Cortical deformation in the Aguacaliente-Navarro fault system (Central Valley, Costa Rica) from Geodetic data (GNSS and InSAR)

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Juan José Portela Fernández[1], Alejandra Staller Vázquez[1], and Marta Béjar Pizarro[2]

1 Universidad Politécnica de Madrid (UPM), ETSI Topografía, Geodesia y Cartografía, Ingeniería Topográfica y Cartografía, Spain (jj.portela@alumnos.upm.es) ; 2 Instituto Geológico y Minero de España (IGME)

POLITÉCNICA

Instituto Geológico y Minero de España

ABSTRACT

The Central Valley, Costa Rica, is subject to moderate seismicity, related to the Central Costa Rica Deformation Belt: a region with diffuse deformation, where Caribbean, Cocos and Nazca Plates, as well as the Panama Micro-plate, interact. The Eastern part of the valley is dominated by the Aguacaliente-Navarro fault system. The city of Cartago was destroyed by an earthquake Ms 6.4 in 1910, associated with the rupture of the Aguacaliente fault. Volcanic unrest –mainly in Turrialba Volcano, with recent activity reported- is present in the area, thus resulting in a very complex interaction zone, where seismic hazard studies are crucial.

In this context, we process GNSS observations from five different campaigns -2012, 2014, 2016, 2018 and 2020- in 13 stations in the area, in order to estimate their Caribbean-fixed velocities, hence the regional cumulative strain. Additionally, we use both InSAR and GNSS data to evaluate volcanic deformation, aiming to refine the computed velocities by removing volcanic deformation from the tectonic signal.

The refined velocities will allow us to assess a more precise cumulative strain for the Aguacaliente-Navarro fault system, which is useful to improve seismic hazard assessment in Cartago, one of the most important cities on the region.

VOLCANO-TECTONIC CONTEXT

The Central Valley of Costa Rica lies in a very complex interaction zone, dominated by the subduction of Cocos Plate beneath the Caribbean Plate and the Panama Microplate (at a rate of ~8 cm y^{-1}, De Mets et al., 2010), with the additional contributions of Nazca Plate and the Cocos Ridge (Álvarez-Gómez et al., 2019). This results in a band of diffuse deformation and seismic activity: the Central Costa Rica Deformation Belt (**Fig. 1A**).

The deformation associated to the Aguacaliente – Navarro fault system, located in the Central Valley, is far from known. The 1910 Cartago earthquake (Ms 6.4), the most destructive in the history of Costa Rica, is related to the rupture of the Aguacaliente fault (Alonso-Henar et al., 2013). Additionally, the presence of the Irazú and Turrialba volcanoes –the latter still experiencing an unrest period- contributes to the complexity of the area.

In this context, the ZFACNA net was established for GNSS campaign measurements, aiming to provide a frame to study the cortical deformation in the Central Valley (**Fig. 1B**).

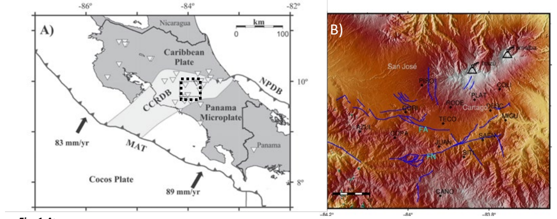

***Fig. 1. A) Tectonic setting of Costa Rica**. CCRDB - Central Costa Rica Deformation Belt. The dashed square corresponds approximately to the study area. Modified from Araya et al., 2015. **B) Study area.** Fault traces figure as blue lines (FA – Aguacaliente, FN – Navarro), while black dots represent ZFACNA net GNSS campaign stations.*

METHODOLOGY

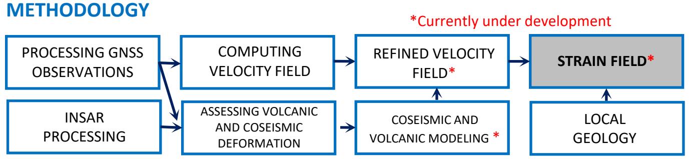

Fig. 2: Flow chart summarizing the different steps of our methodological approach

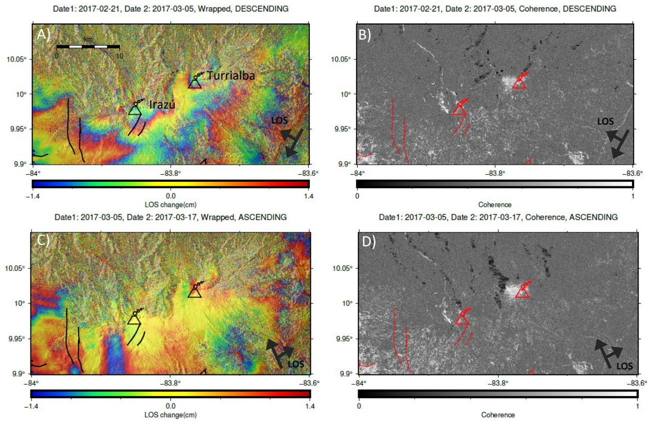

Fig. 3: Differential interferograms (A,C) and coherence maps (B,D) in ascending and descending geometry over the Irazú and Turrialba volcanoes . Continuous lines represent active faults.

The followed methodological approach is summarised in **Fig. 2**. We used Bernese 5.0 (Dach et al., 2015) in order to process the GNSS observations with relative positioning technique, obtained from 2012, 2014, 2016, 2018 and 2020 campaigns in the ZFACNA network, located in the Central Valley of Costa Rica. Orbit and clock information, as well as Earth Rotation Parameters and atmospheric models, were downloaded from CODE (Center for Orbit Determination in Europe) database. The velocity for each station was then computed (e.g. **Fig. 4**).

Sentinel-1 IW SLC InSAR data were processed using the European Space Agency Geohazards Exploitation Platform (https://geohazards-tep.eu/). We used two different approaches. On the one hand, the Diapason service (TRE Altamira) was used to produce short-term differential interferograms associated to volcanic events occurred in the Irazú – Turrialba system between October 2014 – March 2020. Our preliminary results (**Fig. 3**) show low coherence due to dense vegetation, which makes it difficult to identify volcanic deformation. On the other hand, we used the Parallel Small BAseline Subset (P-SBAS) technique (Manunta et al. 2019) to produce LOS displacement time series and mean LOS velocity maps over the Irazú and Turrialba volcanoes. The low coherence of the area only allowed to recover the signal in isolated patches, mainly over urban and rocky areas. Over the Irazú-Turrialba system, coherence was maintained only in the rocky volcanic edifices for ascending geometry in certain periods of time (e.g. **Fig. 5**)

We then computed a preliminary strain field from a grid-based approach, using GEOSTRAIN software (Goudarzi et al., 2015).

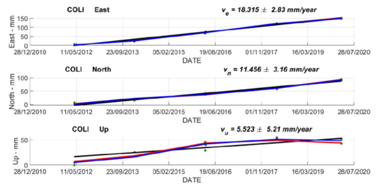

Fig. 4: Observed GNSS time series for CORI station (green dots), along with the computed trend (black line), seasonality (red line) and seasonality-corrected trend (blue line).

PRELIMINARY RESULTS

VELOCITY FIELD

The velocities obtained (**Fig 5**) are coherent with an active deformation zone. Observing the relative motion of some stations with respect to CANO, a cumulative deformation of over 1 cm/y has been estimated between the North and the South of the Aguacaliente-Navarro Fault System. The velocities present a behavior in line with a left-lateral strike-slip system.

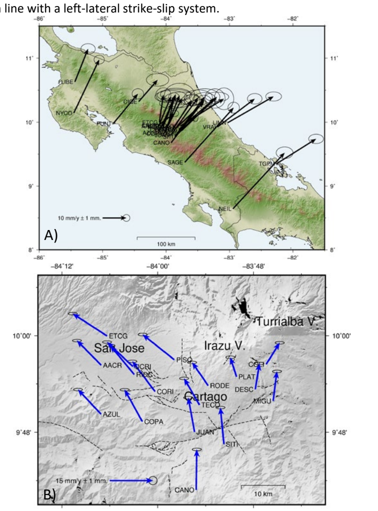

***Fig. 5. A**: Horizontal (e,n) ITRF2014 absolute velocities of processed stations in Costa Rica. **B**: Horizontal (e,n) Caribbean-fixed velocities for ZFACNA net stations. Error ellipses given at 65% of confidence.*

STRAIN FIELD

The preliminary strain field determined from our GNSS observations is consistent with the regional tectonics. Negative deformation, i.e., compression, can be observed between the two main left-lateral faults: Aguacaliente and Navarro (**Fig. 6A**). Similarly, the highest reliable values of maximum shear strain rate can be discerned between the two faults (**Fig. 6B**).

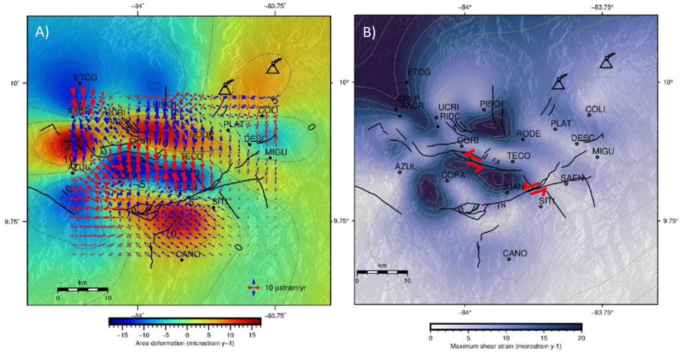

***Fig. 6. A**: Area deformation rate and strain rate tensors (red arrows show compression, blue arrows, extension). **B**: Maximum shear strain rate. Red arrows represent the left-lateral dynamics of the Aguacaliente (FA) and Navarro (FN) faults. GNSS campaign stations figure as black dots, while other GNSS permanent stations used for the computation figure as diamonds, although some of them lie outside the shown area.*

CURRENT WORK

To estimate both, volcanic deformation associated to activity in the Turrialba-Irazú volcanic complex and cosesimic deformation associated to the seismic events occurred near the study area during the observation period (e.g. 2016 Capellades Mw 5.5 or 2012 Nicoya Mw 7.6) we will use L-Band SAR data, which should be more effective in areas with dense vegetation such as central Costa Rica (Pritchard et al, 2018), supported by GNSS data.

The GNSS velocities are to be corrected from both coseismic offsets -regardless the sparseness of observations over time- and volcanic-related deformation, hence a refined velocity field.

This will allow us to build a more precise strain field for the Central Valley of Costa Rica, thus assessing crustal deformation in the area and slip rates for the main faults, namely Aguacaliente and Navarro faults. This information is critical for a better understanding of the seismic hazard imposed to the densely populated Central Valley.

CONCLUSIONS

- ❑ GNSS observations suggest that over 1 cm/y deformation is accumulating between the southern and northern parts of the Aguacaliente-Navarro Fault System, in a congruent way with the regional deformation pattern.
- ❑ Furthermore, the determined strain field interpretation is coherent with a left-lateral, strike-slip fault system, presenting compression and maximum shear strain rates between Aguacaliente and Navarro faults.
- ❑ Coseismic offsets –primarily from 2012 Mw 7.6 Nicoya earthquake- seem to have a considerable impact on the trend estimation in our time series, despite the long distances to the rupture zones. Refinement of the velocity field seems necessary in order to estimate accurately the deformation field in the Central Valley.
- ❑ C-band SAR data shows very low effectiveness in the area of study, probably due to the dense vegetation, resulting in very low coherence on the volcanoes. L-band SAR data from satellite ALOS will be used in future studies.

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