



When batholiths exploded: The Mogollon-Datil volcanic field, southwestern New Mexico

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WHEN BATHOLITHS EXPLODED: THE MOGOLLON-DATIL VOLCANIC FIELD, SOUTHWESTERN NEW MEXICO

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ABSTRACT — Beginning in 1950, studies of the Mogollon-Datil volcanic field contributed to documenting a mid-Tertiary *ignimbrite flareup* (~40-15 Ma on a continental scale, 36-24 Ma in New Mexico). During this event, parts of western Mexico and the southwestern USA were periodically flooded by incandescent magma foam erupted from heaving calderas up to tens of kilometers in diameter, atop exploding granitic batholiths. The discovery of similar events on other continents and geologic periods was strong evidence for the then-disputed magmatic origin of granite, a problem fundamental to understanding the origin and nature of continents.

During a proposed *extensional orogeny*, volcanism of the North American ignimbrite province began in the continental back arc of an ocean-to-continent convergent western plate margin. Regional chemical variations reflect location, thickness, and state of stress of the extending cratonic lithosphere. The unique 1200-km maximum distance of the province from the plate boundary resulted in part from ductile extension, in response to underplating of the continent by hot young oceanic lithosphere. Extension accelerated after the collision of the North American and Pacific plates and the transition from plate convergence to a lengthening transform plate boundary. Rising under extensional stress, mantle diapirs induced crustal melting. Siliceous magmas evolved as melting rose from lower to upper crustal levels. Contemporaneous high-Fe intermediate-to-mafic magmas evolved in the opposite direction, toward less depleted “primitive” magmas from progressively deeper mantle levels. Subsequent brittle extension of a cooling plate resulted in the present Basin-and-Range configuration and basaltic magmatism.

INTRODUCTION

In the middle of the 20th century, a big red patch on the USGS Geologic Map of New Mexico (Darton, 1928) was the only guide to the volcanic geology of southwestern New Mexico. It was labeled *arl* and described as Cretaceous to Tertiary “andesite, latite, rhyolite and basalt, tuff, agglomerate, ash and unclassified igneous rocks, mostly extrusive.” In other words, *igneous rocks of uncertain ages and classes, undifferentiated*. Within the scope of the 2008 NMGS Field Conference, details were available only for two mining districts, Silver City/Santa Rita (Paige, 1916; Spencer and Paige, 1935; Lasky, 1936) and Mogollon (Ferguson, 1927).

Tertiary volcanic rocks were widely despised as mere overburden to Laramide ore deposits, even though they were known to be mineralized, as at Mogollon. They were not considered worthy of serious study until 1950, when out-of-state graduate students were attracted to New Mexico by a fellowship program instituted by Dr. Eugene (Pat) Callaghan, Director of what is now the NM Bureau of Geology and Mineral Resources (*The Bureau*). The project grew for several decades, involving participants from Bureau staff, the USGS, and numerous academic institutions, including NM Tech, NMSU, and UNM. Their sweat and boot leather played a small but significant part in establishing siliceous volcanism as a global-scale geologic process. *Super-volcano* (Savino and Jones, 2007) has even entered the popular vocabulary, for explosions of granite batholiths which obliterate landscapes under torrents of incandescent magma foam.

This paper is a historical review, intended to fit Mogollon-Datil discoveries into the context of pre-1990 controversies concerning the origin of granite and the transition from Old to New Global Tectonics. Details of the discovery process can be found in Elston (2001); details of structure, stratigraphy, geochemistry and petrology in Chapin et al. (2004). That excellent summary covers mid-Tertiary volcanism in all of southwestern New Mexico, including the Boot Heel volcanic field, south of Mogollon-Datil. The author of the present paper is most familiar with workers of the UNM

group; if names associated with UNM are disproportionately cited, no slight of other groups is intended. For many reasons, work by academic researchers (and to a lesser degree by Bureau and USGS personnel) slackened after 1990, leaving much to be finished by future generations.

Two terms call for definition: *Caldera* was originally a topographic term for a hole on a volcano bigger than a crater. The meaning changed when it was discovered that post-collapse magma upheavals (resurgent doming) had made the center of the Valles Caldera its highest point. It is now used for topography of a volcano which had collapsed at some stage. *Cauldron* refers to the subsurface structure of a collapsed volcano. Cauldrons must be laboriously reconstructed from pieces brought to light by tectonic disturbances and erosion.

GEOGRAPHIC AND TECTONIC SETTING: A MEXICAN PERSPECTIVE

A glance at the map (Fig. 1) shows southwestern New Mexico to be a minor sub-province of a vast mid-Cenozoic (late Eocene to early Miocene) volcanic province. If viewed from a Mexican perspective, it extends from southern Mexico to the Great Basin of Utah and Nevada. It generally coincides with the Neogene Basin and Range province, which began to assume its present structure and topography as volcanism died down. In the central Mexican Highlands, volcanism and Basin-and-Range fault blocks are superimposed on a Laramide fold-and-thrust belt. To the west lies the Sierra Madre Occidental, one of the greatest volcanic plateaus on Earth, only modestly disrupted by Basin and Range faults. The Mogollon-Datil volcanic field can be considered its New Mexico outlier. Between them is the Boot Heel volcanic field (McIntosh and Bryan, 2000), where the Mexican Highlands split into two branches. The main branch heads northwest through southern Arizona and fans out in the Great Basin like a stretched-out accordion. The Rio Grande rift zone is the north-trending lesser branch, a system of big cracks and late volcanism (including the

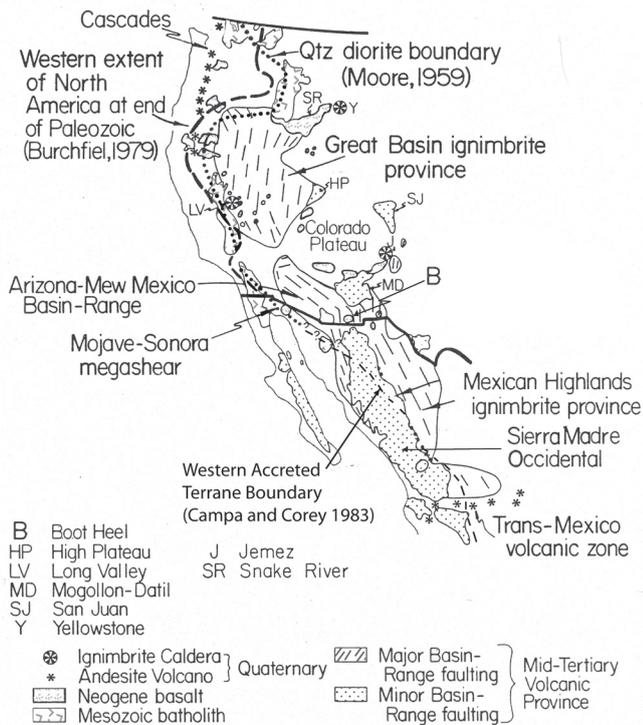


FIGURE 1. Major Mesozoic and Cenozoic igneous provinces of western North America. The mid-Tertiary ignimbrite flareup includes the region of later Basin and Range faulting (short lines) and relatively undisturbed volcanic plateaus (stippled). The quartz diorite boundary corresponds closely to the border between cratonic and accreted terranes; it divides high-K magmatic suites (east) from low-K suites (west). Modified from Elston (1984b).

Valles Caldera) which developed when the mobile western third of North America pulled away from the relatively stable interior. Before the Rio Grande rift dies out in central Colorado, it slices through another mid-Tertiary volcanic field, dividing the main mass of the San Juan field from its southeastern outlier, the Latir field at Questa, New Mexico. In a general way, the San Juan and Mogollon-Datil volcanic fields are mirror images on opposite sides of the Colorado Plateau. The succession of volcanic stages is similar, but there are differences in the degrees to which the stages developed. Both are late Eocene to early Miocene and both owe their relative stability to overlaps onto the Colorado Plateau.

FIRST STEP: A MOGOLLON-DATIL STRATIGRAPHIC FRAMEWORK

After the first quarter-century of hard effort, Darton's *arl* had given way to 135 named stratigraphic units (Elston, 1976) in just the northern (Mogollon-Datil) part of the volcanic sub-province of southwestern New Mexico. Today there would be over 200 entries, if the Boot Heel (beyond the scope of this paper) were included.

There were some bumps on the road. With investigators coming from different directions (geographic and mental), there were bound to be duplications and disputes. Early reconnaissance mappers (including, for his sins, Elston, 1960), confusingly extended the Datil Formation from its type locality north of Magdalena (Winchester, 1920; redefined by Wilpolt et al., 1946) over the entire Mogollon-Datil field. On their word, the compilers of a new USGS Geologic Map of New Mexico (Dane and Bachman, 1965) raised the Datil Formation to Datil Group of Miocene(?) age, and divided Mogollon-Datil volcanic rocks into pre-Datil andesite, Datil rhyolite and related siliceous rocks, and post-Datil basalt. The result was an ill-defined medley of intertonguing units, composed without any means of establishing long-range correlations (for details, see Elston, 1976, p. 134; 1994). The Miocene(?) age assignment for the Datil Group had the unfortunate effect of obscuring similarities between the San Juan and Mogollon-Datil volcanic fields for at least another 20 years (e.g., Bayer, 1983).

Eventually, a degree of order was imposed by K-Ar dates, determined mainly by P. E. Damon and associates (University of Arizona). By the early 1970s, a stratigraphic framework began to emerge (Elston et al., 1973), with rocks ranging in age from about 38 to 18 Ma, i.e., late Eocene to early Miocene, with peaks in the Oligocene. Unfortunately, K-Ar dates lacked precision. Conflicting interpretations arose, some of them from systematic differences between determinations based on sanidine and more accurate ones from biotite. Precision arrived with a combination of Ar-Ar dating and paleomagnetic measurements (McIntosh et al., 1991).

It turned out that there are two rhyolitic "Datil" sections, 36.1 to 31.3 Ma (with subsidiary pulses at 36.1 to 33.5 and 32.0 to 31.3 Ma) and 28.9 to 27.3 Ma (with a late outbreak at 24.3 Ma). They contributed >50% of the (conservatively estimated) 10^4 km³ volume of the Mogollon-Datil field. Calc-alkalic lavas of intermediate-to-mafic composition (dacite to basaltic andesite) erupted before, between, and after rhyolitic pulses. From about 32 Ma, they tend to be Fe-rich and dark; commonly mistaken for basalt. In the area covered by the present guidebook, true basalt remained rare until the later stages of Basin- and-Range faulting, locally at ~6 Ma (minipaper, Day 2, Stop 3, this volume).

THE RHYOLITE PROBLEM

The Voice of Authority: Rhyolite is Unimportant

The prevalence of siliceous volcanic rocks had surprised the early workers. In 1950, leading textbooks relied on the high authority of R. A. Daly of Harvard, who had integrated outcrop areas of volcanic rocks on all available North American geologic maps and questioned whether "... the total volume of the visible rhyolites of North America is as much as 1 per cent of the visible volume of basalt or that of the visible andesites" (Daly, 1914, p. 49). In plutonic rocks the felsic/mafic proportions are reversed; granite is vastly more voluminous than gabbro. Daly was aware of the rhyolites at Yellowstone, but dismissed them as unique and unrepresentative. Textbooks described rhyolite lavas

as too viscous to flow over more than short distances and one of them dismissed pyroclastic rocks with a footnote: "... the number of tuffs sent to petrographers for microscopic examination is out of all proportion to their abundance in the field" (Grout, 1932, p. 117). The leading European textbook proclaimed: "rhyolite does not have wide distribution" ("*Der Rhyolith hat keine grosse Verbreitung.*" Barth et al, 1960).

Authority Questioned: Mysterious Rhyolite Sheets of Silver City

Authority had long been contradicted in the Silver City quadrangle, where Paige (1916) had identified columnar jointed sheets as rhyolite lava flows. Beginning in 1950, mapping in adjoining areas (minipaper; Day 2, Stop 5, this volume) found that some of these sheets, from a few meters to cumulatively >100 m thick, had flowed for >100 km. The solution to the viscosity problem was offered by Pat Callaghan, who had seen similar rocks in the Great Basin: these rocks were not lava flows but *welded tuffs*, i.e., inflated hot pyroclastic flows of minimal viscosity, in which a matrix of incandescent glass shards had welded into hard rock. However, the degree of welding can vary, even within a single flow. As not all pyroclastic flows (also called *ash flows*; Smith, 1960) are welded, *ignimbrite* (Marshall, 1935) or *ash-flow tuff* (Ross and Smith, 1961) have replaced *welded tuff*. The volcanic province of Figure 1 was the site of a mid-Cenozoic *ignimbrite flareup* (term used by P. J. Coney in a letter to W. E. Elston, dated December 16, 1976; does any reader know of an earlier use in print?). It is now known that similar events have occurred on all continents, in all Phanerozoic geologic periods, and to even greater extents in the Precambrian.

Recognition of pyroclastic transport left unanswered the question of where and how the rhyolite sheets had erupted. Textbooks taught that small-volume rhyolite flows came from lava domes, but where did rhyolite sheets come from? Were they fed by hidden bodies of granite magma? Did not leading Authorities question the very existence of voluminous granite magma?

CONTROVERSY: IS GRANITE MAGMATIC OR METASOMATIC?

Confrontation: the Great Debate of 1947

From the 1930s into the 1960s, a fierce debate raged over the magmatic vs. metasomatic origin of granite. Granite is fundamental to continental basements and cores of continental mountain ranges. In our solar system, only planet Earth has well-defined continents and ocean basins. Basalt is the universal in rocky planets, but voluminous granite is diagnostic of Earth.

The climactic confrontation came at a symposium during the annual meeting of the Geological Society of America at Ottawa in 1947. The chief protagonists were H. H. Read (Royal School of Mines, London) on the side of those who held most granites to be transformed sedimentary rocks, and N. L. Bowen (Geophysical Laboratory, Washington), on the side of the magmatists. Their backgrounds illustrate two different approaches to geology: field

work ("The best geologist is he who has seen the most rocks;" Read, 1940) and the experimental observation of rocks "in process of formation" (Bowen, 1948, p. 80). Among advanced thinkers of that day, Bowen, father of the *reaction series*, was regarded as a reactionary

Read: The Case for Metasomatism

In the Ottawa symposium, Read (1948) conceded that there were *granites and granites* (the title of his presentation) but stated that he could not follow "the vertical leap from rhyolite to granite" (p. 3). While meditating upon granite in a WWII air-raid shelter, Read (1943-44) had cited Daly (1914) to conclude that rhyolites were insignificant and unrelated to most granites. Following Kennedy (1938), he restricted the term *igneous* to volcanic rocks, overwhelmingly basalt and andesite. Granite and related rocks belonged to a *plutonic* class, with metamorphic rocks and migmatites, i.e., mixed granitic and metasedimentary rocks.

The term *migma* or *ichor* was originally used to describe a granitic residual magma, highly enriched in fluids. It produced migmatites by soaking into metasedimentary rocks (Sederholm, 1933). In the hands of Wegmann (1935), it became a vaguely defined fluid that could turn sedimentary rocks into metasomatic granite by migration (*Stoffwanderung*). Read (1948) identified metasomatic granite by its *basic front* (Reynolds, 1947), a ferromagnesian aureole flushed from sedimentary rocks during granitization. Perrin and Roubault (1939) dispensed with fluids altogether. In their view, the ichor consisted of ions diffusing in the solid state.

Bowen Strikes Back: Granite and Rhyolite are Comagmatic

Bowen (1948) minced no words, beginning with the title of his presentation: *The granite problem and the method of multiple working prejudices*. He found large-scale solid-state diffusion to be contrary to the laws of physics, and ichor to be a substance which always did exactly what its proponents wanted it to do. Not finding any evidence for a basic front around great Mesozoic batholiths of western North America, he called "that corollary of wet granitization...a basic affront to the intelligence of the geologic fraternity" (p. 88). In Bowen's (1948, p. 86) "at the moment not very respectable" opinion, "most ... granitic rock ... was formed by crystallization of an intrusive molten magma closely resembling... rhyolitic lavas." Such magma could be formed in several ways, but "...most granites have been produced throughout geologic time by differentiation of basic (basaltic) magma..." (p. 87).

A year earlier, Bowen had contrasted petrologists who pontificated from solid experimental evidence with those who transformed rocks by soaking them with ichors, calling them "pontiffs and soaks...the soak must have his liquor in lavish quantities, but the former handles his liquor like a gentleman" (Bowen, 1947, p. 264). To which Read (1948, p. 1) cheerfully responded: "...pontiffs, I suggest to Professor Bowen, while capable of a greater number of good deeds, are also capable of a greater number of bad deeds than the village drunk."

Retrospect: Rhyolite has the Last Word

Today, the proceedings of the 1947 symposium (Gilluly, 1948) make curious reading. In the entire volume there is not a single chemical equation, nor is there a phase diagram (not even by Bowen). In the discussion section, only a junior member of the audience, Donald E. White (USGS), ventured the opinion (p. 124) that isotopes, “a new and untested approach,” might “conceivably” throw some light on the problem. Equally remarkable is the emotional fervor aroused by what is, after all, only a kind of rock. Sidney Paige (Columbia) remarked (p. 131) that “the symposium seemed at times to take on a slight flavor of the days of Werner.” Nobody challenged the supposed scarcity of rhyolite; even Paige never mentioned the rhyolites he had mapped in his youth at Silver City, New Mexico.

The decades since 1947 have brought consensus: Large granite bodies (as distinct from granite gneiss) are magmatic (victory for Bowen), commonly with an aureole of migmatites (consolation prize for Read). Criteria for recognizing magmatic granite have come from experiments (Tuttle and Bowen, 1958), major- and trace-element analyses, and isotopic determinations, but the ultimate proof for the existence of voluminous granitic magma has come from the connection between granite plutons and the abundant rhyolites of ignimbrite flareups.

All speakers in the 1947 Ottawa symposium assumed granite to be a deep-seated (abyssal) phenomenon, generated in the bowels of geosynclines. It would have caused a scandal if anyone had suggested that, under extensional stress, a body of granite magma could rise within a few thousand meters of the surface and explode, leaving a huge ignimbrite caldera as a lasting scar (Fig. 2). When evidence for such catastrophes accumulated in the 1960s, the Jemez and San Juan fields played a major role, followed closely by the Mogollon-Datil field. By 1967, Hamilton and Myers wrote of shallow batholiths independent of geosynclines, covered by their own volcanic ejecta. Even now, the batholith-rhyolite connection requires vigorous defense (Lipman, 2007).

EXPLODING BATHOLITHS AND RESURGENT CAULDRONS

The Denudation Series, Pro and Con

In 1887, Eduard Suess proposed a *denudation series*, which connected surficial volcanism to abyssal magma via a hypabyssal connection. The later discovery of ring complexes provided the hypabyssal level: as visualized for the Devonian ring complex of Glencoe, Scotland, volcanism was fed by ring dikes connected to a pluton. On the surface, a caldera formed by *cauldron subsidence* of the unsupported roof of the drained magma chamber (Clough et al., 1909).

The denudation series was rejected by the “soaks”, even for the two “anomalous” rhyolite provinces then known, Yellowstone (Iddings, 1899) and Lake Toba on Sumatra (van Bemmelen, 1939). To bolster his case, Read (1948) cited a dialog-in-print between two high European Authorities, the volcanologist Alfred

Rittmann and the structural petrologist Hans Cloos. When Rittmann opined that “plutonism and volcanism... have nothing to do with each other,” Cloos responded with “...the denudation series of Suess is no longer valid.” Rittman agreed: “Genuine plutons are... migmatic or palingenetic... transformed *in situ* by gaseous or fluid material... Migmatic material can become mobilized and exceptionally becomes extrusive... Rhyolites of Yellowstone Park and Lake Toba... are erupted diapiric migmatite plutons” (Cloos and Rittmann, 1939, translation by WEE). As before, the most radical opinion came from Doris L. Reynolds (1956, p.367-368): “Calderas are still explained in terms of supposed happenings in invisible and hypothetical magma chambers... Acid ejectamenta (of Lake Toba) are transfused sialic basement rocks (fused by gases) of the order of 1350°C.” No convincing evidence was provided for any of these extraordinary claims.

Resurgent Cauldrons: Valles Caldera and San Juan Volcanic Field

The nature and abundance of rhyolite ignimbrite (or *ash-flow tuff*) was documented by Smith (1960) and Ross and Smith (1961), bringing fame to New Mexico’s own Bandelier Tuff. *Valles-type caldera* became an international term. The denudation series was resurrected by Smith *et al.* (1961), who interpreted the ring of rhyolite domes in the moat of the Valles Caldera (diameter 20 km) as the surface expression of a ring dike. This was broadened into a sequence (Fig. 2a-d) in which a granite batholith leaked, exploded and collapsed, resurged, and rejuvenated, creating a *resurgent cauldron* (Smith and Bailey, 1968; Smith, 1979; Hildreth, 1979). Ignimbrite cauldrons are indeed “windows into the tops of granitic batholiths” (from the title of Lipman, 1984).

By the 1960s, cauldrons were being documented on the Nevada Test Site (Byers et al., 1963, 1978) and the San Juan Mountains of Colorado (max. diameters in the tens of kilometers; Steven and Ratté, 1965; Luedke and Burbank, 1968; Steven and Lipman, 1968). Gravity and aeromagnetic surveys outlined the San Juan pluton, at 2-7 km depth (Plouff and Pakiser, 1972). A large literature now covers the association of San Juan cauldrons with ore deposits, by combination genetic and (mostly) structural controls (Lipman et al., 1976). The explosive stage of cauldron development (Fig. 2b) disperses trace elements of potential economic value, but hydrothermal activity associated with ring-fracture intrusions (Fig. 2d) can concentrate them.

Lipman (1976) cited breccia wedges engulfed in massive ignimbrite as evidence for simultaneous caldera collapse and caldera filling. Previously, the breccias had either been given tectonic interpretations or were simply labeled *chaos*. Caldera-collapse megabreccias (clasts 1 to hundreds of meters) played an important role in documenting the Bursum and Emory cauldrons of the Mogollon-Datil field (Fig. 3, nos. 3, 12; minipapers, Day 2, Stop 3, Day 1, Stop 2; this volume) and in the interpretation of certain Arizona copper porphyries as ring-fracture intrusions into Laramide cauldrons (Lipman and Sawyer, 1985). However, the Santa Rita (Chino) porphyry of New Mexico is not of this type (minipaper, Day 1, Stop 5).

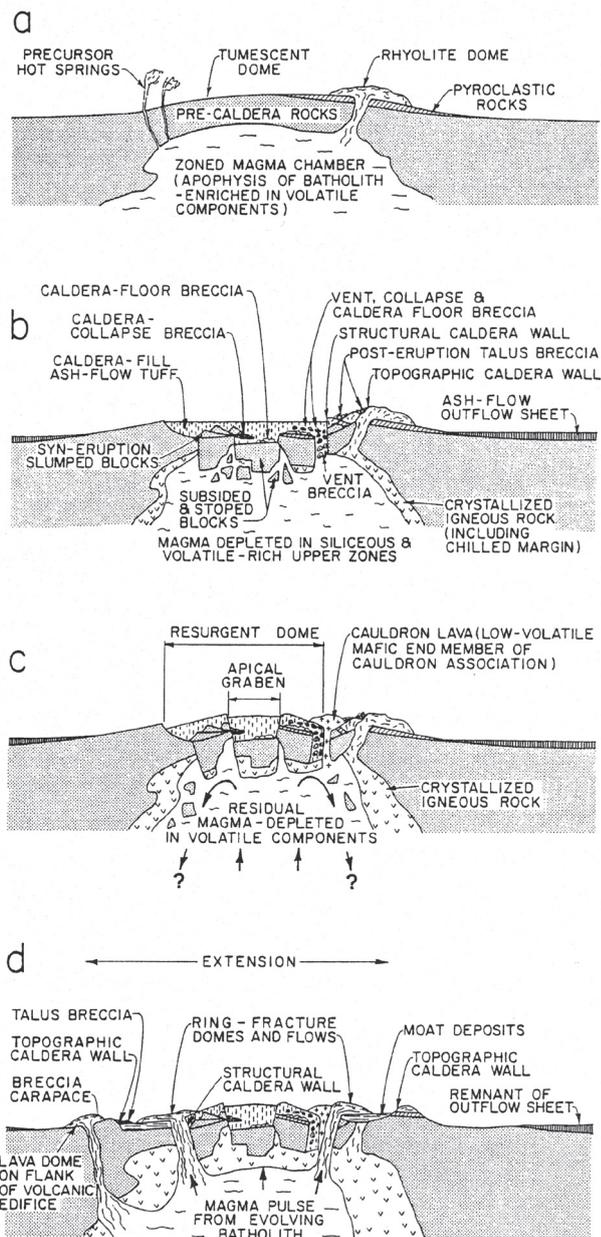


FIGURE 2. Idealized stages in the evolution of a resurgent ignimbrite cauldron and the underlying magma chamber. Actually, no two cauldrons are alike. They can be asymmetrical (including trapdoor-type half-cauldrons); stages in development can be omitted or repeated. Modified from Elston (1984a).

a. Precursor stage: Surface inflation, leakage from the magma chamber.

b. Stage of explosion, eruption, and caldera collapse: Massive ignimbrite (ash-flow tuff) fills the caldera; the overflow forms a thinner but widespread outflow sheet. Note the varieties of breccias.

c. Resurgence stage: Defluidized residue leaks from the magma chamber, forms lava domes. Continued rise of the magma chamber raises the caldera into a dome, usually (but not always) with a central keystone graben.

d. Moat and ring-fracture dome stage: Erosion widens the caldera into a moat filled with pyroclastic and sedimentary deposits. Rejuvenated magma leaks through ring fractures, forms one or more rings of rhyolite lava domes. At an intermediate erosion level, the root of the caldera would be a ring complex with subsided central cauldron.

The Mogollon-Datil Volcanic Field

At the core of the Mogollon-Datil field, the Mogollon Plateau (Fig. 3) is a roughly circular basin, drained by the headwaters of the Gila, and surrounded by a ring of mountains. A controversy over the origin of lunar craters (impact vs. volcanism) was hot in the 1960s, and Elston (1965a) cited the Mogollon Plateau as a possible volcano-tectonic terrestrial analog. This suggestion did not survive the Apollo landings but a NASA-sponsored field investigation eventually evolved into a long-term UNM group project with various sponsors. The first year, 1964-65, laid an early basis for a developing stratigraphic framework (Elston, 1965b), including a sequence of ignimbrite sheets and intertonguing intermediate-to-mafic lavas. The mountainous rim of the Gila Basin holds a discontinuous ring of rhyolite lava flows and domes, of several post-29 Ma ages. By analogy with the Valles Caldera, it could be interpreted as the surface expression of a ring complex and the entire Mogollon Plateau as the surface expression of a composite batholith, 125 km in diameter (Fig. 3; Elston et al., 1976a). Its existence was confirmed by the gravity survey of Krohn (1976). Taking a cue from the USGS San Juan experience, cauldrons were identified, superimposed on the pluton(s) (Coney, 1976; Rhodes, 1976, Deal and Rhodes, 1976). The first decade of work (by the UNM Group and many others) was summarized in a memorial volume dedicated to Rodney Rhodes (Elston and Northrop, 1976) and a field guide (Chapin and Elston, 1978).

It appears that prior to 31 Ma, cauldrons developed over widely scattered plutons; after 29 Ma siliceous magmatism was consolidated into a batholith 125 km wide, outlined by the rhyolite lavas of the Mogollon Plateau ring complex. The Magdalena-San Mateo Mountains cauldron cluster may be underlain by a separate pluton. Figure 3 shows the outline of only the inferred post-29 Ma pluton(s). Between ~31 and 29 Ma and after ~24 Ma, dark high-Fe intermediate-to-mafic magmas, largely mantle-derived, were able to reach the surface, unhindered by a pillow of low-density siliceous magma. Figure 4 shows the alternation of siliceous and intermediate-to-mafic magmatism.

By the late 1960s and into the 80s, other groups had become active, notably from the USGS in the Mogollon Mountains (Ratté and Gaskill, 1975; Ratté et al., 1984; Ratté, 1989) and Black Range (Erickson et al., 1970; Hedlund, 1977), The Bureau in the Socorro-Magdalena area (Chapin et al., 1978; Osburn and Chapin, 1983; Chapin, 1989), NMSU in the Las Cruces area and Black Range (Seager, 1981; Seager et al., 1976, 1982), and other academic institutions (e.g., Sr-isotope studies by Stinnet and Stueber, 1976, and Bikerman, 1989). The Mogollon Plateau pluton was reconfirmed by gravity and seismic studies of Schneider (1990). Additional names can be found in Ratté et al. (1989), Elston (2001), and Chapin et al. (2004). Documentation for cauldrons in Figure 3 is uneven; more details can be found in the extended caption of figure 2 in Elston (1984a). There are indications of other cauldrons, but documentation is insufficient for inclusion in Figure 3. Another cauldron cluster is located in the Boot Heel (Deal et al., 1978; modified by McIntosh and Bryan, 2000).

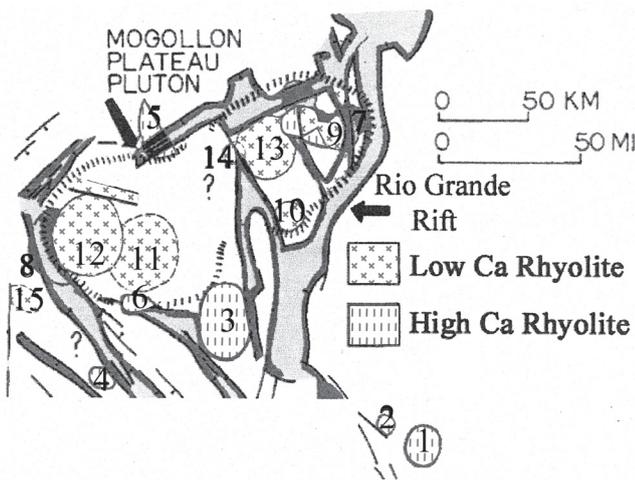


FIGURE 3. Tectonic sketch map of the Mogollon-Datil volcanic field, showing cauldrons, the inferred post-29 Ma Mogollon Plateau pluton and its Magdalena-San Mateo appendage or subsidiary, and the surrounding post-20 Ma graben system, modified from Chapin et al. (2004) and Elston (1984a). Cauldrons differ in degrees of documentation; ages of cauldrons are for the main eruptive ignimbrite eruptive (Fig. 2b); dates are Ar^{39}/Ar^{40} determinations (errors are in the range of ± 0.4 to 0.14 Ma) by McIntosh *et al.* (1991), unless otherwise indicated. Cauldrons, in order of age: 1- Organ, 36.1. 2- Doña Ana, 35.4. 3- Emory, 34.8. 4- Schoolhouse Mountain, limits uncertain, 33.5. 5- Crosby Mountain half-cauldron, 32.7 ± 1.3 , fission track (Jones, 1980). 6- Twin Peaks, limits uncertain, 31.3. 7- Socorro, 32.1. 8- Mogollon, fragmental exposures, undated, ~ 32 . 9- Sawmill Canyon-Magdalena, 28.8. 10- Nogal Canyon, 28.5. 11- Gila Cliff Dwellings, uncertain, ~ 28 . 12- Bursum, 28.1. 13- Mount Withington, 27.4. 14- Bear Trap. 24.3. 15- Mule Creek half-cauldron, not dated; bracketed 25-18.8 Ma (Elston, 1984a).

As in Colorado, there are correlations between mineralization and cauldron margins (Elston et al., 1976b). At Mogollon, the control is structural rather than genetic (minipaper, Day 1, Stop 2, this volume); for most of the other examples, the genetic connection (or lack of it) is unclear.

Granite-rhyolite consanguinity was first demonstrated in New Mexico for the Juniper cauldron, Boot Heel field, on the basis of zircon morphology (Alper and Poldervaart, 1957). It is clearest in the partially preserved Organ cauldron (Fig. 3 no. 1), where a 3-km section of caldera-fill ignimbrite subsided into a granitoid batholith (Seager, 1981). The shallow Crosby Mountain asymmetrical "trapdoor" half-cauldron (Fig. 3, no. 6) is noted for clasts of quartz monzonite porphyry, identical in age and composition with tuff breccia cauldron fill. Additional clasts of jasperoid with delicately zoned crusts of skarn minerals were interpreted as sedimentary rocks from the roof of a magma body, successively hydrothermally altered, ejected as accidental xenoliths in tuff breccia, and metamorphosed after deposition (Jones, 1980; Ratté and Modreski, 1989). In the fill of the Emory cauldron (Fig. 3, no. 3), O'Brien (1986) interpreted megaclasts of a unique high-temperature ($>900^\circ$), low-pressure (<1 kb), granite-aplite-pegmatite assemblage, with sanidine as the K-spar phase, as cogenetic with a rhyolite porphyry-ignimbrite assemblage.

MAGMA SUITES: EVOLUTION IN OPPOSITE DIRECTIONS?

The victory won by Bowen (1948) in the campaign for magmatic granite proved to be incomplete. The compositional trends of volcanic rocks in the Mogollon-Datil field and elsewhere in the mid-Tertiary province do not show the smooth basalt-andesite-rhyolite transitions implied by his reaction principle. Instead, they show two magma suites developing in opposite directions (Fig. 4), a siliceous one increasingly evolved and "continental," the other intermediate-to-mafic and increasingly primitive and "oceanic:"

(1) A high-potassium siliceous suite began about 38 Ma with andesite and evolved through high-Ca rhyolite ($\sim 36-31$ Ma) to high- SiO_2 , low-Ca rhyolite ($\sim 28-24$ Ma). On Figures 3, 4, and

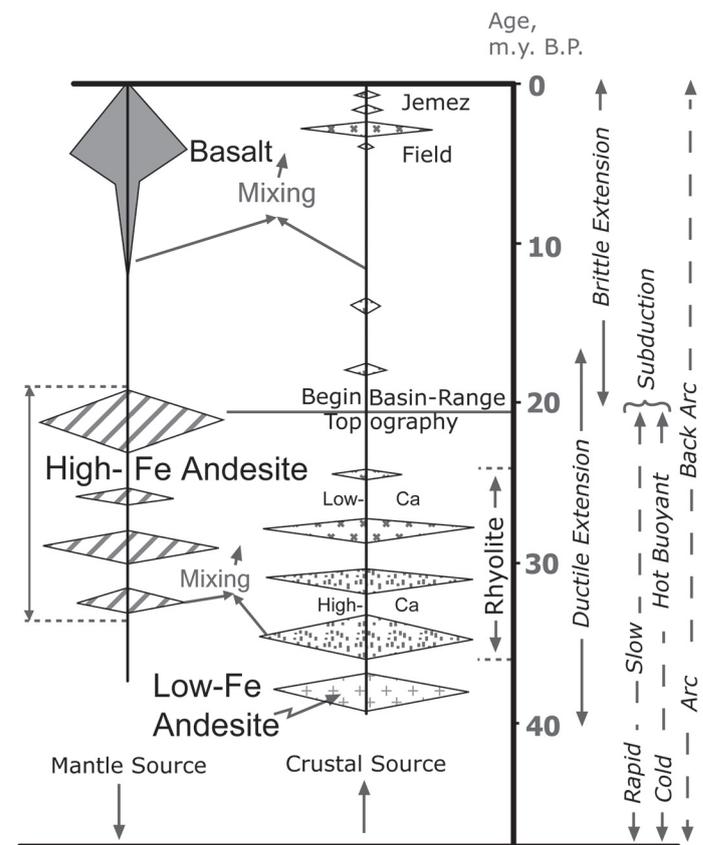


FIGURE 4. Cenozoic magma suites, southwestern New Mexico and Rio Grande rift.

Right branch, crustal suite: Low-Fe andesite (++) ~ 38 Ma, high-Ca rhyolite (stipples), 36-31 Ma; low-Ca rhyolite (xx), 28-24 Ma; renewed eruptions in Valles caldera, 2 Ma-50 Ka.

Left branch, mantle suite: High-Fe intermediate-to-mafic basaltic andesite (slanted lines), pre-20 my: Continuous beyond the Mogollon Plateau pluton, between and after siliceous pulses on the Mogollon Plateau.

Left branch, top: Basalt post-15 Ma, locally post-6 Ma

Right side: Transitions in magma suites correlated with proposed tectonic regimes (Fig. 5).

5, different patterns distinguish the high- and low-Ca suites. By geochemical criteria (e.g., a growing Eu anomaly) and in Sr isotopes (Bornhorst and Brookins, 1988) the trend is toward an increasingly evolved state, which can be attributed to a combination of fractional crystallization of andesitic magma and melt zones progressively rising from enriched upper mantle to lower crust and upper crust (Bornhorst 1980, 1988a; Abitz, 1989). The final product is “moonstone tuff,” i.e. a highly evolved rhyolite characterized by crystals of quartz and sanidine cryptoperthite (“moonstone”), which plots at the ternary minimum of the system Q-Or-Ab-H₂O (i.e., the final residue of fractional crystallization; Tuttle and Bowen, 1958). A prominent example is Bloodgood Canyon Tuff, probably early outflow from the Bursum cauldron (Fig. 3, no. 12; minipaper, Day 1, Stop 2, this volume). The transition from high-Ca and low Ca-rhyolite at about 30 Ma is widespread in the ignimbrite province.

Applying trace-element determinations by Bornhorst (1980) to the discrimination diagrams of Pearce et al. (1984), the high-Ca siliceous rocks have characteristics of granites from convergent continental plate margins. The younger and chemically more evolved low-Ca group has “within-plate” continental characteristics. High-alkali rocks from the northern edge of the field, which overlaps the Colorado Plateau, have “within-plate” characteristics from the beginning (Elston and Bornhorst, 1986; Elston et al., 1987; Abitz and Elston, 1988).

(2) A high-Fe calc-alkalic suite of intermediate-to-mafic (mainly andesite and basaltic andesite) composition (~32-18 Ma). The most mafic end members have ~51% SiO₂ and normative quartz; olivine has characteristically altered to goethite (“iddingsite”). A tendency toward less depleted and more primitive “oceanic” basaltic magmas from progressively deeper mantle sources became marked after 18 Ma. During a transition interval, the melt zones passed from lithospheric to asthenospheric mantle and then yielded true alkali olivine basalts (Fodor, 1975; Bornhorst, 1980, 1988b; Davis and Hawkesworth, 1993; Davis et al., 1993).

The contradiction of one place being both “within-plate continental” and “oceanic” challenges the tectonic classification of rock suites, and calls for explanation.

SOLUTIONS FROM GLOBAL TECTONICS, OLD AND NEW

Failure of the Old Global Tectonics

The mid-Tertiary North American ignimbrite province does not fit easily into any tectonic model. Authorities of the Old Global Tectonics (e.g., Stille, 1940) linked volcanic suites to specific stages of the geosynclinal-orogenic cycle, but the province in Figure 1 ignores the boundaries of geosynclines and orogenic belts. In attempts to fit the tectonics of both Americas into his world-wide cycles, Stille (1940, 1950) established a special *subsequent* magmatic stage, characterized by orogenic magmatism and post-orogenic timing. The North American type locality was sited between Bisbee, Arizona, and the Colorado Plateau, which presumably includes the Mogollon-Datil volcanic field. The classification failed because the few thousand meters of pre-volcanic

epicontinental Paleozoic and Cretaceous strata of the Silver City area do not a geosyncline make, not even one of the many types created by Kay (1951; embellished by his students by the addition of *microgeosyncline*, formerly known as *ripple mark*). This fact also ruled out generation of granite at the depths of geosynclines, as assumed by both sides of the origin-of-granite debate.

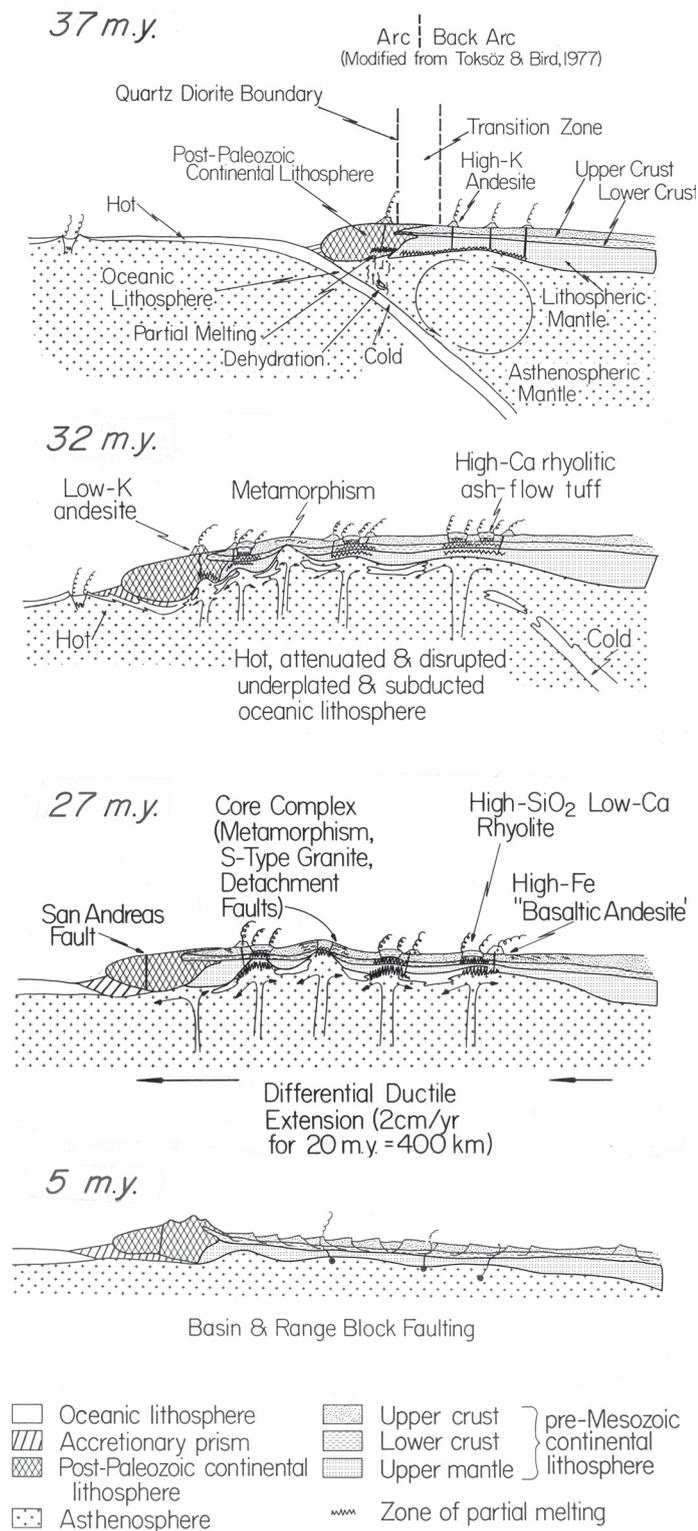
A Proposed Plate-Tectonic Scenario

With the advent of New Global Tectonics, it became apparent that timing of the North American ignimbrite flareup coincided with a transition of the western plate boundary, from convergent to transform (McKenzie and Morgan, 1969; Atwater, 1970; 1989; Lipman et al., 1972; Coney, 1972; Sevringhaus and Atwater, 1990). Based on this event, a tectonic scenario (Fig. 5) was designed to explain (1) the unique width of the province, 1200 km from the western plate margin to Trans-Pecos Texas (Fig. 1); (2) the continuation of volcanism after subduction had ceased; (3) the apparent contrary directions in the evolution of the two principal volcanic rock suites (Fig. 4); and (4) an increase in alkalis of igneous rocks, from the Pacific coast across western North America (as noted by Lindgren, 1915, and Callaghan, 1951).

At the beginning of mid-Tertiary volcanism, high-K andesite was generated in the back arc of an ocean-to-continent convergent plate margin, by partial melting at the base of the cratonic lithosphere (Fig. 5a). Had subduction continued, back-arc extension might have separated the western Cordillera from North America, to form small oceans in place of the Great Basin and Rio Grande Rift (cf., Sea of Japan and Gulf of California). Instead, the Pacific spreading center approached North America (Fig. 5b), the remains of the subducting Farallon plate (squeezed between the North American and Pacific plate) splintered, slab-pull ceased to operate (Carlson et al., 1983), and young, low-density, hot, and thin oceanic lithosphere was underplated beneath the continent. Under increasing back-arc extension, upwellings of hot mantle induced partial melting of the lower crust, generating the high-Ca siliceous magmas which fed the older ignimbrite cauldrons (Fig. 4 lower right).

A crucial change in stress directions occurred between ~35-30 Ma, as the Pacific plate collided with North America (Fig. 5c). As a lengthening transform boundary took the place of plate convergence, high-Ca plate-margin ignimbrites gave way to low-Ca within-plate varieties. The timing varies with latitude and local conditions; in the Mogollon-Datil field it coincides with the ~30 Ma switch from convergent plate-margin to plate-interior volcanic suites.

After ~30 Ma, the continental plate was free to extend. As the continental lithosphere thinned under ductile extension, crustal core complexes (Crittenden et al., 1980) and mantle diapirs rose in response (Fig. 5c). By decompression, rising mantle diapirs generated intermediate-to mafic high-Fe magmas from progressively lower and less depleted levels of the mantle (Fig. 4, left side.). Simultaneously, induced crustal melts became increasingly siliceous as solidus isotherms rose from the lower to upper crust. They evolved into low-Ca rhyolite (Fig. 4, right middle; Fig. 5c) by differentiation and by rising zones of partial melting. Under



ductile extension, domino-style listric fault blocks did not pose serious obstacles to spreading ash flows (Chamberlin, 1983).

After ~20 Ma, Basin-and-Range fault blocks developed, as the lithosphere cooled and extension changed from ductile to brittle (Fig. 5d). This transition coincided with the change from the high-Fe basaltic andesite suite to true basalt. Deep faults tapped "primitive" basaltic magma from zones in the mantle less depleted by previous melting episodes (Fig. 4, left top). At intersections of major structures (e.g., Jemez lineament and Rio Grande Rift), accumulations of basaltic magmas at the base of the crust continued to induce crustal melting into Quaternary time. The Valles, Yellowstone, and Long Valley Calderas represent the last flickering embers of the Great North American Ignimbrite Flareup.

Throughout the zone of extension, elevations rose in response to thermal expansion and widespread melting of the lithosphere, creating a large negative Bouguer anomaly (Eaton, 1982). In many places, core complexes or resurgent domes of cauldrons form conspicuous mountains, superimposed on the general uplift. In the Mogollon-Datil field, the highest elevations of the Magdalena and San Mateo Mountains and of the Black Range are within resurgent domes (Fig. 3); in the Mogollon Range the resurgent dome of the Bursum cauldron is topped by basaltic andesite volcanoes (Fig. 1 in minipaper, Day 1, Stop 2, this volume). If *orogeny* is the process of episodic mountain building, the term *extensional orogeny* (Elston, 1984b) seems appropriate, even though it has not found much favor among geologists.

FIGURE 5. Diagrammatic sketches of proposed scenario for tectonic evolution of the mid-Tertiary volcanic province and the Basin and Range province, at the latitude of southern New Mexico, modified from Elston (1984b).

a. 37 Ma, stage of steep subduction: Low-K andesite erupts in a plate-margin zone on accreted terrane, above the subducting Farallon plate. High-K andesite erupts on a broad and extending back arc, generated at the crust-mantle boundary by heat transferred by induced convection above the descending oceanic plate (Toksöz and Bird, 1971).

b. 32 Ma, pre-collision stage of shallow subduction: As Pacific spreading center approaches American continent, slab-pull subduction ceases (Carlson *et al.*, 1983). Young, hot, thin oceanic lithosphere ceases to be a heat sink; becomes buoyant, and ruptures as it underplates the extending continental back arc. Mantle diapirs rise through ruptured underplated oceanic lithosphere, generate high-Ca siliceous magma by induced melting of lower continental crust. Siliceous magma bodies rise and explode in caldera-forming eruptions.

c. 27 Ma, post-collision stage of maximum ductile extension in former back-arc: Lengthening of oblique transform plate boundary places continental lithosphere under increasing extensional stress; lithosphere yields by ductile extension; weak zones rise as core complexes. Mantle diapirs generate melts from progressively lower mantle zones, which mix with lower crustal melts to generate the high-Fe mafic-to-intermediate magma suite. Crustal melt zones rise; shallow, low-Ca siliceous plutons explode in caldera-forming eruptions.

d. 5 Ma, stage of brittle extension: Cooling continental lithosphere is under continuing extensional stress from oblique transform plate boundary. Brittle zone of lithosphere thickens, upper crust fractures into listric Basin and Range fault blocks; faults flatten at the brittle-ductile boundary. Basaltic magma rises from local melt pockets in the upper mantle, tapped by deep fractures.

Discussion

Figure 5 is an updated version of a scenario in Elston (1984b), one of many attempts to link mid-Tertiary plate-tectonic and volcanic events. Lipman et al. (1972) were first to correlate plate collision at ~30 Ma to a transition in volcanic suites from a plate-margin calc-alkalic (high-Ca) suite to what they called a bimodal basalt-rhyolite association. Their rhyolites are the low-Ca within-plate rocks of this report, but their basalts are dark high-Fe intermediate-to-mafic calc-alkalic flows, distinct from post-20 Ma true basalts (Fig. 4, left). The high-Fe rocks (mainly basaltic andesite) are abundant in relatively stable areas, e.g., the Mogollon Rim of New Mexico and Arizona (including the Mogollon-Datil field; see figure 10 in Elston et al., 1976a) and the Sierra Madre Occidental (the SCORBA suite of Cameron et al. 1989). They are scarce in the Basin and Range country, e.g., the Boot Heel and adjacent Chihuahua and Arizona.

Lipman et al. (1972) related the eastward increase in alkalis to the K-h relationship of Hatherton and Dickinson (1969), who had correlated increasing potassium with depth to a steeply dipping subducted slab (or twin slabs, according to Lipman et al., 1972). If the scenario in Figure 5 is valid, the subducted slab ceased to dip steeply as the Pacific spreading center approached North America (Fig. 5b). As a test, an alternative plot of the data points in Lipman et al. (1972) was drawn (figure 4 in Elston, 1984b). The result found K values to correlate well with composition, thickness and state of stress of the lithosphere: low-K igneous rocks west of the quartz diorite boundary of Moore (1956) and high-K rocks to the east (Figs. 1, 5). Highest values plotted on the fringe of the relatively stable Colorado Plateau and Great Plains, the area where within-plate chemistry prevailed throughout the ignimbrite flareup.

The quartz diorite boundary closely matches the margin of cratonic North America at the end of the Paleozoic (Burchfiel, 1979; Fig. 1). West of it are the predominantly oceanic “suspect” terranes of Coney et al. (1980), accreted to North America during the Mesozoic. It is also marked by changes in Pb and Sr isotope ratios (Zartman, 1974; Kistler and Peterman, 1978). Where the boundary between craton and accreted terranes (Fig. 1) crosses the Sierra Madre Occidental (Campa and Coney, 1983; Albrecht and Goldstein, 2000), low-K ignimbrites to the west are characterized by phenocrysts of quartz, plagioclase, and orthopyroxene; high-K ignimbrites to the east by quartz, sanidine±plagioclase, and biotite. New Mexico lies on the high-K craton. Petrography and timing of eruptive stages are similar for the Mogollon-Datil and Boot Heel fields, but trace-element and Sr-isotope systematics are different. This suggests that their protoliths belonged to separate lithosphere blocks, accreted to the North American craton at different times during the Proterozoic (data from many sources, summarized by Chapin et al., 2004, tables 3, 4, 5).

AFTERWORD

After 1990, mapping by Bureau staff continued in the Socorro area (notably Chamberlin, 2001) and by members of the USGS, especially in the northern part of the Mogollon-Datil field (com-

piled by Ratté, 2001). McMillan et al. (2000) reported on continued NMSU geochemical and petrogenetic studies in the southern region, along the Rio Grande. However, with diminished academic effort, the work of earlier decades is in danger of being forgotten. Sad to say, the latest 1:500,000 Geologic Map of New Mexico (Anderson et al., 2003) does not depict any cauldrons in southwestern New Mexico (likened to a performance of *Hamlet* without the Prince of Denmark). The latest version of the NMGS-Bureau 1:1,000,000 New Mexico Geologic Highway map (Wilks et al., 2005) shows them only on an insert, appropriately labeled “*Supervolcanoes.*”

If research is to revive, what would be the next step? Pre-1990 petrogenetic and tectonic models need to be brought up to date. The sources of many ignimbrite sheets remain to be found. There have been no systematic studies in physical volcanology. Deeply dissected areas of alteration (e.g., Alum Mountain on the edge of the magnificent Gila Canyon) offer opportunities for studying hydrothermal-geothermal processes in three dimensions. Above all, much remains to be learned about the interactions of plutonic and volcanic magmatism. With all the attention lavished on ignimbrites, the fluid-depleted rhyolite lavas have been neglected. These signature rocks of the proposed Mogollon Plateau ring complex were examined in the Mogollon Mountains (Rhodes, 1976), the Sierra Diablo (Seaman, 1988) and the Taylor Creek district of the northern Black Range (Eggleston and Norman, 1983; Duffield and Ruiz, 1992) but have seen no comprehensive study. The ubiquitous andesitic lavas at the base of the volcanic section have not been integrated into the total picture. None of their eruptive centers are known. With detailed knowledge of volcanic stratigraphy, the Mogollon-Datil field offers unequalled opportunities for studies of magmatic processes, with sampling at every stage. Mapping remains incomplete, especially in the Boot Heel field, where Basin-and-Range faulting caused 10 km of structural relief, down to plutonic roots. Opportunities abound: this paper was written in the hope that a new generation of researchers will build upon the foundations laid by their predecessors, to improve, verify, or falsify their interpretations.

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For the past 50 years, my attempts at unraveling New Mexico geology were part of a group effort, shared with dozens of students and former students who became friends and valued associates. Stimulation has come from colleagues at the University of New Mexico and many other institutions. I cherish the fondest memories of the independent yet ever-helpful people of a gloriously wild and remote corner of the United States. Financial support over the years came from the now-New Mexico Bureau of Geology and Mineral Resources, NASA, National Science Foundation, USGS, NM Energy Research and Development Agency, and the University of New Mexico. A fruitful 1986 sabbatical at the Open University (UK), sponsored by the Royal Society, resulted in a grant from the Natural Environmental Research Council (UK) to C.J. Hawkesworth for the study of intermediate-to-mafic rocks by J.M. Davis. Finally, my sincere thanks to Chuck Chapin and Barry Kues for their helpful reviews.

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