Morphometric Evaluation of the Relative Uplift Rates along the Vigan-Aggao Fault in Ilocos Norte, Philippines

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Abstract The Vigan-Aggao Fault (VAF) in northern Luzon Island is a NNE-trending sinistral fault divided by fault bends, which are associated with local variations in the fault’s kinematics. In this study, we examined the relative uplift rates across the fault bend in the San Juan–Vintar segment of the VAF using morphometric indices. Basin-based indices, namely hypsometric integral, basin shape, basin elongation ratio, and basin asymmetry factor, and non-basin-based indices, namely stream length-gradient index, normalized stream length-gradient index, and mountain front sinuosity were calculated to isolate and examine the surface processes that influence landscape development. We then integrated the basin-based results with geological data to create a relative tectonic activity index (RTAI). Clustering analysis of the results revealed hotspots along the bent section of the fault indicating more values that suggest higher relative uplift rates during the development of the landscape. The morphometric indices showed that the highest uplift rates are along the central VAF strands. This study describes and evaluates the relative uplift rates of a known active fault system in Ilocos Norte, in the absence of detailed field structural data. This study also reinforces the utility of morphometry in identifying priority sites for detailed paleoseismic and seismic hazard analyses.

Non-technical summary Morphometric indices are ratios of topographic parameters that can describe the shape of a landscape, providing information regarding its formation and development. When used along faults, they can be used to gauge how fast the region is being uplifted or deformed. The Vigan–Aggao Fault (VAF) is a NNE-trending fault marked with bends that usually cause differences in the type of movement along the fault. We examined the relative uplift rates along one bent trace of the San Juan–Vintar segment of the VAF using various morphometric indices. The morphometric indices showed that values indicating higher uplift rates were located at the bent area of the fault. Additionally, most of the higher uplift rates were concentrated along the central VAF strand. In this study, we used a new approach to describe and evaluate the relative uplift rates of a known active fault system with limited field structural data.

1 Introduction

Tectonic forces often leave imprints on the landscape making it suitable for morphometric analysis. Landforms associated with surface deformation, such as folds, fault scarps, and offset streams, are among the most common markers of a tectonically active area. Continual deformation can locally rejuvenate a landscape and can lead to steeper slope gradients and deeply incised valleys (Whipple and Tucker, 1999). When deformation is recent (i.e. at least Quaternary), analyzing multiple morphometric indices can be effective in determining the influence of tectonics in an area (i.e. Bull and McFadden, 1977; Chen et al., 2003; Dehbozorgi et al., 2010; El Hamdouni et al., 2008; Krystopowicz et al., 2020; Li, 2004; Mulyasari et al., 2017; Rimando and Schoenbohm, 2020; Rockwell et al., 1985). A morphometric index is, in its essence, the relationship between two dimensions of a landscape. The index can be used as a metric for analyzing internal and surficial processes that influence landscape development. Using a multi-index approach enables us to recognize morphological attributes and relationships that reflect the effects of tectonic processes. The study by El Hamdouni et al. (2008) attempted to express the analyses of multiple morphometric indices in Sierra Nevada, Spain into a single index of relative active tectonics (Iat). The Iat was made by combining the results of multiple morphometric indices as well as geological information such as the erosional resistance. The values of the individual morphometric indices were classified following the general breaks in values that were obtained in the region. This classification scheme for morphometric indices is general enough to be used in other study areas. Dehbozorgi et al. (2010) evaluated the Iat of the Zagros fold and thrust belt in northern Iraq using the approach of El Hamdouni et al. (2008) and demonstrated that the methodology was also applicable to oblique strike-slip faults. Since then, their methodology has been adapted by multiple authors to suit their studies of active tectonics (e.g., Das et al., 2019; Mulyasari et al.,...
Figure 1  Tectonic setting of the Philippine archipelagos and Ilocos Norte. (a) Map showing the Philippines and its tectonic features. Trenches are represented by saw-toothed lines and labeled. Active faults are represented by the red lines. The extent of 1B is shown by the black rectangle. Black arrows show the relative plate motion; labels of the black arrow indicate the rate of motion (Bird, 2003). The plates are labeled SP for the Sunda Plate, PMB for the Philippine Mobile Belt, and PSP for the Philippine Sea Plate. (b) Map of northwestern Luzon mainland showing the active fault traces of the northern Philippine Fault Zone (i.e. West Ilocos Fault System). The purple lines in B represent the faults belonging to the Vigan–Aggao Fault as described by Rimando and Rimando (2020), while the yellow highlighted region is the municipal boundary of Badoc, Ilocos Norte. The extent of Fig. 2 is shown by the black rectangle. Base maps for both A and B were sourced from ESRI, which used data from GEBCO, NOAA, National Geographic, NCEI, and Natural Earth. Traces of faults and trenches were modified from the map of the Philippine Institute of Volcanology and Seismology (2016) and Rimando and Rimando (2020).

2017; Saber et al., 2018). More recently, Saber et al. (2020) used both the Analytic Hierarchy Process (AHP) and the Iat method to evaluate the active tectonics of the Aras drainage basin in the Turkish-Iranian plateau. The AHP is a method for complex decision-making that utilizes an eigenvalue approach to make pairwise comparisons (Saaty, 1980; Sipahi and Timor, 2010; Tavana et al., 2023; Vaidya and Kumar, 2006). Their study found that the AHP was more consistent with the GPS data in the region than the use of Iat. The study further suggests that the addition of a statistical approach can improve the accuracy of the results of morphometric analyses. Studies involving morphometric indices would be useful in an actively deforming area such as the Philippines. The country is host to numerous fault systems that are too extensive to study in detail if surveyed using traditional field methods. A multi-index approach could therefore prove useful in isolating the effects of tectonics in a landscape that is also actively developed by hillslope processes.

The assessment of the characteristics and behavior of active faults is important, especially in tectonically active regions such as the Philippine archipelago. The fault systems in the country are mostly oblique strike-slip faults belonging to the Philippine Fault Zone (PFZ) (Fig. 1) (Aurelio, 2000b; Barrier et al., 1991; Tsutsumi and Perez, 2013). The PFZ is composed of multiple fault segments and spans over 1200 km from the northern island of Luzon in the Philippines (e.g., Rimando and Rimando, 2020) to the southern island of Mindanao (e.g., Marfito et al., 2022; Perez and Tsutsumi, 2017) (Fig. 1a). Previous authors suggest that the faults were a result of the stress from oblique convergence between the Philippine Sea Plate and the Philippine Mobile Belt accommodated through shear partitioning (Aurelio, 2000a; Fitch, 1972). Currently, the prevailing theory regarding the nature of these faults is that the westward compressional stress brought about by the northwesterly convergence of the Philippine Sea Plate and the Sunda Plate is being accommodated by subduction to the east as well as by the PFZ through complex shear partitioning (Rimando et al., 2020). Segments of the PFZ, particularly in northern Luzon, have generated destructive earthquakes in the past. The Mw 7.7 1990 Luzon Earthquake killed 2,412 people and caused USD 369 million of damage to properties and infrastructure (Punongbayan et al., 1992; Nakata et al., 1990, 1996). Another surface rupturing event in the northern PFZ was the 1983 Laog Earthquake, which killed 17 people and injured 80 people in the city of Laog. Damage to structures was also extensive, especially along floodplains and reclaimed stream channels (Santiago and Rillon, 1983; Valenzuela and Garcia, 1983). The epicenter of the 1983 event was near the trace of the Vigan–Aggao Fault (VAF), one of the splays of the PFZ in northwest Luzon. A more recent damaging earthquake occurred in 2022 and affected Vigan, a heritage city in the southern province of Ilocos Sur. The earthquake was attributed to the movement of another fault to the east of the VAF called the Abra River fault (Perez et al., 2023; Rimando et al., 2022). Such
events demonstrate both the frequency and seismic risk of earthquakes in the Ilocos Region.

The VAF is a NNE-trending oblique sinistral strike-slip fault in the greater region of Ilocos. It is approximately 140 km long and stretches from the city of Vigan in the south to the municipality of Aggao in the north. Previous studies have observed localized bending and stepping of the fault traces (Pinet and Stephan, 1990; Rimando and Rimando, 2020; Ringenbach et al., 1993). One such bend is located at the San Juan–Vintar segment near the municipality of Badoc in Ilocos Norte. The right-stepping nature of the sinistral fault resulted in the formation of a restraining bend, which causes localized shortening in the area. The localized shortening resulted in steeper and more prominent ridges inside such areas (Rimando and Rimando, 2020). Due to the fault’s recent activity and complex geometry, we utilize morphometric indices to deduce variability in tectonic deformation along its traces. We have chosen the area at Badoc where the San Juan–Vintar segment of the fault starts to bend from NNE towards the south to NE towards the north.

In this study, we aim to establish the relative uplift rate along the bent section of the San Juan–Vintar segment. We calculated four basin-based namely hypsometric integral ($HI$), basin shape ($BS$), basin elongation ratio ($R_e$), and basin asymmetry factor ($Af$), and two non-basin-based indices, namely stream length-gradient index ($SL$) and mountain front sinuosity ($S_m$), from Interferometric Synthetic Aperture Radar Digital Elevation Model (IFSAR DEM) data (5 m resolution). Calculation of the indices was performed using spatial analyst tools in ArcMap. The results of the $HI$, $BS$, and $R_e$ were then integrated with geological information to create a relative tectonic activity index (RTAI) map, which allowed us to infer relative uplift (i.e. higher or lower rates of vertical deformation) along the fault. This geomorphological and morphometric approach demonstrates the usefulness of DEM-based terrain analysis in evaluating the activity of faults at a regional scale and in areas with limited structural information. Moreover, this study also provides insights into areas with a higher seismic hazard potential (i.e. higher uplift rate) and can assist in prioritizing areas for future detailed work.

2 Study Area

The municipality of Badoc and its vicinities are bounded by the Manila Trench to the west and the West Ilocos Fault System to the east. The Manila Trench marks the convergent boundary where the Sunda Plate subducts eastward beneath the Philippine Mobile Belt while the West Ilocos Fault System is a series of primarily sinistral strike-slip faults splaying from the Philippine Fault Zone (Fig. 1) (Pinet and Stephan, 1990; Ringenbach et al., 1993). The Vigan–Aggao Fault (VAF) is a NE-trending active fault located in the northwestern area of Luzon island and forms a major part of the West Ilocos Fault System (Fig. 1b). The recent activity of the fault is due to the westward propagation of the strike-slip activity of the Philippine Fault Zone during the Middle Miocene (Pinet and Stephan, 1990). Previously, the VAF was thought to have originally been a normal or transtensional tectonic feature that was bounding an ultradeformal suite and a sedimentary basin to the west. The VAF was then reactivated as a strike-slip fault during the Pliocene to Quaternary (Pinet and Stephan, 1990). Ringenbach et al. (1993) also noted that the thrust component of the VAF increases northward. A more recent study by Rimando and Rimando (2020), however, described the VAF as a primarily strike-slip fault with localized zones of extension and compression at fault bends. Their study made use of vertical-to-horizontal displacement (V/H) ratios along piercing points of offset features, such as offset streams and spurs. The segments outside of the fault bend and stepover zones showed consistent sinistral motion. On the other hand, the bends/stepovers along NE-trending sections of the VAF showed high (> 1) V/H ratios, indicative of a localized dip-slip regime. This observation is consistent with the historical seismicity of the area (Fig. 2), wherein the two GCMT focal mechanism solutions show the main thrust nature of earthquakes near the fault trace (Dziewonski et al., 1981; Ekström et al., 2012). Since the areas with high dip-slip components are only localized, it may be that the dip-slip component along the VAF may have been previously overestimated. This would mean that the compressive stress from the northwest convergence of the Philippine Sea Plate against the Sunda Plate is being accommodated not only by strike-slip motion along the VAF but possibly also by thrust/reverse faulting on other nearby structures (Rimando and Rimando, 2020).
Figure 3  Photographs and images of the different geomorphic features in the study area (see Fig. 2 for locations). (a) Coastal plain at Currimao, Ilocos Norte. (b) Uplifted marine terrace at Currimao, Ilocos Norte. (c) Sand dunes at Culili Point, north of Currimao. (d) View of the coastal plain, low land hills, and high lands at Cabugao, Ilocos Sur. (e) Pressure ridges with offset triangular facets in Batac, Ilocos Norte. Triangular facets are outlined with white dashed lines. (f) Highlands as viewed from Banna, Ilocos Norte. (g) Google Earth image (Landsat/Copernicus) of offset streams and spurs along a section of the VAF in Badoc. The yellow lines mark the apex of the ridges while the red line is the trace of the VAF on the surface. The blue arrows are offset streams with the arrowhead pointing downstream. The displacement of these features demonstrates the dominantly sinistral motion of the fault, modified from Rimando and Rimando (2020).

Rimando and Rimando (2020) also divided the VAF into multiple segments based on its structure, geology, and geometry. One of the segments defined by the study was the San Juan–Vintar Segment, which was characterized by the presence of a major NE-trending bend at the municipality of Badoc and continuing southward in a NNE trend. The fault is marked by pressure ridges with elevations ranging from about 100 to 400 m (Fig. 3c, 3g). Morphotectonic features such as pressure ridges, offset spurs and streams, and linear valleys and ridges among others were also observed, which can aid in interpreting the results of the morphometric analysis (Rimando and Rimando, 2020; Ringenbach et al., 1993). There are also uplifted marine terraces and other coastal landforms (e.g., beach ridges, dunes) that further imply regional coastal uplift (Fig. 3a-d) (Maeda et al., 2004;
Maxwell et al., 2018; Shen et al., 2010). Residual hills from bedrock erosion also outcrop on the alluvial plain, which can suggest a period of tectonic dormancy when erosional processes dominated. A portion of the Paoay Sand Dunes can also be observed to the north of the study area.

In addition to the VAF, the Mines and Geosciences Bureau (1983) reported a normal fault that separates the Ilocos Peridotite from the Laaog Formation to the southeast. This normal fault forms part of the West Ilocos Fault System and seems to connect with the Abra River Fault (ARF) segments to the southwest (Philippine Institute of Volcanology and Seismology, 2016; Ringenbach et al., 1990).

Several sedimentary formations, as well as an igneous unit, are exposed in the study area (Fig. 4). Most of the study area is underlain by clastic sedimentary rocks of the Late Eocene to Late Oligocene Bangui Formation (Fig. 5a), Middle to Late Miocene Batac Formation (Fig. 5d), and Early Pliocene to Pleistocene Laaog Formation (Fig. 5B) (Mines and Geosciences Bureau, 2010). The Bangui Formation is exposed in the eastern lowland hills and is composed of clastic sedimentary rocks including olistostromes (Pinet, 1990; Pinet and Stephan, 1990; Mines and Geosciences Bureau, 2010). Sandstones and shales of the Batac Formation outcrop at the central highlands and are traversed by the VAF (Pinet, 1990; Mines and Geosciences Bureau, 2010). In the western lowland hills, the Laaog Formation is composed of interbedded sandstones and mudstones with some bioclastic limestones of Early Pliocene to Pleistocene age (Pinet, 1990; Mines and Geosciences Bureau, 2010). A few limestone formations, belonging to the Late Miocene Pasuquin Limestone (Fig. 5c) and the Late Pleistocene Uplifted Coral Reefs (Fig. 5a), also occur within the study area. The older Pasuquin Limestone is exposed in the northeastern highland mountains near the VAF traces (Mines and Geosciences Bureau, 2010). The formation is composed mostly of bedded bioclastic limestones with a basal conglomerate unit. The more recent uplifted coral reefs are composed mostly of coralline limestone with some portions composed of calcirudite (Mines and Geosciences Bureau, 2010; Smith, 1907). Recent studies on these emergent coastal geomorphic features report a Late Pleistocene to Holocene age (Maeda et al., 2004; Maxwell et al., 2018; Berdin et al., 2004; Ramos et al., 2017). Towards the southeast is a vast mountainous area where the Cretaceous Ilocos Peridotite is exposed and in normal fault contact with the Bangui Formation (Fig. 5f). This igneous unit is composed of mostly serpentinitized peridotite with some lenses of gabbros (Pinet and Stephan, 1990).

The higher-order streams in the study area include the Sinait River, Badoc River, Apait River, Gang River, Quiato River, and Magalis Creek that drain to the West Philippine Sea (Fig. 2). In terms of climate, the area experiences a pronounced dry season from November to April and a wet season from May to October (Flores and Balagot, 1969).

3 Data and Methods

Morphometric indices were calculated using the IFSAR DEM (5 m horizontal resolution and 1 m vertical resolution) data obtained from the National Mapping and Resource Information Authority (NAMRIA) (2013). It should be noted that the use of DEMs with high horizontal and vertical resolution leads to an increase in processing time, more specifically when calculating the flow accumulation raster. Streams and drainage basins were first extracted using the geographic information system (GIS) software ArcMap 10.8. Pre-processing using the fill tool was performed on the DEM to remove errors in the data such as sinks. The flow direction and flow accumulation tools were used to determine the hydrological characteristics of the study area. Flow accumulation results were then reclassified using a channel formation threshold value of 5000, which is suitable for a large-scale map (1:0–1:600,000) (Cooley, 2015). The stream link tool was then used to obtain pour points, which were then input into the watershed tool to generate sub-basins at every confluence of two same-ordered streams. This method of generating sub-basins was preferred to systematically study the extent and effects of the fault movement. Sub-basins were calculated for the major drainage basins transected by the fault strands. In addition, the sub-basins west of the fault traces that are underlain by alluvium were excluded from the analysis because of their distance from the VAF. Sub-basins that appeared to be processing artifacts (i.e. undefined geometry) were also excluded. A few sub-basins to the east of the VAF that were underlain by alluvium were included in the analysis because of their proximity to both the VAF and the normal fault (Fig. 6). Streams were extracted from the resultant flow accumulation using the con (conditional), stream order, and stream to raster tools in ArcMap. Stream orders were classified based on the method of Strahler (1957), where all streams without tributaries are designated as first-order and the or-
Photographs of the different geologic units in the study area. (a) Cemented corals and coral fragments comprise the uplifted coral reef in Currimao, Ilocos Norte. (b) Siltstone and mudstone of the Laoag Formation exposed in Currimao, Ilocos Norte. (c) Recrystallized coraline limestone belonging to the Pasuquin Limestone in Pasuquin, Ilocos Norte. (d) Interbedded sandstone and mudstone of the Batac Formation in Batac, Ilocos Norte. (e) Sandstone interbeds of the Bangui Formation in Bangui, Ilocos Norte. (f) Serpentinized peridotite (i.e. Ilocos Peridotite) exposed in Pasuquin, Ilocos Norte.

Map of sub-basins analyzed as well as their respective flow directions. A total of 2,391 sub-basins were delineated using the Hydrology tools in ArcMap following the method of Cooley (2015). The color of the sub-basins represents the general stream flow direction.

Drainage basin-based geomorphic indices such as hypsometric integral ($HI$), basin shape ($Bs$), basin elongation ratio ($Re$), and asymmetry factor ($Af$) were computed for the delineated sub-basins (Fig. 7). These indices were selected due to their sensitivity to the dip-slip component of fault movement and can allow for the examination of relative tectonic activity along the fault traces (e.g., Gao et al., 2017; Miccadei et al., 2021). The value of the $HI$ describes the distribution of areas per elevation, with higher values suggesting that areas with higher elevations have not been substantially eroded and may correspond to a younger landscape. Both $Bs$ and $Re$ measure the elongation of a basin, which can be associated with the basin’s maturity. Younger basins tend to be more elongated because energy is mostly directed to the main stream, which leads to more downcutting. Through time, the downcutting subsides and allows for the widening of the basin, which will even-
Figure 7 Diagrams of the different morphometric indices used in the study. (a) The calculation of the hypsometric integral ($HI$) employs the elevation relief ratio method of Pike and Wilson (1971), which estimates $HI$ to be the ratio between the difference of the mean elevation and the minimum elevation, and the range of all the elevation values in a basin. (b) Basins shape index ($Bs$) is the ratio of the longest axis of the basin and its width perpendicular to the longest axis (Cannon, 1976; Ramirez-Herrera, 1998). (c) Basin elongation ratio ($Re$) is the ratio between the diameter of the circle with the same area as the basin and the longest segment of the basin (Schumm, 1956). (d) Basin asymmetry factor ($Af$) is the ratio of the area to the right of the main river ($Ar$) and the total area of the basin (Hare and Gardner, 1985; Keller and Pinter, 2002). (e) Stream length-gradient index ($SL$) is the ratio of the change in height and the distance between two points multiplied by the distance from the drainage divide to the midpoint between the two points (Hack, 1973). (f) Mountain front sinuosity ($Sm_f$) is the ratio between the sinuous length of the mountain front and its straight length (Bull and McFadden, 1977).
ologic units based on their corresponding lithology’s conformity to the Davsonian cycle of erosion or landscape developments (Davis, 1899). A value of 1 was assigned to sedimentary rocks while a value of 2 was assigned to igneous rocks because their resistant nature makes their response to erosion slower (Table 1). A value of 3 was assigned to areas underlain by unconsolidated materials because they do not possess a homogeneous structure and therefore do not conform to the Davsonian model. This is akin to the classification of Selby (1980) with the sedimentary rocks being the moderately strong rocks, the igneous units being the strong rocks, and the alluvium and other loose sediments composing the very weak rocks. Because of the limited extent of the study area (552 km²), the effect of climate was deemed to be negligible based on available global precipitation measurement (GPM) datasets by Huffman et al. (2019) and Tropical Rainfall Measuring Mission (TRMM) (2011) datasets and was not integrated into the RTAI map. The reclassified values for geologic formations were rasterized and were then combined with the morphometric indices using the equal weights raster overlay method to establish the relative tectonic activity index (RTAI). The values of the RTAI range from 1 to 3, with Class 1 indicating a high relative tectonic activity and Class 3 indicating a low relative tectonic activity in an area. Table 2 summarizes the classification of morphometric index values used to establish the relative tectonic activity of the VAF.

In addition to the basin-based morphometric indices, stream length-gradient index (SL) and mountainfront sinuosity (Smf) were also computed to detect tectonic signatures. The SL and Smf are computed on a per-pixel basis and as such, cannot be integrated directly into the RTAI because of the variabibitex paper28-Canilleption in spatial extent and resolution (i.e. different cell sizes). Interpretations for SL and Smf were independently conducted and were then correlated with the RTAI classifications.

### 3.1 Hypsometric integral (HI)

Hypsometric integral (HI) is the numerical expression of an area’s hypsometric curve and can be expressed by this equation (Pike and Wilson, 1971):

\[
HI = \frac{\text{Average Elevation} - \text{Minimum Elevation}}{\text{Maximum Elevation} - \text{Minimum Elevation}}
\]

The hypsometric curve describes the distribution of the area per elevation in a region (Fig. 7a). High values (> 0.5) of HI describe a convex hypsometric integral that indicates a young or rejuvenated landscape while low HI values (< 0.4) describe a concave hypsometric curve, which indicates a more mature landscape. To get the variables needed for the computation of the HI, zonal statistics as table tool was applied to the sub-basins. Results ranged from 0.1 to 0.76 and were classified following the concavity or convexity of the hypsometric curve described by the HI (Dehbozorgi et al., 2010; El Hamdouni et al., 2008; Mulyasari et al., 2017). In a study by El Hamdouni et al. (2008) on the Sierra Nevada in southern Spain, Class 1 are basins with HI > 0.5, Class 2 are basins with HI values between 0.4 and 0.5 (0.4 < HI < 0.5), and Class 3 are basins with HI < 0.4 (Table 2).

### 3.2 Basin Shape (Bs)

Basin shape (Bs) expresses the elongation of a basin as a numerical value. It is most often expressed by this equation (Cannon, 1976; Ramírez-Herrera, 1998):

\[
Bs = \frac{\text{Basin Length}}{\text{Basin Width}}
\]

Higher Bs values denote more elongated basins while lower Bs values are associated with more circular basins (Fig. 7b). The elongation of a basin is often related to the age of the landscape. Basins are typically elongated when the region is young. With time, the basins become more rounded as the river laterally erodes more of the landscape. Uplift can also cause the elongation of basins as it increases the energy of the streams, which in turn promotes increased downcutting. Hence, higher Bs values can be associated with higher levels of tectonic activity while lower Bs values can indicate lower degrees of tectonic activity (Ramírez-Herrera, 1998). The tool Minimum Bounding Geometry in ArcGIS was used on the sub-basins to obtain the length and width for the calculation of the ratio.

Bs values ranged from 1.04 to 5.83 and were classified into three following the method of El Hamdouni et al. (2008), who used morphometric indices to investigate the actively uplifting southwestern Sierra Nevada Mountain range. In their study, Bs value boundaries were determined based on the range of values obtained in the Sierra Nevada Mountain range. Following the example, the boundaries set for this study were based on the range and distribution of the values obtained using the Jenks optimization method and were rounded off.

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**Table 1** Weights assigned to geological formations based on lithological properties.

<table>
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<th>Lithology</th>
<th>Age</th>
<th>Weight</th>
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<td>Coraline Limestone</td>
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<td>Sandstone and Mudstone</td>
<td>Early Pliocene to Pleistocene</td>
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<td>Sandstone and Shale</td>
<td>Middle to Late Miocene</td>
<td>1</td>
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<tr>
<td>Banguit Formation</td>
<td>Clastic Sedimentary Rocks</td>
<td>Late Eocene to Late Oligocene</td>
<td>1</td>
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<td>Serpentinitized Peridotite</td>
<td>Cretaceous</td>
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</tbody>
</table>

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**Table 2** Summary of the Classification of the Hypsometric Integral (HI) and Basins Shape (Bs), with Class 1 indicating high relative tectonic activity and Class 3 indicating low relative tectonic activity. The reclassified values for geologic formations were rasterized and were then combined with the morphometric indices using the equal weights raster overlay method to establish the relative tectonic activity index (RTAI). The values of the RTAI range from 1 to 3, with Class 1 indicating a high relative tectonic activity and Class 3 indicating a low relative tectonic activity in an area. The tool Minimum Bounding Geometry in ArcGIS was used on the sub-basins to obtain the length and width for the calculation of the ratio. Bs values ranged from 1.04 to 5.83 and were classified into three following the method of El Hamdouni et al. (2008), who used morphometric indices to investigate the actively uplifting southwestern Sierra Nevada Mountain range. In their study, Bs value boundaries were determined based on the range of values obtained in the Sierra Nevada Mountain range. Following the example, the boundaries set for this study were based on the range and distribution of the values obtained using the Jenks optimization method and were rounded off.
Class 1 are basins with $Bs \geq 3$, Class 2 are basins with $2 \leq Bs < 3$, and Class 3 are basins with $Bs \leq 2$ (Table 2).

### 3.3 Basin Elongation Ratio ($R_e$)

Similar to basin shape ($Bs$), the basin elongation ratio ($R_e$) also defines the elongation of the basin. However, $R_e$ measures the elongation of a basin based on its closeness to a perfect circle (Fig. 7c). Instead of using metrics like length and width, the $R_e$ uses the basin’s area and compares its actual length to the diameter of a circle with an equal area as the basin, which might be more useful for more irregularly shaped basins. This index can be defined using the equation (Schumm, 1956):

$$R_e = \frac{\text{Diameter of Circle}}{\text{Length of Basin}}$$

The $R_e$ values ranged from 0.3 to 0.94 and were classified into three following the study of Bull and McFadden (1977) and Sharma et al. (2018b) on the morphometric characteristics of the active Garlock Fault and Alaknanda Basin, respectively. This classification was based on Bull and McFadden (1977) and Sharma et al. (2018b). Values ranged from 0.7 to 1.2 (Table 2).

### 3.4 Asymmetry Factor ($Af$)

The basin asymmetry factor ($Af$) expresses the symmetry of the basin by comparing the area to the right of the main river with the total area, can be defined by this equation (Hare and Gardner, 1985; Keller and Pinter, 2002) (Fig. 7d):

$$Af = 100\left(\frac{\text{Tight Basin Area}}{\text{Total Basin Area}}\right)$$

$Af$ values close to 50 are generally considered symmetric while larger deviations from 50 are associated with asymmetric basins (Keller and Pinter, 2002). Results of the $Af$ calculations ranged from 1.65 to 96.42. El Hamdouni et al. (2008) defined a classification for $Af$ that related it to possible tectonic tilting. In the study, deviations higher than 15 ($Af > 65$ or $Af < 35$) are assigned Class 1, which indicates that the basin is asymmetric enough to be caused by tectonic tilting (Table 2). A deviation of 7 to 15 from 50 ($65 > Af > 57$ or $35 < Af < 43$) is defined to be Class 2 and indicates a mild asymmetry that may or may not be caused by tectonics. Class 3 are basins with $Af$ deviations of 7 or less from 50 ($57 > Af > 43$) and are considered to be symmetric and untitled. The classification system of El Hamdouni et al. (2008) was adopted in this study since the effects of tectonic tilting on basins apply either to compressive or tensional regimes, as corroborated by multiple succeeding studies (e.g., Dehbozorgi et al., 2010; Kumar and Durarh, 2020; Ntokos et al., 2016; Pérez-Peña et al., 2010). For this study, we are interested in determining which areas are possibly tilted or are showing signatures of tectonic activity. The main river was traced manually on ArcGIS to divide the basin into two. The basin area was calculated using the field calculator of ArcGIS software.

### 3.5 Stream Length-Gradient Index ($SL$) and Normalized Stream Length-Gradient Index ($SL/k$)

Stream length-gradient index ($SL$) is used in geomorphological studies to detect changes in the longitudinal profile of the river, usually in the form of knickzones. Hack (1973) describes the equation to be:

$$H = C - SL(\log L)$$

where $H$ is the elevation of a given point along the stream channel, $L$ is the distance of the point from the drainage divide, $C$ is a constant, and $SL$ is the stream length-gradient index. The equation can then be derived with respect to $L$, which will yield the following equation (Fig. 7e):

$$SL = \left(\frac{dH}{dL}\right)L$$

This equation was applied to the rivers of the major drainage basins in the area. The application was done through the SLIX toolbox developed by Placentini et al. (2020) for ArcGIS. Values ranged from 0.0001 to 1489.92 and were classified into three following previous studies (i.e., Dehbozorgi et al., 2010; El Hamdouni et al., 2008; Mulyasari et al., 2017): Class 1 (> 500), Class 2 (300 – 500), and Class 3 (< 300) (Table 2). To better visualize the effects of tectonics and lithologic competence on these channels, the normalized stream length-gradient index was calculated from the $SL$ values. In Taiwan, Chen et al. (2003) examined the morphological
signature of a compressional environment using hypsometric curve and stream length-gradient index analyses. They demonstrated that $SL$ can be normalized against graded slope ($k$) to improve the detection of steep segments along a stream, resulting in $SL/k$. The steepness of streams is often attributed to changes in stream power or lithological competence. Changes in stream power are often associated with young or rejuvenated landscapes, which makes $SL/k$ more useful in detecting tectonic signatures. The resulting $SL/k$ values ranged from 0.00001 to 150.04 and were divided into classes based on the steepness of the section. To be consistent with the previous indices, the classes by Chen et al. (2003) were reclassified into three: Class 1 are very steep river sections with high $SL/k$ ($SL/k > 12$), Class 2 are moderately steep sections with moderate $SL/k$ ($6 < SL/k \leq 12$), and Class 3 are gently dipping to subhorizontal sections with low $SL/k$ ($SL/k \leq 6$). The $SL$ and $SL/k$ were preferred over normalized steepness index (ksn) and chi ($\chi$) analysis because $SL$, and by extension $SL/k$, allows the analysis of a river via smaller segments along the stream. Rivers cannot normally be expressed as a single logarithmic profile, so it is better to analyze a large river by subdividing the stream into smaller segments along the stream profile.

### 3.6 Mountain Front Sinuosity ($S_{mf}$)

Mountain front sinuosity ($S_{mf}$) is a measure of the linearity of a mountain front (Fig. 7f). This is often expressed by the equation (Bull and McFadden, 1977):

$$S_{mf} = \frac{\text{Actual Length of Mountain Front}}{\text{Straight Length of Mountain Front}} (7)$$

Mountain fronts were delineated using the method of Rimando and Schoenbohm (2020). The mountain fronts were delineated using a slope map (classified into $< 15^\circ$ and $> 15^\circ$ to highlight the slope break) that was superimposed onto a shaded relief map of the area. The mountain fronts were only delineated for areas near the fault. Low mountain front sinuosity values associated with a straight mountain front could be indicative of fault movement. Mountain fronts were digitized to get their actual length. Lines spanning the whole mountain front were then constructed to derive the straight length.

The values of the $S_{mf}$ ranged from 0.11 to 2.02 and were then classified following El Hamdouni et al. (2008). Class 1 values are the straightest mountain ranges with $S_{mf} < 1.1$ while the most sinuous mountain fronts are classified as Class 3 with $S_{mf} \geq 1.5$ (Table 2). Class 2 mountain fronts have intermediate sinuosity with values of $1.1 \leq S_{mf} < 1.5$ (Dehbozorgi et al., 2010; El Hamdouni et al., 2008; Mulyasari et al., 2017).

### 4 Results

#### 4.1 Morphometric Indices

Fig. 8 summarizes the results of the basin-based morphometric indices while the results of the non-basin-based morphometric indices are shown in Fig. 9. To better visualize the clustering of values, local spatial autocorrelation using Getis-Ord (Gi*) statistics was performed for the $HI$, $Bs$, $Re$, and $SL/k$ (Fig. 10). Gi* statistics relates the value of a sample and its neighbors to the overall average of values to detect hot spots (i.e. a cluster of high values) and cold spots (i.e. a cluster of low values).

Results of the $HI$ show that the younger Class 1 and 2 sub-basins are located along the VAF traces as well as in the southeastern highland mountains (Fig. 8a). Meanwhile, most mature Class 3 sub-basins are mostly found in low-lying areas. Clustering of the values derived from $Gi^*$ statistics shows that the hot spots are located consistently along the central VAF strands (Fig. 10a). Hot spots were also observed to the south of the normal fault.

The analysis of $Bs$ showed that most of the basins are rounded and belong to Class 3 (Fig. 8b). As for the higher classes, Class 1 and Class 2 values were observed to mostly occur near the traces of the VAF. However, another cluster of Class 2 values, with a few clusters in Class 1, was found in the mountainous highlands to the southeast. The hot spot analysis of the $Bs$ shows that most of the hot spots are located at the northern, NE-trending section of the VAF (Fig. 10b).
Class 3 are river sections with fronts (Fig. 8c). Like the previous indices, the very elongated basins are moderately elongated and fall under Class 2 parent distribution pattern. Hotspots for the mountains. Circular Class 3 basins are generally distributed along or near the VAF traces as well as in the southeastern highland. Class 1 basins are generally distributed along or near the VAF. The $S_mf$ in the study area was calculated for the mountain fronts along the fault traces (Fig. 9c). Results show that Class 1 values, which represent straight mountain fronts, were only found adjacent to the northern section of the east VAF strand. Other strands of the VAF both in the north and south sections appear moderately straight (Class 2). Sinuous Class 3 mountain fronts were found for the mountain fronts along the normal fault trace to the southeast.

4.2 Relative Tectonic Activity Index (RTAI)

The RTAI shows sub-basins that have consistently high $HI$, $B_s$, and $R_e$ (Fig. 9d). Results show the RTAI Class 1 and RTAI Class 2 values to be mostly in the highlands in between the west and central VAF strands as well as in the lowlands in the fault’s immediate vicinity (Fig. 9d). There were also a few RTAI Class 1 and Class 2 values in the southeast mountains. As expected, RTAI Class 3 values were observed to be clustered in the lowlands underlain by alluvium and river deposits.

5 Discussion

5.1 Morphometric Indices

In this study, $HI$ values show that the clusters of the youngest or rejuvenated basins are found adjacent to or along the central VAF strands, which are underlain by sedimentary sequences (Fig. 10a). Because the sub-basins along the VAF are mostly underlain by sedimentary formations, we can relate the morphometric indices along the fault to possible tectonic activity. Fault movement, especially dip-slip faults, can also produce a high-relief landscape where active uplift rejuvenates the landscape and can lead to higher $HI$ values (El Hamdouni et al., 2008). Based on the hot spots of the $HI$, signs of tectonic activity can be observed throughout the VAF.

The $HI$ also revealed young or rejuvenated basins at the mountain range underlain by the Ilocos Peridotite to the southeast. The clusters of young landscapes at the southeastern mountain range could either reflect the tectonic deformation associated with the normal fault or the induration of underlying lithologies (Fig. 10a). Compared to weaker lithologies such as sandstones and siltstones, more resistant igneous rocks are harder to erode and would produce high-relief landscapes under the same erosional conditions (e.g., fluvial erosion) (Pérez-Peña et al., 2009; Hurtrez and Lucazeau, 1999; Sedrette et al., 2016).

Hot spots of $B_s$ values were observed along and downstream of the west and central VAF strands. However, unlike the $HI$, these clusters seem to only occur at...
Figure 10  Spatial autocorrelation analysis of the $HI$ (a), $Bs$ (b), $Re$ (c), and $SL/k$ (d) values. Hot spots (red points) indicate the clustering of high values whereas cold spots (blue points) indicate the clustering of low values. (a) For the $HI$, most hot spots are found in between the traces of the VAF while the cold spots are found in the lowland hills and alluvial plains. (b) Hot spots for $Bs$ are mostly located in the northern section of the VAF. (c) Similar to B, the hot spots of the $Re$ are found mostly at the northern, NE-trending section of the VAF. (d) The hot spots for the $SL/k$ are also concentrated in the northeast-southwest trending mountain range that is traversed by the Vigan–Aggao Fault as well as in the southeastern mountainous terrain south of the normal fault. Similar to the RTAI, the cold spots for the $SL/k$ are concentrated in the lowlands near the coast to the west as well as in the alluvial plains.

the northern, NE-trending section of the VAF (Fig. 10b). The elongation of basins downstream of the fault can be the result of increased uplift at the bent section of the VAF. Uplift at this section of the fault increases the incision power of the streams, which increases downstream erosion. As such, basins downstream of the fault trace would also be affected and appear elongated (Bahrami, 2013; Sharma et al., 2018a). Hot spots can also be observed in the southeast mountain range. However, there is a considerable decrease in the number of hot spots of the $Bs$ compared to the hot spots of the $HI$. We can also observe that the few hot spots that can be observed at the southeast mountain range are oriented obliquely to the normal fault trace. The oblique alignment of the long axes of the basins with respect to the fault would mean that the elongation of such basins is due to other factors, such as hillslope processes or lithological competence, rather than tectonic activity.

Like the $Bs$, the $Re$ shows that the elongated basins are also located along and downstream of the west VAF strands (Fig. 10c). The hot spot analysis of the $Re$ also shows a similar clustering as the $Bs$. These results from the $Re$ support the result of the $Bs$ and indicate that the basins at the northern bent section of the fault are more elongated. Meanwhile, cold spots can be more observed between the west and central VAF strands. The VAF in the study area splays into three strands that form a positive flower structure (Pinet and Stephan, 1990). Hence, the streams in between the fault traces would be uplifted as a block and would experience an almost equal amount of uplift. The equal uplift would result in a smaller increase in stream energy and would explain the cluster of rounded basins or cold spots. Similar to the $Bs$, there are hot spots of the $Re$ at the southeast mountain range, but these are fewer than the hot spots of the $HI$. Assuming that the hot spots of the $HI$ are due to the tectonic activity of the normal fault, we expect to see that both $Bs$ and $Re$ at the southeast mountain range, but these are fewer than the hot spots of the $HI$. Assuming that the hot spots of the $HI$ are due to the tectonic activity of the normal fault, we expect to see that both $Bs$ and $Re$ should also be elongated perpendicular to the fault trace. However, because the results show the opposite, these hot spots may be due to lithology. The discrepancy in the results of $Bs$ and $Re$ suggests that the clusters of high $HI$ values are not due to tectonics but rather to a difference in the resistance of the underlying lithology.

Unlike the previous indices, the $Af$ values are scattered and do not show a distribution pattern. The random scattering of $Af$ values indicates that the results are inconclusive as regards the tilting of the sub-basins due to tectonic activity. In addition, uplift can only cause tilting of the sub-basins if the uplift was more substantial on one half of the basin. If the uplift was equal throughout the basin, then the basin would not appear
titled and would be classified as a symmetrical basin (i.e. Delcaillau et al., 2022). As such, we infer that most of the sub-basins have experienced uplift but were not tilted. Because of these assumptions, the results of the AF were not incorporated in the calculation of the RTAI.

The $SL$ and subsequent $SL/k$ calculations show that Class 1 values are located along the VAF traces and at the southeastern mountain range (Fig. 9a). Because the southeastern mountain range was underlain by igneous rocks rather than sedimentary rocks, the high $SL$ and $SL/k$ values can be due to the higher lithological competence as both the $Bs$ and $Re$ results do not imply tectonic activity in the area (Chen et al., 2003). The $SL/k$ results were similar to the $HI$ values, wherein a dense cluster of values is found in the northern section of the fault compared to the southern section (Fig. 10b). Since higher $SL/k$ implies steeper stream segments, the northern section may have experienced more uplift than the southern section of the west and central VAF. Since the VAF traces lie within the same formation, variations in the terrain characteristics are possibly attributed to tectonic forces. Another cluster of $SL/k$ values was observed in the southeastern mountain range. Since the area to the southeast is underlain by more resistant igneous rocks, this could be one of the causes of the high $SL/k$ values. Aside from this, it is also possible that the normal fault that cuts through the southeastern mountain range is active. However, the degree to which the fault is active, independent of bedrock geology, cannot be determined solely by the results of the $SL/k$.

Notably, the $S_{mf}$ results show that Class 1 mountain fronts are found along the northern section of the east VAF strands while the rest of the VAF traces exhibited Class 2 mountain fronts (Fig. 9c). The only Class 3 mountain front was found along the normal fault east of the VAF strands. The VAF and the normal fault cut different formations; sedimentary rocks of the Batac Formation for the VAF and igneous rocks of the Ilocos Peridotite for the normal fault. Igneous rocks are more resistant and tectonic geomorphic features such as fault scarps would not be eroded as easily as scarps on sedimentary rocks. Therefore, we can expect mountain fronts cut by faults to also be resistant to erosion and should remain straight for a longer period. However, for our study area, the mountain front underlain by the Ilocos Peridotite was less straight than the mountain fronts underlain by the relatively weaker sedimentary Batac Formation near the VAF. This implies that the VAF is more active than the normal fault to the southeast.

### 5.2 Relative Uplift Rate along the Vigan–Aggao Fault

The morphometric indices composing the RTAI are more sensitive to dip-slip deformation than strike-slip deformation. Hence, the areas that are more actively deforming as defined by the RTAI can be more accurately characterized as areas with a different relative uplift rate. The different relative uplift rates within the locality have produced the localized tectonic geomorphic features observed in Fig. 3.

The RTAI Class 1 values along the VAF were mostly observed in the northern VAF. Specifically, the northern sections of the west, central, and east VAF strands show more RTAI Class 1 values compared to the southern section. From this distribution of RTAI values, it can be posited that the northern sections of the west, central, and east VAF strands have experienced a higher relative uplift rate compared to the southern section. This hypothesis is supported by historical seismicity, which shows more earthquakes in the northern section of the west, central, and east VAF strands.

Since the effect of the lithology has already been taken into account with the computation of the RTAI, we attribute the southeastern clusters to the effect of the normal fault, implying that this fault is also active. However, the smaller number of Class 1 RTAI values coupled with the result of the $S_{mf}$ leads us to infer that the normal fault has a lower relative uplift rate compared to the VAF.

Additionally, we can observe a dense cluster of RTAI Class 1 values along the VAF strands (Fig. 9d). However, another possible cause of high RTAI values along the VAF is the change of local stress regime induced by the bending and stepping of the fault. Previous studies have reported that the change in the trend of the VAF from NNE to NE resulted in a shift from a dominantly lateral strike-slip motion to localized compression (Pinet and Stephan, 1990; Rimando and Rimando, 2020). Compared to the strike-slip component of oblique faults, the higher relative uplift rate at the northern section of the VAF creates more prominent geomorphic features that affect the calculation and analysis of morphometric indices. Because the basin-based morphometric indices are better at detecting vertical deformation than strike-slip deformation, the relative tectonic activity observed by the RTAI is more probably related to relative uplift rates. Therefore, based on the distribution of RTAI values, the northern section of the San Juan–Vintar segment exhibits a higher relative uplift rate than the southern section. The $SL$ and $SL/k$ also show that the northern section exhibits a higher relative uplift rate. As for $S_{mf}$, straight mountain fronts were generally observed at the northern section of the east VAF strands, suggesting that the northern section is more active. We further infer that the higher relative uplift rates observed in morphotectonic landforms and indices are attributed to the restraining bend of the San Juan–Vintar segment as previously reported by Rimando and Rimando (2020). The observed highest relative uplift rates in the northern section are concentrated at the central VAF strands which accommodate most of the shortening and localized compression.

### 6 Conclusion

Variations in the relative uplift rates along the three sub-parallel strands of the VAF were explored using morphometric analysis. The $HI$ indicates that the basins at the northern section of the fault are younger or rejuvenated. Meanwhile, the $Re$ and $Bs$ both show that more basins in the northern section are elongated. The $AF$ results reveal that the apparent tilting of the sub-basins in the area is not primarily associated with tec-
tonic processes. As for $S_{mf}$, the straightest mountain fronts were only found at the northern section of the VAF. All these morphometric indices indicate that uplift rates are higher in the northern strands of the VAF. This is further supported by the RTAI results and subsequent hot spot analyses of the $HI$, $Bs$, $Re$, and $SL/k$. The hot spot clusters for the $Bs$, $Re$, and $SL/k$ plotted more on the northern section of the VAF than on the south, suggesting a higher relative uplift on the former. The increase in relative uplift in the northern section is attributed to the restraining bend of the fault and supports the morphotectonic observations of Rimando and Rimando (2020). The morphometric indices also reveal that most of the uplift is found at the central VAF strands where the restraining bend experiences compression and crustal shortening. Hot spots for the $HI$, $Bs$, $Re$, and $SL/k$, as well as the RTAI Class 1 values, were also observed in the southeastern mountains bounded by a normal fault. While this normal fault is assumed to be active, the number of hot spot clusters observed was fewer than those observed along the VAF. The result of the RTAI coupled with the Class 3 $S_{mf}$ values at the fault-bound mountain front, suggests either lower relative uplift rates or lower tectonic activity of the normal fault relative to the San Juan–Vintar segment of the VAF.

The study was limited to using erosional resistance and morphometric index classifications derived from previous studies. To improve the accuracy of morphometric analysis in future research, establishing a database of rock mass strength classification (e.g., Goudie, 2006; Selby, 1980) specifically for the Philippine setting is recommended. Further research can also be conducted to examine the proper scale of sub-basins that can be used in studying the neotectonics of certain localities. Lastly, more morphometric studies should be conducted within the Philippines to establish a unique classification scheme that is more fit for the dynamic tectonic setting of the country.

For the first time, this study demonstrates the utility of morphometric indices in characterizing active or potentially active faults in the Philippines with scarce geophysical and structural information. Results from morphometric analysis of the VAF further provide additional insights into its relative uplift rates and seismic hazard potential. With this baseline information presented, future investigations of active faults in the northern Ilocos region can be prioritized for paleoseismic studies and seismic hazard analyses.

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Data and Code Availability

Datasets related to this article can be found at https://doi.org/10.17632/2dskyyk3vyc-2, an open-source online data repository hosted at Mendeley Data.

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