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Steven Semken

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BLACK ROCKS PROTRUDING UP: THE NAVAJO VOLCANIC FIELD

STEVEN SEMKEN
WERC Navajo Dryland Environments Laboratory, Diné College, Shiprock, Navajo Nation, New Mexico 87420-0580

Abstract.—The mid-Tertiary-age volcanoes, dikes, and sills of the Navajo volcanic field are classic and geologically-distinctive landforms of the Colorado Plateau. They are the products of structurally-controlled magma ascent, explosive eruptions, and deep post-eruptive exhumation. Igneous rock types include potassic lamprophyres, serpentinized tuffs, and exotic mafic and ultramafic intrusives. These rocks, along with a variety of crustal and mantle xenoliths that they have brought to the surface, have been used to map the petrology and history of the lithosphere and upper mantle beneath the Colorado Plateau. The landforms of the Navajo volcanic field also figure prominently in the empirical knowledge and culture of the indigenous Navajo people.

INTRODUCTION

The Navajo volcanic field (Gregory, 1917; Williams, 1936) encompasses more than 80 Oligocene to Miocene (ca. 28-19 Ma) volcanoes and intrusive features distributed across the Colorado Plateau in a roughly crescent-shaped array extending from the Cerros de las Mujeres southeast of Zuni, New Mexico, approximately 300 km northwest to the Four Corners and Mesa Verde, thence about 125 km west-southwest to the Monument upwarp on the Utah-Arizona border. As Figure 1 shows, most of the centers in the main part of the field occur along the Defiance, Hogback, and Comb Ridge monoclines, all Laramide structures. Although the volcanoes are not situated along exposed faults, magma ascent was probably facilitated by fractures at depth (Delaney, 1987).

The exhumed and erosion-sculpted igneous features of this potassic mafic province, termed *tsézhiin 'íí 'áhí* ("black rocks protruding up") by the Navajo people, include some of the most distinctive and renowned landforms in the Southwest, particularly the 500-meter-tall Ship Rock or *Tsé bit'a'í* ("rock with wings"), an icon of the Four Corners region (Fig. 2).

Dikes and necks are the most numerous and prominent features in the Navajo volcanic field, but among less-dissected centers in the Lukachukai and Chuska Mountains of western New Mexico and eastern Arizona there are several lava flows (Sonsela Buttes and The Palisades), sills (Beautiful Mountain and Dinehbi-keyah), and at least one maar crater (Narbona Pass; Appledorn and Wright, 1957; Ehrenberg, 1978). Detailed geologic descriptions of the major centers in the Navajo volcanic field can be found in the paper by Akers et al. (1971).

NAVAJO VOLCANISM

The eruptive centers of the Navajo field are maar-diatreme volcanoes. These were formed by hydrovolcanic (or phreatomagmatic) eruptions, in which magma in upward-migrating dikes encounters groundwater, and heats it to steam under confining pressure (Sheridan and Wohletz, 1983; Wohletz and Heiken, 1992). The result is a series of explosive eruptions that excavate a shallow maar crater at the surface, flanked by bedded pyroclastic ejecta. The blasts migrate downward as the aquifer is locally depleted, leaving a conical breccia pipe that incorporates magma and wallrock (Lorenz, 1973, 1986; Ort et al., 1998; Fig. 3). Magma may subsequently intrude the diatreme breccia, lavas may fill or overflow the maar crater, and the upper part of the diatreme often slumps. Depending on how deeply a maar-diatreme volcano is exhumed, various facies from a tuff ring and lava flows to the root zone (feeder dike) may be exposed (Ort et al., 1998).

As a consequence of post-eruptive uplift and dissection of the Colorado Plateau, the majority of the volcanoes in the Navajo field are moderately to deeply exhumed. These are typified by Ship Rock, a neck of tuff-breccia at mid-diatreme, with some slumping visible just below its summit, and shot through with

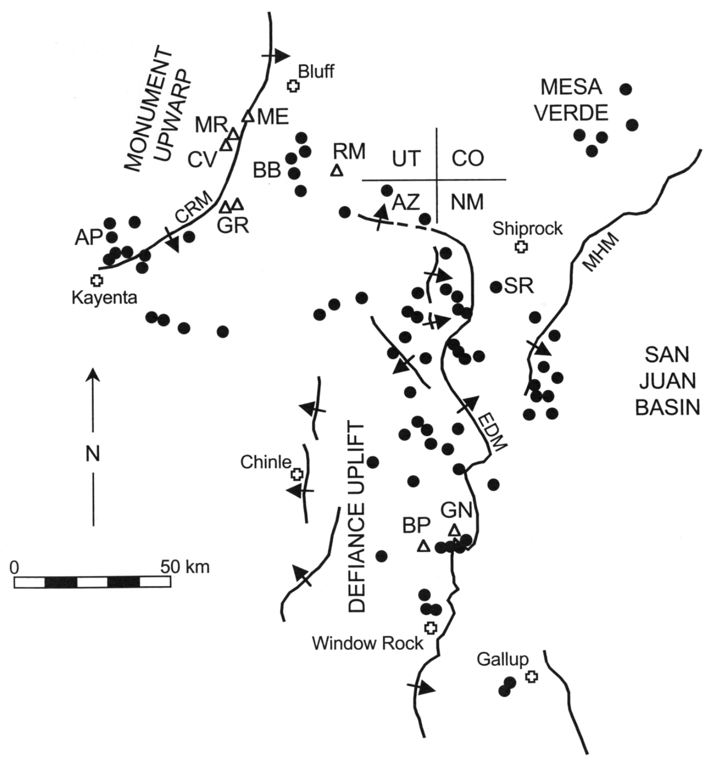

FIGURE 1. Location map of the central Navajo volcanic field, after Smith and Levy (1976) and McGetchin *et al.* (1977). Dark circles indicate minettes; open triangles represent SUMs. Monoclines are indicated by heavy lines. Abbreviations: AP, Agathla Peak; AZ, Arizona; BB, Boundary Butte; BP, Buell Park; CO, Colorado; CRM, Comb Ridge Monocline; CV, Cane Valley; EDM, East Defiance Monocline; GN, Green Knobs; GR, Garnet Ridge; ME, Mule Ear; MHM, Mesaverde Hogback Monocline, MR, Moses Rock; NM, New Mexico; RM, Red Mesa; SR, Ship Rock; UT, Utah. Major communities are also shown.

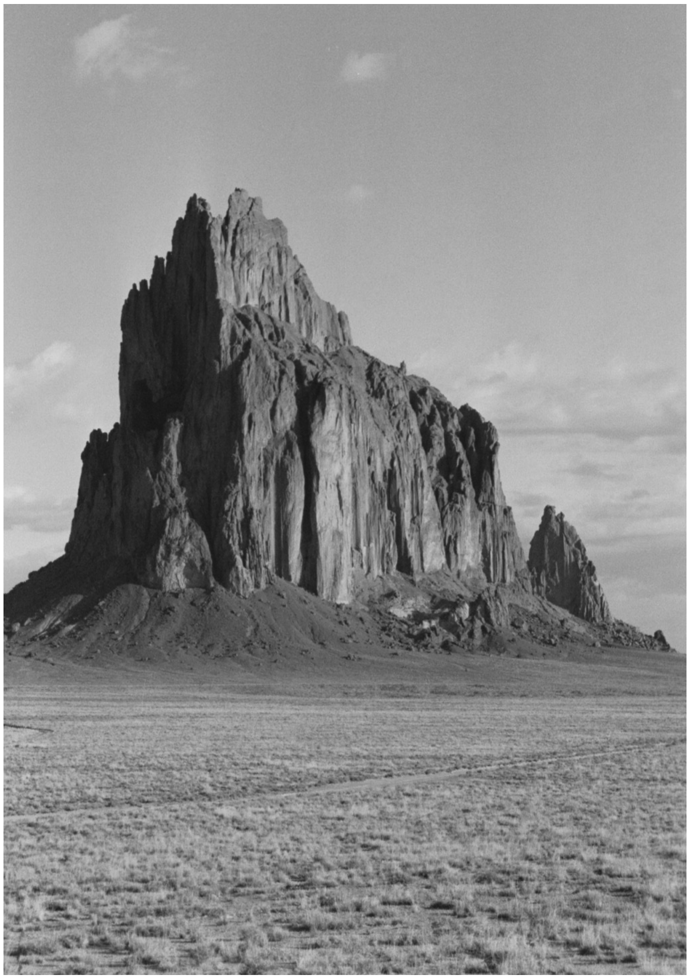

FIGURE 2. *Tsé bit'a'í*, Rock with Wings, the Ship Rock exhumed diatreme. Photograph by S.C. Semken.

small branching dikes. Three large and several minor radial dikes are exposed in the surrounding area, but the root zone of the diatreme remains buried. From regional stratigraphy, Delaney and Pollard (1981) estimated that the maar at the Ship Rock volcano was situated approximately 1,000 m above the present-day land surface. The radial dikes are formed of en echelon segments of varying length. Three dikes on the east side of Ship Rock are aligned with small necks that may have fed minor vents within, or flanking, the maar (Delaney and Pollard, 1981).

Surface and near-surface facies are still present at several vents in the Chuska Mountains. Notable among these is the volcano at Narbona Pass (formerly called Washington Pass) near Sheep Springs, New Mexico, where a partly-eroded maar crater flanked by bedded pyroclastics and lava flows, and intruded by three plugs, still exists (Ehrenberg, 1978). The faulted remnant of a possible second crater (Ehrenberg, 1978) occurs about 1 km to the south. Approximately 18 km to the west of Narbona Pass, West Sonsela Butte is a crater formed of bedded tuff and capped by lava; adjacent East Sonsela Butte is capped by three lava flows (Appledorn and Wright, 1957). Figure 4 compares the relative depths of exhumation at Ship Rock, West Sonsela Butte, and Narbona Pass.

PETROLOGY OF THE IGNEOUS ROCKS

The two principal rock types in the Navajo volcanic field are minette and serpentinized ultramafic microbreccia. Minette (Delesse, 1856) is a potassic mica lamprophyre, greenish-grey to black in color, characterized by an aphanitic groundmass of alkali feldspar (typically sanidine), diopside, biotite-phlogopite, and apatite, with phenocrysts of biotite-phlogopite, clinopyroxene, and, less commonly, olivine. Minettes are enriched in potassium (K_2O ~ 6 weight %) and magnesium, and depleted in aluminum; thus, alkali feldspar replaces plagioclase. Most of the minettes in the Navajo volcanic field are mafic, containing about 50 weight percent SiO_2, although felsic minettes with up to 60 weight percent SiO_2 occur at some localities (Ehrenberg, 1978; Roden, 1981).

The origin and emplacement of the Navajo minettes has been of considerable interest to researchers because of the unique chemistry of the rocks and their xenolith population (described below), and because these relatively sparse magmas were the only ones penetrating the Colorado Plateau at the end of the Laramide orogeny (ca. 30 Ma), when magmatism around its borders was voluminous.

Mantle metasomatism, thought to be important in the origins of many alkalic magmas (Bailey, 1984), may have affected the mantle beneath the Colorado Plateau at various times. The origin of Navajo minettes has been variously attributed to partial melting of a K-metasomatized mantle peridotite (Roden, 1981), a melt-depleted and metasomatized peridotite (Schaefer et al., 2000), and a mixture of metasomatized peridotite and Proterozoic mafic mantle intrusions (Carlson and Nowell, 1999, 2001). Proterozoic metasomatism beneath the Plateau is supported by the presence of fluid-derived oxide inclusions in pyrope garnet xenocrysts from the Garnet Ridge locality (Wang et al., 1999). Cenozoic melt metasomatism is supported by the presence of zoned garnets in peridotite xenoliths in minette from The Thumb (Smith and Ehrenberg, 1984). Some metasomatism may be related to volatiles released from the underlying Farallon plate, as its angle of subduction beneath North America increased after Laramide time (Laughlin et al., 1986; Smith et al., 2002).

Fractional crystallization of an ultramafic magma was proposed as an alternative model for minette generation by Roden et al. (1990). The less-common felsic minettes in the Navajo volcanic field are thought to have been derived by fractional crystallization of mafic minette magma in the upper mantle (Roden, 1981).

The emplacement temperature of mafic minette at the Ship Rock dikes was estimated at 1000 ± 75 °C by Delaney and Pollard (1981). Melting experiments on a Navajo mafic minette from Buell Park, Arizona by Esperanca and Holloway (1987) have indicated that emplacement temperatures may have ranged from 1000 to 1200 °C.

Trachybasalt, the extrusive equivalent of minette, forms the flows and shallow plugs in the Chuska and Lukachukai Mountains. The pyroclastic rocks formed by hydrovolcanic eruption in the minette diatremes and maars are referred to as "minette tuff-breccia." These consist of coarse-sand-sized to gravel-sized fragments of minette and diverse crystalline and sedimentary rocks in a finer comminuted matrix.

Eight Navajo diatremes, mostly clustered along the Defiance and Comb Ridge monoclines (Fig. 1), are composed of an olive-green to brown tuff or microbreccia, rather than minette. These rocks consist of a matrix of serpentine, chlorite, clay minerals, and talc; they contain xenocrysts of olivine, enstatite, chrome diopside, chlorite, garnet, titanoclinohumite, oxide minerals, and apatite, as well as abundant crustal and mantle xenoliths (Allen and Balk, 1954; Schmitt et al., 1974; Roden and Smith, 1979). They were initially identified as kimberlites (Allen and Balk, 1954). However, these tuffs were not directly derived from magma, their mantle-derived inclusions are xenocrysts rather than phenocrysts, and they lack incompatible-element-rich minerals that typify kimberlites (Smith and Levy, 1976; Roden, 1981). They are more accurately described as serpentinized ultramafic microbreccias or SUMs (McGetchin and Silver, 1972; Roden, 1981) and are thought to be a lower-temperature, volatile-rich mixture formed where Navajo minette magma interacted with hydrous mantle rocks (Smith and Levy, 1976; Roden, 1981).

In some localities such as the Cerros de las Mujeres (Vaniman et al., 1985), minor sodic lamprophyres (monchiquites, with $Na_2O > K_2O$) erupted concurrently with minettes. Even rarer and more exotic lamprophyre species have been identified within the Navajo volcanic field, including olivine melilitite and katungite, which has an SiO_2 content of only 33.6 weight percent (Laughlin et al., 1986; Laughlin et al., 1989).

Abundant published data on the petrology and geochemistry of the rocks of the Navajo volcanic field are available (Williams, 1936; Nicholls, 1969; McGetchin and Silver, 1970; Smith and Levy, 1976; Roden, 1977; Ehrenberg, 1978; Hunter, 1979; Roden and Smith, 1979; Roden, 1981; Jones and Smith, 1983; Vaniman et al., 1985; Alibert et al., 1986; Laughlin et al., 1986; Roden et al., 1990; Nowell, 1993; Nowell and Rogers, 1993).

XENOLITHS

Navajo volcanoes have erupted a considerable variety of upper-crustal, lower-crustal, and upper-mantle xenoliths, and many of these types have undergone considerable petrologic, trace-element, isotopic, and geochronologic study (McGetchin and Silver, 1972; Ehrenberg, 1978, 1982; Ehrenberg and Griffin, 1979; Padovani et al., 1982; O'Brien, 1983; Broadhurst, 1986; Wilshire et al., 1988; Roden et al., 1990; Smith et al., 1991; Wendlandt, 1992; Wendlandt et al., 1993, 1996; Alibert, 1994; Smith, 1995; Mattie, 1996; Riter and Smith, 1996; Mattie et al., 1997; Selverstone et al., 1999; Wang et al., 1999; Smith, 2000; Roden and Shimizu, 1993, 2000; Lee et al., 2001; Crowley et al., 2002; Smith et al., 2002). The SUM diatremes, particularly those in the Monument upwarp, tend to be richer in xenolith diversity than the minette diatremes (Selverstone et al., 1999).

Mantle xenoliths from the Navajo volcanic field include spinel peridotites and rarer garnet peridotites (Ehrenberg, 1982; Smith et al., 1991). Trace-element and isotopic studies of these xenoliths (Riter and Smith, 1996; Smith, 2000, Roden and Shimizu, 2000; Lee et al., 2001) indicate that the Colorado Plateau is underlain by a stable, cool, depleted mantle root analogous to those beneath Archean cratons.

The lower-crustal xenoliths, such as garnet granulite, amphibolite, gabbro, pyroxene granulite, eclogite, and felsic gneiss, have been used to map the origin and evolution of the regional lithosphere and crust. Sm-Nd isotopic and trace-element studies of these xenoliths by Wendlandt et al. (1993) and Mattie et al. (1997) suggest that nearly all of the present Colorado Plateau crust and mantle lithosphere were formed between 2.0 and 1.75 Gy ago, and that little or no underplating or other addition from the mantle has occurred since. However, Crowley et al. (2002) obtained U-Pb

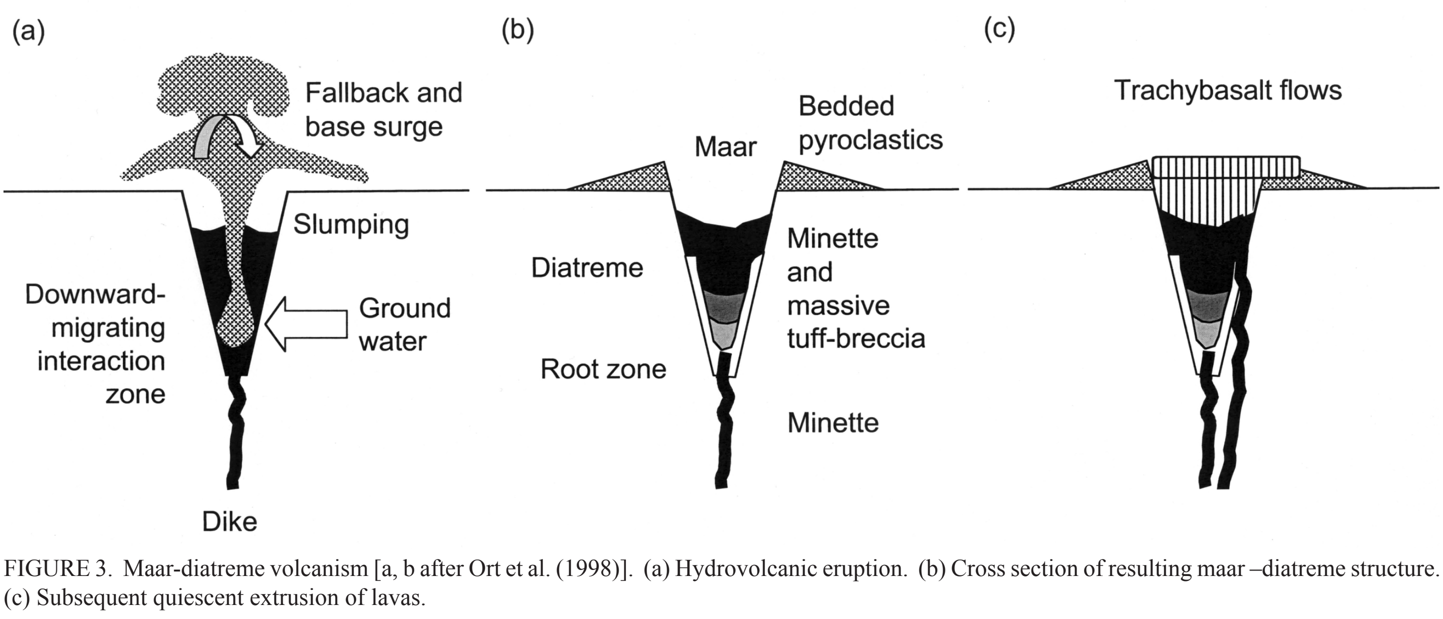

FIGURE 3. Maar-diatreme volcanism [a, b after Ort et al. (1998)]. (a) Hydrovolcanic eruption. (b) Cross section of resulting maar –diatreme structure. (c) Subsequent quiescent extrusion of lavas.

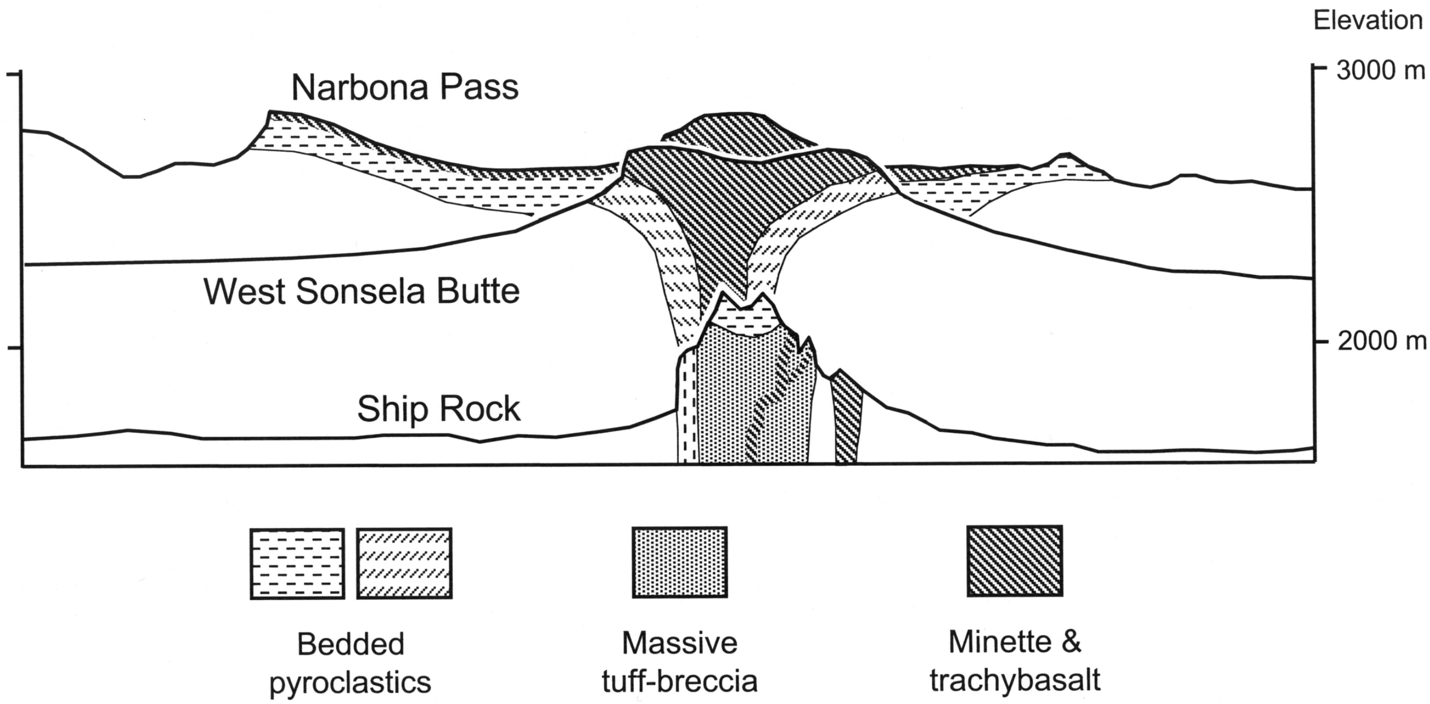

FIGURE 4. Comparative exhumation of the Ship Rock, West Sonsela Butte, and Narbona Pass volcanoes, after Ehrenberg (1978).

ages ca. 1.4 Ga for lower-crustal xenoliths from The Thumb and Red Mesa diatreme, which may indicate mafic underplating, or resetting of older ages by Paleoproterozoic tectonism.

Selverstone et al. (1999) used petrologic variations in Navajo crustal xenoliths to map a northwest-dipping convergent boundary between the Early Proterozoic Yavapai and Mazatzal crustal provinces, which is thought to strike northeast-southwest and pass just to the south of the Four Corners.

Many of the diatremes also contain large (tens of meters in size), mostly intact blocks of Phanerozoic sedimentary rocks that slumped in from the walls during eruption.

GEOCHRONOLOGY OF THE IGNEOUS ROCKS

Dating of the Navajo rocks has been complicated by the prevalence of wallrock-contaminated tuffs and breccias, and by alteration of many dikes. The first ages were obtained by Naeser (1971) by fission-track dating of apatites in minettes and inclusions. These ages range from 22.8 to 45.0 Ma, with most between 28 and 35 Ma.

Roden et al. (1979) obtained a K-Ar age of 25 Ma for the Buell Park diatreme, based on analyses of phlogopites from several minette dikes and from inclusions. Laughlin et al. (1986) subsequently published K-Ar ages from twelve phlogopites in dikes that range from 19.4 to 27.7 Ma. These were obtained using revised age constants, and Laughlin et al. (1986) have argued that the most reliable time span for Navajo volcanism is 28 to 19 Ma, late Oligocene to early Miocene. Recent $^{40}Ar/^{39}Ar$ geochronologic studies on Navajo minettes and trachybasalts have yielded good ages in this same range. G. Nowell (personal commun., 2002) reported ages ranging from 21.1 to 27.5 Ma for seven Chuska Mountain and Comb Ridge centers, and Cather et al. (this guidebook) obtained a mean age of 25.05 Ma for trachybasalts at Narbona Pass.

STORIES AND ETHNOGEOLOGY OF THE NAVAJO VOLCANIC FIELD

The *Diné* (Navajo people) invoke a direct connection between their cultural identity and the physical attributes of *Diné bikéyah*, their homeland on the Colorado Plateau. All landforms here have stories and histories associated with them, and the distinctive *tsézhiin 'íí 'áhí* of the Navajo volcanic field are certainly no exception. The roles of *Tsé bit'a'í* and other igneous features in the creation stories of the *Diné* can be found in the compilations by Matthews (1897) and Zolbrod (1984) and the children's book by Browne and Whitethorne (1993). It is important to note that such stories should be retold only with great respect and only during the winter months.

The indigenous *Diné* knowledge system also includes empirical knowledge of nature accrued through millennia of living in direct contact with their environment. That knowledge pertaining directly to the Earth is *Diné* ethnogeology, or *tsé na'alkaah* ("rock study").

A central principle of *Diné* ethnogeology holds that Earth materials and features result from continuous interactions of processes that operate in paired environmental systems referred to as *Nohosdzáán* (Earth) and *Yadiłhil* (Sky). Dynamic processes operating in the Earth can be equated to endogenic or solid-Earth processes such as magmatism and orogeny, and those operating in the Sky can be equated to exogenic or fluid-Earth processes such as the water cycle and weathering (Semken and Morgan, 1997). This model of endogenic-exogenic interaction is similar to that of process geomorphology (e.g., Summerfield, 1994), although traditional *Diné* see these processes as manifestations of living systems. A second duality is that between destructive or "male-like" processes, and constructive or "female-like" processes (Semken and Morgan, 1997).

These models can be combined to describe the origin and evolution of the Navajo volcanic landforms in a way that is logical and familiar to traditional *Diné* people (Semken, 1998): violent (male-like) interaction between magma (Earth) and meteoric water (Sky) formed the diatremes, and subsequent interaction between Colorado Plateau uplift (Earth-driven; female-like) and weathering and erosion (Sky-driven; male-like) exposed and sculpted the diatremes and dikes into their present shapes. *Diné* ethnogeology and other place-based, culturally-integrated scientific concepts are now being used to enhance science education in Navajo Nation colleges and schools (Semken, 2000).

IMPORTANT NOTICE

Many of the most spectacular features of the Navajo volcanic field can be observed from the major highways crossing the Four Corners region, but those located on lands of the Navajo Nation must not be accessed nor sampled without a permit obtained in advance from the Navajo Nation Minerals Department in Window Rock, Arizona.

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REFERENCES

Allen, J.E., and Balk, R., 1954, Mineral resources of the Fort Defiance and Tohatchi quadrangles, Arizona and New Mexico: New Mexico Bureau of Mines Mineral Resources Bulletin 36, 140 p.

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., 1994, Peridotite xenoliths from western Grand Canyon and The Thumb: a probe into the subcontinental mantle of the Colorado Plateau: Journal of Geophysical Research, v. 99, p. 21605-21620.

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.

Bailey, D.K., 1984, Kimberlite: the "mantle sample" formed by ultrametamorphism; in Kimberlites, I. Kimberlites and related rocks, Amsterdam, Elsevier, p. 323-333.

Broadhurst, J.R., 1986, Mineral reactions in xenoliths from the Colorado Plateau: Implications for lower crustal conditions and fluid composition; in Dawson, J.B., Carswell, D.A., Hall, J., and Wedepohl, K.H., eds., The nature of the lower continental crust: Geological Society of London Special Publication 24, p. 331-349.

Browne, V., and Whitethorne, B., 1993, Monster birds, a Navajo folktale: Flagstaff, Northland Publishing, 30 p.

Carlson, R.W., and Nowell, G.M., 1999, Re-Os evidence for a mafic mantle source for mafic-alkalic volcanism in the Colorado Plateau: Eos, Transactions, American Geophysical Union, v. 80, p. F-1131.

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.

Cather, S.M., Peters, L., Dunbar, N.W., and McIntosh, W.C., in press, Genetic stratigraphy, provenance, and new age constraints for the Chuska Sandstone (upper Eocene-lower Oligocene), New Mexico-Arizona: New Mexico Geological Society, Guidebook 54.

Crowley, J.L., Matzel, J.P., Bowring, S.A., Williams, M.L., Farmer, G.L., and Karlstrom, K.E., 2002, Paleoproterozoic to Mesoproterozoic evolution of southwestern North America: the view from the lower crust: Geological Society of America Abstracts with Programs, v. 34, no. 6, p. 253.

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

Delaney, P.T., and Pollard, D.D., 1981, Deformation of host rocks and flow of magma during growth of minette dikes and breccia-bearing intrusions near Ship Rock, New Mexico: U.S. Geological Survey Professional Paper 1202, 61 p.

Delesse, A., 1856, Memoire sur la minette: Annales des Mines, v. 10, p. 317-319.

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.

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

Ehrenberg, S.N., and Griffin, W.L., 1979, Garnet granulite and associated xenoliths in minette and serpentinite diatremes of the Colorado Plateau: Geology, v. 7, p. 483-487.

Esperança, S., and Holloway, J.R., 1987, On the origin of some mica-lamprophyres: experimental evidence from a mafic minette: Contributions to Mineralogy and Petrology, v. 95, p. 207-216.

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.

Hunter, W.C., 1979, The Garnet Ridge and Red Mesa kimberlitic diatremes, Colorado Plateau: geology, mineral chemistry, and geothermobarometry [Ph.D. thesis]: Austin, University of Texas, 231 p.

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.

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

Laughlin, A.W., Charles, R.W., and Aldrich, M.J., Jr., 1989, Heteromorphism and crystallization paths of katungites, Navajo volcanic field, Arizona, USA; in Ross, J., Jaques, A.L., Ferguson, J., Green, D.H., O'Reilly, S.Y., Danchin, R.V., and Janse, A.J.A., eds., Kimberlites and related rocks: Sydney, Geological Society of Australia, p. 582-591.

Lee, C.T., Yin, Q., Rudnick, R.L., and Jacobsen, S.B., 2001, Preservation of ancient and fertile lithospheric mantle beneath southwestern USA: Nature, v. 411, p. 69-73.

Lorenz, V., 1973, On the formation of maars: Bulletin Volcanologique, v. 37, p. 183-204.

Lorenz, V., 1986, On the growth of maars and diatremes and its relevance to the formation of tuff rings: Bulletin of Volcanology, v. 48, p. 265-274.

Matthews, W., 1897 (reprinted 1994), Navaho legends: Salt Lake City, University of Utah Press, 303 p.

Mattie, P.D., 1996, Geochemical study of xenoliths from the Navajo volcanic field, Arizona, New Mexico, and Utah [M.S. thesis]: Socorro, New Mexico Institute of Mining and Technology, 100 p.

Mattie, P.D., Condie, K.C., Selverstone, J., and Kyle, P.R., 1997, Origin of the continental crust in the Colorado Plateau: geochemical evidence from mafic xenoliths from the Navajo volcanic field, southwestern USA: Geochimica et Cosmochimica Acta, v. 61, p. 2007-2021.

McGetchin, T.R., and Silver, L.T., 1970, Compositional relations in minerals from kimberlite and related rocks in the Moses Rock dike, San Juan County, Utah: American Mineralogist, v. 55, p. 1738-1771.

McGetchin, T.R., and Silver, L.T., 1972, A crustal-upper mantle model for the Colorado Plateau based on observations of crystalline rock fragments in the Moses Rock dike: Journal of Geophysical Research, v. 77, p. 7022-7037.

McGetchin, T.R., Smith, D., Ehrenberg, S.N., Roden, M., and Wilshire, H.G., 1977, Navajo kimberlites and minettes field guide: Santa Fé, Second Annual Kimberlite Conference, 40 p.

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

Nicholls, J.W., 1969, Studies of the volcanic petrology of the Navajo-Hopi area, Arizona [Ph.D. thesis]: Berkeley, University of California, 107 p.

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

Nowell, G., and Rogers, N.W., 1993, Petrogenesis of the Navajo ultrapotassic volcanics and uplift-related magmatism on the Colorado Plateau: Terra Abstracts, v. 5, p. 57.

O'Brien, T.F., 1983, Evidence for the nature of the lower crust beneath the central Colorado Plateau as derived from xenoliths in the Buell Park-Green Knobs diatremes [Ph.D. thesis]: Ithaca, Cornell University, 205 p.

Ort, M., Dallegge, T.A., Vazquez, J.A., and White, J.D.L., 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, p. 35-58.

Padovani, E.R., Hall, J., and Simmons, G., 1982, Constraints on crustal hydration below the Colorado Plateau from Vp measurements on crustal xenoliths: Tectonophysics, v. 84, p. 313-328.

Riter, J.C.A., and Smith, D., 1996, Xenolith constraints on the thermal history of the mantle below the Colorado Plateau: Geology, v. 24, p. 267-270.

Roden, M.F., 1977, Field geology and petrology of the minette diatreme at Buell Park, Apache County, Arizona [M.A. thesis]: Austin, University of Texas, 148 p.

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 Shimizu, N., 1993, Ion microprobe analyses bearing on the composition of the upper mantle beneath the Basin and Range and Colorado Plateau provinces: Journal of Geophysical Research, v. 98, p. 14,091-14,108.

Roden, M.F., and Shimizu, N., 2000, Trace element abundances in mantle-derived minerals which bear on compositional complexities in the lithosphere of the Colorado Plateau: Chemical Geology, v. 165, p. 283-305.

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, D.C., American Geophysical Union, p. 364-381.

Roden, M.F., Smith, D., and McDowell, F.W., 1979, Age and extent of potassic volcanism on the Colorado Plateau: Earth and Planetary Science Letters, v. 43, p. 279-284.

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.

Schaefer, B.F., Turner, S.P., Rogers, N.W., Hawkesworth, C.J., Williams, H.M., Pearson, D.G., and Nowell, G.M., 2000, Re-Os isotope characteristics of postorogenic lavas: implications for the nature of young lithospheric mantle and its contribution to basaltic magmas: Geology, v. 28, p. 563-566.

Schmitt, H.H., Swann, G.A., and Smith, D., 1974, The Buell Park kimberlite pipe, northeastern Arizona: Geology of Northern Arizona: Flagstaff, Geological Society of America Rocky Mountain Section, p. 672-698.

Selverstone, J., Pun, A., and Condie, K.C., 1999, Xenolithic evidence for Proterozoic crustal evolution beneath the Colorado Plateau: Geological Society of America Bulletin, v. 111, p. 590-606.

Semken, S.C., 1998, Rooted in the Earth: culturally-integrated, place-based teaching: Geological Society of America, Abstracts with Programs, v. 30, p. A-246-A-247.

Semken, S.C., 2000, Indigenous geoscience education on the Navajo Nation: Eos, Transactions, American Geophysical Union, v. 81, p. S-64.

Semken, S.C., and Morgan, F., 1997, Navajo pedagogy and Earth systems: Journal of Geoscience Education, v. 45, p. 109-112.

Sheridan, M.F., and Wohletz, K.H., 1983, Hydrovolcanism: basic considerations and review: Journal of Volcanology and Geothermal Research, v. 17, p. 1-29.

Smith, D., 1995, Chlorite-rich ultramafic reaction zones in Colorado Plateau xenoliths: recorders of sub-Moho hydration: Contributions to Mineralogy and Petrology, v. 121, p. 185-200.

Smith, D., 2000, Insights into the evolution of the uppermost continental mantle from xenolith localities on and near the Colorado Plateau and regional comparisons: Journal of Geophysical Research, v. 105, p. 16769-16781.

Smith, D., and Ehrenberg, S.N., 1984, Zoned minerals in garnet peridotite nodules from the Colorado Plateau: implications for mantle metasomatism and kinetics: Contributions to Mineralogy and Petrology, v. 86, p. 274-285.

Smith, D., Griffin, W.L., Ryan, C.G., and Soey, S.H., 1991, Trace-element zonation in garnets from The Thumb: heating and melt infiltration beneath the Colorado Plateau: Contributions to Mineralogy and Petrology, v. 107, p. 60-79.

Smith, D., and Levy, S., 1976, Petrology of the Green Knobs diatreme and implications for the upper mantle below the Colorado Plateau: Earth and Planetary Science Letters, v. 29, p. 107-125.

Smith, D., Moser, D.E., Connelly, J.N., Manser, K., and Schulze, D.J., 2002, U-Pb zircon ages of eclogites, garnetites, and Cenozoic rock-water reactions in Proterozoic mantle below the Colorado Plateau: Geological Society of America Abstracts with Programs, v. 34, no. 6, p. 253.

Summerfield, M.A., 1994, Global geomorphology: Essex, UK, Longman, 537 p.

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.

Wang, L., Essene, E.J., and Zhang, Y., 1999, Mineral inclusions in pyrope crystals from Garnet Ridge, Arizona, USA: implications for processes in the upper mantle: Contributions to Mineralogy and Petrology, v. 135, p. 164-178.

Wendlandt, E.D., 1992, Isotopic and geochemical studies of continental lithosphere in cratons and active rifts: xenoliths from the Colorado Plateau and Río Grande Rift regions [Ph.D. thesis]: Los Angeles, University of California at Los Angeles, 217 p.

Wendlandt, E., DePaolo, D.J., and Baldridge, W.S., 1993, Nd and Sr isotope chronostratigraphy of Colorado Plateau lithosphere: implications for magmatic and tectonic underplating of the continental crust: Earth and Planetary Science Letters, v. 116, p. 23-43.

Wendlandt, E., DePaolo, D.J., and Baldridge, W.S., 1996, Thermal history of Colorado Plateau lithosphere from Sm-Nd mineral geochronology of xenoliths: Geological Society of America Bulletin, v. 108, p. 757-767.

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

Wilshire, H.G., Meyer, C.E., Nakata, J.K., Calk, L.C., Shervais, J.W., Nielson, J.E., and Schwarzman, E.C., 1988, Mafic and ultramafic xenoliths from volcanic rocks of the western United States: U.S. Geological Survey Professional Paper 1443, 179 p.

Wohletz, K., and Heiken, G., 1992, Volcanology and geothermal energy: Berkeley, University of California Press, 432 p.

Zolbrod, P.G., 1984, Diné bahane'—the Navajo creation story: Albuquerque, University of New Mexico Press, 431 p.