic dike swarms exposed in the study area (Fig. 2) are consistent with a regional period of northwest to west extension at the time of magma

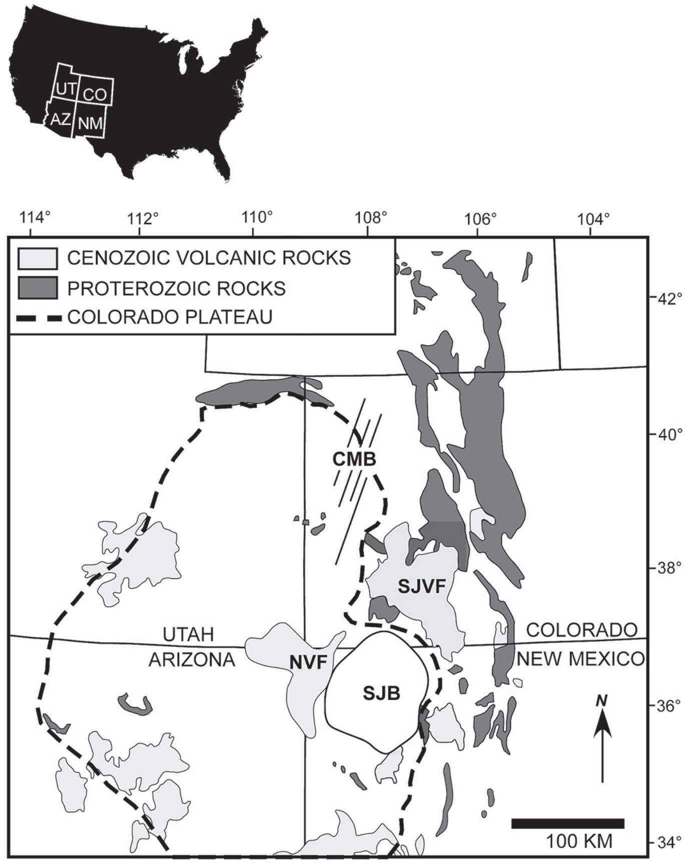

FIGURE 1. Generalized geologic map showing the locations of the Navajo volcanic field (NVF), San Juan volcanic field (SJVF), San Juan Basin (SJB), and Colorado Mineral belt (CMB). The dashed line shows the approximate location of the Colorado Plateau.

emplacement (e.g., Delaney, 1987; Gonzales et al., 2006; Gonzales, 2009). These trends are aligned with the overall trend of the Colorado Mineral belt (Fig. 1) that may have a Proterozoic lineage (McCoy et al., 2005), and the mantle-linked Aspen anomaly (Karlstrom et al., 2005). Reactivation of older structures in the region in the Tertiary might have provided a main avenue for mantle magmas to invade the crust and form diatreme systems in the Four Corners area (Mutschler et al., 1987; McCoy et al., 2005; Karlstrom and Humphreys, 1998; Karlstrom et al., 2005; Gonzales et al., 2006).

In southwestern Colorado, diatreme-dike complexes are exposed at Johnson Canyon, Wetherill Mesa, and Weber Mountain (Fig. 2). In these diatremes, elliptical bodies of tuff and tuff breccia formed during the emplacement of several generations of dikes (Figs. 3-5). Diatremes exposed at these locations bud from the dikes, showing a close relationship in time and space to dike emplacement and volatile release. These diatremes are exposed ~2000 feet below the mid-Tertiary paleogeographic surface in Upper Cretaceous marine sedimentary rocks of the Mancos Shale and Mesa Verde Group (Figs. 3-5). The depth of exposure of these diatremes is similar to the lower exposed portion of Ship Rock (Fig. 2) which provides a baseline for comparison of different geometry and emplacement mechanisms for diatreme-eruptive centers in the area.

All of the diatreme complexes in southwestern Colorado consist of massive to bedded tuff and tuff breccia deposits with angular to subrounded ash- to block-sized fragments of aphanitic to porphyritic minette, earlier generations of minette-tuff breccia, Proterozoic to Cretaceous wall-rock xenoliths, and rare garnet-pyroxene peridotite xenoliths. Bedding in the breccia deposits dip between 25° to 60° away from central dike-cored zones (Figs. 3-5), as opposed to the typical steep-conical geometries of diatremes in the NVF in New Mexico and Arizona (e.g., Ship Rock and Barber Peak). Tuff deposits in the diatremes preserve graded bedding, cross lamination, and scour surfaces that we interpret as evidence for rapid lateral transport of fragmented material. In some locations, bedding surfaces in adjacent Late Cretaceous sedimentary units localized lateral-breccia eruptions, as indicated by interbedded tuff breccia and sandstone.

PETROGRAPHY AND GEOCHEMISTRY OF DIKES

Minette dikes exposed near MVNP (Fig. 2) are up to 1 km long, but most of the dikes are less than 4 meters wide. The dikes are aphanitic to porphyritic aphanitic with phenocrysts or glomerocrystals of phlogopite and diopside set in a finer assemblage of mostly phlogopite, diopside, sanidine, and opaque minerals along with minor apatite. Mineral assemblages in these dike rocks also occur in the matrices of tuff breccias in the diatremes. The dominant mineral associations in these rocks are similar to those in minette dikes throughout the NVF (Nowell, 1993), though some of the dikes in the Mesa Verde area contain some of the highest concentrations (>40%) of sanidine in the entire field.

Prior to recent work done by the author and students it was thought that minette dikes related to the NVF were not exposed north of Mancos, Colorado (Fig. 2). A survey of the literature indicated that mafic alkaline dikes were exposed up to 75 kilometers farther north..

Bromfield (1967) mapped and described lamprophyre dikes between Mount Wilson and Lizard Head in the Mount Wilson quadrangle (Fig. 2). They described these dike rocks as two types of lamprophyre dikes, one group with phenocrysts of pyroxene and hornblende, and another with phenocrysts of pyroxene, biotite, and olivine. An investigation of these rocks by two of the authors (Gonzales and Holnback) found that hornblende-pyroxene dikes were extensively altered, but some samples did contain relatively unaltered sanidine and biotite. The pyroxene-biotite-olivine dikes of Bromfield (1967) were found to contain phenocrysts of augite in finer-grained assemblages of biotite, opaque minerals ± glass ± minor olivine. All of the rocks encountered in the Mount Wilson area contained large vugs and pockets of calcite, similar to rocks in the NVF.

Bush et al., (1959) mapped and described several north-northwest trending dikes near Placerville (Fig. 2) as biotite monchiquites with phenocrysts of biotite and augite in a groundmass of biotite, augite, analcine (?), magnetite, and calcite. Recent petrographic work on these rocks by Gonzales found that they contain mineral assemblages similar to minette dikes in the NVF

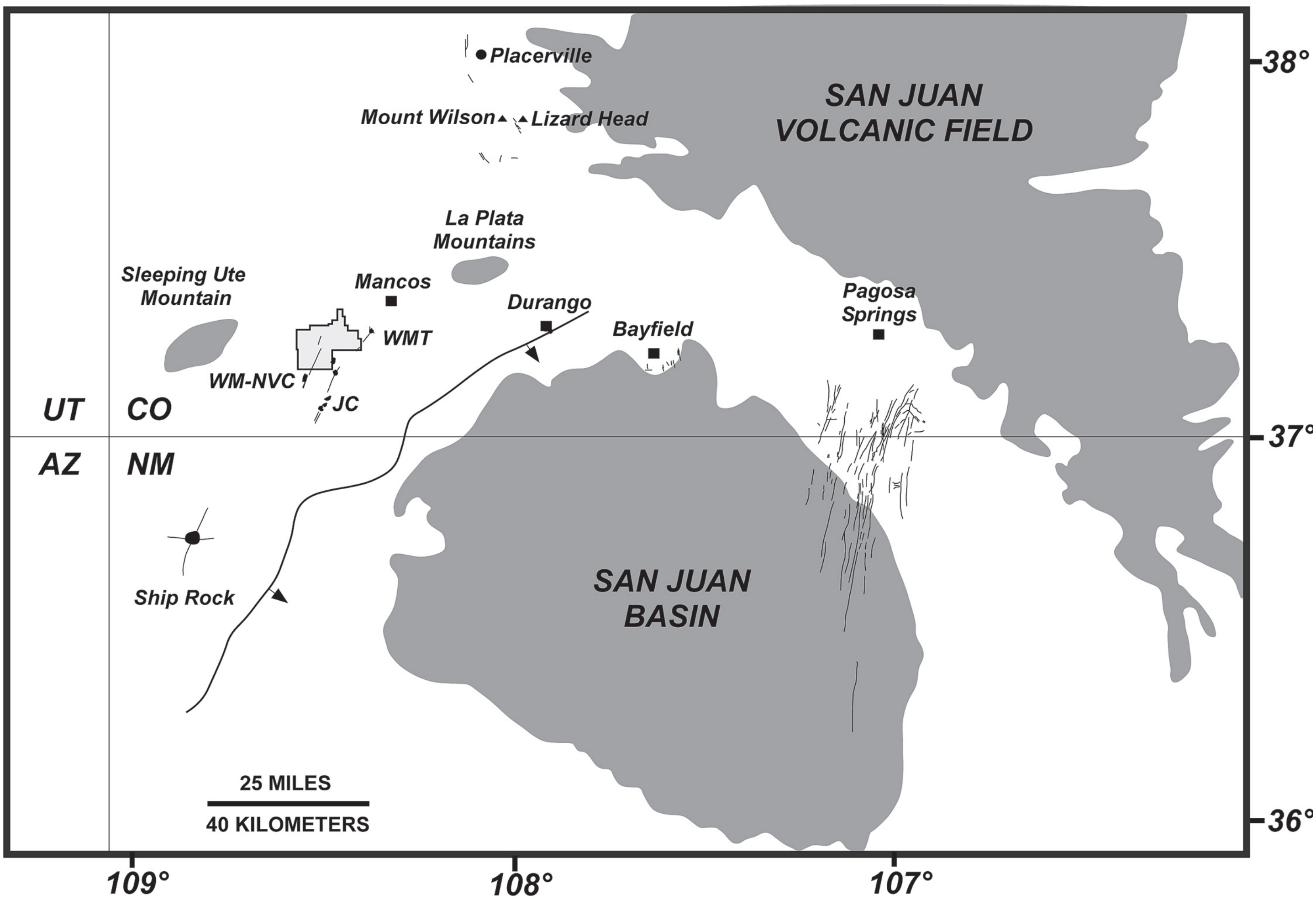

FIGURE 2. Generalized map showing some of the main physiographic and geologic features in southwestern Colorado. Mafic dikes are shown as thin black lines. Diatreme complexes are indicated by the following abbreviations: JC = Johnson Canyon diatreme, WM-NVC = Wetherill Mesa diatreme and dikes that extend to the northwest in Navajo Canyon, and WMT = Weber Mountain diatreme. Mesa Verde National Park is shown in light gray.

with phenocrysts of biotite and augite, and sanidine blades in the groundmass.

Numerous studies on rocks in the NVF in the past fifty years have been done to gain insight into the origin and evolution of magmas from their time of formation to emplacement. Geochemical studies have generated major, trace element, and isotopic data (Re-Os, Lu-Hf, Sm-Nd, Rb-Sr, and Pb) (Powell and Bell, 1970; Ehrenberg, 1979, 1982a, 1982b; Roden and Smith, 1979; Roden, 1981; Jones and Smith, 1983; Rowell and Edgar, 1983; Vaniman et al., 1985; Alibert et al., 1986; Laughlin et al., 1986, 1989; Roden et al., 1990; Nowell, 1993; Beard and Johnson, 1997; Carlson and Nowell, 2001). These published data establish that mantle magmas involved in diatreme formation in the NVF range from potassic to ultrapotassic with an overall trend of less evolved compositions (katungite) to more evolved rock suites (nephelinite, minette). These rocks are mostly considered partial-melt derivatives of metasomatized lithospheric mantle (Roden and Smith, 1979; Roden, 1981; Alibert et al., 1986; Laughlin et al., 1986, Roden et al., 1990; Nowell, 1993; Beard and Johnson, 1997; Carlson and Nowell, 2001).

FIGURE 3. Photograph of the Johnson Canyon diatreme showing the main features. The boundary of the diatreme is defined by the dashed white line. Dikes are shown as heavy solid white lines and the general trend of bedding within the tuff deposits is shown by thin white lines. Photograph courtesy of Kim Gerhardt.

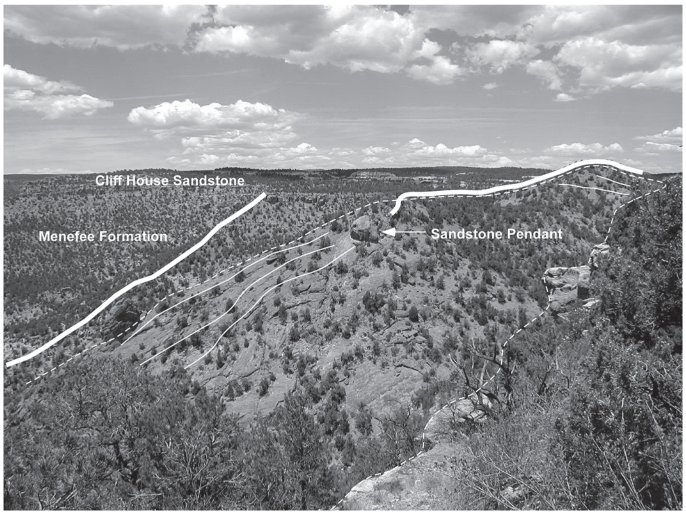

FIGURE 4. Photograph of the Wetherill Mesa diatreme showing the main features. The boundary of the diatreme is defined by the dashed white line. Dikes are shown as heavy solid white lines and the general trend of bedding within the tuff deposits is shown by thin white lines. Note the large sandstone pendant on top of the tuff deposits and the overall dome shape of the diatreme. Photograph courtesy of Kim Gerhardt.

A geochemical comparison of rocks samples from the minette dikes near Mesa Verde National Park, Placerville, and the unaltered mafic dikes exposed in the Mount Wilson-Lizard Head area indicate strong chemical similarities. All of the samples plot in alkaline and potassic basalt to basaltic-andesite fields with SiO_2 ranging between 40 and 55 weight percent (Fig. 6). These rocks also have strong enrichments of large-ion lithophile elements

FIGURE 5. Photograph of the Weber Mountain diatreme showing the main features. The boundary of the diatreme is defined by the dashed white line. Dikes are shown as heavy solid white lines and the general trend of bedding within the tuff deposits is shown by thin black lines. The diatreme has a dome geometry created by deposition of breccias from laterally-directed eruptions that developed from the central dike in the complex. Photographic courtesy of Kim Gerhardt.

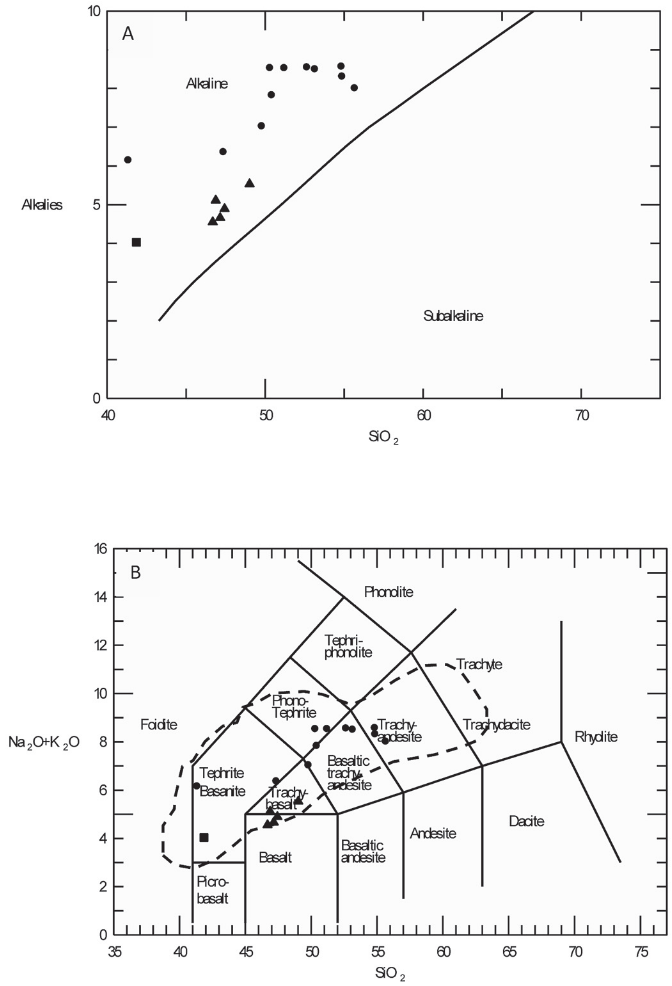

FIGURE 6. (A) Plots of SiO_2 versus total alkalies (Irving and Baragar, 1971) for mafic dike rocks from southwestern Colorado. All samples are alkaline with high K_2O/Na_2O. (B) Plot of sample data on the SiO_2 versus alkalies ($K_2O + Na_2O$) after Le Maitre et al., (2002). The area outlined with the heavy dashed black line is the general field where potassic rocks from other parts of the NVF plot. Black circles are sample data from Mesa Verde National Park area, black triangles are sample data from the Mount Wilson-Lizard Head area, and the black square is data for a sample exposed near Placerville.

(e.g., K, Sr, Rb, Ba) and LREE relative to chondritic values (Fig. 7). All of the chemical signatures observed in these rocks are similar to minette-dike rocks over the entire NVF (e.g., Nowell, 1993).

The most striking difference in geochemical signatures is between the mafic dikes exposed near MVNP and those from the Mount Wilson-Placerville area. On selected "spider" diagrams (Fig. 8) the samples from near MVNP have pronounced downward spikes in Nb-Ta and Ti, and pronounced upward spikes in Pb relative to the other samples. The element trends for the MVNP samples are similar to those observed for other minette samples from the NVF while those for the samples from the Mount Wilson-Placerville area are slightly different. The significance of these different trends is not clearly understood at this time, but it could reflect variations in magma sources or perhaps minor contamina-

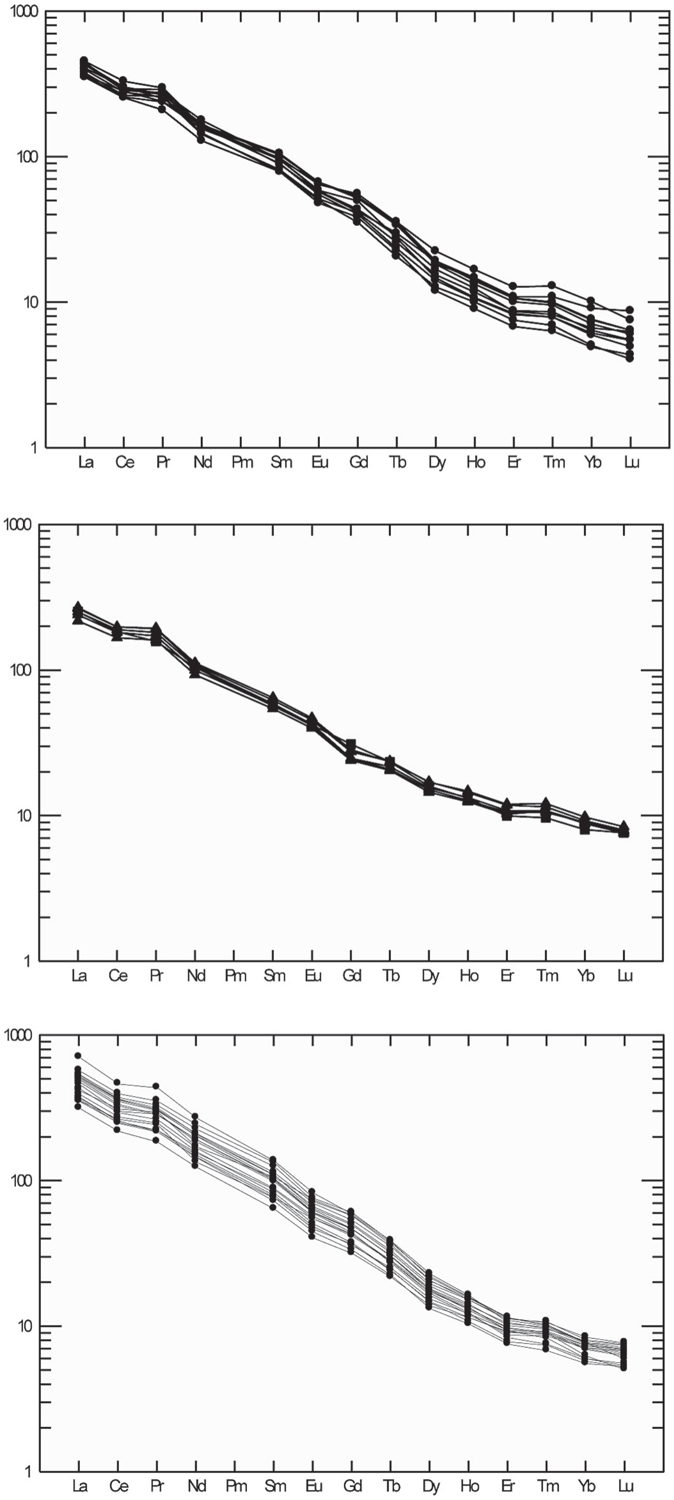

FIGURE 7. Plot of mafic dike rocks in southwestern Colorado against chondrite. This plot is after Nakamura (1974). All of the samples show a relative enrichment of light rare-earth elements which is similar to other minette rocks in the NVF. Plot A = sample data from MVNP; plot B = sample data from the Mount Wilson-Lizard Head area; and plot C = sample data for minette dikes in other parts of the NVF (unpublished data of Gonzales).

tion from country rock. It has been demonstrated (e.g., Gibson et al., 1993) that mafic magmas emplaced from 30 Ma to 20 Ma in the region tend to have chemical affinities consistent with melting of metasomatized mantle whereas magmas emplaced after 10 Ma were generated by melting of several different magma sources including ocean-island basalts (Leat et al., 1988). These different chemical trends indicate a shift in magma sources over time which may also be the case for rocks in southwestern Colorado.

^{40}AR/^{39}AR AGE CONSTRAINTS ON DIKE ROCKS

New ^{40}Ar/^{39}Ar ages for minette dike samples have been determined in the past several years. All of the analyses were conducted by Lisa Peters and Matt Heizler at the New Mexico Geochronology Research Laboratory at Soccoro, New Mexico.

A sample from a minette dike exposed in Navajo Canyon within Mesa Verde National Park (Fig. 2) was submitted by Paul Carrara of the U.S. Geological Survey. Biotite from the sample of this dike was analyzed with the furnace incremental heating age spectrum method. This analysis was assigned a weighted mean age of 25.65 ± 0.08 Ma (Peters, 2007, NMGRL-IR-578). Another sample submitted by Carrara from a dike exposed on the west side of Mancos Canyon yielded a weighted mean age of 24.97 ± 0.12 Ma (Peters, 2007, NMGRL-IR-647). A sample from a biotite-rich minette dike exposed on the north side of Weber Mountain diatreme (Fig. 2) was collected by Gonzalez for analysis. Biotite from this sample was also analyzed with the furnace incremental heating age spectrum method, and yielded a weighted mean age of 24.90 ± 0.05 Ma.

A whole-rock 40Ar/39Ar analysis was conducted on a sample of mafic dike collected by Gonzales and Holnback in the Mount Wilson-Lizard Head area. A whole-rock fraction was analyzed, rather than a phlogopite separate, due to the fine-grained texture of the rock (personal commun., Matt Heizler, April 2009). This sample yielded an integrated age of 6.67 ± 0.03 Ma. This is the youngest age for any of the mafic dikes in the region. The age spectrum for this sample showed a minor amount of disturbance, but the integrated age was thought to be reliable constraint of the crystallization age of the rocks. If this age is indeed valid then it indicates that alkaline magmatism happened over a protracted period of time and became younger to the north. Similar trends are recognized in the magmatism in the northernmost extent of the Rio Grande rift where the latest stage of potassic magmatism took place in northern Colorado from 14 Ma to 7 Ma (Leat et al., 1988; Thompson et al., 1990; Beard and Johnson, 1993). A sample of a minette dike, which contains coarse blades of phlogopite, exposed near Placerville (Fig. 2) is currently being analyzed at the NMGL laboratory. The results of this analysis are pending.

DIATREME COMPLEXES

Johnson Canyon diatreme

The diatreme complex exposed at Johnson Canyon is located on the Ute Mountain Ute Indian Reservation several miles

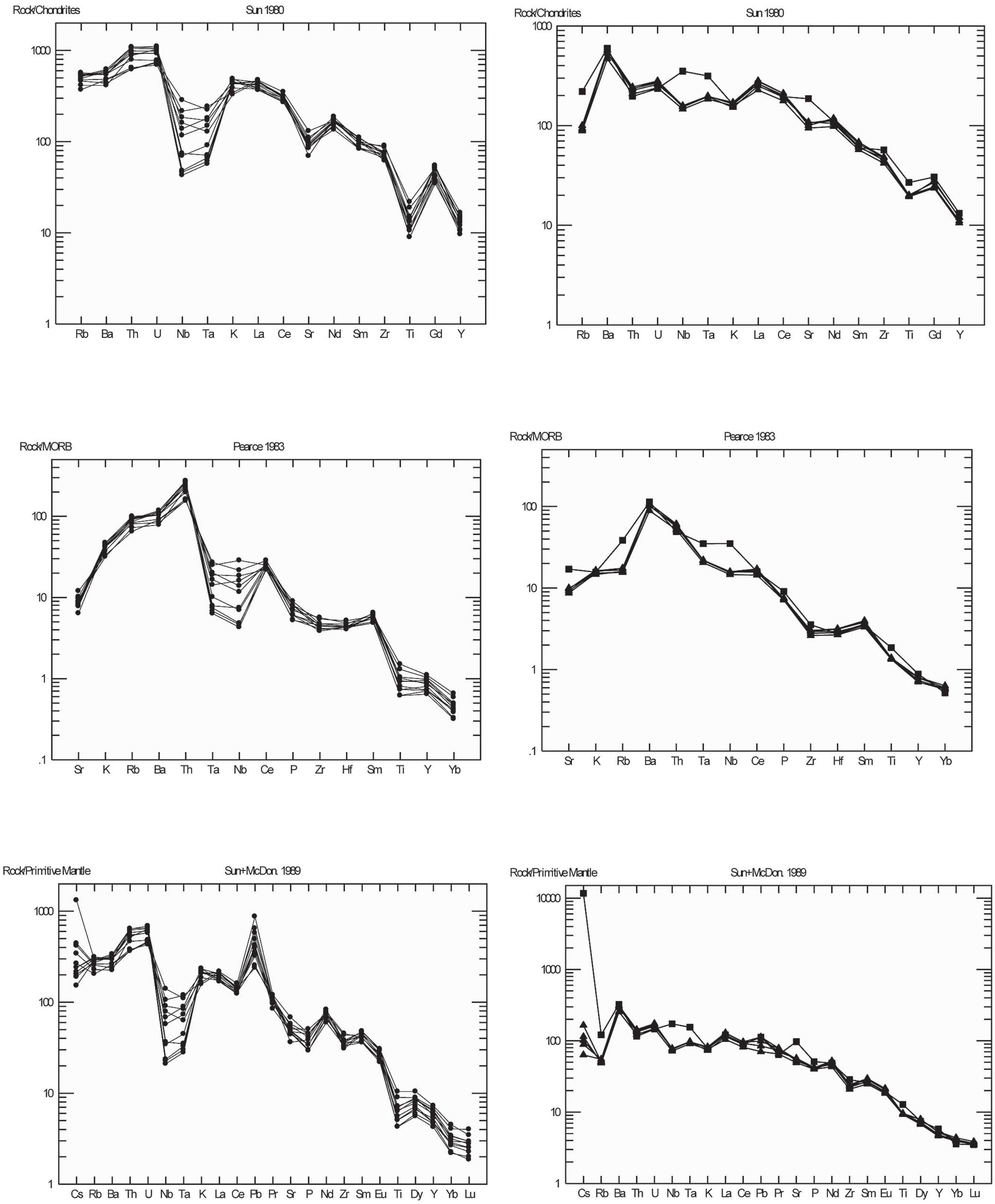

FIGURE 8. Selected spider plots for samples of mafic dike rocks from MVNP (on the left) compared to samples from the Mount Wilson-Placerville area (on the right). The upper plots are a comparison of rock versus chondrite (Sun, 1980). The middle plots are a comparison of the samples against mid-ocean ridge basalt (Pearce, 1983). The lower plots are samples normalized against primitive mantle (Sun and McDonough, 1989). Note the pronounced negative anomalies for Nb-Ta and Ti of the MVNP samples relative to the Mount Wilson-Placerville samples on these plots, and the high positive Pb anomalies of the MVNP samples.

south of Mesa Verde National Park (JC on Fig. 2). This complex contains a northeast-oriented elliptical deposit of tuff and tuff breccias about 2 kilometers long and 1 kilometer wide. The tuff deposits are transected by a series of mafic dikes that have a dominant northeast trend with several dikes trending east-west (Fig. 3). North of the diatreme complex, small breccia "buds" and "towers" are exposed adjacent to northeast-trending dikes, revealing the initial stages of volatile release and dike fragmentation that is gradational into breccias deposits.

The diatreme at Johnson Canyon is composed mostly of massive breccia deposits with lapilli- to block-sized fragments. In several locations, especially in the northern part of the diatreme complex, the deposits are bedded with some beds showing a crude reverse grading of fragments. Trends of bedding in the deposits reveal a dome-shaped geometry in which beds of breccia dip beneath surrounding Upper Cretaceous sedimentary rocks (Fig. 3). On the southwestern edge of the complex, tuff breccias were injected into the bedding surfaces of adjacent host rocks forming "sill" like masses.

Wetherill Mesa diatreme

Wetherill Mesa lies within Ute Mountain Ute Indian Reservation on the southern edge of the Mesa Verde National Park (WM on Fig. 2). At this location the diatreme complex is about 1 kilometer long and 0.5 kilometers wide, and elongate to the northeast. A series of north to northeast-trending dikes are associated with this complex, and the main diatreme complex is cored by a dike (Fig. 4). Breccia in the Wetherill Mesa diatreme is bedded, with the dip of bedding from 30° to 75° away from the central dike in the diatreme complex; bedding is better defined on the west side of the complex. The bedding trends define an overall dome geometry for the diatreme. At several locations in the western part of the complex, pendants of sandstone are exposed on the upper surface of the diatreme complex (Fig. 4). Bedded deposits in the Wetherill Mesa diatreme are fine to coarse grained with some outcrops having pronounced grading, scouring and bed truncation, and cross lamination. There are numerous fragments of minette dikes in these deposits indicating disaggregation of dikes during the eruptive phases. The bedded nature of the deposits indicates that there were multiple stages of eruptions during the evolution of the diatreme complex.

Weber Mountain diatreme

The diatreme-dike complex at Weber Mountain (WMT on Fig. 2) lies northeast of Mesa Verde National Park, on the east side of the Mancos River Canyon. At Weber Mountain, a roughly circular diatreme deposit about 1 kilometer in diameter is exposed along with a series of dominantly north- to northeast-trending dikes (Fig. 2). The main dike in this system is up to 15 meters wide and transects the central part of the diatreme complex (Fig. 5). At its northern extent the dike curves to the northwest, and in several locations it branches to the northeast and east. Distinct bedding in the diatreme deposits at Weber Mountain reveals a half-dome structure with beds dipping 30° to 60° to the east beneath adjacent Upper Cretaceous sedimentary units (Fig. 5) (Burgess and Gonzales, 2006). Ash- to block-sized fragments of dike rock and previously formed minette breccias are exposed in the diatreme deposits with beds ranging from several centimeters to tens of centimeters thick. No dominant structures or grading were observed in these deposits.

The main dike in this complex is gradational to deposits in the adjacent diatreme apron. Blocks and fragments of the dike rock are present in tuff deposits that grade into the margins of the dike. The dike also contains xenoliths of earlier breccia indicating that there were at least several pulses of dike emplacement, volatile release, and fragmentation to form the breccia deposits. In several locations near the margins of the dike there are breccia deposits with calcite infilling fractures. The calcite-rich breccia zones only occur in close proximity to the main dike margins and appear to be related to emplacement and devolatilization of the dike magma.

PROPOSED DIATREME EMPLACEMENT MECHANISMS

Two dominant models (summarized by Mitchell, 1986) are proposed to explain the emplacement mechanism of diatremes, mostly from research on diatreme pipes around the world. The first model involves the decompression of mantle magma that contains high concentrations of magma-derived volatiles. Upon emplacement of the magma the volatile pressure increases and at some shallow depth fluidization and eruption of the gases and magma happens (e.g., Dawson, 1971; Woolsey et al., 1975; McCallum, 1976; Clement, 1982; Field and Scott-Smith, 1999). A second dominant model posits that the eruptive phase of diatreme systems is generated by mantle magmas interacting with a groundwater aquifer creating "fuel" to generate an explosion that is directed downward at the point of magma and water interaction (e.g., Lorenz, 1975, 1985; Ort et al., 1998; Lorenz et al., 1999). The formation of subsurface "embryonic" magma pipes are invoked in both models within the deeper root zones (Clement, 1982). In the first model, volatiles are intimately related to the magma source whereas in the second model the source of the gas is external to the magma pipes. Volatiles from both sources are possible, but the emplacement mechanism in the development of these diatremes is different.

The most-widely accepted model invoked for the generation of the NVF diatremes is that mantle magmas rose and interacted with groundwater reservoirs to create explosive near-vertical eruptions (e.g., Semken, 2001; Brand et al., 2008). Most interpretations for the emplacement of diatremes in the NVF call for the eruption of gas-charged mafic magma in steep cone-shaped "vents" in which downward excavation may have occurred. This is clearly evident in some diatremes such as Ship Rock (Fig. 2) and Barber Peak where the outer margins of the diatremes are defined by steeply dipping beds inclined inward towards the center of the diatreme. Brand et al., (2008) documented evidence for near-surface development of a maar crater eruption at Narbona Pass where minette magma interacted with groundwater in the Eocene-Oligocene Chuska Sandstone. Though their phreatomagmatic model is consistent with development of near-surface maar craters it may not adequately explain the development of deeper diatreme pipes in the NVF, especially for those diatremes where there is no clear evidence of interaction with regional aquifers such as the Chuska Sandstone.

The emplacement mechanism for the NVF diatreme complexes in southwestern Colorado are distinctly different from most other diatremes in the NVF, but a clear relationship between dike emplacement and diatreme growth is apparent. Multiple phases of dike emplacement, volatile release and fluidization of gas-charged magma, and explosive subsurface eruptions are supported by field evidence obtained at these sites. Explosive phases associated with the diatreme pipes preserve high-energy sedimentation features that include cross stratification, bedding, and graded bedding (Gonzales et al., 2006). Field studies clearly establish that the diatremes at Johnson Canyon, Wetherill Mesa, and Weber Mountain (Fig. 2) formed by lateral subsurface emplacement of explosive materials into adjacent Upper Cretaceous sandstones and shales. Mantle magmas that expanded and fragmented at similar stratigraphic levels led to mostly subsurface eruptions that injected into and domed the adjacent country rock creating "blind" diatremes. The reasons for the development of these lateral subsurface eruptions are not well understood, but it is possible that the fracture density and development in this area did not allow for easy transport of magma and gases to the surface. In any case, the magmas that generated diatremes in southwestern Colorado did not interact with a regional near-surface aquifer such as the Chuska Sandstone (Brand et al., 2008), and there is no evidence that they interacted with a significant aquifer at or near the level of current exposure.

It is here proposed that the diatreme complexes in southwestern Colorado formed by the ascent of mantle magmas to zones of lower lithostatic pressure which induced expansion of gas and magmatic fluidization. This led to explosive subsurface to surface eruptions that generated "blind" subsurface diatremes and diatreme pipes. Evidence in support of this interpretation comes from field observations that diatremes bud off of different generations of dikes at different stratigraphic levels, multiple eruptive events in which early-formed dikes and breccias are remobilized in later eruptive phases, and fluorite- and calcite-rich breccias that suggest at least some component of magmatic volatiles.

Although critical questions regarding the source of volatiles in NVF eruptions remain poorly constrained, late-stage crystallization of calcite and fluorite in the breccia zones in some NVF diatremes and dikes indicates that volatiles rich in CO_2, H_2O, and F were liberated from magmas associated with these events (Gonzales and others, 2006; Turner and Gonzales, 2006). More recent work by Gonzales on rocks throughout the NVF shows that the most primitive magmas with 30-35 percent SiO_4 (i.e. katungites exposed in Hasbidito Valley) are fluorine rich providing further evidence in support of magmatic volatiles.

DISCUSSION AND CONCLUSIONS

Dikes and diatremes in the northeastern part of the NVF in southwestern Colorado have many similarities to other diatreme-dike complexes in the region, but there are significant differences that have important implications to the evolution of the diatreme complexes in the NVF. The diatreme complexes in southwestern Colorado evolved from multiple injections of gas-charged magma fed from dikes with mostly northeast trends. These dike trends are similar to those observed for post-30-Ma dikes exposed along the northern edge of the San Juan Basin that fall between 350° and 45° (Fassett and Hinds, 1971; Gonzales, 2009). Dikes trends and fracture patterns in the region are consistent with north to northeast compression followed by the onset of regional crustal extension starting ~30 Ma. Crustal extension provided avenues for invasion of mantle magmas that gave rise to dikes in the northeastern part of the NVF and further east near Pagosa Springs, CO in the northeast part of the San Juan Basin (Fig. 2).

The character of the diatreme complexes in the northeastern NVF also indicates a different emplacement mechanism for gas-charged magmas than what is preserved in other parts of the field. The vertical-cone geometry observed in many other diatreme complexes (e.g., Ship Rock) contrasts sharply with the dome-shaped geometries of the complexes in southwestern Colorado. For the most part, all of the diatremes in southwestern Colorado are exposed at similar levels to those on the eastern flank of the NVF (i.e., Ship Rock, Barber, Peak, Bennett Peak), but the magma did not pierce the surface. Instead the multiple gas eruptions eroded into the adjacent sedimentary sections laterally, lifting the sections enough for gas-rich flow to occur and produce "sedimentary" features. Why the emplacement mechanisms differ in this area is unclear, but there must have been different factors and conditions that influenced magma emplacement and eruptive events. Our working hypothesis for the formation of the diatreme centers in southwestern Colorado is that they were initiated by decompressive-volatile release and "budding" as gas pressures in the magma systems exceeded lithostatic pressure. Magma transported and emplaced on northeast fracture systems acted as catalysts to gas-rich, subsurface eruptions that created the diatreme "buds" and aprons.

New petrologic and petrochemical studies establish that mafic dikes previously assigned to the northeastern NVF have strong affinities to other mafic dikes exposed up to 75 kilometers to the north (Fig. 2). Although the dikes in the Mount Wilson-Placerville area are not abundant they hint that potassic magmatism similar to that in the NVF extended further north than previously documented. The ^{40}Ar-^{39}Ar ages of minette dikes exposed near Mesa Verde National Park are consistent with the age range of rocks assigned to the NVF (summarized in Nowell, 1993). The age of the sample from the Mount Wilson-Lizard Head area, however, may indicate either a protracted period of potassic magmatism in the region from 30 Ma to 7 Ma or a younger pulse of potassic magmatism that is unrelated in any way to the magmatism in the NVF. More age constraints and chemical data are needed to fully assess these two hypotheses. Additional age constraints and geochemical data will allow better constraint on these regional trends, but the current data are consistent with the idea that potassic magmatism of the NVF magmatism was more extensive in space and time than previously thought.

One of the more intriguing questions related to magmatic events in the Four Corners region is the relationship of magmatism in the NVF with the voluminous and violent eruptions of the San Juan volcanic field (Fig. 1). Tertiary mafic dikes exposed on the northern margin of the San Juan Basin are close in time (30 Ma to 20 Ma) and space to large-scale volcanic events in the adjacent San Juan Mountains, and mantle magmas could have triggered crustal melting and extensive volcanism in the adjacent San Juan field. Farmer et al., (2008) proposed that 50 percent or more of the magmas involved in the San Juan and Mogollon-Datil volcanic event were contributed by partial melting of a lithospheric mantle source. This is also a dominant magma source for mafic magmas in the NVF. These authors argued that there is no evidence for a regional extensional event to call upon that may have been the catalyst to allow melting and emplacement of mafic magmas into the crust and to generate large volumes of intermediate to felsic magmas of the San Juan volcanic field.

The strong northeast trend of the NVF dike swarms, in alignment with large crustal anistropy (Fig. 1, CMB) and residual zones of partial melting in the mantle (the Aspen anomaly) hint that the NVF may have developed along a failed rift system that is roughly parallel to the Rio Grande rift. A zone of east-west extension along the northeastern part of the San Juan Basin is also defined by the widespread emplacement of dike swarms in the region in the Middle Tertiary (Fig. 2). Emplacement of potassic mantle magmas that gave rise to the NVF may have been the manifestation of regional melting of lithospheric mantle (Farmer et al., 2008) that served as a catalyst to the formation of the San Juan volcanic field (Gonzales, 2009). In addition, the high-fluorine potassic magmas of the NVF may also have influenced Middle Tertiary mineralization in the region. For example, the diatreme-dike complexes in southwestern Colorado are aligned with an alkaline stock in the La Plata Mountains (i.e., Allard stock) that has anomalous concentrations of platinum-group elements (PGE) that are concentrated along a set of northeast-trending fractures (Werle et al., 1981). Mooney (1994) notes that PGE mineralization is favored by the formation of alkaline mafic magmas enriched in volatile species (e.g., Cl, F, CO_2) similar to those found in the minette rocks of the NVF (Gonzales, ongoing research). One explanation for the development of PGE mineralization in the Allard stock was enhanced or developed by the flux of chlorine-fluorine-CO_2 gases in the system that complexed and transported the PGE to zones of mineralization. Although this idea is entirely conjectural, it does offer a working hypothesis to consider for the development of some of the mineralized zones adjacent to the NVF.

REFERENCES CITED

Akers, J.P., Shorty, J.C., and Stevens, P.R., 1971, Hydrogeology of the Cenozoic igneous rocks, Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah: U.S. Geological Survey Professional Paper 521-D, 18 p.

Alibert, C., Michard, A., and Albarede, F., 1986, Isotope and trace-element geochemistry of Colorado Plateau volcanics: Geochimica et Cosmochimica Acta, v. 50, p. 2735-2750.

Appledorn, C.R., and Wright, H.E., 1957, Volcanic structures in the Chuska Mountains, Navajo Reservation, Arizona-New Mexico: Geological Society of America Bulletin, v. 68, p. 445-468.

Beard, B.L., and Johnson, C.M., 1993, Hf isotope composition of late Cenozoic basaltic rocks from northwestern Colorado, USA: New constraints on mantle enrichment processes: Earth and Planetary Science Letters, v. 119, p. 495-509.

Bromfield, C. S., 1967, Geology of the Mount Wilson Quadrangle, Western San Juan Mountains, Colorado: U.S. Geological Survey Bulletin, 1227, 100 p., 6 plates.

Bush, A.L., Bromfield, C.S., and Pierson, C.T., Areal geology of the Placerville quadrangle, San Miguel County, Colorado: U.S., Geological Survey Bulletin 1072-E, 384 p.

Burgess, R.T., and Gonzales, D.A., 2005, New insight into the formation of diatremes in the northern Navajo volcanic field, Weber Mountain, southwestern Colorado: Geological Society of America Abstracts with Programs v. 37, No. 6, p. 11.

Carlson, R.W., and Nowell, G.M., 2001, Olivine-poor sources for mantle-derived magmas: Os and Hf isotopic evidence from potassic magmas of the Colorado Plateau: Geochemistry, Geophysics, Geosystems, v. 2, paper number 2000GC000128.

Clement, C.R., 1982, A comparative geological study of some major kimberlite pipes in the Northern Cape and Orange Free state: Unpublished Ph.D. thesis, University of Cape Town, 432 p.

Condon, S.M., 1991, Geologic and structure contour map of the Ute Mountain Ute Indian Reservation and adjacent areas, southwest Colorado and northwestern New Mexico: U.S. Geological Survey Map I-2083, scale 1:100,000.

Dawson, J.B., 1971, Advances in Kimberlite geology: Earth Science Reviews, v. 7, p. 187-214.

Delaney, P.T., 1987, Ship Rock, New Mexico: the vent of a violent volcanic eruption; *in* Beus, S.S., ed., Geological Society of America Centennial Field Guide, Rocky Mountain Section, v. 2, p. 411-415.

Ehrenberg, S.N., 1978, Petrology of potassic volcanic rocks and ultramafic xenoliths from the Navajo volcanic field, New Mexico and Arizona [Ph.D. thesis]: Los Angeles, University of California at Los Angeles, 256 p.

Ehrenber, S.N., 1979, Garnetiferous ultramafic inclusions in minette from the Navajo volcanic field, *in* Boyd, F.R., and Meyer, O.A., eds., The mantle sample: Inclusions in kimberlites and other volcanic rocks: Proceedings of the Second International Kimberlite Conference, v. 2, American Geophysical Union, Washington, D.C., p.330-344.

Ehrenberg, S.N., 1982a, Petrogenesis of garnet lherzolite and megacrystalline nodules from The Thumb, Navajo volcanic field: Journal of Petrology, v. 23, p. 507-547.

Ehrenberg, S.N., 1982b, Rare earth element geochemistry of garnet lherzolite and megacrystalline nodules from minette of the Colorado Plateau province: Earth and Planetary Science Letters, v. 57, no.1, p.191-210

Farmer, G.L., Bailey, T., Elkins-Tanton, L.T., 2008, Mantle source volumes and the origin of the mid-Tertiary Ignimbrite flare-up in the Southern Rocky Mountains, western U.S.: LITHOS, v. 102, p. 279-294.

Fassett J.E., and Hinds, J.S., 1971, Geology and Fuel Resources of the Fruitland Formation and Kirtland Shale of the San Juan Basin, New Mexico and Colorado: U.S. Geological Survey Professional Paper 676, 76 p.

Field, M., and Scott-Smith, B.H., 1999, Contrasting geology and near-surface emplacement of kimberlite pipes in southern Africa and Canada: Red Roof Design, VII[th] International Kimberlite Conference, Proceedings: The J.B. Dawson Volume, Cape Town, p. 214–237.

Gibson, S.A., Thompson, R.N., Leat, P.T., Morrison, M.A., Hendry, G.L., Dickin, A.P., and Mitchell, J.G., 1993, Ultrapotassic magmas along the flanks of the Oligo-Miocene Rio Grande rift, U.S.A.: Monitors of the zone of lithospheric mantle extension and thinning beneath a continental rift: Journal of Petrology, v. 34, part 1, p. 187-228.

Gonzales, D.A., 2009, Insight into middle Tertiary crustal extension and mantle magmatism along the northern margin of the San Juan Basin at the onset of volcanism in the San Juan Mountains: Geological Society of America Abstracts with Programs, 61[st] Annual Meeting (11-13 May 2009), paper no. 10-4, v. 41, no. 6, p. 18.

Gonzales, D.A., Burgess, R.T., Critchley, M.R., and Turner, B.E., 2006, New perspectives on the emplacement mechanisms involved in diatreme formation in the northeastern Navajo volcanic field, southwestern Colorado: Geological Society of America Abstracts with Programs, RMS 58[th] Annual Meeting, v. 38, no. 6, abstract 2-2, p. 4.

Gregory, H.E., 1917, Geology of the Navajo country: a reconnaissance of parts of Arizona, New Mexico, and Utah: U.S. Geological Survey Professional Paper 93, 161 p.

Irvine, T.N., and Baragar, W.R.A., 1971, A guide to the chemical classification of the common volcanic rocks: Canadian Journal of Earth Science, v. 8, p. 523-548.

Jones, A.P., and Smith, J.V., 1983, Petrological significance of mineral chemistry in the Agathla Peak and The Thumb minettes, Navajo volcanic field: Journal of Geology, v. 91, p. 643-656.

Karlstrom, K.E., and Humphreys, E.D., 1998, Persistent influence of Proterozoic accretionary boundaries in the tectonic evolution of southwestern North America: Interaction of cratonic grain and mantle modification events: Rocky Mountain Geology, v. 33, no. 2, p. 161-179.

Karlstrom, K.E., Whitmeyer, S.J., Dueker, K., Williams, M.L., Bowring, S.A., Levander, A., Humphreys, E.D., Keller, G.R., and the CD-ROM Working Group, 2005, Synthesis of results from the CD-ROM experiment: 4-D image of the lithosphere beneath the Rocky Mountains and implications for understanding the evolution of continental lithosphere, *in* Karlstrom, K.E., and Keller, G.R., eds., The Rocky Mountain Region: An Evolving Lithosphere (Tectonics, Geochemistry, and Geophysics), Geophysical Monography Series 154, p. 421-441.

Laughlin, A.W., Charles, R.W., and Aldrich, M.J., 1989, Heteromorphism and crystallization paths of katungites, Navajo volcanic field, USA *in* Ross, J., ed., Kimberlites and Related Rocks, v. 1, Proceedings of the Fourth International Kimberlite Conference: GSA Special Publication No. 14, p. 582-591.

Laughlin, A.W., Aldrich, M.J., Shafiqullah, M., and Husler, J., 1986, Tectonic implications of the age, composition, and orientation of the lamprophyre dikes, Navajo volcanic field, Arizona: Earth and Planetary Science Letters, v. 76, p. 361-374.

Leat, P.T., Thompson, R.N., Morrisson, M.A., Hendry, G.L., and Dickin, A.P., 1988, Compositionally-diverse Miocene-Recent rift-related magmatism in northwest Colorado: partial melting and mixing of mafic magmas from 3 different asthenospheric and lithospheric mantle sources: Journal of Petrology, Special Lithosphere Issue, p. 351-377.

LeMaitre, R.W., and others (eds.), 2002, Igneous rocks: A classification and glossary of terms: Cambridge University Press, Cambridge, UK.

Lorenz, V., 1975, Formation of phreatomagmatic maar-diatreme volcanoes and its relevance to kimberlite diatremes: Physics and Chemistry of the Earth, v. 9, p. 17-27.

Lorenz, V., 1985, Maars and diatremes of phreatomagmatic origin, a review: Transactions of the Geological Society of South Africa, v. 88: 459-470.

Lorenz, V., Zimanowski, B., Büttner, R., and Kurszlaukis, S., 1999, Formation of kimberlite diatremes by explosive interaction of kimberlite magma with groundwater: Field and experimental aspects: Red Roof Design, VIIth International Kimberlite Conference, Proceedings: The P.H. Nixon Volume, p. 522–528.

McCoy, A., Karlstrom, K.E., and Shaw, C.A., 2005, The Paleoproterozoic ancestry of the Colorado Mineral Belt: 1.4 Ga shear zone system in central Colorado *in* Karlstrom, K.E., and Keller, G.R., eds., The Rocky Mountain Region: An Evolving Lithosphere (Tectonics, Geochemistry, and Geophysics), Geophysical Monography Series 154, p. 71-90.

Mitchell, R. H., 1986, Kimberlites: mineralogy, geochemistry and petrology: New York, Plenum Press, 442 p.

Moomey, T.C., 1994, Platinum-group elements in alkaline igneous rocks: Master's Thesis, Eastern Washington University, Cheney, Washington, 84 p.

Mutschler, F.E., Larsen, E.E., and Bruce, R.M., 1987, Laramide and younger magmastism in Colorado: Colorado School of Mines Quarterly, v. 82, p. 1-45.

Naeser, C.W., 1971, Geochemistry of the Navajo-Hopi diatremes: Journal of Geophysical Research, v. 76, p. 4978-4985.

Nakamura, N., 1974, Determination of REE, Ba, Fe, Mg, Na, and K in carbonaceous and ordinary chondrites: Geochim. Cosmochim. Acta, v. 38, p. 757-773.

Nowell, G.M., 1993, Cenozoic potassic magmatism and uplift of the western United States [Ph.D. thesis]: Milton Keynes, UK, Open University.

Ort, M., et al., 1998, Volcanism and sedimentation in the Miocene-Pliocene Hopi Buttes and Hopi Lake; *in* Duebendorfer, E.M., ed., Geologic excursions in northern and central Arizona: Flagstaff, Northern Arizona University, 205 p

Pearce, J.A., 1983, The role of sub-continental lithosphere on magma genesis at active continental margins, *in* Hawkesworth, C.J., and Norry, M.J., eds., Continental basalts and mantle xenoliths: Shiva, Nantwich, p. 230-249.

Peters, L., 2007, $^{40}Ar/^{39}Ar$ geochronology results from a Navajo Canyon dike in Mesa Verde National Park: Internal Report, New Mexico Geochronology Research Laboratory Internal Report NMGRL-IR-578, 8 p.

Peters, L., 2009, $^{40}Ar/^{39}Ar$ geochronology results from a Mancos Canyon dike in Mesa Verde National Park: Internal Report, New Mexico Geochronology Research Laboratory Internal Report NMGRL-IR-647, 8 p.

Powell, J.L., and Bell, K., 1970, Strontium isotopic studies of the alkalic rocks: Localities from Australia, Spain, and the western United States: Contributions to Mineralogy and Petrology, v. 27, p. 1-10.

Roden, M.F., 1981, Origin of coexisting minette and ultramafic breccia, Navajo volcanic field: Contributions to Mineralogy and Petrology, v. 77, p. 195-206.

Roden, M.F., and Smith, D., 1979, Field geology, chemistry, and petrology of Buell Park minette diatreme, Apache County, Arizona; *in* Boyd, F.R., and Meyer, H.O.A., eds., Kimberlites, diatremes, and diamonds: their geology, petrology, and geochemistry: Washington, American Geophysical Union, p. 364-381.

Roden, M.F., Smith, D., and Murthy, V.R., 1990, Chemical constraints on lithosphere composition and evolution beneath the Colorado Plateau: Journal of Geophysical Research, v. 95, p. 2811-2831.

Rowell, W.F., and Edgar, A.D., 1983, Cenozoic potassium-rich volcanism in the western U.S.A.: Its relationship to deep subduction: Journal of Geology, v. 91, p. 338-341.

Semken, S.C., 2001, The Navajo volcanic field in Crumpler, L.S., Lucas, S.G., eds., Volcanology in New Mexico: New Mexico Museum of Natural History and Science Bulletin 18, p. 79-83.

Sun, S, S., 1980, Lead isotopic study of young volcanic rocks from mid-ocean ridges, ocean, islands, and island arcs: Philosophical Transactions of the Royal Society of London, A297, p. 409-445.

Sun, S.S., and McDonough, W.F., 1989, Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes in Saunders, A.D., and Norry, M.J., eds., Magmatism in ocean basins: Geological Society of London Special Publication 42, p. 313-345.

Thompson, R.N., Leat, P.T., Dickin, A.P., Morrison, M.A., Hendry, G.L., and Gibson, S.A., 1993, Strongly potassic mafic magmas from lithospheric mantle sources during continental extension and heating: evidence from Miocene minettes of northwestern Colorado, U.S.A.: Earth and Planetary Science Letters, v. 98, p. 139-153.

Trofimov, V.S., 1971, On the origin of diamantiferous diatremes: Bulletin Volcanol, v 24, p. 767-776.

Trofimov, V.S., 1980, Role of intermediate magma chambers in the formation of kimberlites and diamonds: International Geologic Review, v. 22, no. 24, p. 490-496.

Turner, B., and Gonzales, D.A., 2006, An investigation of the geology and emplacement history of the Wetherill Mesa diatreme, southwestern Colorado: Geological Society of America Abstracts with Programs, RMS 58th Annual Meeting, v. 38, no. 6, abstract 19-2, p. 19.

Vaniman, D., Laughlin, A.W., and Gladney, E.S., 1985, Navajo minettes in the Cerros de las Mujeres, New Mexico: Earth and Planetary Science Letters, v. 74, p. 69-80.

Wanek, A.A., 1954, Geologic map of the Mesa Verde area, Montezuma County, Colorado: U.S. Geological Survey Oil & Gas Investigations Map OM 152, scale 1:63,360.

Werle, J.L., Ikramuddin, M., and Mutschler, F.E., 1984, Allard strock, La Plata Mountains, Colorado: an alkaline rock-hosted porphyry copper-precious metal deposit: Canadian Journal of Earth Sciences, v. 21, p. 630-641.

Williams, H., 1936, Pliocene volcanoes of the Navajo-Hopi country: Geological Society of America Bulletin, v. 47, p. 111-172.

Woolsey, T.S., McCallum, M.E., Schumm, S.A., 1975, Modeling of diatreme emplacement by fluidization: Physics and Chemistry of the Earth, v. 9, p. 29-42.