LARGE-SCALE SILICIC VOLCANISM - THE RESULT OF THERMAL MATURATION OF THE CRUST

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Abstract

Large Silicic Volcanic Fields (LSVF) are considered the surface manifestations of batholith formation at depth and they are commonly associated with “ignimbrite flare-ups”. The Late Miocene to Recent Altiplano-Puna Volcanic Complex (APVC) is one of the largest and best preserved LSVF in the world. Here, available age and volume data on major ignimbrite eruptions in the APVC shows that ignimbrite volcanism in the region initiated at ~10Ma with several large but regionally restricted units such as the Artola and Sifon ignimbrites and ignimbrites of the Vilama-Corutu center. Activity continued for 10 Ma to the recent but appears to have “pulsed” with major episodes of activity at ~8, 6, and 4 Ma. Activity since 4Ma has been minor with the largest eruptions being those of the Purico and Laguna Colorado centers at ~1Ma. Three characteristics of the available age and volume data are: 1) Pulsing of the ignimbrite eruptions with an approximate two million year period. 2) Trend to larger volume eruptions climaxing at about 4 Ma. 3) Markedly diminished activity since 4 Ma. Interestingly the pattern of sudden onset of spatially diffuse, volumetrically minor eruptions leading to a focused catastrophic episode that is followed by quiescence seems to be a feature of other large silicic volcanic fields. This suggests a consistency of process during ignimbrite flare-ups in space and time. We present a model of these large silcic volcanic fields as the result of progressive thermal (and mechanical) maturation of the crustal column due to advection of heat by magmatism and its effects on lithosphere strength. Elevation of the brittle-ductile transition to within a few kilometers of the surface leads to the development of large magma chambers. Mechanical failure of the crust above the magma chambers results in catastrophic failure of the crust and explosive eruptions of thousands of cubic kilometers of magma as regionally extensive ignimbrites.

Introduction

Intense episodes of explosive silicic volcanism, known as ignimbrite flare-ups, characterize active continental margins in particular points of space and time. These flare-ups are represented in the geologic record by large silicic volcanic fields (LSVF) like the Sierra Madre Occidental of Mexico (Ferrari et al., 2004), the Mogollon-Datil Mountains of New Mexico, (Elston, 1984; McIntosh et al., 1992) ;San Juan Mountains of Colorado, USA (Lipman et al., 1978), and volcanic fields of the Great Basin of Utah and Nevada (Gans et al., 1989; Best et al., 1989; Sawyer et al., 1994). The main components of these are regionally extensive ignimbrite sheets, typically dacitic “monotonous intermediates” (Hildreth, 1991), and large, complex, multi-cyclic, calderas. One of the youngest and best preserved LSVF’s is the Altiplano-Puna Volcanic Complex of the Central Andes (de Silva, 1989a,b). This large silicic volcanic field occupies an area of about 70,000 km^2 located between 21 and 24 ^{o}S around the intersection of political boundaries of Chile, Argentina, and Bolivia (Figure 1). Here, an ignimbrite flare-up produced at least 30,000 km^3 of ignimbrites between 10 and 1Ma. The long-lived, nested, resurgent “calderas” and ignimbrite shields that were the eruptive sites appear to be the surface manifestation of a major intrusive complex, the remnants of which have recently been revealed by geophysical techniques (e.g. Zandt et al., 2003; Brasse et al., 2002; Götze and Krause, 2002; de Silva and Zandt, 2005; Figure 1). The most recent activity from the APVC has been a series of Quaternary (<100 ka) large volume (5 to 26 km^3) autonomous flow/domes that bear a strong family resemblance to the ignimbrite producing magmas (de Silva et al., 1994; Watts et al., 1999). These, in addition to the numerous geothermal sources and evidence for active surface deformation, suggest that the APVC remains active with potential for future eruptions.

In this paper we highlight the temporal development of the APVC ignimbrite flare-up. Integration of the geochronological data with petrological and geophysical data allows us to show that the ignimbrites represent the integrated history of intrusion, assimilation and melting of crust, and subsequent differentiation (e.g. Hildreth, 1981; Hildreth and Moorbath, 1988; Johnson, 1991). This history is common to many other LSVF's and suggests a consistency of process and mechanism in their development. We suggest that the fundamental control is the impact of intrusion on the mechanical strength of the crust. The prodigious volumes erupted at LSVFs imply high magma productions rates, and these in turn require high intrusion rates of parental magmas. The advection of heat into the crust must have a profound effect on the mechanical state of the thin crustal "lid" above the accumulating magma bodies, allowing the possibility that eruptions are triggered by mechanical failure of the crust.

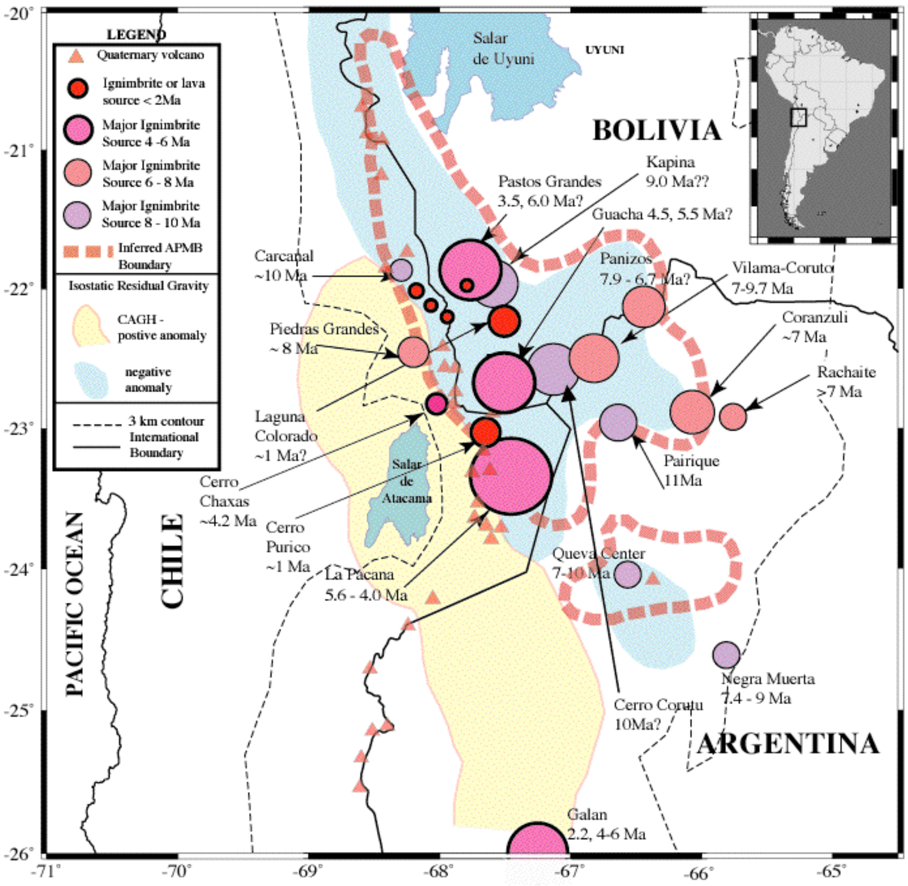

Figure1. Distribution of major ignimbrite sources of the APVC and surrounding areas keyed to age. This shows the apparent focusing of activity with time to the western part of the APVC. Also shown is the extent of the Altiplano-Puna Magma Body (APMB) constrained on the basis of seismic and gravity data. Note that most of the ignimbrite sources are located in the Lipez region of Bolivia – the least well known part of the APVC – but are coincident with the area of the APMB. Cerro Galan in Argentina is shown for reference. (Modified from de Silva and Zandt, GSA Today, forthcoming)

The Altiplano-Puna Volcanic Complex

The APVC forms a barren, contiguous highland with an average elevation of ~4000 m and individual volcano summits of nearly 6000 meters. It is located about 100 to 250 km above the Benioff zone of the Nazca plate at the southward transition of the ~3.8 km high Altiplano plateau and the 4.5 km high Puna, a change associated with a rapid southward thinning of the South American lithosphere without an attendant change in slab dip (Whitman et al., 1996; Allmendinger et al., 1997). Crustal seismicity levels are very low in the APVC, as they are throughout the Central Andes, due to the unusually thick and weak crust (Beck et al., 1996; Zandt et al., 1996; Beck and Zandt, 2002). This is the result from crustal thickening between Late Oligocene to Early Miocene time in a series of eastward-migrating shortening episodes (e.g. Isacks, 1988; Allmendinger et al., 1997; McQuarrie, 2002; Horton et al, 2001; DeCelles and Horton, 2003). The main phase of shortening and thickening of the Andean crust (the Quechua phase) largely preceded the ignimbrite flare-up. The lower lithosphere beneath the Puna may have delaminated as a consequence of the crustal thickening (Kay and Kay, 1993; Kay et al., 1999). This is consistent with the geophysical evidence for the thinner lithosphere and would have initiated a catastrophic thermal input into the sub-APVC crust.

The ignimbrites (and domes) of the APVC are typical of the large “monotonous intermediate” genre (c.f. Hildreth, 1991) and are crystal-rich, calc-alkaline, high-K dacites to rhyodacites, with volumetrically very minor rhyolites. The magmas contained a low-pressure assemblage with quartz, plagioclase, amphibole, biotite, and Fe-Ti oxides as the major mineral phases with occasional sanidine, and ubiquitous apatite, and titanite. These volcanics are clearly related to subduction and formation of the volcanic arc as they show trace element ratios like high Ba/Nb, Ba/La etc. that are characteristic of subduction related magmas. The abundance patterns of rare earth elements (REE) are only moderately steep as shown by the ratios Ce/Yb ~ 50, and La/Yb_n ranging between 10 and 15, and there is little evidence of depletion of the heavy rare earth elements (HREE). It has long been established that Central Andean ignimbrite magmas were dominated by continental crust (e.g. Klerkx et al., 1977) but several lines of evidence indicate they are most likely 30:70 mixtures of mantle-derived magmas and melts of the crust respectively (de Silva, 1989a; Coira, et al., 1993; Ort et al., 1996). The similarity of the APVC ignimbrite isotope compositions with the range of available basement compositions (e.g. Lucassen et al., 1999; 2001) supports a dominantly crustal source. Depth of origin of the magmas is constrained between 15 and 30 km based on isotope and trace element systematics of Sr and the lack of HREE depletion (Figure 2). Later magma evolution at between 110 and 220 MPa, or between 4 and 8 km, is required by pressure estimates using the Al-in-hornblende geobarometer, saturation pressures for H_2O in melt inclusions, and equilibration pressures determined for the high-Si rhyolitic glass matrix in pumices (e,g, de Silva et al., 1994; Lindsay et al., 2001; Schmitt et al, 2001).

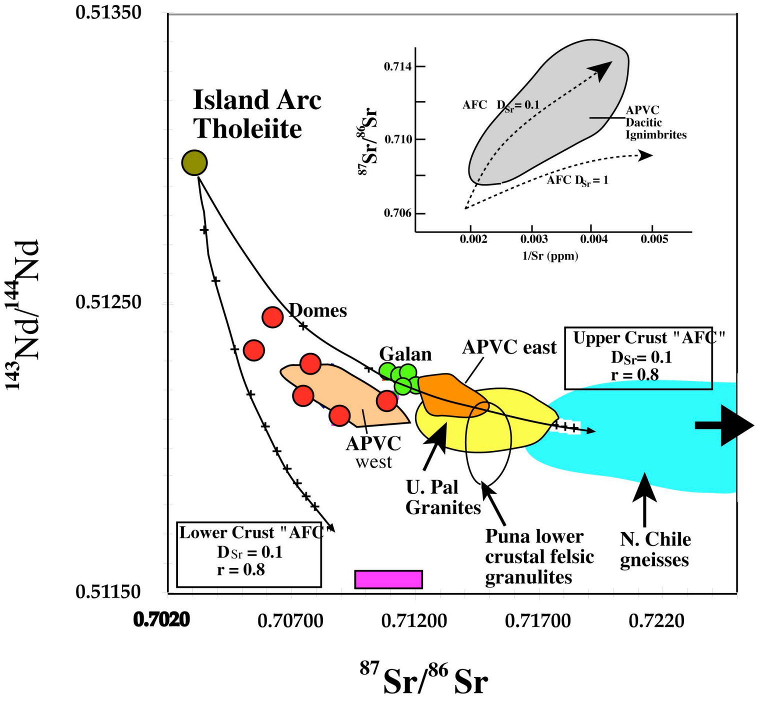

Figure 2. Summary of the Sr- and Nd-isotopic characteristics of the APVC ignimbrites. It is generally accepted that these are best reconciled with a model where at least 30-40% mantle-derived magma is mixed-in with crustal melts. Lower crustal composition is from Taylor and McLennan (1985). The similarity of the APVC ignimbrite isotope compositions with the range of available basement compositions (e.g. Lucassen et al., 1999) is consistent with a dominantly crustal source. The lack of a residual garnet signature suggests that the depth of origin of the magmas has to be less than ~30km. For the Purico system, Schmitt et al. (2001) suggested that magmas originated in the depth range of 30 to 15km; the upper limit being set by assimilation and fractional crystallization calculations that require an assemblage poor in plagioclase; Sr would therefore be incompatible ($D_{Sr}<1$). Note the apparent regional difference in isotopic compositions between eastern and western APVC centers. Cerro Galan (Francis et al., 1989) shown for reference. Data sources are all mentioned in the text. (From de Silva and Zandt, GSA Today, forthcoming).

The presence of a very active benioff zone beneath the APVC has allowed P-to-S (seismic wave) converted phases (receiver functions) from distant earthquakes and underlying subduction zone events, to be used to identify a very-low-velocity layer, the Altiplano Puna Magma Body (APMB), beneath the APVC (Chmielowski et al., 1999; Zandt et al., 2003; Leidig and Zandt, 2003). Modeling of the converted phases from the top and bottom of the magma body constrain the shear velocity to be ~ 1 km/s and this yields a thickness of 1-2 km and a depth of between 17 and 19 km. High surface heat flow and a broad highly conductive zone in the middle crust detected by magnetotelluric studies further support the interpretation of the APMB (Springer, 1999; Brasse et al., 2002). Schilling and Partzsch (2001) marshaled arguments from several different data sets to estimate the percentage of partial melt to be ~20 vol%, and further argued that surface heat flow constrains the melt temperature to be significantly below 1000 °C. They proposed that the melt was felsic rather than basaltic in composition. A strong negative anomaly over the APVC (Götze and Krause, 2002), provides still more evidence for the APMB and constrains the main portion of the body to be centered in southern Bolivia underneath the Cerro Guacha caldera system, with a narrowing northward extension that parallels the active volcanic arc (Figure 1). Although the resolution of the seismic and gravity data is insufficient to determine whether the APMB is a single contiguous body or several smaller bodies with small differences in depth and partially overlapping edges, we can use the area of the APMB (~45,000 km^2), a conservative thickness of 2 km, and the minimum melt percentage of 20% to estimate a minimum volume of melt as 18,000 km^3. While it likely that this melt is dispersed through a mush this range of values establishes the APMB as one of the largest zones of partial melt on Earth discovered to date (de Silva and Zandt, 2005).

In summary, the petrologic-geochemical and geophysical characteristics of the APVC indicate that the volcanic field is the surface manifestation of a major episode crustal magmatisim. The ignimbrite-producing magmas were formed predominantly from a mixture of invading mafic magmas from the mantle and crustal melts at depths of between 30 and 15 km. The geophysically imaged APMB is probably the time-integrated remnant of the main zone of accumulation and storage of these magmas. From the APMB magmas subsequently rose to depths of between 4 and 8 km where they crystallized further before erupting (pumice crystallinities are typically ca. 50%).

Temporal Development of Ignimbrite Volcanism in the APVC

A compilation of available age data for the APVC shows that ignimbrite-producing volcanism in the APVC initiated ~10Ma (Figure 3) with several large (>100 km^3) but regionally restricted units (de Silva, 1989b; Petrinovic, 1994; Coira et al., 1996; Ort, 1993).

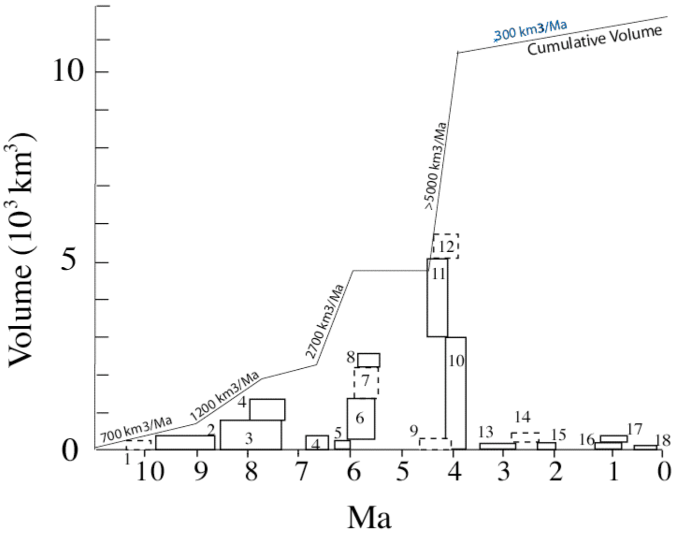

Figure 3. Age-volume data for known major ignimbrite eruptions in the APVC. Solid rectangles are for eruptions that have been well characterized by age dating, correlation criteria, and volcanological studies. Width of rectangles represents 2σ errors. Dashed rectangle outlines are for known eruptions but where the volumes are poorly known. All volumes are deposit volumes and are regarded as minimum estimates based on known distribution as no estimate of co-ignimbrite ash is included. Based on measured density data, DRE volumes will be about 60 to 70 % of the volumes of the units shown. 1 Artola ; 2. Vilama-Corutu I; 3. Sifon ignimbrite; 4. Panizos; 5.Vilama-Corutu II; 6. Chuhuhuilla; 7. Pujsa; 8. Pelon; 9. Toconao; 10; Atana; 11. Puripicar; 12; Tara; 13; Juvina; 14.Patao; 15; Pampa Chamaca; 16. Laguna Colorado; 17. Purico; 18. Filo Delgado. Also show is the eruption rate per Ma for the main pulses of activity.

Activity continued for 10 Ma to the recent but was clearly punctuated by pulses of activity at 8, 6, and 4 Ma with eruption rates of 750 km^3/Ma, 2000 km^3/Ma, and 5000 km^3/Ma respectively (de

Silva and Zandt, 2005). At ~4 Ma, eruptions of La Pacana, Guacha, Chaxas calderas and the source of the Tara ignimbrite (Lindsay et al, 2001) most probably in Bolivia, represent the climactic stage of the APVC (Figure 1). The temporal trend is paralleled by a spatial trend - activity migrated from widely distributed volcanism of relatively small volume prior to about 6 Ma to much larger eruptions focused on the western part of the APVC from about 6 to 4 Ma (Figure 1). Activity since 4 Ma has been comparatively minor (eruption rate of 200 km^3/Ma.) with the largest eruptions being those of the Purico and Laguna Colorado centers at ~1 Ma. Three key observations arise from the available radioisotopic and volume data (Figures 1 and 3):

(i) Ignimbrite eruptions pulsed with ~2 myr periodicity.
(ii) Eruptions trend toward larger volumes over time, culminating at ~ 4 Ma.
(iii) Markedly diminished activity since 4 Ma.

The locus of most recent activity in the APVC is focused on the western margins and to the south of the Pastos Grandes caldera complex (Figure 1). Here, a group of large late Pleistocene domes, exemplified by the Chao dacite in Chile (Guest and Sanchez, 1968; de Silva et al., 1994), and the Chascon-Runtu Jarita complex in Bolivia (Watts et al, 1999), share a strong physical and petrological resemblance to the ignimbrites and are probably “leaks” from the same magma system that fed the large ignimbrites.

Discussion

It has long been suggested that the large ignimbrite producing eruptions are the natural culmination of a long history of intrusion into the crust (e.g. Elston, 1984; Lipman, 1984) and our observations from the APVC confirm this. We find geophysical evidence of a large intrusive complex, the APMB, beneath the volcanic field. The petrological evidence suggests that the APMB is not the pre-eruptive magma chambers but the remnant of a deeper magma accumulation zone, that is probably large mush zone with little eruptible magma (de Silva and Zandt, 2005). The APMB is the integrated result of at least 10 ma of crustal processing by delamination related mantle derived melts. A catastrophic event like delamination is consistent with the sudden onset of the flare-up and the elevated thermal input from the mantle that resulted punctuated the ongoing background subduction related flux of magmas. Crustal processing in the lower to middle crust resulted in melts accumulating at their neutral buoyancy level, the APMB. A persistent flux from beneath (mantle-derived) likely maintained and grew the APMB during the ignimbrite flare-up. As magmas continued to inflate the APMB and to ascend from there to the 4 – 8 km level from which they erupted, the thermal profile of the sub-APVC crust would have been considerably altered.

The ascent and emplacement of thousands of cubic kilometers of hot magma to shallow crustal levels results in advection of heat throughout the crustal column and this would have exerted a profound effect on the rheological and mechanical state of the crust. In Figure 4 we show simply that persistent intrusion into mid-and upper-crustal levels results in major changes to the thermal profile of the crustal column. Elevation of the geotherms results in a corollary change in the strength profile of the crust. In particular, the brittle-ductile transition, taken as the 450°C isotherm, moves rapidly upward, resulting in a very thin elastic lid above the upper level chambers where all the strength of the crust is focused.

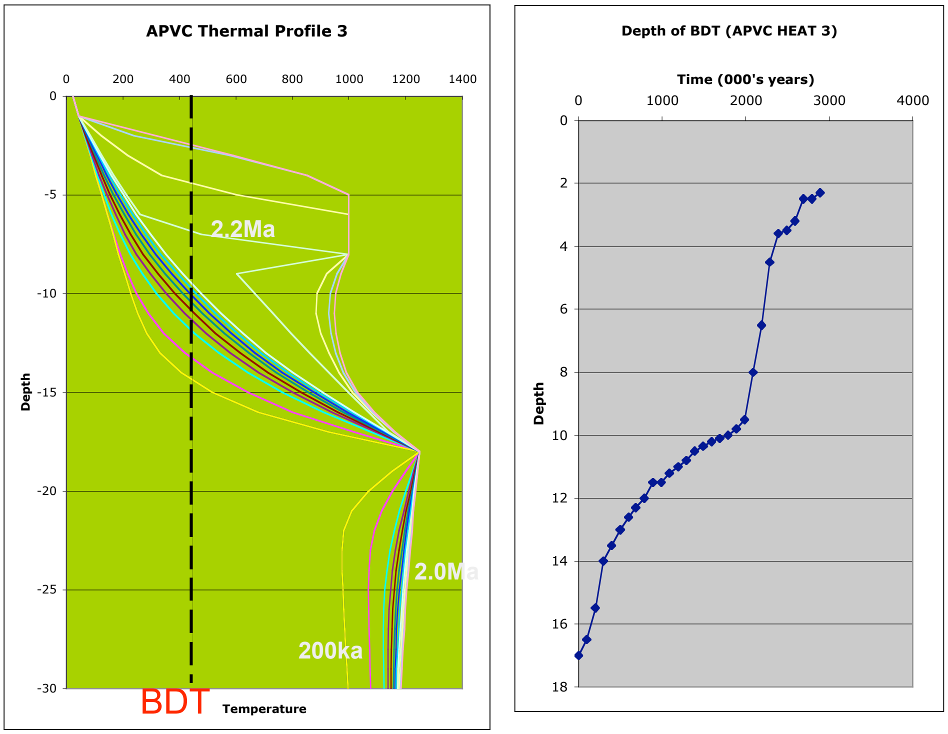

Figure 4. A. Thermal profiles extracted from 2D conductive/convective numerical models of a three million-year time period of intrusion into the upper APVC crust using the HEAT3D code (Wohletz, 2005). The simulations show the thermal impact of intrusion of a 1km thick basaltic sill that is maintained at constant temperature (1200 °C) through continuous replenishment from below for a period of 2.5 Ma. This is meant to illustrate the formation and stabilization of the APMB and the sub APVC magmatic system. User-defined parameters include: crustal density $\rho = 2650$ kg/m^3; k = 2.00 W/m K, Cp = 980 J/kg K. Heat loss from the sill is through convection. Evolving thermal profile of the sub APVC crust shows the significant elevation of the geotherms as a consequence of the intrusion history. B. The time-depth evolution of the local Brittle-Ductile transition (BDT) above the growing APVC intrusive complex modeled in A. The BDT is tracked using the 450°C isotherm through each 100ka time-step of the model. The impact of the intrusive history is that the BDT is elevated to within a couple of kilometers of the surface representing significant thermal softening of the sub-APVC crust.

Emplacement of the thousands of cubic kilometers of magmas at 8 to 4 km is accommodated by both lateral growth (slab-like chambers) and uplift (the APVC has the highest base elevations in the CVZ), which further extends the thin, hot, crustal lid. Analyses like that of Kuznir and Park (1987) show that under normal strain rates the strength of the continental lithosphere strongly depends on heat flow. So, the accumulation of the APMB and its higher-level derivatives would have caused upward compression of the thermal gradient and a highly elevated heat flow. Locally elevated brittle-ductile transitions developed at the tops of the pre-eruptive magma chambers. This process, added to the regional extensional stress associated with plateau collapse, and local uplift, resulted in failure of the crust above the shallow-level derivatives from the APMB. Foundering of the roof into the magma was likely aided by a density inversion resulting from an upper "foamy" magma zone that resulting from volatiles concentrating in the upper parts of the magma. Thus "blistering" the tops of the ephemeral magma chambers resulted in voluminous ignimbrite eruptions.

The increasing size of the eruptions suggests that successively larger batches of magma had to accumulate before they were erupted. Growth of larger magma bodies may have been facilitated by increased thermal softening by successive pulses of intrusion into the pre-eruption levels (8 – 4 km). This may lead to the wall rocks of the growing magma body to behave in an increasingly viscous way and accommodate the growth of larger bodies later in the evolution of the system (e.g. Newman et al.,2001,; Jellinek and DePaolo, 2003) .

The model developed for the APVC may have applications in other large silicic volcanic provinces. Workers in other regions have recognized the potential role of thermal softening and failure of the crust as a trigger for ignimbrite flare-ups (Gans, et al., 1989; Best and Christiansen, 1991). Flare-ups in space and time share major characteristics that suggest a communality of origin and evolution. They involve the eruption of prodigious volumes of ignimbrite over short periods of time. They are often associated with large negative bouguer anomalies (Lipman, 1984), and involve catastrophic crustal processing in response to transient thermal events that result in high crustal magma production rates. These thermal events have been attributed to catastrophic thermal input into the crust from upwelling asthenosphere in response to delamination (Francis et al,. 1989), slab detachment (Ferrari, 2002), slab-roll back (Humphries, 1995). Best et al. (1991) showed that ignimbrite flare-ups in the western US have a sudden onset, and pulsing history. In detail it is remarkable how similar the volume-time graphs of different volcanic fields are to that of the APVC (Figure 5).

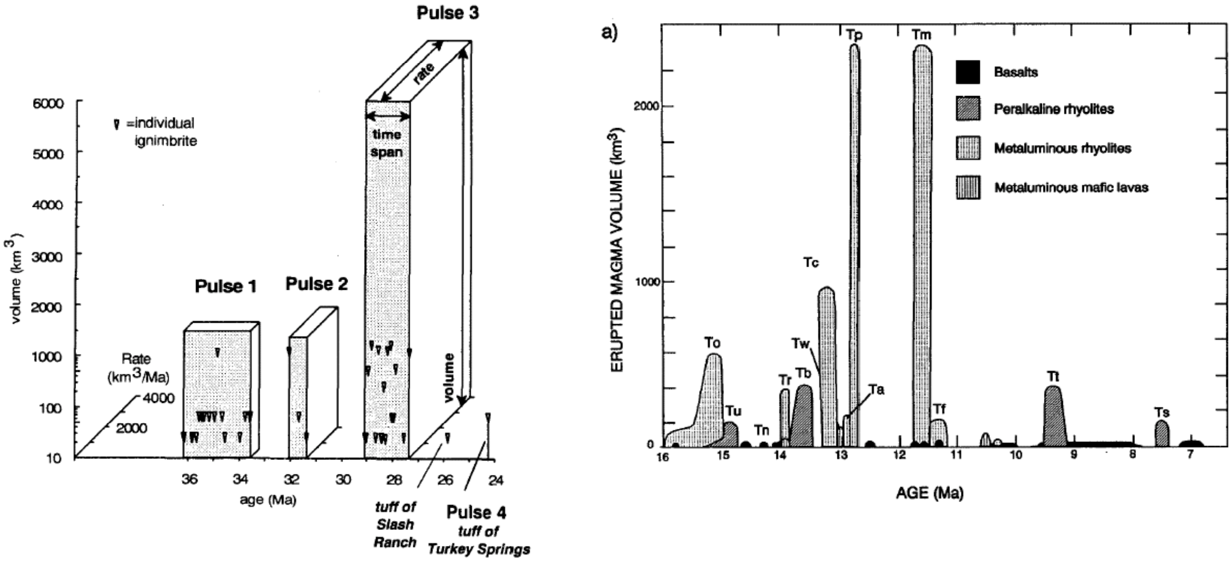

Figure 5. A. Time, volume, and mean effusion rate for ignimbrite pulses in the Mogollon-Datil volcanic field, New Mexico, U.S.A (McIntosh, et al., 1992). B. Time-volume data for the Southwestern Nevada Volcanic Field, U.S.A (Sawyer, et al., 1994). These are representative of data from other ignimbrites flare-ups such as the Indian Peaks volcanic field (e.g. Best et al., 1989) that show strongly episodic nature and increasing intensity of volcanism followed by rapid diminution.

The data for the Mogollon-Datil Volcanic Field of New Mexico (McIntosh et al., 1992), the Southwest Nevada Volcanic Field (Sawyer et al., 1994), and the Great Basin (Best et al., 1989) reveals the strong resemblance to the APVC and confirms that flare-ups evolve slowly but build to a catastrophic episode followed by markedly diminished activity and that eruptive activity is episodic, increasing in intensity with time. This resonance suggests that the model of increasing thermal impact of the presented for the APVC maybe applicable to other ignimbrite flare-ups.

Concluding remarks

The Altiplano Puna Volcanic Complex (APVC) of the Central Andes is one of the best preserved large silicic volcanic fields on the Earth. Spatiotemporal, petrological, and geophysical evidence reveals that the ignimbrite flare-up is the surface response to the development of a regional mid to upper-crustal intrusive complex now represented by the Altiplano-Puna Magma Body. This geophysically imaged "mush"zone is approximately 1-2 km thick with an upper surface at ~17 km. The prodiguous magma production and intrusion rates implied by the erupted volumes of the APVC and the inferred extent of the APMB require an equally profound input of heat, which was triggered by delamination of the lower lithosphere some time prior to the initiation of the ignimbrite flare-up ~10 Ma. Delamination resulted in a catastrophic increase in mantle power input (flux of basaltic magma) that punctuated the background subduction related flux. The pre-flare-up APVC crust had been thermally prepared (elevated geotherms) through ongoing arc magmatism and crustal thickening, thus the increased mantle power input resulted in catastrophic and widespread crustal magmatism. The impact of this transient thermal input was an intense period of generation, transport and storage of thousands of km^3 of magma in the mid crust. Advection of heat through the crustal column had a profound effect on the rheological and mechanical state of the upper crust. Ignimbrite eruptions are preceded by ascent and storage of large volumes of felsic magma at 4 to 8km in the crust. Preliminary thermal modeling shows that magma accumulation causes rapid elevation of the brittle-ductile transition with the consequence that the strength of the crust is concentrated in an ever-thinner elastic layer (lid) above the magma chamber. The massive eruptions represented by ignimbrites are triggered by mechanical failure of the roof of the magma chamber and initially driven by foundering of the roof into the magma chamber. The similarity in character of the APVC ignimbrite flare-up with other well-studied flare-ups from the western US and Mexico suggest a consistency of process and we suggest that the model presented for the APVC may be generally applicable.

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References Cited

Allmendinger, R.W., Jordan, T.E., Kay, S.M., and Isacks, B.L., 1997. The evolution of the Altiplano-Puna plateau of the Central Andes. Annual Reviews of Earth and Planetary Science, v.25, p. 139-174.

Beck S. L. and G. Zandt, 2002, Nature of orogenic crust in the central Andes, *J. Geophys. Res.*, *107*, NO. B10, 2230, doi:10.1029/2000JB000124.

Beck, S.L., Zandt, G., Myers, S.C., Wallace, T.C., Silver, P.G., and Drake, L., 1996. Crustal-thickness variations in the central Andes. Geology, v.24, p.407-410.

Best, M.G., and Christiansen, E.H., 1991. Limited extension during peak Tertiary volcanism, Great Basin of Nevada and Utah. Journal of Geophysical Research, v. 96, B8, p. 13,509 – 13,528.

Best, M.G., Christiansen, E.H., and Blank, J.H. Jr., 1989. Oligocene caldera complex and calc alkaline tuffs and lavas of the Indian Peak volcanic field, Nevada and Utah., Geological Society of America Bulletin, v. 101, p.1076-1090.

Brasse, H., Lezaeta, P., Rath, V., Schwalenberg, K., Soyer, W., and Haak, V., 2002. The Bolivian Altiplano conductivity anomaly. Journal of Geophysical Research, v. 107 no. B5, doi: 10.1029/2001JB000391.

Chmielowski, J., Zandt, G., and Haberland, C., 1999. The central Andean Altiplano-Puna Magma Body. Geophysical Research Letters, v. 26, p. 783-786.

Coira, B., Caffe, P.J., Kay, S.M., Diaz, A., and Ramirez, A., 1996. Complejo volcanico Vilama-Sistema calderico del Cenozoico superior en Puna, Jujuy. XIII Congreso Argentino de Geologia, Buenos Aires, Actas 3, p. 603-602.

Coira, B., Mahlburg-Kay, S., and Viramonte, J., 1993. Upper Cenozoic magmatic evolution of the Argentine Puna - A model for changing subduction geometry. International Geological Review, v.35, p. 677-720.

DeCelles, P.G., and Horton, B.K., 2003, Implications of early-middle Tertiary foreland basin development for the history of Andean crustal shortening in Bolivia. Geol. Soc. of Am. Bull., 115, 58-77.

de Silva, S.L., 1989a. The Altiplano-Puna Volcanic Complex of the Central Andes. Geology, v.17, p. 1102-1106.

de Silva, S.L., 1989b. Geochronology and stratigraphy of the ignimbrites from the 21°30’ S to 23°30’S portion of the Central Andes of northern Chile. Journal of Volcanology and Geothermal Research, v. 37, p. 93-131.

de Silva, S.L., and Zandt, G., 2005. The development and architecture of ignimbrite flare-ups – insights from the Altiplano-Puna Volcanic Complex of the Central Andes. GSA Today in review.

de Silva, S.L., Self, S., Francis, P.W., Drake, R.E., and Ramirez, C.R., 1994. Effusive silicic volcanism in the Central Andes: The Chao dacite and other young lavas of the Altiplano-Puna Volcanic Complex. Journal of Geophysical Research, v. 99, p. 17805-17825.

Elston, W.E., 1984. Subduction of young oceanic lithosphere and extentional orogeny in southwestern North America during mid-Tertiary time. Tectonics, v. 3, p. 229-250

Ferrari, L., Lopez-Martinez, M., and Rosas-Elguera, J., 2002. Ignimbrite flare-up and deformation in the southern Sierra Madre Occidental, western Mexico: Implications for the late subduction history of the Farallon plate. Tectonics, v. 21, No. 4, 10.1029/2001TC001302,

Francis P.W., Sparks, R.S.J., Hawkesworth, C.J., Thorpe, R.S., Pyle, D.M., Tait, S.R., Mantovani, M.S.M, and McDermott, F., 1989. Petrology and geochemistry of volcanic rocks of the Cerro Galan caldera, northwest Argentina. Geological Magazine, v. 126, p. 515-547.

Gans, P.B., Mahood, G.A., and Schermer, E.R., 1989. Synextensional magmatism in the Basin and Range Province; a case study from the eastern Great Basin. Geological Society of America Special Paper 233, p. 1-53.

Götze, H.-J., and Krause, S., 2002. The Central Andean gravity high, a relic of an old subduction complex? Journal of South American Earth Sciences, v. 14, p. 799-811.

Guest and Sanchez, 1968. A large dacitic lava flow in Northern Chile. Bulletin of Volcanology, v. 33, p. 778-790.

Hildreth, E.W., 1981. Gradients in silicic magma chambers: Implications for lithospheric magmatism. Journal of Geophysical Research, v.86, p. 10,153-10,192.

Hildreth, E.W. and Moorbath, S., 1988. Crustal contributions to arc magmatism in the Andes of Central Chile. Contribution to Mineralogy and Petrology, v. 98, p. 455-489.

Horton, B.K., Hampton, B.A., Waanders, G.L., 2001, Paleogene synorogenic sedimentation in the Altiplano Plateau and implications for initial mountain building in the Central Andes. Geol. Soc. Am. Bull. 113, 1387-1400.

Isacks, B.L., 1988. Uplift of the central Andean plateau and bending of the Bolivian orocline. Journal of Geophysical Research, v. 93, p. 3211-3231.

Jellinek, A.M., and DePaolo, D.J., 2003. A model for the origin of large silicic magma chambers: precursors of caldera forming eruptions. Bulletin of Volcanology, v. 65, p., 363-381.

Johnson, C.M., 1991. Large-scale crustal formation and lithosphere modification beneath Middle to Late Cenozoic calderas and volcanic fields, western North America. Journal of Geophysical Research, v. 96, B8, p. 13485 – 13507.

Kay, R. W., and Kay, S., 1993. Delamination and delamination magmatism, Tectonophysics, v. 219, p.177 – 189.

Kay, S.M., Mpodozis, C., and Coira, B., 1999. Magmatism, tectonism and mineral deposits of the Central Andes (22° - 33°S latitude). In Skinner, B.J., and Holland, R., (eds) Geology or Ore deposits of the Central Andes. Society of Economic Geologists Special Publication, 7, p. 27-59.

Klerkx, J., Deutsch, S., Pichler, H., and Zeil, W., 1977. Sr-isotopic composition and trace element data bearing on the origin of the Cenozoic volcanic rocks of the Central and Southern Andes. Journal of Volcanology and Geothermal Research, v. 2, p. 49-71.

Kuznir, N.J., & Park, R.G., 1987. The extensional strength of the continental lithosphere: its dependance on geothermal gradient, crustal composition, and thickness. In: Continental Extensional tectonics (Coward, M.P., Dewey, J.F., and Hancock, P.L., eds.) Geological Society of London Special Publication, v. 28, p 35-52.

Leidig, M. and G. Zandt, 2003, Highly anisotropic crust in the Altiplano-Puna volcanic complex of the central Andes, *J. Geophys. Res., 108*, NO. B1, 2014, doi:10.1029/2001JB000649.

Lindsay, J.M., Schmitt, A.K., Trumbull, R.B., de Silva, S.L., Siebel, W., and Emmermann, R., 2001. Magmatic evolution of the La Pacana Caldera System, Central Andes, Chile: Compositional variation of two cogenetic large-volume felsic ignimbrites. Journal of Petrology, v. 42, p. 459-486.

Lipman, P.W., 1984. The roots of ash-flow calderas in North America: Windows into the tops of granite batholiths. Journal of Geophysical Research, v. 89, p. 8801-8841

Lipman, P.W., Doe, B.R., Hedge, C.E., Steven, T.A., 1978. Petrological evolution of the San Juan volcanic field, southwestern Colorado; Pb and Sr isotopic evidence. Geological Society of America Bulletin, v. 89, p. 59-82.

Lucassen, F., Franz, G., Thirlwall, M., and Metzger, K., 1999. Crustal recycling of metamorphic basement: Late Paleozoic granites of northern Chile (~22°S); Implications for the composition of the Andean crust. Journal of Petrology, v. 40, p. 1527-1551.

Lucassen, F., Becchio, R., Harmon, R., Kasemann, S., Franz, G., Trumbull, R., Romer, R.L. and Dulski, P., 2001. Composition and density model of the continental crust in an active continental margin – the Central Andes between 18° and 27°S. Tectonophysics, v. 341, p. 195-223.

McIntosh, W,C,, Chapin, C.E., Ratte, J.C., and Sutter, J.F., 1992. Time-stratigraphic framework for the Eocene-Oligocene Mogollon-Datil volcanic field, southwest New Mexico. Geological Society of America Bulletin, v. 104, p. 851-871.

McQuarrie, N., 2002, Building a high plateau: The kinematic history of the central Andean fold-thrust belt, Bolivia. Geol. Soc. of Am. Bull. v. 114, p. 950-963.

Newman, A.V., Dixon, T.H., Ofoegbu, G., Dixon, J.E., (2001). Geodetic and seismic constraints on recent activity at Long Valley Caldera, California: evidence for viscoelastic rheology. Journal of Volcanology and Geothermal Research, v. 105, p. 183-206.

Ort, MH, 1993, Eruptive processes and caldera formation in a nested downsag-collapse caldera: Cerro Panizos, central Andes Mountains, Journal of Volcanology and Geothermal Research,., v. 56, p. 221-252.

Ort, M.H., Coira, B.L., Mazzoni, M.M., 1996. Generation of a crust-mantle mixture; magma sources and contamination at Cerro Panizos central Andes. Contributions to Mineralogy and Petrology, v. 123, p. 308-322.

Petrinovic, I., 1994. Volcanismo cenozoico asociado al lineamento Calama Olacapata-El Toro en el tramo comprendido entre San Antonio de los Cobres y Olacapato, Provincia de Salta. Ph.D. thesis Universidad Nacional de Salta, 174pp.

Sawyer, D.A., Fleck, R.J., Lanphere, M.A., Warren, R.G., Broxton, D.E., Hudson, M.R., 1994. Episodic caldera volcanism in the Miocene southwestern Nevada volcanic field: revised stratigraphic framework, $^{40}Ar/^{39}Ar$ geochronology and implications for magmatism and extension. Geological Society of America , v. 106, p. 1304-1318.

Schilling, F. R., and Partzsch, G. M., 2001. Quantifying partial melt fraction in the crust beneath the central Andes and the Tibetan Plateau. Physics and Chemistry of the Earth, v. 26, p. 239-246.

Schmitt, A.K., de Silva, S.L., Trumbull, R. and Emmermann, R., 2001. Magma evolution in the Purico ignimbrite complex, northern Chile: evidence for zoning of a dacitic magma by injection of rhyolitic melts following mafic recharge. Contributions to Mineralogy and Petrology, 140, 680-700.

Springer M., 1999. Interpretation of heat-flow density in the Central Andes. Tectonophysics, v. 306, p. 377-395.

Taylor, S.R. and McLennan, S.M., 1985. *The Continental Crust: Its Composition and Evolution*. Blackwell Scientific Publication, Oxford, UK., 312 pp.

Watts, R.B., de Silva, S.L., Jimenez, G., and Croudace, I.W., 1999. Effusive silicic volcanism triggered and fueled by recharge: a case study of the Cerro Chascon-Runtu Jarita complex of SW Bolivia. Bulletin of Volcanology, v.60, p. 241-264.

Whitman, D., Isacks, B.L., and Kay, S.M., 1996. Lithospheric structure and along-strike segmentation of the central Andean Plateau: Topography, tectonics, and timing. Tectonophysics, 29, p. 29-40.

Wholetz, K., 2005. K-Ware-HEAT3D. http://www.ees1.lanl.gov/Wholtez/Heat.htm. Accessed multiple times in 2004/2005.

Zandt, G., Beck, S.L., Ruppert, S.R., Ammon, C.J., Rock, D., Minaya, E., Wallace, T.C., and Silver, P.G., 1996. Anomalous crust of the Bolivian Altiplano, central Andes: Constraints from broadband regional seismic waveforms. Geophysical Research Letters, v.23, p.1159-1162.

Zandt, G., Leidig, M., Chmielowski, J., Baumont, D., and Yuan, X., 2003. Seismic detection and characterization of the Altiplano-Puna magma body, central Andes, PAGEOPH Aki Symposium Volume, vol. 160, 789-807.