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Uncertainty Analysis of Moment Tensor Solutions for Local Earthquakes around Colombia using ISOLA2024

Patricia Pedraza, Viviana Dionicio and William Peñaranda

Servicio Geológico Colombiano

INTRODUCTION AND MAIN RESULTS

Seismic moment tensor catalogs are essential for analyzing seismicity, active faults, and seismic hazards. However, the quality of these catalogs, especially for small and moderate earthquakes, is often influenced by significant uncertainties in their moment tensors. These uncertainties can arise from the inversion process or complex tectonic settings.

The uncertainty for local earthquakes in Colombia with m>5 is less than 10% across all components of the Moment Tensor. Conversely, for earthquakes with m<5, the uncertainty rises to 27%.

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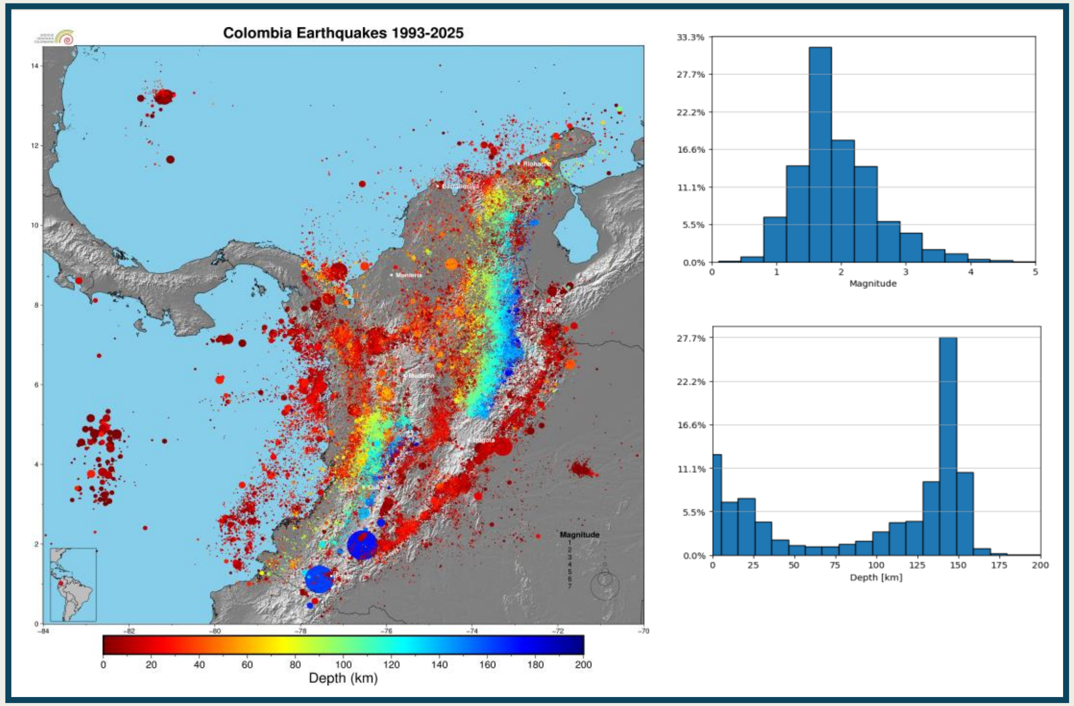
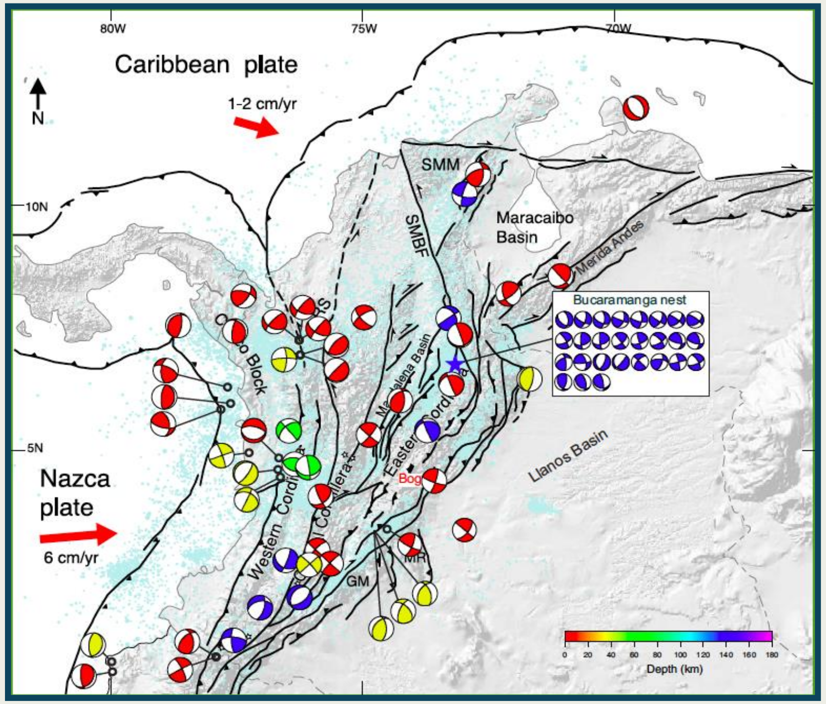
Introduction

Seismic activity in Colombia is influenced by the complex interactions between the Caribbean, Nazca, and South American tectonic plates, along with the Panama-Chocó Block. The country experiences a high level of seismic activity, averaging around 2,500 earthquakes each month. However, the majority of these earthquakes are of low magnitude, with over 99% having magnitudes below 4.0.

The Colombian Geological Survey has greatly enhanced its capability to calculate the Seismic Moment Tensor for earthquakes. This improvement was achieved through the use of various waveform inversion methods, which have enabled a deeper understanding of the country's seismic sources. Recently, Gisola software was adopted to automatically generate solutions. Its accuracy is assessed by comparing these with manual solutions obtained using Isola2024.





http://bdrsnc.sgc.gov.co/sismologia1/sismologia/focal_seiscomp_3/index.html

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Methods/Data

ISOLA2024 calculates Moment Tensor (MT) by the least-square solution in a grid point analogous Vackář et al., 2017.

$$m = (G^T\, Cd^{-1}\, G)^{-1} G^T\, Cd^{-1}\, d$$

m → model parameter (results)
G → matrix of Green's functions
Cd → data covariance matrix
d → data vector

Uncertainties given by model parameter covariance matrix

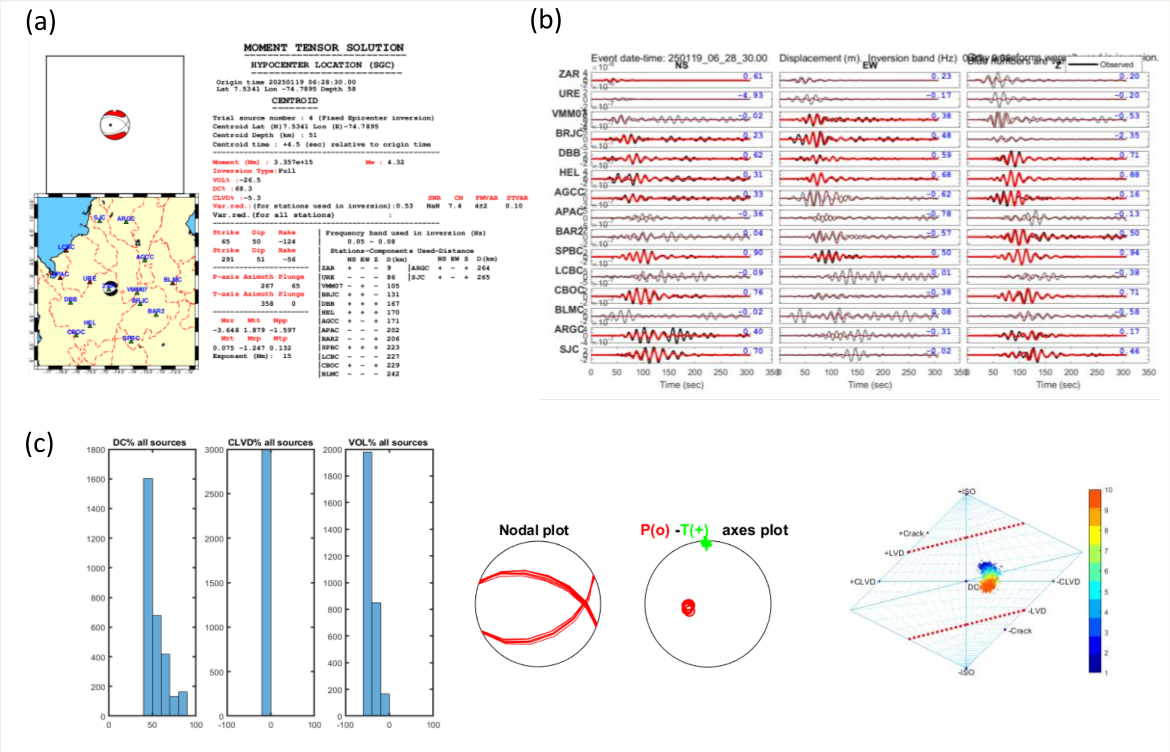
$$C^M = (G^T\, G_D^{-1}\, G)^{-1}$$

MT uncertainty depends on the source-station geometry, frequency range, and Earth's structure through G, and on data error through Cd.

$$misfit = (d_{obs} - G\,m)^T C_D^{-1} (d_{obs} - G\,m)$$

The Probability density (PPD) integrated over all MT parameters in a given space-time grid point.

$$C_i = \frac{1}{c}\sqrt{(2\pi)^6 \det C_i^M \exp\left(-\frac{1}{2} misfit_i\right)}$$



Example. Zaragoza, Antioquia earthquake. (a)Tensor moment calculated, epicenter (focal mechanism plot) and stations. (b) Waveform comparison at 0.05–0.08 Hz; observed (black) and synthetic seismograms (red) for the best-fil solution. Components with a disturbance (gray) were removed from inversion. (c) The uncertainty estimates.

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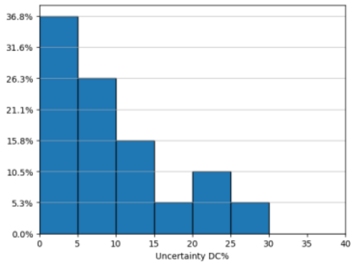
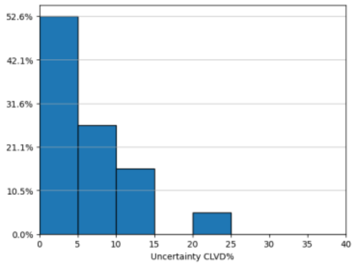
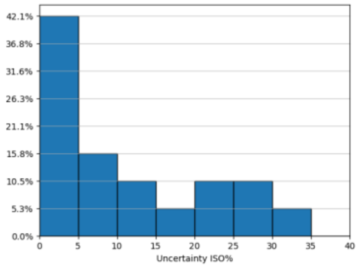
Results and conclusions

We assess the uncertainty of Centroid Moment Tensor (CMT) solutions using the latest features of the ISOLA2024 software, which includes basic statistics of non-DC components and their variations across grid-searched source positions. This allows us to evaluate the robustness of the solutions. Small and moderate earthquakes typically have significant uncertainties in their moment tensors (MT) and are likely artifacts of inversion or result from complex tectonic settings.

	Date	Frequency Range (Hz)	Plane 1 s/d/r (°)	plane 2 s/d/r (°)	Mw	DC(%) Best	CLDV (%) Best	ISO (%) Best	DC(%) μ ± σ	CLDV (%) μ ± σ	ISO (%) μ ± σ	VR
1	**2019-12-24**	**0.02-0.05**	**212/70/152**	**312/64/22**	**5.92**	**67.7**	**-31.4**	**-0.9**	**61.6 ± 6.0**	**-15.2±15**	**2.9±20.6**	**0.52**
2	2020-04-02	0.04-0.08	358/52/-115	216/45/-61	4.84	13.7	73.3	13.0	13.8 ± 1.0	72.1±1.2	14.1±1.8	0.57
3	**2020-04-15**	**0.02-0.04**	**6/78/-92**	**197/12/-79**	**5.80**	**79.6**	**-11.2**	**-9.2**	**82.5 ± 2.6**	**-9.4 ± 0.5**	**7.8 ± 3.5**	**0.75**
4	2020-05-10	0.05-0.08	61/80/92	228/10/77	4.51	42.9	56.9	-0.2	42.4 ± 5.2	54.9 ± 2.5	-1.6 ± 5.9	0.51
5	2023-04-05	0.05-0.08	294/54/83	127/36/100	3.82	50.6	33.8	33.8	42.2 ± 4.0	23.9 ± 2.9	33.9 ± 4.9	0.68
6	**2023-05-25**	**0.01-0.02**	**153/18/136**	**285/78/77**	**6.48**	**78.5**	**-20.0**	**-1.5**	**78.3 ± 4.3**	**-18.4 ± 3.3**	**-1.9 ± 3.3**	**0.90**
7	**2023-08-27**	**0.02-0.05**	**60/71/170**	**153/80/20**	**5.76**	**83.8**	**-7.5**	**8.7**	**83.7 ± 3.9**	**-7.8 ± 3.8**	**8.5 ± 0.8**	**0.68**
8	**2024-01-19**	**0.03-0.06**	**136/72/133**	**244/46/25**	**5.53**	**69.9**	**-8.1**	**22.0**	**85.9 ± 9.3**	**1.4 ± 6.0**	**8.9 ± 8.1**	**0.68**
9	**2024-01-21**	**0.03-0.06**	**112/78/28**	**15/63/166**	**4.94**	**53.8**	**32.6**	**13.7**	**54.3 ± 0.6**	**34.0 ± 2.3**	**11.7 ± 2.8**	**0.61**
10	2024-04-02	0.03-0.06	236/84/-178	146/88/-6	4.76	71.6	-27.4	-1.1	45.6 ± 26.6	-36.6 ± 11.1	15.4 ± 18.9	0.61
11	2024-06-07	0.04-0.07	70/87/-169	339/79/-3	4.13	88.5	-3.8	-3.8	75.6 ± 12.3	2.1 ± 8.8	-16.6 ± 11.2	0.49
12	2024-06-30	0.03-0.06	49/79/-25	145/65/-167	4.59	73.2	7.8	19.0	73.3 ± 0.8	7.3 ± 1.1	19.5 ± 1.2	0.57
13	2024-07-30	0.03-0.06	152/84/34	58/56/172	4.12	66.7	29.0	4.3	58.9 ± 5.4	31.8 ± 8.3	-3.5 ± 9.1	0.66
14	2024-08-28	0.05-0.08	13/81/-127	271/38/-15	4.75	81.7	-14.6	3.7	80.4 ± 4.6	-14.7 ± 4.0	4.9 ± 1.1	0.62
15	2024-10-31	0.05-0.08	255/82/165	347/75/8	4.13	83.4	0.1	-16.5	40.5 ± 23.4	22.1 ± 14.3	-29.5 ± 26.4	0.56
16	2024-10-31	0.05-0.08	213/57/118	349/42/54	3.99	81.0	15.4	3.6	58.3 ± 19.2	13.7 ± 8.3	24.2 ± 23.2	0.49
17	2024-12-24	0.05-0.09	186/75/123	297/36/25	4.06	88.3	-0.8	-10.9	67.4 ± 10.0	3.4 ± 3.2	16.2 ± 25.0	0.78
18	2024-12-24	0.05-0.08	47/53/-82	213/37/-101	4.55	42.4	39.6	-18	36.3 ± 5.4	40.1 ± 2.3	-23.6 ± 4.9	0.56
19	**2024-12-26**	**0.03-0.06**	**271/30/-44**	**37/64/-120**	**5.04**	**90.0**	**-0.8**	**-9.2**	**85.6 ± 6.0**	**-9.7 ± 6.4**	**-3.4 ± 8.0**	**0.75**
20	2025-01-04	0.05-0.08	72/31/151	187/76/63	4.32	46.1	34.3	-19.7	43.7 ± 1.8	36.8 ± 1.6	-19.4 ± 3.4	0.56
21	**2025-01-10**	**0.03-0.05**	**175/58/95**	**345/32/81**	**5.62**	**31.0**	**-52.5**	**-16.6**	**34.5 ± 7.7**	**-43.7 ± 10.9**	**-8.7 ± 21.6**	**0.60**
22	**2025-01-19**	**0.05-0.08**	**65/50/-124**	**291/51/-56**	**4.32**	**68.3**	**-5.3**	**-26.5**	**53.6 ± 11.3**	**-5.2 ± 1.3**	**-41.2 ± 10.8**	**0.53**
23	2025-03-10	0.05-0.08	128/40/57	348/58/114	4.06	53.3	14.0	32.6	24 ± 21.4	26.5 ± 24.6	30.5 ± 30.9	0.42
24	2025-04-18	0.03-0.06	127/76/-158	31/68/-15	4.90	97.4	2.0	0.7	91.0 ± 4.9	5.3 ± 3.13	1.2 ± 4.1	0.59
25	**2025-06-08**	**0.02-0.05**	**217/54/96**	**27/36/82**	**6.41**	**41.9**	**-44.2**	**-13.9**	**42.6 ± 2.1**	**-44.2 ± 2.3**	**-13.2 ± 2.6**	**0.64**







The uncertainty for Colombian local earthquakes m>5 is less than 10% for all components of the Moment Tensor. Conversely, for lower magnitude earthquakes m<5, the uncertainty rises to 27%.

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Results and conclusions

Comparison GCMT - ISOLA2024 and GISOLA solutions

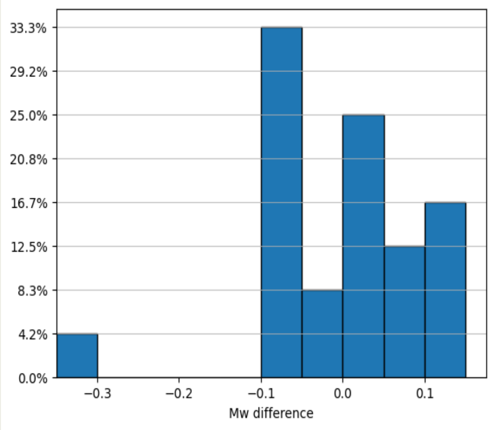
For earthquakes with Mw > 5.0, the reliability of the CMT is assessed by comparing it with the Global-CMT solutions. The automatically generated solutions show similar quality to those produced manually. The average Kagan angle between the manual solutions is 12°, and for the automatic solutions, it is 17°.

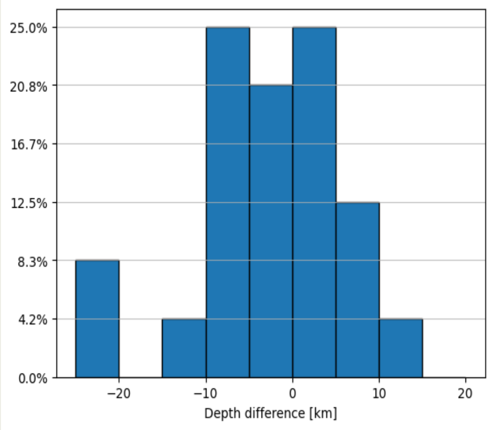
Event ID	Location	GCMT	ISOLA24			GISOLA		
		FM	FM	Kagan angle	Quality	FM	Kagan angle	Quality
20191224	Mesetas, Meta			5.4	A		19.0	B
20200415	Mompós, Bolivar			10.4	A		12.2	A
20230525	Golfo de Urabá			2.4	A		16.3	B
20230827	Cantón, Chocó			18.1	B		17.6	B
20240119	Ansermanuevo, Valle			6.4	A		7.4	A
20240121	Nido de Bucaramanga			12.9	A		24.8	B
20241226	Tarazá, Antioquia			14.9	A		12.4	A
20250110	Oceano Pacífico			23.3	B		37.9	C
20250608	Medina, Cundinamarca			14.9	A		5.2	A

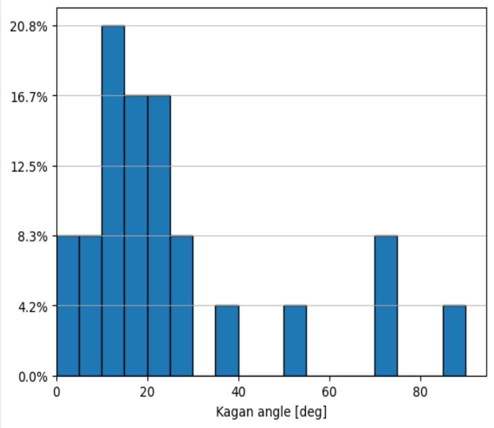
Kagan angle	Similarity between mechanisms
0 - 15°	Very high (almost identical)
15 - 30°	Good correspondence
30 -45°	Moderate differences
> 45°	Distinct mechanisms

Comparison ISOLA2024 and GISOLA solutions

The moment tensor solutions for 25 events calculated by the automatic method of Gisola are compared with those obtained manually using ISOLA2024, which were derived from the complete seismic tensor inversion.







Comparing Gisola solutions with ISOLA2024 showed that for most of the 25 events, the results were consistent, with magnitude differences under 0.1, depth differences below 20 km, and an average Kagan angle of 28°.

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