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Jurassic Evolution of the Northwestern Corner of Gondwana: Present Knowledge and Future Challenges in Studying Colombian Jurassic Rocks

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Abstract This chapter summarizes knowledge (published up to February 2019) of metamorphic, plutonic, volcanic, carbonate, and clastic sedimentary Jurassic rocks that are exposed from northern Perú to Venezuela. This compilation allows an evaluation of three tectonic models that have been proposed for the evolution of the northwestern corner of Gondwana: an extensional model, a subduction–dominated model, and the along–marginal migration of blocks model, that last of which considers the interaction of western subduction and the north–south separation of continental blocks. We conclude that (1) the Jurassic evolution of this orthogonal margin cannot be represented in a single paleogeographic map that represents a dominant geodynamic process; (2) future analyses must consider the superposition of both Pacific subduction and proto–Caribbean extensional processes; (3) extensional basins in La Guajira, the serranía de Perijá, and the Mérida Andes include the sedimentary record of predominantly proto–Caribbean extension, whereas western–subduction processes are recorded by a batholith chain that extends from southern Ecuador to the Santa Marta Massif in northern Colombia; and (4) a Middle Jurassic unconformity separates Lower to Middle Jurassic sedimentary and volcanic successions, which are related to subduction magmatism and the separation of the North and South American Plates, from Upper Jurassic continental and marine deposits in extensional basins along the northern margin, which record the opening of the proto–Caribbean Sea. Future geochemical studies in Jurassic intrusive bodies should be able to evaluate the contamination from Triassic versus Grenvillian and older continental crust. Metamorphic studies should concentrate on the petrology and the pressure–temperature–time (P–T–t) paths. The chronostratigraphic framework of sedimentary basins should be improved by resuming paleontological investigations and geochronological analysis at the base and top of volcanoclastic rocks. Sedimentological analysis should focus on establishing the geometry of sedimentary basins, the relationship of basin generation with magmatic centers, and documenting the record of paleo–climate indicators in order to establish possible paleo–latitudinal variations of tectonic blocks. Paleomagnetic studies should be conducted at different localities in Lower – Middle Jurassic rocks to test whether tectonic blocks have been static or record northward translations. The strong decrease in magmatic activity during the Late Jurassic time should be explained within a regional tectono–magmatic framework.

Keywords: *Jurassic, tectonic evolution, Gondwana, orthogonal margins, geodynamics.*

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Resumen Este capítulo resume el conocimiento (publicado a febrero de 2019) sobre las rocas metamórficas, plutónicas, volcánicas y sedimentarias calcáreas y clásticas de edad jurásica expuestas desde el norte de Perú hasta Venezuela. Esta compilación permite evaluar tres modelos tectónicos propuestos para la evolución de la esquina noroccidental de Gondwana: un modelo de extensión, uno de subducción y uno de movimiento de bloques paralelo a la margen que considera la interacción de la subducción al occidente y la separación norte–sur de bloques continentales. Concluimos que (1) la evolución tectónica del Jurásico en esta margen ortogonal no puede ser representada en un solo mapa paleogeográfico que represente un proceso geodinámico dominante; (2) futuros análisis deben considerar la superposición de la subducción en el Pacífico y los procesos extensionales del proto–Caribe; (3) cuencas extensionales en La Guajira, la serranía de Perijá y los Andes de Mérida contienen el registro sedimentario predominantemente de la extensión proto–Caribe, mientras que los procesos de subducción en la margen occidental están registrados por la cadena de batolitos que se extiende desde el sur de Ecuador hasta el Macizo de Santa Marta en el norte de Colombia; (4) una discordancia del Jurásico Medio separa las sucesiones sedimentarias y volcánicas del Jurásico Inferior a Medio, que están relacionadas con magmatismo de subducción y con la separación de las placas de Norteamérica y de Suramérica, de depósitos continentales y marinos en cuencas extensionales a lo largo del margen norte de edad Jurásico Superior que registran la apertura del mar proto–Caribe. Futuros estudios geoquímicos en rocas plutónicas jurásicas deben evaluar si la contaminación más antigua proviene de corteza continental triásica o grenvilliana, o más vieja. En las rocas metamórficas, los estudios deben enfocarse en análisis petrológicos y trayectorias de presión–temperatura–tiempo (P–T–t). Reanudar los estudios paleontológicos y los análisis geocronológicos en la base y tope de las sucesiones volcanoclásticas mejorará el marco cronoestratigráfico de las cuencas sedimentarias. Los análisis sedimentológicos deben centrarse en establecer la geometría de las cuencas sedimentarias, la relación genética de estas cuencas con los centros magmáticos y la documentación de los marcadores paleoclimáticos que permitan establecer las variaciones paleolatitudinales de bloques tectónicos. Se deben realizar estudios paleomagnéticos en diferentes localidades de rocas del Jurásico Inferior y Medio para probar si los bloques tectónicos han sido estáticos o registran translaciones hacia el norte. La fuerte disminución en la actividad magmática durante el Jurásico Superior debe ser explicada en un contexto de análisis tectonomagmático.

Palabras clave: *Jurásico, evolución tectónica, Gondwana, márgenes ortogonales, geodinámica.*

1. Introduction

Why is studying the Jurassic record in the northern Andes important? After the collision of several blocks to form the western margin of Pangea during the end of the Permian and the beginning of the Triassic (247– 299 Ma) (see summary in Martini & Ortega–Gutiérrez, 2016; Torsvik & Cocks, 2016), the northwestern corner of Gondwana became bounded by two active margins: (1) a western active margin, which experienced the long–lived subduction process of the Oceanic Pacific (Farallón) Plate; and (2) a northern tectonic boundary, which was dominated by the breakup of Pangea, separation of the North and South American Plates, and consequent opening of the proto–Caribbean Sea. Well–exposed Jurassic magmatic, sedimentary and documented metamorphic rocks in the northern Andes (Figure 1) are the key to understanding the evolution of these two active tectonic margins and testing different hypotheses of the westward and northward continental growth of Gondwana.

The interaction of these two margins led to a complex and controversial internal organization of Gondwana and peri–Gondwana blocks in the Middle Triassic to Jurassic (145–247 Ma) (see summary in Martini & Ortega–Gutiérrez, 2016; Spikings et al., 2015). New geochronological data available in the literature, demand a revision of the former identification of tectonic terranes (see discussion in Rodríguez et al., 2018), and paleomagnetic data test the concept that continental crustal blocks to the east of the Romeral Suture Zone (Figure 1) have an autochthonous origin (Bayona et al., 2006, 2010). Therefore, the understanding of the Jurassic tectonic evolution of these two orthogonal margins of Gondwana requires the clear identification of terrane boundaries of continental blocks, its paleogeographic

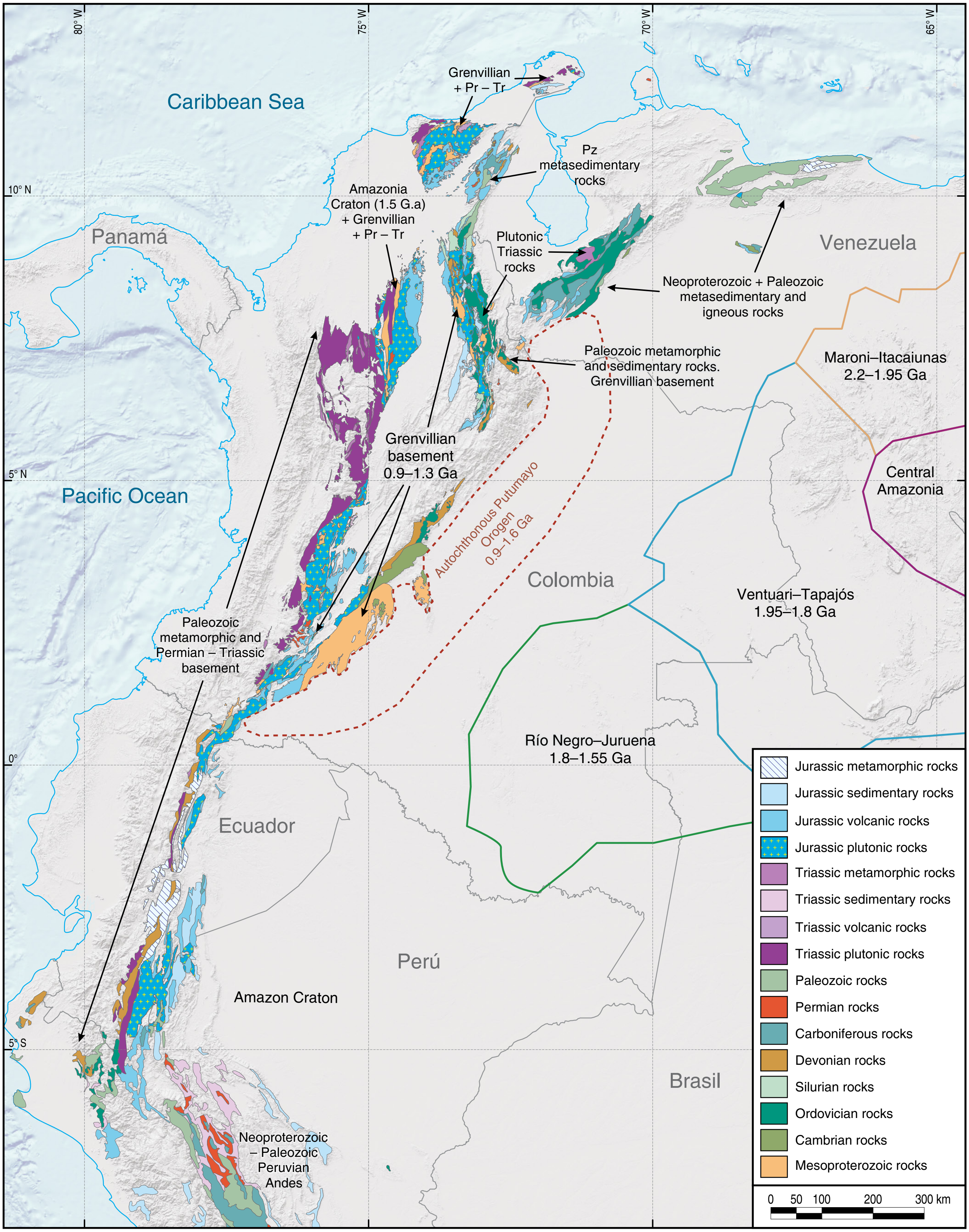


Figure 1. Exposure of Jurassic and pre–Jurassic basement and sedimentary rocks that are in intrusive/faulted/depositional contact in the northern Peruvian to Venezuela Andes. Faults are not shown for simplicity. The basement provinces in the Amazon Craton and Putumayo Orogen are modified from Ibañez–Mejia et al. (2011 and references therein). Simplified and modified from Gómez et al. (2019).

distribution, and how these continental blocks interacted with one or both of these margins.

Although geochronological data has improved the age control of plutonic and volcanic rocks, the age control of sedimentary and volcanoclastic rocks shows little advance since the review presented in Toussaint (1995) and Mojica et al. (1996). Recent papers about Triassic – Jurassic magmatism focus their studies in restricted areas (e.g., van der Lelij et al., 2016, for Santander Massif and Mérida Andes; Cuadros et al., 2014, for serranía de San Lucas; Bustamante et al., 2016, for Ibagué Batholith; Rodríguez et al., 2018, for southern Upper Magdalena batholiths; Quandt et al., 2018, for Santa Marta Massif). Triassic – Jurassic sedimentary record has been used for the analysis of tectonic–basin forming processes (see summary in Kammer & Sánchez, 2006; Sarmiento–Rojas et al., 2006), proposing the generation of narrow extensional basins related to four tectonic events (Sarmiento–Rojas et al., 2006): Triassic, Late Triassic to Middle Jurassic, Middle Jurassic, and latest Jurassic – Cretaceous events. In these studies, there is not an integration of magmatism and basin evolution processes, and it is necessary to incorporate new evidences of Jurassic metamorphism (e.g., Blanco–Quintero et al., 2014; Bustamante et al., 2017; Rodríguez et al., 2018; Zuluaga et al., 2017).

Tectonic models that have been proposed for the Triassic – Jurassic evolution of the NW corner of Gondwana may be grouped into three tectonic settings (Figure 2), keeping in mind that most of these models use the concept of a single tectonic framework for the ca. 100 my of the Triassic and Jurassic (Figure 1). These three models show different options of continental margin growth:

- The static configuration of Jurassic intracontinental rifts that formed at the northwestern margin of Gondwana as the result of extensional tectonism (taphrogenesis; Mojica & Kammer, 1995; see Cediel et al., 2003 for details of the Bolívar Aulacogen). In the Jurassic (Figure 2a), continental growth was supported by plutonic rocks occupying space that was generated by extension.
- The static configuration of the continental margin with the lateral migration of magmatic arcs that resulted from subduction–zone migration. The growth or destruction of the western continental margin occurred if the subduction zone migrated westward (see Cochrane et al., 2014a; Spikings et al., 2015, for details) or eastward (e.g., Rodríguez et al., 2018), respectively (Figure 2b). The tectonic activity of the northward margin was not considered as a relevant factor in terms of modifying the intraplate tectonic settings of Gondwana.
- Changes in the convergence angle between Pacific and western Gondwana Plates, which controlled subduction processes, the generation of magmatic arcs, and the marginal mobilization of para–autochthonous terranes (Bayona et al., 2006, 2010; Toussaint, 1995) or the accretion of marginal magmatic arcs (Rodríguez et al., 2018) (Figure 2c). In this hypothesis, extensional tectonism occurred simultaneously along the northward margin affecting the intraplate internal tectonic configuration of Gondwana (Bayona et al., 2013a, 2013b).

The continental–crust growth mechanism in active continental margins differs among models (see discussion in Cochrane et al., 2014a). Juvenile magmatism is the only mechanism that generates continental crust in the dominant extensional model; volcanism occurs before extension in active rifting settings, whereas volcanism is uncommon and only ever occurs during and/or after rifting in passive rift settings (see discussion in Frizon de Lamotte et al., 2015). In the second model, subduction rollback favors the migration of the magmatic arc (Cochrane et al., 2014a), but subduction may also erode the continental margin if the advancement occurs in the opposite direction, as suggested by Rodríguez et al. (2018). In the third model, plutonism also induces the growth of the continental margin; the northward migration of continental blocks favors the growth of the margin to the north but also the loss of the crustal margin to the south.

This work is a compendium that summarizes advances in different disciplines regarding the evolution of Jurassic rocks in the northwestern corner of Gondwana (presently the northern Andes and northern Peruvian Andes) based on a comprehensive analysis of the Jurassic metamorphism, plutonism, volcanism, and sedimentation that were documented by several authors. This study is not intended to solve all the problems but will provide some insights regarding how to improve our understanding of the geodynamic evolution the complex, tectonically active northwestern corner of Gondwana, which was affected by different tectonic mechanisms. Most of these publications analyzed a specific type of rock in one area. The strength of this work is the integration of these findings to examine the complete rock system; we do not describe details of published data, but we provide some suggestions regarding what discipline must be implemented to gain knowledge and obtain better constraints in the interpretations. This manuscript focuses on understanding what documentation we have, how the new data fit among the above three models (Figure 2), and in which directions we should move to achieve a robust collection of data for future interpretations. Future research in Jurassic rocks must constrain robust models to better define terranes and interpret the pre– and post–Jurassic tectonic evolution.

2. Materials and Methods

A total of nine "continental crustal blocks" were defined according to (1) the presence and dominance of one or two of volcanic, plutonic, metamorphic, or sedimentary rocks and (2) its present geographic position and relationship with major massifs or ranges (Figure 3). These blocks are bounded by Cenozoic structures and Cenozoic – Quaternary sediments may cover im-

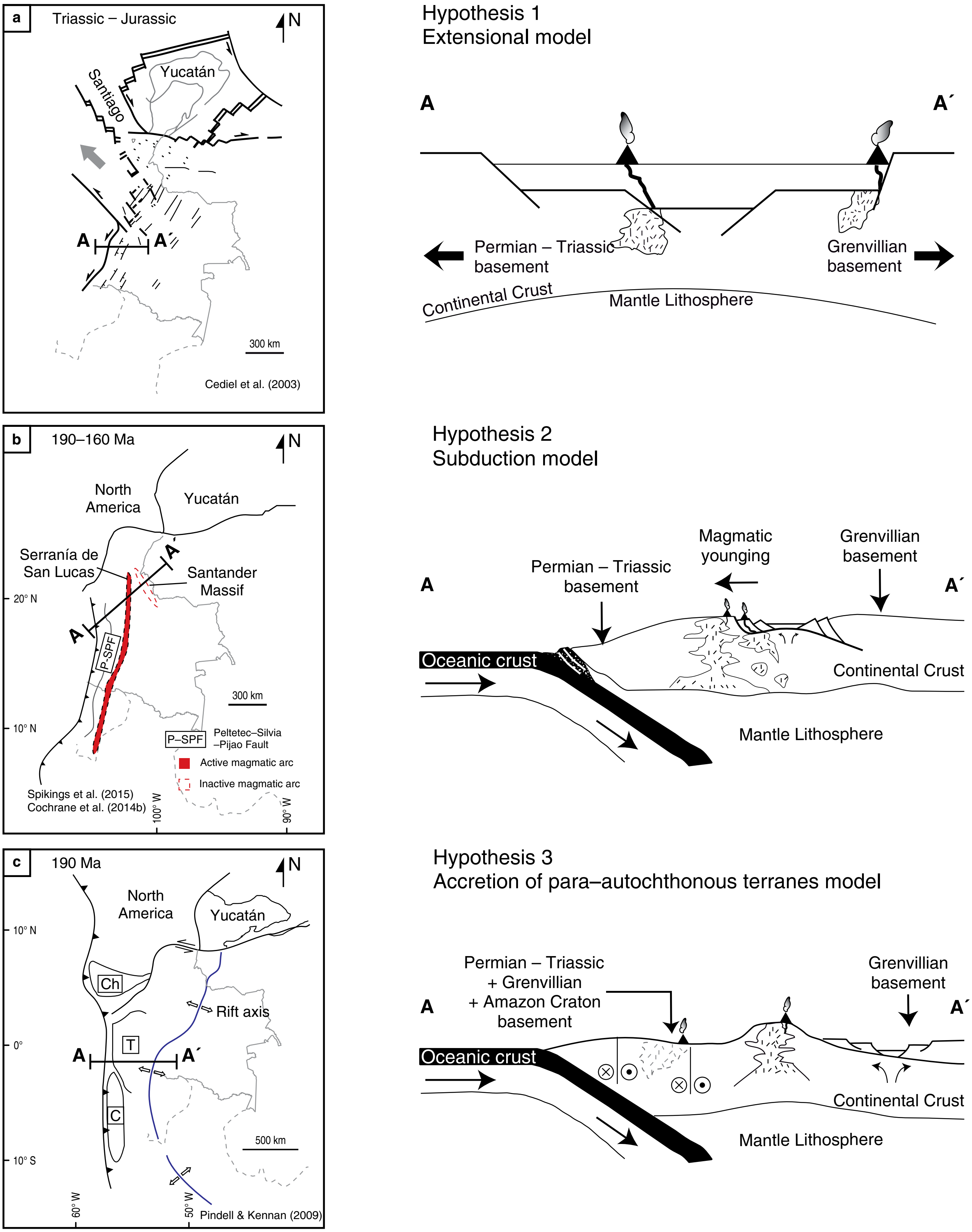
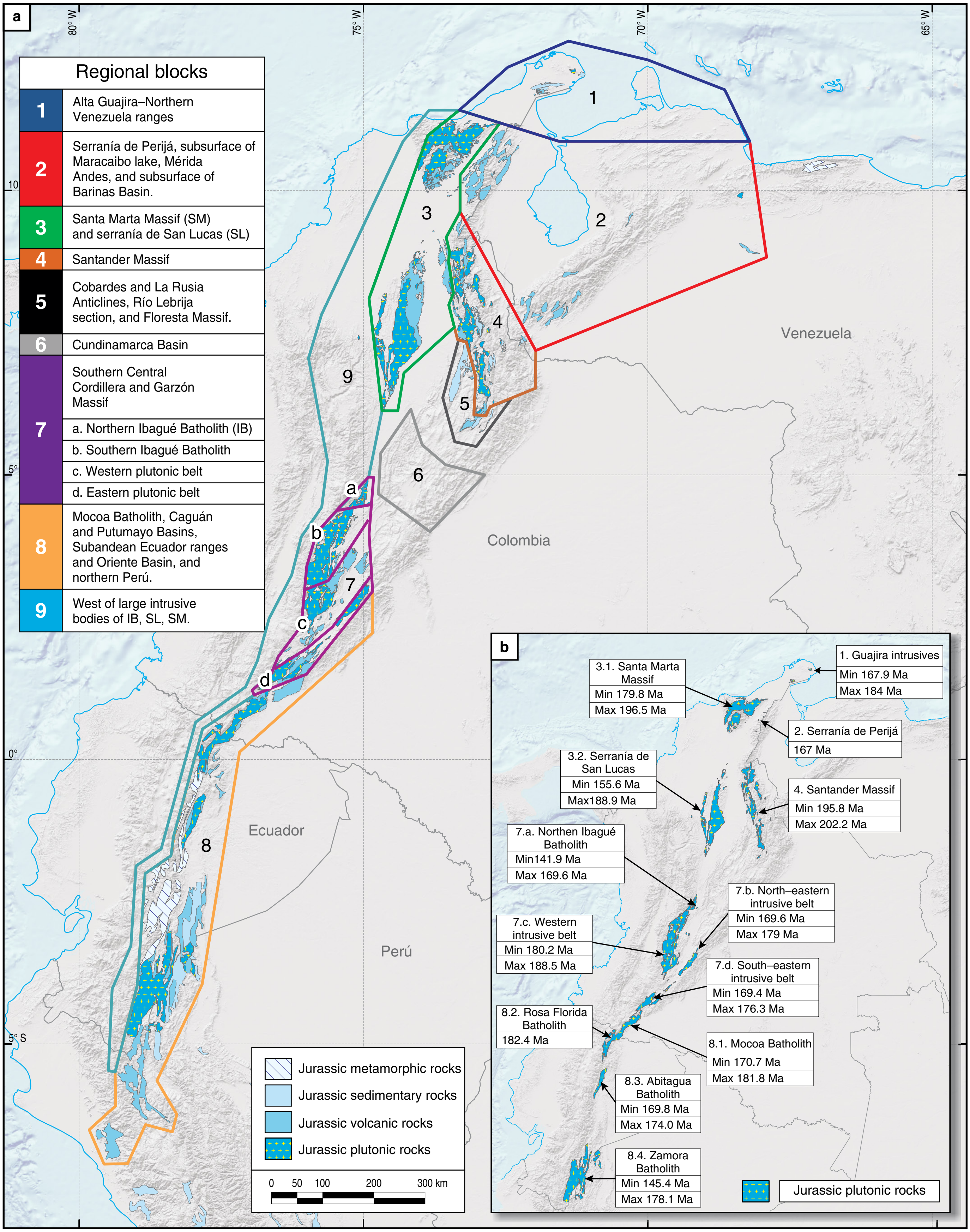


Figure 2. Map view and cross section of the proposed tectonic models for the Jurassic, and the mechanism of continental growth: **(a)** extensional, **(b)** subduction–related, **(c)** along–marginal migration of continental crust models: (Ch) Chortis Terrane, (T) Tahamí Terrane, and (C) Calima Terrane. The cross sections only show the geodynamic processes at the western margin.


a
80° W
75° W
70° W
65° W
10°
5°
0°
5° S
Regional blocks
1 Alta Guajira–Northern Venezuela ranges
2 Serranía de Perijá, subsurface of Maracaibo lake, Mérida Andes, and subsurface of Barinas Basin.
3 Santa Marta Massif (SM) and serranía de San Lucas (SL)
4 Santander Massif
5 Cobardes and La Rusia Anticlines, Río Lebrija section, and Floresta Massif.
6 Cundinamarca Basin
7 Southern Central Cordillera and Garzón Massif
a. Northern Ibagué Batholith (IB)
b. Southern Ibagué Batholith
c. Western plutonic belt
d. Eastern plutonic belt
8 Mocoa Batholith, Caguán and Putumayo Basins, Subandean Ecuador ranges and Oriente Basin, and northern Perú.
9 West of large intrusive bodies of IB, SL, SM.
1
2
3
4
5
6
7
8
9
a
b
c
d
Venezuela
Colombia
Ecuador
Perú
Jurassic metamorphic rocks
Jurassic sedimentary rocks
Jurassic volcanic rocks
Jurassic plutonic rocks
0 50 100 200 300 km
b
1. Guajira intrusives
Min 167.9 Ma
Max 184 Ma
3.1. Santa Marta Massif
Min 179.8 Ma
Max 196.5 Ma
2. Serranía de Perijá
167 Ma
3.2. Serranía de San Lucas
Min 155.6 Ma
Max188.9 Ma
4. Santander Massif
Min 195.8 Ma
Max 202.2 Ma
7.a. Northen Ibagué Batholith
Min141.9 Ma
Max 169.6 Ma
7.b. North–eastern intrusive belt
Min 169.6 Ma
Max 179 Ma
7.c. Western intrusive belt
Min 180.2 Ma
Max 188.5 Ma
7.d. South–eastern intrusive belt
Min 169.4 Ma
Max 176.3 Ma
8.2. Rosa Florida Batholith
182.4 Ma
8.1. Mocoa Batholith
Min 170.7 Ma
Max 181.8 Ma
8.3. Abitagua Batholith
Min 169.8 Ma
Max 174.0 Ma
8.4. Zamora Batholith
Min 145.4 Ma
Max 178.1 Ma
Jurassic plutonic rocks

←

Figure 3. (a) Division of the nine continental crustal blocks that were used to present the Jurassic rock data. **(b)** Age ranges of the uppermost Triassic and Jurassic plutonic rocks from Ecuador to northern Colombia (Rodríguez–García et al., 2020). The ages in the Santander Massif and serranía de San Lucas are younger to the west but older to the north (the plutonic rocks in the Santa Marta Massif are older than those in the serranía de Perijá) and south (the Ibagué Batholith and western belt have older ages than the eastern intrusive belt). See the text for a complete reference of the age control in plutonic and volcanic rocks for each block. Simplified and modified from Gómez et al. (2019).

portant subsurface structures, so we do not provide a specific reference regarding fault limits. Instead, we concentrate on the internal relationships of Jurassic rocks and the contacts with overlying Cretaceous and underlying older rocks to understand the expected boundaries, which are affected by Cretaceous and Cenozoic tectonic activity.

In the next section, we provide a brief description of the present knowledge and summarize the interpretations of each of these blocks. We follow this organization for each block:

- Metamorphism: mineral assemblage, grade of metamorphism, geochronological control, and protolith identification.
- Plutonism: age control (U/Pb), geochemical data (Hf, REE, trace, and other), and inferred tectonic setting (subduction related or rifting). We clearly indicate if another absolute geochronology method is used, but we limit the age reference to U/Pb ages.
- Volcanism: age control (U/Pb), geochemical data (REE, trace, and other), stratigraphic relationships of Jurassic units with underlying (Triassic and older) and overlying (Cretaceous) units, lateral changes in thickness, fault–controlled deposition, inferred tectonic setting (subduction related or rifting), and relationship with plutonism.
- Sedimentation: lithology (siliciclastic, volcanoclastic, carbonate, or mixed); paleontology (macro and micro), stratigraphic relationships of Jurassic units with underlying (Triassic and older) and overlying (Cretaceous) units, lateral changes in thickness, fault–controlled deposition, depositional environments, provenance and detrital geochronology, and tectonic setting.
- Paleomagnetism: results of paleomagnetic directions (declination and inclination), timing of magnetization, and the implications of paleomagnetic directions for vertical–axis rotations and paleolatitudinal location.

For simplicity, references that are related to each stratigraphic section for each block are shown in the respective figure.

3. Jurassic Rocks in Continental Crust Blocks

3.1. Block 1: Alta Guajira and Northern Venezuela Ranges (Figure 4)

3.1.1. Metamorphism

Jurassic rocks in the Cosinas Anticline, Punta Espada, Paraguana Peninsula, and Cordillera de la Costa belt areas show high deformation and strong cleavage fabric but were more likely produced during Cenozoic deformation (Irving, 1972; Zuluaga et al., 2009).

3.1.2. Plutonism

The Ipapure Granodiorite is of Lower Jurassic age (see age control in volcanic units), whereas the Siapana Granodiorite is of Middle Jurassic age (167 ± 9.4 Ma; Cardona et al., 2006). Both bodies show a geochemical signature that is related to subduction–zone magmatism (Zuluaga et al., 2015).

3.1.3. Volcanism

Zuluaga et al. (2015) mapped and dated the Ipapure–Cerro La Teta Rhyodacite, which has a mean age of 183.5 ± 2.9 Ma (N=3 samples), and is genetically related to the Ipapure Granodiorite.

3.1.4. Sedimentation

The La Guajira ranges have the most complete upper Middle to Upper Jurassic succession, which encompasses (1) continental fluvial strata at the base (Rancho Grande and Chertelo Formations), (2) a marine ingression at the Oxfordian (Caju and lower Uitpana Formations) followed by a progradation of marginal environments of the Chinapa and upper Uitpana Formations, and (3) a marine ingression at Kimmeridgian – Tithonian (Nova–Rodríguez et al., 2017; Zuluaga et al., 2009). Lateral changes in the thickness of the upper two units and the up–section dominance of marine strata indicate accumulation in extensional settings (Cuisa Formation). The Rancho Grande Formation rests unconformably upon the Ipapure–Cerro la Teta Rhyodacite, whereas the uppermost marine Jurassic rocks are covered disconformably by Lower Cretaceous rocks. Marine and marginal deposits of Upper Jurassic age are also reported in the northernmost exposures of the Jurassic rocks in the Paraguana Peninsula and Cordillera de la Costa belt of Venezuela. These units rest unconformably upon metamorphic and intrusive rocks of Paleozoic age and are overlain in an unconformable contact with Lower Cretaceous marginal siliciclastic or calcareous marine rocks (Salazar, 2010).

3.1.5. Paleomagnetism

Reported results in Jurassic rocks show eastward declinations with positive inclinations suggesting magnetization events in

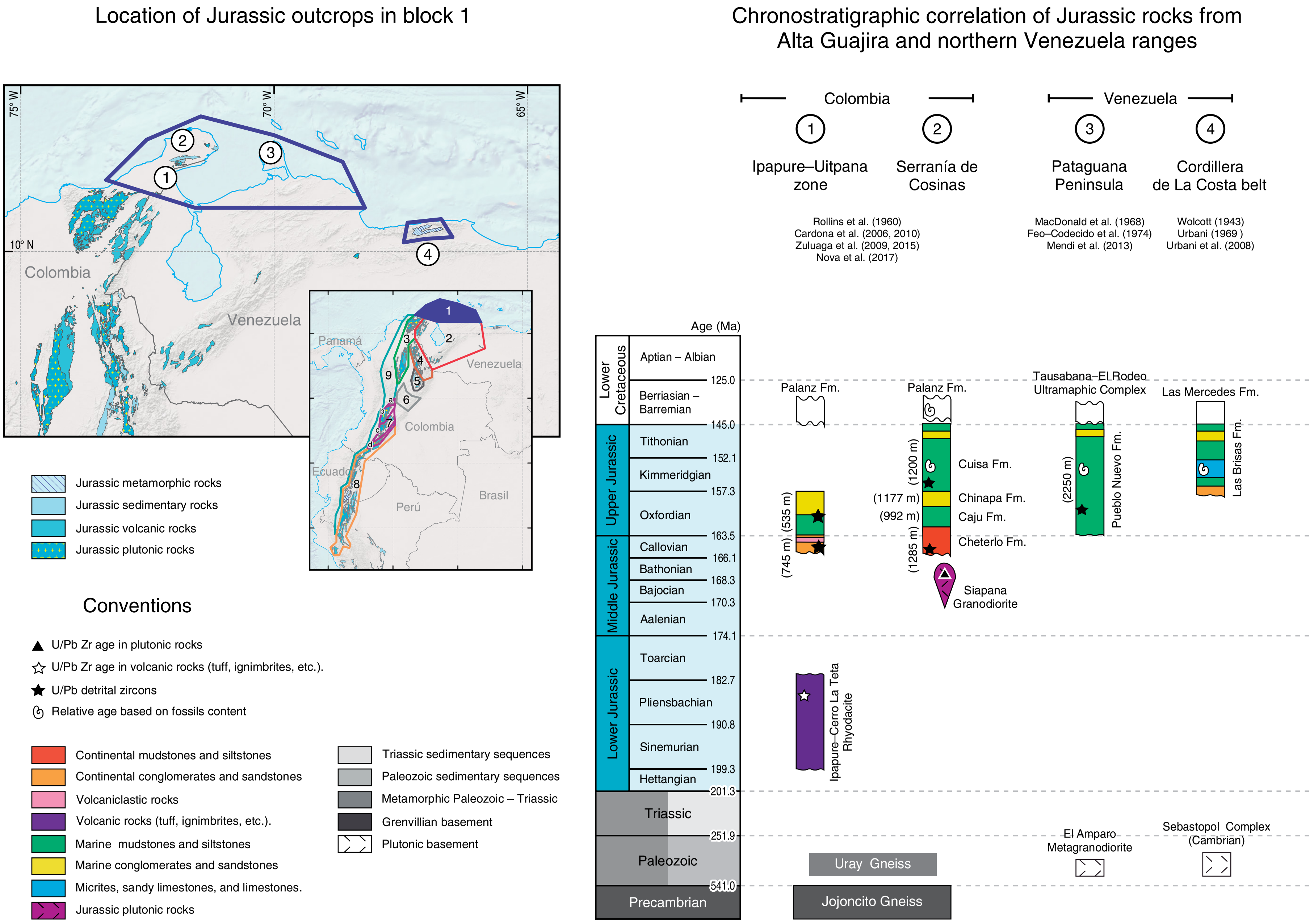


Figure 4. Chronostratigraphic correlation of Jurassic rocks in block 1: Alta Guajira and northern Venezuela ranges.

northern paleolatitudes (Bayona et al., 2016; MacDonald & Opdyke, 1972; Nova–Rodríguez et al., 2017) and ca. 90º of clockwise rotations with respect to the stable South America Plate, which is consistent with the nearly eastward–to–northeastward strike of the Cosinas Anticline.

3.2. Block 2: serranía de Perijá (Machiques Basin), Subsurface of Maracaibo Lake (Uribante Basin), Mérida Andes (Barquisimeto Basin), and Subsurface of the Barinas Basin (El Espino Basin) (Figure 5)

3.2.1. Metamorphism

No evidence of metamorphism or deformation in Jurassic rocks has been reported in this block.

3.2.2. Plutonism

Small intrusive bodies (167 ± 3 Ma) have been documented within the La Quinta Formation (Dasch, 1982) but have not been mapped independently of the La Quinta Formation.

3.2.3. Volcanism

Volcanoclastic rocks are the dominant lithology of La Quinta Formation, with localized interbeds of volcanic rocks at different stratigraphic positions (Forero, 1970; Maze, 1984; Ortega–Montero et al., 2012). The reported ages of these volcanic rocks on the western side of the serranía de Perijá vary from 162 to 183 Ma (Bayona et al., 2012a; Dasch, 1982; González et al., 2015a; Montaño, 2009). The major– and trace–element geochemical signatures show intermediate composition (Maze, 1984). van der Lelij et al. (2016) reported tuffs with a 202 Ma age at the base of La Quinta Formation in the Mérida Andes.

3.2.4. Sedimentation

The Machiques, Uribante, Barquisimeto, and Espino extensional basins have a record of Jurassic rocks with abrupt changes in thickness within the same basin but of different age ranges (Eva et al., 1989; Forero, 1970; Maze, 1984; Ortega–Montero et al., 2012). The oldest record (Triassic? to Lower Jurassic) is reported in the Barquisimeto Basin, which exhibits continental fluvial accumulation with interbeds of volcanoclastic and volcanic deposits. Upper Jurassic sediments consist of continental to marginal (lacustrine) deposits that dominate over the volcanic–related rocks. In contrast, basaltic lavas are reported in Upper Jurassic continental deposits in the El Espino Basin. In this block, Jurassic rocks rest unconformably upon Paleozoic sedimentary strata and are overlain disconformably by Lower Cretaceous continental fluvial deposits of the Río Negro Formation or by marine carbonate rocks of the Cogollo Group (Aptian age).

3.2.5. Paleomagnetism

Reported results in Jurassic rocks from the serranía de Perijá show northeastward declinations with positive inclinations (Gose et al., 2003; Nova–Rodríguez et al., 2012), suggesting magnetization events at northern paleolatitudes and ca. 45º of clockwise rotations with respect to the stable South America Plate, which is consistent with the NE strike of the serranía de Perijá. In the Mérida Andes, reported paleomagnetic data shows northern declinations and shallow positive inclinations (Castillo et al., 1991), suggesting no rotations and magnetization at northern paleolatitudes.

3.3. Block 3: Santa Marta Massif and serranía de San Lucas (Figure 6)

3.3.1. Metamorphism

The Jurassic rocks to the east of the Santa Marta Massif do not show evidence of metamorphism.

3.3.2. Plutonism

Large intrusive bodies of Lower – Middle Jurassic age constitute the Santa Marta and San Lucas Massifs. In the San Lucas Massif, intermediate–composition batholiths have ages ranging from 193 Ma to 162 Ma (Cuadros et al., 2014; González et al., 2015b). In the Santa Marta Massif, the ages range from 192 to 180 Ma (Quandt et al., 2018). Geochemical signatures of those batholiths indicate tectonic settings of magmatic arcs adjacent to subduction zones (Quandt et al., 2018; Vásquez et al., 2006). Jurassic magmatism affected Grenvillian basement rocks in both massifs, but Cuadros et al. (2014) reported older basement rocks (1.5 Ga).

3.3.3. Volcanism

Thick volcanoclastic and volcanic deposits of very variable thickness from the Noreán Formation are exposed in the eastern flank of the San Lucas Massif and western flank of the Santander Massif, and volcanic deposits of poor lateral continuity are exposed in the eastern flank of the Santa Marta Massif. In the Santa Marta Massif, the volcanic rocks have reported ages between 187 and 176 Ma (Quandt et al., 2018). In the San Lucas Massif, two ages of 200 and 163 Ma have been reported in the Noreán Formation and equivalent unit in the subsurface (La Malena volcanic unit) (González et al., 2015b; Horton et al., 2015; Leal–Mejía, 2011). Correa–Martínez et al. (2019) reported two U–Pb ages in andesite lavas (192 and 185 Ma) and

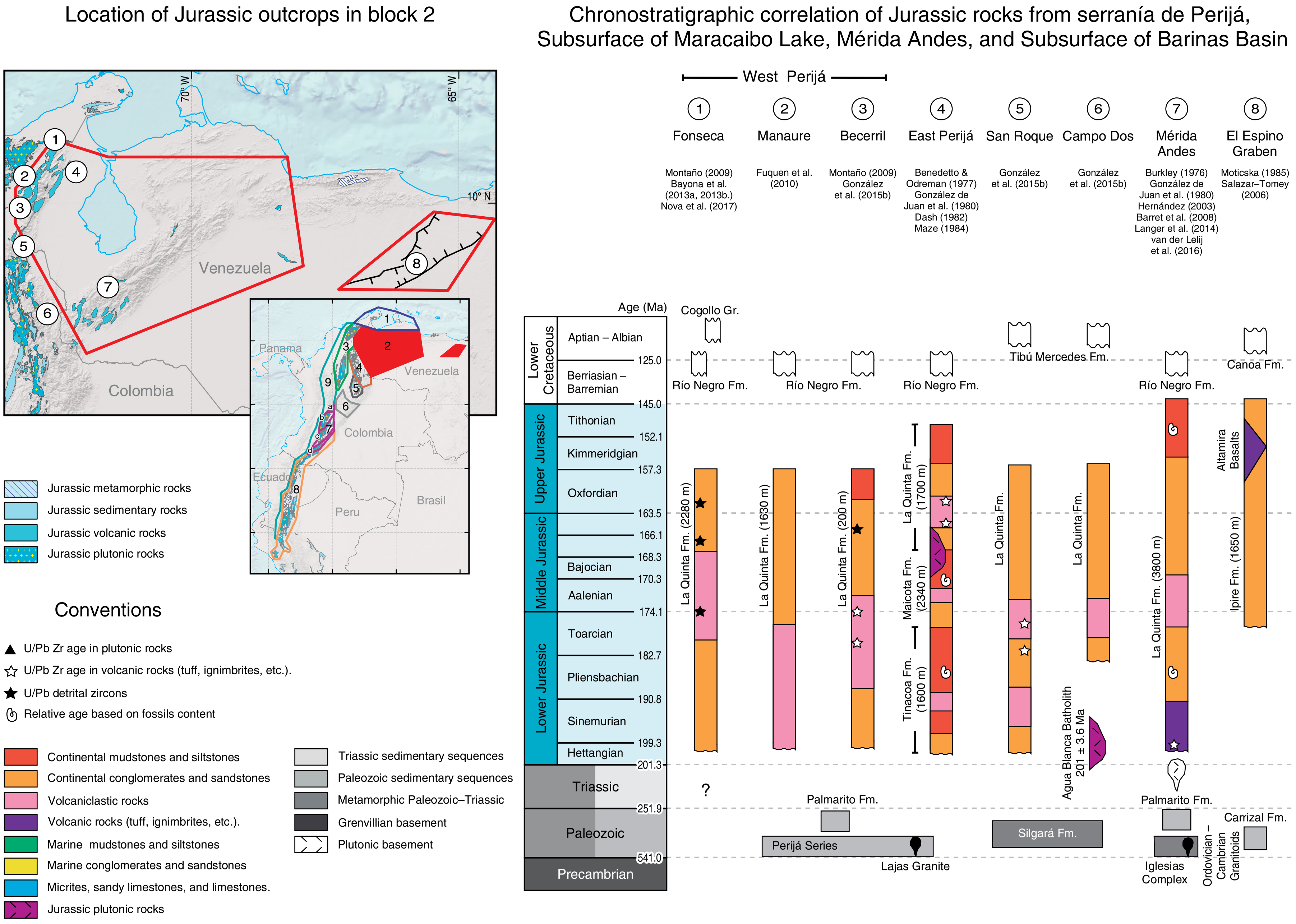
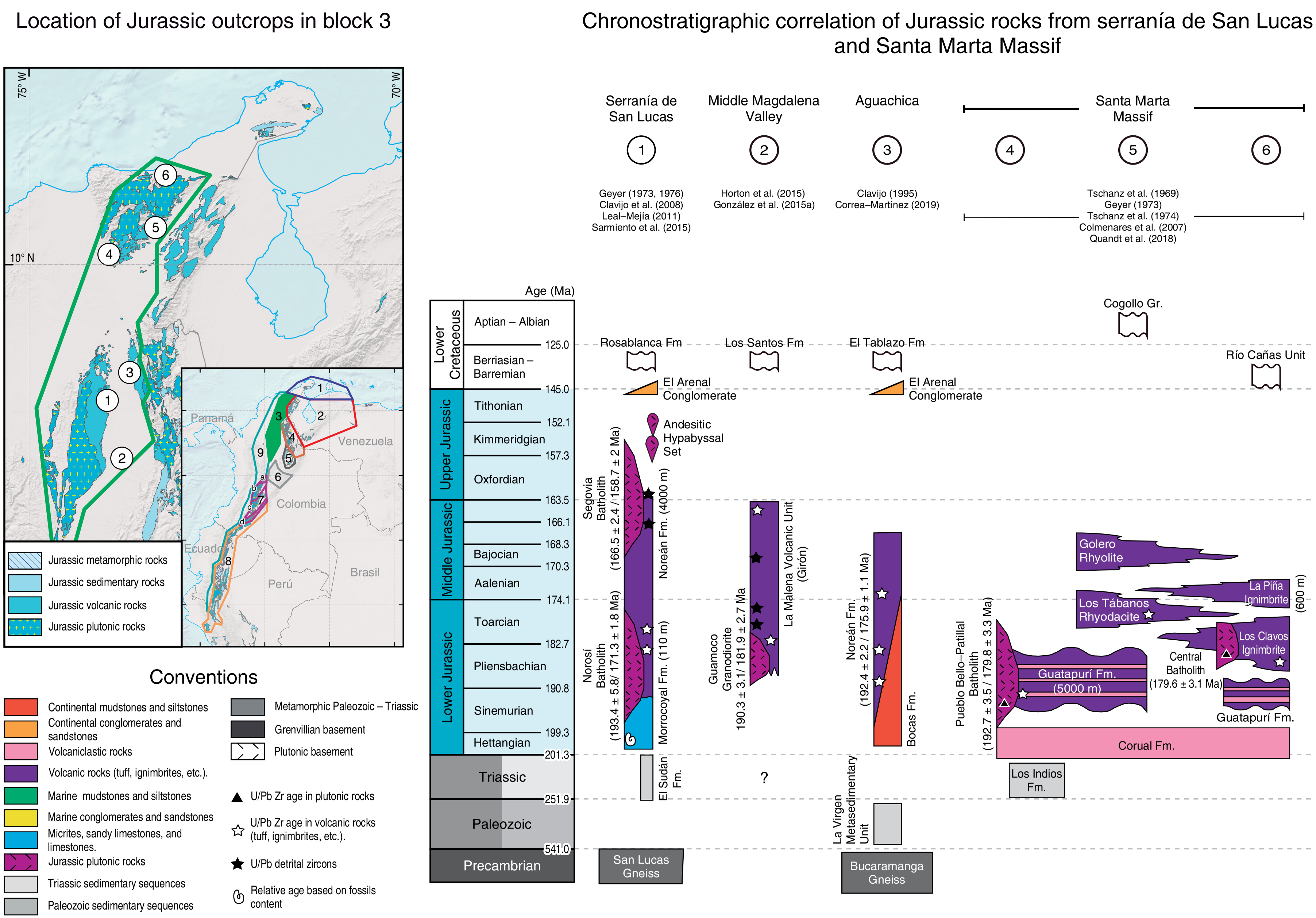


Figure 5. Chronostratigraphic correlation of Jurassic rocks in block 2: serranía de Perijá (Machiques Basin), subsurface of Maracaibo lake (Uribante Basin), Mérida Andes (Barquisimeto Basin), and subsurface of the Barinas Basin (El Espino Basin).



Location of Jurassic outcrops in block 3

Chronostratigraphic correlation of Jurassic rocks from serranía de San Lucas and Santa Marta Massif

Figure 6. Chronostratigraphic correlation of Jurassic rocks in block 3: Santa Marta Massif and serranía de San Lucas.

another age in a rhyolite lava (176 Ma); all analyzed volcanic rocks show geochemical signatures of continental magmatic arcs.

3.3.4. Sedimentation

Short periods of continental fluvial deposition are recorded in some units from the Guatapurí Formation in the Santa Marta Massif (Tschanz et al., 1974), whereas most of the record in the Noreán Formation may be related to gravity–flow deposits (Clavijo et al., 2008). Volcanic deposits rest disconformably upon marine to marginal deposits of Upper Triassic age in the Santa Marta Massif (Los Indios Formation) or lowermost Jurassic age in the San Lucas Massif (Morrocoyal Formation). The onset of Cretaceous deposition is diachronous in both massifs; the lowermost marginal to marine Cretaceous rocks overlie the San Lucas Massif and northern face of the Santa Marta Massif, whereas accumulation began in the Aptian in most areas with a record of marine deposits of the Cogollo Group or equivalent units.

3.3.5. Paleomagnetism

The reported results in Lower Jurassic volcanic rocks from the Santa Marta Massif indicate an NNE declination and negative inclinations, suggesting moderate clockwise rotations and magnetization at southern paleolatitudes (Bayona et al., 2010). No studies have been conducted in the serranía de San Lucas.

3.4. Block 4: Santander Massif (Figure 7)

3.4.1. Metamorphism

The Bucaramanga Paragneiss reached granulite–facies metamorphism during the Early Ordovician (zircon U–Pb ages from 490 to 450 Ma in van der Lelij et al., 2016), whereas rocks of the Silgará Formation were affected by this Ordovician regional metamorphism and maybe by a younger event in the late Paleozoic (Cardona et al., 2016). These metamorphic rocks are overprinted by a thermal anomaly and low–pressure metamorphism associated to the Late Triassic – Early Jurassic magmatism, as suggested by the growth of cordierite (Cardona et al., 2016; Zuluaga et al., 2017). This metamorphism was related to the subduction of oceanic crust from the proto–Pacific Ocean beneath western Pangea (Zuluaga et al., 2017).

3.4.2. Plutonism

The Santander Massif records the earliest magmatic activity after Pangea's break–up according to the U–Pb in zircon ages, which span from ca. 213 to 196 Ma (Correa–Martínez et al., 2016; Mantilla–Figueroa et al., 2013; van der Lelij et al., 2016). Geochemical data that were reported by Correa–Martínez et al. (2016) and van der Lelij et al. (2016) indicate that the granitoids are mildly peraluminous and have K_2O and Na_2O compositions that are typical of I–type granites. The geochemical data indicate a convergent margin setting because of the similar trends of the trace elements and REE abundances compared to the upper crust. In the same work, the Pb isotopic ratios were interpreted as indicative of crustal sources. These authors interpreted that the voluminous shallow batholiths from the Santander Massif formed in a subduction zone with coeval extension because of a slab rollback process. In the southernmost extension of the Santander Massif, plutonic rocks show similar macroscopic composition (Vargas et al., 1981), but geochemical and geochronological studies are required to test their Triassic – Jurassic age.

3.4.3. Volcanism

The documented volcanic rocks in the Santander Massif have local extension and an inferred Jurassic age. Basalts with porphyritic and amygdalar texture have been formalized as the Nogontova Formation by Moreno–Sánchez et al. (2016). These undated rocks might be of Lower Jurassic age because the composition and texture are similar to the basalts from the Jordán Formation (Ayala–Calvo et al., 2005). In the southernmost extension of the Santander Massif, porphyritic rhyolites have been reported next to plutonic rocks and intruding Paleozoic metasedimentary rocks; the relationship with interpreted Jurassic sedimentary rocks is not clear (Vargas et al., 1981).

3.4.4. Sedimentation

A thin record (a few hundred of meters) of continental fluvial sandstones and conglomerate deposits has been correlated with the Girón Formation, which accumulated to the east of the Bucaramanga Fault. Similarly, the record of lacustrine to marine deposits has been associated with the Bocas Formation, but with no report of clear marine–fossil associations. Some areas have interbeds of volcanoclastic deposits within this unit. A rhyolitic unit that cuts through the Bocas Formation has been dated to 250 Ma (van der Lelij et al., 2016); this relationship should be revised because this age suggests a Paleozoic age for the Bocas Formation. No provenance analyses in the Girón Formation have been conducted in this block. These deposits rest unconformably upon Paleozoic sedimentary and metamorphic rocks and are overlain by either continental Lower Cretaceous continental deposits or by marginal to marine Aptian deposits.

3.4.5. Paleomagnetism

No studies have been conducted in these units.

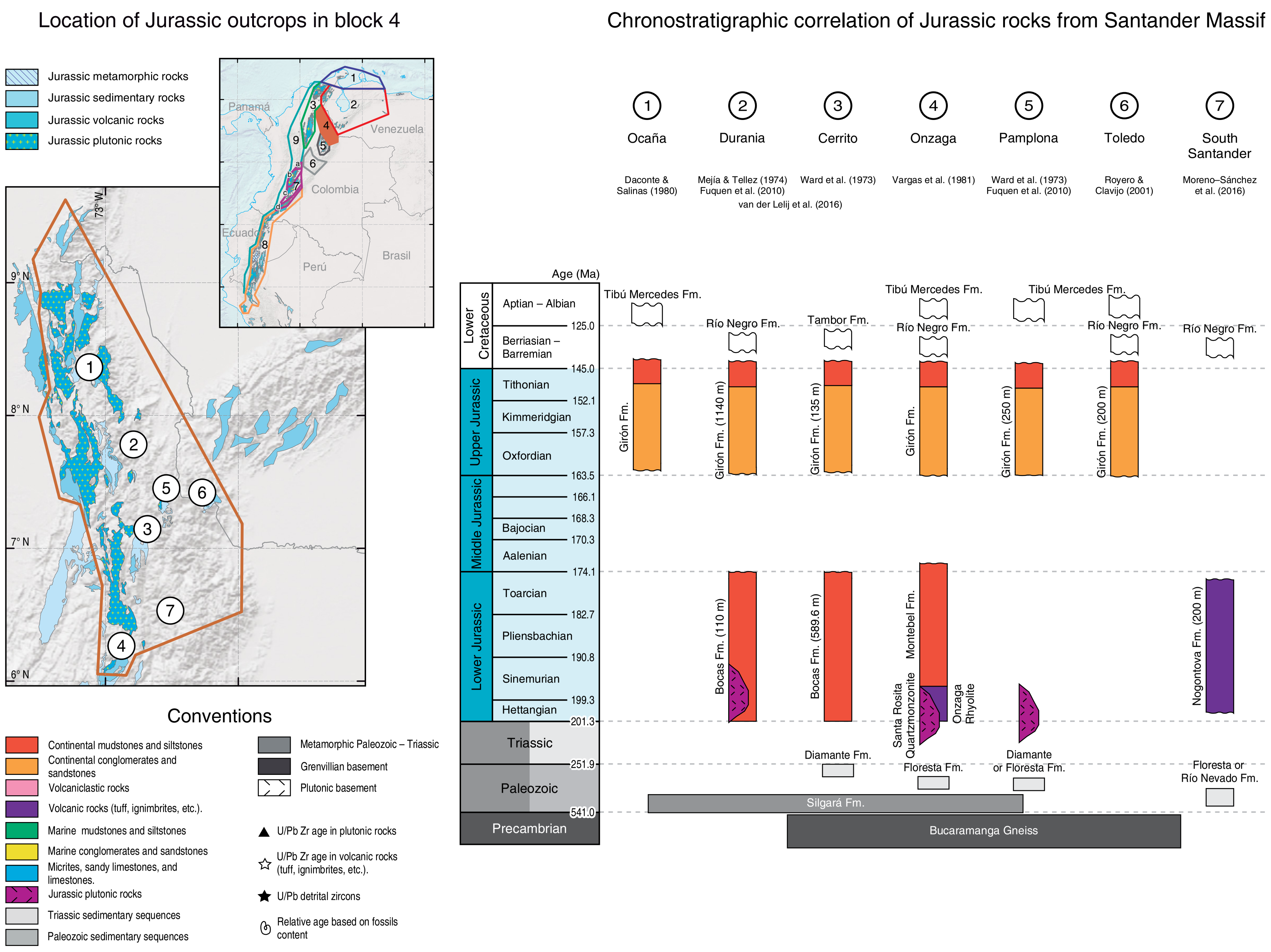


Figure 7. Chronostratigraphic correlation of Jurassic rocks in block 4: Santander Massif.

3.5. Block 5: Los Cobardes and La Rusia Anticlines, Río Lebrija Section, and Floresta Massif (Figure 8)

3.5.1. Metamorphism

No evidence of metamorphism has been reported in this block, but strong cleavage in the La Rusia Anticline records deformation processes that have not been documented in other Cretaceous rocks.

3.5.2. Plutonism

No record of Jurassic plutonic rocks exists in this block.

3.5.3. Volcanism

Jordán and La Rusia Formations show thin interbeds of volcanic and volcanoclastic rocks, which have been identified in previous studies (Cediel, 1968; Suárez & Díaz, 2016). Ayala–Calvo et al. (2005) reported very altered basalts (sericite and chlorite) that were interbedded with red mudstones of the Jordán Formation. Suárez & Díaz (2016) made petrographic and macroscopic identification of those volcanoclastic rocks interbedded with rhyolitic tuffs, feldspar–bearing sandstones and red mudstones and locally cut by mafic dikes. The Jordán Formation accumulated in fluvial–lacustrine systems affected by volcanic activity (Suárez & Díaz, 2016). Field observations of the Jordán and La Rusia units by the main author noted that "red siltstones" may really correspond to "red fine tuff beds". These units are in two localities with the most continuous record of Jurassic deposition in this block.

3.5.4. Sedimentation

The accumulation of siliciclastic rocks dominated in extensional basins. Two major depocenters have the most complete record of Jurassic deposition: the Río Lebrija section and La Rusia Anticline. In these two areas, Lower Jurassic rocks rest unconformably upon sedimentary and metamorphic Paleozoic rocks and consist of fluvial (Palermo–Montebel Formations in La Rusia Anticline) and marginal deposits (Bocas Formation in Río Lebrija). In the La Rusia Anticline, this succession changes up–section to high–energy fluvial and volcanoclastic deposits of the Middle Jurassic La Rusia Formation, whereas that in the Río Lebrija section has low–energy continental and volcanoclastic deposits of the Middle Jurassic Jordán Formation. A short period of deformation (local angular unconformity with range of 10–15º, Ward et al., 1973) separates the accumulation of the Upper Jurassic continental Girón and Arcabuco Formations, both units passing up–section conformably to the marine transgression that was recorded by the lowermost Cretaceous units. In other areas outside of these two depocenters, the Jurassic record is coeval with the accumulation of the Upper Jurassic Girón Formation; however, this accumulation is accompanied by strong changes in stratigraphic thickness from tens of meters in the La Mesa de Los Santos region (Ayala–Calvo et al., 2005) to ca. 4 km of thickness in the Río Lebrija section (Cediel, 1968). Osorio–Afanador (2016) argues that the strong lateral variation in thickness and depositional systems in continental settings makes difficult the correlation of the Upper Jurassic Girón Formation. Provenance analysis (petrography and detrital zircons) shows supply from nearby areas in the Santander and Floresta Massifs.

3.5.5. Paleomagnetism

The reported results in Jurassic rocks from the La Mesa de Los Santos to Lebrija area and in the Floresta Massif show that the northward declinations of Middle Jurassic rocks have negative inclination, whereas Upper Jurassic rocks and Lower Cretaceous rocks show positive inclinations (Bayona et al., 2006). These results, alongside the lack of paleosol development in Middle Jurassic rocks and extensive paleosol development in Upper Jurassic rocks, support the hypothesis of the northward translation of blocks from southern paleolatitudes and dry conditions to northern paleolatitudes and humid conditions (Bayona et al., 2010). Jiménez et al. (2017) documented moderate clockwise rotation and shallow positive inclinations (northward paleolatitudes) for the Girón Formation in Los Cobardes Anticline.

3.6. Block 6: Cundinamarca Basin (sensu Sarmiento–Rojas et al., 2006) (Figure 9)

3.6.1. Metamorphism, Plutonism, and Volcanism

Metamorphic and magmatic events have not been reported in this block.

3.6.2. Sedimentation

Uppermost Jurassic to lowermost Cretaceous marine deposits have been reported in this block, which have variable lithofacies association (Mora et al., 2009). In the eastern margin of the Cretaceous Cundinamarca Basin, gravity–flow deposits of the Brecha Buenavista Formation and carbonate rocks of the Guavio Formation record the irregular onset of accumulation prior to the Cretaceous marine ingression. In the depocenter of the basin, evaporate accumulation may record the onset of accumulation.

3.6.3. Paleomagnetism

No studies have been conducted in Jurassic rocks from this block.

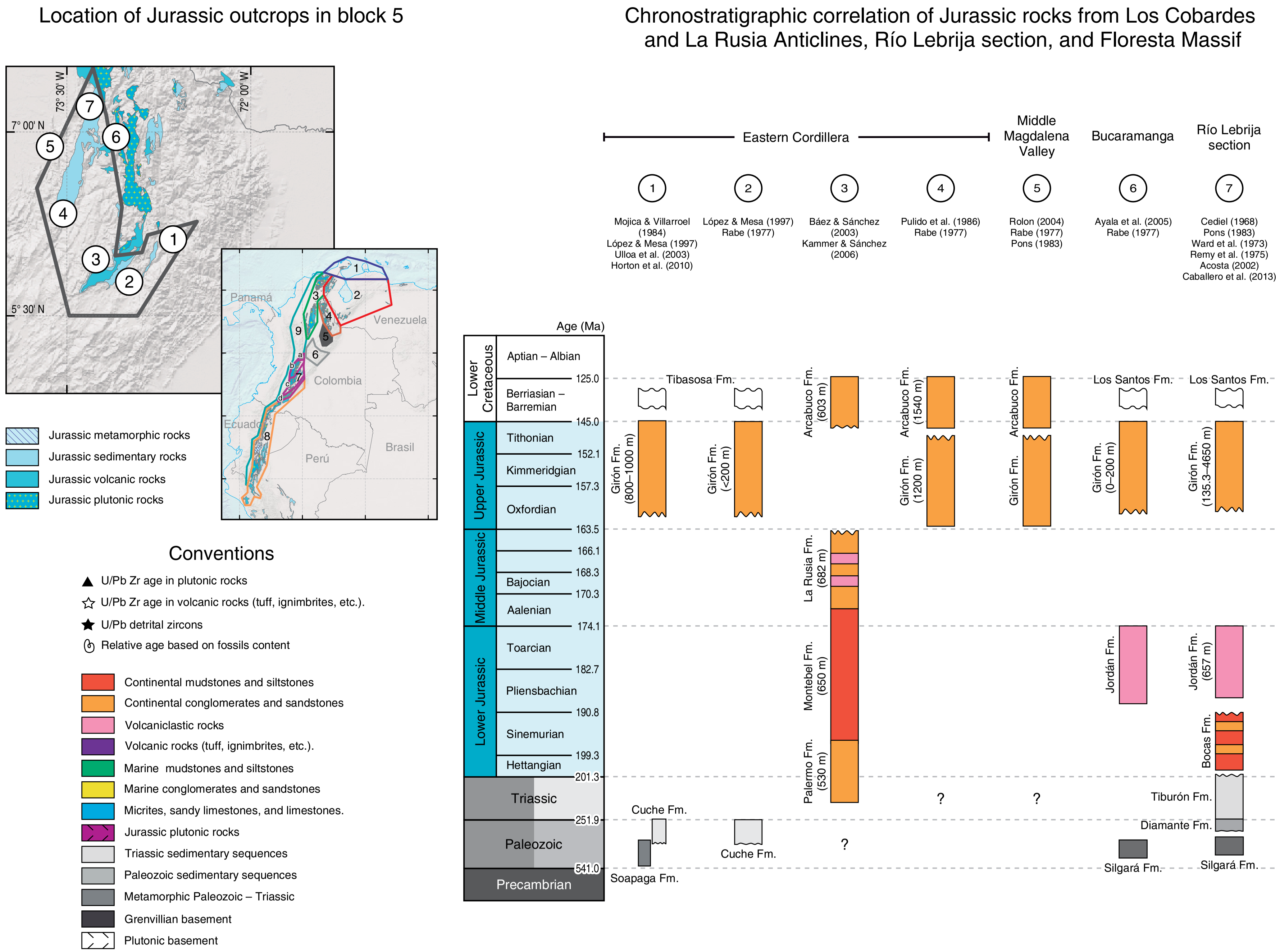


Figure 8. Chronostratigraphic correlation of Jurassic rocks in block 5: Los Cobardes and La Rusia Anticlines, and Floresta Massif.

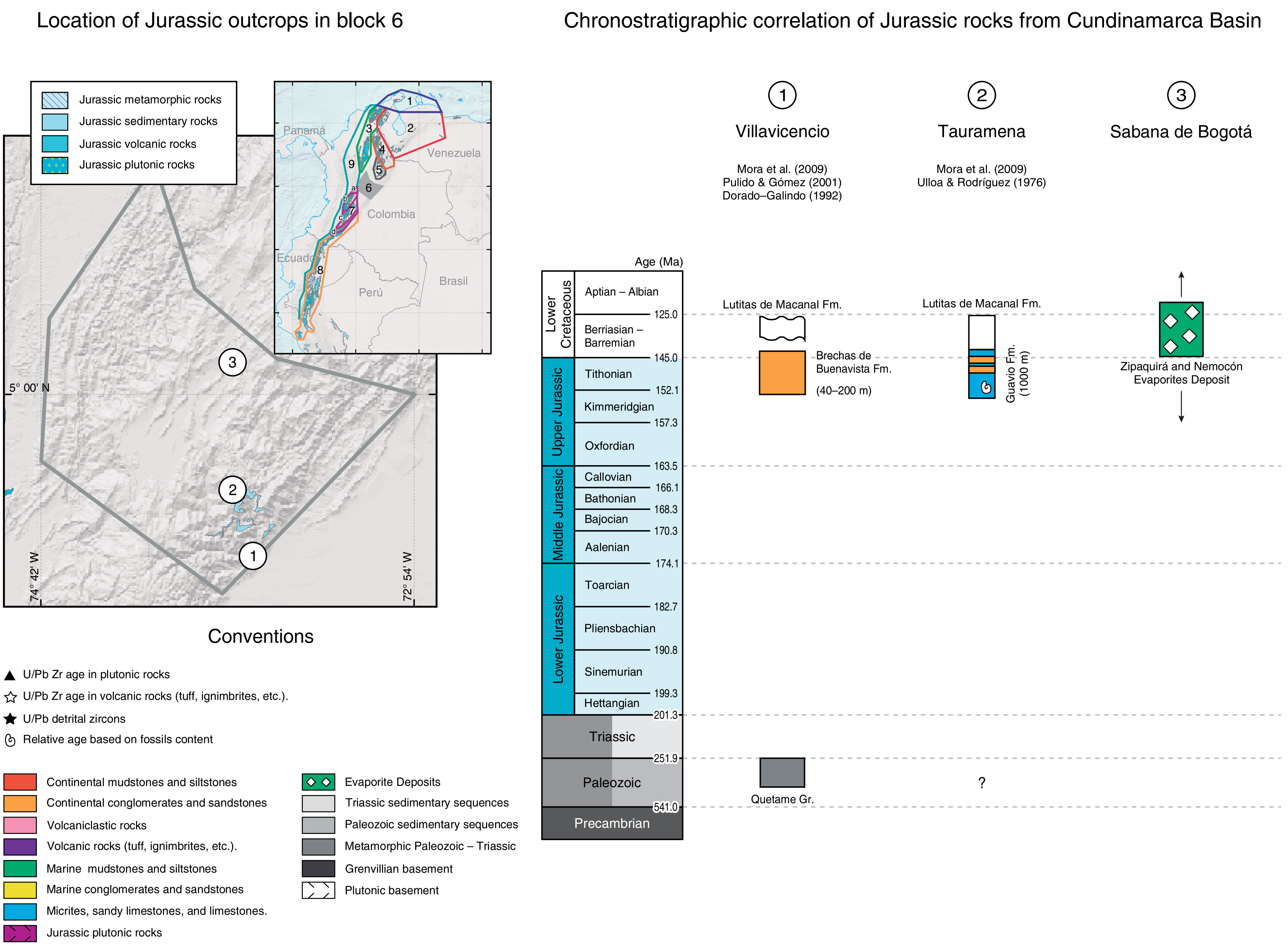


Figure 9. Chronostratigraphic correlation of Jurassic rocks in block 6: Cundinamarca Basin (sensu Sarmiento–Rojas et al., 2006).

3.7. Block 7: Jurassic Rocks between the Southern Central Cordillera and Garzón Massif (Figure 10)

3.7.1. Metamorphism

Rodríguez et al. (2018) reported Jurassic metamorphism (ca. 154 Ma) in the Tierradentro Gneisses and Amphibolites, coeval with the emplacement of a metatonalite between 158 and 150 Ma, which reached the amphibolite facies.

3.7.2. Plutonism

The Ibagué Batholith is the largest plutonic body to the north and west of the Inzá, La Plata, and Chusma Fault System. This plutonic rock formed from successive pulses of magmatism between ca. 189 Ma and 138 Ma (Bustamante et al., 2010, 2016; Cochrane et al., 2014b; Rodríguez et al., 2018). The whole–rock geochemistry that was presented in several works and compiled in Bustamante et al. (2016) shows enrichment in LREE over HREE (chondrite normalized) and pronounced negative Nb and Ti anomalies (primitive mantle normalization). The reported Hf and Nd isotopic compositions in these works also show clear crustal source of the older pulses and an increase in the juvenile component with time, where the youngest pulses record a depleted mantle source (Bustamante et al., 2016; Cochrane et al., 2014b). The whole–rock geochemistry and isotopic data suggest a subduction–related magmatism for the origin of the Ibagué Batholith.

Plutonic rocks to the east and south of the Inzá, La Plata, and Chusma Fault System show petrographic and geochemical signatures of a continental magmatic arc that was related to a subduction zone, with plutons being older (195–186 Ma) and of intermediate composition in the western belt than in the eastern belt, which are younger (173–169 Ma) and granitic in composition (Rodríguez et al., 2018). Rodríguez et al. (2018) argued that the differences in the ages of the plutonic rocks and type of basement rocks to the north and south of the Inzá, La Plata, and Chusma Fault System are evidence to separate these two areas into different magmatic arcs.

3.7.3. Volcanism

The volcanic and volcanoclastic succession of the Saldaña Formation is of intermediate to felsic, calc–alkaline composition based on petrography and major and trace–element analysis (Bayona et al., 1994; Cajas, 2003; Rodríguez–García et al., 2016; Vásquez et al., 2006). The reported U/Pb ages range from 189 to 173 Ma (Rodríguez–García et al., 2016). One Ar–Ar age in a plagioclase mineral from a subvolcanic andesitic rock that intruded the Saldaña Formation yielded an age of 159.3 ± 0.5 Ma (Rodríguez–García, 2018), whereas U–Pb ages of 151 to 155 Ma were reported from volcanic and subvolcanic dykes of rhyolitic to andesitic composition (Hincapié–Gómez, 2018). Any calculation of thickness among areas is relative because of structural complexities and a lack of exposed lower and upper contacts. The Saldaña Formation to the west of Inzá, La Plata and Chusma Fault System rests conformably upon Upper Triassic – Lower Jurassic rocks (see descriptions below), whereas the Saldaña Formation to the east of these faults rests unconformably upon sedimentary Paleozoic or Precambrian units (Rodríguez et al., 2018). Geochemical data indicate a subduction–related tectonic setting (Rodríguez et al., 2018; Vásquez et al., 2006).

3.7.4. Sedimentation

Upper Triassic – Lower Jurassic deposits to the north and west of the Inzá, La Plata, and Chusma Fault System consist of a marine sequence from the Payandé Formation (Norian to Rhaetian, Geyer, 1982) resting unconformably upon the Luisa Formation. Thin interbeds of sedimentary carbonate rocks at the base of the Saldaña Formation (Chicalá and Río Frío units, Mojica & Llinás, 1984; Mojica & Prinz–Grimm, 2000; Rodríguez et al., 1995) that accumulated in shallow–marine environments are considered of Lower Jurassic age. Fluvial and lacustrine deposits within the Saldaña Formation are present but regionally very uncommon (Bayona et al., 1994; Cajas, 2003). Detrital U–Pb geochronological data from clastic and pyroclastic rocks of the Luisa Formation yielded the youngest age population from 270 to 278 Ma suggesting accumulation in mid–Permian (Hincapié–Gómez, 2018); therefore, the Luisa Formation should not be considered as part of the Triassic – Jurassic succession.

3.7.5. Paleomagnetism

Bayona et al. (2005, 2006) reported paleomagnetic directions with northern and negative inclinations (or its reversal) in rocks from the Saldaña Formation at both sides of the Inzá, La Plata, and Chusma Fault System. These directions differ from the northern and positive inclinations in rocks from the Aptian Yaví Formation. These directions allow the interpretation of the northward migration of these blocks during Middle to Late Jurassic.

3.8. Block 8: Mocoa Batholith, Caguán and Putumayo Basins, Subandean Ecuador Ranges and Oriente Basin, and Northern Perú (Figure 11)

3.8.1. Metamorphism

Quartz–feldspar schists from the La Cocha–Río Téllez Complex yielded U–Pb zircons ages of 163.6 ± 4.7 Ma, which were interpreted by Zapata–García et al. (2017) as the metamorphism age of a sequence of pelites that reached the amphibolite facies. According to these authors, these rocks could be correlated with

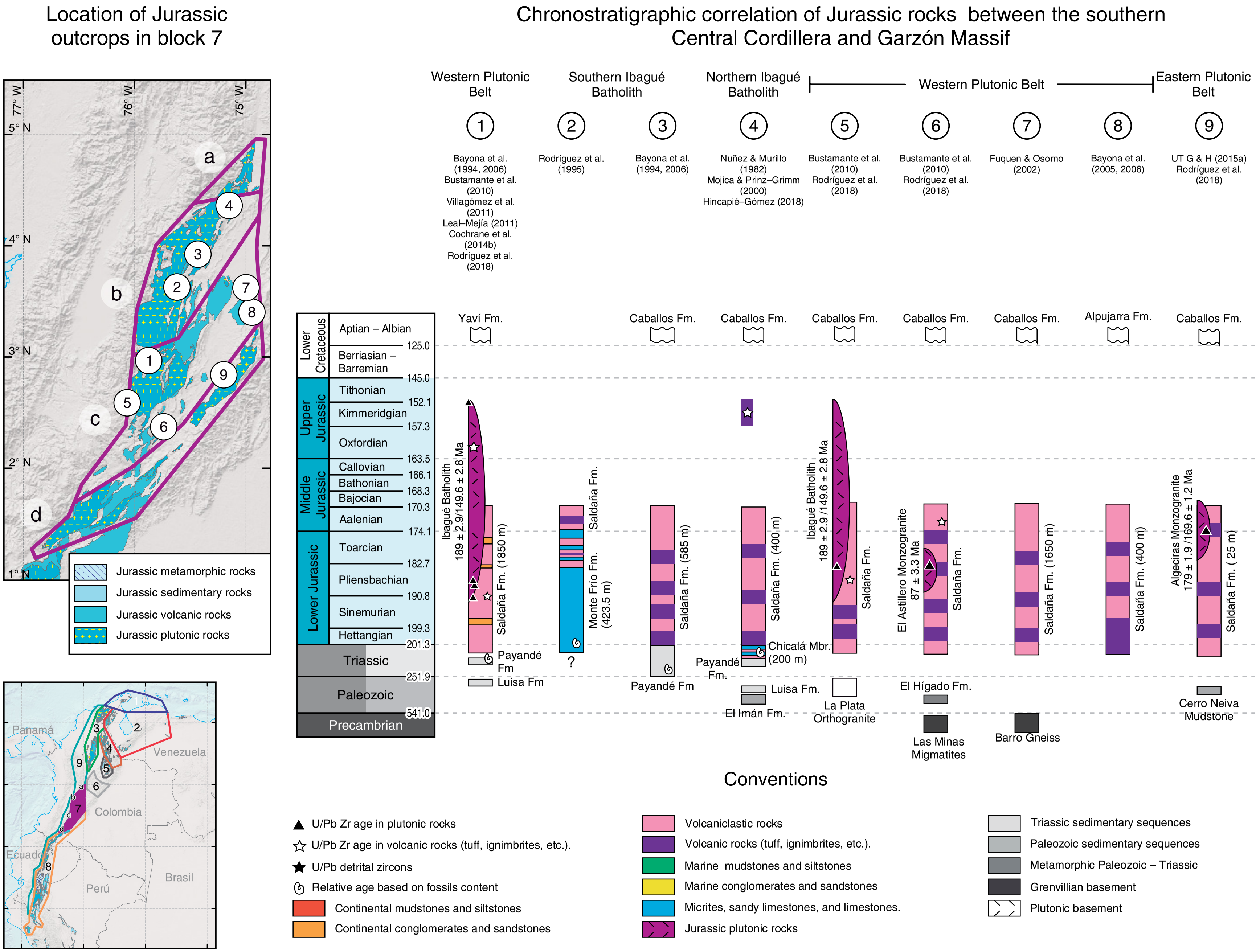
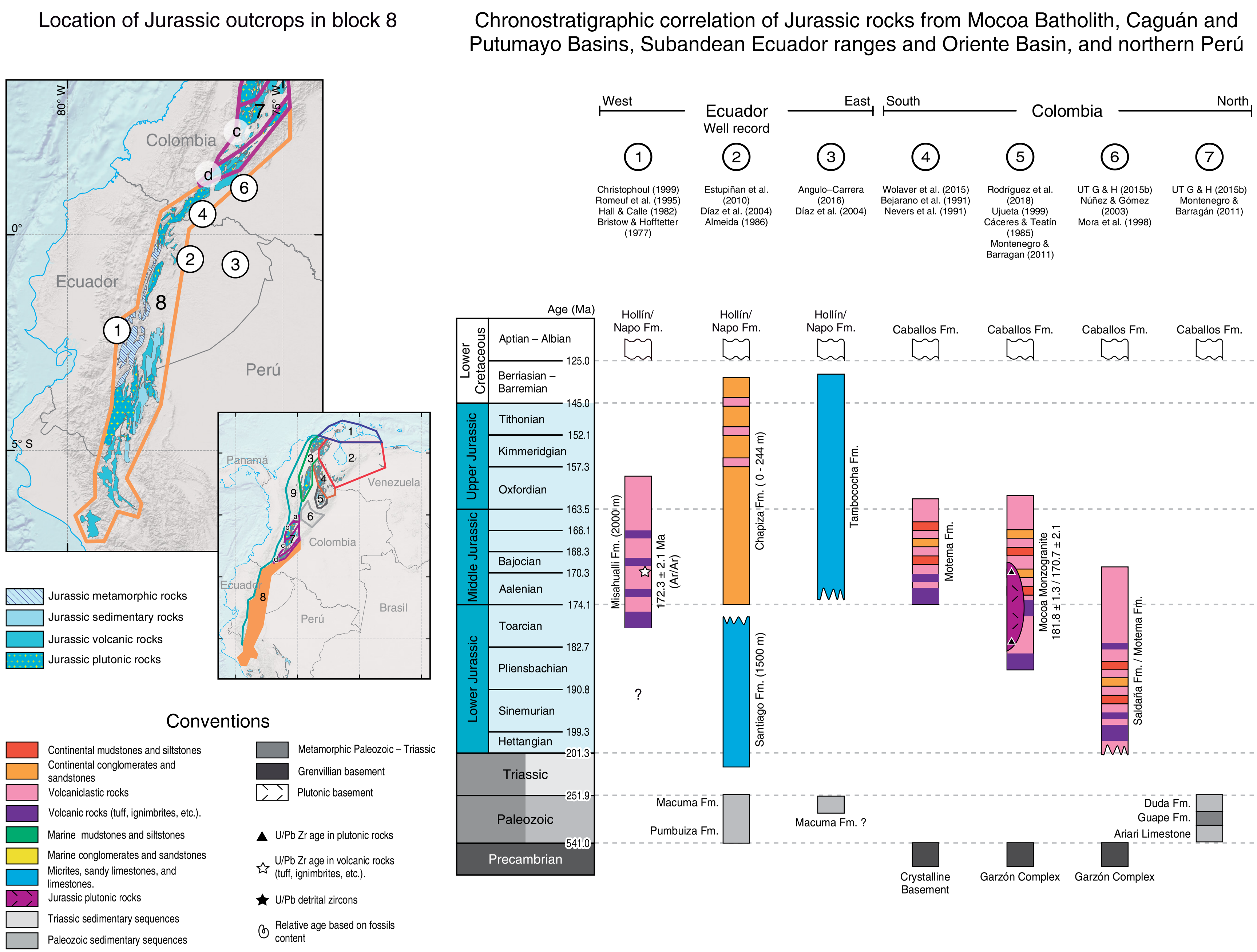


Figure 10. Chronostratigraphic correlation of Jurassic rocks in block 7: Jurassic rocks between the southern Central Cordillera and Garzón Massif.


Location of Jurassic outcrops in block 8

Chronostratigraphic correlation of Jurassic rocks from Mocoa Batholith, Caguán and Putumayo Basins, Subandean Ecuador ranges and Oriente Basin, and northern Perú

Figure 11. Chronostratigraphic correlation of Jurassic rocks in block 8: Mocoa Batholith, Caguán and Putumayo Basins, Subandean Ecuador ranges and Oriente Basin, and northern Perú.

schists from the Cajamarca Complex, which outcrops to the west of the Ibagué Batholith.

3.8.2. Plutonism

The Mocoa Batholith is a poorly studied plutonic body that outcrops in southern Colombia. Available U–Pb geochronological and whole–rock geochemistry data (Cochrane et al., 2014a; Leal–Mejía, 2011; Rodríguez et al., 2018; Zapata et al., 2016) indicates 181 to 170 Ma U–Pb crystallization ages for a high–K calc–alkaline granitoid with typical Nb and Ti negative anomalies compared to primitive mantle. The latter indicates an arc–related granitoid. The εNd value from Leal–Mejía (2011) in samples of the Mocoa Batholith revealed a crustal source. In Ecuador, the ages become younger southward; the Rosa Florida Batholith has an age of 182 Ma; the ages of the Abitagua Batholith range from 174 to 170 Ma, whereas Jurassic ages of the Zamora Batholith to the south range from 178 to 145 Ma (Spikings et al., 2015). The geochemical signatures are similar to the reported results for the Mocoa Batholith.

3.8.3. Volcanism

Rhyolite–dominated Pitalito volcanic rocks have a similar reported U–Pb age to those of the plutonic rocks (183–168 Ma; Rodríguez et al., 2018). In the Putumayo Basin in Colombia and Ecuador, intermediate and felsic volcanic and volcanoclastic rocks have been grouped as the Motema and Misahualli Formations, the latter with an Ar/Ar age of 172.3 ± 2.1 Ma (Romeuf et al., 1997). In the sub–Andean zone of Ecuador, the Misahualli Formation consists of basaltic andesites to rhyolitic lavas that are interbedded with felsic pyroclastic flows (Romeuf et al., 1997); this unit is covered unconformably by Aptian beds. The southern extension of the Misahualli Formation in Perú is named the Colán Formation (Pardo & Sanz, 1979) or Oyotun Formation (Jaimes et al., 2011), with a similar geochemical composition of volcanic and pyroclastic rocks. However, the Colán Formation rests upon carbonate rocks of the Upper Triassic Pucara Group and is covered by Neocomian quartzites (Mourier et al., 1988).

3.8.4. Sedimentation

In Ecuador, Lower Jurassic shales and carbonate rocks from the Santiago Formation include to the top some volcanic interbeds with tholeiitic affinity, which are related to an extensional event of Triassic to Early Jurassic age. This marginal to marine unit changes northward to continental red beds of the Sacha Formation (Díaz et al., 2004; Gaibor et al., 2008). An angular unconformity separates the Chapiza Formation, which consists of clastic red beds that accumulated in continental dry conditions; to the west, this unit changes to volcanoclastic rocks from the Misahualli Formation (Díaz et al., 2004), which represents the southern continuity of the volcanic rocks in Colombia. To the east, the Tambococha Formation has been interpreted as marine deposits of Middle to Upper Jurassic age (Díaz et al., 2004). The tectonic setting of these units has been related to extension from an active subduction zone to the west (Díaz et al., 2004). In northern Perú, the Upper Triassic to Lower Jurassic Pucara Group includes (1) bituminous and fossiliferous (ammonites and brachiopods) black limestones with thin pyroclastic levels of the La Leche Formation at the base and (2) black shales with thin interbeds of sandstones and limestones with ammonites of the Sávila Formation at the top (Jaimes et al., 2011).

3.8.5. Paleomagnetism

No studies have been conducted in these units. However, clockwise rotation and the northward displacement of southern terranes in Ecuador (Jaillard et al., 1999; Mourier et al., 1988) have been considered to have occurred in the Late Jurassic (Spikings et al., 2015).

3.9. Block 9: West of Large Intrusive Bodies of the Ibagué Batholith, serranía de San Lucas, and Santa Marta Massif (Figure 3)

3.9.1. Metamorphism

A Jurassic metamorphic event was defined by Blanco–Quintero et al. (2014) in metabasites and metapelites from the Cajamarca Complex (Nelson, 1962). Metamorphic cooling ages from Ar–Ar in hornblende ranged from ca. 146.5 ± 1.1 Ma to 157.8 ± 0.6 Ma, and the age in one phengitic mica from a pelitic schist was 157.5 ± 0.4 Ma. The hornblende + plagioclase + epidote + quartz assemblage defines the amphibolite facies of the sequence; according to Blanco–Quintero et al. (2014) and Bustamante et al. (2017), this sequence may constitute a continuous Jurassic metamorphic belt that extends from Ecuador possibly until Santa Marta, always to the west of the Jurassic batholiths. The San Lorenzo Schists on the Santa Marta Massif consist of low– to middle–grade and high–pressure metamorphic bodies, including amphibolites, eclogites, mica schist, and phyllite with zircon ages from 188 to 157 Ma, which are considered either detrital fragments (Cardona et al., 2010) or components of a Jurassic protolith (Piraquive, 2017).

4. Discussion and Consideration of Future Works

4.1. Review of Geologic Data

4.1.1. Metamorphic Rocks

Defined metamorphic sequences require adequate studies on the metamorphic petrology to detail the pressure–temperature–time

(P–T–t) paths. These sequences likely require a compressional setting to produce amphibolite facies metamorphism, which cannot be satisfied with a slab rollback process (Spikings et al., 2015), where extensional forces are dominant. Additionally, researchers must establish these sequences' relationships with the large intrusive bodies and surrounding basement rocks to establish the type of metamorphism (contact versus regional). Determining their correlation with contemporary rocks in similar tectonic positions in Ecuador is critical.

The main problems that must be solved are related to the recent recognition of a Late Jurassic collisional metamorphic event in the Central Cordillera (Blanco–Quintero et al., 2014; Zapata–García et al., 2017). An adequate cartography and microstructural description is lacking, and the limit of this metamorphic belt is not clear, nor is its southern prolongation along the Central Cordillera towards the Cordillera Real in Ecuador. Although Blanco–Quintero et al. (2014) indicated that this belt is in faulted contact with the Ibagué Batholith, Rodríguez et al. (2018) suggested that the Jurassic metamorphic belt is syntectonic with the magmatism based on U–Pb geochronology. However, the latter model did not discuss the presence of Triassic metamorphic roof pendants (Bustamante et al., 2017) in the same tectonic position as the Jurassic metamorphic rocks. One possibility is that the metamorphic event that was recorded by Rodríguez et al. (2018) corresponds to a dynamic event that affected the mafic facies of the Ibagué Batholith.

4.1.2. Plutonic Rocks

U–Pb geochronology and geochemical studies have increased the knowledge of Jurassic magmatism in the northern Andes. Although geochemical data from these studies show a clear evidence of magmatism from subduction processes, and the crustal origin of magmatic material, we must consider the effects of contamination of different types of continental crust and its position relative to extensional geodynamic processes that have occurred in the north since the Early Jurassic.

As examples, Lower and Middle Jurassic granitoids from the Upper Magdalena Valley intrude Grenvillian basement rocks (0.9–1.2 Ga) both to the east and to the west of the valley, but the sedimentary cover differs in both areas. In the western belt of the Upper Magdalena Valley, Lower and Middle Jurassic granitoids affect Triassic sedimentary rocks (Rodríguez et al., 2018) and are in faulted contact with Triassic metamorphic rocks (Figure 1). The northern Ibagué Batholith intruded Jurassic and Triassic metamorphic basement rocks from the Central Cordillera (Blanco–Quintero et al., 2014; Rodríguez et al., 2018). Similarly, Upper Triassic and Lower – Middle Jurassic plutonic rocks from the Garzón Massif, serranía de San Lucas, Santander Massif, and Mérida Andes intruded different sets of Precambrian and Paleozoic rocks, which record different histories of tectonic evolution (Figure 1). The San Lucas Massif has a protolith age from 1.54 to 1.50 Ga, whose basement has been related with the Río Negro Province of the Amazon Craton (Cuadros et al., 2014); this range does not include the thick Paleozoic record that is preserved in the Mérida Andes and Santander Massif (Rodríguez et al., 2017; van der Lelij et al., 2016). The serranía de San Lucas represents one portion of the Amazonia Basement, whereas the Santander and Santa Marta Massifs correspond to peripheral basins, microcontinents or island arcs that were metamorphosed in the Grenvillian event (Cardona et al., 2010). The Mérida Andes corresponds to the northern segment of the Guiana Shield (van der Lelij et al., 2016). Therefore, future geochemical analyses may elucidate whether Jurassic granitoids intruded rocks of the same terrane or different tectonic terranes.

Reported geochronological data show no clear trend of the migration of magmatic activity. Spikings et al. (2015) proposed a westward migration of magmatism by comparing Upper Triassic plutonic rocks from the Santander Massif and Lower–to–Middle Jurassic plutonic rocks from the serranía de San Lucas. However, similar trends cannot be compared along the margin because of a lack of regional Late Triassic magmatism in other ranges (Figure 1). Lower to Middle Jurassic magmatism in the other ranges showed, in present geographic position, either a static behavior (e.g., the Zamora and Ibagué Batholiths) or an eastward migration, as suggested by Rodríguez et al. (2018) for the batholiths in the southern Upper Magdalena Valley. Considering the autochthonous hypothesis, an eastward widening of magmatic activity is documented in the Santa Marta Massif and serranía de Perijá (González et al., 2015a; Quandt et al., 2018) (Figure 2a, 2b).

The abrupt interruption of regional magmatism in the early Late Jurassic should also be investigated. Some authors argued that the peak of magmatism was related to orthogonal plate convergence, whereas a decrease in magmatic activity may have been related to oblique convergence between plates (Bustamante et al., 2016). A similar cessation of volcanic arc magmatism because of the oblique convergence of oceanic plates is recorded between the early and middle Eocene (Bayona et al., 2012b). The strong decrease in magmatic activity in the Late Jurassic should be explained within a regional tectono–magmatic framework by considering the event that caused the Middle Jurassic unconformity and the change in sedimentation patterns in northeastern Colombia and Venezuela.

4.1.3. Volcanic Rocks

Although the amount of geochemical and geochronological data from volcanic rocks has increased, published data did not consider the stratigraphic position of these rocks. Geochronological investigations at different stratigraphic positions of volcanic successions (e.g., the Saldaña and Noreán Formations) should supply value information regarding (1) the duration of

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Figure 12. Middle Jurassic unconformity that was identified in three areas: **(a)** serranía de San Lucas foothills, Rosablanca Formation resting upon the deformed Noreán Formation, **(b)** Upper Magdalena Valley, Aptian – Albian strata of the Yaví and Caballos Formations resting upon the Saldaña Formation with a significant angular unconformity, **(c)** La Mesa de Los Santos, where strata of the Girón and Los Santos Formations are nearly horizontal, with a low–angle angular unconformity (10–15º) documented by Ward et al. (1973). Note the large change in thickness of the Girón Formation from 0 to 100 m in La Mesa de Los Santos, increasing northward and westward to hundreds of meters.

the magmatic activity in the area, (2) the documentation of pulses of volcanism, and (3) explanations for composition changes in volcanic rocks (from more felsic to more intermediate or mafic). Hincapié–Gómez (2018) and Rodríguez–García (2018) documented 151 to 159 Ma subvolcanic dykes that intruded the Saldaña Formation, but these subvolcanic rocks originated from a different tectono–magmatic event.

These changes in the composition of the volcanic rocks may also represent supply from different volcanic arcs. Rodríguez et al. (2018) argued that the composition of the western magmatic belt in the southern Upper Magdalena Valley is intermediate, whereas the eastern magmatic belt is more felsic.

Defining the timing and rates of accumulation of volcanic rocks within extensional basins may also supply information regarding the mechanism of extension (tectonic or magmatic). Rift basins may migrate or completely shift laterally. Large magmatic bodies may explain the faster evolution of rift systems, whereas an evolved magmatic stage with lower magma supply may cause cessation (Villamor et al., 2017).

The location of the plutonic belt in relation to the geometry of the accumulation of volcanic and sedimentary rocks, and the position of major faults are elements necessary to identify whether a basin is "intra–arc" or "retroarc" or whether it formed within a complex rift system that was dominated by strike–slip faults, such as in central Perú in the Early Triassic (Rosas et al., 2007). For the serranía de Perijá and the Mérida Andes, the intrusive bodies are very small and more likely components of rift systems. In the Santa Marta Massif and Upper Magdalena Valley, volcanic rocks are surrounded by regional intrusive rocks, which may record changes from continental retro–arc to intra–arc systems (upper plate extension and active volcanism in a subduction zone). In the serranía de San Lucas, the intrusive belt is clearly to the west and volcanic rocks accumulated to the east in a more typical retro–arc system. However, this relationship must be analyzed from a palinspastic position rather than the present geographic position.

4.1.4. Sedimentary Rocks

Detailed sedimentological and paleontological studies of Jurassic rocks in the northern Andes have significantly decreased over the last decade. New efforts should be made to conduct these types of studies in the future to establish the temporal and spatial extension of stratigraphic units, which is currently confusing in the literature, as discussed below.

Detrital zircons geochronology is one of the few tools that shed some light regarding the age of red continental successions, such as the Girón Formation. However, a lack of coeval magmatic activity may cause a misleading interpretation. The erosion of Upper Triassic plutonic rocks supplied the youngest zircon population to the Upper Jurassic Girón Formation in the Santander Massif and Los Cobardes Anticline (Horton et al., 2010; Valencia et al., 2011). Farther to the south in the Floresta Massif, the youngest population corresponds to Ordovician zircons because of the absence of these plutonic rocks in the source area (Saylor et al., 2011). In the La Quinta Formation in the serranía de Perijá and Rancho Grande Formation in the Alta Guajira, the documented coeval magmatism with sedimentation supports the assumption that the youngest age population nearly corresponds to the depositional age. Thin interbeds of volcanic rocks at the top of carbonate units with ammonites (e.g., the base of the Monte Frío and Chicalá Members of the Saldaña Formation) must be used to calibrate ammonite zonation in the Early Jurassic.

The analysis of Jurassic sedimentary successions should be the key to understanding whether terrains have been in the same paleo–latitudinal position since the Mesozoic. The absence or presence of paleosol profiles in continental red beds was an argument that was proposed by Bayona et al. (2006, 2010) as an evidence of latitudinal climate differences as response to northward translation of terranes. If terrains have been in the same paleolatitudinal position since the Triassic, as proposed by the two static models (Figure 2a, 2b), Upper Triassic carbonate rocks must have accumulated in similar tropical conditions as Lower Cretaceous carbonate rocks, and clastic sequences may be able to generate paleosol profiles if humid conditions were constant in the Jurassic.

Based on the comprehensive analysis of magmatic and sedimentary data, we can propose that the Jurassic succession may be divided by a regional unconformity in the Middle Jurassic (Figure 12). Marine and continental accumulation in Lower Jurassic units is rapidly covered by volcanoclastic and volcanic units in most of the basins. A few exceptions occur in the Mérida Andes, Lebrija area, and La Rusia Anticline, where continental deposition was dominant and only few interbeds of volcanic material have been documented (or needed to be documented) or in the La Guajira region, where volcanic activity was dominant. This regional dominance of volcanic deposition is coeval with a regional peak of magmatism in the early Middle Jurassic in all the regional batholiths (Figure 3). In the Late

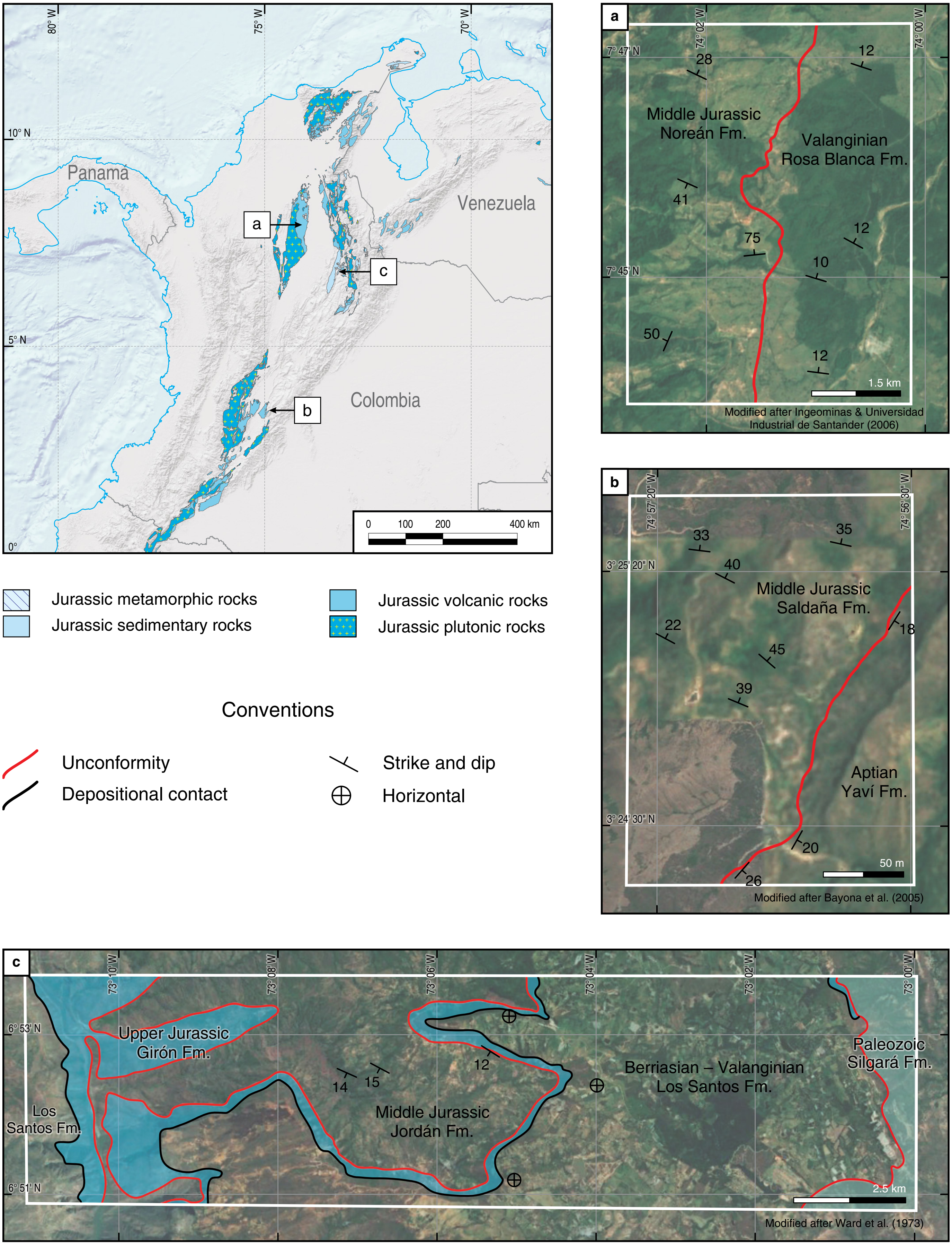

80° W
75° W
70° W
10° N
5° N
0°
Panama
Venezuela
Colombia
a
b
c
0 100 200 400 km
Jurassic metamorphic rocks
Jurassic sedimentary rocks
Jurassic volcanic rocks
Jurassic plutonic rocks
Conventions
Unconformity
Depositional contact
Strike and dip
Horizontal
a
74° 02' W
74° 00' W
7° 47' N
7° 45' N
28
12
Middle Jurassic
Noreán Fm.
Valanginian
Rosa Blanca Fm.
41
75
12
10
50
12
1.5 km
Modified after Ingeominas & Universidad Industrial de Santander (2006)
b
74° 57' 20" W
74° 56' 30" W
3° 25' 20" N
3° 24' 30" N
33
35
40
Middle Jurassic
Saldaña Fm.
22
18
45
39
Aptian
Yaví Fm.
20
26
50 m
Modified after Bayona et al. (2005)
c
73° 10' W
73° 08' W
73° 06' W
73° 04' W
73° 02' W
73° 00' W
6° 53' N
6° 51' N
Upper Jurassic
Girón Fm.
14
15
12
Berriasian – Valanginian
Los Santos Fm.
Paleozoic
Silgará Fm.
Los
Santos Fm.
Middle Jurassic
Jordán Fm.
2.5 km
Modified after Ward et al. (1973)

Figure 13. Early Jurassic tectonic evolution according to the **(a)** extensional, **(b)** subduction–related, **(c)** along–marginal migration of continental crust tectonic models. See the text for discussion.

Jurassic, the onset of continental deposition with the absence of coeval volcanic activity occurred in blocks 2, 4, and 5 (Figure 3), recording the Upper Jurassic Girón Formation and equivalent strata in the Mérida Andes (lacustrine beds of the upper La Quinta Formation; Hernández, 2003). Next to the regional batholiths (Mocoa, Upper Magdalena Valley, serranía de San Lucas, and Santa Marta Massif), sedimentation resumed in the Early Cretaceous; therefore, the lacuna of the Middle Jurassic unconformity increased towards these areas. In contrast, the sedimentation processes in the La Guajira and northern Venezuela areas changed from continental to marine in the Late Jurassic (Figure 4).

Deformation occurred in different areas since the end of the Middle Jurassic volcanic activity because different degrees of angular unconformities have been documented between Middle Jurassic rocks and overlying units (Upper Jurassic or Lower Cretaceous) (Figure 12). In the latest Jurassic, in areas where accumulation continued (e.g., Lebrija area), eustatic changes caused the incision and later filling of incised valleys with marginal to marine clastic deposits supplied from cratonic areas (contact of the Girón and Tambor–Los Santos Formations in Los Cobardes Anticline).

Therefore, this study concludes that the simplification of "Triassic – Jurassic rocks in Colombia" is misleading and should be avoided. The lithology (e.g., conglomerates), sandstone/conglomerate composition and reddish color are not enough evidence for a correlation between the La Quinta Formation in the serranía de Perijá and the Girón Formation in the Santander Massif or between the Girón and Noreán Formations in the serranía de San Lucas. As discussed in the next section, the mechanism of basin generation may differ depending upon the assumptions of the different tectonic models.

4.2. Review of Tectonic Models

The change from broad volcanic deposition in the Middle Jurassic to restricted continental accumulation in extensional basins in the Late Jurassic reflects a re–organization of tectonic plates (Figures 13, 14, 15). Collected geological data in northwestern Gondwana (northern Perú to Venezuela) were input into three tectonic models that were proposed by several authors to discuss (1) how each model explains the growth of continental plates and (2) whether each model explains the tectonic–plate reorganization along the northwestern corner of Gondwana. Extensional (e.g., Cediel et al., 2003) and subduction (e.g., Spikings et al., 2015) models with static continental blocks only consider one geodynamic model as the main driver to control the Triassic – Jurassic record. The third model of para–autochthonous terranes along both margins (Bayona et al., 2010; Pindell & Kennan, 2009; Toussaint, 1995) requires the reorganization of major plates because of changes in the Pacific–subduction and proto–Caribbean extensional geodynamic processes, similar to the model that was proposed for southern Mexican terranes (Martini & Ortega–Gutiérrez, 2016). This reconstruction does not emphasize the conjugate margin of peri–Gondwana terranes (see discussion in Spikings et al., 2015).

In the Early Jurassic (Figure 13), the onset of magmatism and coeval sedimentation could be explained by either extensional or subduction tectonic processes, although geochemical data support the latter. The extensional model considers that Early Jurassic magmatism was closely related to the extension and thinning of the continental crust (Cediel et al., 2003) (Figure 13a). In contrast, the second model considers that Late Triassic – Early Jurassic extension was related to the rollback of the subduction zone, producing subduction–related magmas with less contamination of continental crust (Spikings et al., 2015). Widespread extension in western Gondwana caused the separation of peri–Gondwana terrains and intraplate aulacogens, such as the Middle Triassic Mitú Graben in Perú (Figure 13b). In the Mérida Andes, van der Lelij et al. (2016) reported 202–Ma tuffs at the base of the La Quinta Formation, coeval with the separation between North and South America, and the generation of proto–Caribbean oceanic crust at 180 Ma (Spikings et al., 2015). The relationship between this extension and subduction in western Gondwana is unclear (Spikings et al., 2015).

In these two static models, Lower Jurassic marine, continental and volcaniclastic strata accumulated in intraplate extensional basins. Marine strata in the Upper Magdalena Valley and northern serranía de San Lucas are not connected with the Perú–Ecuador marine system (Figure 13a, 13b); instead, they record isolated marine deposition along the margin, and these rocks were covered with volcanoclastic deposits. These two models do not explain the presence of volcanic rocks in northern Perú because no Jurassic batholiths have been documented in northern Perú. Additionally, why some extensional basins only have a record of continental deposits (e.g., Lebrija and La Rusia areas) yet others have volcanic deposits remains unclear.

The third hypothesis, which considers paleomagnetic data and the presence of Amazon cratonic rocks in the serranía de San Lucas (Cuadros et al., 2014), considers that marine strata in the Upper Magdalena Valley and northern serranía de San Lucas are connected with marine to marginal basins that developed in Ecuador and Perú since the Late Triassic (Bayona et al., 2010; Sarmiento–Rojas et al., 2006) (Figure 13c). Rosas et al. (2007) interpreted the accumulation of these marine strata

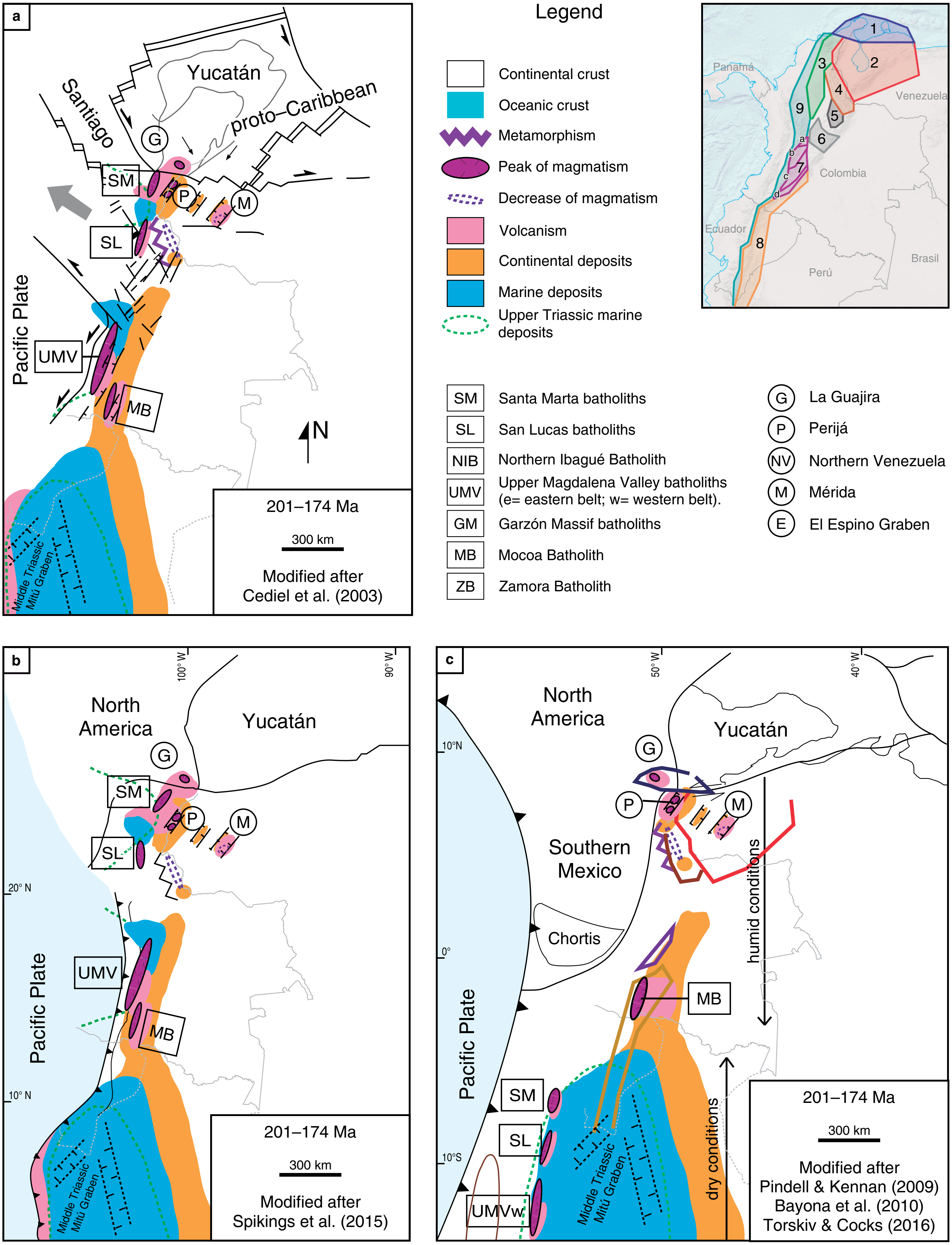

a
Yucatán
Santiago
proto–Caribbean
G
SM
P
M
SL
Pacific Plate
UMV
MB
N
Middle Triassic
Mitú Graben
201–174 Ma
300 km
Modified after
Cediel et al. (2003)
Legend
Continental crust
Oceanic crust
Metamorphism
Peak of magmatism
Decrease of magmatism
Volcanism
Continental deposits
Marine deposits
Upper Triassic marine deposits
SM Santa Marta batholiths
SL San Lucas batholiths
NIB Northern Ibagué Batholith
UMV Upper Magdalena Valley batholiths (e= eastern belt; w= western belt).
GM Garzón Massif batholiths
MB Mocoa Batholith
ZB Zamora Batholith
G La Guajira
P Perijá
NV Northern Venezuela
M Mérida
E El Espino Graben
Panamá
Venezuela
Colombia
Ecuador
Perú
Brasil
1
2
3
4
5
6
7
8
9
a
b
c
d
b
100° W
90° W
North America
Yucatán
G
SM
P
M
SL
20° N
Pacific Plate
UMV
MB
10° N
Middle Triassic
Mitú Graben
201–174 Ma
300 km
Modified after
Spikings et al. (2015)
c
50° W
40° W
10°N
North America
Yucatán
G
P
M
Southern Mexico
Chortis
0°
humid conditions
Pacific Plate
MB
SM
SL
10°S
UMVw
Middle Triassic
Mitú Graben
dry conditions
201–174 Ma
300 km
Modified after
Pindell & Kennan (2009)
Bayona et al. (2010)
Torskiv & Cocks (2016)

Figure 14. Middle Jurassic tectonic evolution according to the **(a)** extensional, **(b)** subduction–related, **(c)** along–marginal migration of continental crust tectonic models. See the text for discussion.

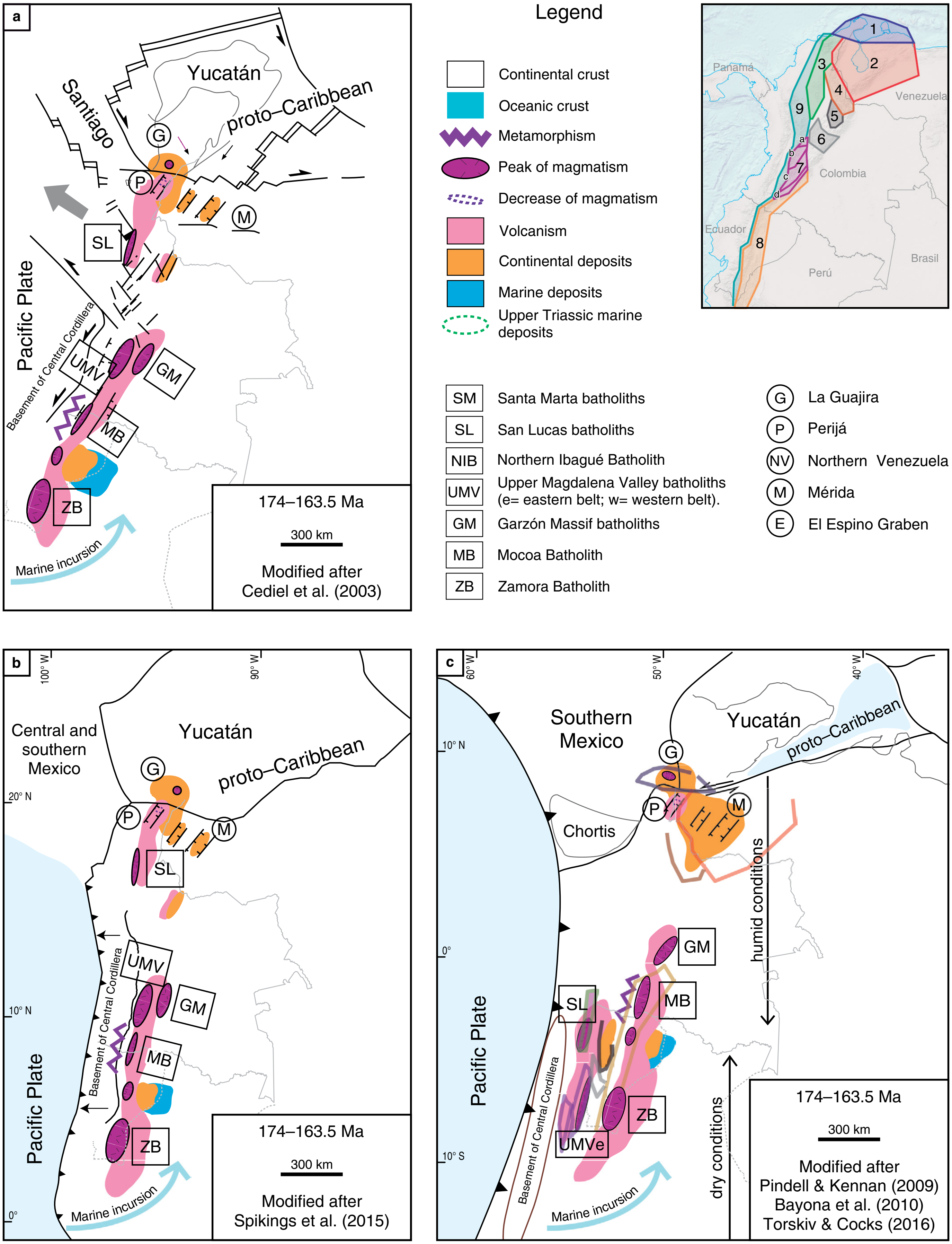
(limestones, fine–grained organic–rich clastics, and evaporites) as a record of a post–rift regional sag following the Middle Triassic structures of the Mitú extensional system. Interbedded volcanic rocks in northwestern Perú, the western Upper Magdalena Valley and the serranía de San Lucas have a volcanic–arc affinity (Romeuf et al., 1997; Rodríguez et al., 2018; Vásquez et al., 2006), whereas volcanic rocks farther to the southeast in Perú have an intraplate affinity (Rosas et al., 2007). The Lower Jurassic extensional system in northern Gondwana was related to the separation of the North and South American Plates, generating intraplate rift basins (transtensional basins) that were filled with continental to marginal strata and minor interbeds of volcanic rocks; these rocks' geochemistry indicates subduction settings, reflecting the superposition of both Pacific subduction and proto–Caribbean extensional processes, as documented in southern Mexican terranes (Martini & Ortega–Gutiérrez, 2016) (Figure 13c).

One possible peri–Gondwana conjugate margin of these terranes is the Oaxaquia continental block. According to Ramos (2008) and Ramos & Aleman (2000), the trilobite assemblages were similar to those in northern Perú. Graptolite associations in Ordovician rocks that unconformably underlie volcanic rocks from the Saldaña Formation in the Upper Magdalena Valley (Río Venado section) have been associated with Argentine–Bolivian graptolites (Moreno–Sánchez et al., 2008).

<u>In the Middle Jurassic</u> (Figure 14), magmatic activity reached its maximum extension, with the exception of the Santa Martha Massif, where magmatic activity ended in the Early Jurassic. Marine deposition was only restricted to Ecuador within isolated extensional basins (Díaz et al., 2004). In the extensional model, volcanic deposits rapidly filled extensional basins to the south, whereas continental deposition with minor volcanic activity occurred in northern extensional basins (Figure 14a); no explanation is offered for this change in magmatic activity. In the subduction–related model, a marginal volcanic arc formed after the westward rollback of the subduction zone (Spikings et al., 2015) (Figure 14b); however, a gap in the volcanic arc was created between the Upper Magdalena Valley and serranía de San Lucas batholiths. At this time, the magmatism in the Upper Magdalena Valley migrated eastward and became more felsic in composition; therefore, volcanic accumulation occurred in intra–arc volcanic basins (Rodríguez et al., 2018) (Figure 14b). To the north, volcanic rocks in the serranía de San Lucas accumulated in a retro–arc basin, whereas isolated plutons, volcanism and continental deposition in the serranía de Perijá occurred in an intra–plate extensional basin. Neither model explains the isolated magmatic activity and continental deposition in the La Guajira area (block 1). Middle and Late Jurassic metamorphic events are not shown in these two models.

In the third model, the magmatic front that grew in northwestern Perú and Ecuador (acting as the source of volcanic material in northwestern Perú) began to migrate northward (Figure 14c). Both continental (e.g., La Rusia, Jordán, and Chapiza Formations) and volcanic deposition lack evidence of paleosol development, suggesting accumulation at southern paleolatitudes under dry conditions. The northward migration and collision of the arc induced (1) the cessation of magmatism from north to south (Santa Marta Massif, serranía de San Lucas, and eastern belt of the Upper Magdalena batholiths), (2) metamorphic activity adjacent to the Mocoa Batholith and in the northern and western Upper Magdalena Valley, and (3) the deformation of Middle Jurassic continental and volcanic rocks in intraplate extensional basins (Figure 12). Volcanic rocks that were related to the evolution of these magmatic arcs accumulated in retro–arc and intra–arc basins. In contrast, continental extension in the northern region of Gondwana (La Guajira, the serranía de Perijá, and the Mérida Andes) is associated with the onset of the counterclockwise rotation of the Yucatán Block and generation of the proto–Caribbean seafloor. Small intraplate batholiths are documented in the Alta Guajira and serranía de Perijá, and thick continental deposition with thin volcanic interbeds are common in this northern area. This northward migration of terranes along the northwestern margin of Gondwana was first interpreted by Toussaint (1995) by comparing of the Jurassic succession between the block 9 (one portion of his Tahamí Terrane) and the blocks to the east of block 9.

<u>In the Late Jurassic</u> (Figure 15), magmatism ceased to the west as subduction became more oblique, with the exception of the Zamora and Ibagué Batholiths and localized subvolcanic units to the west; in northern basins, only the El Espino Graben has a record of volcanism. Marine deposition is only recorded in La Guajira and northern Venezuela, likely connected with the proto–Caribbean ocean, and in isolated basins in Ecuador (Díaz et al., 2004). For the first two models, the cessation of magmatism must have been related to either the end of extensional tectonism or the end of subduction (Figure 15a, 15b). However, extensional deformation in northern Gondwana resumed according to the broad accumulation of the Girón and upper strata of the La Quinta Formation in the Mérida Andes. The extensional model does not explain the end of extension in the Upper Magdalena Valley and Putumayo regions (Figure 15a). The westward retreat of the subduction zone must have created a new volcanic arc to the west in the basement rocks of the Central Cordillera, but this process does not explain the


a
Yucatán
Santiago
proto–Caribbean
G
P
M
SL
Pacific Plate
Basement of Central Cordillera
UMV
GM
MB
ZB
Marine incursion
174–163.5 Ma
300 km
Modified after Cediel et al. (2003)
Legend
Continental crust
Oceanic crust
Metamorphism
Peak of magmatism
Decrease of magmatism
Volcanism
Continental deposits
Marine deposits
Upper Triassic marine deposits
SM Santa Marta batholiths
SL San Lucas batholiths
NIB Northern Ibagué Batholith
UMV Upper Magdalena Valley batholiths (e= eastern belt; w= western belt).
GM Garzón Massif batholiths
MB Mocoa Batholith
ZB Zamora Batholith
G La Guajira
P Perijá
NV Northern Venezuela
M Mérida
E El Espino Graben
Panamá
Venezuela
Colombia
Ecuador
Perú
Brasil
1
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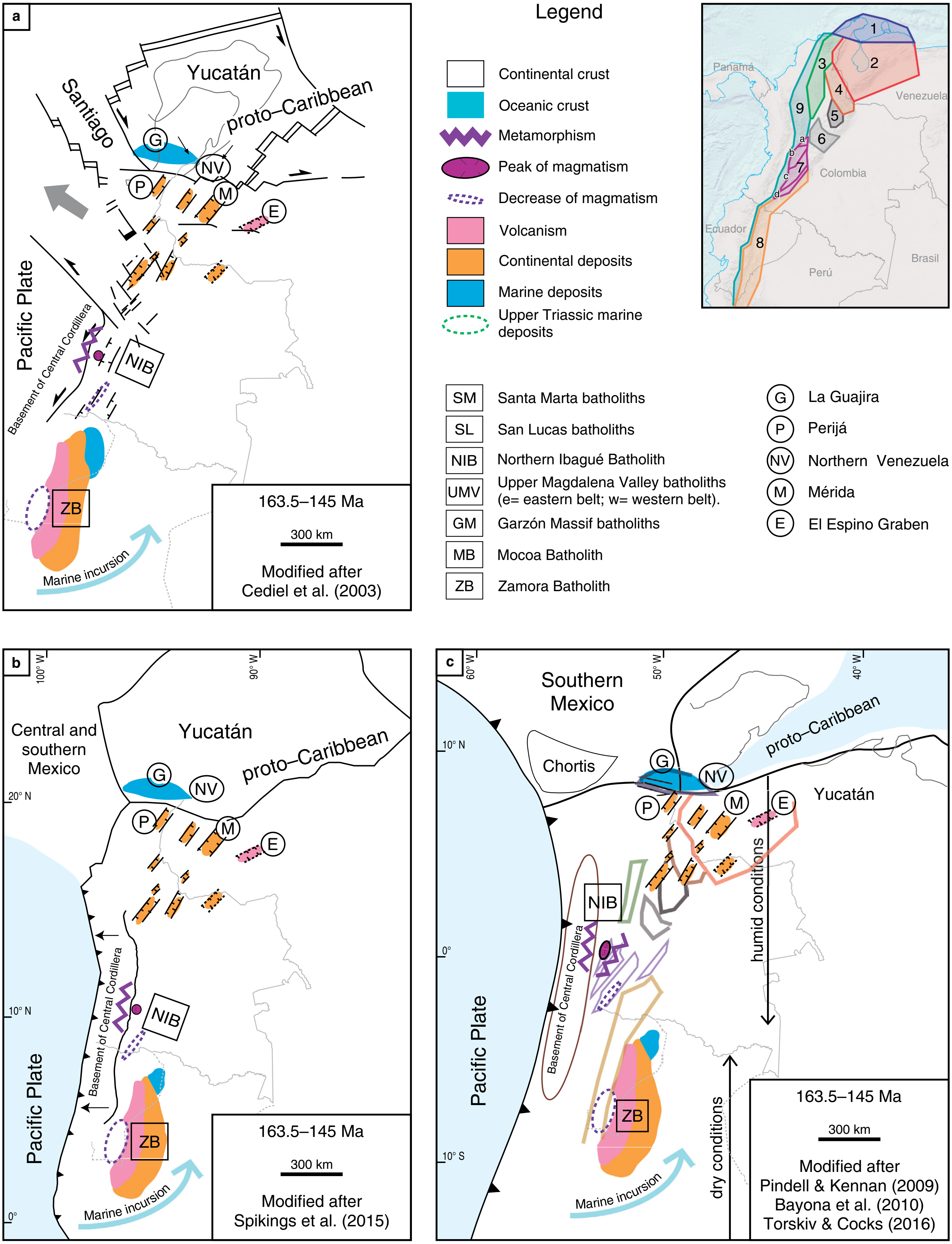
3
4
5
6
7
8
9
a
b
c
d
b
100° W
90° W
20° N
10° N
0°
Central and southern Mexico
Yucatán
proto–Caribbean
G
P
M
SL
UMV
GM
MB
ZB
Pacific Plate
Basement of Central Cordillera
Marine incursion
174–163.5 Ma
300 km
Modified after Spikings et al. (2015)
c
60° W
50° W
40° W
10° N
0°
10° S
Southern Mexico
Yucatán
proto–Caribbean
Chortis
G
P
M
humid conditions
dry conditions
GM
MB
SL
UMVe
ZB
Pacific Plate
Basement of Central Cordillera
Marine incursion
174–163.5 Ma
300 km
Modified after Pindell & Kennan (2009) Bayona et al. (2010) Torskiv & Cocks (2016)


a
Yucatán
Santiago
proto–Caribbean
G
NV
P
M
E
Pacific Plate
Basement of Central Cordillera
NIB
ZB
Marine incursion
163.5–145 Ma
300 km
Modified after
Cediel et al. (2003)
Legend
Continental crust
Oceanic crust
Metamorphism
Peak of magmatism
Decrease of magmatism
Volcanism
Continental deposits
Marine deposits
Upper Triassic marine deposits
SM Santa Marta batholiths
SL San Lucas batholiths
NIB Northern Ibagué Batholith
UMV Upper Magdalena Valley batholiths (e= eastern belt; w= western belt).
GM Garzón Massif batholiths
MB Mocoa Batholith
ZB Zamora Batholith
G La Guajira
P Perijá
NV Northern Venezuela
M Mérida
E El Espino Graben
1
2
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4
5
6
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8
9
a
b
c
d
Panamá
Venezuela
Colombia
Ecuador
Perú
Brasil
b
100° W
90° W
Central and southern Mexico
Yucatán
proto–Caribbean
20° N
10° N
0°
G
NV
P
M
E
Basement of Central Cordillera
NIB
Pacific Plate
ZB
Marine incursion
163.5–145 Ma
300 km
Modified after
Spikings et al. (2015)
c
60° W
50° W
40° W
Southern Mexico
Chortis
proto–Caribbean
10° N
0°
10° S
G
NV
P
M
E
Yucatán
NIB
Basement of Central Cordillera
humid conditions
Pacific Plate
ZB
dry conditions
Marine incursion
163.5–145 Ma
300 km
Modified after
Pindell & Kennan (2009)
Bayona et al. (2010)
Torskiv & Cocks (2016)

←

Figure 15. Upper Jurassic tectonic evolution according to the **(a)** extensional, **(b)** subduction–related, **(c)** along–marginal migration of continental crust tectonic models. See the text for discussion.

end of accumulation to the south or the continuous extensional accumulation to northern Gondwana (Figure 15b).

Continuous continental extension in the northward region is related to the counterclockwise rotation of the Yucatán Block and spreading of the proto–Caribbean seafloor (Pindell & Kennan, 2009) (Figure 15c). The final accretion of para–autochthonous terranes from oblique subduction produced the westward migration of the subduction zone and the lack of continental deposition near the collisional margin (e.g., Perijá, San Lucas, Upper Magdalena Valley, and Mocoa Batholith areas). However, other continental crust blocks and oceanic terranes continued accretion in the Cretaceous (Hincapié–Gómez et al., 2018; Spikings et al., 2015) and Cenozoic (Cediel et al., 2003). The development of paleosol profiles to the top of the Girón Formation shows evidence of humid conditions at tropical latitudes (Bayona et al., 2010).

5. Conclusions

The Jurassic record in the northern Andes (northern Perú to Venezuela) is important to analyze the onset of the development of an orthogonal margin in the northwestern corner of Gondwana, where no single geodynamic process may explain the complex configuration and record of metamorphism, magmatism, and sedimentation.

Despite the growing evidence of Lower to Middle Jurassic magmatism that was related to Pacific subduction systems, which created the large intrusive bodies along the western margin of Gondwana (Santa Marta, San Lucas, Upper Magdalena Valley, and Mocoa), extensional tectonism in northern Gondwana (Perijá, La Guajira, northern Venezuela, and the Mérida Andes) was related to the separation of the North and South America Plates, the anticlockwise rotation of the Yucatán Block and seafloor spreading in the proto–Caribbean ocean. Northern Gondwana intraplate transtensional basins were filled with continental to marginal strata and minor interbeds of volcanic rocks. The geochemistry in these intraplate basins indicates subduction settings, reflecting the superposition of both Pacific subduction and proto–Caribbean extensional processes. The Middle Jurassic unconformity at the top of the continental and magmatic successions in this study documents both (1) the cessation of subduction–related magmatism along the western margin as para–autochthonous continental blocks collided and (2) increasing extensional tectonism along the northern margin from the opening of the proto–Caribbean crust.

Future geochemical studies should evaluate the contamination of young (Triassic) versus old (Grenvillian) continental crust, whereas sedimentological analysis should focus on the geometry of sedimentary basins in relation to magmatic depocenters and the record of paleo–climate indicators to document possible paleo–latitudinal variations. Paleomagnetic studies should be conducted at different localities in Lower and Middle Jurassic rocks to test the hypothesis of the along–marginal migration of terranes.

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Explanation of Acronyms, Abbreviations, and Symbols:

HREE	Heavy rare earth element	REE	Rare earth element
LREE	Light rare earth element	SGC	Servicio Geológico Colombiano

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