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# Topographic quantitative analysis of the Salado river's basin – Atacama Region – Chile

## *Análise topográfica quantitativa da bacia do rio Salado – Região do Atacama – Chile*

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**Abstract:** Quantitative analysis of topographic-digital data is a fundamental step in structural geomorphological (modern tectonic) and dynamic geomorphological (mass movement) investigations. Initially, there were a limited number of standard algorithms for analyzing topographic data, including the widely used "Stream Profiler". Meanwhile, the digitization of many of the topographic analysis methods democratized access to such algorithms through the development of freely available open-source code. Flexible tools, such as TopoToolBox (TTB) and the Topographic Analysis Kit (TAK). TTB contains few products in its command set, however, it has unique functions that allow complex analysis on a regional scale. Already TAK allows the evaluation of a large amount of data in a short period. The objective of this study is to identify anomalous break points distributed in the drainage network. It is also proposed to investigate the drivers responsible for maintaining the spatial distribution pattern, such as lithological controls and incision pulse propagation. The main result obtained in this study is that there are several continuous and discrete breaks in the longitudinal profiles. Another fact about the spatial distribution of the breaks is that most of them occur in the proximity between tributary confluences and the entrenched valley of the collecting rivers.

**Keywords:** Drainage capture; GIS; morphotectonics.

**Resumo:** A análise quantitativa dos dados topográfico-digitais é um passo fundamental nas investigações geomorfológicas estruturais (tectônicas modernas) e geomorfológicas dinâmicas (movimento de massa). Inicialmente, havia um número limitado de algoritmos padrão para análise de dados topográficos, incluindo o amplamente utilizado "Stream Profiler". A digitalização de muitos dos métodos de análise topográfica democratizou o acesso a tais algoritmos através do desenvolvimento de código aberto livremente disponível. Ferramentas flexíveis, tais como TopoToolBox (TTB) e o Kit de Análise Topográfica (TAK). O TTB contém poucos produtos em seu conjunto de comando, porém, possui funções únicas que permitem análises complexas em uma escala regional. O TAK já permite a avaliação de uma grande quantidade de dados em um curto período. O objetivo deste estudo é identificar pontos de ruptura anômalos distribuídos na rede de drenagem. Também é proposto investigar os condutores responsáveis pela manutenção do padrão de distribuição espacial, tais como controles litológicos e propagação de pulso de incisão. O principal resultado obtido neste estudo é que existem várias quebras contínuas e discretas nos perfis longitudinais. Outro fato sobre a distribuição espacial das quebras é que a maioria delas ocorre na proximidade entre as confluências tributárias e o vale entrincheirado dos rios coletores.

**Palavras-chave:** Captação drenagem; GIS; morfotectônica.

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## 1. Introduction

The topographic analysis tools available in the geographic informational system software along with the high-resolution satellite products have enabled the necessary technological development to carry out studies on the evolution of the relief on a regional scale and with a spatial resolution down to the very detail.

The Chilean geological context, due to its constant eprogenic movement and elevation, represents a distinct landscape that generates potential energy for the emergence of tectonic structures controlling the fluvial outline. This kind of landscape is characteristic and propitious to the occurrence of fluvial captures (BINNIE et al., 2020).

Fluvial captures occur when a captured channel is deflected to a captor channel, which represents a bigger erosive potential (SORDI et al., 2022; WU et al., 2022).

The captor channel, generally, has bigger slopes and, along with the soil characteristics and the precipitations that may occur in the place, the captor channels can expand their draining areas. This phenomenon of drainage capture in some landscapes is associated with the active tectonic and the lifting of blocks that act as controllers of the drainage network (PASTOR, 2013; RODRIGUES et al., 2022).

Another morphometric aspect associated with the capture phenomena is the erosion, or more precisely the potential energy of the channels. The difference between the incision speed of the channels is directly connected to the capture process. The incision rate is linked to the terrain's lifting rate. Thus, higher lifting rates represent bigger rates of fluvial incisions (CHRISTOFOLETTI, 1981; OLIVEIRA, 2010; MARTOS and ROURE, 2019).

This study's goal is to investigate the spatial distribution pattern of the knickpoints and the topographical metrics (for instance, Ksn, slope and topographic range) at the basin of the Salado River in the Atacama Desert region, in the Central Andes. All these attributes were extracted using the analysis tools existing in the TTB and TAK programs. The goal is to apply the Chi method to quantify the Ksn (inclination of the normalized channel's index), identify the knickpoints using KickpointFinder algorithm, and perform topographic metrics extraction (FORTE and WHIPPLE, 2019).

The Salado River basin was selected because occurrence of mass movement, and especially because of its fault lines that cross the river's channels, shaping the morphological aspects of that basin's valleys. Atacama's fault line system is highlighted by north-south traces and secondary faults in the northeast (Cerro Salado fault) direction between the Chañaral and Diego de Almagro municipalities, where Jurassic (La Negra Formation) and Cretaceous (Llanta Formation) formations can be observed in the east.

## 2. Methodology

### 2.1 Study area

The Salado river's basin is in the northern sector of the Atacama region and covers a 7.400km2 long area. The basin's geology incorporates a great amount of non-consolidated deposits where the incisive valleys are located, as well as the rocky formations of the Paleozoic and Cenozoic ages. The lithology, in general, is divided between intrusive and stratified rocks (sedimentary and volcano-sedimentary) (CORNEJO et al., 1998a; CORNEJO et al., 1998b; GODOY and LARA, 2005).

Along the Salado River, fault lines cross the river's channels, shaping the morphological aspects of that zone's valleys. The Atacama's fault line system is highlighted by north-south traces and secondary faults in the northeast (Cerro Salado fault) direction between the Chañaral and Diego de Almagro municipalities, where an overlap of blocks can be seen to the east of the Jurassic (La Negra Formation) e Cretaceous (Llanta Formation) formations is observed (Figure 1).

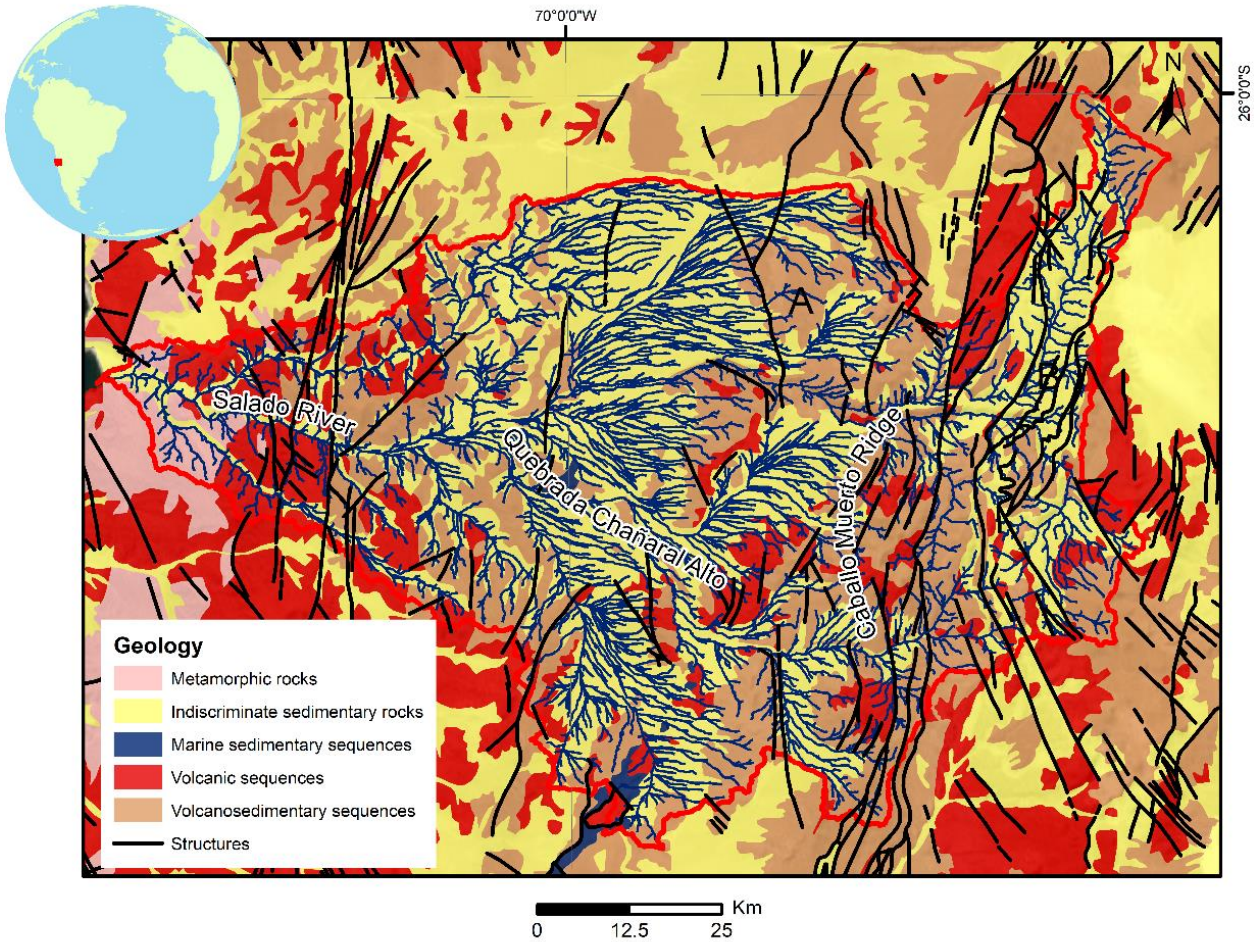


*Figure 1 – Location of the study area: The Salado river's basin is in the northern sector of the Atacama region, Chile. Source: Authors (2023).*

The quaternary formations include wind and thin sand deposits; colluvial deposits of monomictic composition located on the hillside; alluvial deposits composed of gravel, sand, and silt with varied granulometry associated to waste flows (GODOY et al., 2011); and recent saline deposits of the Pedernales Salar composed by silt and halitas (TOMLINSON et al., 1999). The anthropic deposits (Holocene) are associated with the mining waste extracted from the El Salvador mining facility (CORNEJO et al. 1998).

The present geomorphologic units are the Coastal Cordillera with the coastal platform, the Longitudinal Valley, the Pre-Cordillera, the salar's Depression, and the Andes Cordillera. Also, being located at the orogenic andine of active tectonic system, there are active volcanos in the high Andes Cordillera, of the stratovolcanic type, and great plains of extrusive material (LORCA, 2016). The altitude increases from the Fluvial Plains towards the Domeyko Cordillera, going gradually up until the Ondulada Pampa. The Coast's Cordillera usually does not surpass 1.500 m, and the Domeyko Cordillera reaches 3.000 m, where the riverbeds are oriented in the north-south direction, mainly due to the influence of the faults.

The predominant soils in the areas where the human settlements are located, in the Chañaral and Diego de Almagro municipalities, are the calcareous yermosols and the ochric cambisols, respectively. In the proximities of the Pedernales Salar predominate the fluviosols (GOMES, 2016).

### 2.2 Normalized Declivity Index (Ksn)

To extract metrics of the relief, a Digital Elevation Model (DEM) derived from the Alaska Satellite Facility - (ALOS PALSAR) spatial resolution of 12,5 meters was utilized. While the digital topography presents an inherent noise, a CRS algorithm was utilized to remove depressions and spurious thresholds in the longitudinal profiles. Based on that, the Normalized Declivity Index (Ksn) was calculated by the Chi (χ) or integral method, developed by Perron and Royden (2013), for the drainage network. Rivers in a state of balance are expected to present χ profiles versus elevation in a straight line, meanwhile, transient profiles present inflections in this relation. Those inflections can be associated with spatial alterations in the incision rates, differential uplift, base level drop signal propagation, and the control of the structures and lithology associated with the geological settings, for instance. Therefore, it can be defined:

$$z(x) = z(\chi_b) + \left(\frac{U}{K{A_0}^m}\right)^{\frac{1}{n}} \chi$$

In which χ:

$$\chi = \int_{x_b}^{x} \left(\frac{A_0}{A(x)}\right)^{\frac{m}{n}} dx$$

In the equation above z(x) represents the elevation according to the distance, z(xb) symbolizes the elevation of the basin's exutory, A(x) is the drainage area according to the distance, and dx defines the fixed gap in which the mentioned variables are registered (BELAYNEH, et al., 2022; KUBWIMANA et al., 2021; MICCADEI, et al., 2021; MARRUCCI et al., 2018). As can be noticed, the variable of interest (Ksn) is defined by the declivity of the stretch of the bivariate relationship between the χ and z(x) variable. To standardize the measures and render them comparable to other studies, a reference concavity (θref) of 0.45 was defined, a value frequently utilized in geomorphologic studies of rocky riverbeds that drain mountainous regions (e.g.,). Additionally, knickpoints were mapped through the KnickpointFinder algorithm with a vertical tolerance of 100 meters defined by the profile correction via CRS, in addition to the inclination angle of the slopes and the topographic range. All the analyses were processed with the aid of the TopoToolbox software and the Topographic Analysis Toolkit.

## 3. Results

On the Salado River basin, 37 knickpoints were mapped, with a vertical tolerance of 100 meters. The majority of the knickpoints are located over the high course of the main channel, between the geomorphologic provinces of the Prealtiplanic Cordillera and the Central Depression. However, another nucleus of knickpoints occurs on the Salado river's biggest tributary, in the High Chañaral Valley, which represents 8% of the total (n = 3), and in the Prealtiplanic Cordillera. Only one knickpoint occurs in the Coastal Cordillera, in contact between basalt and continental sedimentary sequences, upwind of the Atacama fault system, which is the main tectonic feature of this sector (Brown et al., 1993). Over 32% (n = 12) of the ruptures are over sedimentary sequences, 22% (n = 8) over volcanic areas, and 46% (n = 17) are over volcano-sedimentary sequences. (Figure 2 and 3).

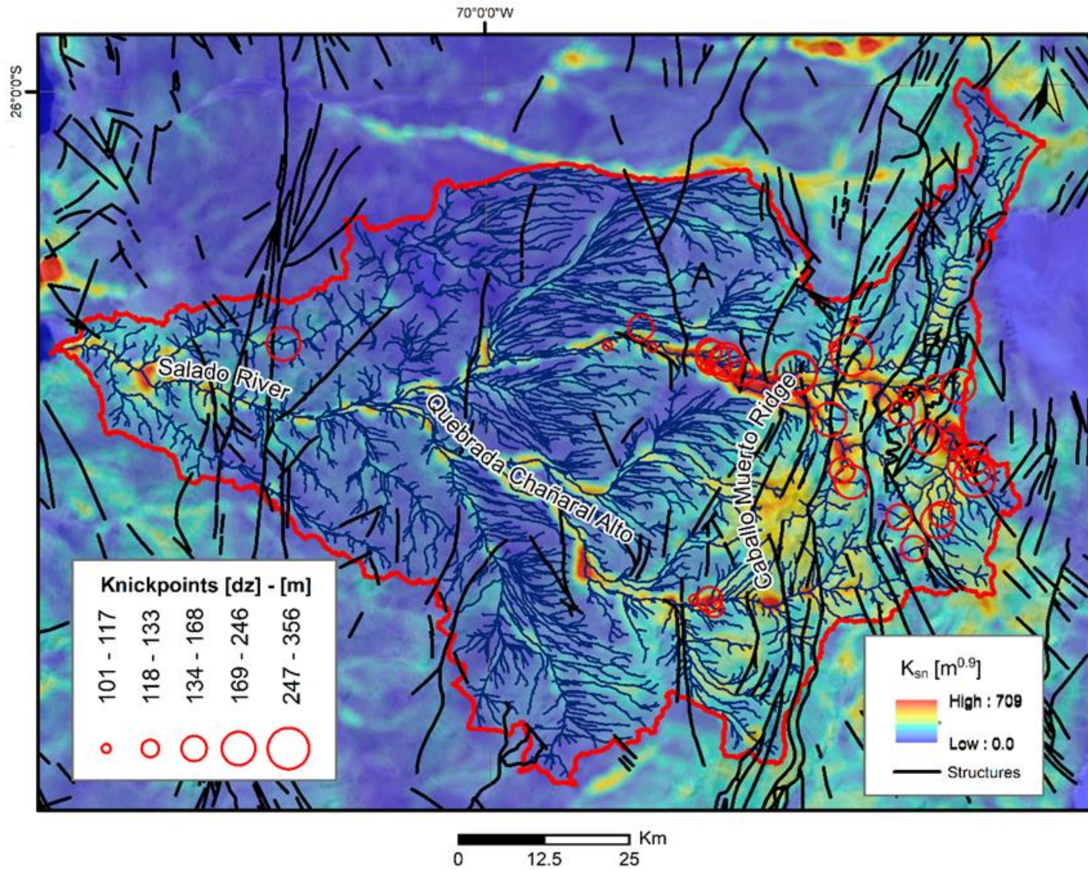


*Figure 2 – Ksn's spatialization and basin's knickpoints.*
*Source: Authors (2023).*

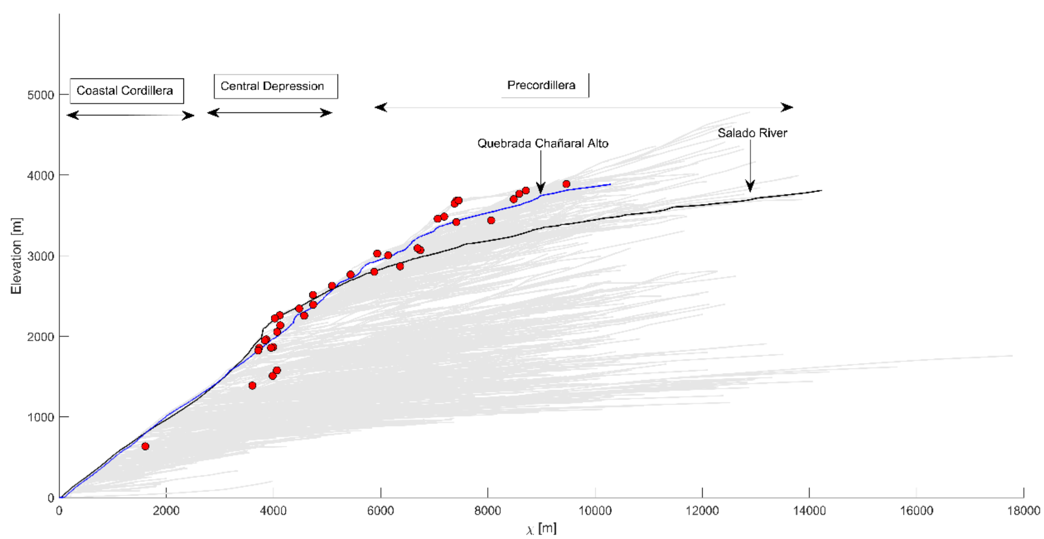


*Figure 3 – The χ-z profiles with emphasis on the main profile of the Salado River and the High Chañaral Valley.*
*Source: Authors (2023).*

The most resistant rocks to the erosive processes of the volcano-sedimentary sequences, such as rhyolite, andesite, breccia, and trachyte rocks encompass the biggest knickpoint concentration. For example, if we add the number of knickpoints over volcano-sedimentary and volcanic rocks we have 68% (n = 25) of the total mapped, however, the lithologic control is not a first-order constraint in that landscape, since there is an active uplift that affects all the regional topography, and, consequently, the longitudinal profiles. In comparison, fewer knickpoints were mapped over sedimentary sequences, represented by silt, sand, and gravel. Analyzing the rupture magnitude (dz) parameter of the knickpoints, the volcanic sequences, such as granite, diorite, and tonalite were verified to possess a higher average dz, with 174 meters. The volcano-sedimentary and sedimentary sequences possess relatively lower dz, with 145 and 142 meters, respectively (Figure 4).

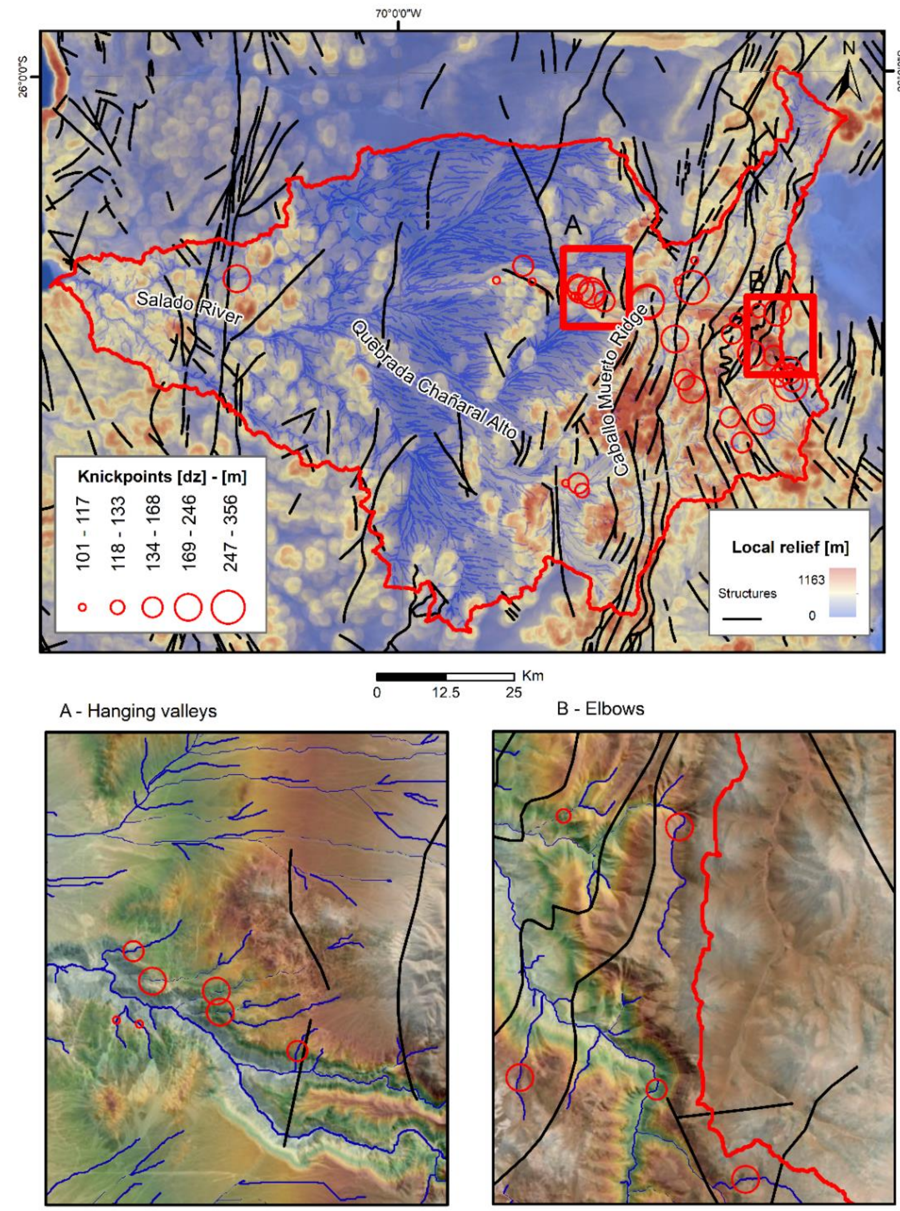


*Figure 4 – Topographic amplitude with a 1 km ray in the Salado river's basin. The presence of valleys and elbows hanging at the headwater is highlighted.*
*Source: Authors (2023).*

The segments of drainage plans regulated by local fractures typically have minor knickpoints and the traces of normal faults (Figure 5a-b). On the other hand, it is evident that the knickpoints in the area's east and west are situated on potential seismic faults with undetermined kinematics.

The data analysis and correlation demonstrate that the neotectonic regime controls the bulk of knickpoints in the Salado River basin. Any analysis of the evolution of a landscape should still consider other morphostructural analysis techniques, such as the symmetry of watersheds and other relief anomalies.


*Figure 5 – Big fall in west (a) 422485.05mE/7088312.43mS and big fall in east (b) 370143.76mE/7087432.87mS. Source: Authors (2023).*

### 3.1 Discussions

The average elevation of the mapped knickpoint was 2.636 meters and the median was 2.640 meters, above the basin's elevation average, 1.940 meters. The elevation's standard deviation was 826 meters. The analyses of $\chi$ versus elevation profile presented an ungrouped knickpoint pattern which indicates controls over the erosive efficiency and drainage reorganization process. These processes are part of the set of the hydrographic basin's autogenic dynamics, described by Gallen et al. (2018), and Scheingross et al. (2020). This also suggests that the knickpoints are not connected to a single morphogenetic process. Such interpretation is also supported by the elevation's dispersion of the ruptures. The internal contrast between the $\chi$ values of the sub-basins also suggests processes of rearrangement of the drainage net. Especially at the Prealtiplanic Cordillera, a great number of drainage anomalies, such as elbows and lowered drainage divisors are observed, which indicates that fluvial piracy is a fundamental process of the basin's internal dynamic (BISHOP, 1995).

The contrasting values of $\chi$ values among headwaters denote contrasting erosion rates that may deflagrate processes of capture and rearrangement of the hydrographic net. Higher $\chi$ values indicate lesser erosive potential, as well as lower values, indicate high erosion rates. In many passages, there is a contrast between the $\chi$ values amid the affluent's headwaters of the tributaries of the Salado river and the headwaters of the High Chañaral Valley. The $\chi$-z profiles present expressive convexities and a transition between the Coastal Cordillera and the Central Depression alongside the Prealtiplanic

Cordillera. The rate with which the channel's declivity reduces, with the basin's drainage area known as the basin's concavity index, was 0,35, inferior to the adopted as a reference, 0.45. The fluvial incision rates were also investigated by the spatialization of the declivity normalized index (Ksn). The average Ksn values reach 67 m0,9 and the maximum were 700 m0,9. The standard deviation of that metric was 40 m0,9. The biggest values are concentrated in the higher hierarchy valleys. On the high course, at the Prealtiplanic Cordillera, the values reach 353 m0,9 and on the surfaces with soft reliefs the values are 13 and 20 m0,9. Many knickpoints mark the contact between the transition of incisive valleys and conservated surfaces, with lower levels of the vertical incision.

A clear relation between the higher Ksn values and the altimetric amplitude, with a 1 km ray, was not observed, especially in the region of the Caballo Morto Sierra. The biggest values are concentrated west, at the Prealtiplanic Cordillera, and reach over 1 km of amplitude. At the Central Depression, the values are reduced to 100 m and when they come close to the coastline they increase once more, on the Coastal Cordillera, with 300 and 600 meters of amplitude. Both regions with higher altimetric amplitude are perpendicularly cut by fault systems mostly north-south oriented, and the drainage net with east-west preferential direction. Some rivers, which mark clear inflections in the drainage flow, oriented towards the north-south direction and flowing into east-west valleys, like the High Chañaral Valley's headwaters, may have been captured.

Another fact concerning the spatial distribution of the ruptures is that most of them occur between the proximity of confluences and the entrenched valley of the collector rivers. While the Salado River drainage area is 7.557 km² wide, the rupture's upstream average area is only 54 km² wide. Since many of them occur in confluences, that suggests that they follow a suspended valley pattern, especially along the Salado river's canyon. These features are responsible for maintaining a low altimetric amplitude surface conserved above the ruptures, and soft slope or a relict landscape, whose geomorphologic expression demonstrates conditions that precede the higher grade and intensity fluvial incision. Along the Salado river's canyon, suspended valleys present unevenness that surpasses 400 meters, with few signs of remontant migrations. Hanging valleys were also mapped by Gasparini and Whipple (2014) in the Bolivian Andes and were associated with the presence of recent and sudden regional uplift of an erosion surface.

Paleogeographic studies of the Salado River basin (NALPAS et al., 2008) demonstrate that the fluvial reorganization process, with abandonment and filling of valleys, is a process that constitutes the internal dynamic of that system and dates to the Oligocene-Miocene. Adds to this the paleoclimatic changes that alter the hydrological functioning of the fluvial systems and the transportation of the sediments, and fundamentally the orogen's tectonic regime. The excavation grade of the andine piedmont valleys inside alluvial fans (ALVES et al., 2021) may be associated with the active uplift and with drainage reorganization processes. With basins gaining drainage areas, becomes possible to increment the fluvial incision, alter the sediment flow, and disengage other captures (GIACHETTA and WILLET, 2018). Special attention must be prior to the west divisor of the Salado River basin at the Prealtiplanic Cordillera. Those internal controls may, inclusively, exert influence over waste flows that are frequent at the basin.

## 4. Conclusions

The morphometrical analysis of the drainage net of the Salado River basin allowed us to verify that there are several continuous and discrete ruptures at the longitudinal profiles. Since the landscape possesses active uplifting, the lithological control at the nucleation of those ruptures is secondary, nevertheless, a correspondence between the magnitude of the ruptures and the volcanic and volcano-sedimentary sequences is observed. The knickpoints do not possess the same origin. Therefore, two main nucleation processes were verified: areal contrast between tributary and rivers and collector channels, forming suspended valleys and suggestive drainage captures.

The presence of elbows and lowered divisors, which are geomorphologic indicators of drainage net reorganization processes, were observed. Previous studies report that those are long-term processes in the Salado river's basin, especially over the Central Depression. The combination of those processes to the nucleation of the knickpoints maintains a low contribution area upward of the ruptures. The higher Ksn values are in the main valleys, especially along the Salado river's canyon. The topographic amplitude also distributes systematically according to the geomorphologic compartments of the basin. The application of the digital topography using modern analysis tools showed itself as a facilitator to enlarge the extension of the analyzed area in less time, in addition, to refine the values and to allow the reproducibility of the results.

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