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TECTONIC ACTIVITY AND ITS IMPACT ON THE INTEGRITY OF HYDROCARBON TRANSPORT PIPELINES

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ABSTRACT

Mass movements have historically been one of the main geohazards affecting the integrity of hydrocarbon transport pipelines (HTP), especially in mountainous regions such as the Andes. Contributing factors generally include geology, topography, and groundwater levels, with triggering mechanisms such as earthquakes, rainfall, and anthropogenic activity. However, one factor that is rarely considered and insufficiently studied is tectonic activity, which, depending on its displacement rate, can act as a conditioning factor or a trigger.

Tectonic activity refers to the deformation of the Earth's crust, which can occur at different rates. The movement of tectonic plates and the uplift of mountain ranges typically occurs at a rate of centimeters per year—slow processes that often go unnoticed yet contribute to terrain instability and channel incision. Faster tectonic movements are related to seismogenic faults, which can cause ground displacement in seconds, potentially producing destructive effects.

This article describes how tectonic activity induces processes in the Earth's crust that impact pipeline integrity and highlights the importance of understanding these phenomena to optimize maintenance programs for existing HTP and the design of future ones.

Keywords: Tectonic plate, Active fault, Neotectonics

1. TECTONIC REAMEWORK

Colombia, located in the northwestern corner of South America, lies within an active geotectonic zone where the Nazca, Caribbean, and South American plates interact (see Figure 1). This interaction results in stress fields with various orientations, which over geological time have shaped the current landscape of the Colombian Andes. Notably, this region contains numerous geological faults, several of which are active.

Most major faults in the Colombian Andes have formed as a result of subduction, accretion, and plate interaction processes that have likely occurred from the Triassic–Jurassic to the Cenozoic. These faults are generally aligned in NNE–NNW directions, parallel to the orientation of the mountain ranges (Paris et al., 1993).

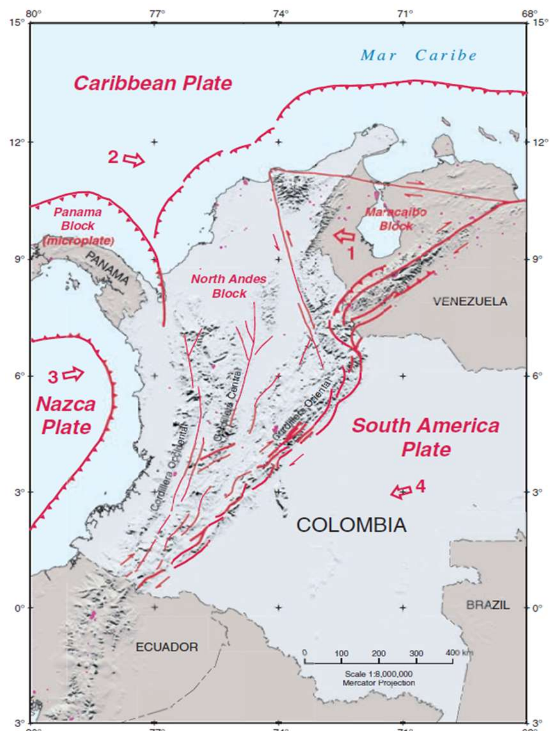
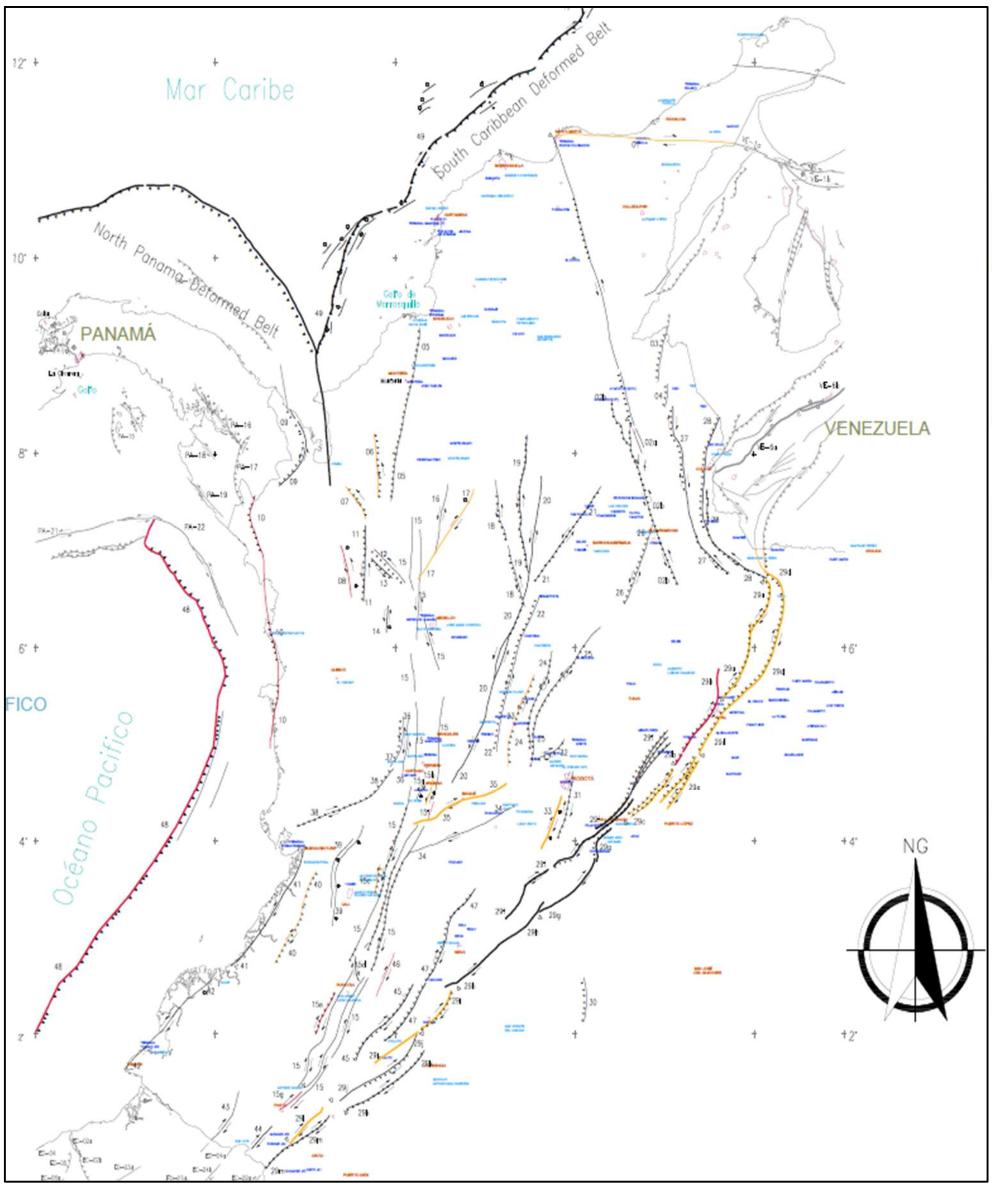


Figure 1. Major plates boundaries for Colombia. 1: South America Plate (v= 1.3cm/yr), 2: Caribbean Plate (v= 1.3cm/yr), 3: Nazca Plate (v= 6.3cm/yr) and 4: South America Plate (v= 6.6cm/yr). Source: Map of Quaternary Faults and Folds of Colombia and Its Offshore Regions, scale 1:8.000.000.

Among the NNE-trending systems—the most frequent—those with local evidence of Quaternary tectonic activity include: the Llanos Foothill Fault System (Frontal Fault System of the Eastern Cordillera), faults bordering the Magdalena Valley, and the prominent Romeral and Cali–Patía Fault Systems located along the western edge of the Central Cordillera. Along the Pacific coast, some recent active faults have contributed to the current coastal morphology (Paris et al., 1993). The main NNW-trending structure is the Santa Marta–Bucaramanga Fault System.

The "Map of Quaternary Faults and Folds of Colombia and Adjacent Oceanic Regions" (USGS & Paris, 2000) identifies 49 Quaternary faults. However, neotectonic research coverage in Colombia does not exceed 10% of fault traces with potential to develop into seismogenic structures. Most identified active faults are located in regions with a history of catastrophic seismic episodes that have driven localized seismotectonic investigations (see Figure 2). Regions with potential for high-magnitude, high-recurrence seismic events remain largely unknown, indicating the need for further research.



01	**Oca fault**	Right-lateral
02	**Santa Marta-Bucaramanga fault system**	----------
02a	Santa Marta section	Left-lateral/reverse
02b	Bucaramanga section	Left-lateral/reverse
03	**Caño Tomas fault**	Reverse
04	**Tarra fault**	Reverse
05	**Montería fault**	Reverse
06	**Tucura fault**	Reverse/left lateral(?)
07	**Mutatá fault**	Left-lateral/reverse
08	**Murindó fault**	Left-lateral
09	**Unguía fault**	Reverse/right lateral
10	**Bahia Solano fault**	Reverse
11	**Murri fault**	Reverse/left-lateral
12	**Cañasgordas fault**	Reverse/left-lateral
13	**Abriaqui fault**	Reverse/left-lateral
14	**Urrao fault**	Left-lateral
15	**Romeral fault system**	----------
15a	Montenegro (fault) section	Normal/left-lateral
15b	Armenia (fault) section	Normal/left-lateral
15c	Paraiso section	Thrust/right-lateral
15d	Piendamó (fault) section	Reverse/right-lateral
15e	Rosas-Julumito (fault) section	Reverse/right-lateral
15f	Cordoba-Navarco (fault) section	Left-lateral
15g	Buesaco-Aranda (fault) section	Right lateral
16	**Santa Rita fault**	Left-lateral
17	**Espiritu Santo fault**	Normal and right-lateral
18	**Otú Norte fault**	Left lateral/reverse
19	**Bagre Norte fault**	Left lateral and reverse
20	**Palestina fault**	Reverse/left-lateral
21	**Cimitarra fault**	Reverse/left-lateral(?)
22	**Mulato-Getudo fault**	Reverse/left-lateral
23	**Honda fault**	Reverse/left-lateral?
24	**Alto del Trigo fault (part of Salinas fault system)**	Reverse/left-lateral?
25	**Bituima fault (part of Salinas fault system)**	Reverse/left-lateral
26	**Suarez fault**	Reverse/left-lateral
27	**Morronegro-Las Mercedes fault system**	Reverse/strike-slip
28	**Chitaga-Pamplona faults**	Reverse and left-lateral
29	**Eastern Frontal fault system**	----------
29a	Northern Guaicaramo section	Reverse/right-lateral
29b	Central Guaicaramo section	Reverse/right-lateral
29c	Southern Guaicaramo section	Reverse/right-lateral
29d	Yopal (fault) section	Reverse/right-lateral
29e	San Pedro-Cumaral section	Reverse/slight right-lateral
29f	Servita-Santa Maria (fault group) section	Reverse/right-lateral?
29g	Guayuriba (fault) section	Reverse/left-lateral
29h	Algeciras (fault) section	Right-lateral
29i	Garzon-Pitalito (fault) section	Right-lateral(?) & reverse
29j	Suaza (fault) section	Right-lateral & reverse
29k	Mocoa (fault) section	Reverse/right-lateral
29l	Sibundoy (fault) section	Right-lateral
29m	Afiladores (fault) section	Reverse/right-lateral
30	**La Macarena fault**	Reverse
31	**Bogotá fault**	Reverse/right-lateral
32	**Viani fault**	Reverse/right-lateral
33	**Usme fault**	Normal/right-lateral
34	**Cucuana fault**	Right-lateral
35	**Ibagué fault**	Right-lateral, slight oblique
36	**Toro fault**	Left-lateral
37	**Argelia fault**	Reverse/right lateral?
38	**Garrapatas fault**	Reverse/right lateral?
39	**Dagua-Calima fault system**	Normal
40	**El Tambor fault**	Reverse/right lateral?
41	**Naya-Micay fault**	Right-lateral/oblique
42	**Remolino-El Charco fault**	Probably right-lateral/oblique
43	**Piedrancha fault**	Probably right-lateral/oblique
44	**Guaitara fault**	Right-lateral
45	**La Plata (Chusma) fault**	Right-lateral/reverse
46	**Irlanda fault**	Right-lateral
47	**La Dina fault**	Reverse/right-lateral
48	**Nazca subduction zone**	Thrust
49	**South Caribbean deformed belt (Colombia fault)**	Thrust/dextral oblique

Figure 2. Quaternary Faults of Colombia, most of them have experienced tectonic activity within the last 1.6my (black), some display Holocene surface rupture, less than 10.000 years (yellow) and a limited number exhibit historical o contemporary activity (red). Source: Map of Quaternary Faults and Folds of Colombia and Its Offshore Regions, scale 1:2.500.000 – International Lithosphere Program.

2. TECTONICS AND ITS IMPACT ON HTP

Tectonic processes vary greatly in their temporal scale—from the formation of mountain chains and oceanic basins over millions of years to the sudden creation of fault scarps during seismic events. Regardless of speed, tectonic movements can compromise HTP integrity—ranging from slow, continuous crustal displacements of centimeters per year to fault ruptures that propagate at speeds from 1 m/s to several km/s.

Common scenarios where hydrocarbon pipelines may be compromised by tectonic activity include:

2.1 Longitudinal gradient change in river channel

When a river or stream intersects a fault with vertical displacement—whether normal or reverse—a change occurs in the local base level. This creates a steeper gradient and increases channel erosion, which propagates upstream from the fault scarp. The resulting incision affects both the main channel and its tributaries. This can impact the right-of-way (ROW) and pipelines in two main ways:

- Increased slope height and steepness along the watercourse banks, which may trigger localized instability (rockfalls, landslides, etc.) with unstable masses depositing directly in the channel, affecting hydraulic capacity. This local instability can propagate upslope, potentially leading to larger failures and compromise the integrity of pipeline. The geological process begins in the riverbed but its effects extend to adjacent valley slopes.

- Increased channel bed incision, which can damage geotechnical works (check dams, retaining walls, etc.) and in more severe cases, expose the pipeline. The extent of incision depends greatly on the geologic material in the bed. Pipelines buried in alluvial, colluvial, or residual soils are more vulnerable to scouring and cover loss, while those in bedrock are better protected.

2.2 Regional tectonic uplift

In ROW located within tectonically active zones, vertical terrain displacement favors the development of higher and steeper slopes. Although this is a slow process (on the order of cm/year), over time (e.g., pipelines reaching 40–50 years), the cumulative movement can surpass the stability threshold and induce failure. Initially, this instability manifests as soil creep, but it may evolve into earthflows or landslides. This effect is more pronounced in slopes made up of thick colluvial or residual soil deposits (>5 m).

2.3 Ground rupture caused by fault movement

During seismic events, faults may rupture the ground surface, creating scarps that range from tens of meters to 100 km in length and from <1 m to 8 m in vertical displacement (Keller, 2002). Horizontal displacements can range from <1 m to up to 5 m (Hart et al., 1993). These instantaneous movements can cause severe damage; however, longer-term ground deformation can also occur via tectonic creep. In this process, active faults move slowly at rates of cm/year with imperceptible seismicity, yet over 3–4 decades, the accumulated deformation can significantly affect pipelines.

Each fault type affects pipelines differently. Faults with large vertical or horizontal displacement pose the greatest threat due to shear stress. Strike-slip faults exhibit larger horizontal movements, whereas normal and reverse faults have a stronger vertical component. The impact depends on the orientation of the fault relative to the pipeline axis.

In Colombia, most active faults trend NNE, parallel to the Andes. The main hydrocarbon transport pipelines cross the country east-to-west, intersecting multiple faults—many of which are poorly understood or insufficiently studied. A similar condition exists in other Andean nations, where several pipelines traverse Andes mountains to carry hydrocarbons from eastern Andean foothill basins and the Amazon Basin to Pacific ports and urban centers.

3. CONCLUSION

- Colombia´s location in a tectonic plate interaction zone favors the formation of active geological faults, which are distributed throughout the country and generally parallel the Andean.
- Active faults deform the Earth's crust and play a key role in shaping the land surface and influencing seismic activity
- Fault activity can impact the stability of pipeline ROWs and the integrity of the pipelines themselves. Slope failures, erosion, and deformation issues affecting HTP may be linked to neotectonic activity.
- Comprehensive knowledge of active faults and crustal displacement along ROWs is essential to optimize maintenance programs and improve pipeline integrity
- Neotectonic research coverage in Colombia is limited, less than 10% of fault traces with potential seismogenic behavior have been studied. Large-magnitude, high-recurrence seismic hazard zones remain largely unknown and warrant further investigation

ACKNOWLEDGEMENTS

This document is the result of several years of fieldwork and geotechnical assessment of ROW pipeline in Colombia, Ecuador, and Peru, through which the relationship between neotectonics and pipeline integrity has been evidenced.

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