Magnetostratigraphy of the Girón Group, Colombia (northern Andes, Colombia)

Giovanny Jiménez1,2, Helbert García-Delgado1, and John W. Geissman2,4

1Escuela de Geología, Universidad Industrial de Santander, Carrera 27 Calle 9, Bucaramanga 680002, Colombia
2Department of Geosciences, University of Texas at Dallas, ROC 21, 800 West Campbell Road, Richardson, Texas 75080, USA
3Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131, USA

ABSTRACT

We report paleomagnetic results from the Jurassic to Lower Cretaceous continental sedimentary succession exposed in the eastern limb of the Los Yariguíes anticlinorium, Eastern Cordillera, Colombia. About 820 m of a stratigraphic section of the upper part of the Girón Group (Angostura del Río Lebrija and Los Santos Formations) was sampled to construct a magnetic polarity stratigraphy. A total of 199 independent samples that yield interpretable and acceptable data have a characteristic remanent magnetization component (ChRM) isolated between 400 °C and 680 °C in progressive thermal demagnetization. Demagnetization behavior and rock magnetic properties are interpreted to indicate that hematite is the principal magnetization carrier with a possible contribution by magnetite in some parts of the section. After tilt correction, 123 samples are of normal polarity (declination $\Delta = 44.9^\circ$, inclination $I = +9.7^\circ$, $R = 110.64$, $k = 9.87$, and $\alpha_{95} = 4.3^\circ$), and the other 76 accepted samples are of reverse polarity ($\Delta = 216.4^\circ$, $I = -6.1^\circ$, $R = 68.29$, $k = 9.72$, and $\alpha_{95} = 5.5^\circ$). The statistical reversal test conducted on virtual geomagnetic poles is acceptable (class B). Based on paleontologic age estimates for the Cumbre and Rosablanca Formations, we assume a Berriasian age for the Los Santos Formation. The magnetostratigraphic data from the Girón Group strata are interpreted to suggest an age for the sampled part of the section between early Kimmeridgian and early Valanginian (ca. 157–139 Ma). The age of the Angostura del Río Lebrija Formation is estimated as between early Kimmeridgian and early Tithonian (ca. 157–146.5 Ma). The age of the Los Santos Formation is estimated between early Tithonian and early Valangian (146.5–139.3 Ma). With our proposed, but nonunique, correlation with the Geomagnetic Polarity Time Scale, the Jurassic-Cretaceous boundary is interpreted to be located within the Los Santos Formation. The Girón Group is characterized by two periods of high (>8 cm/k.y.) and two periods of low (<2 cm/k.y.) sedimentation rates. An inferred clockwise rotation of ~44°, based on paleomagnetic declination data from the Girón Group, is similar to rotation estimates reported in some previous studies in the general area, and this facet of deformation could be related to local and regional response to displacement along regional-scale strike-slip faults.

INTRODUCTION

The early Mesozoic tectonic evolution of northwestern South America (i.e., the northernmost Andes) has been the subject of several decades of research, yet some aspects of the tectonic history of this area remain controversial. At least three different tectonic settings for northwestern South America during the Triassic and Jurassic Periods have been proposed: (1) an intracontinental rift (Mojica and Kammer, 1995; Cediel et al., 2003), (2) an essentially static configuration of the continental margin attending the slab rollback (Spikings et al., 2015), and (3) an array of parautochthonous to autochthonous terranes along the westernmost margin of the South American paleoplateau (Bayona et al., 2006, 2010, 2020) that were partly disrupted via structures with right-sense transtensional shear component (Bayona et al., 2006; Sarmiento-Rojas et al., 2008).

Extensive exposures of Jurassic sedimentary rocks are present in the Colombian Andes, and these sequences form the sedimentary core of several regional northeast-trending structures. Structures include the regional-scale Arcabuco and Los Yariguíes anticlinoria in isolated igneous-metamorphic masifs such as the Floresta, Santander, and the Santa Marta massifs, or exhumed areas adjacent to major regional structures such as the Perijá Range (Fig. 1). In our study area, the Los Yariguíes anticlinorium (also known as the Los Cobardes anticline), sedimentary strata thought to be Jurassic to Early Cretaceous in age are considered to be part of the Girón Group, a thick, continental, largely fluvial-facies sedimentary sequence that is well exposed along the Eastern Cordillera (Figs. 1 and 2) (Cediel, 1968; Pons, 1982; Etayo-Serna and Rodriguez, 1985; Laverde, 1985; Horton et al., 2010, 2015; Osorio-Afandar, 2018).

One of the key challenges regarding a better understanding of the tectonic setting and the evolution of the continental margin in northwestern South America is the lack of reliable chronostratigraphic control for stratigraphic sequences that could be used for tectonostratigraphic analysis and improved regional correlations. Most sedimentary sequences, inferred to be of Jurassic age, in the area contain limited fossil assemblages (specifically, plant fossils); the uncertainty in ages is basically due to poor fossil preservation in the depositional environment of these strata (Brueckner, 1954; Langenheim, 1961; Pons, 1982). Detrital zircons yield U-Pb dates that imply an approximate maximum deposition age of ca. 166 Ma (Horton et al., 2010, 2015). Approaches for dating...
the Jurassic sequences in the Middle Magdalena Valley have resulted in a
low-resolution chronologic framework (Brueckner, 1954; Langenheim, 1961;
Cediel, 1968; Pons, 1982; Etayo-Serna and Rodríguez, 1985; Horton et al., 2010,
2015), leading to complexities in inferring the tectonic setting at the time of
deposition (Fig. 2). The importance of a better understanding of the deposi-
tional history of the Girón Group is based on the need to correlate middle
Mesozoic continental sequences in northwestern South America (Fig. 2), thus
providing improved resolution among existing tectonic models. The main
goal of our present study is to provide improved depositional age estimates
for the sequence of Girón Group strata based on magnetic polarity stratig-
raphy, and this information in turn provides estimates of the overall rate of
sediment deposition for this sequence. We also interpret the paleomagnetic
data from these rocks in the overall context of post–Girón Group deformation,
including estimates of latitudinal translation of the general study area since
the deposition of the Girón Group.

Previous Paleomagnetic Investigations of Jurassic Sedimentary Strata

The earliest paleomagnetic studies in the northern Andes of Colombia
focused on Jurassic–Cretaceous rocks exposed in La Guajira (MacDonald and
Opdyke, 1972), the Bucaramanga area (Creer et al., 1970), the Santander massif
(Hargraves et al., 1984), the Perijá Range (Maze and Hargraves, 1984), and the
Santa Marta massif (MacDonald and Opdyke, 1984) (Fig. 1). Paleomagnetic
results from Middle Jurassic and Lower Cretaceous strata in Mérida Andes,
Venezuela (Castillo et al., 1991), have been interpreted to suggest no significant
paleolatitudinal translations. Paleomagnetic results in the Floresta massif and Bucaramanga zone (Bayona et al., 2006) and the Santa Marta massif (Bayona et al., 2010) are interpreted to suggest the Lower to Middle Jurassic rocks were translated from more southern to near-equatorial latitudes. We note that the interpretations provided by the authors in all of these studies, however, did not account for the possibility of appreciable inclination shallowing due to sediment compaction and related processes. According to Bayona et al. (2006), in the Bucaramanga area, the inferred counterclockwise rotations of ~90°, as based on paleomagnetic declination data, are related to the displacement of arrays of fault-bounded blocks. These workers argued that these rotations took place before syn-extensional deposition of Jurassic to Lower Cretaceous sequences. Further south, in the Upper Magdalena Valley, Jiménez et al. (2012) documented moderate (~15° to ~30°) clockwise rotations for Jurassic and Cretaceous strata and hypothesized that these modest-magnitude rotations were related to displacement along structures bounding the Central Cordillera and Magdalena Valley. Based on paleomagnetic results from Jurassic (La Quinta Formation) and Cretaceous (Rionegro Formation) strata (Figs. 1 and 2), Gose et al. (2003) and Nova et al. (2012) suggested clockwise rotations of at least 40° for parts of the Perijá Range. Nova et al. (2019) suggested clockwise rotations of as much as 90° of the Guajira block relative to the stable South American craton.

### Structural and Stratigraphic Setting

The Late Jurassic– to Early Cretaceous–age Tablazo-Magdalena and Cocuy sub-basins are the two main structural components of the Eastern Cordillera,
This ENE-WSW structure has an apparent normal sense of movement, and as expressed by Jiménez et al., 2016) (Fig. 1). The Suárez fault is a regional-scale tectonically inverted structure that controlled the exhumation of the Los Yariguíes anticlinorium and has been considered a pre-existing early Mesozoic–age normal fault (Tesón et al., 2013; Jiménez et al., 2016) with reverse sinistral displacement during crustal shortening (Paris et al., 2000; Acosta et al., 2004; Sarmiento-Rojas et al., 2006; Tesón et al., 2013) (Fig. 1). A transverse zone, referred to here as the El Monje fault, controls the map-view trend of the Suárez fault. This ENE-WSW structure has an apparent normal sense of movement, and it is responsible for basin segmentation and subsidence during Girón Group sedimentation (Araque and Otero, 2016) (Fig. 1). The Los Yariguíes anticlinorium is a regional structure trending NNE that formed as a consequence of the inversion of older Mesozoic normal faults (Jiménez et al., 2016) and the exhumation of the Eastern Cordillera in the Cenozoic during crustal shortening (Cooper et al., 1995; Tesón et al., 2013). The section we examined is located in the eastern limb of the Los Yariguíes anticlinorium, formerly known as the Los Cobardes anticline (Figs. 1 and 2).

**Stratigraphy of the Girón Group**

Girón Group strata have been investigated by several workers, and these studies have prompted considerable debate involving concerns over the lateral extent of each section, the overall thickness of the group, how sections may be correlated, and even the age of these deposits. In addition, the thickness of the type section remains under debate, because workers have measured and proposed different values, without any consensus (Fig. 1). According to Langenheim (1959), the thickness of the Girón Group is 3500 m; however, Navas (1963) reported 2650 m, while Cediél (1968) reported 4840 m. The composition and thickness of the Girón Group vary along the strike length (>100 km) of exposure, making it difficult to correlate each of the members proposed for the type section as described by Langenheim (1959) and Cediél (1968). Notably, the Girón Group thickness varies from almost 2 km for exposures in the hanging wall of the Suárez fault to ~100 m in the footwall of the Suárez fault (Fig. 1). The first descriptions are from near the towns of Girón and Zapatoca by Hetnner (1932), and his descriptions refer to these strata as “Girón beds,” a series of drab sandstones, muddy sandstones, and red beds. Later, more regional studies including those by Schuchert (1938), Oppenheim (1940), Dickey (1941), and Trumpy (1943) used the name Girón Formation for many exposures of similar rocks in other parts of the northern Andes, and, in addition, chrono-logic and stratigraphic correlations with the La Quinta Formation (Venezuela) were made. Langenheim (1959) proposed the type section, located in the gorge of the Lebrija River, ~10 km north of Bucaramanga (Fig. 1). Cediél (1968) described the type section, proposed the name Girón Group, and suggested eight members from base to top (A to H). According to Cediél (1968), the Los Santos Formation corresponds to member H. According to Etayo-Serna (1989), the stratigraphic nomenclature and terms used in previous studies (Hedberg, 1931; Morales, 1958), including Jiron Group, Tambor Formation, and Las Palmas Formation, have been confused and misunderstood. Etayo-Serna (1989) formally proposed the name Girón Group, to be composed of the Angostura del Río Lebrija and Los Santos Formations, and suggested that terms like Tambor or Las Palmas Formations should be avoided. The Girón Group strata overlie the Lower Jurassic Jordán Formation, and this contact is defined as a regional unconformity. In the southernmost part of the studied area, in Mesa de Los Santos (Fig. 1), this unconformity is defined by the appearance of Los Santos Formation strata overlaying the Jordán Formation (Julivert, 1958).

Early paleontologic examination of mainly poorly preserved plant fossils was reported by Brueckner (1954), Langenheim (1961), and Pons (1982), who proposed a broad age of depositional ages ranging from late Paleozoic to Early Cretaceous. At the type section, an assemblage of pecopterids (Rodheda, Caldermites) from the lowest part of the Girón Formation (Angostura del Río Lebrija Formation) was reported by Langenheim (1961), therefore implying an age as old as Late Pennsylvanian. At the Mensuli gully, ~20 km to the south of the type section (Fig. 1), Ptilophyllum sp., fragments of Elato cladus, and fruit-like structures were also reported by Langenheim (1961), implying a Jurassic age. According to Etayo-Serna (1989), the Los Santos Formation is Berriasian given the absence of unconformities with the overlying Berriasian to Valanginian Cumbre and Rosablanca Formations. Other authors, on the basis of stratigraphic correlations (Mojica and Kammer, 1995; Mojica et al., 1996; Bayona et al., 2006; Kammer and Sánchez, 2006; Sarmiento-Rojas et al., 2006) and U-Pb dates on detrital zircons (e.g., Horton et al., 2010, 2015) have proposed a range of depositional ages from Middle Jurassic (Angostura del Río Lebrija Formation) to Berriasian (Los Santos Formation). According to Cooper et al. (1995), the Angostura del Río Lebrija Formation (Girón Formation) is Middle Jurassic, and the Los Santos Formation (Tambor Formation), Cumbre, and Rosablanca Formations are all Early Cretaceous (Berriasian to Valanginian?) with disconformities between Jurassic and Cretaceous successions (Fig. 2) according to Sarmiento-Rojas et al. (2006), the Girón Group (undifferentiated) is late Kimmeridgian to Valangian, and the Rosablanca Formation is Valangian to Hauterivian. Etayo-Serna and Rodriguez (1985) suggested a late Valanginian age for the Rosablanca Formation based on ammonites (Fig. 2). Gómez-Cruz et al. (2015) and Rojas and Sandy (2019) suggested an early Valanginian age for the Rosablanca Formation based on crustaceans and brachiopod fauna (Fig. 2).

Horton et al. (2010), based on detrital zircon U-Pb age data from outcrop samples of the Angostura del Río Lebrija Formation (Girón Formation),
proposed a mean maximum depositional age of ca. 184.5 ± 4.2 Ma and suggested that the observed distributions of detrital zircon U-Pb dates are related to spatial and temporal variations in provenance. Horton et al. (2015) reported U-Pb dates on zircons from two subsurface samples from the Middle Magdalena Valley. These samples yield similarly unimodal age populations of Jurassic age zircons ranging from 200 to 165 Ma. The youngest grains define a population at ca. 166 Ma, providing a maximum depositional (stratigraphic) age constraint for the subsurface Girón Group (Horton et al., 2015) (Fig. 2). Strata from the Lower Cretaceous succession (Los Santos, Rosablanca, and Paja Formations) also show a Jurassic (ca. 200–150 Ma) detrital zircon age provenance (Horton et al., 2015).

The study section is located at the Cuchilla del Ramo hill. The Cuchilla del Ramo section (CRS) was considered for this initial magnetostratigraphic study because of the excellent exposure of the uppermost part of the Girón Group, with a total thickness of ~820 m. At the CRS, the Girón Group is characterized at the exposed base by a gravel conglomerate, as much as 20 m thick, with abundant lithic clasts of metamorphic and igneous rocks, quartz, and muddy intraclasts. Most of the section, however, consists of arkosic to lithic medium-to fine-grained sandstones, intercalated with red siltstones and mudstones (Osorio-Afanador, 2016). At the top of the sequence, red beds and paleosoils with reduction spots are subordinate. According to Laverde and Clavijo (1985), the Los Santos Formation is defined from base to top by (1) medium- to fine-grained feldspathic sandstones with trough cross-bedding, interbedded with sandy mudstones reflecting low-sinuosity rivers and floodplain environments; (2) red beds interbedded with lenticular, wavy-bedded to parallel-bedded, fine-grained sandstones related to interdistributary plains and crevasse splay environments; and (3) conglomeratic sandstones with intraformational mud clasts varying to fine-grained sandstones and burrow-disturbed mudstones.

**METHODS**

We examined the CRS in detail prior to carrying out a field sampling campaign that focused on hematitic mudstones and silty fine sandstones of the Girón Group (Angostura del Río Lebrija and Los Santos Formations) exposed at this section (Fig. 3). We follow the stratigraphic nomenclature proposed in Etayo-Serna (1989), and the stratigraphic column that we compiled was based on the stratigraphic columns reported in Laverde and Clavijo (1985) and Osorio-Afanador (2016) at the CRS, both of which were measured using a Jacob’s staff. We acquired a total of 365 independent core samples from

![Geologic map of the study area with principal structures, stratigraphic units, and the location of the Cuchilla del Ramo stratigraphic section (composed of the Angostura del Río Lebrija and Los Santos sections). Formation boundaries and faults follow the regional geologic map of Macías and Cabanzo (2017). Fm—Formation.](http://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/doi/10.1130/GES02186.1/5421550/ges02186.pdf)
exposed fine-grained beds at an average stratigraphic interval of one sample per ~2 m, but sampling density is variable as a function of appropriate material to sample, and some sample intervals are as much as ~5 m. We used a portable gas-powered drill cooled by water and oriented in situ with a corrected magnetic compass (~8°) according to the World Magnetic Model and calculated using the U.S. National Geophysical Data Center web page, http://www.ngdc.noaa.gov/geomag-web/). After field sampling, core samples were cut into standard specimens of 2.2 cm in length and 2.5 cm in diameter (typically one conventional specimen per sample) using a nonmagnetic bronze saw blade. We conducted the measurements of the natural remanent magnetization (NRM) and the subsequent demagnetization using a cryogenic magnetometer (2G Enterprises, USA) with a magnetic intensity sensitivity of ~1 × 10⁻⁴ A/m.

Thermal demagnetization, using ASC Scientific TD48 furnaces, was successfully used on most samples to yield full demagnetization trajectories, with almost no apparent formation of new magnetic phases or spurious behavior during heating, based on progressive thermal demagnetization that involved 14-16 heating steps from 100 °C to 700 °C until the maximum unblocking temperature of hematite was reached. Thermal demagnetization data were plotted on orthogonal vector diagrams (Zijderveld, 1967), and the magnetization components were isolated by principal component analysis (Kirschvink, 1980) using the AGICO software Remasoft 3.0. The mean directions were evaluated by Fisher’s (1953) statistics (Table 1), and the virtual geomagnetic poles (VGP)s were calculated using Remasoft 3.0. Bingham distribution statistics (Table 2) were calculated using PmagPy software (Tauxe et al., 2016).

### Table 1. Summary of Paleomagnetic Results

| Unit            | n/N | Coordinates | Bedding | In situ | Tilt corrected | Rotations (I) | Flattening (I) | Rotations (II) | Flattening (II) |
|-----------------|-----|-------------|---------|---------|---------------|--------------|---------------|---------------|-----------------|
|                 |     | Base        | Top     |         |               |              |               |               |                 |
|                 |     | Latitude    | Longitude | Latitude | Longitude | Dip azimuth | Dip          | D              | I              | α₉⁵  | k            | R              | D              | I              | α₉⁵  | k            |
| Girón Group     | 199/390 | 6.8435 | 73.2982 | 6.8405 | 73.2849 | 108°-295 | 64-75 | 17.0 | 26.3 | 3.3 | 10.1 | 179.4 | 41.7 | 8.4 | 13.8 | 9.6 | 3.4 | 44.7 ± 5.7 |
| Los Santos Formation | 86/199 | 6.8405 | 73.2849 | 6.8405 | 73.2849 | 113°-304 | 56-72 | 22.4 | 27.0 | 4.2 | 14.1 | 80.0 | 40.0 | 14.0 | 22.6 | 12.1 | 4.6 | 48.6 ± 6.1 |
| Angostura del Río Lebría Formation | 113/199 | 6.8401 | 73.2914 | 6.8401 | 73.2914 | 105°-288 | 69-77 | 12.8 | 25.5 | 4.8 | 8.6 | 99.9 | 42.9 | 3.9 | 6.5 | 8.7 | 4.8 | 45.9 ± 6.3 |
| Cretaceous      | 60/199  | 6.8389 | 73.2899 | 6.8405 | 73.2849 | 117°-304 | 57-72 | 17.9 | 20.5 | 5.0 | 14.0 | 58.6 | 31.5 | 14.6 | 23.5 | 14.6 | 5.0 | 40.1 ± 6.4 |
| Jurassic        | 139/199 | 6.8435 | 73.2982 | 6.8389 | 73.2899 | 105°-289 | 66-77 | 16.8 | 28.3 | 4.2 | 8.6 | 130.1 | 46.1 | 5.5 | 9.1 | 9.3 | 4.2 | 49.1 ± 6.1 |

**Note:** n/N is the number of samples giving reliable results/number of studied samples. Geographic coordinates are referenced to World Geodetic System 1984 (WGS84) datum. Bedding is expressed in average values with dip azimuth and dip value; * indicates overturned beds.

### Table 2. Paleomagnetic Results from Bingham Distribution Parameters

| Unit            | N  | In situ | Tilt corrected | Rotation (I) | Flattening (I) | Rotation (II) | Flattening (II) |
|-----------------|----|---------|---------------|--------------|---------------|---------------|-----------------|
|                 |    | D       | I            | E₁₂⁰ | E₁₂⁰ | Z₁₂⁰ | Z₁₂⁰ | Z₆₀⁰ | Z₆₀⁰ | Z₁₂⁰ | Z₁₂⁰ | Z₆₀⁰ | Z₆₀⁰ | Z₁₂⁰ | Z₁₂⁰ | Z₆₀⁰ | Z₆₀⁰ | Z₁₂⁰ | Z₁₂⁰ | Z₆₀⁰ | Z₆₀⁰ | Z₁₂⁰ | Z₁₂⁰ | Z₆₀⁰ |
| Girón Group     | 199| 16.8    | 28.5          | 280.8 | 11.6 | 169.4 | 60.7 | 3.1  | 3.4  | 41.8 | 9.0  | 13.8 | 314.3 | -15.1 | 282.0 | 72.3  | 3.1  | 3.8  | 44.8 ± 5.6 | -1.3 ± 9.9 | 59.5 ± 7.9 | 25.7 ± 10.0 |
| Los Santos Formation | 86 | 22.4    | 26.9          | 318.7 | -41.0 | 268.8 | 37.0 | 2.3  | 5.1  | 40.1 | 14.0 | 22.6 | 310.1 | 0.0  | 220.2 | 75.9  | 2.3  | 5.6  | 48.7 ± 5.2 | -0.03 ± 8.5 | 54.2 ± 5.9 | 10.8 ± 8.4 |
| Angostura del Río Lebría Formation | 113 | 11.8    | 263.3         | 263.9 | 31.8 | 313.2 | -46.5 | 3.6  | 5.5 | 43.0 | 4.5  | 6.5 | 138.8 | 51.6 | 120.2 | 37.9 | 4.1 | 5.1 | 45.9 ± 5.9 | 6.0 ± 10.1 | 60.7 ± 8.2 | 32.9 ± 10.3 |
| Cretaceous      | 60 | 17.6    | 20.6          | 307.4 | -42.0 | 268.6 | 40.9 | 2.7  | 5.4  | 30.1 | 14.5 | 23.5 | 301.8 | -2.9 | 223.1 | 75.2  | 2.7 | 6.1 | 38.7 ± 5.3 | -0.9 ± 8.6 | 44.2 ± 6.0 | 9.9 ± 8.5 |
| Jurassic        | 139 | 16.1    | 29.5          | 250.7 | 327.1 | -49.2 | 3.7  | 4.6  | 46.6 | 6.2  | 9.1 | 142.4 | 42.3 | 309.8 | 46.9  | 3.7 | 4.6 | 49.6 ± 5.8 | 3.4 ± 10.0 |

**Note:** N is the set of reliable samples. See Table 1 for details. D and I are section mean declination and inclination, respectively, calculated before and after tectonic correction; I is the inclination corrected after inclination shallowing reported in Table 3. E₆₀⁰ is the declination of major ellipse axis, E₁₂⁰ is the inclination of major ellipse axis, Z₁₂⁰ is the declination of minor ellipse axis. Z₆₀⁰ is the inclination of minor ellipse axis. Zeta and Eta are the minor and major ellipses, respectively. Section mean rotation and flattening axes and associated errors are according to Demarest (1983), and these are calculated relative to coeval D and I South America values expected at the sampling area based on the 150 and 140 Ma poles from (I) Torsvik et al. (2012) and 145 and 140 Ma poles from (II) Kent and Irving (2010). Poles are rotated into the coordinates of South American plate (Koymans et al., 2016). Cells with dashes have no data because Kent and Irving (2010) have no reported 150 Ma pole.
Rock magnetic experiments were conducted to identify the main magnetization carriers. Isothermal remanent magnetization (IRM) acquisition and backfield demagnetization, the thermal demagnetization of three-component IRM (TM-IRM) (Lowrie, 1990), and thermomagnetic (bulk susceptibility versus temperature) curves were obtained for representative specimens. For IRM acquisition curves, representative specimens were subjected to at least 25 sequence steps from 10 to 2800 mT, and for backfield demagnetization, at least 12 sequence steps from 10 to 700 mT. DC fields were applied using an IM-10-30 pulse magnetizer (ASC Scientific). Coercivity spectra from IRM acquisition curves were evaluated using the MAX UnMix software (Maxbauer et al., 2016). For TM-IRM, a set of representative specimens was magnetized in an IM-10-30 impulse magnetizer (ASC Scientific); a magnetic field was applied to z, y, and x axes (z = 2.7 T, y = 0.6 T, and x = 0.12 T, respectively, with the highest field first) in order to saturate the highly coercive to low-coercive minerals represented by the hard, medium, and then soft fractions of the magnetic mineralogy. Thermal demagnetization was carried out with a TD48 (ASC Scientific) thermal unit in 17 steps between 100 °C and 700 °C. In the IRM and the TM-IRM experiments, after each step, the remanence was measured with a JR6-A dual speed spinner magnetometer (AGICO). Thermomagnetic curves were also obtained to complement the identification of the magnetization carriers in representative samples. Thermomagnetic curves were measured on powders from representative specimens using a CS4 furnace coupled with a MFK1 Kappabridge (AGICO). Polished thin sections of three representative samples of the Girón Group were studied using an Olympus BX51 microscope, equipped with a DP72 camera, in both transmitted- and reflected-light mode. Magnetic measurements were done in shielded rooms in the Laboratório de Paleomagnetismo at University of São Paulo (USPmag; Brazil) and in the Paleomagnetism Laboratory at the University of Texas at Dallas (USA).

## RESULTS

### Magnetic Mineralogy Characterization

The thermomagnetic experiments (susceptibility versus temperature), conducted in an oxygen-free environment, reveal some changes to the magnetic mineralogy over elevated-temperature intervals (Fig. 4). In some samples, heating and cooling curves are reversible or partially reversible (Figs. 4A–4B and 4D–4G), indicating slight changes in the magnetic mineralogy during heating. The heating and cooling curves show a main Curie temperature at ~580 °C and also a Neel temperature of ~680 °C (Fig. 4). The heating curves show a principal decay over the temperature interval between ~600 °C and 690 °C, suggesting the presence of hematite (Fig. 4). Only sample GR45 (Fig. 4C) shows a decay between ~580 °C and 600 °C, suggesting the presence of appreciable magnetite and/or maghemite. In this sample, the increase between ~250 °C and 300 °C in the heating curves suggests a neo-production of maghemite transformed from some less-magnetic Fe-hydroxides during the heating process (Florindo et al., 1999; Liu et al., 2005; Duan et al., 2014).

The reversible or partially reversible cooling curves (Figs. 4A–4B and 4D–4G) show a susceptibility acquisition in cooling between 700 °C and 600 °C, suggesting hematite. The nonreversible cooling curves (Figs. 4C, 4H, and 4I) show a susceptibility acquisition between 590 °C and 570 °C, suggesting the production of magnetite. Samples GR45 and GR61 (Figs. 4C and 4D) show a peak in susceptibility upon cooling below 400 °C, suggesting a nonstoichiometric oxidation of maghemite produced during the experiment. In all samples (Fig. 4), the cooling curves show a well-developed Hopkinson effect associated with coarse magnetite.

The IRM acquisition and backfield demagnetization experiments (Fig. 5) show a similar shape for the acquisition curves for all specimens investigated. The IRM data show a relatively shallow positive slope at fields below ~300 mT and that saturation is typically not complete at 2500 mT, indicating a high-coercivity mineral fraction, likely hematite (Fig. 5). Backfield demagnetization of near-saturation IRM yields approximate coercivity of remanence values ranging from 400 to 630 mT. The IRM unmixing model reveals up to four coercivity components from the IRM acquisition curve (Fig. 5). Component 1 has a mean coercivity (Bh; see Fig. 5) ranging from 1.50 to 2.10 log units (32–126 mT) and interpreted as a detrital soft magnetite grain population (Egli, 2004). The intermediate-coercivity component 2 has Bh ranging from 2.28 to 2.65 log units (190–447 mT) and is interpreted as possibly coarse detrital hematite or hemo-ilmenite (Egli, 2003). Components 3 and 4 with Bh >2.65 log units (>447 mT) are consistent with hematite and goethite.

Magnetic mineralogy analysis based on three-component IRM thermal demagnetization results (Lowrie, 1990) shows that hematite and minor amounts of maghemite are the main magnetic carriers. Samples from the Girón Group show that the hard- and medium-coercivity fractions are demagnetized between 600 °C and 680 °C, suggesting the presence of hematite. The smooth drop of the medium and soft component between 300 °C to 580 °C may reflect the presence of minor magnetite (Fig. 6).

The identification and textural characteristics of opaque phases in the thin polished sections reveal the presence of abundant authigenic hematite as a cement, as part of grain coatings (Fig. 7), and contains a low concentration (<1 vol%) of opaque, detrital oxide grains, including specular hematite (Fig. 7). These observations are consistent with the IRM acquisition data from these rocks.

### Demagnetization Behavior

The specimens from the CRS are moderately magnetic, with average NRM intensities of ~4.3 × 10⁻³ A/m. However, ~40% of the specimens can be considered magnetically weak, with intensities below ~10⁻⁴ A/m. In general, the magnetic behavior of these sedimentary rocks in the CRS is straightforward, with a ChRM that is isolated over a range of laboratory unblocking
Figure 4. Magnetic susceptibility versus temperature curves for nine representative samples; red lines indicate heating, and blue lines, cooling steps. All experiments were performed in an inert (argon) atmosphere. See text for details and interpretations.
Figure 5. Isothermal remanent magnetization (IRM) acquisition and backfield direct field demagnetization curves for representative specimens. Coercivity distribution data (gray dots) follow the unmixing protocol of Maxbauer et al. (2016) derived from the IRM acquisition measurements. The shaded area represents error envelopes of 95% confidence intervals. Bh represents the mean coercivity of an individual grain population, Dp is dispersion parameter, sd is the standard deviation of a set of values, and P is the proportion factor.
temperatures and readily identified in the orthogonal demagnetization diagrams (Fig. 8).

Demagnetization diagrams of Girón Group specimens show univectorial and multivectorial paths for the Angostura del Río Lebrija Formation (Fig. 8A) and the Los Santos Formation (Fig. 8B). The univectorial paths (e.g., samples GR10, LS46, LS96; Figs. 8A and 8B) define magnetizations that are oriented to the northeast with high laboratory unblocking temperatures in the range from 500 °C to 680 °C. Samples with univectorial paths are characterized by erratic or scattered behavior (e.g., samples GR02, GR196, LS100, LS111; Figs. 8A and 8B). Multivectorial paths are characterized by two components (e.g., samples GR08, GR135, GR144, LS89, LS163; Figs. 8A and 8B). The component with low laboratory unblocking temperature is oriented randomly; the component with high unblocking temperature is interpreted as either normal or reverse polarity, with northeast declinations and usually shallow positive inclinations, and southwest declinations and usually shallow negative inclinations, respectively.

A viscous magnetization was removed over the first few steps of thermal treatment up to ~200 °C (Fig. 8). A ChRM is typically resolved between 500 °C and 680 °C (in some specimens, the ChRM was isolated between 400 °C and 680 °C), suggesting that hematite is the main magnetization carrier (Fig. 8). The maximum angular deviation (MAD) average value is ~10°, and ~80% of the samples have MAD values <15°.

A total of 272 (out of 365) specimens yield interpretable paleomagnetic directions in progressive thermal demagnetization, based on at least five data points defining a linear segment with MAD values, calculated by means of principal components analysis (Kirschvink, 1980) and utilizing unanchored line fits, between 2.2° and 20.0° (Fig. 8). The additional criteria employed to develop the magnetostratigraphy in the CRS involved rejecting ChRM directions with a MAD value >20° and removing transitional directions, including those with steep inclinations (>55°), and applying the 45° cutoff in the Paleomagnetism.org application using the geomagnetic directions module (www.paleomagnetism.org) (Koyman et al., 2016). As a result, a total of 199 specimens passed the above quality criteria, and these are indicated in Table S1 in the Supplemental Material and were classified as reliable for compiling the magnetostratigraphy of the study area.

After tilt correction, 123 samples are of normal polarity (north-seeking and shallow positive inclination) (declination [D] = 44.9°, inclination [I] = +9.7°, α95 = 9.0°), and the other 76 samples are of reverse polarity (south seeking and shallow negative inclination) (D = 216.4°, I = −6.1°, α95 = 6.0°) (Fig. 9A; Table S1 [footnote 1]). The fold test performed (Koyman et al., 2016; Tauxe and Watson, 1994) is indeterminate. The statistical reversal test classification based on VGP positions is positive, class B (angle between directions = 174.46°, critical angle = 6.27°) (Koyman et al., 2016; McFadden and McElhinny, 1990). The contribution of paleosecular variation to
the dispersion of the ensemble of 199 accepted sample directions was evaluated using the $A_{95\text{min}}$ and $A_{95\text{max}}$ parameters to quantify the minimum and maximum amount of dispersion (Deenen et al., 2011). We calculated the $A_{95\text{min}}$, $A_{95\text{max}}$, and $A_{95}$ distribution parameters following the method of Koymans et al. (2016). In tectonic (strata tilt corrected) coordinates, $A_{95}$ = 2.9°, $A_{95\text{min}}$ = 1.4°, and $A_{95\text{max}}$ = 2.9°. The $A_{95\text{max}} \geq A_{95} > A_{95\text{min}}$ result suggests that paleo–secular variation is adequately recorded in the ensemble of data and that the data set is not affected by any form of systematic remagnetization process (Deenen et al., 2011; Koymans et al., 2016).

We utilized the elongation-inclination (E-I) method (Tauxe et al., 2008) to evaluate the possibility of the need for a correction for inclination shallowing, incorporating all our 199 accepted sample directions of the CRS, and also divided in the 113 sample directions of the Angostura del Río Lebrija Formation and 86 sample directions of the Los Santos Formation (Table 1). The unflattening procedure for the CRS data of the upper part of the Girón Group (Angostura del Río Lebrija and Los Santos Formations) tracks the changes from inclination of ~8.4° before unflattening (observed) to ~18.1° after unflattening, and is associated with a flattening factor ($f$ value) of ~0.45 (Fig. 10A). The unflattening procedure for the Angostura del Río Lebrija Formation tracks the observed inclination of 3.9° to an unflattened inclination of 6.5° with an $f$ value of ~0.6 (Fig. 10B). The unflattening procedure for the Los Santos Formation tracks the observed inclination of 14.0° to an unflattened inclination of 43.1° with an $f$ value of ~0.26 (Fig. 10C). The estimated $f$ value for the Los Santos Formation data set is unusually low for these kinds of sedimentary rocks, and we suspect that this is simply an artifact of a relatively small sample set. To avoid a possible bias for the Los Santos Formation, we also evaluated the inclination shallowing effects based on the equation:

$$\tan l_i = \tan l_m / f,$$

where $l_m$ is measured inclination and $l_i$ is corrected inclination. We used three $f$ values (0.5, 0.6, and 0.7) to evaluate possible inclination shallowing effects over a suitable range of flattening factors. These values have been considered realistic for the type of sedimentary rocks studied (Bilardello and Kodama, 2010), and the results are summarized in Table 3.

**Magnetostratigraphy**

Directional data and corresponding VGP latitudes for each sample are interpreted as recording the normal- and reverse-polarity time intervals in the CRS (Fig. 11). From base to top, the successive pairs of normal (N) and reverse (R) polarity are assigned to ascending numerical order. A composite magnetic polarity stratigraphy based on 199 accepted samples from the Girón Group includes 26 polarity couplets consisting of normal-polarity (N1 to N26) and reverse-polarity (R1 to R26) magnetozones. In Figure 11, gray intervals represent poorly constrained or determined magnetozones of inferred normal polarity, and cross-hatched intervals represent poorly constrained or determined magnetozones of inferred reverse polarity, defined by only one sample, marginally acceptable MAD values, or narrow gaps in the stratigraphic section.

We applied the jackknife statistical technique (Tauxe and Gallet, 1991) to the CRS data set (Fig. 10D). The $J$ value calculated for the CRS data is ~0.5, and this approach recovered ~80% of the polarity units to test the reliability of a magnetostratigraphic section. According to Tauxe and Gallet (1991), a robust magnetostratigraphic data set is considered to be represented by $J$ values from 0 to ~0.5.

It is not possible to define a unique magnetic polarity age model for the CRS. Taking this point into consideration, we used two plausible approaches to define a coherent magnetic polarity age involving deterministic and stochastic modeling. In the deterministic model A (Fig. 11B), we assign the youngest...
Temperature (°C)

Figure 8. (A) Orthogonal vector diagrams, the natural remanent magnetization intensity decay (M) normalized, and stereograms showing typical demagnetization response for representative specimens from the Angostura del Río Lebrija Formation (in situ coordinates). (B) Orthogonal vector diagrams, the natural remanent magnetization intensity decay normalized, and stereograms showing typical demagnetization response for representative specimens from the Los Santos Formation (in situ coordinates). M/NRM is the natural remanent magnetization intensity decay normalized. Solid and open symbols represent projections on the horizontal and vertical planes, respectively. Demagnetization step values are in °C and are plotted along selected data points in the vertical projection. (Continued on following page.)
Figure 8 (continued).
Figure 9. (A) Equal-area projections of paleomagnetic directions from the 199 samples yielding interpretable results. Solid and open symbols represent upper and lower hemisphere projections, respectively. The tilt correction procedure was realized by rotating the NRM direction with respect to bedding.

(B) Site or locality mean directions of Angostura del Río Lebrija Formation, Los Santos Formation, and overall Girón Group, including directions reported in Gose et al. (2003), Nova et al. (2012), and Bayona et al. (2006). Open ellipses are the projections of the 95 cones about the mean directions. Different circle colors are negative/positive inclinations. Blue star represents the normal-polarity recent geocentric axial dipole field direction (declination = 0°, inclination = +14°) calculated using the dipole equation for the Bucaramanga latitude (7.13°N).

Table 3. Inclination Corrections

| Unit                        | Uncorrected | Inclination shallowing $f'$ | Inclination shallowing $f''$ | Inclination shallowing $f'''$ |
|-----------------------------|-------------|-----------------------------|-----------------------------|-------------------------------|
|                             | $l_0$       | $l_0'$                      | $l_0''$                     | $l_0'''$                     |
|                             | Latitude (°N) | Longitude (°E) | $dp$ | $dm$ | $A_{95}$ | Latitude (°N) | Longitude (°E) | $dp$ | $dm$ | $A_{95}$ | Latitude (°N) | Longitude (°E) | $dp$ | $dm$ | $A_{95}$ |
| Girón Group                 | 8.4         | 48.4                       | 18.5                        | 1.7                          | 3.4                          | 2.4                          | 16.4          | 48.7       | 12.3       | 1.8                          | 3.5                          | 2.5                          | 13.8          | 48.6       | 14.4       | 1.8                          | 3.5                          | 2.5                          | 11.9          | 48.6       | 15.8       | 1.8                          | 3.5                          | 2.5                          |
| Los Santos Formation        | 14.0        | 50.3                       | 14.3                        | 2.4                          | 4.7                          | 3.4                          | 26.5          | 50.1       | 3.5        | 2.7                          | 5.0                          | 3.7                          | 22.6          | 50.3       | 7.0        | 2.6                          | 4.9                          | 3.6                          | 19.6          | 50.4       | 9.6        | 2.5                          | 4.8                          | 3.5                          |
| Angostura del Río Lebrija Formation | 3.9         | 46.9                       | 21.7                        | 2.4                          | 4.8                          | 3.4                          | 7.8           | 47.2       | 18.8       | 2.4                          | 4.8                          | 3.4                          | 6.5           | 47.1       | 19.8       | 2.4                          | 4.8                          | 3.4                          | 5.6           | 47.1       | 20.4       | 2.4                          | 4.8                          | 3.4                          |
| Cretaceous                  | 14.6        | 58.8                       | 14.3                        | 2.6                          | 5.1                          | 3.7                          | 27.5          | 58.2       | 0.6        | 3.0                          | 5.5                          | 4.0                          | 23.5          | 58.5       | 5.0        | 2.8                          | 5.3                          | 3.9                          | 20.4          | 58.7       | 8.3        | 2.8                          | 5.2                          | 3.8                          |
| Jurassic                    | 5.5         | 43.9                       | 19.9                        | 2.1                          | 4.2                          | 3.0                          | 10.9          | 44.2       | 16.1       | 2.2                          | 4.3                          | 3.0                          | 9.1           | 44.1       | 17.4       | 2.1                          | 4.2                          | 3.0                          | 7.8           | 44.0       | 18.3       | 2.1                          | 4.2                          | 3.0                          |

Note: Paleomagnetic poles uncorrected and corrected based on flattening factors ($f$). Measured inclinations ($l_0$), corrected inclinations ($l_0'$), and selected flattening values: $f' = 0.5$, $f'' = 0.6$, and $f''' = 0.7$ for inclination correction. $dp$ and $dm$ are the semi-axis of the ellipse of confidence. $A_{95}$ is the radius of its associated circle of 95% confidence = $\sqrt{(dp)(dm)}$. 

**In Situ**

**Tilt corrected**

**Geocentric axial dipole field direction expected at Bucaramanga (Latitude 7.13°N)**
- Los Santos Formation
- Angostura del Río Lebrija Formation
- Girón Group
- Los Santos Formation (Bayona et al., 2006)
- Girón Formation (Bayona et al., 2006)
- Girón-Tibasosa Formation (Bayona et al., 2006)
- Perijá Range (Gose et al., 2003)
- Perijá Range (Nova et al., 2012)
- Down
- Up

**Perijá Range**
- Gose et al., 2003
- Nova et al., 2012
- Bayona et al., 2006

**Girón-Tibasosa Formation**
- Bayona et al., 2006
Figure 10. (A–C) Unflattening (corrected) inclinations (after the simple restoration of sedimentary bedding to the paleohorizontal, the "tectonic correction") determined according to the elongation-inclination (E-I) method of Tauxe et al. (2008) and generated using www.paleomagnetism.org (Koymans et al., 2016) for the full sequence of Girón Group strata (A), only for the data from the Angostura del Río Lebrija Formation (B), and only for the data from the Los Santos Formation (C). (D) Magnetostratigraphic jackknife analysis for the studied section of Girón Group strata. The plot shows the relationship between the average percentage of polarity zones retained and the percentage of sampling sites deleted, where the slope $J$ is related directly to the robustness of the results. (E) Observed paleolatitudes based on the observed distribution of inclinations and inclination data corrected for shallowing related to sediment compaction and related processes. Confidence intervals are boundaries containing the central 95% of the corrected inclinations. Error bars for paleolatitude estimates are given by the $\alpha_{95}$ values. Paleolatitudes reported in Jurassic strata are derived from uncorrected inclinations (Castillo et al., 1991; Bayona et al., 2006, 2010; Nova et al., 2012).
Table 1. Magnetostratigraphic and stratigraphic position of the Girón Group strata at the Cuchilla del Ramo section based on Osorio-Afanador (2016) (Angostura del Río Lebrija Formation) and Laverde and Clavijo (1985) (Los Santos Formation). The column shows the stratigraphic position, inclination value, and virtual geomagnetic pole (VGP) latitude for all 199 samples accepted for magnetic polarity stratigraphic analysis. M—mud, S—sand, G—gravel. The sample code is labeled by a constant interval of 10 samples. From base to top, the successive black and white intervals indicate pairs of normal-polarity (N) and reverse-polarity (R) magnetozones, assigned to ascending numerical order, and includes 26 normal-polarity (N1 to N26) and 26 reverse-polarity (R1 to R26) magnetozones. Uncertain polarity intervals defined by only one sample, marginally acceptable maximum angular deviation values, or narrow gaps in the stratigraphic section are gray (inferred to be of normal polarity) or cross-hatched (inferred to be of reverse polarity).

![Diagram](http://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/doi/10.1130/GES02186.1/5421550/ges02186.pdf)
The Tithonian (ca. 160–148 Ma), and the Los Santos Formation is estimated as late Oxfordian to early Tithonian (ca. 157 to ca. 148 Ma) (Etayo-Serna and Rodriguez, 1985; Etayo-Serna, 1989). In doing so, the observed magnetic polarity stratigraphic record can be compared with the Geomagnetic Polarity Time Scale (GPTS) (Ogg et al., 2016) for this time interval. From the base to the top of the section, the Angostura del Río Lebrija Formation is inferred to be defined by magnetozones N1–N18 and R1–R18. This interval pattern is interpreted to correspond to chron M26 to part of the M20 chron of the GPTS (Fig. 11). The Los Santos Formation is then defined by magnetozones N19–N26 and R19–R26. In turn, this interval pattern matches with chron M20 to chron M14 of the GPTS (Fig. 11). The magnetostratigraphic data are consistent with a plausible age of the Girón Group in CRS ranging from early Kimmeridgian to early Valanginian (ca. 157 to ca. 139 Ma) (Fig. 11B). The inferred age of the uppermost strata of the Angostura del Río Lebrija Formation is early Kimmeridgian to early Tithonian (ca. 157 to ca. 148 Ma) (Fig. 11B). The age of the Los Santos Formation thus is interpreted to span the early Tithonian to early Valangian (ca. 148 to ca. 139 Ma) (Fig. 11B).

To evaluate the ambiguities of the deterministic model A as described above, we performed the stochastic model B (Fig. 11B) based on a dynamic time warping algorithm, using the open-source software Qupydon (Lallier et al., 2013). The input data are the reference Geomagnetic Polarity Time scale (GPTS) (Ogg et al., 2016) and the thicknesses of polarity magnetozones as measured in the CRS. Following the methods described in Lallier et al. (2013) and Coutand et al. (2016), we used the GPTS segment that covers all the possible depositional ages of the Girón Group, which range from chron M10n to M30 (ca. 136 to ca. 160 Ma). The software parameter is the maximum substitution, which is the maximum number of reference chron that may be related to one chron of the study section. The gap factor yields correlations with different sedimentation rates. A gap factor of 0 yields a correlation with higher sedimentation rate, while a gap factor of 10 stretches the correlation within the imposed reference time scale. The substitution distance evaluates short-term variations (= 1) and local variations of the sedimentation rates inverting gaps in the correlation (>1) (Lallier et al., 2013; Coutand et al., 2016). We ran a series of models with different parameter values reported in Coutand et al. (2016). We obtained the best correlation via the best fit or “minimum cost” of 27.3 based on the maximum substitution of five, the gap factor of 0, and a substitution distance of 1. The “minimum cost” is the best match between the polarity chron of the reference scale and the polarity zone of the studied column (Lallier et al., 2013). The resulting model B, based on stochastic correlation (Fig. 11B), correlates the N26 magnetozone of the top of the CRS with the chron M16n, and the base of the section correlates R1 with the chron M30r. In model B, the age of the Girón Group is estimated to be between late Oxfordian and late Berriasian (ca. 160–140 Ma). In addition, the Angostura del Río Lebrija Formation is estimated as late Oxfordian to early Tithonian (ca. 160–148 Ma), and the Los Santos Formation is estimated as late Tithonian to late Berriasian (148 to ca. 140 Ma) (Fig. 11B).

Separate paleomagnetic poles were estimated from the data sets from the Angostura del Río Lebrija and Los Santos formations, based on inclination-corrected grand mean directions for the two formations (Table 3). We assume that these paleomagnetic poles represent the time interval from the Late Jurassic to the Early Cretaceous for these strata (Table 3). The paleomagnetic poles, based on inclination values that were corrected by an f value of 0.6, were compared to respective-age paleopoles for the South American continent (Kent and Irving, 2010; Torsvik et al., 2012) and also previous paleomagnetic results reported by Bayona et al. (2006) and Nova et al. (2012) from similar-age rocks in nearby areas (Fig. 12). The apparent polar wander paths of Kent and Irving (2010) and Torsvik et al. (2012), ranging in age from 200 to 140 Ma, are rotated into the coordinate frame of the South American plate (Koymans et al., 2016) (Fig. 12).

We calculated rotation and flattening parameters in paleomagnetic directional space, again with inclination values that have been corrected using an f value of 0.6 (Table 3), for our reported Late Jurassic and Early Cretaceous populations of sample directions according to Demarest (1983), utilizing expected directions derived from the 140 Ma (latitude 72.12°N, longitude 237.60°E, A_m = 6.8°) and 145 Ma (latitude 66.92°N, longitude 240.88°E, A_m = 9.0°) poles of Kent and Irving (2010), and the 140 Ma (latitude 80.22°N, longitude 227.39°E, A_m = 6.0°) and the 150 Ma (latitude 87.0°N, longitude 187.30°E, A_m = 6.4°) poles of Torsvik et al. (2012) (Tables 1 and 2).

**DISCUSSION**

Although the CRS sampled in the current study does not include the entire Girón Group stratigraphic sequence, it does include the uppermost 817 m of the...
The magnetic mineralogy of Girón (inferred to be of Early Cretaceous age) and 299 m of the Los Santos Formation Group strata is defined with isothermal remanent magnetization (IRM) acquisition, thermal demagnetization of three-component IRM (Lowrie, 1990), and susceptibility versus temperature data. With respect to any possible difference in depositional environments between the Angostura del Río Lebrija and Los Santos Formations (oxidizing to reducing environment transition), there are no apparent differences in magnetic mineralogy discerned in this study, in that hematite (both detrital and authigenic) and relatively minor magnetite (with possibly some maghemite) are the main magnetization carriers in both rock sequences.

At face value, paleontologic work (Brueckner, 1954; Langenheim, 1961; Pons, 1982) suggested that the Girón Group strata have an unrealistically wide age range, from Late Pennsylvanian to Early Cretaceous. Detrital zircon U-Pb dates provide maximum depositional age estimates for Jurassic to Lower Cretaceous Girón Group strata in the Middle Magdalena Valley and suggest a maximum depositional age of ca. 166 Ma (Horton et al., 2010, 2015). More recently reported zircon U-Pb dates from the Noreán Formation range between 175.9 ± 1.1 Ma and 192.4 ± 2.2 Ma (Correa-Martínez et al., 2019), and those from the Jordán Formation range between 199.4 ± 0.3 Ma and 198.5 ± 0.3 Ma (Alarcón and Rodriguez, 2019). As noted above, a regional Middle Jurassic–age low-angle angular unconformity (10°–15°) (Bayona et al., 2020; Ward et al., 1973) separates the Lower and Middle Jurassic sedimentary and volcanic successions (Jordán Formation) from entirely continental Upper Jurassic strata (Girón Group). The new Early Jurassic age estimates for the Noreán and Jordán Formations and the regional angular unconformity are consistent with the likelihood that deposition of overlying Girón Group strata initiated after the Middle Jurassic.

Our magnetostratigraphic results from the Girón Group, assuming the deterministic model A (Fig. 11B), are approximately valid and provide an improved chronologic control for Upper Jurassic to Lower Cretaceous strata in the northern Andes. Based on a Berriasian age for the Los Santos and Cumbre Formations (Cediel, 1968; Etayo-Serna and Rodriguez, 1985; Etayo-Serna, 1989) and a Valanginian age for the Rosablanca Formation (Etayo-Serna and Rodriguez, 1985; Etayo-Serna, 1989; Cooper et al., 1995; Sarmiento-Rojas et al., 2006; Gómez-Cruz et al., 2015; Rojas and Sandy, 2019), the compiled magnetic polarity succession of the Girón Group can be compared with the Geomagnetic Polarity Time Scale (GPTS) (Ogg et al., 2016). The age of the Girón Group is estimated to be between early Kimmeridgian and early Valanginian (ca. 157–139 Ma). Based on further correlations with the GPTS, the Angostura del Río Lebrija Formation is estimated as early Kimmeridgian to early Tithonian (ca. 157–148 Ma) (Fig. 11B). The Los Santos Formation was deposited conformably on the Angostura del Río Lebrija Formation, without major discontinuity, and we infer an age between early Tithonian and early Valanginian (148 to ca. 139 Ma). The Jurassic-Cretaceous boundary is thus likely located within the Los Santos Formation, and our estimated ages imply that the Los Santos Formation is older than previous estimates (Cediel, 1968; Etayo-Serna and Rodriguez, 1989; Etayo-Serna, 1989; Cooper et al., 1995; Sarmiento-Rojas et al., 2006).

We have plotted the thickness of the CRS and our interpreted magnetic polarity stratigraphy versus the GPTS (Ogg et al., 2016) and have calculated two sedimentary accumulation rates for age correlation models A and B (Fig. 13). According to Garcés (2015), a correlation between a local magnetostratigraphy and the GPTS requires that sedimentation rates do not change significantly.

Girón Group, consisting of 518 m of the Angostura del Río Lebrija Formation (inferred to be of Late Jurassic age) and 299 m of the Los Santos Formation (inferred to be of Early Cretaceous age). The magnetic mineralogy of Girón Group strata is defined with isothermal remanent magnetization (IRM) acquisition, thermal demagnetization of three-component IRM (Lowrie, 1990), and susceptibility versus temperature data. With respect to any possible difference in depositional environments between the Angostura del Río Lebrija and Los Santos Formations (oxidizing to reducing environment transition), there are no apparent differences in magnetic mineralogy discerned in this study, in that hematite (both detrital and authigenic) and relatively minor magnetite (with possibly some maghemite) are the main magnetization carriers in both rock sequences.

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![Figure 12. Near-polar plot showing paleomagnetic poles calculated for the Girón Group and Angostura del Río Lebrija and Los Santos Formations obtained in this study and derived from corrected inclinations using a flattening factor (f) value of 0.6 for each of the three poles shown (Table 3). Paleomagnetic poles derived from uncorrected inclinations reported by Bayona et al. (2006) and Nova et al. (2012) and the apparent polar wander paths of Kent and Irving (2010) and Torsvik et al. (2012) from 200 to 140 Ma are rotated into the coordinates of South America using www.paleomagnetism.org (Koymans et al., 2016) and plotted in GPlates (Müller et al., 2018). Ellipses of 95% confidence are shown for each paleopole labeled by age.](http://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/doi/10.1130/GES02186.1/5421550/ges02186.pdf)
over the time scale of typical geomagnetic polarity chrons. However, in continental settings dominated by alluvial and fluvial processes, sedimentation is typically episodic. Sedimentation rates calculated for both of the models are similar (Fig. 13) and show two periods showing rates of ~8–10 cm/k.y. related to alluvial fans and meandering channels. The lowest sedimentation rates of ~2 cm/k.y. are related to floodplains facies. However, the upper part of the Angostura del Río Lebrija Formation is dominated by floodplain facies and shows an acceleration of sedimentation rates to as much as 10 cm/k.y., and we infer that this change is probably related to the magnitude of sediment supply (Liu et al., 2019).

The sedimentation rates estimated for the Girón Group are feasible for explaining the ~850-m-thick sequence of continental strata deposited over this time interval in the Late Jurassic to Early Cretaceous in the CRS. The inferred variations in sedimentation rates in the Girón Group are possibly related to changes in displacement rate along regionally traceable normal faults (e.g., Suárez and Bucaramanga faults) that were active in the Late Jurassic and Early Cretaceous (Cooper et al., 1995; Sarmiento-Rojas et al., 2006; Bayona et al., 2006) (Fig. 14). Fast subsidence events have been identified in the study area (Sarmiento-Rojas et al., 2006; Spickert, 2014). According to Sarmiento-Rojas et al. (2006), in the region west of the Bucaramanga fault, latest Jurassic–Early Cretaceous tectonism is characterized by fast subsidence and lithosphere stretching with ENE-WSW–striking normal faults controlling the basin configuration during the deposition of continental sequences (Fig. 14). Spickert (2014), based on one-dimensional modeling and burial history data, suggested a late Tithonian to Early Cretaceous subsidence event in the Middle Magdalena Valley Basin.

Alluvial fan, fluvial, and lacustrine facies deposits, as components of the Jurassic sedimentary sections, represent the lowstand of the overall sequence (Rolon, 2004). The carbonate and tidal flat sequences of the Cumbre and Rosablanca Formations represent transgressive systems tracts, and the inner
to middle shelf deposits characterized by the Paja and Tablazo Formations represent highstand systems tracts (Rolon, 2004). Abrupt changes in the thickness of these sequences suggest that their accumulation took place concurrent with normal-sense displacement along regional faults in the area (Rolon, 2004) and that the displacement rates varied in time and space.

According to Martins-Neto and Catuneanu (2010), episodic pulses of extension in typical rift basins create space for sediment accumulation with high rates of deposition. Stages of rapid mechanical subsidence are followed by more extended periods of tectonic quiescence when sediment supply gradually consumes and fills the available accommodation space (Martins-Neto and Catuneanu, 2010). Bayona et al. (2006) suggested a relationship between extensional tectonism, block rotations, and deposition in parts of northwestern South America. Deformation has occurred in different areas since the Middle Jurassic, as evidenced by a regional angular unconformity within Jurassic sequences, and areas where accumulation continued (e.g., Lebrija section) were later affected by eustatic changes, thus causing incision and later filling of incised valleys (Bayona et al., 2020).

This type of structure-controlled sedimentation pattern is common in extensional and/or transtensional basins (Sylvester, 1988; Cooper et al., 1995; Bayona et al., 2006; Kammer and Sánchez, 2006; Sarmiento-Rojas et al., 2006). According to Sarmiento-Rojas et al. (2006), the Triassic–Jurassic transtensional basins were narrow and progressively increased in width as the strike-slip component of deformation gradually decreased and the dip-slip extensional component increased.

**Vertical Axis Rotations**

According to Bayona et al. (2020), the change from broad volcanic deposition in the Middle Jurassic to restricted siliciclastic sediment accumulation within extensional basins in the Late Jurassic reflected a reorganization of tectonic plates along the Pacific subduction and proto-Caribbean margins. The Lower to Middle Jurassic sediments and volcanic successions are related to subduction magmatism and the relative motion of the South American plate away from the North American plate. The Upper Jurassic continental and marine deposits in extensional basins record the opening of the proto-Caribbean Sea (Bayona et al., 2020, 2010; Nova et al., 2019; Pindell and Kennan, 2009) (Fig. 14).
Jurassic to Early Cretaceous tectonic reconstructions suggest that the Maya block (southern Mexico) was juxtaposed against northern South America (Bartok et al., 2015; Pindell and Kennan, 2001) at this time. During Kimmeridgian–Tithonian time, the Maya block continued to rotate, resulting in additional space in the Gulf of Mexico (Pindell, 1985; Rueda-Gaxiola, 2003; Pindell and Kennan, 2009). Pindell and Dewey (1982) suggested that the Yucatán block rotated counterclockwise some 40° to 50°, with a pole of rotation located northeast of the Yucatán Peninsula (Pindell and Kennan, 2001), and was juxtaposed against northern South America (Bartok et al., 2015; Pindell and Kennan, 2001).

The onset of the counterclockwise rotation of the Yucatán block took place after ca. 176 Ma in response to the propagation of seafloor spreading into the proto–Caribbean Sea (Kneller and Johnson, 2011). During Tithonian to Berriasian time, the rotation of the Maya block ceased (Pindell and Dewey 1982; Pindell and Kennan, 2009; Molina-Garza et al., 1992; Godínez-Urban et al., 2011). Workers have proposed that during the Early Cretaceous, Colombia was connected with the inner-shelf sites in the westernmost Mediterranean Tethys and the ancient Gulf of Mexico (Rojas and Sandy, 2019).

Relatively recent compilations of paleomagnetic data have derived different apparent polar wander paths for South America (e.g., Kent and Irving, 2010; Torsvik et al., 2012). According to Fu et al. (2020), the main difference between these apparent polar wander paths is that the compilation by Kent and Irving (2010) utilized only paleomagnetic poles derived from igneous rocks and/or inclination error–corrected sedimentary rocks. The compilation reported by Torsvik et al. (2012), on the other hand, involved computations of a quality-weighted estimated means of all available igneous and sedimentary paleomagnetic poles. Both apparent polar wander paths suggest an anomalous time interval of net pole shift of −30.5° (Kent and Irving, 2010) to 39.9° (Torsvik et al., 2012) during the Late Jurassic (Fu et al., 2020). According to Kent and Irving (2010) and Muttoni and Kent (2019), this “monster shift” in paleomagnetic poles occurred rapidly during the time interval between ca. 160 and 145 Ma. Torsvik et al. (2012), however, called for a relatively constant (lower) rate of change in pole positions during the Jurassic. Fu et al. (2020) suggested that differences in rates and duration of rotations described by apparent polar wander paths during the middle Mesozoic imply dramatically different geodynamic conditions.

Our new paleomagnetic results show that the directional (declination) discordances exhibited by the data from the CRS are clockwise in sense, with respect to the South American craton. In addition, we observe no significant differences between the Fisher and Bingham distributions of directional results (Tables 1 and 2). The separate Angostura del Río Lebrija Formation and Los Santos Formation data sets show discordances relative to directions based on reference poles in Torsvik et al. (2012) and imply clockwise rotations of 45.3° ± 6.3° and 48.8° ± 6.1°, respectively (Tables 1 and 2). The flattening discordance value derived from the Angostura del Río Lebrija formation data set (+32.9° ±10.5°) (Table 1) and (+32.9° ±10.3°) (Table 2) is quite different and statistically insignificant than that for the Los Santos Formation (+10.8° ±8.9°) (Table 1) and (+10.8° ±8.4°) (Table 2). Both flattening discordancy values, based on inclination flattening–corrected data, are relatively small and statistically insignificant: +6.0° (± 10.3°) for the Angostura del Río Lebrija Formation and −0.03° (± 9.1°) for the Los Santos Formation data (Tables 1 and 2).

On the other hand, the Angostura del Río Lebrija Formation and the Los Santos Formation data set discordances relative to directions derived from reference poles in Kent and Irving (2010) imply clockwise rotations of 60.6° (± 8.5°) and 54.1° (± 6.8°), respectively (Tables 1 and 2). Our results from the Yariguies anticlockir can be compared with paleomagnetic data from similar-age strata in the Perijá Range (Gose et al., 2003; Nova et al., 2012) and from those stratigraphic sections exposed as part of the footwall of the Suárez and Boyacá faults (Bayona et al., 2006) (Fig. 9B). The mean directions from the CRS are very similar in declination to the results from the Perijá Range (Gose et al., 2003; Nova et al., 2012) (Fig. 9B). The results from the Los Santos Formation reported by Bayona et al. (2006), however, have a more north-directed declination and also are associated with considerably higher dispersion (Fig. 9B).

The inferred paleomagnetic poles calculated from the CRS in the hanging wall of the Suárez fault from data reported in this study (Table 3), for the Angostura del Río Lebrija Formation (Late Jurassic) (latitude 47.1°N, longitude 19.8°E, A95 = 3.4°), the Los Santos Formation (Early Cretaceous) (latitude 50.3°N, longitude 7.0°E, A95 = 3.6°), and the overall Girón Group (latitude 48.8°N, longitude 14.4°E, A95 = 2.5°) indicate latitudes that are shallower than those of poles reported from similar-age strata exposed in the footwall of the Suárez fault (Bayona et al., 2006) (Fig. 12). We suggest that the contribution provided by declination data to the paleomagnetic pole position discordances (Fig. 12) is related to moderate clockwise rotation of Girón Group strata within the hanging wall of the Suárez fault.

The Bucaramanga and Suárez faults are characterized by having considerable neotectonic activity (Paris et al., 2000; Diederix et al., 2009). Displacement along the Bucaramanga fault is interpreted to have taken place during the Neogene as a response to a transpressional stress state (Jiménez et al., 2015; Siravo et al., 2020). In the Maracaibo block (Fig. 1), paleomagnetically determined clockwise rotations are associated with Neogene displacement along the Bocón fault (Jiménez et al., 2014) (Fig. 14). The area surrounding our study area is characterized by anticlines and synclines with east vergence, and features internal to the folds have been offset by displacement along transverse faults with an apparent (map-sense) left-lateral displacement (Figs. 3 and 14). According to García and Jiménez (2016), in the Eastern Cordillera, the presence of such transverse faults and their influence in the tectonic evolution of this area are not well documented or as well understood. Transverse faults are structural boundaries of the different subbasins within the Eastern Cordillera (Sarmiento-Rojas et al., 2006) and are probably related to basement-rooted inherited structures that have been reactivated since Paleogene time, with an apparent left-lateral displacement produced by block segmentation and clockwise rotations (Garcia and Jimenez, 2018). According to Costantino et al. (2021), the tectonic inversion in the Eastern Cordillera started during the Oligocene and is characterized by a thick-skinned deformation phase with...
basement uplift, and migration of the deformation from northwest to southeast. We propose that the inferred clockwise rotations ranging from \(-40° \pm 6.4°\) (data from Cretaceous rocks) to \(-49° \pm 6.1°\) (data from Jurassic rocks) that we report here (Table 1) likely reflect both regional strike-slip-dominated displacement along the Bucaramanga and Suárez faults and more local strike-slip displacement along the El Monje, El Guayabo, and El Poleo faults (Figs. 1, 3, and 14).

Assuming that the inferred sense of moderate rotation derived from the data reported by Bayona et al. (2006) is clockwise, and thus much less than 90°, and also that this rotation took place during the Neogene to present tectonic inversion phase of deformation that affected the Eastern Cordillera, we suspect that this phase of rotation is related to the reactivation of some transverse structures (El Monje fault) as right-lateral faults (Velandia, 2017). These transverse faults form structural and stratigraphic limits between deforming blocks, defining a systematic pattern of moderate-magnitude clockwise rotation (Fig. 1). Farther to the north, near Bucaramanga, the magnitude of rotation decreases because the magnitude of total displacement along the transverse faults is minor to essentially zero. These types of transverse structures are common in the Eastern Cordillera (García and Jiménez, 2016), where paleomagnetically documented clockwise-sense rotations are a consequence of space accommodation by displacement along secondary faults.

**Crustal Block Translations**

Bayona et al. (2006, 2010) suggested that the Santa Marta massif, a crustal block that exposes Late Triassic to Middle Jurassic strata, had been translated northward with respect to stable South America (Fig. 10E). Previously, Castillo et al. (1991) suggested that the Mérida Andes had not experienced significant latitudinal displacement with respect to the South American craton (Fig. 10E). In addition, according to Nova et al. (2012), the Perijá Range experienced a clockwise rotation of \(-40°\) but no significant latitudinal displacement (Fig. 10E), which suggests the existence of a paleostructure that would explain the latitudinal discrepancy between a stable Perijá Range and the displaced Santa Marta massif. Alternatively, if the inclination data reported by Nova et al. (2012) from the Perijá Range, as well as the results from even earlier studies, were not suitably corrected for inclination shallowing as a result of sediment compaction and related processes, then there is a possibility that paleolatitudes estimated for the Perijá Range area and other northern blocks (e.g., Guajira block) in northwestern South America could be ambiguous, if not problematic, and require more detailed analysis, as suggested by Nova et al. (2019).

Based on the E–I method (Tauxe et al., 2008), the data sets we have obtained from the Angostura del Río Lebrija and Los Santos Formations yield estimated \(I\) values of \(-0.6\) and \(-0.26\), respectively. The estimated \(I\) value for the Los Santos Formation data set is unusually low for the kinds of rocks sampled, and we suggest that the large \(-30°\) discrepancy between the observed \((14.0°)\) and corrected \((43.1°)\) inclinations for these data is a result of a sample population bias. This inclination biasing can be explained because for data sets smaller than \(-100\) data points, the E–I method is less reliable (Tauxe et al., 2008). In addition, the E–I method can lead to an overcorrection of inclination shallowing in areas that have experienced vertical-axis rotations (Kodama, 2012).

The paleolatitude for the Girón Group strata in our study area during Late Jurassic to Early Cretaceous time prior to inclination correction is estimated to have been about 4.2°N. The expected Northern Hemisphere location is based on paleomagnetic pole information from Kent and Irving (2010) and Torsvik et al. (2012) and is consistent with results from previous studies (Bayona et al., 2006; Nova et al., 2012) (Fig. 10E). After correction for inclination shallowing using an \(I\) value of 0.6, the data we report in this study provide an unflattened paleolatitude estimate of \(-7.0°\)N and this corresponds to the modern-day latitude of the sampled section and is slightly lower than the 11.3°N paleolatitude estimate based on uncorrected inclination data reported by Bayona et al. (2006) (Figs. 10E and 14). The flattened and unflattened paleolatitudes estimates lie within the confidence interval of Torsvik et al. (2012) and suggest lower latitudes with respect to paleolatitudes estimated based on poles provided by Kent and Irving (2010) (Fig. 10E). During the Early to Middle Jurassic, the tectonic elements associated with the subduction process of the Farallon plate were located in the Southern Hemisphere at latitudes between about 14°S and 10°S (Bayona et al., 2006; 2010) (Fig. 10E). During the Late Jurassic to Early Cretaceous, at the time of deposition of the Girón Group, those tectonic elements were located in the Northern Hemisphere, at latitudes of \(-7°\)N. The magnitude of the latitudinal translation then decreased, and only minor northward translation may have occurred since the Late Jurassic (Figs. 10E and 14).

**CONCLUSIONS**

Our magnetic mineralogy experiments, a positive reversal test provided by the ensemble of data from the part of the Girón Group that we examined for this study, and a resulting magnetic polarity stratigraphy that is consistent with a Late Jurassic to Early Cretaceous age of deposition for this sequence of continental sedimentary strata all are supportive of a primary origin for the observed ChRM in the Girón Group. These new paleomagnetic data and our proposed correlation with the global Geomagnetic Polarity Time Scale may serve as a key reference for future temporal correlations for continental sequences of Late Jurassic to Early Cretaceous age in the northwestern part of South America, and may also refine tectonic reconstructions involving both stable and translated crustal elements and the timing and overall magnitude of possible terrane translations that ultimately formed this part of South America.

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