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The Coulomb stress transfer and possible interactions between seismic and volcanic activity in the Colca Region (Central Andes)

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Outstanding Student & PhD candidate Presentation contest

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Introduction

The Colca Region in Central Andes, southern Peru, is prone to **small- to moderate-sized (Mw ≤ 6.0) shallow (< 20 km)** earthquakes associated with **normal** and **strike-slip crustal faults** within the overriding plate in the Nazca-South American subduction zone (**Fig. 1**). Along with the activity of the **Sabancaya volcano**, which in recent years comprised mainly of ash and fumarole emissions, the region offers an opportunity to investigate the complex relationship between seismic and volcanic activity, their potential interplay, and triggering factors. The **Coulomb stress transfer** analysis is based on the hypothesis that failure on a fault plane occurs when the Coulomb stress exceeds a certain threshold. Positive Coulomb stress changes are thought to bring faults closer to failure, whereas negative ones inhibit failure. To explore these dynamics, we carried out a Coulomb stress transfer analysis examining the interactions between source faults of 28 significant recent **earthquakes (1991-2022)** as well as the impact of **magmatic inflation (2013-2022)** on seismic events.

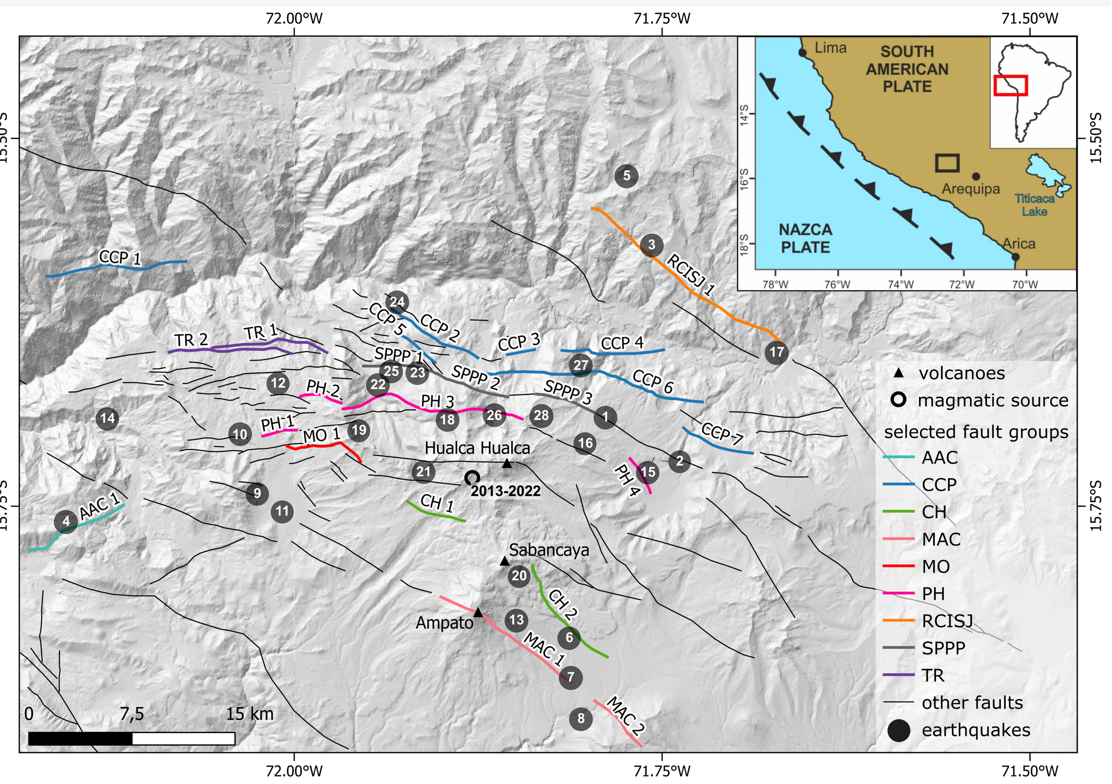

Fig. 1. Study area location (30 m resolution DEM from SRTM) with main crustal faults in the Colca Region (based on Benavente et al., 2017; Ayahua-Abra-Cala (AAC), Chachas-Cabanaconde-Patapampa (CCP), Colihuire-Huatajcucho (CH), Mucurca-Ampato-Casablanca (MAC), Mojopampa (MO), Pungo-Hornilo (PH), Río Cotahuasi-Ichupampa-San Juan de Tarucan (RCISJ), Solarpampa-Puye Puye Pillo (SPPP), Trigal (TR)), the magmatic inflation source (based on MacQueen et al., 2020) and epicenters of shallow earthquakes (1991-2022) used in the Coulomb stress transfer analysis (Woszczycka et al., 2024).

Sharing is encouraged

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Project website **Woszczycka et al. (2024)**

Methods

1. Selection of **28 source earthquakes from 1991-2022** (U.S. Geological Survey (USGS) earthquake catalog, Global Centroid Moment Tensor (GCMT) catalog, Geophysical Institute of Peru (IGP) catalog, and data from the INGEMMET Volcano Observatory (OVI) in Arequipa).
2. Correlation of earthquakes with potential **source faults** based on the **Seismo-Lineament Analysis Method (SLAM)** (Cronin et al., 2008).
3. **Coulomb stress transfer calculations**: on specified receiver faults (**teconic source**) and nodal planes (**magmatic source**).
   Failure on a fault plane occurs when the Coulomb stress crosses a particular threshold value – **0.1 bar** (King et al., 1994). The Coulomb stress change ($\Delta\sigma f$) equation:
   $$\Delta\sigma f \;=\; \Delta\tau \;+\; \mu'\Delta\sigma$$
   Where $\Delta\tau$ is the shear stress change, μ' is the effective coefficient of friction, and $\Delta\sigma$ is the normal stress change. **Positive** $\Delta\sigma f$ values **can bring faults closer to failure**, whereas **negative** values **can discourage failure**.

Results

Coulomb stress change on faults of specified orientation (tectonic source):

We tested 100 possible relations between the selected 28 earthquakes and found:

31 source-receiver interactions that met the set criteria:
- **20 above 0.1 bar,**
- **11 below -0.1 bar** (**Fig. 2**).

Coulomb stress change on nodal planes (magmatic source):

For 23 of the selected earthquakes (2013-2022) we found:

10 examples that met the set criteria:
- **5 with a negative Coulomb stress change on both nodal planes,**
- **4 with a positive Coulomb stress change on both nodal planes,**
- **1 with a positive Coulomb stress change on one nodal plane and negative on the other** (**Tab. 1**).

Tab. 1. Coulomb stress change on nodal planes – magmatic source (numeration as in Fig. 1).

					nodal plane 1				nodal plane 2			
No.	date	time	depth (km)	magnitude	strike 1 (°)	dip 1 (°)	rake 1 (°)	**Coulomb stress change 1 (bar)**	strike 2 (°)	dip 2 (°)	rake 2 (°)	**Coulomb stress change 2 (bar)**
13.	28.08.2015	04:11	10.00	5.4	111	85	-17	**-0.18**	203	73	-175	**-0.13**
18.	30.04.2017	13:29	11.00	5.5	130	69	-71	**-1.61**	265	28	-131	**-2.10**
19.	30.04.2017	17:35	12.00	5.1	127	67	-61	**0.15**	252	36	-138	**0.15**
20.	21.05.2019	13:37	12.00	4.9	27	61	-141	**-1.04**	275	56	-36	**-1.07**
21.	14.08.2020	20:34	7.00	4.4	109	75	-45	**2.26**	214	47	-159	**-4.23**
23.	09.10.2021	05:20	11.00	4.3	101	61	-103	**-0.58**	306	31	-69	**-0.33**
24.	09.10.2021	05:49	10.00	4.2	298	48	-67	**-0.16**	86	47	-113	**-0.24**
25.	09.10.2021	23:11	10.00	4.1	155	69	-73	**0.21**	294	27	-128	**0.17**
26.	12.10.2021	04:00	10.00	4.6	276	49	-62	**1.03**	56	48	-119	**1.34**
28.	16.03.2022	06:06	11.00	5.6	115	88	-7	**0.17**	205	83	-178	**0.21**

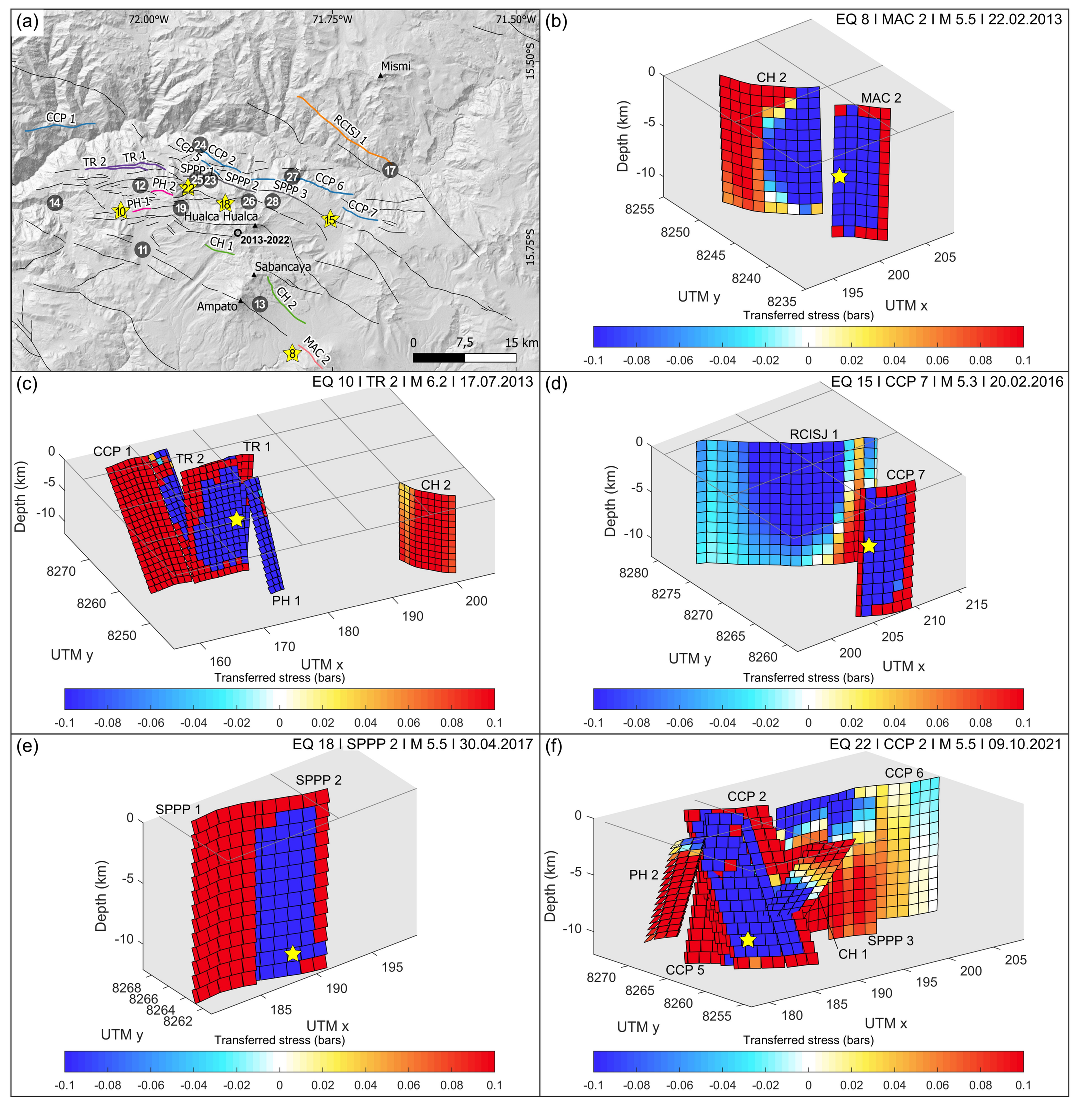

Fig. 2. Coulomb stress change resulting from selected earthquakes (source earthquake, fault, magnitude, date at the top of each frame). a – the study area with considered earthquakes marked with yellow stars, receiver earthquakes marked with gray dots, and source-receiver faults marked with colors (as in Fig. 1); b-f – selected results for the years with a noticeable seismic activity increase (hypocenter locations marked with yellow stars) (Woszczycka et al., 2024).

Discussion

The results indicate that **most earthquakes were not triggered by positive Coulomb stress changes** associated with preceding earthquakes or magmatic inflation. Alternative triggering mechanisms should be considered, particularly for the marked **increase in seismic energy release observed from 2013 onward** (**Fig. 3**). These may include stress changes from distant megathrust events, although the last major subduction earthquake in this segment occurred in 2001 (Mw 8.4). **Volcanic activity** at Sabancaya may also be relevant; however, despite a temporal overlap between **increased fumarole emissions in late 2012** and the 2013 seismicity peak, Coulomb stress modeling does not support a magmatic influence.

Conclusions

The results confirm the **tectonic origin of most earthquakes**, while the magmatic source appears to play a secondary role, primarily amplifying the effects of prior seismic activity. However, the **Coulomb stress transfer** does **not** seem to be **the main factor** impacting the seismicity of the Colca Region, as most of the analyzed source faults were not brought closer to failure due to a positive stress change. **Preceding seismic activity** induced **positive stress changes** on source faults in **43%** of the events, while **negative stress changes** potentially inhibited **25%**. **Magmatic inflation** contributed to **positive stress changes** in **22%** of cases but also induced **negative changes** in **a similar proportion**. Notably, **no direct connection** was identified regarding the **significant increase in seismic activity in 2013**, which appeared to be potentially correlated with the **start of the fumarolic emissions (late 2012)** by the **Sabancaya volcano**.

While the coseismic static Coulomb stress change does not fully account for the complexity of seismic and volcanic activity and their interplay in the Colca Region, it provides valuable insights into active geological processes and **highlights open questions warranting further investigation**.

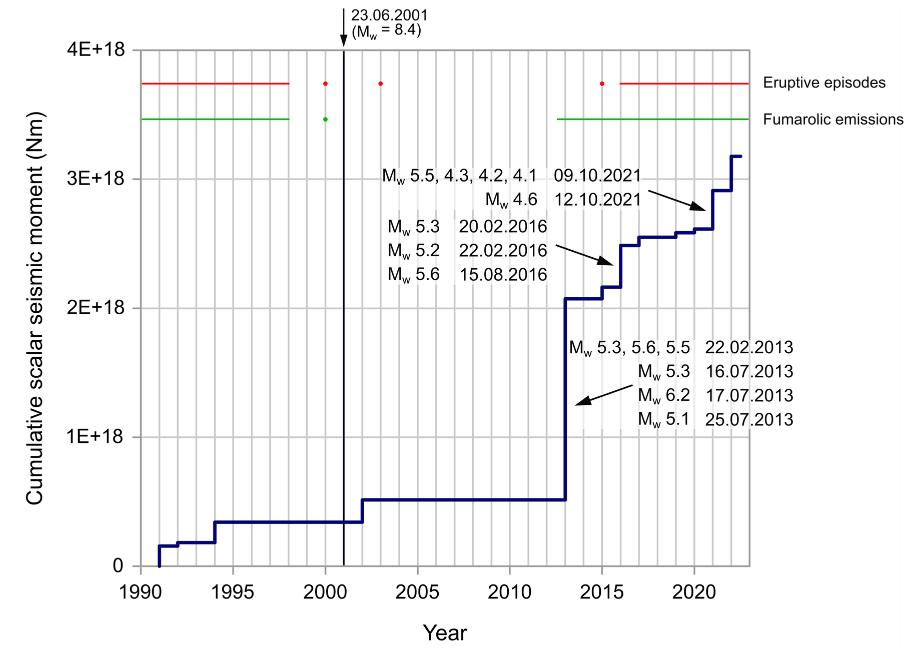

Fig. 3. Cumulative scalar seismic moment release for the years 1991-2022. The major increase episodes are marked with an arrow, with the largest earthquakes listed. The black line indicates the last large megathrust earthquake in this sector of the subduction zone. The volcanic activity of Sabancaya is based on Global Volcanism Program (2022) data (Woszczycka et al., 2024).

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