Introduction: The 36–18 Ma southern Great Basin, USA, ignimbrite province and flareup: Swarms of subduction-related supervolcanoes

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ABSTRACT

During the middle Cenozoic, from 36 to 18 Ma, one of the greatest global expressions of long-lived, explosive silicic volcanism affected a large segment of southwestern North America, including central Nevada and southwestern Utah in the southern Great Basin. The southern Great Basin ignimbrite province, resulting from this flareup, harbors several tens of thousands of cubic kilometers of ash-flow deposits. They were created by more than two hundred explosive eruptions, at least thirty of which were super-eruptions of more than 1000 km³. Forty-two exposed calderas are as much as 60 km in diameter. As in other parts of southwestern North America affected by the ignimbrite flareup, rhyolite ash-flow tuffs are widespread throughout the southern Great Basin ignimbrite province. However, the province differs in two significant respects. First, extrusions of contemporaneous andesitic lavas were minimal. Their volume is only about 10% of the ignimbrite volume. Unlike other contemporaneous volcanic fields in southwestern North America, only a few major composite (strato-) volcanoes predated and developed during the flareup. Second, the central sector and especially the eastern sector of the province experienced super-eruptions of relatively uniform, crystal-rich dacite magmas; resulting deposits of these monotonous intermediates measure on the order of 16,000 km³. Following this 4 m.y. event, very large volumes of unusually hot and dry trachydacitic magmas were erupted. These two types of magmas and their erupted volumes are apparently without parallel in the middle Cenozoic of southwestern North America.

A fundamental goal of this themed issue is to present basic stratigraphic, compositional, chronologic, and paleomagnetic data on the unusually plentiful and voluminous ignimbrites in the southern Great Basin ignimbrite province. These data permit rigorous correlations of the vast outflow sheets that span between mountain-range exposures across intervening valleys as well as correlation of the sheets with often-dissimilar accumulations of tuff within dismembered source calderas. Well-exposed collar zones of larger calderas reveal complex wall-collapse breccias. Calculated ignimbrite dimensions in concert with precise ⁴⁰Ar/³⁹Ar ages provide insights on the growth and longevity of the colossal crustal magma systems. Exactly how these subduction-related magma systems were sustained for millions of years to create multicyclic super-eruptions at a particular focus remains largely unanswered. What factors created eruptive episodes lasting millions of years separated by shorter intervals of inactivity? What might have been the role played by tears in the subducting plate focusing a high rate of mantle magma flux into the crust? What role might have been played by an unusually thick and still-warm crust inherited from earlier orogenies? Are the numerous super-eruptions, especially of the unusual monotonous intermediates and succeeding trachydacitic eruptions, during the Great Basin ignimbrite flareup simply a result of the coupling effect of high mantle-magma flux and a thick crust, or did other factors play a role?

INTRODUCTION

The middle Cenozoic (36–18 Ma) ignimbrite flareup ranks as a premier volcanic event in southwestern North America and is one of the greatest global manifestations in the terrestrial rock record of long-lived explosive silicic volcanism in a continental-margin volcanic arc. Lipman et al. (1971) and Noble (1972) first drew attention to this burst of explosive silicic volcanism and Coney (1978) named it the ignimbrite flareup. Large parts of Nevada, Utah, Colorado, New Mexico, Arizona, and northwestern Mexico are blanketed to depths of silicic ash flows erupted from caldera-forming magma systems (Fig. 1; see also Best and Christiansen, 1991, their figure 4; Best et al., 1989b, their table 1). Many magma systems were active for several million years and were of batholithic scale, manifested by the thousands of cubic kilometers of magma ejected in single eruptive events. The 36–18 Ma subduction-related ignimbrite flareup near the southwestern margin of the North American continental plate is the only one of its magnitude known anywhere in the world of Mesozioc or Cenozoic age that is not related to continental breakup (Bryan et al., 2010; Cather et al., 2009). The magnitude and brevity of the 18 m.y. flareup are all the more remarkable when it is realized that volcanism in southwestern North America related to subduction has persisted more or less continuously and diachronously for some 200 m.y.

In the southern Great Basin ignimbrite province of Nevada and southwestern Utah (Fig. 2), on the order of 250 explosive events during the ignimbrite flareup resulted in at least 70,000 km³ of ash-flow deposits. At least 30 of the events created volumes of more than 1000 km³, thus qualifying as super-eruptions (Rampino and Self, 1992; de Silva, 2008; Miller and Wark, 2008). Forty-two exposed calderas have diameters ranging upwards to 60 km.

Several outstanding problems are associated with the southern Great Basin ignimbrite province and its investigation. Not the least of these problems is its vast size. Ash-flow deposits are found from the foothills of the Sierra Nevada eastward across the Sierra and then across the entire Great Basin into the western Colorado Plateau—a current distance of ~900 km (Fig. 1). Fallout ash deposits occur at least as far as
Introduction: The 36–18 Ma southern Great Basin, USA, ignimbrite province and flareup

Many decades of field work by numerous geologists have established most of the basic stratigraphy of much of the province and many hundreds of samples have provided insights into the composition and radiometric chronology of the ignimbrites. But unresolved correlation problems abound. Many eruptions have yet to be characterized in any detail with respect to dimensions, age, and composition. Many calderas have barely been identified and many more have yet to be discovered. Thermo-barometric interpretations of phase assemblages to elucidate intensive variables in magma systems have been carried out on only a few systems. Only reconnaissance isotopic analyses have been made; far more data will be required to provide meaningful syntheses of magma evolution in individual caldera-forming magma systems as well as the origin of the Great Basin magmatic regime as a whole.

In this introduction to the themed issue of Geosphere, our intent is to provide an overview of the 36–18 Ma southern Great Basin ignimbrite province as a whole. After briefly summarizing the geologic setting of the Great Basin and its volcanism, highlighting previous research, we then discuss the ignimbrites and their associated source calderas, and conclude with a statement of the scope of this themed issue.
REGIONAL GEOLOGIC SETTING OF THE GREAT BASIN

Overview

Strictly speaking, the Great Basin of Nevada and western Utah (Fig. 2) is an area of internal drainage within the broad northern Basin and Range province, which has been created by block faulting during still-ongoing east-west crustal extension. However, tributaries to the Colorado River, which empties into the Pacific Ocean, drain the southeastern segment of Nevada and adjacent Utah in an area we herein include as a part of the Great Basin. Thus, we use the term Great Basin more liberally than in a strict hydrographic sense, for both convenience and brevity.

Prior to late Cenozoic extension, folding and thrusting during multiple late Paleozoic to earliest Cenozoic orogenies (e.g., DeCelles, 2004; Dickinson, 2006) had thickened the crust in the area of the Great Basin to as much as 70 km; we call the resulting high plateau the Great Basin altiplano (Fig. 3; Best et al., 2009) because of its pre-extensional tectono-magmatic resemblance to the present-day central Andean Altiplano (e.g., Kay and Coira, 2009). West of the Precambrian edge, a thick section of Phanerozoic–latest Proterozoic continental-margin carbonate rocks, shales, and sandstones overlies earlier Proterozoic crust composed of medium- to high-grade schist, gneiss, and migmatite and intruded granitic rocks (Stewart, 1980). Intermittent and diachronous subduction-related magmatism occurred during the Mesozoic.

Following a lull in magmatic activity of tens of millions of years, time-transgressive...
Introduction: The 36–18 Ma southern Great Basin, USA, ignimbrite province and flareup

Figure 3. Conceptual east-west cross-section though the middle Cenozoic orogenic plateau, or Great Basin altiplano, at ~38.5° N showing the unusually thick crust, especially beneath the Indian Peak–Caliente caldera complex (IPCC). The crust probably was somewhat thinner beneath the Central Nevada caldera complex (CNCC) and thinner still farther west on the western slope of the altiplano beneath the Western Nevada volcanic field. The western Great Basin is underlain by Phanerozoic accreted terranes whereas the eastern part is underpinned by felsic Proterozoic basement. Note the change in vertical scale at sea level. Figure modified from Best et al. (2009, their figure 17).

subduction-related, or arc, magmatism resumed at ca. 45 Ma in what became the northern Great Basin and swept at a diminishing speed south and southwestward into southern Nevada, where it stalled in the mid-Miocene at ca. 15 Ma (Best and Christiansen, 1991, their figure 2). The sweeping magmatism is widely believed to have developed as a result of progressive steepening, or rollback, of the subducting oceanic Farallon slab from its prior flat configuration because of its decreasing age upon entry beneath the continent and a slowing rate of convergence (Severinghaus and Atwater, 1990). In western Utah and eastern Nevada, this sweeping magmatism is expressed by more-or-less separate, sub-parallel, roughly east-west belts of volcanic rocks and minor granitic intrusions (e.g., Stewart and Carlson, 1976; Christiansen and Yeats, 1992; Rowley, 1998; Rowley and Dixon, 2001). In western Nevada, these belts are less distinct. By about an order of magnitude, the greatest volume of volcanic rocks occurs in a belt extending from the Marysvale volcanic field on the western margin of the Colorado Plateau westward across the southern Great Basin to Reno, Nevada, and beyond into the Sierra Nevada (Fig. 2). Excluding the Marysvale field, which is dominated by intermediate-composition lavas, the belt in the southern Great Basin is composed mostly of silicic ash-flow tuffs produced during the middle Cenozoic, 36–18 Ma, ignimbrite flareup, the topic of this themed Geosphere issue.

Since the classic works of Lipman et al. (1971, 1972) and Christiansen and Lipman (1972), it has been recognized that calc-alkaline rhyolitic to andesitic magmas in the Great Basin older than ca. 20 Ma were created during subduction of oceanic lithosphere beneath the continent; the resulting volcanic rocks possess a characterizing arc chemical signature (e.g., Fig. 4). Basalt, as defined by the International Union of Geological Sciences (Le Maitre, 1989), is essentially absent. After ca. 20 Ma, relatively more-alkaline silicic magmas developed and were accompanied by basalt, which appeared in significant volumes after ca. 17–15 Ma, such as in the central Nevada rift (Zoback and Thompson, 1978) and on the western and eastern margins of the Great Basin (e.g., Nelson and Tingey, 1997). An arc geochemical signature is absent in these rocks less than 20 Ma that typically occur in bimodal suites. This absence reflects derivation from magmas not related to subduction but instead generated in an extensional tectonic regime (e.g., Christiansen et al., 2007; John, 2001).

Crustal Extension

Occurrence Mostly After the Ignimbrite Flareup

The time interval during which the orogenically thickened crust beneath the Great Basin altiplano in the early Cenozoic was subsequently thinned by extensional faulting to its current ~30 km thickness has been controversial. Did the extension take place before, during, or after the middle Cenozoic ignimbrite flareup? Resolution of this question significantly impacts three facets of our investigation of the ignimbrite province: (1) calculation of the areas and volumes of ash-flow deposits created during the ignimbrite flareup based on their present dimensions, (2) the character of the land surface over which the ash flows moved and accumulated, and (3) the crustal environment in which silicic ignimbrite-forming magmas were created.

Although some workers (e.g., Zoback et al., 1981; Gans et al., 1989; Constenius et al., 2003) have claimed broad synchrony of middle Cenozoic volcanism and extension in the Great Basin, we find that little and usually only local extension occurred during the 36–18 Ma ignimbrite flareup; nearly all of the regional tectonic extension took place significantly later than the flareup, resulting in the current basin-and-range topography (e.g., Stewart, 1998). Early work in local metamorphic core complexes had led to the concept of substantial extension in the middle Cenozoic, and this concept was extrapolated to the entire Great Basin. However, in at least one of these metamorphic complexes, the Snake Range east of Ely, Nevada, fission-track dating has revealed that large-magnitude extension in the Early Miocene at 17 Ma had been “seriously underestimated” relative to the originally conceived middle Cenozoic (Late Eocene–Early Oligocene) extension (Miller et al., 1999, p. 902). On the basis of the sedimentary and low-temperature thermochronologic record of upper-crustal extension in a 200 km east-west transect from 118°00’ to 115°30’ W between ~40°00’ and 40°30’ N, Colgan and Henry (2009; see also Henry et al., 2011) concluded that lateral extension took place until ca. 17–10 Ma when major extension occurred. In an east-west transect from ~113°30’ to 117°20’ W (westernmost Utah to central Nevada) between 39° and...
Although a few samples fall in the anorogenic or within-plate field, they nonetheless show an arc characteristic in B. (B) Spidergram for all ignimbrites. The trace-element patterns display obvious negative Nb anomalies typical of subduction-related rocks. Primitive mantle composition from McDonough and Sun (1995).
ash flows were emplaced during the flareup. This conclusion is in opposition to the recent views of Humphreys (2009, his figure 7) and Bryan et al. (2010, p. 208) who indicate synchronicity of the ignimbrite flareup with crustal extension.

Amount of Extension

The amount of extension after deposition of ignimbrites significantly impacts calculations of their areas and volumes in this themed issue. We have not attempted to make detailed palinspastic analyses of the amount of extensional strain in the areas over which the southern Great Basin ignimbrites are exposed (Figs. 2 and 5) but rely instead on the findings of other workers.

In their 335-km-long, east-west transect from easternmost Utah to central Nevada, Smith et al. (1991) cited an overall extension of 55%, but our measurement of their present-day cross-sectional length compared to the palinspastically restored section indicates 101 km of overall extension, or 43%. In their 200-km-long east-west transect in northeastern Nevada, Colgan and Henry (2009; see also Henry et al., 2011) estimated 50–60 km of extension across the 200 km transect, or 33–43%. McQuarrie and Wernicke (2005, their table 1) found in their 287-km-long, east-west transect from the Utah-Nevada state line to 117°23′ W the extension is 74 km, or 35%. In western Utah, to 111°47′ W, estimates of extension are less certain, ranging from 75% to 30%.

These three transects more-or-less correspond with the east-west extent of the central and eastern sectors of the southern Great Basin ignimbrite province (Fig. 5), but lie mostly in the northern part or beyond. To justify extrapolation of the strains from these more northerly transects southward, we note the results of a paleomagnetic study by Hillhouse and Gromme (2011). They demonstrated that the pole of rotation of the Sierra Nevada plutonic block during the Cenozoic was located near the north geographic pole. Hence, the extension of the Great Basin was quasi-rectilinear so that the amount of strain as measured in kilometers is uniform north to south within most of the Great Basin ignimbrite province.

Based on these investigations, authors of this themed issue have adopted values of 50% uniform extension for the Indian Peak–Caliente field (Best et al., this themed issue [a]) and 40% for the Central Nevada field (Best et al., this themed issue [b]). For the Indian Peak–Caliente field,
the 50% extension is consistent with the east-west versus north-south dimensions of ten major 31–18 Ma ignimbrite outflow sheets (Best et al., this themed issue [a], their table 8). Interestingly, in contrasting the relatively greater amount of extension for the Indian Peak–Caliente field with the slightly lower value for the Central Nevada field, we note that, on the basis of much less information at the time, Proffett (1977; see also Henry and Faulds, 2010, their figure 12) suggested that 30%–100% extension was likely in the western and eastern parts of the Great Basin but only 10%–15% in the central.

It should be emphasized that the amount of strain in adjacent structural domains varies significantly. Smith et al. (1991) noted that in their transect, extension ranged from ~110% in eastern Nevada, to ~40% in central Nevada, and nil in between as well as in easternmost Utah. Colgan and Henry (2009, p. 939) found that in their transect, extension was strongly partitioned into highly extended domains (50%–100% or more strain) separated by essentially undeformed crustal blocks. Hence, the assumption of uniform extension throughout the entire Central Nevada and Indian Peak–Caliente fields cannot be justified in detail, but is a convenience we have adopted in the absence of explicit quantitative information on individual strain domains in the fields; the uniform assumption is more likely valid for larger ignimbrite sheets.

Because of their deposition during the middle Cenozoic in irregular stream valleys on the western slope of the Great Basin altiplano (Fig. 3) and due to deformation related to the Walker Lane, volume estimates for most ignimbrites in the Western Nevada field are very approximate (see Henry and John, this themed issue, for details).

Figure 6. East-west extent of 36–18 Ma major ash-flow tuff cooling units in the Central Nevada and Indian Peak–Caliente ignimbrite fields. Note that, because of the general southward sweep of source activity, older tuff units at the bottom of the diagram chiefly occur in the northern part of the fields and younger units in the south. Thus, the diagram may be roughly considered as an inverted map with south at the top; this view is more accurate for the Indian Peak–Caliente field than for the Central Nevada field. Also note overlapping outflow sheets in the two fields in “outflow alley” (see also Fig. 7). Omitted are several small scattered cooling units of 27–23 Ma Isom-type tuffs in the Central Nevada field and many small 24–18 Ma Blawn ash-flow tuffs in the Indian Peak–Caliente field. To prevent overcrowding in the left part of the diagram, some unit names are designated by red letters, as follows: V—tuff of Pott Hole Valley; R—tuff of Orange Lichen Creek; Z, Y, H, X—Upper Tuff, Tikaboo Tuff, Hancock Tuff, and Lower Tuff Members, respectively, of the Shingle Pass Formation. The age of the Marsden Tuff of the Escalante Desert Group in the lower right is only approximate. See also Table 1 in Best et al. (a, b, this themed issue).
Introduction: The 36–18 Ma southern Great Basin, USA, ignimbrite province and flareup

PREVIOUS RESEARCH ON THE SOUTHERN GREAT BASIN IGNIMBRITE PROVINCE

Working in the Iron Springs mining district of southwestern Utah in the 1950s, J. Hoover Mackin (1960) applied a new paradigm fostered by Howell Williams and others to the volcanic rocks, realizing that they were ignimbrites, rather than lavas as previously believed. Mackin gave stratigraphic names to several ash-flow deposits in the southeastern Great Basin, which he characterized as extensive, datable sheets constituting instantaneous time horizons of use in elucidating the structural evolution of the province. While doing geophysical field work as an intern in the summer of 1958, the senior author encountered Williams and Mackin in a jeep on a narrow dirt track in the hills west of Milford, Utah [Fig. 5]. We moved our vehicles aside, exchanged greetings, and went our separate ways.) Two of Mackin’s students, Earl Cook (1965; also unpublished data) and Paul Williams (1967), with the financial assistance of oil companies, successfully correlated ignimbrite sheets over broad areas from southwestern Utah into central Nevada where a newly discovered oil field was hosted in part in ash-flow tuffs. They used phenocryst types and proportions and other petrographic features as well as stratigraphic position in order to overcome the discontinuity of outcrops resulting from dismemberment by post-emplacement basin-and-range faulting. These workers drew the first isopach maps of many of the ignimbrite units. Cook (1965) estimated that the volume of ignimbrite (uncorrected to dense rock equivalent) and for crustal extension in eastern Nevada and southwestern Utah exceeded 20,000 km³ and noted that phenocryst-rich ignimbrites tend to be thicker than phenocryst-poor ones. He also astutely perceived that the ash-flow sheets were emplaced in a relatively brief time interval—the ignimbrite flareup—and that their sources migrated southward through time; these two concepts were later confirmed over a larger part of the Great Basin by Armstrong et al. (1969). Williams (1967) also described, in thorough detail for his time, the petrography and density variations of several ignimbrite cooling units in the southeastern Great Basin. In other work done under Mackin’s tutelage, Richard Blank (1959) mapped and described the volcanic rocks in the Bull Valley district of southwest Utah, Omar Conrad (1969) worked in the central Needle Range, and John Anderson and Peter Rowley (see references in Best et al., this themed issue [a]) mapped many quadrangles in the Iron Springs district and the nearby High Plateaus of central Utah where ignimbrite units first described by Mackin are exposed. In other early work, but independent of Mackin, ignimbrites in the Grant Range, Nevada, were mapped and described by Scott (1965, 1966).

Beginning in 1966, E. Bart Ekren and other geologists of the U.S. Geological Survey with the Nevada Test Site project systematically mapped ignimbrite terranes over thousands of square kilometers, including thick accumulations in the Central Nevada caldera complex (Ekren et al., 1974; see also Best et al., this themed issue [b]). Gromme et al. (1972) demonstrated the utility of paleomagnetism for correlation of dismembered ash-flow sheets. These and other field investigations, supplemented by extensive K-Ar dating throughout the Great Basin (e.g., Marvin et al., 1973), led to a series of province-wide, small-scale maps compiled for four time periods of the Cenozoic by Stewart and Carlson (1976; see also Sargent and Ruggensack, 1984). These maps delineated some of the then-known major caldera sources but were remarkable in showing, for the first time and with unusual clarity, the middle Cenozoic (36–18 Ma) Great Basin ignimbrite flareup and the much less voluminous, contemporaneous andesitic lavas.

In a paper that was prescient for its time and based on only sparse data, Noble (1972) also perceived the ignimbrite flareup in the southwestern United States and recognized, for the Great Basin, that (1) younger ignimbrites were deposited on a surface of little relief, (2) significant crustal extension forming the basin-and-range topography began after ca. 17 Ma, and (3) only minor amounts of andesitic lavas were extruded during the ignimbrite flareup. In addition, he concluded that (4) the southward sweep of arc volcanism was the result of steepening of the subducting oceanic lithosphere, and (5) a very significant amount of mantle magma was necessary to drive the generation of silicic crustal magma systems producing the flareup.

Preliminary overviews of the Central Nevada and Indian Peak caldera complexes and their associated ash-flow tuffs have appeared in Best et al. (1989a, 1989b, 1993) and John (1994) while Nealey et al. (1995), Scott et al. (1995), and Rowley et al. (1995) have described ignimbrites associated with calderas in the Caliente cluster (Fig. 5).

Early work on the Western Nevada field was focused in the area near Reno and included Bonham (1969), Bingler (1978), Proffett (1977), and Proffett and Proffett (1976). Publications on other areas include Stewart et al. (1977), Ekren et al. (1980), and Robinson and Stewart (1984). Since these pioneering efforts, many geologic maps and topical reports have been published, as referenced in Henry and John (this themed issue). Askren et al. (1997) and Barr (1993; see also Best et al., 2009) documented the chemical composition of andesitic lava flows coeval with the Great Basin ignimbrites. Isotopic studies of volcanic rocks include Scott et al. (1971), Larson and Taylor (1986), Unruh et al. (1995), Hart (1997), and Hart et al. (1997).

THE SOUTHERN GREAT BASIN IGNIMBRITE PROVINCE

Delineation

The southern Great Basin ignimbrite province shown in Figure 2 comprises a swath of mostly mountain-range exposures of silicic ignimbrite and lesser rhyolithic to andesitic lava extending through the Sierra Nevada and eastward across the Great Basin to the Colorado Plateau. The Marysvale volcanic field that lies on the western margin of the Colorado Plateau is not included in the ignimbrite province but is shown in Figure 2 to emphasize the dominance of intermediate-composition lavas over silicic ignimbrite (Cunningham et al., 2007). The southern Great Basin ignimbrite province excludes ignimbrites lacking an arc chemical signature that are younger than 18 Ma in age. These tuffs lie in northwestern Nevada (e.g., McDermitt area; Rytuba and McKee, 1984), in the southwestern Nevada volcanic field between Tonopah and Las Vegas (Sawyer et al., 1994), and in the southern part of the Caliente caldera cluster and farther south (Fig. 5; Rowley et al., 1995). We also exclude subduction-related silicic ignimbrites emplaced ca. 41–35 Ma over a present area of ~10,000 km² in the Independence and Tuscara Mountains of northeastern Nevada mostly north of Elko (e.g., Henry and Boden, 1999) and ca. 39–32 Ma ignimbrites exposed over a present area of ~7000 km² in west-central Utah and adjacent east-central Nevada (Stewart and Carlson, 1976; Hintze and Kowallis, 2009). These distinctly separate areas of subduction-related ignimbrite are only one-tenth the area of the ~162,000 km² over which the products of the 36–18 Ma southern Great Basin ignimbrite flareup are found.

Three Ignimbrite Fields Making Up the Province

The southern Great Basin ignimbrite province is readily divided into three contrasting geologic parts or sectors: eastern, central, and western (Figs. 2 and 5). In the eastern sector, calderas astride the Utah-Nevada state line and surrounding associated outflow ignimbrite sheets are designated as the Indian Peak–Caliente caldera complex and ignimbrite field (Best et al. [a], this...
Best et al.

Significant Attributes of the Southern Great Basin Ignimbrite Province

The southern Great Basin ignimbrite province shares many aspects with other volcanic fields involved in the middle Cenozoic ignimbrite flareup in southwestern North America (Fig. 1) including recurrent explosive eruptions of rhyolitic magma, some of super magnitude, from long-lived shallow-crustal silicic magma systems and collapse of multicyclic calderas, some tens of kilometers in diameter. However, two attributes of the southern Great Basin ignimbrite province are especially significant, seemingly requiring special tectono-magmatic conditions for its origin and evolution, as discussed in Best and Christiansen (this themed issue).

First is the relatively small volume (generally ~10%) of intermediate-composition, mostly andesitic, lava flows relative to the volume of contemporaneous ignimbrites; this attribute was obvious in the seminal space-time-composition compilation by Stewart and Carlson (1976) of middle Cenozoic volcanic rocks in the Great Basin, from which our Figure 2 was drawn. Only a few major composite volcanoes or stratovolcanoes existed in the southern Great Basin ignimbrite province prior to the ignimbrite flareup and few during most of its activity. In striking contrast, intermediate-composition lavas dominate over ignimbrite in the two contemporaneous volcanic fields to the east on the margins of the Colorado Plateau (Fig. 1). In the Marysville field on the western margin, lavas are an order of magnitude greater in volume than silicic ignimbrite (Cunningham et al., 2007). In the Southern Rocky Mountain field on the eastern margin, lavas are 1.7 times more voluminous than silicic ignimbrite (Lipman, 2007). In these two fields (Fig. 1), stratovolcanoes dominated the landscape prior to the explosive eruptions of silicic magmas. Clearly, the middle Cenozoic southern Great Basin ignimbrite province is aptly named and, in addition, justifies our use of ignimbrite field rather than the more general volcanic field for its parts.

The second significant attribute of the southern Great Basin ignimbrite province was super eruptions of relatively uniform, phenocryst-rich dacite, or monotonous intermediate, magmas over 4 m.y. followed by voluminous eruptions of unusual, higher temperature, drier trachydacitic magmas over a similar time span. These tandem eruptions had their greatest expression in the Indian Peak field where eruptions of 2000, 5900, and 4400 km$^3$ of monotonous intermediates at 31.13, 30.06, and 29.20 Ma, respectively, were followed by at least nine eruptions totaling 4200 km$^3$ of trachydacitic ignimbrites from 27.90 to 24.55 Ma. In the Central Nevada field these tandem eruptions were less voluminous, including one monotonous intermediate ignimbrite of 4500 km$^3$ at 27.57 Ma followed by eruption of ~600 km$^3$ of trachydacitic magma from ca. 27 to 23 Ma. Such compositions and colossal eruptive volumes appear to be without parallel elsewhere in the middle Cenozoic of the southwestern United States. In the Western Nevada field, data are incomplete, but nothing like the monotonous intermediates to the east are known and only a very small volume of the high temperature, dry trachydacitic magmas were erupted.

Ignimbrites and lavas older than ca. 18 Ma in the Great Basin are magnesian (calc-alkalic) and possess an arc geochemical signature (Fig. 4) resulting from subduction-related magma systems. As expected from the unusually thick crust in which they were spawned, magmas were mostly high-K. Magma systems in the southern Great Basin ignimbrite province contrast sharply with those in typical continental-margin volcanic arcs that are founded on thinner crust in their much greater eruptive volume and corresponding much longer repose times between eruptions as well as their dominance of rhyolite and dacite over less silicic, or andesitic, compositions. The silicic ignimbrites in the Great Basin generally contain phenocrysts in some combination of plagioclase, sanidine, quartz, biotite, hornblende, and Fe-Ti oxides. Pyroxenes and titanite occur in a few tuffs whereas zircon and apatite are ubiquitous in trace amounts. These phases equilibrated at depths of 7–12 km and temperatures of ~700–800 °C (Best et al. [a], this themed issue). Drier, higher temperature (~950 °C) trachydacitic magmas contained sparse phenocrysts of plagioclase, two pyroxenes, and Fe-Ti oxides equilibrated at greater depths, perhaps as much as 30 km.

The relatively minor middle Cenozoic lavas are principally high-K andesite and lesser dacite, latite, and rhyolite (Barr, 1993; Best et al., 2009). However, beginning at roughly 20 Ma lava compositions were increasingly broader, include basalt, and are locally bimodal basalt-rhyolite suites accompanying the demise of plate subduction and transition into an extensional regime; arc geochemical characteristics disappear.

IGNIMBRITES

Definitions

In this themed issue, the synonymous terms ignimbrite and ash-flow tuff will be used interchangeably, or informally and for brevity, tuff. Outflow ignimbrite is deposited beyond its source caldera, in large part, we believe, prior to initiation of caldera collapse. However, some of this early tuff is deposited within the area that subsequently collapses; pre-caldera collapse ignimbrite is, thus, a more inclusive term. The outflow or pre-caldera collapse, ignimbrite typically consists of a simple ash-flow cooling unit, or locally a compound cooling unit, and ranges in thickness from a meter or so to as much as a few hundreds of meters, depending on magnitude of topographic relief in the pre-eruption landscape, on proximity to the source, and on volume of the eruption. Cooling units display zonal variations in welding, compaction, devitrification, and vapor-phase crystallization as described by Smith (1960). Over the course of the ignimbrite flareup, the altiplano in what is now the central and eastern sectors of the southern Great Basin province was progressively smoothed as successive outflow tuff sheets were deposited (Fig. 3; Best et al., 2009). This resulted in, for example, accumulation of many conformable ignimbrite layers to depths of several hundreds of meters in the “outflow alley” between the Central Nevada and the Indian Peak–Caliente caldera complexes (Figs. 5, 6, and 7). In the western Great Basin, ash flows were commonly confined to drainage channels on the western slope of the altiplano (Henry and Faulds, 2010).
Introduction: The 36–18 Ma southern Great Basin, USA, ignimbrite province and flareup

Intracaldera ignimbrite is deposited, commonly as a compound cooling unit, within its source caldera as it is collapsing, as described below. Caldera-collapse ignimbrite is a synonymous term if none of it is deposited outside the caldera.

Caldera-filling ignimbrite is deposited in a pre-existing and unrelated caldera from a source either within or outside the caldera. In the former case, the ash flows are essentially confined within the depression and the resulting deposit can be hundreds of meters thick.

Correlation

To reconstruct the full geographic extent and volume of a particular ignimbrite unit deposited in a single eruptive event, it is necessary to correlate exposures separated by post-emplacement

Figure 7. Panoramic views of conformable stratigraphic sequences of outflow ignimbrite sheets in “outflow alley” between the Central Nevada (CN) caldera complex to the west and the Indian Peak–Caliente (IPC) caldera complex to the east (Fig. 5). (A) Late-afternoon view toward the northeast of the Golden Gate Range (~115°19′ W, 38°13.5′ N) composed of a stack of ten ignimbrite sheets totaling ~500 m in thickness (for additional information see Best et al., [b], this themed issue, Supplemental File 4). Photograph kindly provided by Wanda J. Taylor. From oldest upwards above Paleozoic rocks, the outflow sheets are: 31.13 Ma Cottonwood Wash and 30.06 Ma Wah Wah Springs (~20 m and ~30 m thick, respectively; both derived from IPC but concealed behind the low hill in left foreground); 29.4 Ma Silver King (100 m, IPC); 29.20 Ma Lund (50 m, IPC); 27.57 Ma Monotony (55 m, CN); 27.16 Ma Lower Tuff Member (40 m), 26.82 Ma Hancock Tuff Member (116 m), and 26.36 Ma Upper Tuff Member (30 m; all three members of the Shingle Pass Formation, CN); 23.04 Ma Bauers (15 m, IPC); and 22.93 Ma Pahranagat (60 m, CN). (B) View toward the north from U.S. Highway 93 of the south end of the North Pahroc Range ~70 km south-southeast of the Golden Gate Range (for additional information see Best et al., [a], this themed issue, Supplemental File 5). Tilted mesa on right exposes nine cooling units, including (Scott et al., 1992): ca. 27.3 Ma upper Bald Hills Tuff Member (45 m) and 24.55 Ma Hole-in-the-Wall Tuff Member (15 m, both members of the Isom Formation, IPC); 24.01 Ma Leach Canyon (95 m, IPC); 24.15 Ma Swett (60, IPC); local trachydacite tuff (10 m); 23.04 Ma Bauers (60 m, IPC); 22.93 Ma Pahranagat (10 m, CN); 22.56 Ma Harmony Hills (30 m, IPC); and 18.51 Ma Hiko (100 m, IPC). Mesa on left exposes the same sequence with an additional intervening three cooling units of the Shingle Pass (140 m, CN) and another trachydacite tuff (15 m). Complete section a few kilometers to north that includes six additional ignimbrites below the Bald Hills totals ~900 m thick.
faulting, erosion, and younger deposits. Correlation between mountain ranges across alluvial valleys is an obvious challenge but within a single range, exposures of a particular tuff unit may be separated in one way or another. Lateral variations in the character of an ignimbrite hamper correlation; a case in point is contrasts between intracaldera and outflow ignimbrites deposited during a single eruptive event.

Several methods (Hildreth and Mahood, 1985) can be marshaled to correlate, with varying degrees of certainty, discontinuous exposures of a particular ignimbrite unit. As a case study for an unusually challenging correlation, Best et al. (1995) investigated the ignimbrite of the Pahranagat Formation in the Central Nevada volcanic field using stratigraphic position, chemical and modal composition, 

\[ \text{Ar}/\text{Ar} \] ages, and paleomagnetic direction. The Pahranagat outflow sheet is vertically and laterally zoned in composition and is found in widely scattered exposures over a present area of 26,000 km² where it has been previously designated by four different stratigraphic names in different areas. Additional names have been applied to the intracaldera ignimbrite inside the Kawiw caldera source.

Position in stratigraphic sequence is the most basic correlation tool in the field. Modal composition—types and proportions of phenocrysts—together with other petrographic criteria, such as characteristics of phenocrysts (e.g., size), abundance and nature of lithic and pumice clasts, and character of welding, devitrification, and vapor-phase crystallization, can also be used advantageously in the field. However, modes and the other criteria are compromised by compositional variations in an ignimbrite. In the Pahranagat and Windus Butte tuffs, for example, the quartz/plagioclase ratio ranges over almost an order of magnitude and variations in other mineral proportions are substantial.

Another drawback for the use of modal composition in correlation is the fact that nearly all middle Cenozoic Great Basin ignimbrites contain combinations of phenocrysts of plagioclase, sanidine, quartz, biotite, and Fe-Ti oxides with or without hornblende; only by accurate point counting is it possible to distinguish, in some cases, among so many similar ignimbrite units. Only a few of the more than 200 ignimbrite cooling units possess a unique modal composition. One is the Lower Tuff Member of the Shingle Pass Formation in the Central Nevada field having a phenocryst assemblage of sanidine, plagioclase, quartz, biotite, and, especially, Fe-rich olivine that is not found in any other of the investigated tuffs. Three feldspar phenocryst types (sanidine, anorthoclase, plagioclase) occur in only two middle Cenozoic ignimbrites of which we are aware: the tuff of Clipper Gap in the Central Nevada field and the Nine Hill Tuff in the Western Nevada field. Ignimbrites of the Wah Wah Springs Formation in the Indian Peak–Caliente field are unusual in containing more hornblende than biotite.

Vapor-phase and other post-emplacement alteration of tuffs preferentially destroys some phenocrysts. Titanite and mafic minerals are most commonly susceptible; only quartz is universally immune. Ignimbrites of the hornblende-rich Wah Wah Springs Formation and the titane-bearing Lund Formation, both in the Indian Peak–Caliente field, have commonly been misidentified in hand samples because of the destruction of these diagnostic phases. Nonetheless, unless alteration is extreme, pseudomorphs of critical phases can be recognized in thin section.

Similarly as for modes, few ignimbrite units possess unique bulk chemical compositions. Clearly, magmatic and eruptive processes repeatedly combined through time and space to yield compositionally similar tuffs. Many units overlap to some degree for virtually all of 30 analyzed elements, again limiting the usefulness of chemical composition in correlation. Unique for the entire Great Basin is the petrographically distinct Nine Hill Tuff that has unusually high concentrations of both Nb (26–33 ppm) and Zr (360–430 ppm) (Deino, 1985, 1989). Among the compositionally similar monotonous intermediates, the Wah Wah Springs has unusually high concentrations of Cr.

Chemical composition of constituent phenocrysts is a very useful correlation tool, but one used only sparingly by authors of this themed issue. The superb precision (+0.00 Ma, one sigma) of the \[ \text{Ar}/\text{Ar} \] single-crystal, laser-fusion dating technique has made it a standard tool in correlation of pyroclastic deposits. Deino (this themed issue) describes its application to the Great Basin ignimbrites. Even though most age determinations, especially on sanidine, clearly distinguish among units in a particular ignimbrite field, some units that are distinctly different cooling units in a stratigraphic sequence can have the same age within analytical uncertainty; an example is the compositionally similar tuffs of Lunar Cuesta and Goblin Knobs in the Central Nevada field that have separate source calderas and are distinguished by contrasting paleomagnetic directions.

Paleomagnetism, as just indicated, is a powerful tool for correlation of ash-flow deposits. Gromme et al. (1972) and Gromme and Hudson (this themed issue) describe its application to the Great Basin ignimbrites. Significant differences among paleomagnetic directions negate correlations of stratigraphic units, whereas similarity of directions provides only permissive evidence of a correlation.

Obviously, no single correlation tool is generally sufficient to validate a match between separate exposures of a particular cooling unit because two or more different units can possess similar attributes. The greater the number of independent criteria employed, the more credible is the correlation.

**CALDERAS**

Because all topographic expression of caldera depressions has been obliterated by post-volcanic basin-and-range faulting, erosion, and burial beneath valley fill, recognition of middle Cenozoic source calderas for Great Basin ignimbrites must be based on other criteria. (Some geologists designate deeply eroded ignimbrite sources as “cauldrons” or “caldrons”; however, following Lipman [2000, p. 644], we have adopted the designation _caldera_.) Exposed segments of calderas in uplifted and tilted mountain blocks reveal critical details of the internal structure and stratigraphy to depths of several kilometers as, for example, in the Caetano caldera and the Stillwater caldera complex, both in the Western Nevada field (John et al., 2008; John, 1995; Henry and John, this themed issue).

_Caldera complex_, as used in this themed issue of _Geosphere_, denotes a cluster of source calderas for the sequence of ignimbrites in the Indian Peak–Caliente and Central Nevada volcanic fields (Fig. 5). Most of the calderas in each complex are partially overlapping, or nested (multicyclic) within one another, but some may lie apart. In the Central Nevada field, a mostly exposed caldera lies well to the north of the main caldera cluster (Fig. 5) but is included in the Central Nevada caldera complex because its associated ignimbrite outflow sheet occurs in sequences with those derived from the main caldera complex.

In some instances, the Bouguer gravity field is useful in delineating the relatively lesser density of the filling ignimbrite or underlying plutonic granitic rock as, for example, in the Indian Peak caldera (Best et al. [a], this themed issue, their figure 8C).

The approximate location of a particular caldera in some cases can be inferred from the distribution and thickness of its associated outflow tuff. However, a potential pitfall exists because, although a few calderas are positioned more or less centrally within the area of distribution, others are decidedly eccentrically positioned, especially in the Western and Central Nevada fields (Fig. 5). An example in the latter field is the 22,500 km² outflow of the Windus Butte...
Introduction: The 36–18 Ma southern Great Basin, USA, ignimbrite province and flareup

Formation, which is not found in a 180° arc northwest-west-southwest of the Williams Ridge caldera source.

Unusually thick ignimbrite (e.g., several hundreds of meters) by itself is not necessarily an indication of accumulation within its associated source caldera. Outflow, or pre-caldera collapse, ignimbrites can be as thick as 500 m, such as the Wah Wah Springs north of its Indian Peak caldera source (Best et al. [a], this themed issue) and the Windsoe Butte north of its Williams Ridge caldera source (Best et al. [b], this themed issue). Caldera-filling tuff can accumulate to thicknesses of several hundred meters within an older and unrelated caldera depression.

The most definitive evidence for a caldera is a very thick, locally upwards of 3–5 km, intracaldera deposit that commonly occurs as remnants in uplifted mountain blocks. Such deposits consist of a compound cooling unit or multiple cooling units of intracaldera tuff, together with intercalated lenses of wall-collapse breccia. The intracaldera tuff that accumulated in the deepening depression during continuing explosive eruption has usually suffered variable but pervasive hydrothermal alteration as a result of slow cooling of the massive thickness in the presence of volcanic fluids. The intercalated lenses of breccia are landslide deposits of older rock that intermittently sloughed off the steep and unstable topographic escarpment bordering the caldera as its floor subsided along the circumcruising ring fault (Lipman, 1976). Some landslides traveled as much as a few kilometers into the depression. The breccias range from abundant lithic clasts of older rock of lapilli size within the tuff to lenticular masses few meters to hundreds of meters thick made entirely of fragments of older rock. Megabreccia of automobile- to house-size blocks are not uncommon. In some calderas, such as the Big Ten Peak (Bonham and Garside, 1979; Keith, 1993) in the Central Nevada caldera complex, kilometer-size slabs of more-or-less intact rock lie within intracaldera tuff. Some intracaldera as well as outflow tuffs contain fragments of deeper-crustal rock than those in the caldera wall. Such breccias of older Paleozoic and underlying plutonic and metamorphic rock near the margins of calderas in the Toquima Range are interpreted by Shave and Snyder (1988) to have formed by eruptive processes rather than by landsliding.

Because of the caving of unstable caldera walls, the outermost topographic margin of a caldera can lie as much as several kilometers outside its structural margin, defined by the arcuate ring fault that bounds the down-dropped caldera floor. Where erosion has not cut too deeply, this topographic rim can be manifest by younger, caldera-filling deposits that lap unconformably against older rocks on the topographic margin.

Caldera-filling tuff derived from sources within or outside the caldera after its collapse as well as locally derived lava flows can partially to completely fill the topographic depression. Intracaldera epiclastic deposits of sandstone and conglomerate as well as lacustrine limestone that are produced by weathering and erosion of the caldera escarpment can serve as caldera markers where thick and well exposed. However, such deposits are generally sparse or absent in Great Basin calderas, possibly as a result of the arid conditions on the altiplano.

Exposures of comagmatic intrusions are rare in Great Basin calderas. Examples include the granodiorite porphyry that domed the intracaldera tuff of the Wah Wah Springs Formation in the Indian Peak caldera (Best et al. [a], this themed issue). In the Western Nevada field, the Carico Lake granite porphyry intrudes and domes the Cañada Tuff inside its source caldera (John et al., 2008) and intrusions occur in the Stillwater caldera complex (Henry and John, this themed issue). Post-caldera lava domes positioned along the ring fracture—another facet of the classic Valles caldera cycle (Smith and Bailey, 1968)—are only locally developed, such as in the White Rock caldera source of the Lund ignimbrite in the Indian Peak–Caliente field.

Evidence for resurgent uplift of caldera floors has been found for some calderas where it has not been obscured by subsequent dismemberment and uplift by basin-and-range faulting.

SCOPE OF THIS THEMED ISSUE OF GESOPHERE

Much has been published regarding other volcanic fields and calderas in the southwestern United States manifesting the middle Cenozoic ignimbrite flareup (Fig. 1), including the Southern Rocky Mountain volcanic field in southwestern Colorado, which has been extensively studied by P.W. Lipman and associates (e.g., Lipman, 2007), and the Mogollon-Datil field in southwestern New Mexico, which has been studied by, among others, McIntosh et al. (1992). Although a brief overview of the volcanic rocks in the Great Basin was published more than two decades ago (Best et al., 1989b), as well as work on some individual ignimbrite units and their caldera sources, no comprehensive, up-to-date, integrated treatment has been devoted to the voluminous 18 Ma southern Great Basin ignimbrite province as a whole. The following articles of this themed issue of Geosphere aim to rectify that deficiency, thus characterizing the anatomy of the vast ignimbrite province and highlighting its unusual attributes.

Deino (this themed issue) presents the results of high-precision 40Ar/39Ar laser analysis of 200 separate samples of sandstone and plagioclase prepared from whole-rock samples; sanidines establish the chronological age of the Central Nevada field and plagioclase the Indian Peak–Caliente field. These highly precise ages generally have analytical uncertainties (one sigma) of 0.05–0.11 m.y. on sanidines from a single tuff sample in which six grains were fused. Uncertainties are greater for plagioclase. Replicate analyses from several samples of the same ignimbrite unit yield uncertainties of as little as 0.02 m.y. Such precision not only provides a powerful tool for correlation of ignimbrites found in exposures separated by wide distances but also yields a tight chronology of evolving magma systems.

Gromme and Hudson (this themed issue) present the results of analyses of natural remanent magnetization of ignimbrites in more than 450 sites across the southern Great Basin ignimbrite province. Significant differences among paleomagnetic directions negate correlations of stratigraphic units, whereas similarity of directions provide permissive evidence for correlation. In addition to its utility as a correlation tool, paleomagnetism confirms the deposition of the ash-flow tuffs on a surface of limited relief in the central and eastern parts of the ignimbrite province on the Great Basalt altiplano. In some cases, ignimbrites with analytically indistinguishable ages nonetheless possess contrasting paleomagnetic directions resulting from shifts in the geomagnetic field that have been rapid with respect to the analytical uncertainty of the dating.

Best et al. (a, b, this themed issue) build a basic foundation of stratigraphic, compositional, dimensional, chronologic, and paleomagnetic data for the more than 100 ignimbrite cooling units in the eastern and central sectors of the ignimbrite province (Indian Peak–Caliente and Central Nevada ignimbrite fields, respectively). Many hundreds of samples were collected in these two fields; 830 chemical analyses are reported as well as 960 modal analyses. Data reveal that these two sectors of the ignimbrite province harbor apparently the largest source calderas and ignimbrite deposits, including the super-eruptive monotonous intermediates and voluminous trachydacitic tuffs not seen in other contemporaneous fields in southwestern North America.

Henry and John (this themed issue) describe ignimbrites and calderas in the Western Nevada field on the western slope of the Great Basin altiplano where ash flows were constrained in large part in stream valleys. Several correlations are suggested, linking ignimbrites exposed in the western part of the field with caldera sources as
much as 200 km farther east. Because of sub-
stantial post-caldera tilting of ranges, the inter-
nal structure of the Caetano and Stillwater calderas from floor to the top of the caldera-
filling sequence is exceptionally well exposed, allowing an integrated elucidation of coeval explosive eruption, lava extrusion, caldera col-
apse, plutonism, and hydrothermal activity.
Deino et al. (this themed issue) correlate and describe the 25.48 Ma Nine Hill Tuff. This compositionally unusual, high-silica rhyolite ignimbrite is presently exposed over an area of ~70,000 km², one of the most extensive ash-flow deposits known and certainly the largest in the Great Basin. Nine Hill ash flows traveled from a now-concealed source east of Reno westward via drainages on the western slope of the Great Basin altiplano all the way to what are now the Sierra Nevada foothills in central California, as well as traveling eastward across the altiplano into what is now eastern Nevada almost to Ely (Fig. 5). The origin of the unusual magma and the apparent exceptional mobility of the ash flows require innovative interpretations.

Best and Christiansen (this themed issue) compare the southern Great Basin ignimbrite province with other contemporaneous volcanic fields in the southwestern U.S. as well as the Neogene Altiplano-Puna field in the central Andes. These comparisons with other volcanic fields that experienced an ignimbrite flareup provide valuable insights concerning mantle magma flux into the crust and how east-west variations in crustal thickness across the Great Basin and Colorado Plateau influenced the nature of volcanism. Based on the tectonic set-
tings of these several fields, ignimbrite flareups are conceived to be the result of a steepening in the dip of a once “flat” subducting oceanic lithosphere far inland from the continental margin and unusually high influx of mantle magma into crust thickened by prior orogenic contraction. Striking similarities between the central and, especially, the eastern sector of the southern Great Basin province and the Altiplano-Puna field emphasize the role of exceptionally thick crust in creating gigantic bodies of monoton-
ous intermediate magma and their recurrent super-eruption. Relatively hot and dry trachy-
dacitic magmas resulted from differentiation of mantle magmas with little crustal contamina-
tion because this component had been largely extracted during the generation of the immediately preceding monotonous intermediate magmas.

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quentl, over the next thirty years, some 600 students mapped most of the Indian Peak caldera complex and surrounding areas at various stages of their undergraduate and graduate field work. This was the basis of numerous geologic maps published by the U.S. Geological Survey and Nevada Bureau of Mines and Geology. Lehi’s continuing interest and assistance over four decades have been of immeasurable value. As our study of ash-flow tuffs and calderas was extended farther west in the Great Basin, a valuable resource was the areal photographic and stratigraphic data on ignimbrite units gathered from 1955 to 1971 on some 40 localities by Earl F. Cook. Some of his data were summarized in Cook (1965), but considerable addi-
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