Universidad de los Andes

HYPSOMETRIC AND DRAINAGE NETWORK ANALYSIS OF THE EASTERN CORDILLERA OF THE COLOMBIAN ANDES: EVIDENCE FOR VARIABLE SPATIAL - TEMPORAL UPLIFT INFERRED THROUGH GEOMORPHOLOGICAL PARAMETERS

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1. INTRODUCTION

The Eastern Cordillera of the Colombian Andes is an example of a compressional thrust-reactivation system (Mora et al., 2010). This reactivation occurred within weak preexisting extensional structures that formed during the Mesozoic rifting (Sarmiento-Rojas et al., 2006). This inversion has been suggested to have occurred from late Eocene to early Oligocene for the axial portion of the Cordillera, and from the late Oligocene to early Miocene for most of its eastern flank (Mora et al., 2010). In the northwestern Andes, the triple convergence of the Nazca, Caribbean and South American plate produces shortening and deformation in NE – SW direction. This tectonic forcing direction is almost perpendicular to the Eastern Cordillera strike which is preferentially SSW – NNE (Fig. 1). This compressional regime has produced a bi-vergent fold-thrust system in which the resulting thrust structures have opposite dip directions both flanks (Fig. 1).

One of the main features controlling the extent of deformation within the South Section (SS) of the thrust systems of the Cordillera is its climatic asymmetry (Mora et al., 2008). The southern portion of the eastern flank of the Cordillera exhibits higher precipitation rates as a consequence of the humid air coming from the Amazon river basin, which is unable to cross the mountainous range. It has been hypothesized that this difference in precipitation between flanks, have triggered a higher deformation rate in the eastern flank thrust systems, in consequence the crystalline basement crops out within this portion of the cordillera (Mora et al., 2008).

Among the most controversial topics concerning the Colombian Eastern Cordillera is its uplift history. Currently, it is though that the range gained most of its elevation (>2500m) in the last 6 to 3 My. These ages have been widely supported by paleo botanical data (van der Hammen et al., 1973; Andriessen et al., 1993, Wijninga, 1996) and by exhumation/cooling ages (Mora et al., 2008, 2010a, 2010b, 2014). Nevertheless, recent studies have suggested that the ecological niches of the plants used to determine these elevation changes were hugely underestimated (Fig. 2). Moreover, increased exhumation rates could be the consequence of tectonic-erosion cycles which are not compensated by isostatic rebound.

Finally, recent measured GPS deformation rates have shown that, if constant through time, present day elevations could not have been formed in such a short time period (Mora-Páez et al., 2016).

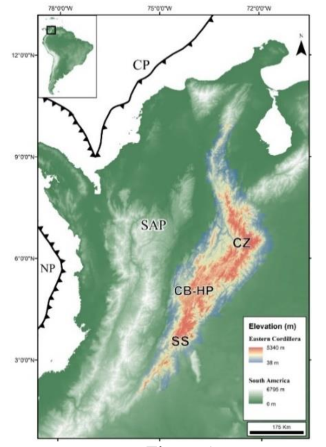

Figure 1. Eastern Cordillera of the Colombian Andes. SAP = South American Plate. NP = Nazca Plate. CP = Caribbean Plate. CZ = Cocuy zone. CB-HP = Cundinamarca Boyacá High Plain. SS = South Section.

Figure 1.

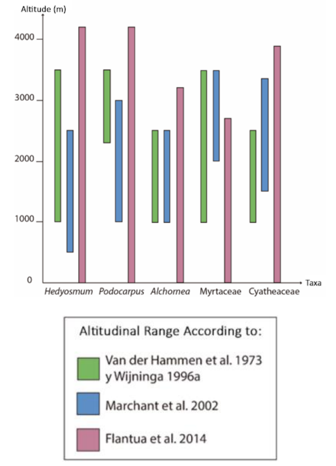

Figure 2. Altitudinal range of different plant taxa used to determine uplift ages and stages for the Eastern Cordillera of the Colombian Andes

Figure 2.

2. MATERIALS AND METHODS

In order to stablish the erosional maturity of drainage basins in both flanks of the Eastern Cordillera we used the ArcMap extension *CalHypso*. This tool is used to calculate the hypsometric integral, kurtosis and skewness for each drainage basin. These values were classified for the whole range to determine the zones with higher values (i.e. younger).

After determining the different zones given by the hypsometric integral, we calculated different geomorphic indexes to see how they relate to this value.

1. Chi (χ) Map to identify geometric divide equilibrium and migration. Drainage divide migrates toward the less tectonically active side. We relate the aggressor watersheds to earlier uplift stages compared to their neighbors.

2. Anomalous streams and anomalous stream density to identify gradients of tectonic control on the development of the stream network. These streams are defined as the ones which orientations differ 45° or more from the generalized slope direction or each watershed. Chi (χ) Maps and anomalous streams calculations are made using MATLAB set of functions for geomorphological analysis called TopoToolbox developed by Wolfgang Schwanghart from the University of Potsdam in Germany.

3. Swath profiles to determine range asymmetry, spatial variation of fluvial incision, and local relief. These profiles represent which zone exhibits more fluvial dissection and greater relief values which account for different uplift stage.

3. RESULTS

3.1 ANOMALOUS STREAMS

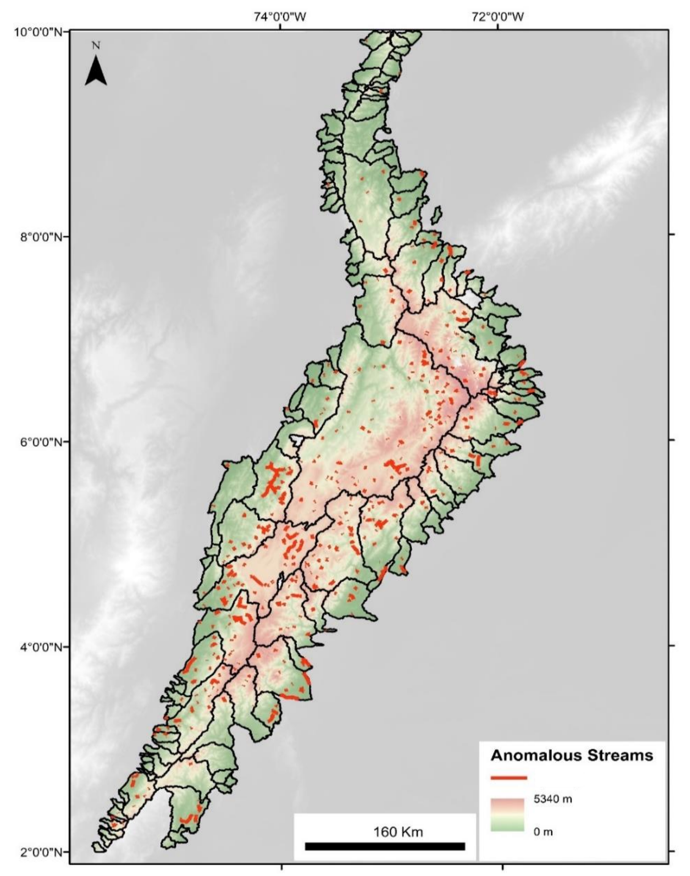

Figure 3. Anomalous stream segments

Anomalous streams are the linearized segments of the stream network in which the difference in orientation between the steepest slope direction and the stream segment is superior to 45° (Fig 3). This anomaly in direction is due to perpendicular shortening of the channels in the stream network.

The density of anomalous stream segments is highest in the Cundimarca - Boyacá High Plain zone while South Section present average anomalous stream densities and the Cocuy Zone exhibits the lower anomalous stream density (Fig. 4).

Anomalous stream density indicates that the Cundinamarca - Boyacá High Plain zone is the zone of the Eastern Cordillera with the most mature basins which, we suggest, might represent an early uplift stage.

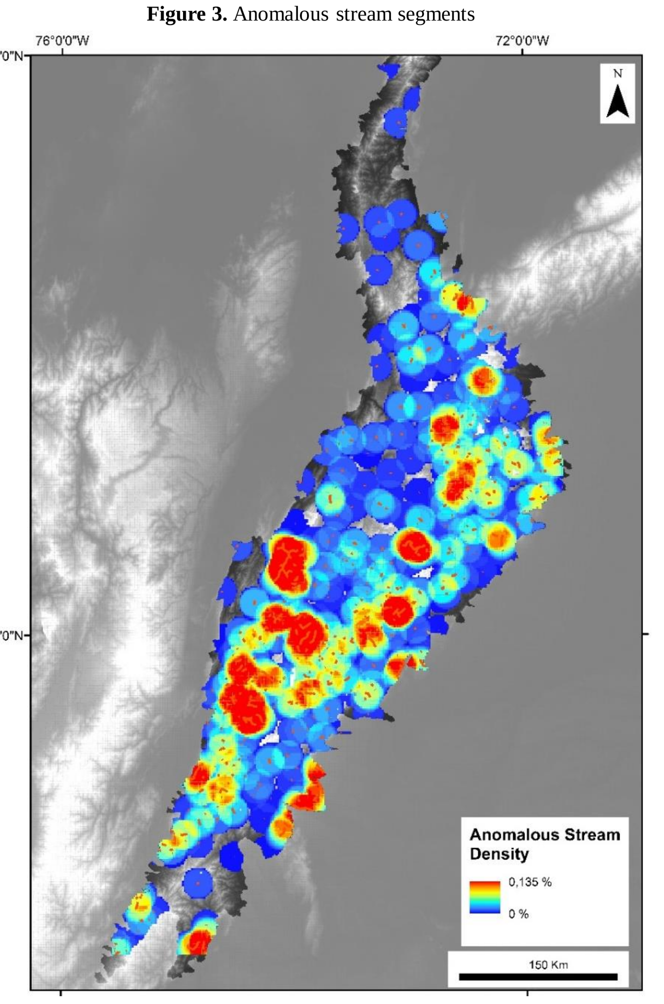

Figure 4. Anomalous stream density for the Eastern Cordillera

3.2 CHI PROXY MAPS

Chi (χ) maps represent a valuable proxy to determine the drainage divide geometric equilibrium in tectonically active mountain ranges (Willett et al. 2014). In the case of the northern part of the Eastern Cordillera, similar values of the χ proxy are seen on both sides of the drainage divide so this section of the mountain range is in geometric drainage equilibrium (Fig. 5A).

The northern part of the Cocuy Zone (CZ) exhibits some minor divide migration towards the eastern flank of the Eastern Cordillera. In the CZ, drainage divide is in geometric equilibrium so there is no major tectonic forcing which causes divide migration. χ proxy and HI value for the CZ suggest this is the oldest section of the Cordillera (Fig. 5B and Fig. 5C).

The Cundinamarca-Boyacá High Plain zone (CB-HP) shows major drainage divide migration towards the north. The high value of the hypsometric integral in this zone, and considerable differences in the χ proxy on opposite sides of drainage divide, show it is a young drainage network and is interpreted as a zone of the range in early uplift stages compared to CZ and South Section. The different χ values indicates that young watersheds are capturing older ones so this approach is consistent with the HI value (Fig. 5C).

The South Section (SS) of the Eastern Cordillera shows general divide equilibrium with capture from the younger watersheds visible in the northern part of this section by watersheds in the CB-HP zone (Fig 5D).

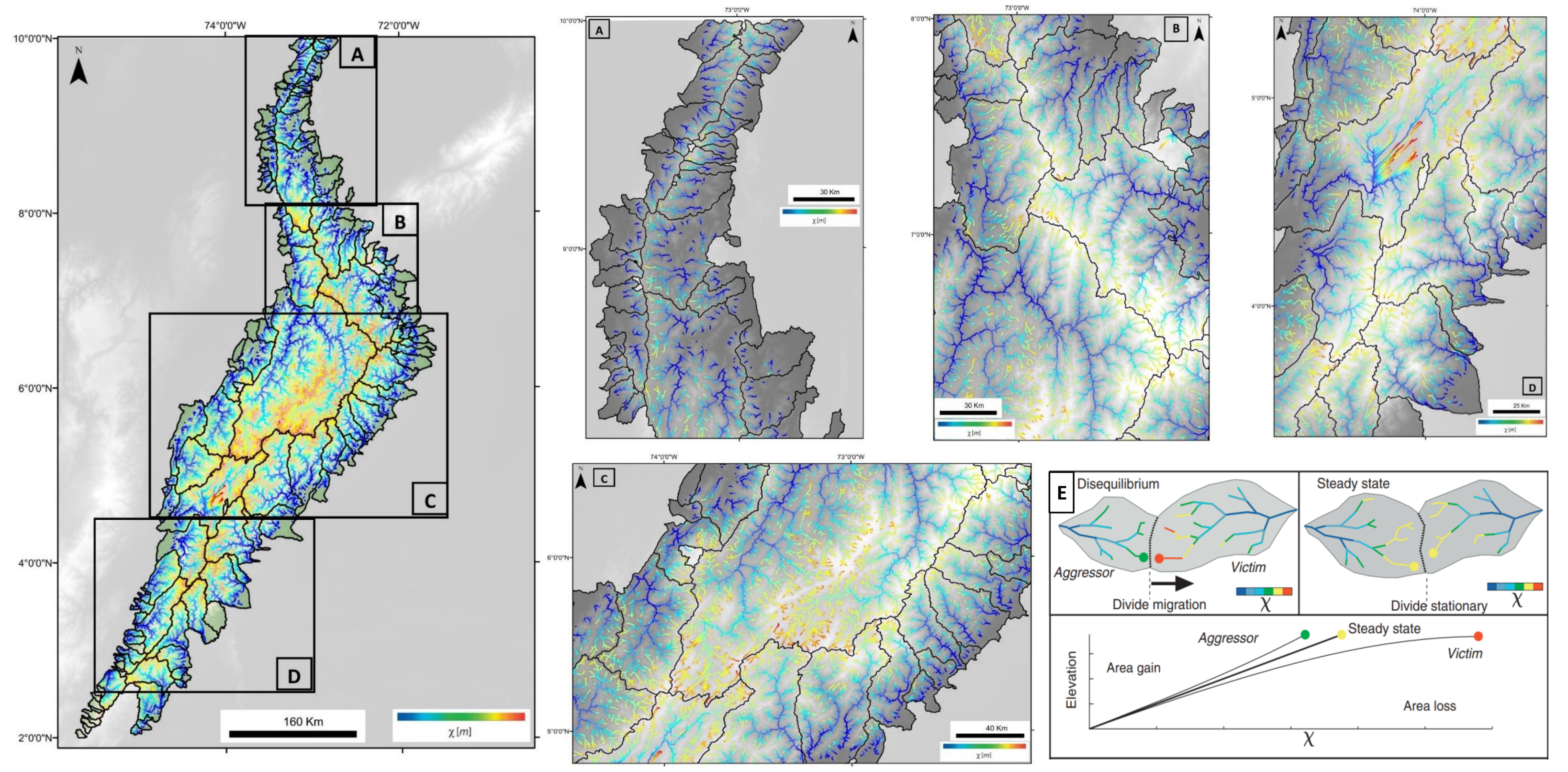

Figure 5. Chi (χ) map of the Eastern Cordillera. **A** = North Zone close-up. **B** = North zone and Cocuy zone close-up. **C** = Cocuy zone and Cundinamarca-Boyacá high plain zone. **D** = South Section close-up. **E** = Interpretation of Chi (χ) maps taken from Willett et al. 2014. Note how the victim watershed presents higher values of the (χ) proxy.

3.3 HYPSOMETRIC INTEGRAL AND RELIEF ANALYSIS

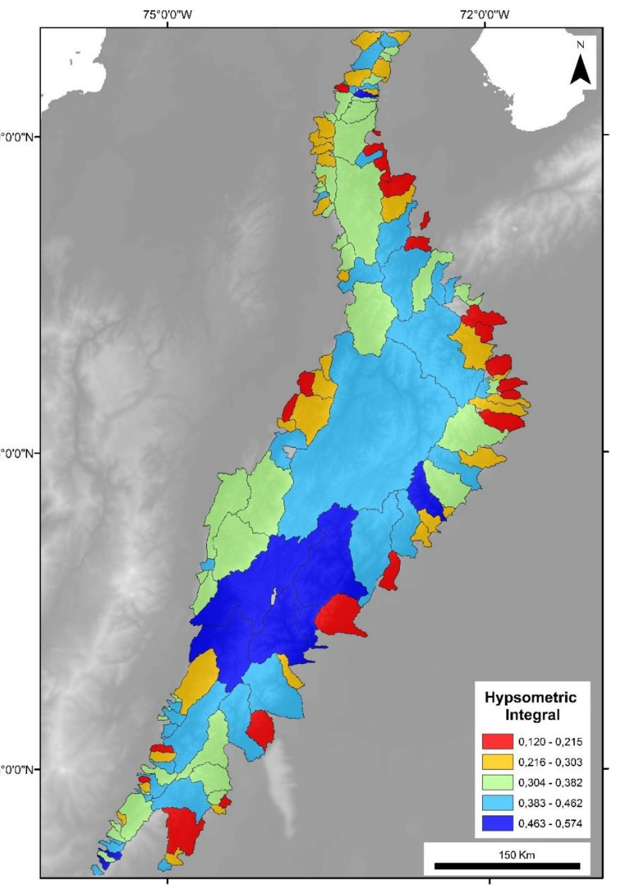

Figure 6. Hypsometric integral value distribution for the Eastern Cordillera of the Colombian Andes.

Hypsometric curves and the hypsometric integral (HI) uses the normalized area and elevation of multiple watersheds as an erosional stage proxy. High values of the area below the hypsometric curve (i.e. the hypsometric integral) indicate a young watershed in which considerable amount of rock volume has not been eroded. In contrast, low HI can be interpreted as mature watersheds in which late erosional stages have been reached.

In the Eastern Cordillera of the Colombian Andes, low HI values indicate a young Cundinamarca – Boyacá High Plane zone (CB-HP), intermediate HI values suggest a middle age South Section (SS) and high HI values point toward an old Cocuy Zone (CZ).

The HI value can be compared to fluvial dissection in relief analysis. Swath profiles made across the whole range can show where this process has taken place and its magnitude. The zones that exhibit greater relief (maximum altitude minus minimum altitude across the profile) are interpreted as more mature zones in which the channel network has dissected topography.

Swath profiles across the SS show low relief values which tend to increase towards the western piedmont, where the highest relief values are seen for the Eastern Cordillera. This profile shows an intermediate state of fluvial dissection and a middle age river network.

Relief values across the CB – HP show the lowest values. This analysis coupled with the HI indicates a lesser maturity of these basins.

The CZ show stable high relief values across the swath profiles. This zone of the Eastern Cordillera, in which the highest peaks of the whole range are located, show a mature and incised stream network.

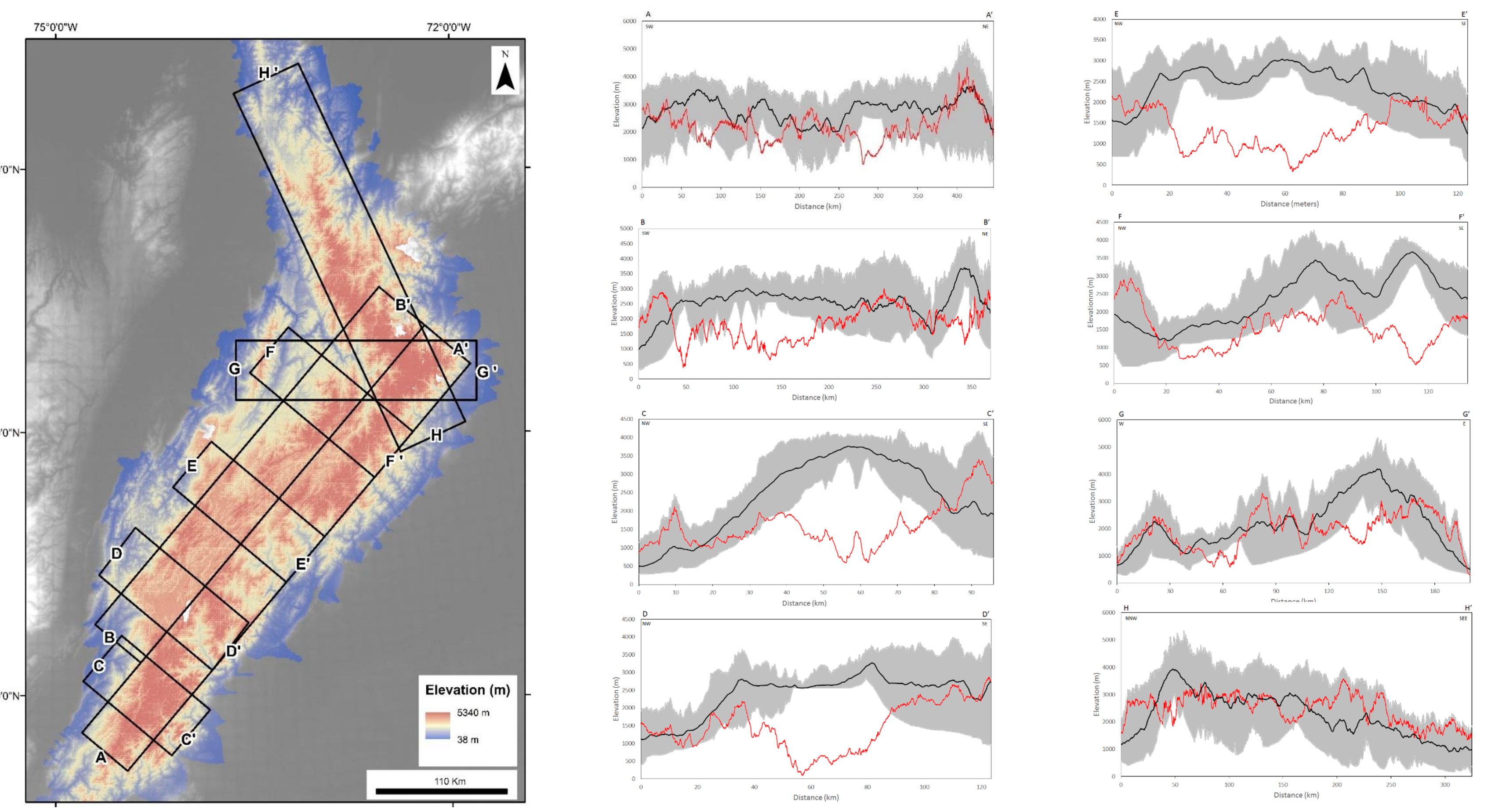

Figure 7. Swath profiles along the Eastern Cordillera. Relief is calculated subtracting the minimum from the maximum.

4. CONCLUSIONS

- The Cocuy Zone of the Eastern Cordillera exhibits advanced uplift and erosional stages. This is the most mature zone based on the lowest values of the hypsometric integral, relief analysis, chi maps drainage divide equilibrium and low anomalous stream density.
- The South Section exhibits intermediate uplift stages with minor drainage divide migration or capture. Moreover, hypsometric integral values, anomalous stream density and relief analysis point towards the same conclusion.
- The Cundinamarca-Boyacá High Plain exhibits major tectonic activity compared to the other zones analyzed. This zone exhibits the highest density of anomalous streams, the most unstable drainage basins divide with considerable differences in the χ proxy, highest value of the hypsometric integral and lowest stream incision values. This analysis suggest advanced uplift and erosional stages.
- The results of this study show there is a temporal and spatial variability in the geomorphological parameters herein analyzed. On this basis, we suggest this variability reflects a more complex uplift history than previously thought.

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