Ground Deformation in the Western Galápagos: Shallow Unrest and Shared Magma Dynamics

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and
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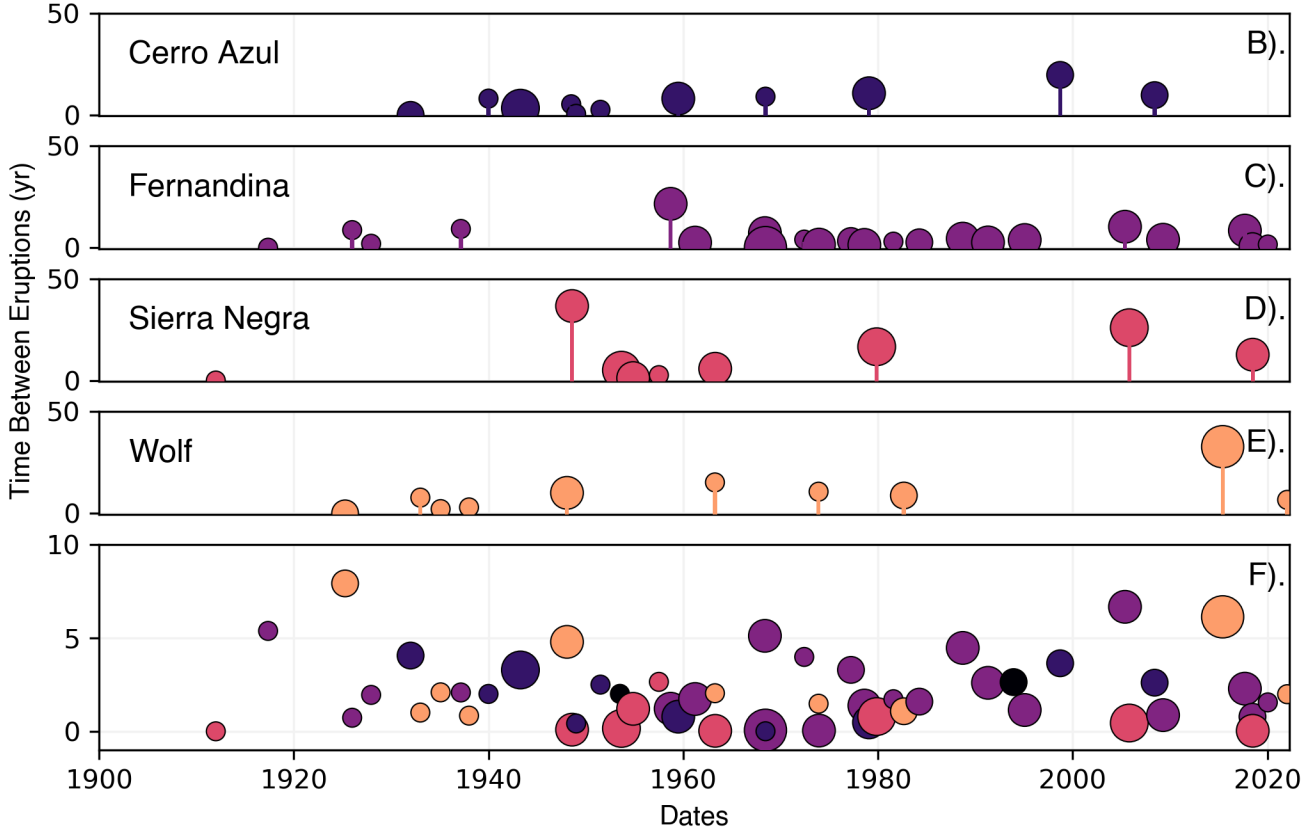
UNIVERSITY OF LEEDS

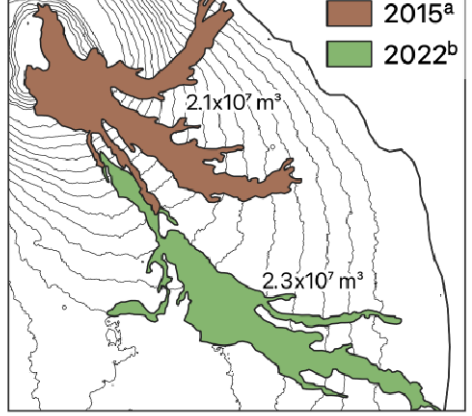
"Case study of volcano interaction: potentially the Galapagos islands" – from 2014(!)
Living Planet Independent Research Fellowship proposal @ University of Bristol

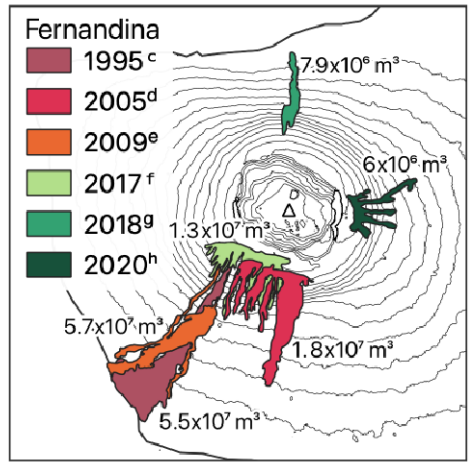
Eoin Reddin's PhD thesis (defended 2023)

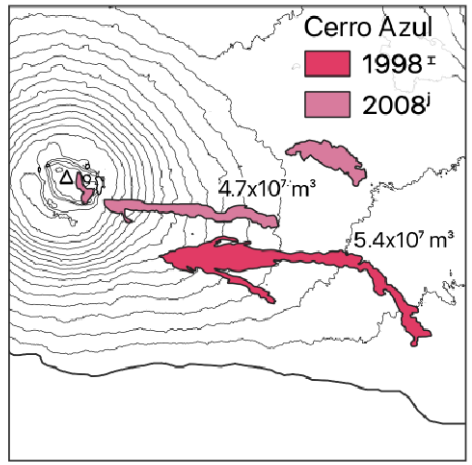
1.	2.	3.
Craters of Habit: Patterns of Deformation in the Western Galápagos	Magmatic Connectivity among Six Galápagos Volcanoes Revealed by Satellite Geodesy	The Contribution of Crystallisation to Decadal Volcano Subsidence

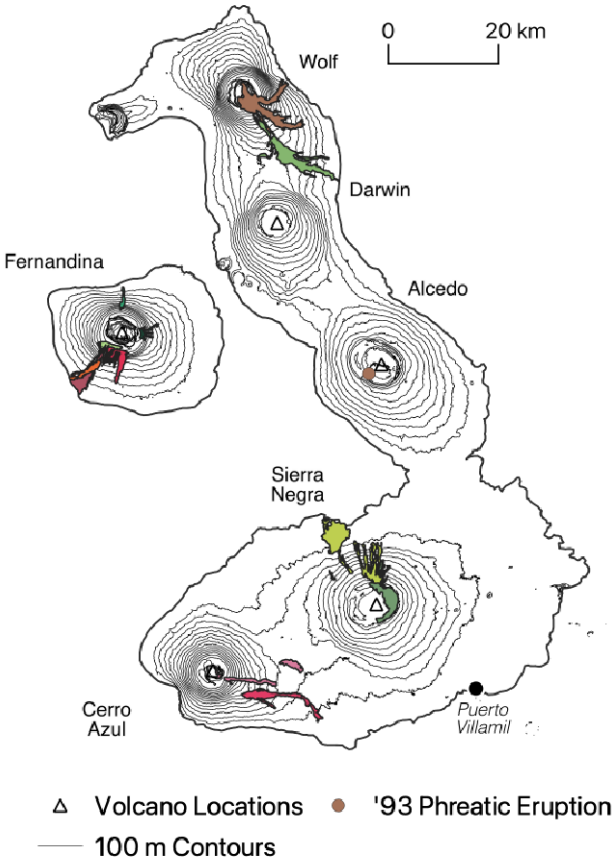


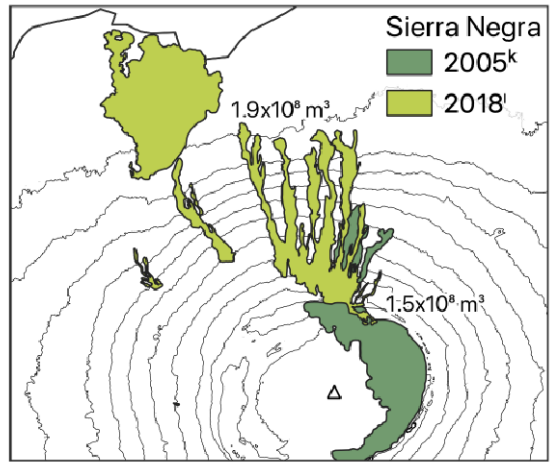
- Exceptionally high rates of eruption, intrusion and geodetic expression
- Six volcanoes, of which five have multiple 20th century eruptions
- Rapid ascent of magma through multiple trans-crustal pathways

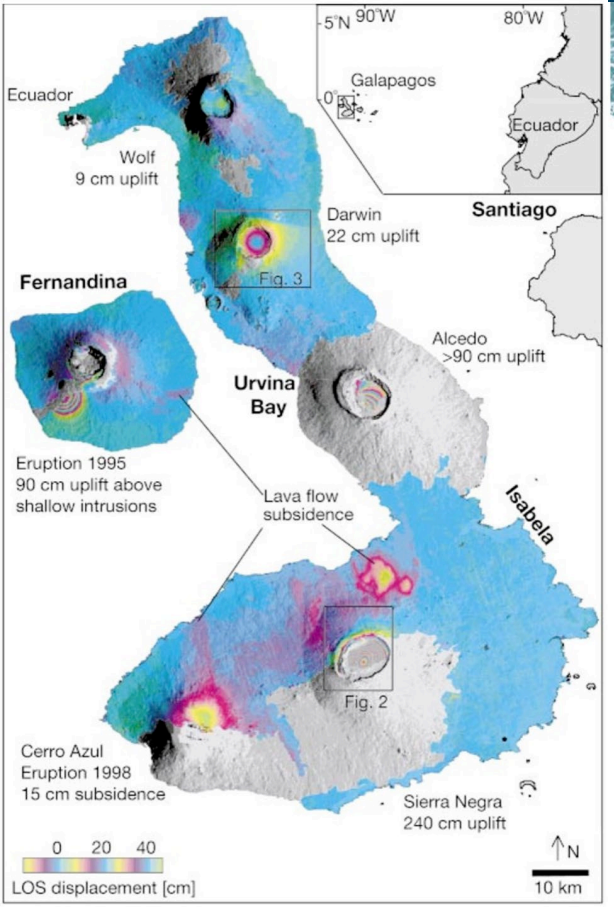




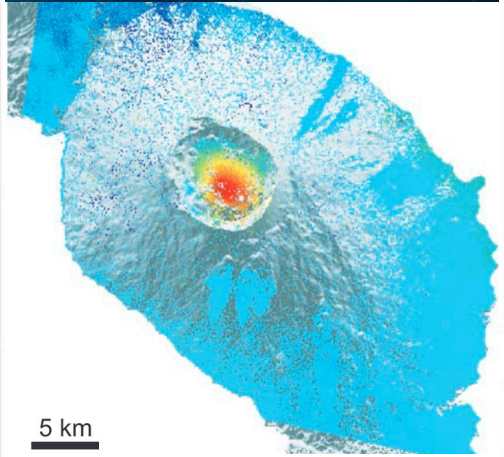




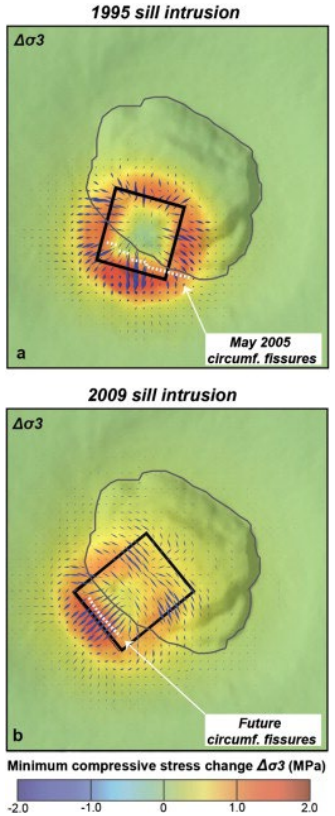




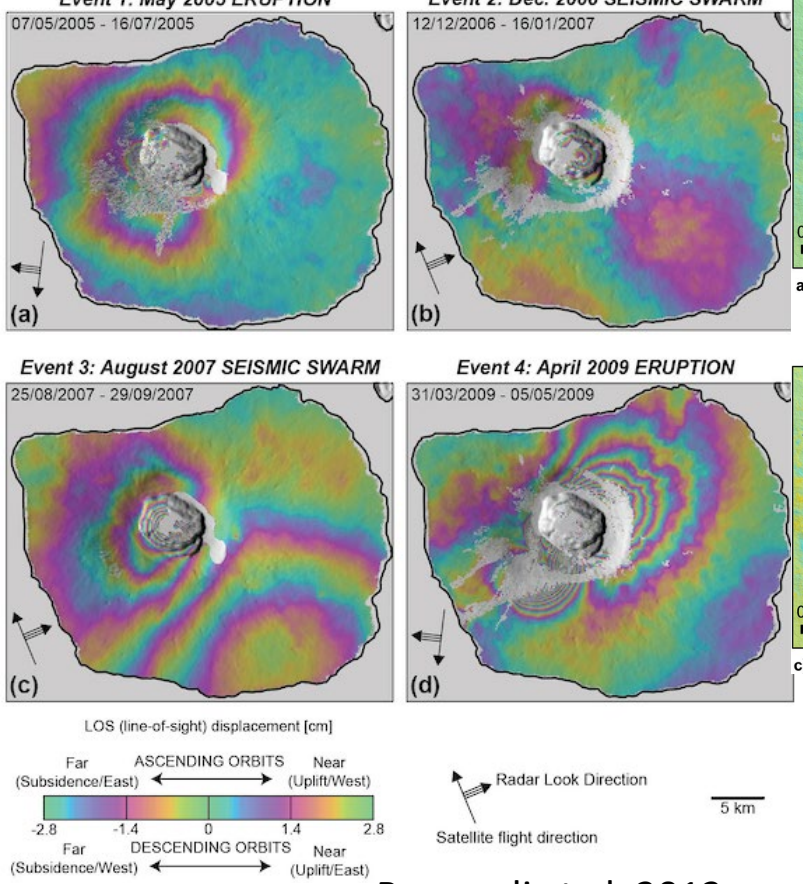
Amelung et al. 2000



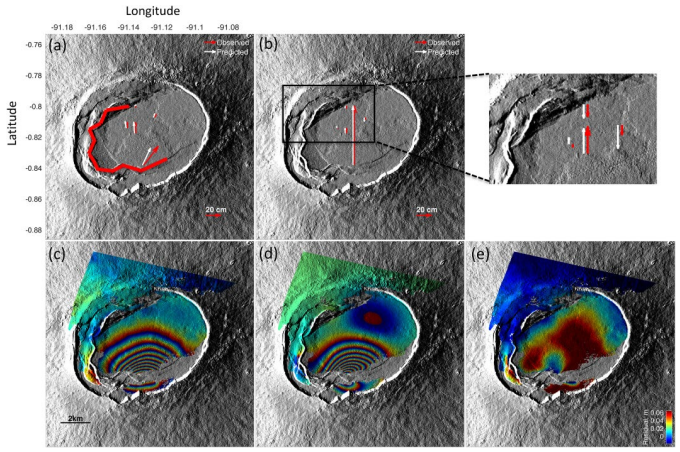
Hooper et al, 2007



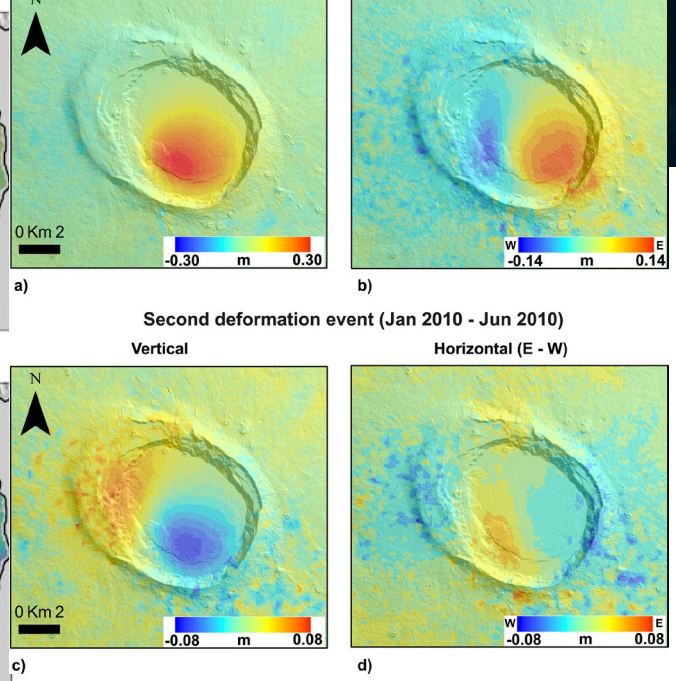
Bagnardi et al, 2013



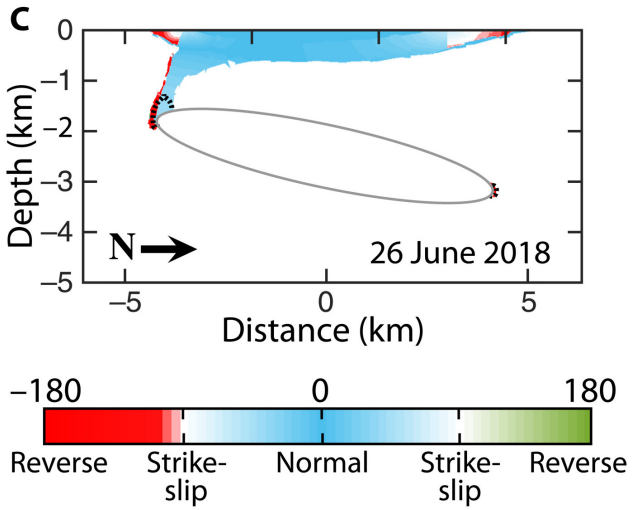
Bagnardi et al, 2012



Zheng et al, 2022

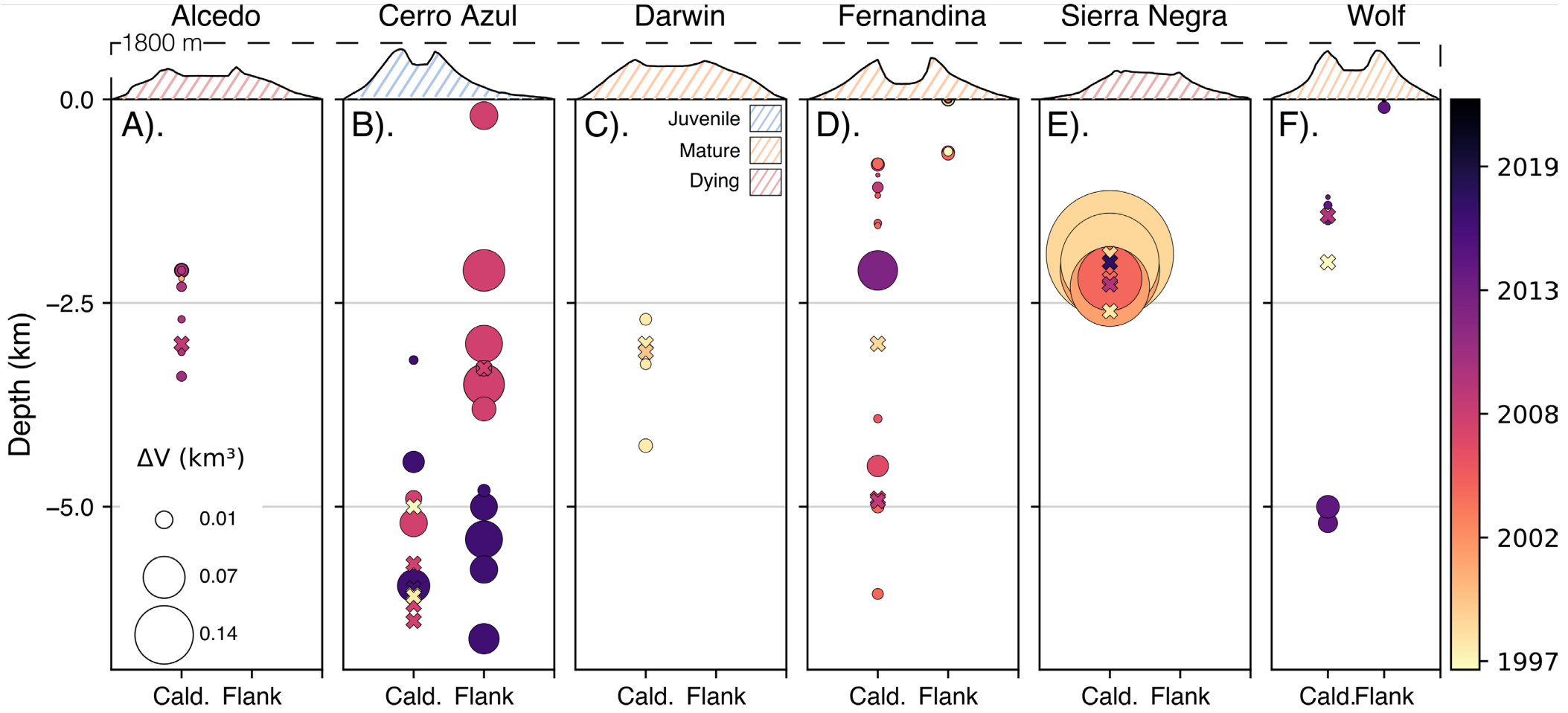


Galetto et al, 2021



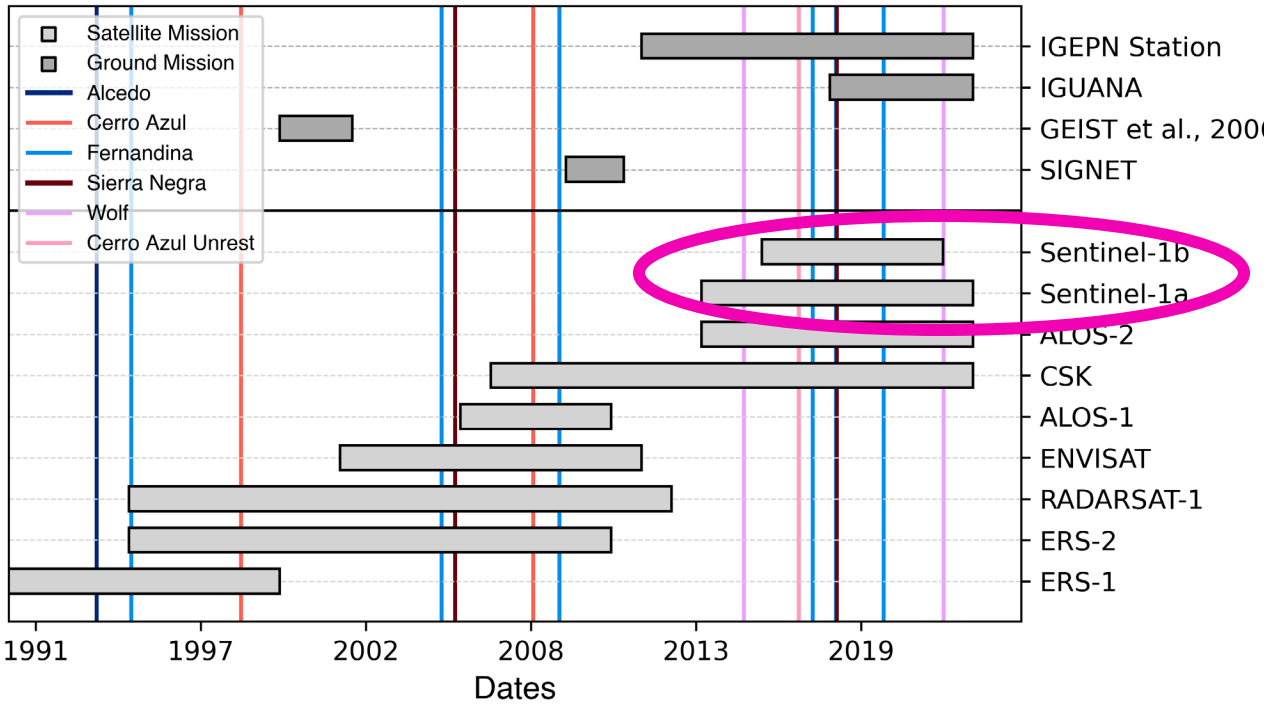
Gregg et al, 2021

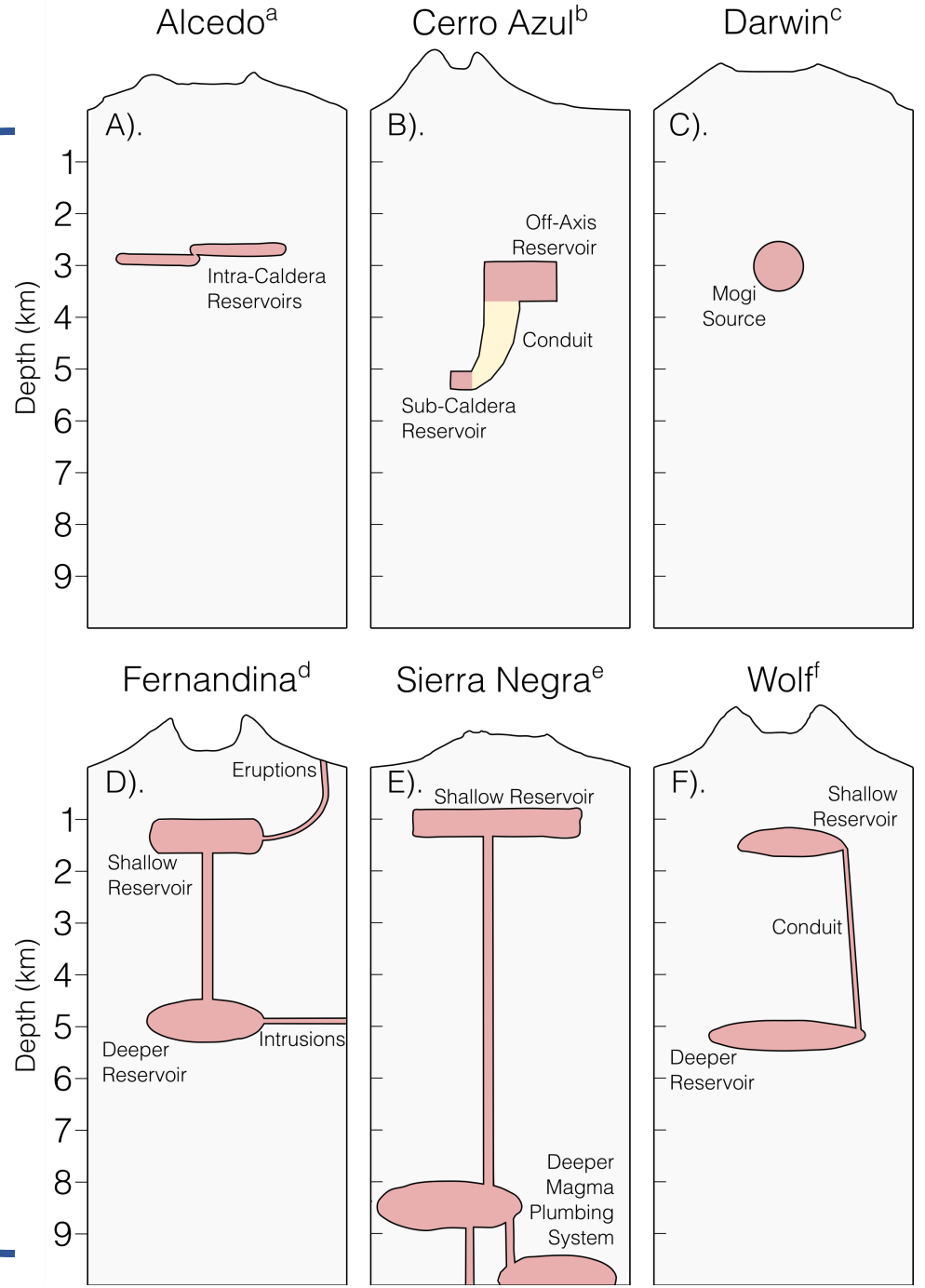
The Western Galapagos are exceptionally well-suited to InSAR measurement – site of important studies about caldera formation, mafic intrusion and stress interactions



All volcanoes have geodetic evidence of shallow reservoirs ~2-3 km depths and several also have evidence of larger storage zones at ~5 km

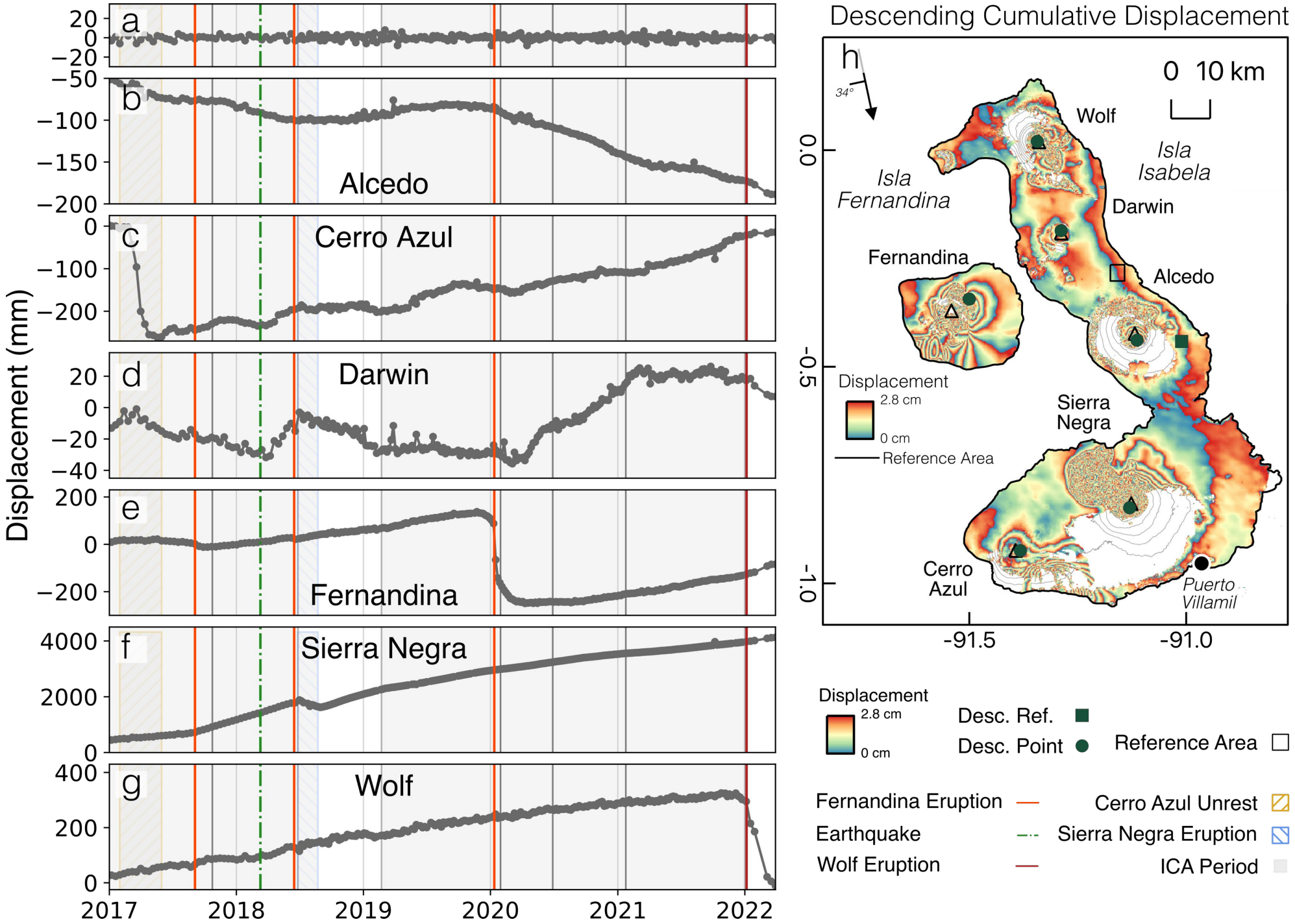
Geodetic investigation of greater depths is limited by island size





- Geodetic data point to persistent magmatic sources present since the 1990s: most solutions are within measurement and modelling uncertainty

What can the relationship between displacements at different volcanoes tell us about magma source?

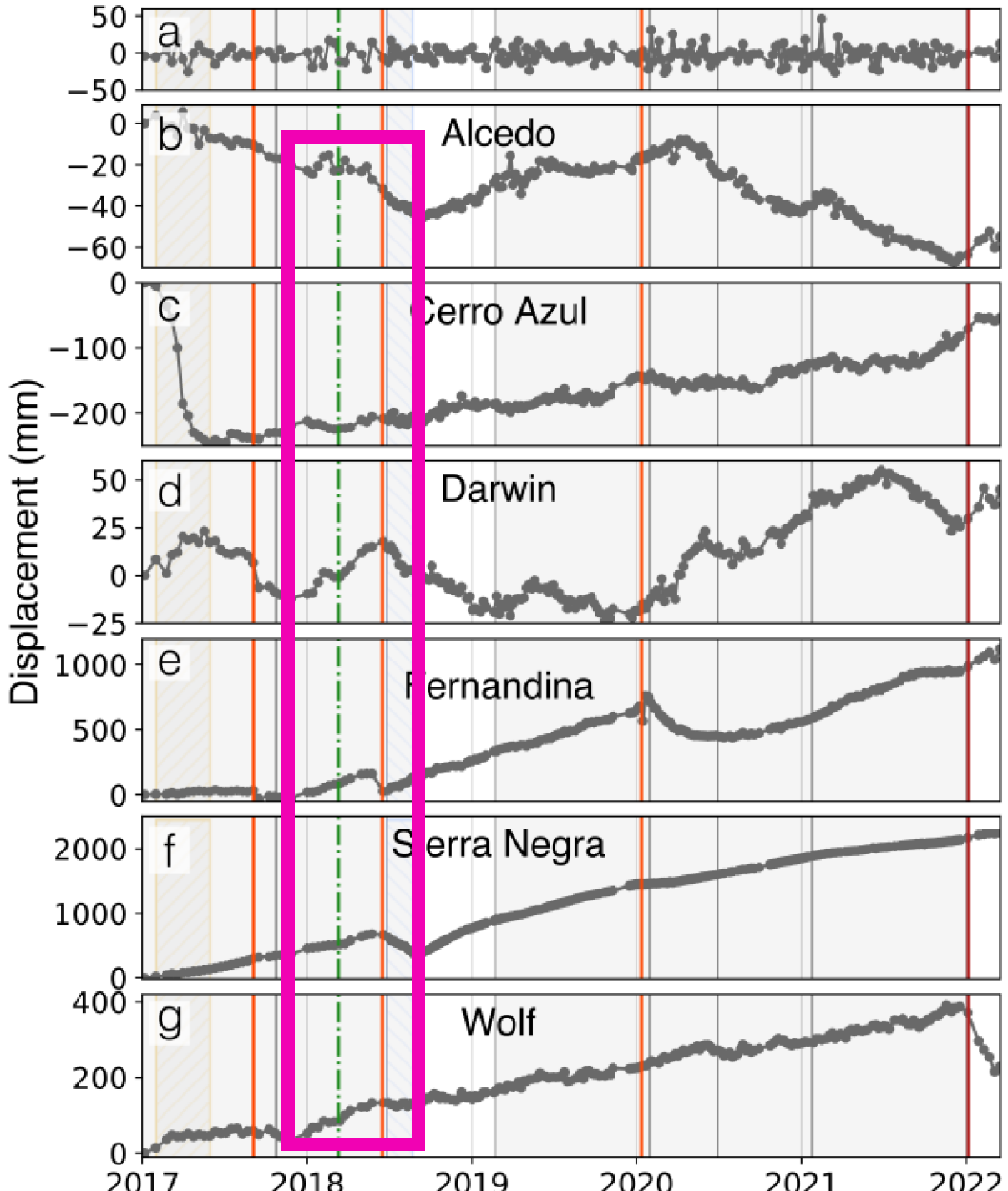


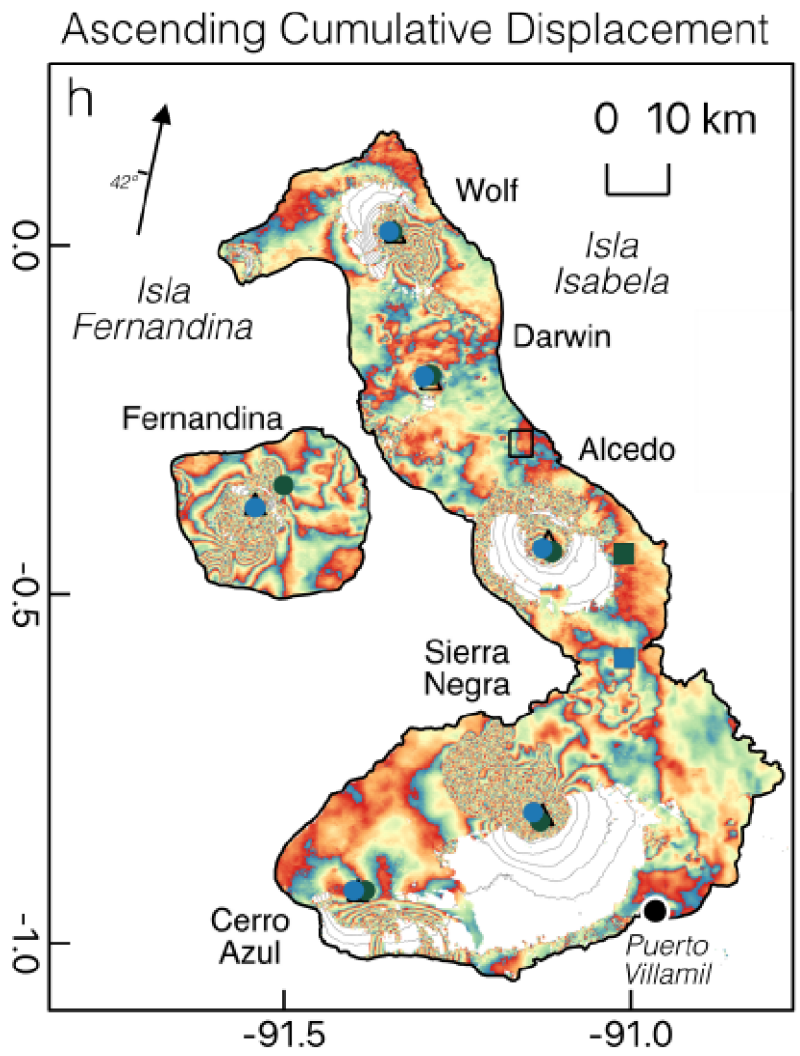
Sentinel-1 time series

Interferograms processed by LiCSAR

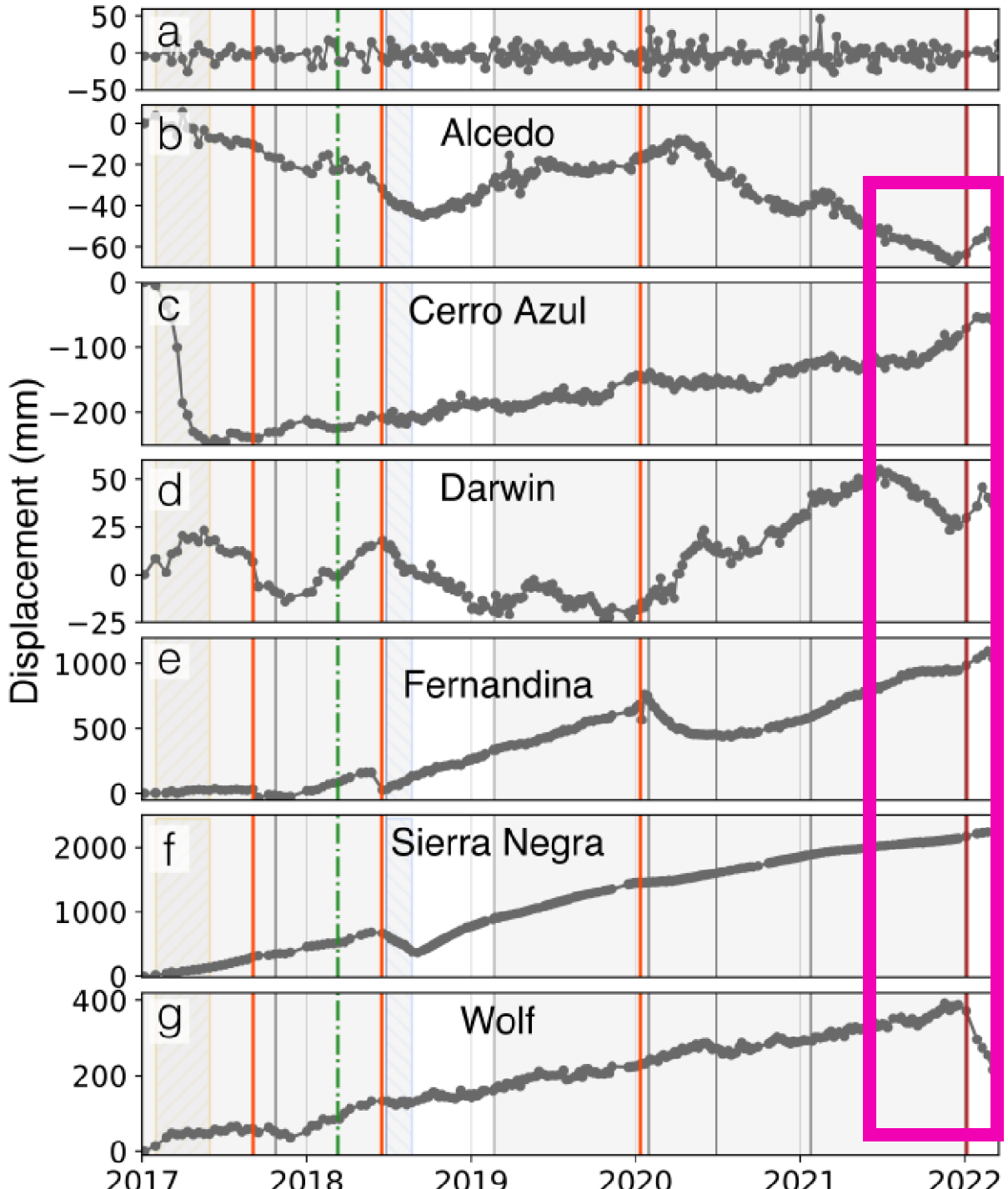
Atmosphere corrected with GACOS

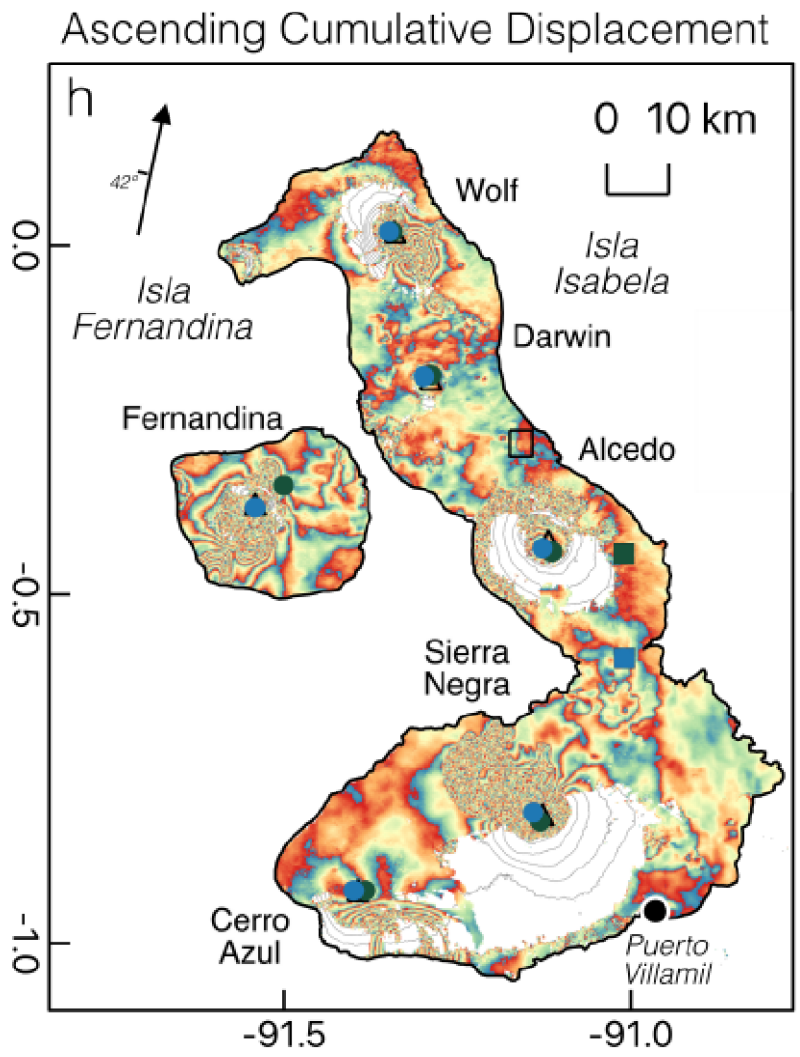
Time-Series constructed with LiCSBAS





Fernandina & Sierra Negra eruptions



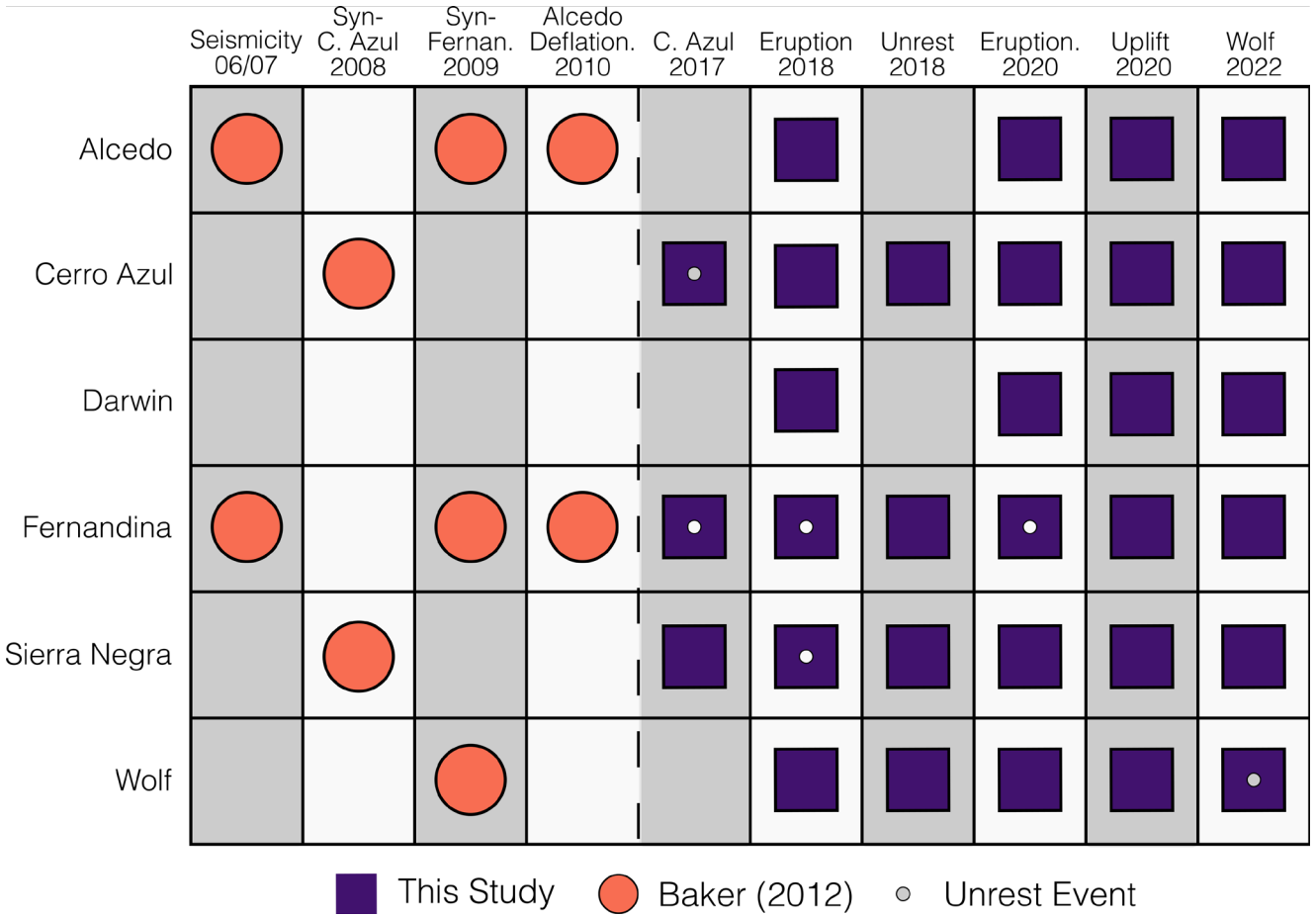


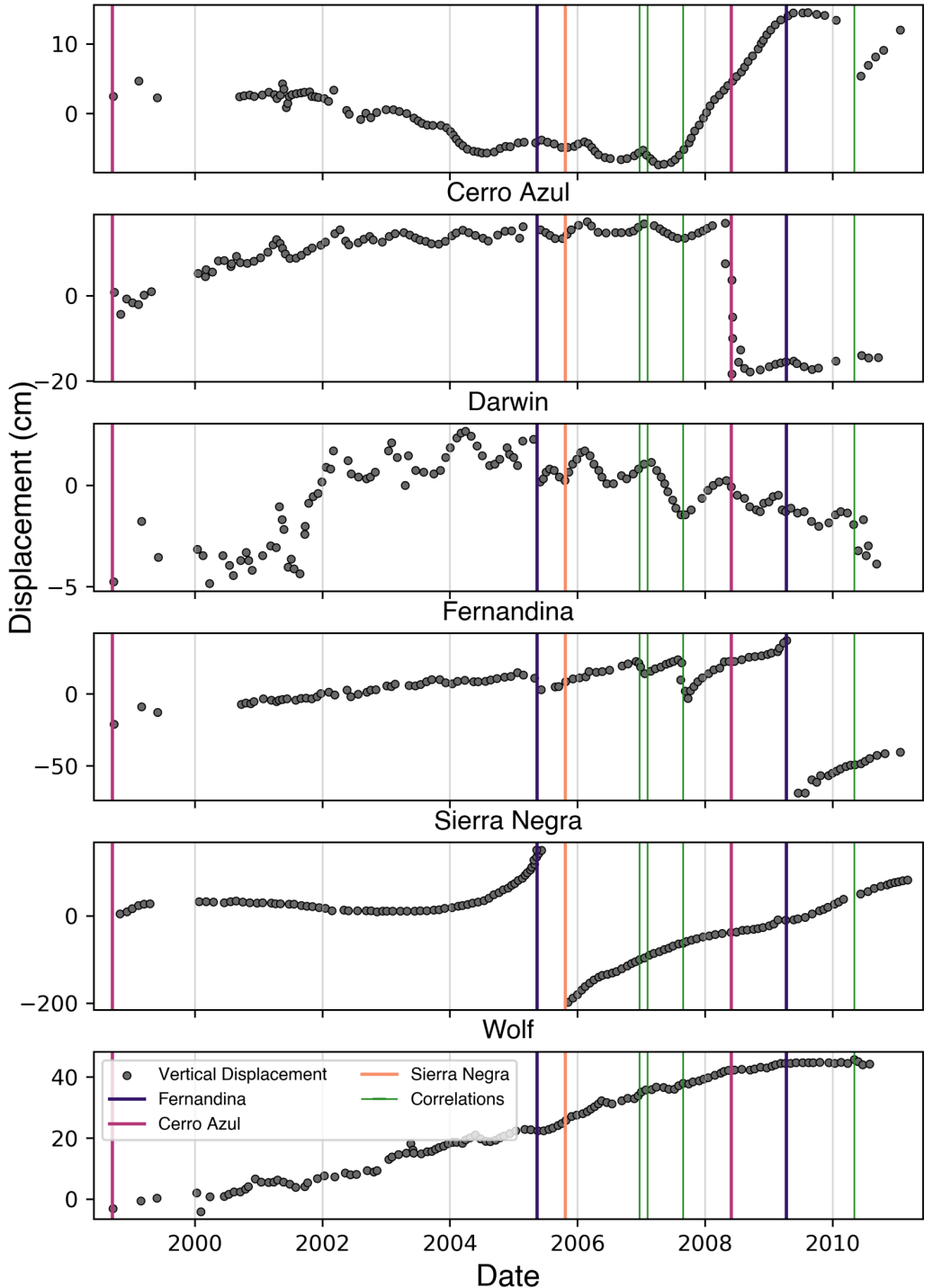
pre-Wolf eruption

Reanalysis of ERS, ENVISAT data from Scott Baker

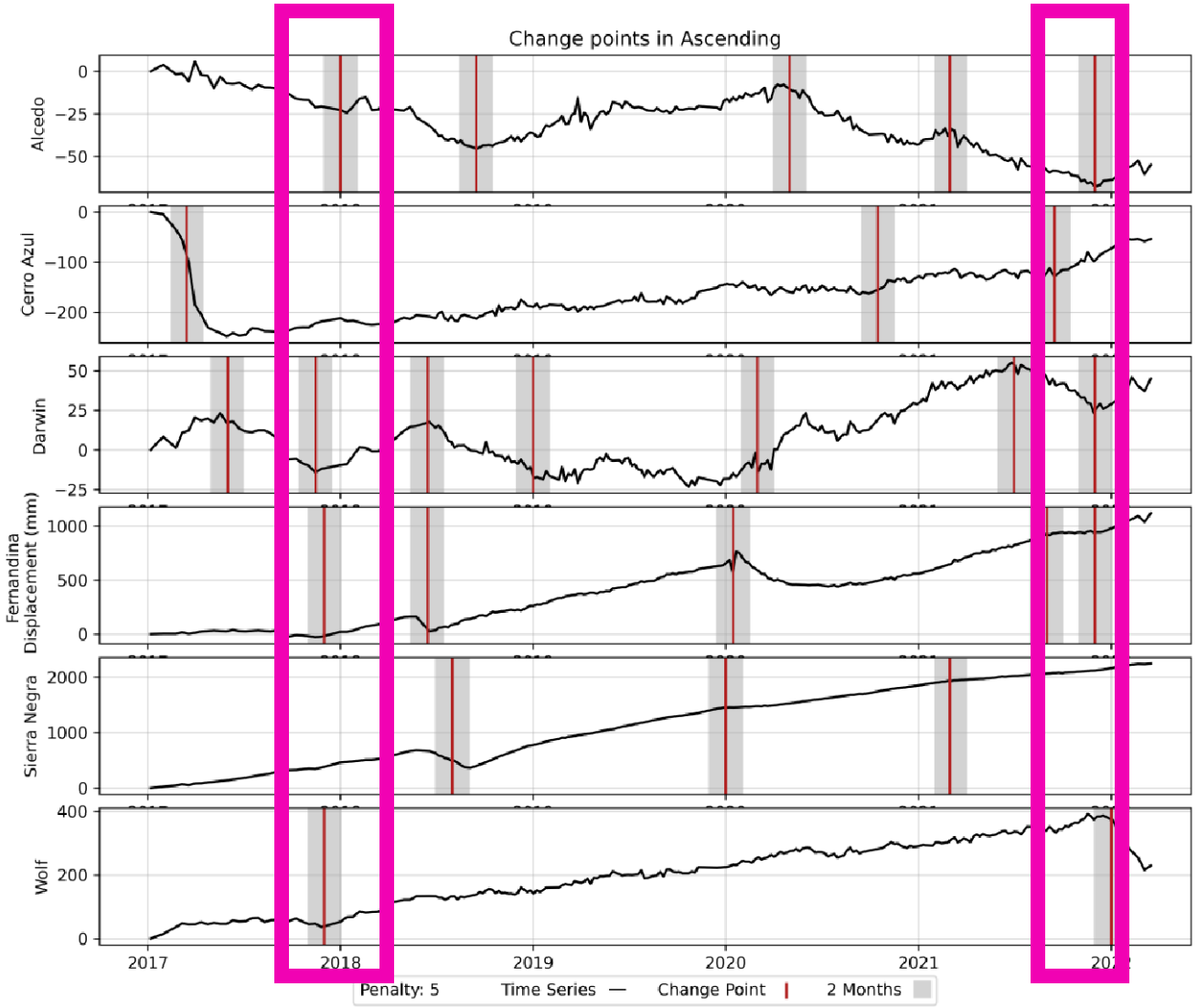
(PhD Thesis, 2012)

1. Deformation and seismicity, 2006–2007.
2. Deformation, Fernandina eruption, 2009.
3. Deformation, Alcedo unrest, 2010.
4. Deformation, Cerro Azul eruption, 2008.



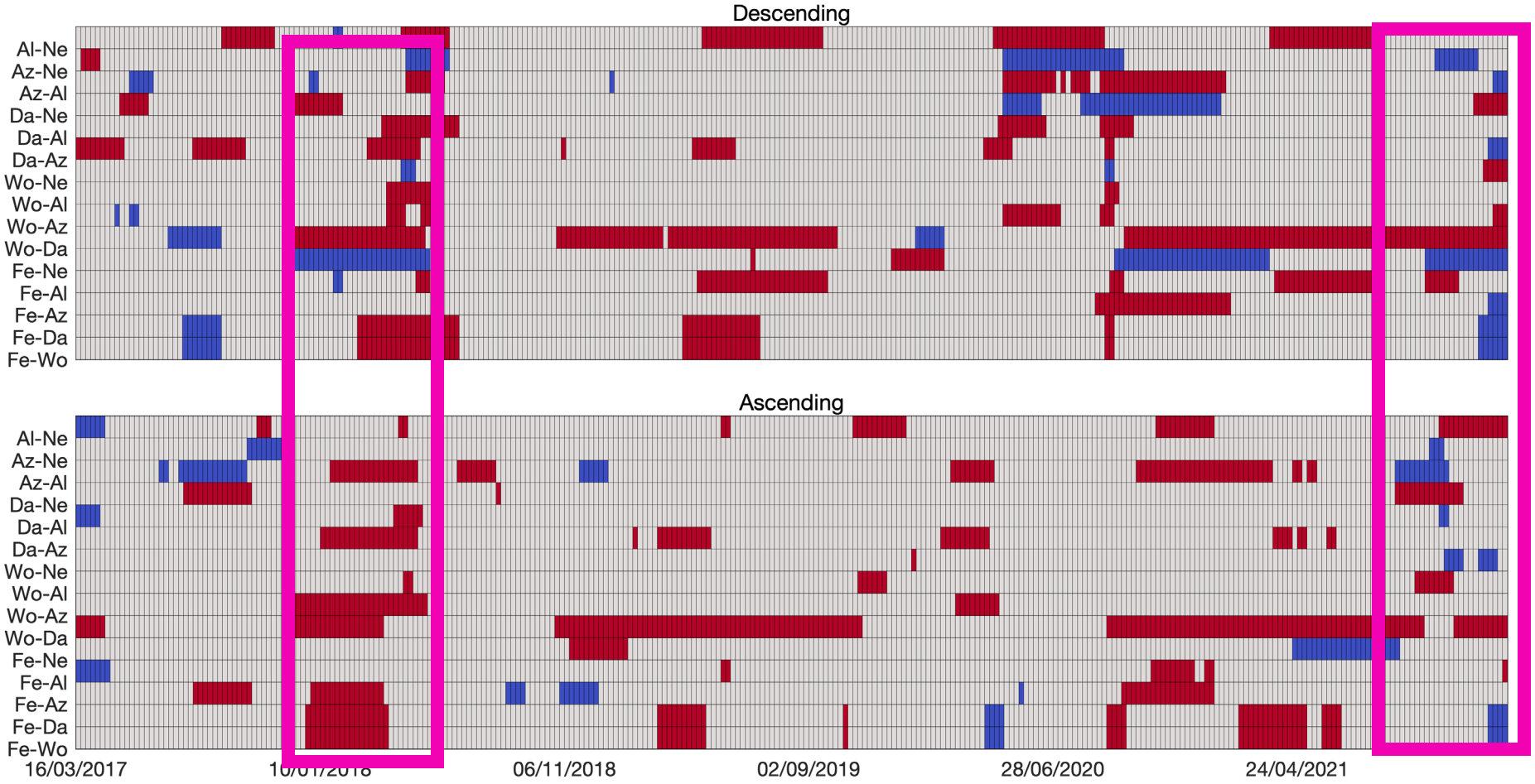


1. Identification of turning points (du/dt=0)



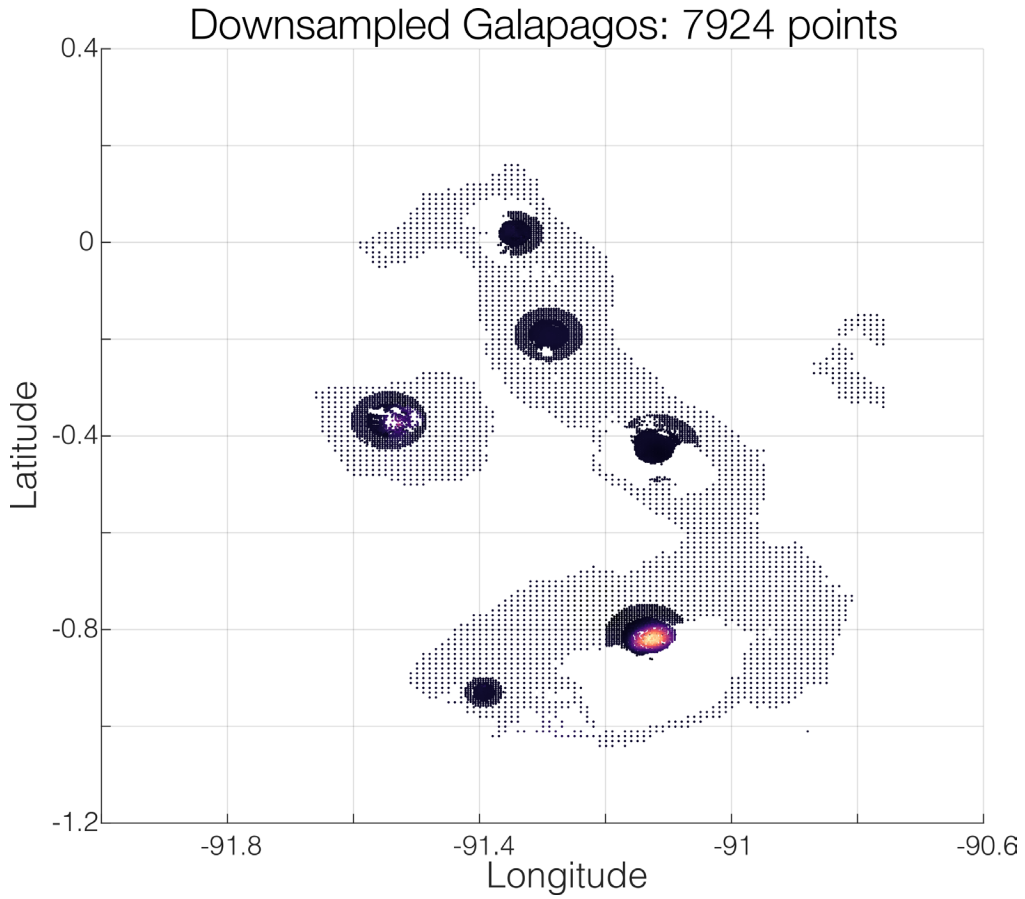
systematic assessment of time series correlation

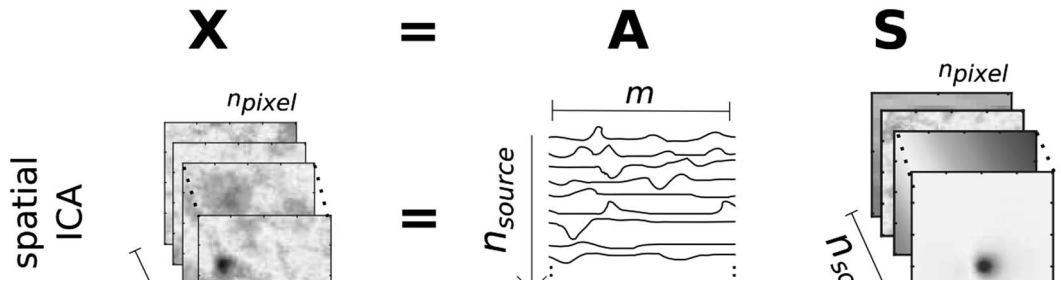
1. Identification of turning points (du/dt=0)
2. Windowed, paired correlation analysis



- 3 month windows
- correlations: |>0.9| plotted
- red = positive correlation
- blue = negative correlation

1. Identification of turning points (du/dt=0)
2. Windowed, paired correlation analysis
3. Temporal Independent Component Analysis



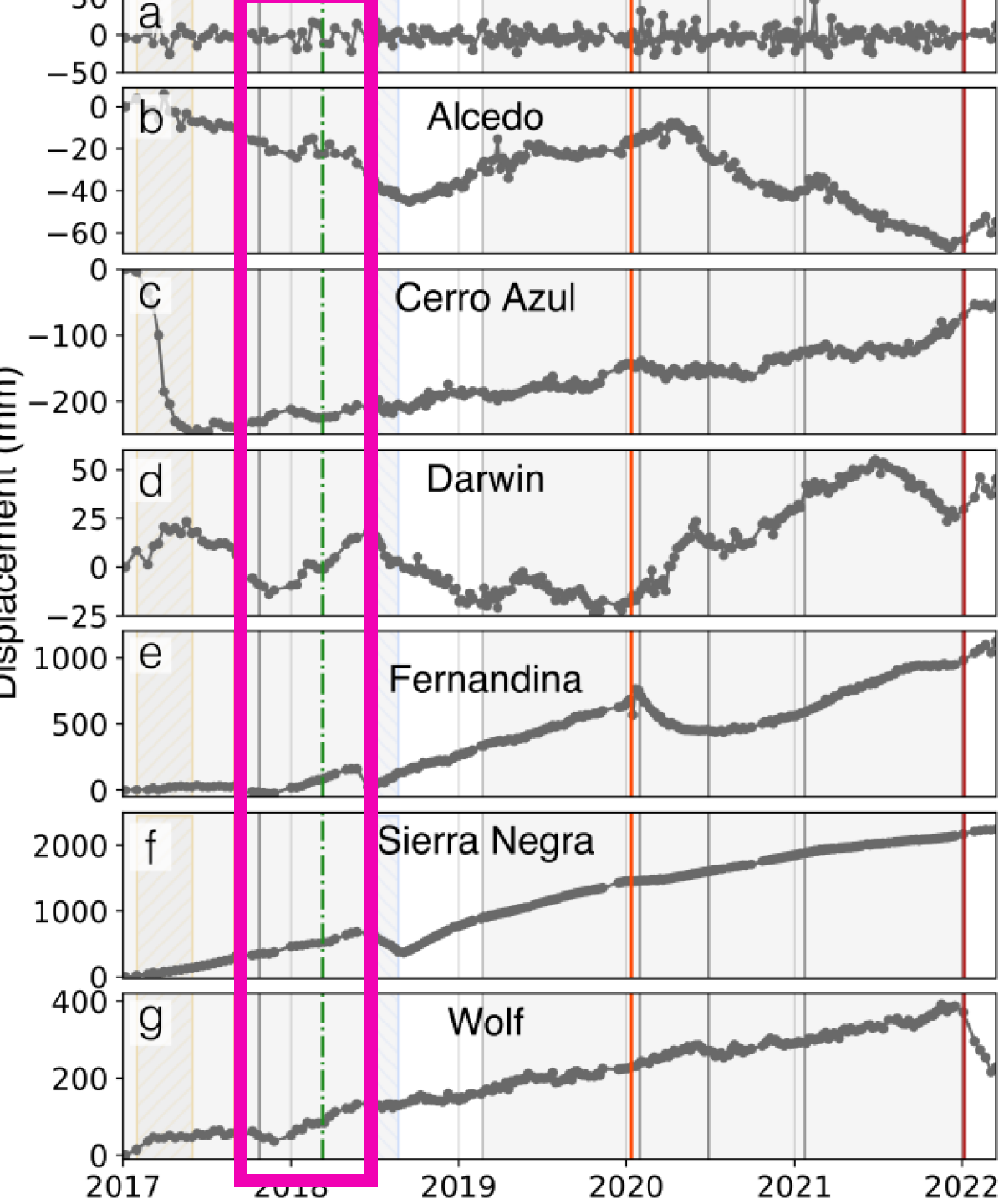


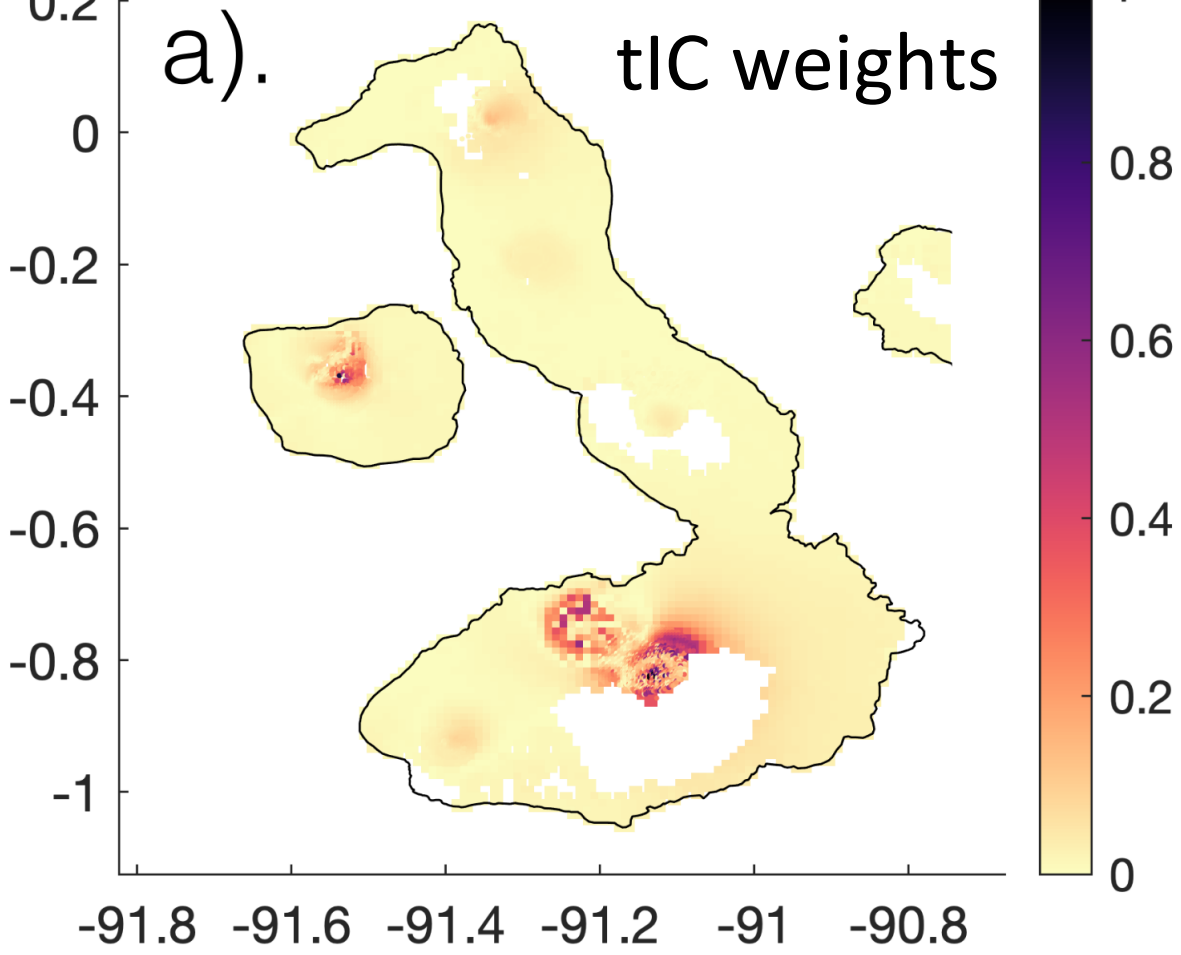
• downsample the number of time-series spatially, based on distance from the caldera

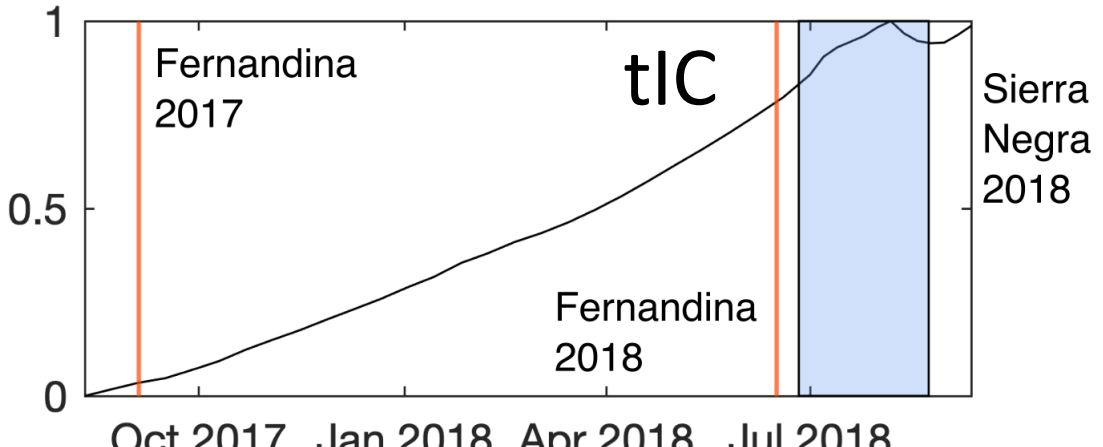
• Apply temporal ICA to ~8000 time series across the Galapagos for time periods where correlations identified from paired analysis

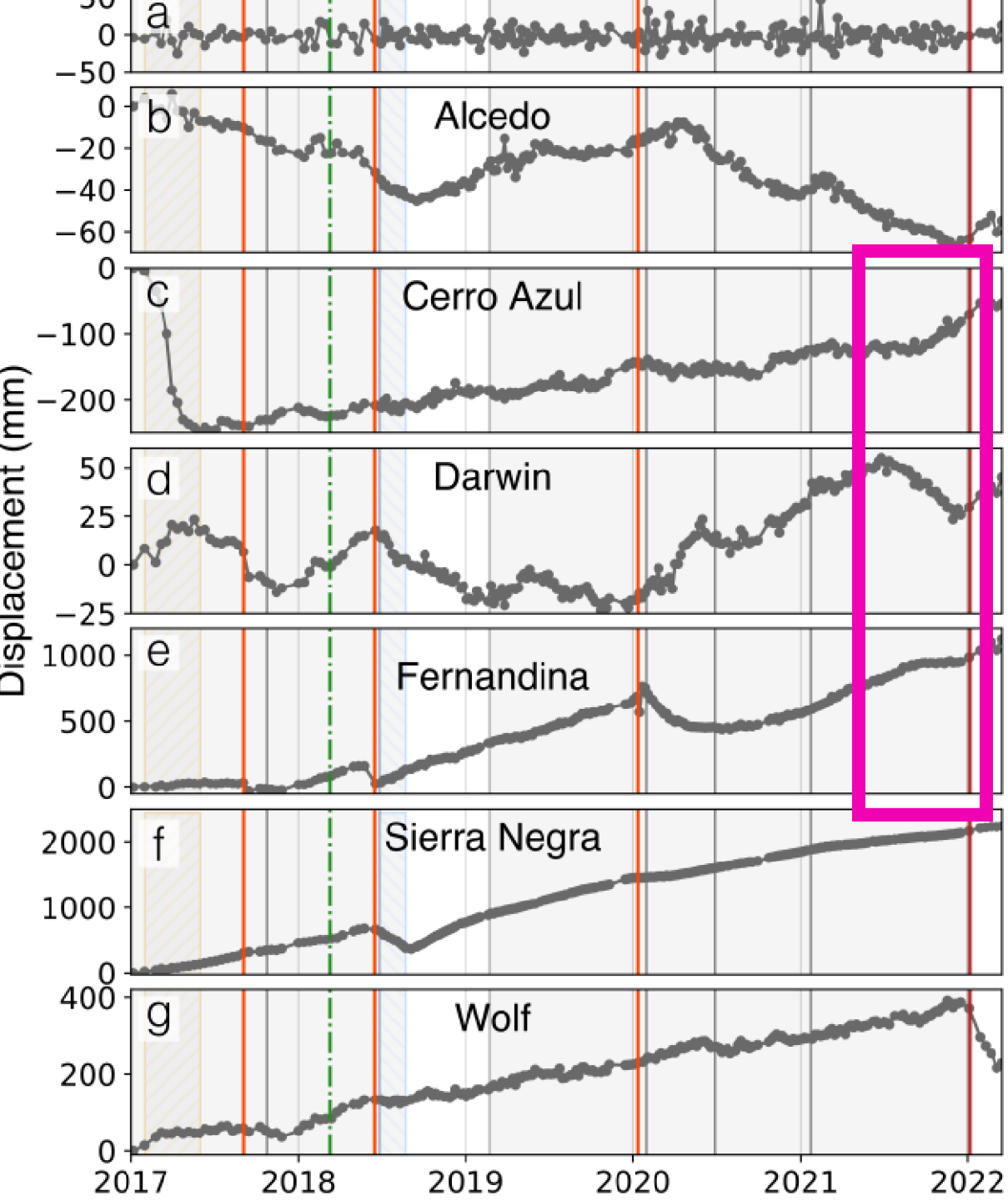
• Cluster retrieved components with k-means

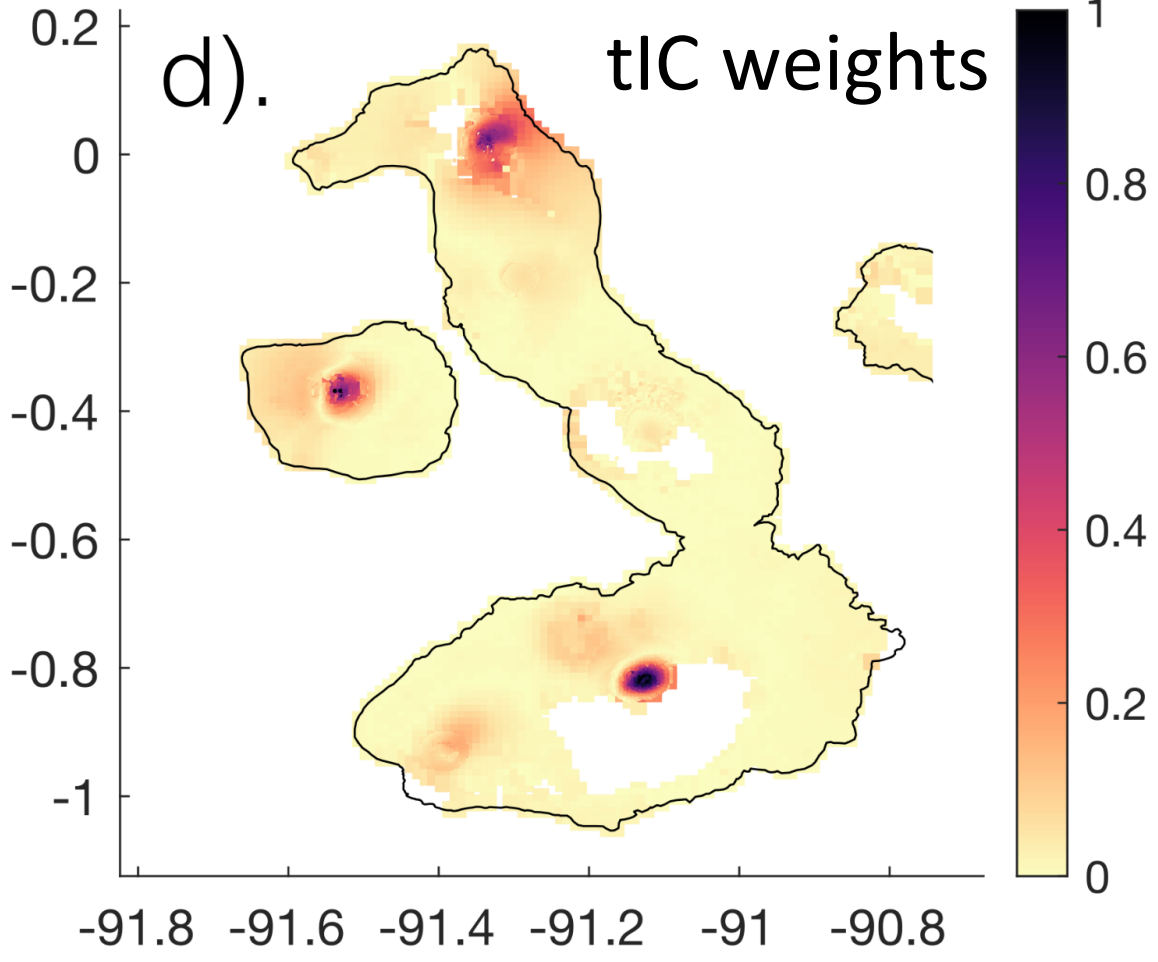
• Analyse spatial pattern of IC strength

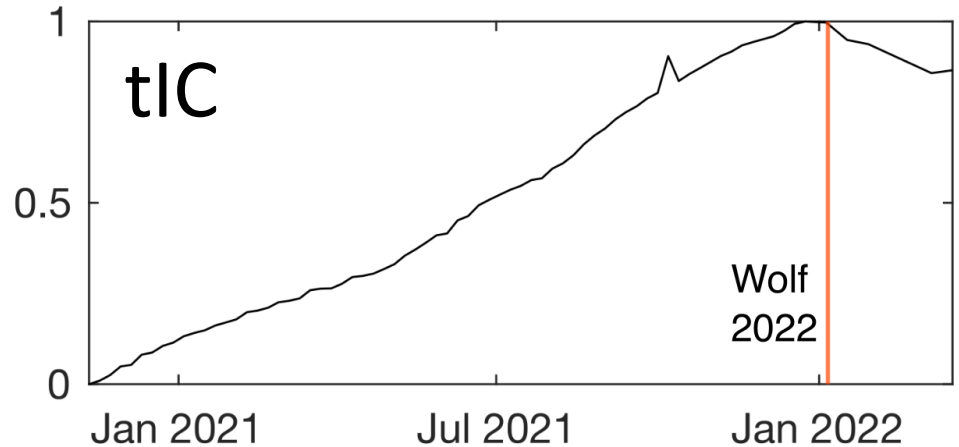

a
b
Alcedo
c
Cerro Azul
d
Darwin
e
Fernandina
f
Sierra Negra
g
Wolf
Displacement (mm)
2017
2018
2019
2020
2021
2022


a).
tIC weights
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-91.8
-91.6
-91.4
-91.2
-91
-90.8
0.8
0.6
0.4
0.2
0


tIC
Fernandina
2017
Fernandina
2018
Sierra
Negra
2018
1
0.5
0
Oct 2017
Jan 2018
Apr 2018
Jul 2018


a
b
Alcedo
c
Cerro Azul
d
Darwin
e
Fernandina
f
Sierra Negra
g
Wolf
Displacement (mm)
2017
2018
2019
2020
2021
2022


d).
tIC weights
-91.8
-91.6
-91.4
-91.2
-91
-90.8


tIC
Wolf
2022
Jan 2021
Jul 2021
Jan 2022

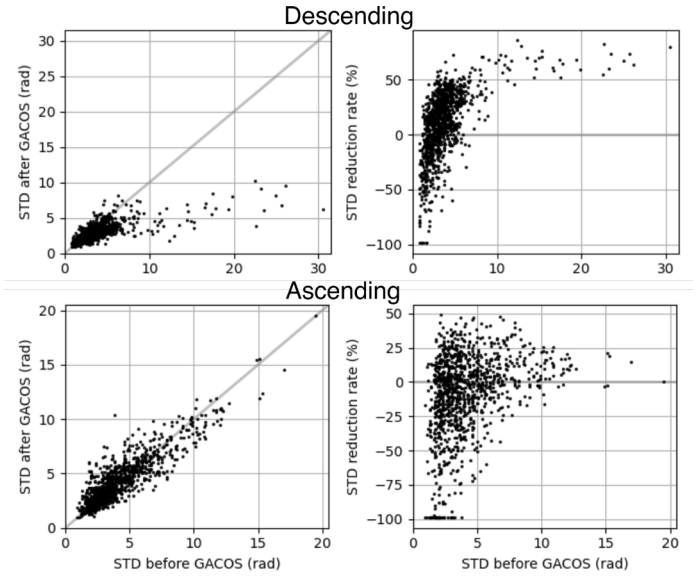
Potential Explanations:

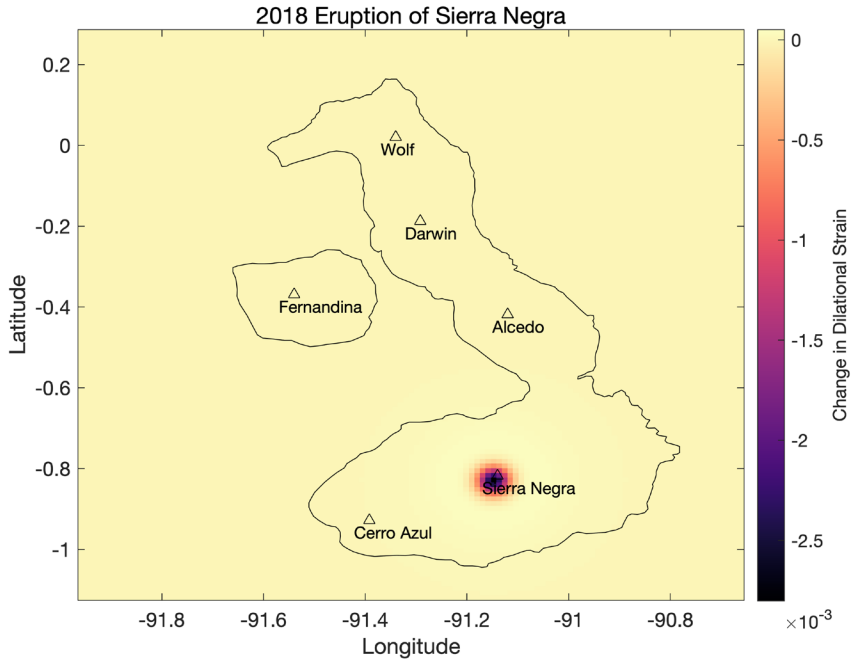
(1) Correlations are artefacts of InSAR processing

(2) Static stress changes associated with eruption and unrest

(3) Shallow hydraulic connections

(4) Deeper connections between magma supplies



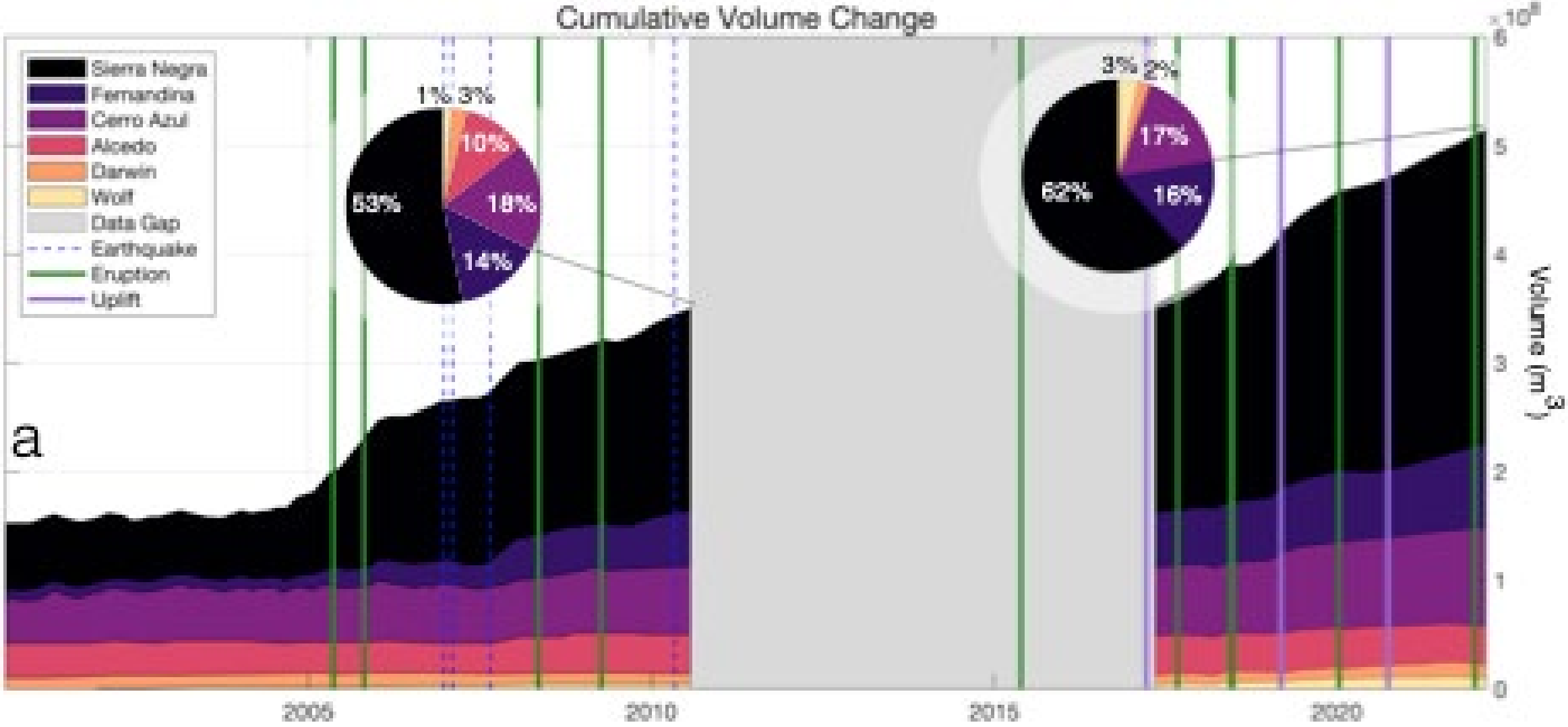


Correlations in displacement occur:

- between all pairs of volcanoes
- during eruptive episodes over days to weeks
- inter-eruptive periods over weeks to years
- in general trends of uplift/subsidence (turning points)
- in small time series variations (tICA, correlation analysis)

• Estimated probability of 2 volcanoes randomly experiencing a major change in deformation rate in the same month to be <1 % (even lower for > 2 volcanoes).

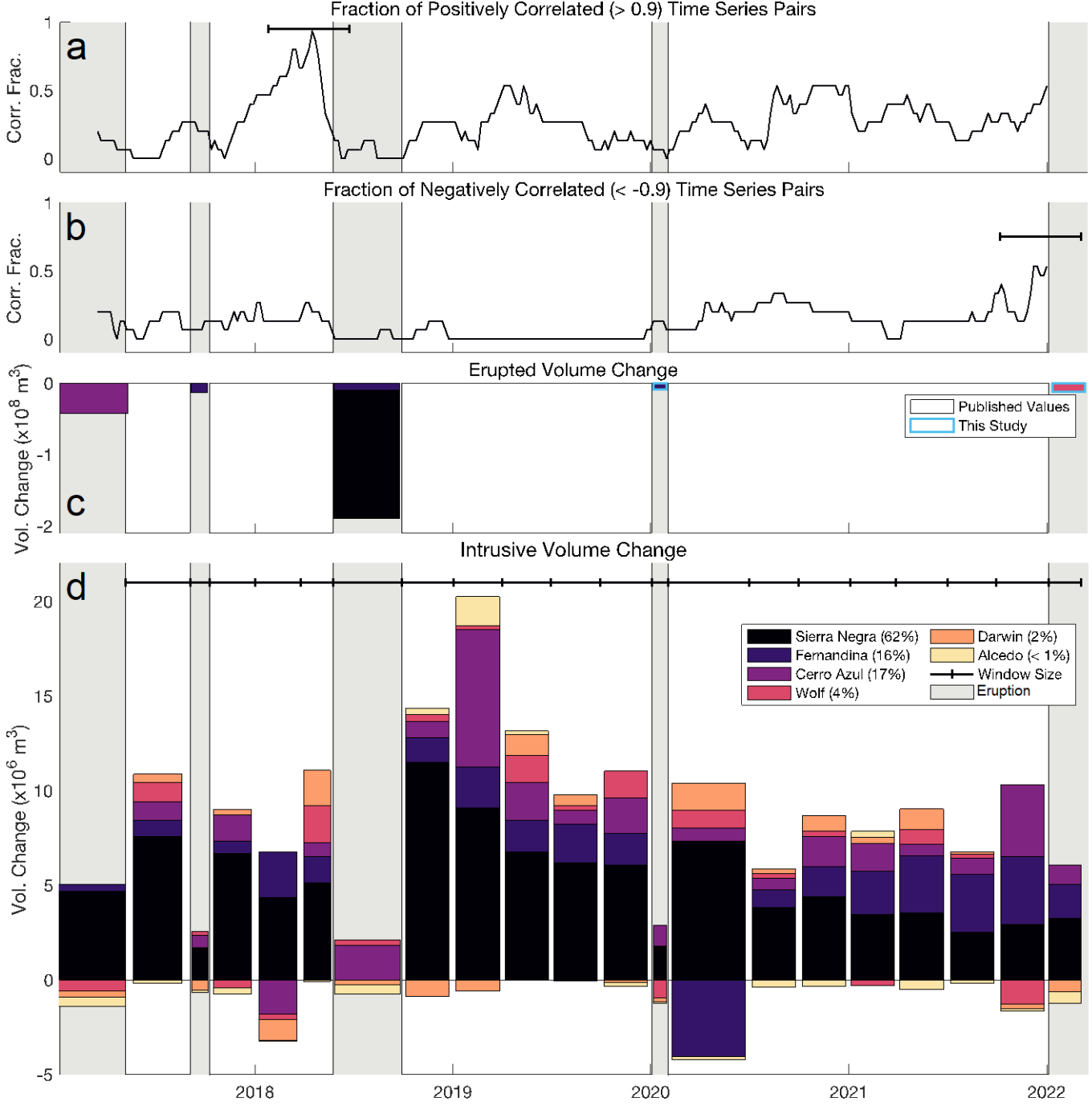
• If eruption timing were random, probability of Sierra Negra and Fernandina erupting within 6 month window <1 %



- total intrusive flux and share of melt varies over decades
- consistent with observations of historical eruption ‘clusters’, episodes of magmatic ‘flushing’ or resurgence

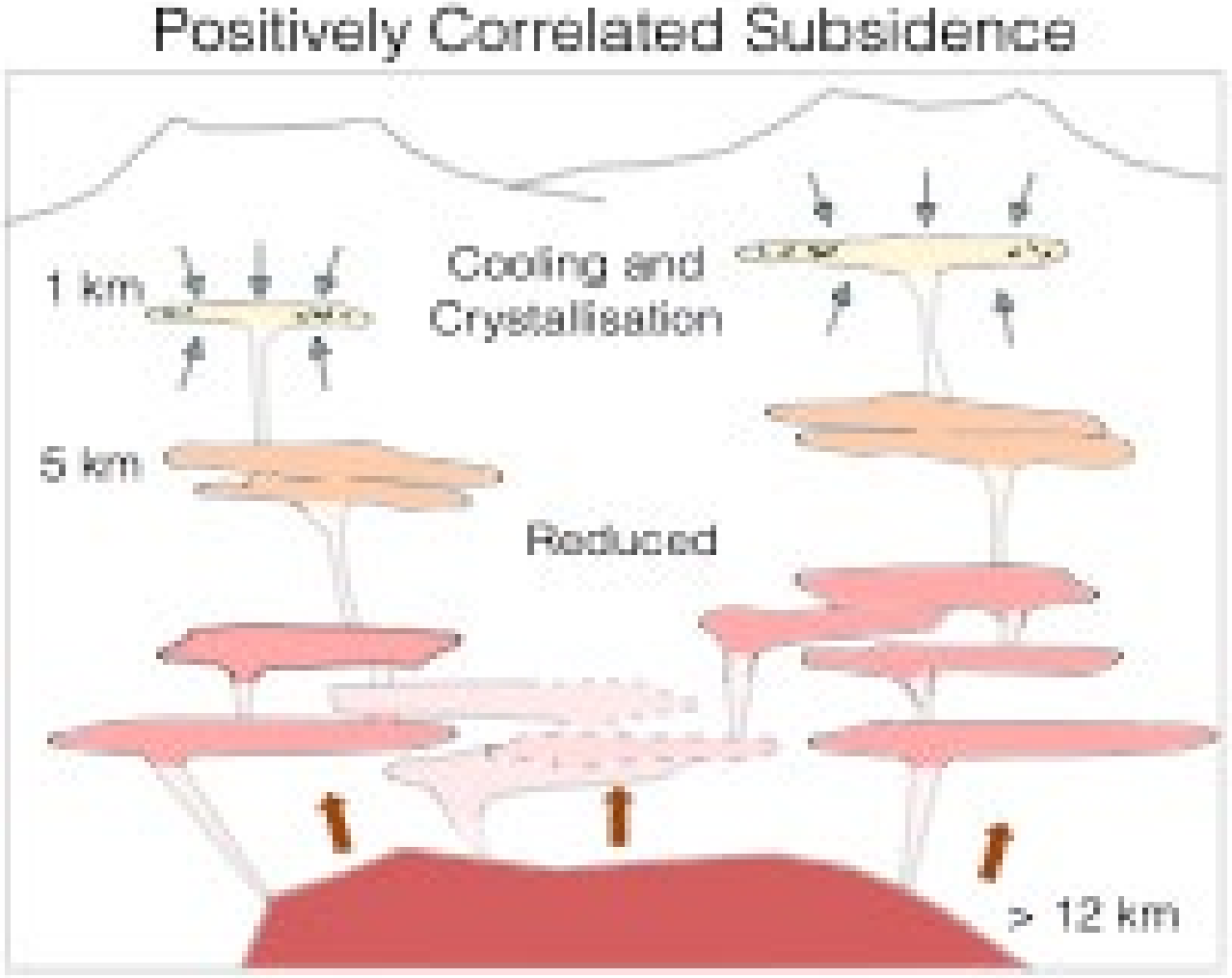
- high correlation counts correspond with episodes of high magma flux (intrusive and eruptive)

- eruptions are associated with magma ‘flushing’ events (Stock et al., 2018,2020)



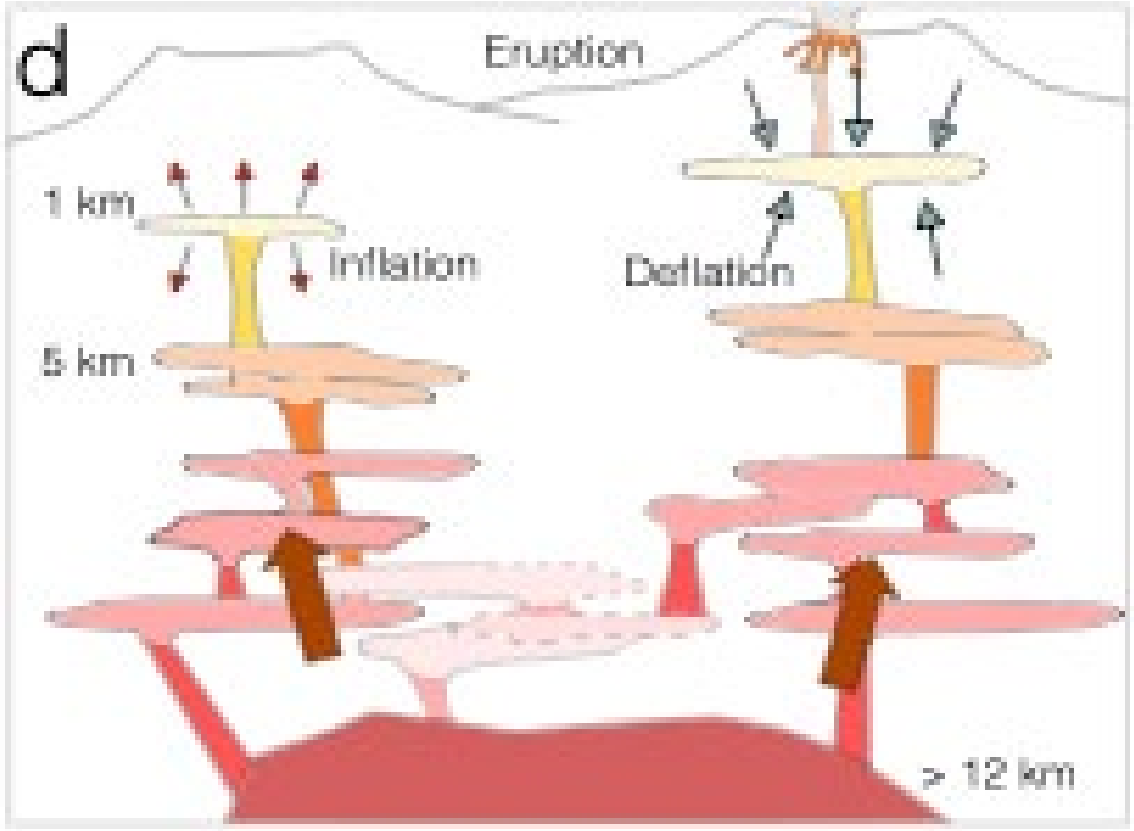
majority of strong correlations between pairs of displacement time series are uplift at multiple systems and correlated with episodes of high melt supply

correlated subsidence associated with drops in supply rate or eruption

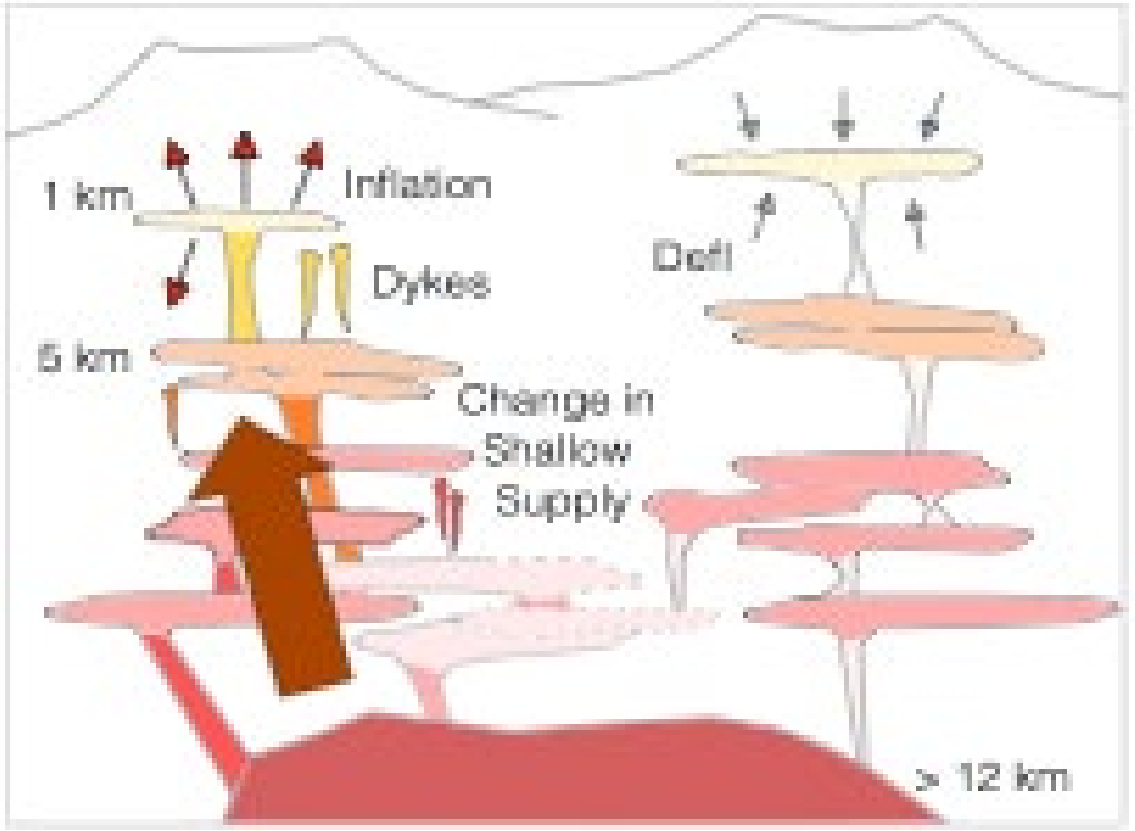


Negatively correlated displacements:

Shallow controls on magma ascent



Deep controls on magma supply

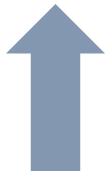


e.g., major eruptions, caldera collapse

variations in supply rate to shallow crust
(enhanced melt production or changing pathways)

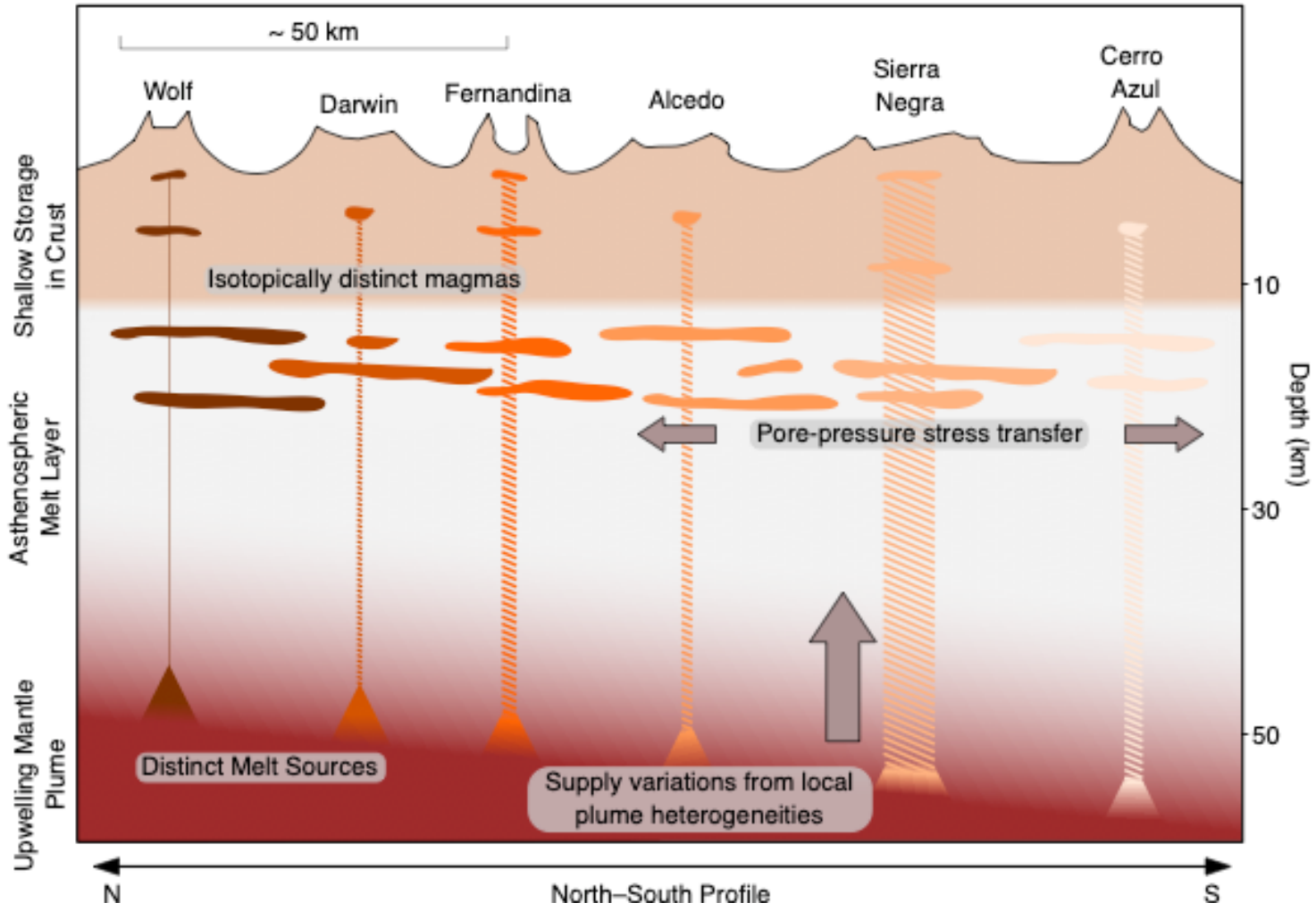
How deep are the connections between volcanoes?

Volcanoes all have distinct lava compositions for the last 10 Ka, each sampling a geochemically distinct part of a heterogeneous plume (e.g., Kurtz & Geist, 1999)



No geodetic detection of lateral transfer

At Hawai'i, an asthenospheric melt layer has been imaged seismically (Gonnerman et al., 2012; Wilding et al., 2023). Magma storage has also been found in the upper mantle at El Hierro (Klügel et al., 2015).



No geodetic detection of lateral transfer

distinct, vertically extensive sub-volcanic magmatic zones

Asthenospheric melt layer?

Isotopically distinct melt sources

- Western Galapagos volcanoes consistently (over a decade) experience correlated displacements, especially during periods of heightened magma supply to the shallow crust

- Correlations in displacement, but distinct isotopic signatures, are indicative of pore-pressure connections at depth, potentially at sub-crustal depths.

relationships between displacements at groups of active volcanoes can provide a window into workings of deeper interconnected transcrustal magmatic systems