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Data article

Moment tensor and focal mechanism data of earthquakes recorded by Servicio Geológico Colombiano from 2014 to 2021

Datos de tensor de momento y mecanismo focal de sismos registrados por el Servicio Geológico Colombiano desde 2014 hasta 2021

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ABSTRACT

The Servicio Geológico Colombiano shows the seismic moment tensors and focal mechanisms calculated for earthquakes located in the national territory and border regions from 2014 to 2021. These solutions were obtained using different methods based on waveform inversion (SWIFT, SCMTV, W phase, and ISOLA) and first-motion polarities (FPFIT). This information is organized in a database and is available to the public through a web page that can be searched by date, circular area, or quadrant. The moment tensor centroid solutions are fundamental to understanding the fault's geometry, the seismic source generated by an earthquake, its magnitude, and the energy released. Likewise, thanks to this information it is possible to make interpretations about tectonic plates, Earth's crust stress analysis and its dynamics, kinematic and dynamic source models, active faults analysis, and tsunamigenic potential of earthquakes, among other aspects.

Key words: Seismic Moment Tensor, Focal Mechanism, SWIFT, SCMTV, W phase, ISOLA, first-motion polarities, seismology

RESUMEN

El Servicio Geológico Colombiano presenta los tensores de momento sísmico y mecanismos focales calculados para sismos localizados en el territorio nacional y regiones fronterizas desde 2014 hasta 2021. Estas soluciones se obtuvieron usando diferentes métodos basados en inversión de formas de onda (SWIFT, SCMTV, Fase W e ISOLA) y polaridades de primeros arribos (FPFIT). Esta información se ha organizado en una base de datos y se ha dispuesto al público mediante una página web por medio de la cual se pueden hacer búsquedas por fechas, área circular o cuadrante. Las soluciones del centroide del tensor de momento son fundamentales para comprender la geometría de la falla, la fuente sísmica que produce un sismo, su magnitud, y la energía liberada por el mismo. Igualmente, gracias a esta información es posible hacer interpretaciones sobre la tectónica de placas, análisis de esfuerzos de la corteza terrestre y su dinámica, modelos dinámicos y cinemáticos de la fuente, análisis de fallas activas y potencial tsunamigénico de sismos, entre otros aspectos.

Palabras clave: Tensor de Momento Sísmico, Mecanismo Focal, SWIFT, SCMTV, W phase, ISOLA, polaridades de primeros arribos, sismología

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1. INTRODUCTION

The Servicio Geológico Colombiano (SGC) made great efforts to calculate earthquakes' Seismic Moment Tensor (SMT) and Focal Mechanism (FM) in recent years, using different methods of waveform inversion and first-motion polarities, to have information that allows us to better understand the country seismic sources. The variety of methodologies is mainly due to the National Seismological Network of Colombia (RSNC, from its abbreviation in Spanish) evolution, station densification in the territory, as well as its instrumental and technological updating in the data acquisition and processing software. Also, having a variety of methodologies for SMT calculation allows for controlling the solution's quality and stability, turning the SGC earthquake catalogs into self-sustainable tools over time.

The Servicio Geológico Colombiano is the official entity that provides information on earthquakes in Colombian territory and is part of the National System for Disaster Risk Management. Therefore, through the RSNC, the SGC monitors seismicity in real-time permanently twenty-four hours a day, seven days a week.

Thus, when an earthquake is recorded, the information associated is immediately calculated, including seismic moment tensor and focal mechanism for those earthquakes that allow it. This information is stored in a database and is available to the public in real-time. This article presents the SMT and FM from 2014 to 2021, but we clarify that this database is constantly updated accounting for the SGC mission.

This database can be used by any researcher interested in geophysics, tectonics, or seismology to do their processing, modeling, or interpretation. Although they allow scientific analysis, they are also important tools for risk management plans and land use planning. Therefore, these data became of great impact on the scientific community as well as decision-makers.

Furthermore, this database extends and enhances efforts historically made determining focal mechanisms in the region at both the national and local levels by other researchers such as Molnar and Sykes (1969), Kafka and Weidner (1981), Pennington (1981); Audemard et al (2005), Cortés and Angelier (2005), Palma et al. (2010), Dicelis et al. (2016), Gómez-Alba et al. (2016), Poli et al. (2016), Posada et al. (2017), Yoshimoto et al. (2017); Monsalve-Jaramillo et al. (2018), Chang et al. (2019), Londoño et al. (2019), Poveda et al. (2022), Quintanar et al. (2022), Tary et al. (2022), Bishop et al. (2023).

Although there are international SMT catalogs with events information in Colombia, like Global Centroid Moment Tensor Catalog (Dziewonski, et al., 1981; Ekström, et al., 2012), the German GEOFON project (Hanka and Kind, 1994; Saul et al., 2011; GFZ, 2023), from the German Research Centre for Geosciences (GFZ) and the United States Geological Survey (https://www.usgs.gov/programs/earthquake-hazards), among others, the SGC can calculate a larger number of solutions since installed seismological stations quality and distribution in the country allow better stability to solutions for earthquakes with moderate magnitudes.

The SGC also has some catalogs with seismicity recorded in the country, which may be useful for the reader: Viewer of seismological information (Visor información sismológica) in real-time at: https://www.sgc.gov.co/sismos, Seismicity catalog (Catálogo de sismicidad) at: http://bdrsnc.sgc.gov.co/paginas1/catalogo/index.php, Accelerations catalog (Catálogo de aceleraciones) at: http://bdrsnc.sgc.gov. co/paginas1/catalogo/index_rnac.php, Macro seismic intensity data and effects of significant earthquakes in Colombia based on historical seismicity studies (Datos de intensidad macrosísmica y efectos de los sismos significativos de Colombia a partir de estudios de sismicidad histórica) at: http://sish.sgc.gov.co/visor/ (Sarabia Gómez et al. 2022), Integrated Seismic Catalog for Colombia (Catálogo Sísmico Integrado para Colombia), as input or reference to generate hazard models and characterize seismogenic sources at: https://catalogosismico.sgc.gov.co/visor/index.html (Montejo et al., 2023).

2. DATA DESCRIPTION

Data correspond to seismic moment tensors and focal mechanisms calculated by the SGC for earthquakes located in the national territory and border regions from 2014 to 2021 (Figure 1). The solutions were obtained using different methods based on waveform inversion and first motion P-waves polarities and systematically compared with calculated Global Centroid Moment Tensor catalog solutions (Dziewonski et al., 1981; Ekström et al., 2012) to ensure their quality (Figure 4). Notice the importance of a station good distribution that records each earthquake to calculate the solutions with those different methods, so the earthquake azimuthal coverage is as homogeneous as possible.

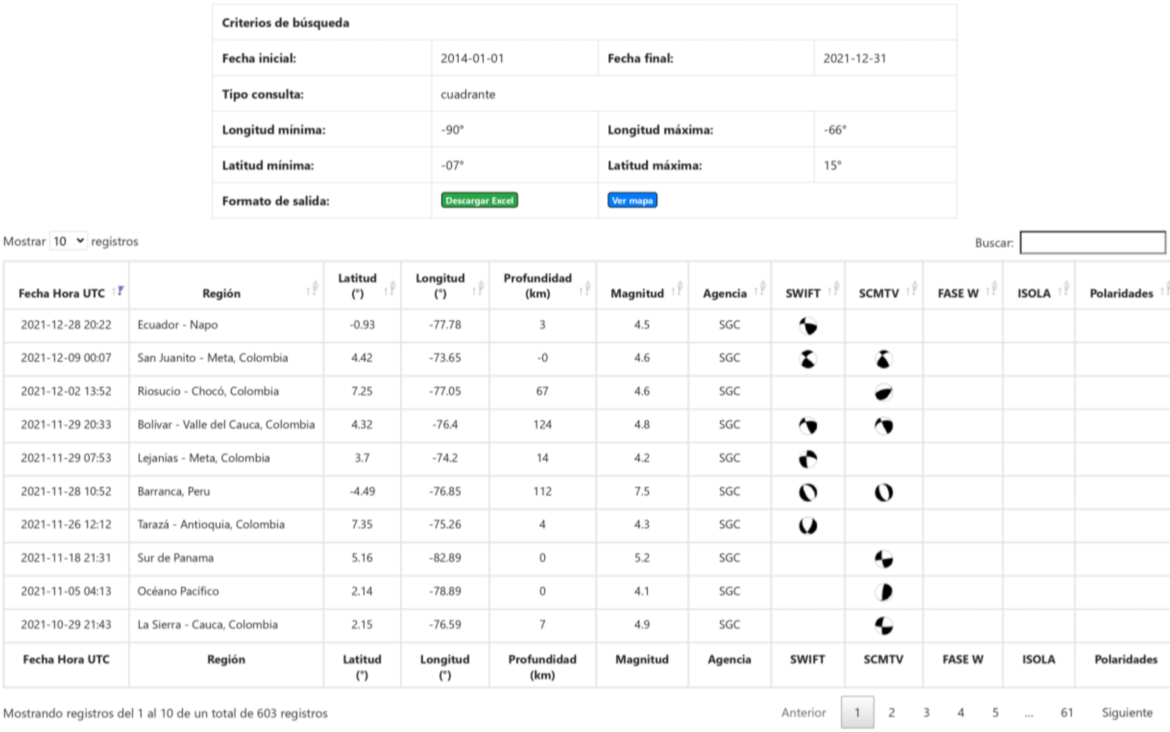
Moreover, for waveform inversion methods it is necessary to use broadband stations; since 2008 the SGC started a densification process and instrumental updating of the National Seismological Network of Colombia (RSNC), achieving a stable and fairly uniform stations distribution in 2014, making possible the proper methodologies implementation for moment tensor calculation and focal mechanisms.

A database stores the results and contains the solutions of each earthquake for the used methods to calculate them (described in "materials and methods"). At the web page http://bdrsnc.sgc.gov.co/sismologia1/sismologia/focal_seiscomp_3/index.html the users can access to focal mechanism and moment tensor catalog data, the search can be simple (including only initial and final dates), or, if preferred, with additional advanced parameters (for example, to select results in a circular geographic region or latitude-longitude quadrant). As a result of this search, a list is obtained with seismic events with focal mechanisms and moment tensors for the selected dates and areas. The table contains: UTC (Universal Time Coordinated) date and time, region, latitude, longitude, depth, magnitude, location agency, and solutions obtained selected by the used method, showing the focal mechanism graphical representation. By clicking on it the user can access further information. The table can be organized by any of its columns and either download an Excel file with the results or be represented automatically on a map (Figures 1 and 2).

For each method, are presented the focal mechanism, the moment tensor solution including the centroid location, moment, moment magnitude (M_w), depth, nodal planes, principal axes, and moment tensor, as applicable.

An example of a solution with the SWIFT method (Source parameter determination based on Waveform Inversion of Fourier Transformed seismograms) is shown in Figure 3. The maps are also shown with the solution, the waveform matches obtained from the inversion with observed and synthesized seismograms, and the source-time function (the latter is only shown for the SWIFT method).

Figure 1. Focal mechanisms calculated by the SGC of earthquakes occurred between 2014 and 2021. From each focal mechanism, the user can access the detail of the moment tensor solutions for each earthquake.



Criterios de búsqueda			
Fecha inicial:	2014-01-01	Fecha final:	2021-12-31
Tipo consulta:	cuadrante		
Longitud mínima:	-90°	Longitud máxima:	-66°
Latitud mínima:	-07°	Latitud máxima:	15°
Formato de salida:	Descargar Excel	Ver mapa	

Mostrar 10 registros — Buscar:

Fecha Hora UTC	Región	Latitud (°)	Longitud (°)	Profundidad (km)	Magnitud	Agencia	SWIFT	SCMTV	FASE W	ISOLA	Polaridades
2021-12-28 20:22	Ecuador - Napo	-0.93	-77.78	3	4.5	SGC					
2021-12-09 00:07	San Juanito - Meta, Colombia	4.42	-73.65	-0	4.6	SGC					
2021-12-02 13:52	Riosucio - Chocó, Colombia	7.25	-77.05	67	4.6	SGC					
2021-11-29 20:33	Bolivar - Valle del Cauca, Colombia	4.32	-76.4	124	4.8	SGC					
2021-11-29 07:53	Lejanias - Meta, Colombia	3.7	-74.2	14	4.2	SGC					
2021-11-28 10:52	Barranca, Peru	-4.49	-76.85	112	7.5	SGC					
2021-11-26 12:12	Tarazá - Antioquia, Colombia	7.35	-75.26	4	4.3	SGC					
2021-11-18 21:31	Sur de Panama	5.16	-82.89	0	5.2	SGC					
2021-11-05 04:13	Océano Pacifico	2.14	-78.89	0	4.1	SGC					
2021-10-29 21:43	La Sierra - Cauca, Colombia	2.15	-76.59	7	4.9	SGC					
Fecha Hora UTC	Región	Latitud (°)	Longitud (°)	Profundidad (km)	Magnitud	Agencia	SWIFT	SCMTV	FASE W	ISOLA	Polaridades

Mostrando registros del 1 al 10 de un total de 603 registros — Anterior 1 2 3 4 5 … 61 Siguiente

Figure 2. Results from a search of the focal mechanism and moment tensor catalog calculated by the SGC.

3. DATA RELEVANCE

This is the catalog of centroid moment tensor solutions and focal mechanisms located in Colombia and its border regions from 2014 to 2021 (this catalog is routinely updated by the SGC, so it contains information from later years), and comprehends the solutions calculated with acceptable quality (variance < 70% usually).

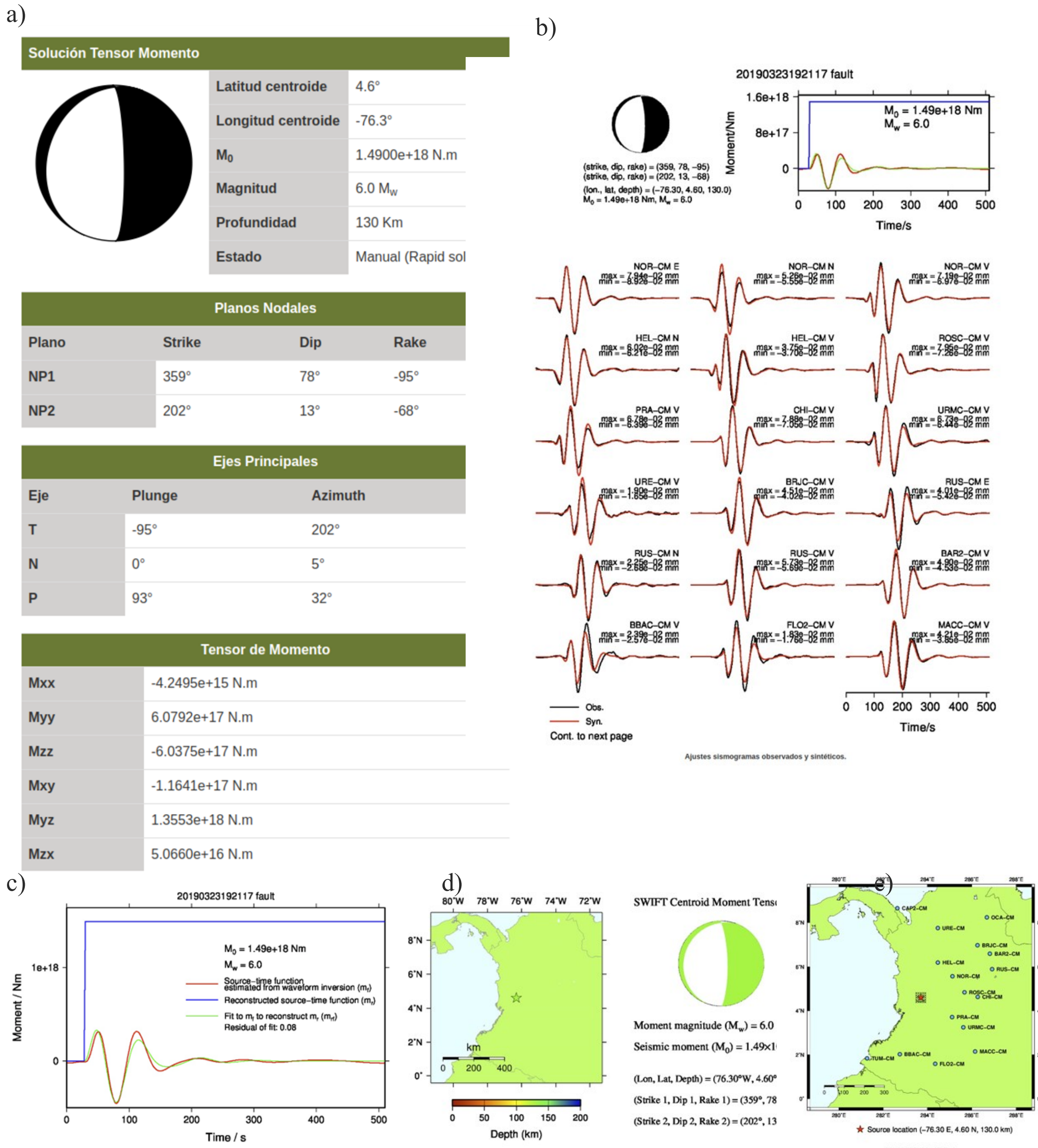
Unlike other international catalogs, the SGC can calculate a greater number of solutions considering the distribution and quality of the seismological stations installed across the country, allowing greater stability in the solutions for earthquakes with moderate magnitudes.

Data can be used by any researcher interested in geophysics, tectonics, or seismology to do their processing, modeling, or interpretation.

Likewise, they are an important tool for the generation of risk management and land-use planning plans. The latter, considering that the information on location, moment magnitude and seismic source characterization of moderate to large magnitude earthquakes can be considered in national and regional seismic hazard maps generation and updating.

4. DATA ACCESS

Data on moment tensor and focal mechanism calculated by the SGC are in a database freely accessible from the institute's website (Table 1).



Solución Tensor Momento	
Latitud centroide	4.6°
Longitud centroide	-76.3°
M_0	1.4900e+18 N.m
Magnitud	6.0 M_W
Profundidad	130 Km
Estado	Manual (Rapid sol

Planos Nodales			
Plano	Strike	Dip	Rake
NP1	359°	78°	-95°
NP2	202°	13°	-68°

Ejes Principales		
Eje	Plunge	Azimuth
T	-95°	202°
N	0°	5°
P	93°	32°

Tensor de Momento	
Mxx	-4.2495e+15 N.m
Myy	6.0792e+17 N.m
Mzz	-6.0375e+17 N.m
Mxy	-1.1641e+17 N.m
Myz	1.3553e+18 N.m
Mzx	5.0660e+16 N.m

Figure 3. Results of a moment tensor solution with the SWIFT method calculated by the SGC for the March 23, 2019 earthquake, located in Versalles - Valle del Cauca, depth 126 km. a) Seismic moment tensor inversion results, b) the waveform matches obtained from the inversion with observed and synthesized seismograms, c) source time function, d) location map and centroid solution of the seismic moment tensor, e) location map of seismic source and the available stations for the inversion.

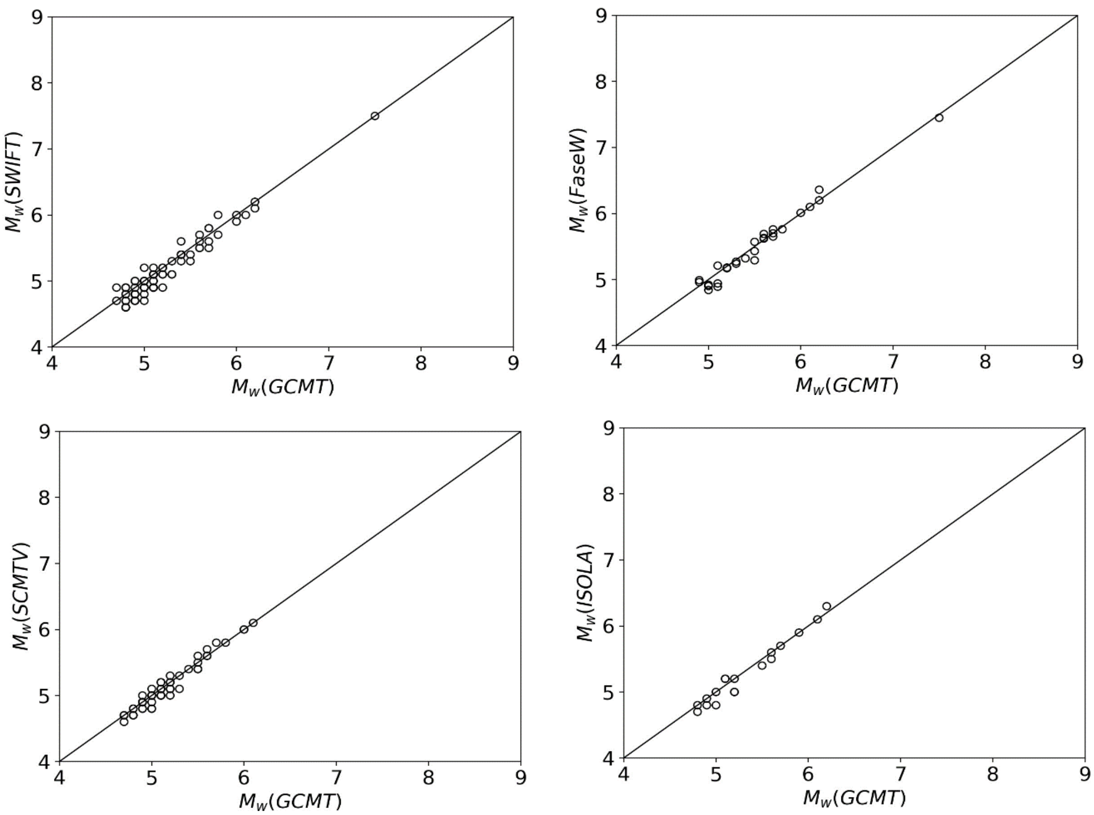


Figure 4. ***M_w*** **from GCMT compared to** ***M_w*** **from SGC resulting after moment tensor inversions calculated through different methodologies for the 2014 - 2021 period. Top left SWIFT, top right W phase, bottom left SCMTV, and bottom right ISOLA.**

Table 1. Data specifications

Subject	Geophysics, seismology, tectonics, geology, geodynamics
Specific subject area	Seismology
Data type	Table/ Image/ Map / Chart /Figure
How data was acquired	Primary data were seismograms from seismological stations (Seismic event data download (Servicio de descarga de datos de eventos sísmicos) at http://sismo.sgc.gov.co:8080/). From short-period stations, only the first-motion polarities data were used (polarities method). From broadband stations, in addition to these, full seismograms were also used in the seismic inversion methods described in the materials and methods section. Furthermore, the locations of the earthquakes were used as initial data (Seismic Catalog (Catálogo sísmico) at http://bdrsnc.sgc.gov.co/paginas1/catalogo/index.php).
Data format	Processing result for focal mechanisms calculation and moment tensor: graphs, figures, and tables.
Data collection parameters	Earthquake location, quality of signals and solutions were considered.
Description of data collection	The database contains all earthquake inversions in the national territory and its borders, for which it was possible to calculate the moment tensor/focal mechanism with a minimum quality to trust the results.
Data source location	South America/Colombia Longitude between -90° and -66° and latitude between -7° and 15°.
Data accessibility	http://bdrsnc.sgc.gov.co/sismologia1/sismologia/focal_seiscomp_3/index.html

5. MATERIALS AND METHODS

The moment tensors and focal mechanisms were calculated using different methods:

5.1 SWIFT (Source parameter determination based on Waveform Inversion of Fourier Transformed seismograms), proposed by Nakano et al. (2008): It is a waveform inversion method to estimate both the moment function and the centroid of the moment tensor of an earthquake quickly and routinely. For this method, the waveform inversion is carried out in the frequency domain to obtain the momentum function faster than when solving in the time domain. A pure double-couple (also called double-pair) source mechanism is assumed to stabilize the solution. The fault and slip orientations are estimated by a grid search respect to strike, dip and slip angles. The time domain moment function is obtained from the inverse Fourier transform of frequency components determined by the inversion. The source location is determined by a grid search using adaptive grid spacing, which is gradually reduced at each step of the search.

5.2 SCMTV (SeisComP Moment Tensor inVersion), a module implemented in the SeisComP3 software package (Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences and gempa GmbH, 2008; https://docs.gempa.de/mt/current/apps/scmtv.html#methodology; https://gfzpublic.gfz-potsdam.de/pubman/faces/ViewItemFullPage.jsp?itemId=item_108170). This algorithm calculates the deviatoric part of the momentum tensor assuming a point source. For this purpose, it inverts the entire waveform (body waves, surface waves, and the W phase). Phase type selection is based on magnitude (for filter selection) and epicentral distance of seismic event (for window calculation upon theoretical arrival times). The inversion methodology is based on Minson and Dreger's (2008) proposal.

5.3 W phase, algorithm proposed by Kanamori and Rivera (2008): It inverts the W phase (Kanamori, 1993), a long period signal arriving before the S-wave, which can be interpreted as the superposition of the fundamental first, second, and third overtones of spheroidal modes or Rayleigh waves and has a group velocity of 4.5 to 9 km s^{-1} in a period range of 100-1000 s. Amplitudes of long-period waves best represent the tsunami potential of an earthquake. Due to the W phase rapid group velocity, most of the energy is contained within a short time window after the P-wave arrival. The time domain deconvolution method is used to extract the W phase of the vertical component of broadband records from seismic networks, and a linear inversion is performed using a point source to determine M_w and the source mechanism.

5.4 ISOLA (ISOlated Asperities), a software package developed by Sokos and Zahradnik (2008, 2013): Performs waveform inversions to find source parameters; is based on FORTRAN codes and provides an easy-to-use MATLAB graphical user interface (GUI) (www.mathworks.com/products/MATLAB). It allows the waveform iterative deconvolution inversion (Kikuchi and Kanamori, 1991) for regional and local events, both for single- and multiple-point-source. The moment tensor is obtained through a least-squares inversion, while the position and origin time of point sources are searched on a grid. Computational options include inversion to recover the full moment tensor (MT), the deviatoric MT, and the pure double-coupled MT. Finite-extent source inversions can also be obtained by prescribing a priori the double-coupled mechanism (to remain homogeneous over the fault plane); Green's functions are obtained by including the near-field terms.

5.5 Polarities: The focal mechanism is computed using the FPFIT program (Reasenberg and Oppenheimer, 1985). It finds the double-coupled fault plane solution (source model) that best fits a given set of observed first-motion polarities for an earthquake. The inversion is done through a two-stage grid search procedure, which identifies the source model by minimizing a normalized weighted sum of first-motion polarity discrepancies. The minimization incorporates two weighting factors: data estimated variance and the absolute value of the theoretical P-wave radiation amplitude (Aki and Richards, 1980). The latter weighting adds a higher weight to observations near radiation lobes, and a lower weight to those close to nodal planes. For each double-couple source model obtained, FPFIT estimates uncertainty model parameters (strike, dip, and rake) by calculating their standard deviation.

Afterward, a uniformly distributed set of solutions is calculated that falls into the estimated uncertainty range. This set is used in the FPPLOT display program (https://www.usgs.gov/software/fpfit-fpplot-and-fppage) via SEISAN software (Ottemöller et al, 2021) to define the orientation range of the P and T axes graphically based on data.

The National Seismological Network of Colombia has improved over time in both seismological instrumentation and data acquisition and processing systems. From 2014 to

2017 the SGC used SEISAN as data processing system, so the FPFIT software was used for focal mechanisms calculation; likewise, to calculate moment tensors mainly focused on tsunami warnings for large earthquakes, the W phase method was implemented calculating automatically SMT and sending the solutions by emails. Moreover, by the same period, the ISOLA method was used to calculate moment tensor for earthquakes with moderate to large magnitudes, but was not automated as the waveforms were processed manually.

Simultaneously, between 2016 and 2017, SeisComP software for data acquisition, processing, publication, and dissemination was installed, configured, and tested, with the great advantage of everything integrated, going into production in March 2018. This system incorporates the SCMTV method for moment tensor inversion, hence it was incorporated as a methodology for real-time processing at the SGC. Likewise, in 2015 the SGC along with other Colombian institutions and the Japan International Cooperation Agency on behalf of different Japanese entities, jointly initiated a SATREPS (Science and Technology Research Partnership for Sustainable Development) project entitled "Project for application of state of the art technologies to strengthen research and response to seismic, volcanic and tsunami events, and enhance risk management*"* with an initial duration of 5 years extended for 2 more years. Under this project, was installed, configured, tested, and put into production SWIFT software for moment tensor calculation, focused on obtaining seismic source information for moderate to strong earthquakes in a reliable and fast way, with a methodology also integrated with SeisComP and everything was articulated to fully link it to SGC information dissemination system.

Currently, the Polarities method is not routinely used, because it is less stable than waveform inversions and is not integrated with our data acquisition and processing software; for waveform inversion methods these polarities are considered. The ISOLA method is used only for some very representative earthquakes in the country or for detailed seismic source studies, but is not routinely used due to the longer processing time; however, the Gisola software (Triantafyllis et al. 2021), based on the same methodology as ISOLA, but automates all the data processing, is currently tested; once it is in production, likely the database information of this article will be updated with those results. W phase, SWIFT, and SCMTV methods work in real-time routinely, automatically, and the results are reviewed by an expert before publishing reports as a fundamental information provided by the SGC to the Risk Management System and to the public.

The SGC considers important to have different calculation methods for seismic moment tensors, not only because depending on the methodology results can be obtained for lower magnitudes, but also to control the quality and stability of solutions for moderate to large magnitude earthquakes, which are ones that could have the greatest impact on the Colombian territory. Comparison of different solutions demonstrates the consistency of the results and allows the various SGC seismic catalogs to be self-sustaining, especially in real-time, since solutions from other international catalogs sometimes take longer to be published.

For all SMT methodologies, the moment magnitude is calculated using the ratio of scalar moment to moment magnitude cited by Kanamori (1977), Hanks and Kanamori (1979) and Bormann et al. (2013):

$$M_w = (\log M_0 - 9.1)/1.5 = (2/3)(\log M_0 - 9.1) \text{ in SI o}$$
$$M_w = (2/3)(\log M_0 - 16.1) \text{ CGS units,}$$

Personal communications with authors of the methodologies confirmed that each of them uses the following ratios: SWIFT implements $M_w = (\log M_0 - 9.1)/1.5$, W phase implements $M_w = (2/3)(\log M_0 - 16.1)$, ISOLA implements $M_w = (2/3)(\log M_0 - 9.1)$ y SCMTV implements $M_w = (\log M_0 - 9.1)/1.5 = (2/3)(\log M_0 - 9.1)$.

6. USES OF THE DATA

Seismic moment tensor centroid solutions are fundamental to understanding fault geometry, the seismic source producing an earthquake, its magnitude, and the energy released (e.g., Stein and Wysession, 2003). Furthermore, using this information, interpretations of plate tectonics, crustal dynamic and stress analysis, kinematic and dynamic source models, and active fault analysis, among others, are possible (e.g., Shearer, 2019). Likewise, based on this data, it is possible to have information on the tsunamigenic potential of an earthquake and thus assess to alert communities for a possible evacuation (Tilling, 2022).

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CONFLICT OF INTEREST

The authors declare that they have no financial interests or competing personal relationships that could affect the work reported in this paper.

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