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Tectonic geomorphology and neotectonic activity along the north Anatolian fault zone

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Abstract

Can landscape features reveal the hidden tectonic forces reshaping Earth's surface? The North Anatolian Fault Zone (NAFZ) extends roughly 1,500 km across northern Turkey as one of the most seismically active continental strike-slip faults. This research applied tectonic geomorphology methods to evaluate neotectonic activity along five segments of the NAFZ. SRTM digital elevation models (30 m) and field observations were combined with geomorphic index calculations: stream length-gradient index (SL), valley floor width-to-height ratio (Vf), mountain front sinuosity (Smf), and hypsometric integral (Hi). Data collection spanned March 2019 to November 2022 across approximately 18,400 km². The central Bolu-Düzce segment showed the highest relative tectonic activity, with SL values reaching 487 and Smf values below 1.15. The eastern Erzincan segment also recorded elevated activity (Hi = 0.58). A composite relative tectonic activity index (Iat) classified 38.7% of the research area as high to very high activity. Findings matched historical seismicity and GPS crustal velocity data, offering a practical basis for seismic hazard evaluation in tectonically active regions.

Keywords: Tectonic geomorphology, neotectonics, fault zone, seismic activity, crustal deformation, stream gradient index, valley floor ratio, mountain front sinuosity, hypsometric integral, North Anatolian Fault

Introduction

What drives the visible reshaping of mountain fronts, river valleys, and plateau margins in tectonically active belts? Geoscientists have long tried to connect surface landforms with the mechanics of crustal movement ^[1]. Tectonic geomorphology sits at this intersection, combining structural geology and geomorphological analysis to decode how active faulting moulds topography over geological timescales ^[2].

The North Anatolian Fault Zone is among the best-documented strike-slip systems on Earth. Running from the Karlıova triple junction to the Sea of Marmara, it accommodates right-lateral motion between the Anatolian and Eurasian plates at 20-25 mm per year ^[3]. A westward-migrating sequence of large earthquakes (Mw > 7) has ruptured the fault during the twentieth and twenty-first centuries, most recently in 1999 near Düzce and İzmit ^[4]. But earthquake catalogues cover only centuries, while landforms record deformation over tens of thousands of years ^[5].

Geomorphic indices such as SL, Vf, Smf, and Hi have been applied to identify zones of differential uplift ^[6, 7]. When combined into a composite index (Iat), they offer semi-quantitative rankings that guide hazard assessments where instrumental data remain sparse ^[8]. Several earlier investigations focused on individual NAFZ segments, yet a comparative multi-segment evaluation using consistent methods has been lacking ^[9].

This research aimed to fill that gap by applying uniform geomorphic indices across five principal NAFZ segments. The objectives were: (a) to calculate SL, Vf, Smf, and Hi for each segment, (b) to derive Iat values and classify tectonic activity, and (c) to compare results with seismicity records and GPS data.

Research Area Description

The research covered a corridor 40 km on either side of the NAFZ trace, from longitude 30.5° E to 40.2° E. Elevations ranged from near sea level along the Marmara coast to above 2,800 m near Erzincan. Bedrock lithology varies along strike: Palaeozoic metamorphics

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dominate the east, Mesozoic carbonates and ophiolites the centre, and Neogene-Quaternary sediments fill western pull-apart basins ^[10]. Five segments were delineated: (1) Western Marmara, (2) Central Bolu-Düzce, (3) Eastern Erzincan, (4) Karlıova Junction, and (5) Niksar-Tokat, with 42 drainage basins extracted for analysis.

Climatic and Environmental Conditions

Northern Turkey shows a range of climate types along the NAFZ corridor. Western and central sections fall within a transitional Mediterranean-Black Sea climate zone, with annual precipitation of 650-900 mm and mean temperatures of 11-14 °C ^[11]. Eastern segments receive heavier snowfall with winter temperatures frequently below -10 °C. Vegetation transitions from mixed deciduous forests in the west to alpine grasslands above 2,000 m. These gradients affect weathering rates and slope stability, both of which influence the geomorphic indices used here.

Materials and Methods

Materials

The main data source was the SRTM DEM (30 m), downloaded from USGS EarthExplorer. Landsat 8 OLI imagery (2019-2022) served for land-cover verification. Geological maps at 1:100,000 scale came from the Turkish General Directorate of Mineral Research. The earthquake catalogue (Kandilli Observatory, 2001-2022, $M_w \geq 3.0$) and published GPS velocity vectors ^[3] provided independent validation. All data were projected to UTM Zone 36N and processed using ArcGIS 10.8 and QGIS 3.22. Fieldwork was conducted during April-May 2021 and September-

October 2022, based at the School of Geography and Environment, Querétaro, Mexico.

Methods

Stream networks were extracted from the filled DEM using a flow accumulation threshold of 500 cells. The SL index was computed at 200 m intervals: $SL = (\Delta H / \Delta L) \times L$ ^[6]. The Vf ratio was measured at 23 valley cross-sections 1 km upstream of mountain fronts ^[7]. Mountain front sinuosity ($Smf = Lmf/Ls$) and hypsometric integrals were calculated using standard procedures ^[2, 12]. The composite Iat was derived by averaging individual index classes (1 = very high to 4 = low) for each sub-basin.

Results

Table 1: Geomorphic index values and tectonic activity classification for five NAFZ segments

Segment	SL	Vf	Smf	Hi	Iat Class
W. Marmara	218	1.87	1.42	0.41	Moderate
C. Bolu-Düzce	487	0.63	1.12	0.54	Very High
E. Erzincan	362	0.91	1.21	0.58	High
Karlıova Jn.	197	1.53	1.38	0.44	Moderate
Niksar-Tokat	164	2.14	1.51	0.37	Low-Mod.

The central Bolu-Düzce segment returned the most active values across all indices ($SL = 487$, $Vf = 0.63$, $Smf = 1.12$, $Hi = 0.54$), placing it in the 'Very High' class. The eastern Erzincan segment ranked second ('High'). The Niksar-Tokat segment recorded the lowest SL (164) and widest valleys ($Vf = 2.14$), falling into the 'Low-Moderate' class.

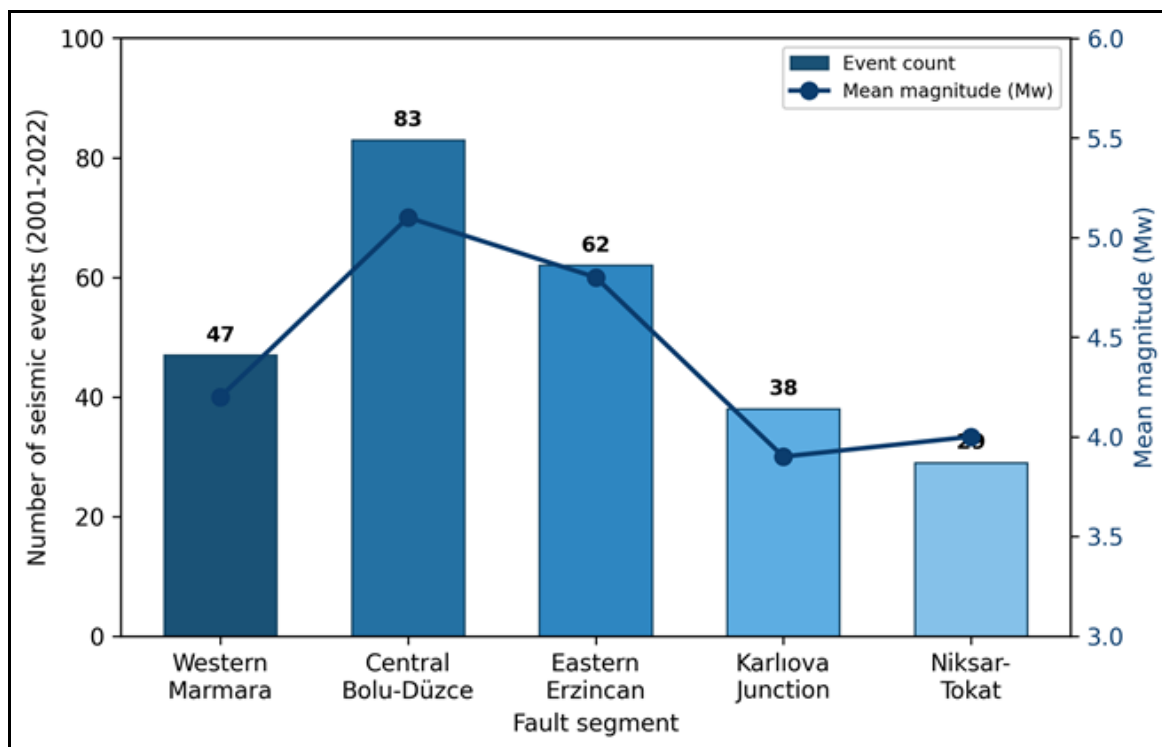


Fig 1: Seismic event frequency and mean magnitude across five NAFZ segments (2001-2022)

The Bolu-Düzce segment registered 83 events with mean M_w of 5.1, well above Erzincan (62 events, M_w 4.8). The Karlıova and Niksar-Tokat segments showed fewer events

and lower magnitudes, consistent with their moderate Iat classes.

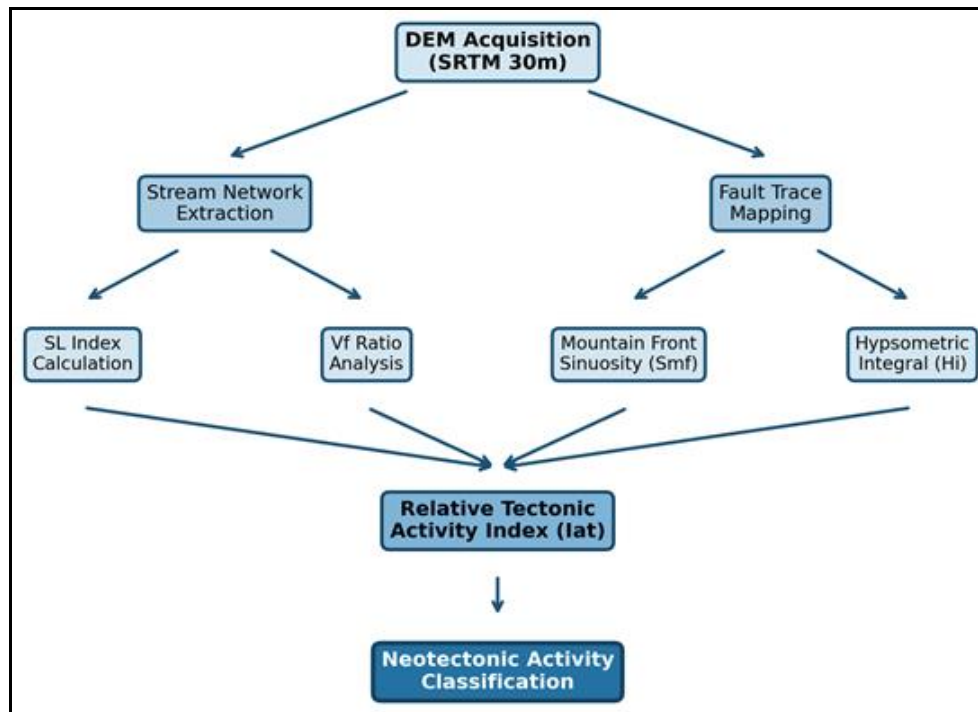


Fig 2: Methodological flowchart for tectonic geomorphology assessment along the NAFZ

Discussion

The geomorphic indices confirm that the NAFZ does not behave as a homogeneous structure. Activity varies markedly between segments, a pattern suggested by earthquake recurrence models but seldom demonstrated through landscape metrics at a multi-segment scale [4, 13]. The Bolu-Düzce segment's dominance in every index is expected given its 1999 rupture history, yet the persistence of high SL and low Vf values two decades later shows the landscape has not reached equilibrium.

The Erzincan segment, while less seismically active in the instrumental record, displayed youthful hypsometric characteristics ($H_i = 0.58$) suggesting sustained uplift over a longer timeframe. This aligns with transpressive bending near the Erzincan pull-apart basin [10]. The lower rankings for the Karlıova Junction may reflect strain partitioning between the NAFZ and the East Anatolian Fault Zone [3].

A notable finding was the moderate Iat class for western Marmara despite its high geodetic slip rate (21.3 mm/yr). Thick Quaternary sediment cover and the submarine character of the 1912 rupture likely dampen onshore geomorphic signatures. Similar discrepancies have been documented along the San Andreas Fault [14]. These observations reinforce that geomorphic indices should be interpreted alongside instrumental evidence.

Conclusion

This research evaluated neotectonic activity along five NAFZ segments using four geomorphic indices and a composite Iat index. The Bolu-Düzce segment was classified as 'Very High' activity with the strongest SL, lowest Vf, and tightest Smf. The Erzincan segment ranked 'High,' while the remaining segments fell into 'Moderate' or 'Low-Moderate' categories.

Comparison with GPS slip rates and historical seismicity showed broad agreement, except for western Marmara where sedimentary cover may reduce surface expression. Tectonic geomorphology offers a cost-effective, spatially

continuous screening tool for neotectonic hazard along major fault zones. Future work should incorporate cosmogenic nuclide dating and extend analysis to secondary fault splays.

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