Ignimbrite flare-ups in the Central Andes: Crustal sources and processes of magma generation

Gerhard Wörner, Elena Belousova, Simon Turner, Jelte Kemann, Axel Schmitt, Axel Gerdes, Shan deSilva
1. Geological setting (review, maybe skipped)
2. Ignimbrite compositions: AIDA data base: (review, maybe skipped)
   Ages, volume and composition through time and space
3. Evidence for large crustal contributions (review, maybe skipped)
4. Zircon U/Pb dating combined with O-isotope and Hf-isotope analyses (new data)

Results (in a nutshell)

-> Contributions of large volume ignimbrite magmas increase from 20 to 70% with thermal maturation of increasingly thickened Andean crust

-> Individual ignimbrite units are isotopically heterogeneous and are amalgamations of crustal melts from distinct Proterozoic sources w/r to age and composition
Ignimbrites:

*message from thickening crust at Andean-type active continental margins*
Large-volume, plateau-forming ignimbrites on the western margin of the Central Andean orogen...

over 30 Ma and 1500 km N-S extension

900 m
Cuno Cuno Section

with > 24 Ma old marine sediments at 1900 m (S. Peru)

1. Geological setting

Uplift, erosion and sedimentation prior to "ignimbrite flares"

Jurassic Sediments

22 Ma Ignimbrites
1. Geological setting

1700 m
What is the source of these voluminous ignimbrites?

Our tools:
- GIS-Data base mapping
- Ages
- Volumes
- Sr-O-isotopes
- O-Hf-U/Pb analyses in zircons
1. Geological setting
1. Geological setting

**Diablo Fmt**
(16-6 Ma, volcaniclastic conglomerates, sands, lacustrine deposits)

- **Oxaya-Ig**
  - $19.38 \pm 20^{(1)}$
  - $19.71 \pm 0.04^{(2)}$

- **Molinos-Ig**

- **Cardones-Ig**
  - $21.92 \pm 0.17^{(2)}$

- **Poconchile (Willi)-Ig**
  - $22.72 \pm 0.15$ San Ar-Ar$^{(1)}$
  - $22.74 \pm 0.02$ Zr U-Pb$^{(2)}$

**Oxaya Fmt**
(rhyolitic ignimbrites > 3000 km² with few intercalated sediments)

**Azapa Fmt**
(35-22 Ma: conglomerates, sandstones, mudstones, sheet-flow deposits)

Base not exposed
1. Geological setting

U-Pb zircon ages and Ar-Ar sanidine ages perfectly overlap!!
Temporal and compositional evolution of „ignimbrite flares“

Based on our Andes Ignimbrite Database (AIDA)

More than 200 ignimbrite sheets GIS-mapped,

more than 1600 samples with geochemical, isotopic,
and many with age data

APVC, 3-10 Ma, 23°S
2. Ignimbrite compositions

La Pacana caldera...as an AIDA - example
2. Ignimbrite compositions

...La Pacana caldera...as an AIDA - example
2. Ignimbrite compositions

...La Pacana caldera...as an AIDA - example

Andes Ignimbrite Database

**Structures**

**Samples**
- 0.0 - 2.0 Ma
- 2.1 - 4.0 Ma
- 4.1 - 7.0 Ma
- 7.1 - 11.0 Ma
- 11.1 - 15.0 Ma
- 15.1 - 18.0 Ma
- 18.1 - 23.0 Ma
- 23.1 - 24.0 Ma
- No age data

**Ignimbrite mapping**
- Undated ignimbrite
- 0.0 - 2.0, 2.01 - 4.0, 4.01 - 7.0, 7.01 - 12.0, 12.01 - 15.0, 15.01 - 17.0, 17.01 - 19.0, 19.01 - 24.0

![La Pacana caldera in the Andes Ignimbrite Database](https://uri-gis.maps.arcgis.com/apps/OnsPanascience/index.html?appid=47998c85032847e9e9fc5e7a27af27bb)

**Atana Ignimbrite**
- **NAME**: Atana Ignimbrite
- **Description**: Plug-dike-to-dike dacitic ignimbrite, crystal-rich hemi-homogeneous
- **Age (Ma)**: 3.8 - 4.2
- **Reference**: Kay et al. (2010)
- **Caldera**: La Pacana Caldera

**Further references**

**Thickness**
- Zoom in/out

---

Brandmeier and Wörner  AIDA Website
2. Ignimbrite compositions

...La Pacana caldera...as an AIDA - example
2. Ignimbrite compositions

Example Lauca and Oxaya ignimbrites: Edit and update the database by authorized users

Brandmeier and Wörner  AIDA Website
2. Ignimbrite compositions

- active and potentially active volcanoes
- monogenetic, mostly mafic, minor centers
- Pleistocene to mid-Miocene volcanic edifices
- mapped ignimbrite sheets of different ages
- ignimbrites, partly below younger cover
- calderas
- outline of Altiplano–Puna Magmatic Body, Altiplano–Puna Volcanic Complex (APVC)

Ignimbrite ages in Ma

2. Ignimbrite compositions

**Age migration of Central Andean Ignimbrites**

![Graph showing age migration of Central Andean Ignimbrites with various plateaus and age ranges.]
2. Ignimbrite compositions

Age migration of Central Andean Ignimbrites

Plateau-forming ignimbrites

Local small volume ignimbrites

Nazca Plateau
Oxaya Plateau
Altos de Pica Plateau
Huayllillas Plateau
Sencca/Lauca/Perez

2. Ignimbrite compositions

Age migration of Central Andean Ignimbrites

- Active and potentially active volcanoes
- Pleistocene to mid-Miocene volcanic edifices
- Monogenetic, mostly mafic minor centres
- Mapped ignimbrite sheets of different ages
- Distribution of ignimbrites, partly below younger volcanic and sedimentary cover
- Outline of the Altiplano-Puna Magmatic Body

Nazca-Plate-South America convergence rate: c. 7 cm/year

- Age migration of Central Andean Ignimbrites
  (5-14 Ma, Thouret et al. 2017, Wörner et al., unpublished data)

Volume of erupted ignimbrite magma (in 10^6 km³)

Mapped area of ignimbrite deposits (in 10^6 km²)

Freytmuth et al. (2015)
2. Ignimbrite compositions

Magmatic compositions
fractionating phases and Sr/Y ratios will remain low. These general principles can be used to link trace-element signatures in magmas to the pressure (i.e. depth within the crust) where magma evolution takes place. In thin-crust settings, where plagioclase, pyroxene, and amphibole dominate the equilibrium assemblage in andesites, the ratios of Sr/Y, Sm/Yb, and Dy/Yb will be low. Increasing pressure of fractional crystallization and/or assimilation processes tends to increase Sr/Y, Sm/Yb and Dy/Yb (Kay et al. 1988, 1999; Coira et al. 1993; Mamani et al. 2010).

Figure 3 shows these three trace-element ratios and their evolution through time. Figures 3A and 3C clearly indicate that – with few exceptions – the maximum Sr/Y and Dy/Yb ratio are found only in intermediate andesites (55–68 wt% SiO₂) that are younger than 5 Ma (Pliocene, blue symbols in Figure 3). Basalts (<52 wt% SiO₂) are rare and lack the high Sr/Y, Dy/Yb, and Sm/Yb ratios indicative of residual garnet. Thus, a strong garnet signature is found in intermediate magmas only after the youngest phase of crustal thickening (<10 Ma) (Figure 3B). Findings such as these have resulted in a recent proliferation of publications linking averaged trace-element ratios to crustal thickness in a quantitative way (e.g. Farner and Lee 2017; Hu et al. 2017). However, as Figure 3 demonstrates clearly, low Sm/Yb, Dy/Yb and Sr/Y ratios occur throughout the Central Andes at any time, Figure 2 shows the distribution of SiO₂ in three broad categories of Central Andean magmas: the intrusive igneous rocks and the two types of extrusive rocks, the lavas and the ignimbrites. Note the distinct bimodal SiO₂ wt% values between lavas (blue) and ignimbrites (yellow), which are controlled by density, viscosity, and the maximum SiO₂ of the eutectic compositions. Older intrusive rocks (red speckled) have a wide compositional range but their maximum is between the modes of the lavas and the ignimbrites.

Abbreviations are as follows: cpx = clinopyroxene; plag = plagioclase feldspar. (A) Ratio of Sr/Y plotted with respect to wt% SiO₂. (B) Ratio of Sm/Yb plotted with respect to age (Ma). (C) Ratio of Dy/Yb plotted with respect to wt% SiO₂. (D) Ratio of Dy/Yb plotted with respect to Sm/Yb. Arrows indicate compositional variations caused by the distinct preference for certain trace elements in the different residual mineral phases during fractional crystallization and/or crustal melting and assimilation. Colors: Quaternary/Pliocene = blue; Miocene/Oligocene = yellow and orange; Eocene/Paleocene = red; Cretaceous = green; Jurassic = black.

MODIFIED FROM Mamani et al. (2010).
2. Igneous compositions

Systematic temporal changes in trace element patterns through time during crustal thickening in the Central Andes
Systematic temporal changes in trace element patterns through time during crustal thickening in the Central Andes

2. Ignimbrite compositions

Mamani et al. (2011) Geol Soc Am Bull
2. Ignimbrite compositions

Systematic temporal changes in trace element patterns through time during crustal thickening in the Central Andes

Not so clear for ignimbrites

Mamani et al. (2011) Geol Soc Am Bull
This study applies cluster analysis (CA) and linear discriminant analysis (LDA) on log-ratio transformed data.

Brandmeier and Wörner (1916)
Compositional variation related to crustal thickening

This study applies cluster analysis (CA) and linear discriminant analysis (LDA) on log-ratio transformed data.

Brandmeier and Wörner (1916)
How much crustal recycling during ignimbrite volcanism?
3. Evidence for large crustal contributions

3. Evidence for large crustal contributions

- APVC ignimbrites
- N. Peruvian ignimbrites
- N. Chile ignimbrites
- Metamorphic basement

Minerals from andesitic lavas

Source contamination


\[ \delta^{18}O \text{ (per mil)} \]

\[ \frac{^{87}Sr}{^{86}Sr} \]

APVC ignimbrites
S. Peruvian ignimbrites
N. Chile ignimbrites
Minerals from andesitic lavas
N. Chile metamorphic basement
3. Evidence for large crustal contributions

- Minerals from andesitic lavas
- N.Chile metamorphic basement
- S. Peruvian ignimbrites
- APVC ignimbrites

\[
\delta^{18}O \quad \text{(per mil)}
\]

\[
\frac{^{87}\text{Sr}}{^{86}\text{Sr}}
\]

Source contamination

Mix 'n MASH

Extended AFC

N of 23 °S

S of 23 °S

Radiogenic Andean Basement

3. Evidence for large crustal contributions

![Graph showing δ¹⁸O vs ⁸⁷Sr/⁸⁶Sr ratio for different ignimbrites and basement samples.](image)

- APVC ignimbrites
- S. Peruvian ignimbrites
- N.Chile ignimbrites
- Minerals from andesitic lavas
- N.Chile metamorphic basement

3. Evidence for large crustal contributions

Which crustal component should we choose in crust-mantle mass balance modelling?

- APVC ignimbrites
- S. Peruvian ignimbrites
- N.Chile ignimbrites
- Minerals from andesitic lavas
- N.Chile metamorphic basement

4. Zircon U/Pb dating combined with O-isotope and Hf-isotope analyses

Are zircons the solution?
Zircon phenocrysts from Oxaya Fmt Ignimbrites (19 – 22 Ma): Shapes

4. Zircon U/Pb dating combined with O-isotope and Hf- isotope analyses
Zircon phenocrysts from Oxaya Fmt. Ignimbrites

Zonation: inherited zircons?

Not really!!
4. Zircon U/Pb dating combined with O-isotope and Hf-isotope analyses

Reference data for potential crustal components in ignimbrite magmas

**Graphical representation:**
- Metasedimentary basement rocks:
  - Quebrada Aroma
  - Sierre de Moreno
  - Sierra del Tigre
- Igneous basement rocks:
  - Belen
  - Rio Loa
  - Cordon Lila

**Mantle values**

**Notes:**
Reference data for potential crustal components in ignimbrite magmas

4. Zircon U/Pb dating combined with O-isotope and Hf-isotope analyses
Reference data for potential crustal components in ignimbrite magmas: *basement rocks*

4. Zircon U/Pb dating combined with O-isotope and Hf-isotope analyses
Reference data for potential crustal components in ignimbrite magmas: zircons in sedimentary archives

Detrital zircons ("Toquepala arc" and "Mesozoic") from Wotzlaw et al (2011)
Reference data for potential crustal components in ignimbrite magmas: **zircons in basement rocks**

**Toquepala arc**
- n=47

**Mesozoic**
- n=222

**Belen metamorphic basement**
- n=38

Detrital zircons ("Toquepala arc" and "Mesozoic") from Wotzlaw et al (2011)

Belen zircons from the Arequipa metamorphic basement from Pankhurst et al (2016)
Zircons in ignimbrites

Toquepala arc  
n=47

Mesozoic  
n=222

Belen metamorphic basement  
n=38

U/Pb ages of inherited zircon in ignimbrite

1172 Ma  1218 Ma

45 Ma

1859 Ma

zircon crustal 
Hf model ages n=53

U/Pb_{zirc} Age (Ma)

This study

Detrital zircons ("Toquepala arc" and "Mesozoic") from Wotzlaw et al (2011)
Belen zircons from the Arequipa metamorphic basement from Pankhurst et al (2016)

\[ T_{DM(\text{crustal})} \] calculated with

\[ \lambda_{176}^{\text{Lu}} = 1.865 \times 10^{-11} \] (Scherer et al., 2001)

\[ ^{176}\text{Lu} / ^{177}\text{Hf (crust)} = 0.015 \]

\[ ^{176}\text{Hf} / ^{177}\text{Hf (crust)} = 0.0384 \]
Reference data for potential crustal components in ignimbrite magmas

Detrital zircons (“Toquepala arc” and “Mesozoic”) from Wotzlaw et al (2011)
Belen zircons from the Arequipa metamorphic basement from Pankhurst et al (2016)

Crustal contributions are mixtures of 1 Ga and 2 Ga old crust!

U/Pb ages of inherited zircon in ignimbrite

U/Pb\textsubscript{zirc} Age (Ma)

\begin{align*}
\text{Toquepala arc} & \quad n=47 \\
\text{Mesozoic} & \quad n=222 \\
\text{Belen metamorphic basement} & \quad n=38
\end{align*}

zircon crustal Hf model ages n=53

$T_{DM\text{(crustal)}}$ calculated with

$\lambda^{178}\text{Lu} = 1.865 \times 10^{-11}$ (Scherer et al., 2001)

$^{176}\text{Lu} / ^{177}\text{Hf (crust)} = 0.015$

$^{176}\text{Hf} / ^{177}\text{Hf (crust)} = 0.0384$
Old crustal components in ignimbrite magmas

4. Zircon U/Pb dating combined with O-isotope and Hf-isotope analyses
Old crustal components in ignimbrite magmas

Zircons from single ignimbrite units are isotope rather heterogeneous!

-> distinct batches of crustal melts from different crustal sources mixed into one single ignimbrite magma

POC-94-134(B)

inherited old zirc in POC

4. Zircon U/Pb dating combined with O-isotope and Hf- isotope analyses
Relations between tectonic shortening and ignimbrite volume and composition
Shortening rate (mm a⁻¹)

Magma flux (km³ Ma⁻¹ km⁻¹)

onset of shortening
accelerated shortening
basal arc magma flux from mantle

Age (Ma)

Shortening rate (mm a⁻¹) vs. Age (Ma)

- Basal arc magma flux from mantle
- Onset of shortening
- Northern segments
- Southern segments
- Accelerated shortening

Magmatic Flux (km³ Ma⁻¹ km⁻¹)

Freymuth et al. (2015)
Surges in additional ignimbrite-related arc magma flux are (minimum) 30-70 km³ Ma⁻¹ km⁻¹ and occur a few Ma after major episodes of crustal thickening and slab steepening.
Summary

Origin of ignimbrite magmas

Ignimbrite „flare-ups“ migrate from N to S and evolve after the passage of the Juan Fernandez-Ridge ("flat slab")

....related to subsequent steepening/roll-back of the slab

Ignimbrite are 20/80 to 70/30 mixtures of crustal melt and magmas derived from the mantle wedge.

Variable compositions and crustal contribution reflect thickness and thermal maturity of the continental crust

Additional ignimbrite-related arc magma flux are 30-70 km$^3$Ma$^{-1}$ km$^{-1}$ and occur after crustal thickening and slab steepening