Episodic magmatism of the Peruvian continental arc

Lance Pompe[1,*], Ana María Martínez Ardila[1], Benjamin Clausen[1,2], Scott Paterson, Orlando Poma[3]

[1]Dept. of Earth and Biological Sciences, Loma Linda University, Loma Linda, California, USA, *lpompe@llu.edu;
[2]Geoscience Research Institute, Loma Linda, California, USA;
[3]Universidad Peruana Unión, Carretera Central, km. 19, Ñaña, Lima, Peru

1. Abstract

The Phanerozoic American Cordillera provides an excellent opportunity to study processes contributing to the creation of continental crust. In this study we characterize and quantify the magmatic history of the Peruvian segment of this continental subduction system. The intensity of magmatism and therefore rate of magma emplacement into the arc over time is non-steady, being composed of a series of high magma addition "flare-ups" against an intermittent and variable lower level of background magmatism. We add new U-Pb ages for igneous bedrock samples and detrital zircons from sedimentary rocks to existing geochronological data to give a picture of the magmatic history of the Peruvian arc. Detrital zircons from three sedimentary samples collected from locations in the west, center and east of the arc show magmatism younging to the west. Flare-ups in magmatism from segments of the Peruvian Coastal Batholith (PCB) and Eastern Cordillera (EC) are analyzed to estimate the volume and rate of mantle magma addition (MMA) to the crust. Average flare-up duration is longer for the EC than for the PCB at ~80 My vs 50 My. Flare-ups are found to have variable durations from ~10 My to ~100 My with variable periods between them, thus being episodic in nature rather than cyclic. Magma volumes are calculated using areas of GIS igneous map units, crustal thickness estimates based on element ratios, and a published calculation method based on tilted crustal sections. Total MMA volume added to the arc crust is estimated at 1070k km3 and 1148k km3 for the PCB and EC respectively, assuming a mantle/crust ratio of 80/20. This contributes ~6900 km3 per My or ~1% of Permian-Paleogene global continental crust growth. We have created a web-based dashboard to facilitate interactive exploration of the mapped flare-ups.

2. Geological setting

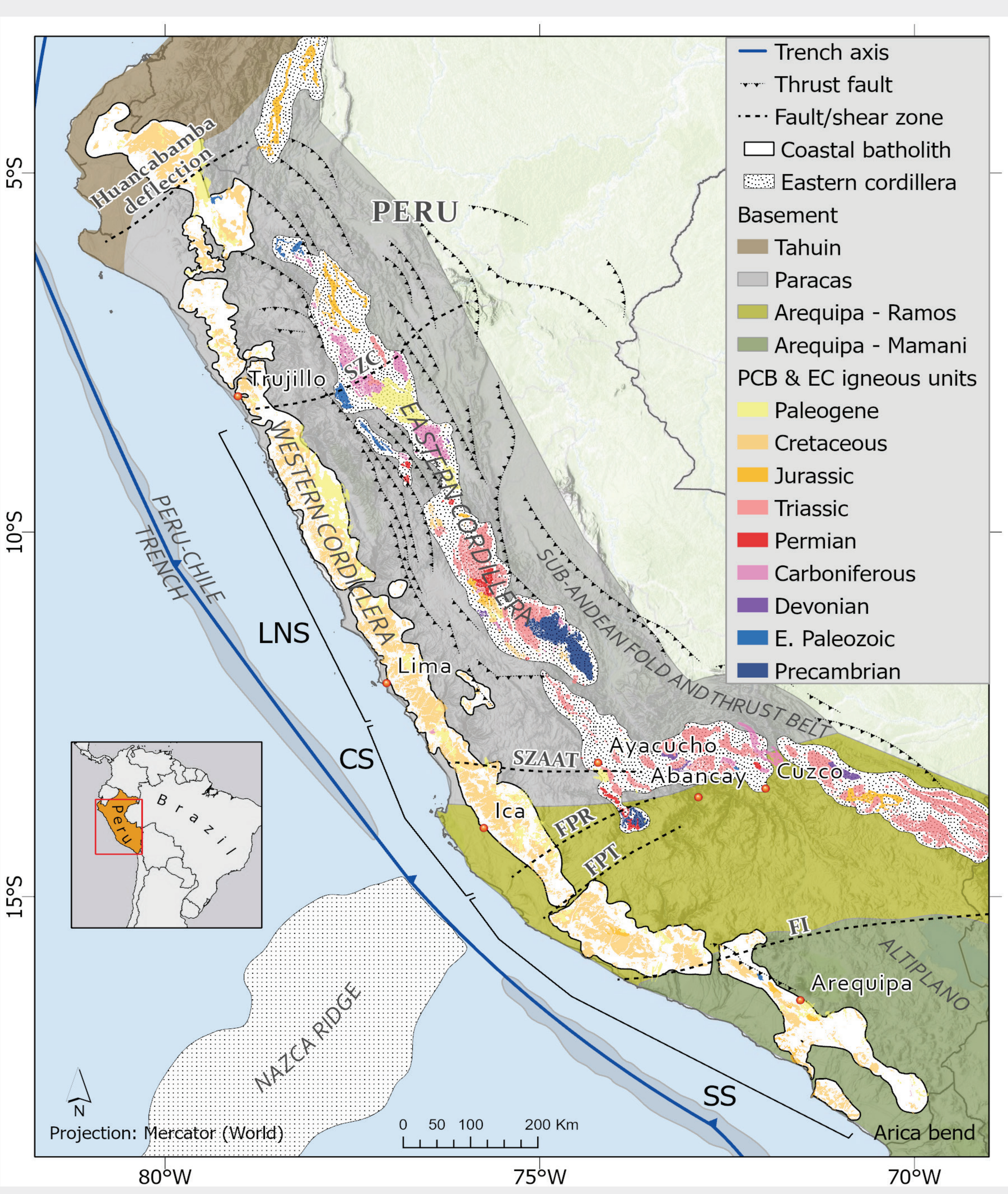

Fig. 1. Map of the Peruvian arc showing the Peruvian Coastal Batholith divided into North, Central and South segments and Eastern Cordillera as well as basement terranes, arc-related igneous rocks, faults and shear zones. SZC = Contaya shear zone, SZAAT = Abancay-Andahuaylas-Tambuco shear zone, FPR = Puyentimari fault, FPT = Patacancha Tambuco fault, FI = Iquipi fault system. Plutonic and volcanic igneous rock units in the PCB and EC are from the Peruvian Instituto Geológico Minero y Metalúrgico (INGEMMET, 2021).

3. Regional & across arc age spectra

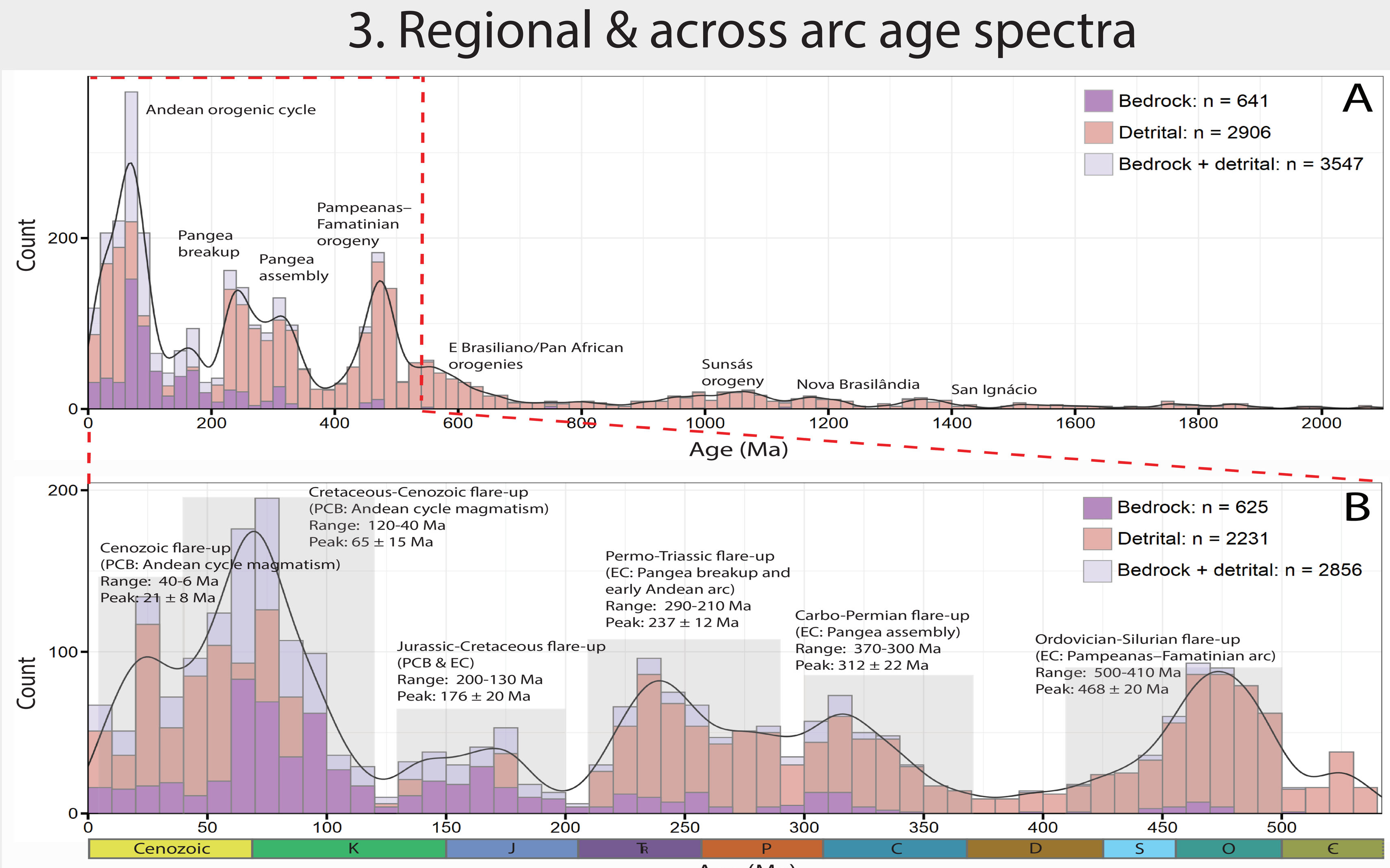

Fig. 2. Igneous bedrock zircon and detrital zircon U-Pb age spectra providing a history of arc magmatism in (A) the entire Peruvian arc with (B) an expanded view of the Phanerozoic. Peak height does not indicate magma volume and the voluminous Neogene volcanism of some areas is excluded. Data are compiled from existing sources and augmented with our new igneous bedrock and detrital zircon data. Detrital zircon data are individual zircon grains and igneous bedrock ages are sample ages. Orogenies and supercontinent events are as suggested by Miškovic et al. (2009).

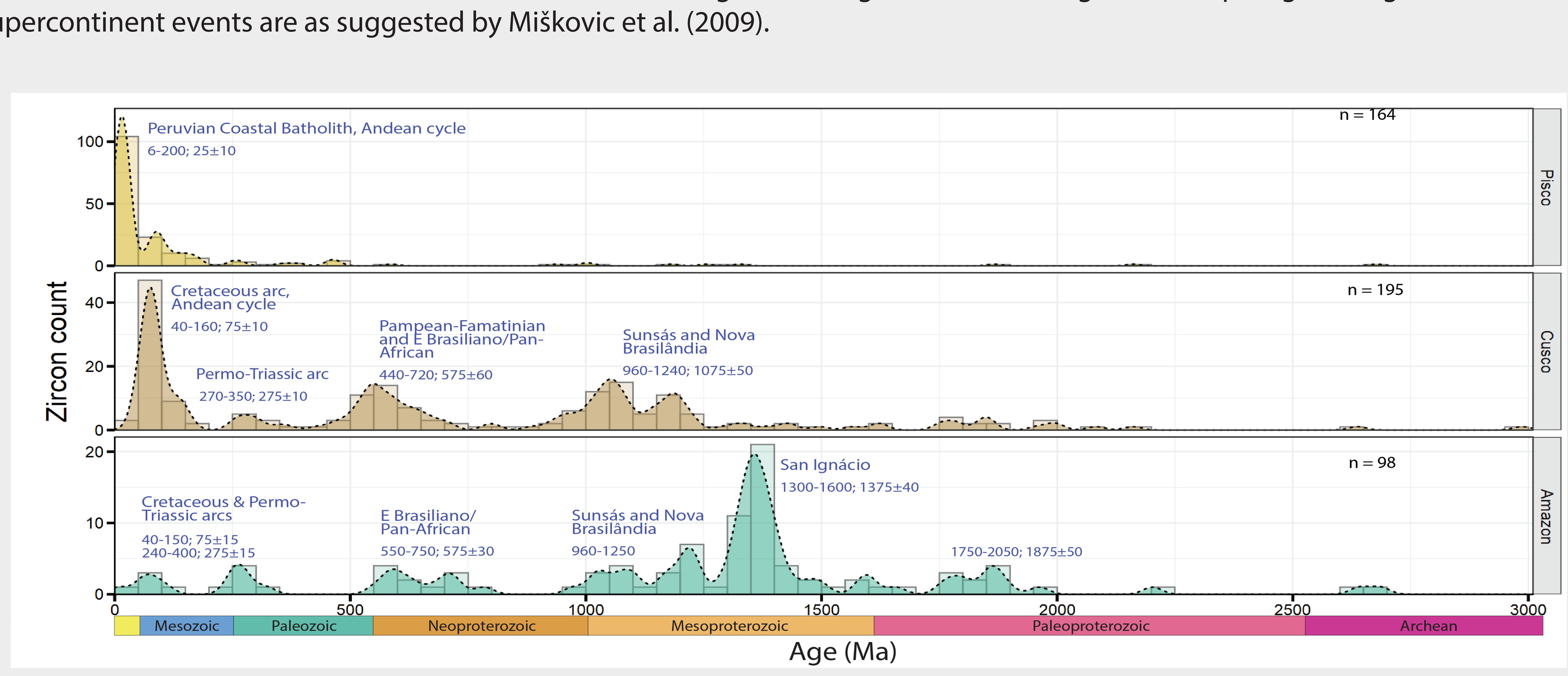

Fig. 3. Across-arc detrital zircon U-Pb age spectra for samples taken from near Ica Pisco (Miocene sandstone), Cusco (Cretaceous sandstone) and the Amazon just east of the arc (Cretaceous quartzite). Ranges and peaks of flare-ups are in Ma. Orogenies are from Mišković et al. (2009)

4. Peruvian Coastal Batholith & Eastern Cordillera age spectra

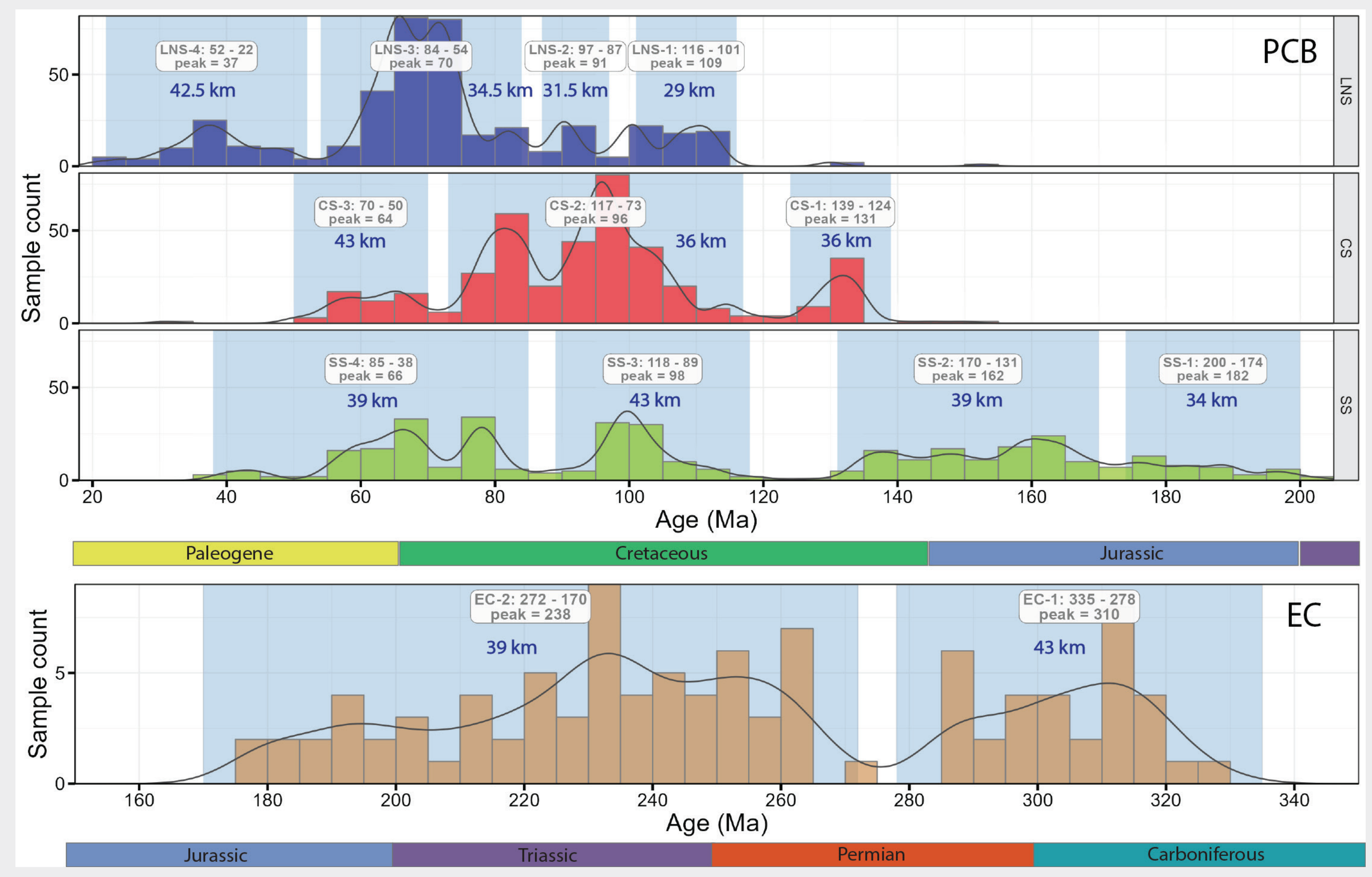

Fig. 4. U-Pb bedrock age spectra for the three PCB segments and the EC showing flare-up range and peak. Peak height is not an indication of magma volume. Data are from published and unpublished sources including the compilation by Kirsch et al. (2016), augmented with our new igneous bedrock age data. Data total 1022 samples with dating techniques including U-Pb, K-Ar, Ar-Ar and Rb-Sr. Bin width is 5 My. Crustal thickness estimates (in km) are from the mohometer approach of Luffi and Ducea (2022). LNS = lower north segment, CS = central segment, SS = south segment. Detrital zircon data is not used in these plots since location is poorly constrained. Flare-ups were visually determined for each PCB segment and the EC.

5. Peruvian Coastal Batholith & Eastern Cordillera magma volume

Method used

- Mantle magma addition rate is mantle magma volume normalized by flare-up duration.
- End member mantle/crust ratios of 80/20 and 50/50 are given to constrain upper and lower limits on mantle magma addition.
- Mantle magma addition (MMA) volume was adjusted from estimates for the Famatinian arc by Ratschbacher et al. (2019) using their estimated Ordovician crust thickness of 63 km.
- Volumes used for the arc crust from Ratschbacher et al. (2019):
  - 3.73 km^3/km^2 for the volcanic section and factoring in a volcanic to plutonic ratio of 1/20,
  - 4.61 km^3/km^2 for the upper crust (0 – 10 km),
  - 9.32 km^3/km^2 for the mid crust (10 – 20 km),
  - 8.3 km^3/km^2 for the deep crust (20 – 30 km), and
  - 24.89 km^3/km^2 for the unexposed crust.
- Paleo-crustal thickness
  - The Chemical "mohometer" approach of Luffi and Ducea (2022) was used to estimate the paleo-thickness of the arc crust in the PCB and EC corresponding to flare-ups using a number of sensors or paleo-crustal thickness proxies.
- Surface areas
  - GIS software was used to select arc-related igneous units (both plutonic and volcanic) from INGEMMET geological unit data covering the whole land surface of Peru.
  - An age was given to each unit from the average of all sample ages it contained. If no sample ages were found, an estimated average value based on the geological period implied by the name of the unit was given.

Mantle magma addition volumes

Table 2. Total flare-up and lull mantle magma addition volumes.

	Total flare-up MMA (km3, 80/20 crust/mantle)	Total lull MMA (km^3, 80/20 crust/mantle)	Total MMA (km^3 80/20 crust/mantle)
PCB	967k	103k	1070k
EC	1030k	118k	1148k

Table 1. Flare-up parameters for the three PCB segments and the EC.

Flare-up	Range (Ma)	Duration (My)	Peak (Ma)	Moho Depth (km)	Area (1000 km^2)	MMA (km^3/km^2)		MMA rate (km^3/km^2/My)		MMA volume (1000 km^3)	
						80/20	50/50	80/20	50/50	80/20	50/50
LNS-1	116-101	15	109	29	4.1	20.4	13.7	1.36	0.91	83.7	56.0
LNS-2	97-87	10	91	29	3.9	20.4	13.7	2.04	1.37	79.6	53.3
LNS-3	84-54	30	70	34.5	3	25.8	17.3	0.86	0.58	77.5	51.9
LNS-4	52-22	30	37	42.5	3.8	34.1	22.8	1.14	0.76	129.5	86.7
CS-1	139-124	15	131	36	0.32	27.4	18.3	1.83	1.22	8.8	5.9
CS-2	117-73	44	96	36	7.6	27.4	18.3	0.62	0.42	208.1	139.4
CS-3	70-50	20	64	43	0.11	34.6	23.2	1.73	1.16	3.8	2.5
SS-1	200-174	26	182	34	0.6	25.3	17.0	0.97	0.65	15.2	10.2
SS-2	170-131	39	162	39	1.3	30.5	20.4	0.78	0.52	39.6	26.5
SS-3	118-89	29	98	43	8.6	34.6	23.2	1.19	0.80	297.6	199.3
SS-4	85-38	47	66	39	0.78	30.5	20.4	0.65	0.43	23.8	15.9
EC-1	335-278	57	310	39	5	30.5	20.4	0.53	0.36	152.4	102.0
EC-2	272-170	102	238	43	25.4	34.6	23.2	0.34	0.23	879.0	588.6

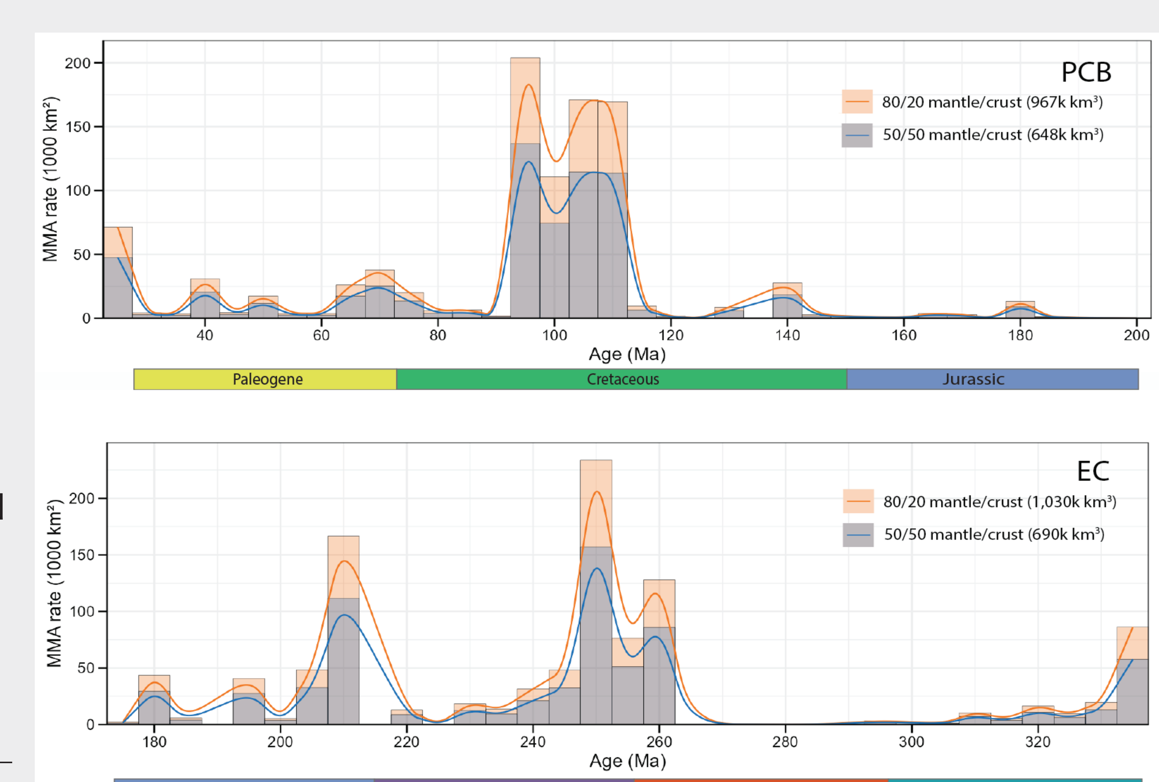

Fig. 5. Calculated mantle magma addition (MMA) rates and implied volumes (area under curves) for 5 My age bins over geological time for flare-ups of the Peruvian Coastal Batholith and the Eastern Cordillera using 80/20 and 50/50 mantle/crust ratios.

6. Observations, implications and interactive dashboard

Observations

- Low magma volumes
  - Late Carboniferous and Early to Mid Permian (EC)
  - Jurassic to Early Cretaceous (PCB)
- High magma volumes
  - Late Permian to Early Triassic (EC)
  - Mid Cretaceous (PCB)

Implications

- Continental crust growth rates
  - Assuming a mantle/crust ratio of 80/20, the PCB and EC account for a combined MMA volume (flare-ups and lulls) of ~2218k km^3 during the Permian-Paleogene.
  - Averages ~6688 km^3/My for the PCB and ~7175 km^3/My for the EC.
  - This is a contribution of ~0.8 – 1.2 % to global continental crustal growth, using the estimates of Hawkesworth et al. (2019).

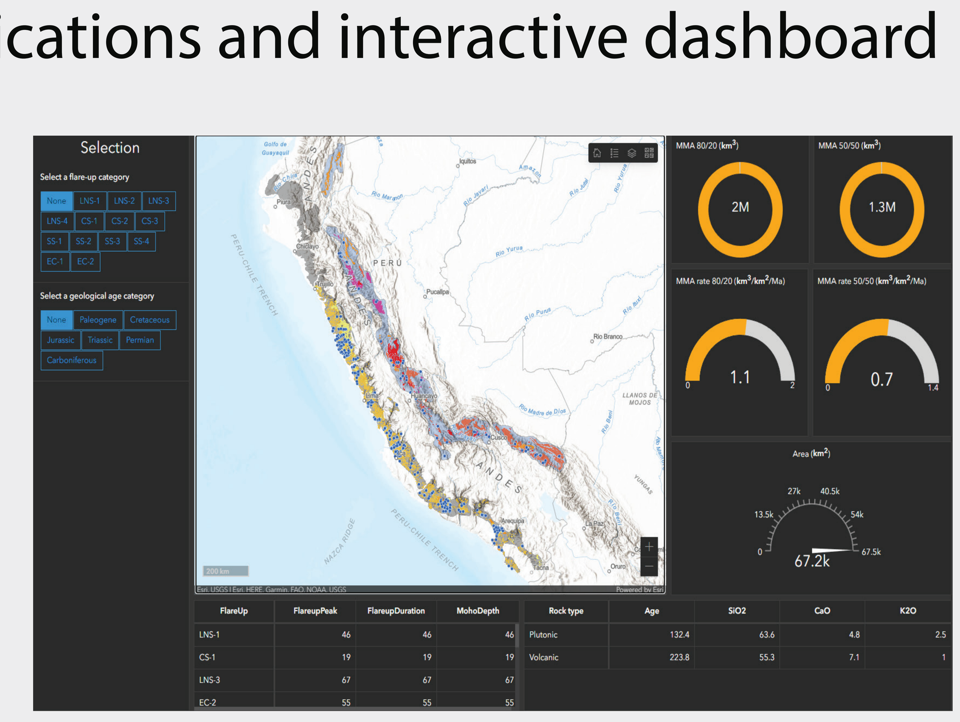

Fig. 6. Peruvian Flare-up Explorer – interactive dashboard for exploring spatiotemporal patterns in flare-ups in the Peruvian Coastal Batholith and Eastern Cordillera. Selections can be made for flare-up and geological age categories, causing the map to zoom to the selected features and the gauges to adjust. Gauges display mantle magma addition volumes and rates for 80/20 and 50/50 mantle/crust ratio and area covered by igneous rocks. Tables show parameters for flare-ups and U-Pb age samples.

Acknowledgments

We would like to thank the Geoscience Research Institute and Loma Linda University Department of Earth and Biological Sciences for funding this research. We acknowledge support from NSF grants EAR 1649254 and AR-1624854 for the Arizona LaserChron Center, and EAR-0929777 for image acquisitions at the Arizona LaserChron SEM Facility.

References

Hawkesworth, C., Cawood, P. A., and Dhuime, B., 2019, Rates of generation and growth of the continental crust: Geoscience Frontiers, v. 10, no. 1, p. 165-173.

Mišković, A., Spikings, R. A., Chew, D. M., Košler, J., Ulianov, A., and Schaltegger, U., 2009, Tectonomagmatic evolution of Western Amazonia: Geochemical characterization and zircon U-Pb geochronologic constraints from the Peruvian Eastern Cordilleran granitoids: Geological Society of America Bulletin, v. 121, no. 9-10, p. 1298-1324.

Paterson, S. R., and Ducea, M. N., 2015, Arc magmatic tempos: gathering the evidence: Elements, v. 11, no. 2, p. 91-98. Peruvian Andes, p. 93-101.

Pitcher, W. S., Atherton, M. P., Cobbing, E. J., and Beckinsale, R., 1985, Magmatism at a plate edge: the Peruvian Andes, Wiley.

Ratschbacher, B. C., Paterson, S. R., and Fischer, T. P., 2019, Spatial and depth-dependent variations in magma volume addition and addition rates to continental arcs: Application to global CO2 fluxes since 750 Ma: Geochemistry, Geophysics, Geosystems, v. 20, no. 6, p. 2997-3018.