compositions took their place (Christiansen et al., 2007a, their fig. 11). The extension-related bimodal suite included both aluminous and peralkaline rhyolites (e.g., Farmer et al., 1991). During the ignimbrite flareup, extrusion of intermediate-composition, chiefly andesitic, lavas was an order of magnitude smaller in volume than silicic explosive eruptions (Fig. 2; Best et al., 2013b, 2013c).

In western Utah and eastern Nevada, southward-sweeping magmatism (ca. 45–18 Ma) is expressed by more or less separate, subparallel, roughly east-west belts of volcanic rocks and minor granitic intrusions (e.g., Stewart and Carlson, 1976). The greatest volume of mid-Cenozoic volcanic rocks occurs in a swath of mostly mountain-range exposures of silicic ignimbrite and lesser andesitic lava extending from the southwestern corner of Utah westward across the southern Great Basin and beyond into the Sierra Nevada (Fig. 2). This is the 36–18 Ma southern Great Basin ignimbrite province.

Absence of Significant Regional Tectonic Extension during the Ignimbrite Flareup

Controversy surrounds the time when the orogenically thickened crust in the Great Basin altiplano was subjected to significant extensional faulting and thinning to its current thickness of ~30 km (Allmendinger et al., 1987). The timing of extensional thinning of the crust—before, during, or after the ignimbrite flareup—has a critical bearing on the role of crustal thickness in the ignimbrite flareup.

Prevolcanic extension has been advocated by, for example, DeCelles (2004, p. 149), who concluded that, in view of the excess gravitational potential energy residing in a thick orogenic plateau, “Within limits of available temporal resolution, hinterland extension and frontal thrusting were coeval in the
Rock Compositions

Rhyolite ignimbrites of all ages (36–18 Ma) occur throughout the province and are accompanied by temporally more restricted dacite and trachydacite ignimbrites, especially in the eastern sector (Fig. 7). Most ignimbrites contain variable proportions of plagioclase, sanidine, quartz, biotite, hornblende, Fe-Ti oxides, pyroxene, and trace amounts of zircon, apatite, and, rarely, titanite, that equilibrated in relatively wet magmas at shallow crustal depths of 7–9 km. Dacites show phenocryst-rich compositions, upward of 50% of the tuff on dense rock equivalent basis (Best et al., 2013b); nearly all formed by super-eruptions, and their relatively unzoned, uniform nature qualifies them as monotonous intermediates in the sense of Hildreth (1981). These dacite magmas are interpreted to have originated by mixing of andesitic and rhyolitic magmas in the deeper crust (Best et al., 2013b). Unusual trachydacites (Best et al., 2013b) have sparse (<15%) phenocrysts of plagioclase, two pyroxenes, and Fe-Ti oxides that were derived from drier, hotter magmas equilibrated at greater crustal depth. These Isom-type tuffs (Figs. 7–9) have >300 ppm Zr and high TiO₂/CaO ratios. Ignimbrites are alkalic to calcic (Fig. 8); their high-K to shoshonitic nature (Fig. 9) is consistent with the thick crust in which the magmas originated.

Intermediate-composition lavas in the southern Great Basin province are mostly high-K andesite (Best et al., 2009). Notably, their volume is an order of magnitude less than that of silicic ignimbrite (Table 1; Stewart and Carlson, 1976; Best et al., 2013b, 2013c). As previously indicated, basalt is absent until after ca. 20 Ma.

Lavas and ignimbrites have an arc geochemical signature—wet, oxidized, with low Fe/Mg ratios, enrichments of fluid-soluble elements, and depletions of high field strength elements, producing high Ba/Nb ratios (Best et al., 2013b, 2013c; Henry and John, 2013). Sr and O isotopic ratios are high and consistent with the assimilation of large proportions of felsic crust in the eastern sector of the Great Basin province; Sr isotope ratios are much lower in the western sector, where the crust is younger and more mafic (Figs. 5 and 10).

Three Sectors

The southern Great Basin province is conveniently divided into three contrasting sectors, each corresponding to discrete clusters of calderas surrounded by more or less separate ignimbrite outflow fields (Fig. 6; Table 1). In the eastern sector, the Indian Peak–Caliente field (Best et al., 2013b) surrounds the nested calderas of the Indian Peak–Caliente caldera complex astride the Utah-Nevada state line. In the central sector of the southern Great Basin province, the Central Nevada caldera complex of nested sources is surrounded by the Central Nevada field, the defining ignimbrite outflow sheets of which partly overlap those of the Indian Peak–Caliente field. All but one ash flow from Central Nevada caldera sources lie entirely to the east of a north-south topographic barrier, or drainage divide, near the western edge of the Precambrian basement (Figs. 2, 3, and 6; Best et al., 2009, 2013c). In the western sector of the Great Basin province, the Western Nevada ignimbrite field surrounds 23

Figure 7 is interactive. You can view different items in the legend by moving the cursor over them or you can toggle the symbols on and off with the Layers panel in Adobe Acrobat or Adobe Reader.
them or you can toggle the symbols on and off with the Layers panel in Adobe Acrobat or Adobe Reader.

Figure 8 is interactive. You can view different items in the legend by moving the cursor over them or you can toggle the symbols on and off with the Layers panel in Adobe Acrobat or Adobe Reader.

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Figure 8 is interactive. You can view different 

Figure 8. Modified alkali-lime index (Frost et al., 2001) for southern Great Basin ignimbrites. (A) Central Nevada and Indian Peak-Caliente fields. Nearly all alkaline and alkali-calcic samples are trachy dacitic Isom-type ignimbrites (yellow shade). (B) Western Nevada field. Four ignimbrite units are shaded, as in Figure 7. Calcic ignimbrites are absent; compare with A.

known source calderas that are more widely scattered and apparently smaller than those to the east.

In the western sector, dacites are rare, and rhyolites dominate (Figs. 7, 11, and 12); subordinate trachydacites have mineral assemblages that equilibrated—like rhyolites—in relatively wet magmas. Notably, ignimbrites are relatively more alkalic overall (Figs. 8 and 9) because of greater concentrations of Na2O. In contrast, all trachydacites to the east are Isom type. These tuffs are especially voluminous in the eastern sector, where immediately older phenocryst-rich dacites, or monotonous intermediates, are the dominant ignimbrite. In the central sector, both Isom-type tuffs and monotonous intermediate ignimbrites are less voluminous than to the east.

Figure 13A reveals further details of the ignimbrites in the eastern sector. After a few million years of small, precursory rhyolite eruptions, three super-eruptions totaling 12,300 km³ of monotonous intermediate magmas occurred from 31.1 to 29.2 Ma (all ⁴⁰Ar/³⁹Ar ages are based on an age of 28.20 Ma for the Fish Canyon Tuff). The source calderas of these three eruptions overlap (Fig. 14), indicating a sustained and narrowly focused supply of a large volume of crystal-rich dacite magma to the shallow crust in just a few million years. Following this burst of activity, at least four Isom-type trachydacite ignimbrites totaling 3600 km³ were erupted from a concealed source just to the southeast at 279 to 273 Ma (Fig. 6). After a hiatus in explosive activity of ~4 m.y., voluminous eruptions from nested calderas in the Caliente complex (Fig. 6) occurred episodically until ca. 18 Ma; rhyolite dominated, but a super-eruption of 2200 km³ at 22.6 Ma created an unusual phenocryst-rich, andesite-lavite ignimbrite that may be a monotonous intermediate unit.

The central sector of the province (Fig. 13B) shares aspects with the adjacent sectors to the west and east. To the west, most eruptions were of rhyolite, but, in the central sector, three super-eruptions totaling 4500 km³ of monotonous intermediate dacite occurred in rapid succession at 278 Ma. Only about 600 km³ of slightly younger Isom-type trachydacite is recognized. In lieu of an earlier monotonous intermediate ignimbrite paralleling the brief burst of this activity in the eastern sector, 4800 km³ of zoned rhyolite-dacite erupted at 31.7 Ma.

As previously noted, during the mid-Cenozoic ignimbrite flareup, the crust in the western sector of the southern Great Basin province was thinner (~50 km), younger, and more mafic (accreted Phanerozoic oceanic terranes) than the two eastern sectors, which were founded on thicker Precambrian metamorphic-granitoid basement covered by a thick wedge of sedimentary rock (Fig. 3). How these east-west contrasts in the crust influenced the contrasting nature of the ignimbrites in the province will be considered after a review of other Cenozoic volcanic fields.

COMPARISONS WITH OTHER CENOZOIC VOLCANIC FIELDS

Mid-Cenozoic fields in southwestern North America (Fig. 1; Table 2) developed on continental crust above subducting oceanic lithosphere (e.g., Severinghaus and Atwater, 1990; DeCelles, 2004; Dickinson, 2006; Humphreys, 2009).
Indian Peak–Caliente fields. Nearly all of the shoshonitic samples with <73 wt% SiO₂ are trachy-dacitic Isom-type ignimbrites. (B) Western Nevada field. Four ignimbrite units are shaded.

The mid-Cenozoic volcanic rocks in these fields possess arc chemical signatures consistent with a subduction heritage: Marysvale (Cunningham et al., 1997); Southern Rocky Mountain (Lipman et al., 1978; Askren et al., 1997; Bachmann et al., 2002; Parat et al., 2005); Mogollon-Datil (Bornhorst, 1980; Davis et al., 1993); Sierra Madre Occidental (Ferrari et al., 2007). The flareups, which totaled perhaps 400,000 km² of ignimbrite in these volcanic fields, were nearly synchronous from ca. 36 to 18 Ma, with the greatest eruptive volumes ca. 32 to 23 Ma.

Marysvale Volcanic Field and Colorado Plateau Laccoliths: No Ignimbrite Flareup

This modest-sized field, which contains a cluster of small calderas, lies just east of the southern Great Basin ignimbrite province on the northwestern margin of the Colorado Plateau; it was active ca. 28–19 Ma (Table 2; Figs. 1
Figure 16 is interactive. You can view different items in the legend by moving the cursor over them or you can toggle the symbols on and off with the Layers panel in Adobe Acrobat or Adobe Reader.

Figure 16. Chemical compositions of ignimbrites in the Southern Rocky Mountain volcanic field. Because of alkali (mainly Na₂O) enrichment, some tuffs designated as dacite on the basis of silica content by Lipman (2007) plot in the trachydacite field. Isom Fm. (yellow shade) refers to Isom-type trachydacite in the eastern sector of the Great Basin province (Fig. 7A). (A) International Union of Geological Sciences (IUGS) classification. Green line divides alkalic rhyolite (above) from calc-alkaline (below). (B) CaO-TiO₂. (C) Zr-K₂O.
The Central Andean Neogene ignimbrite province produced by the flareup covers the length and breadth of the Central Andes (de Silva and Francis, 1991; de Silva et al., 2006; Freymuth et al., 2015) over an area of ~250,000 km², comparable to that of the flareup in the United States (Fig. 19). Like the mid-Cenozoic North American flareup, several distinct fields and associated calderas developed (Fig. 19). What little is known about the entire province suggests that it was time transgressive, with the age of volcanism decreasing from north to south (de Silva, 1989; Freymuth et al., 2015). Available isotopic data indicate that the older ca. 20 Ma ignimbrites in the north are less “crustal” than the younger <10 Ma ignimbrites south of 22°S (Freymuth et al., 2015). Seismic and petrologic evidence in the Central Andes indicates the presence of delaminated slabs of lower continental crust, which are believed to include dense garnetiferous residua from melting, as well as mantle lithosphere sinking into the underlying hotter mantle (Kay, 2014); some of the uplift might have been the result of delamination of dense crustal material.

**Ignimbrite Flareup in the Altiplano-Puna Volcanic Complex**

A distinct flareup within the Neogene Central Andean ignimbrite province produced the most voluminous ignimbrite plateau in the southern half of the province from 22°S to 24°S, the Altiplano-Puna volcanic complex (Fig. 19A; de Silva, 1989). Here, the crust is now 58-76 km thick (Yuan et al., 2002; McGlashan et al., 2008). Ignimbrite eruptions began at ca. 10 Ma and continued until ca. 1 Ma, with a distinct pattern of waxing, climax, and waning in three main pulses: >2400 km³ at 8.41–8.33 Ma, >3000 km³ at 5.65–5.45 Ma, and >5400 km³ at 4.09–2.88 Ma (Fig. 20; Salisbury et al., 2011). This ignimbrite flareup created at least six major calderas as much as 60 km in diameter and several smaller ignimbrite shields (de Silva and Gosnold, 2007; Salisbury et al., 2011). The volume-time pattern of explosive activity is like that of the central and eastern sectors of the southern Great Basin (Fig. 13).

Ignimbrites in the Altiplano-Puna volcanic complex include dacite and rhyolite with minor trachydacite, andesite, and latite (Fig. 21). The compositional pattern of these ignimbrites resembles those of the eastern sector of the southern Great Basin ignimbrite province more closely than the dominantly rhyolitic and more alkaline fields previously discussed (Fig. 7A).

![Figure 18B is interactive. You can view different items in the legend by moving the cursor over them or you can toggle the symbols on and off with the Layers panel in Adobe Acrobat or Adobe Reader.](image-url)
Summaries in de Silva et al. (2006), de Silva and Gosnold (2007), Lipman and McIntosh (2008, their table 4), and Kay et al. (2010) underscore the similarities between the dacite ignimbrites in the Altiplano-Puna volcanic complex and eastern sectors of the Great Basin and the Southern Rocky Mountain volcanic field. These are phenocryst-rich, calc-alkaline, high-K dacitic to rhyodacitic ignimbrites of the “monotonous intermediate” type of Hildreth (1981). The 40% to 50% phenocrysts are a low-pressure assemblage of quartz, plagioclase, biotite, and Fe-Ti oxides with accessory apatite and titanite. Amphibole is common in some northern Puna ignimbrites near the arc, minor amounts of clinopyroxene and orthopyroxene can occur in ignimbrites with <67% SiO$_2$, and sanidine is found in some dacite and rhyolite units. Pre-eruptive temperatures are generally near 700 °C to 850 °C, with pressures before eruption corresponding to depths of 5 to 10 km, while magmatic oxygen fugacities (~2 log units above Quartz-Fayalite-Magnetite [QFM]) are similar to many silicic tuffs of the Great Basin. Detailed information on specific monotonous intermediate ignimbrites in the Central Andes is available from Lindsay et al. (2001) for the 3.9 Ma, 2500 km$^3$ Atana ignimbrite, and Schmitt et al. (2001) for the 1 Ma, 100 km$^3$ Purico ignimbrite and 3.69 Ma, >800 km$^3$ Tara ignimbrite. Rhyolites are less common, the largest being the ~300 km$^3$ Toconao ignimbrite, which is interpreted to be from the upper zone of the Atana-Toconao magma reservoir (Lindsay et al., 2001).

A suite of peraluminous ignimbrites in the eastern Altiplano-Puna volcanic complex (Figs. 10 and 19) has the most “crustal” Sr and Nd isotopic compositions, attesting to the influence of a metapelitic basement in the east (Caffee et al., 2012). These are also monotonous intermediates and testify to hypersolidus temperatures in the organically thickened crust, in a similar manner as the Late Cretaceous peraluminous granites just north of the caldera complex in the eastern sector of the Great Basin province.