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Earth Sciences

Original article

Fossil leaves, woods, gastropods, and a crocodile tooth: Is the Amagá Formation worth exploring?

Fósiles de hojas, maderas, gasterópodos y un diente de cocodrilo, ¿vale la pena explorar la Formación Amagá?

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Abstract

We have generated a spatial framework for macrofossil searching based on the current knowledge of fossil localities and fossil beds reported for the Amagá Formation in the northwestern Andes in Colombia. Our results show that twenty-three fossil localities and ninety-five fossil beds are distributed along this sedimentary succession. Preservation potential is higher in the Lower Member, given the high accommodation space and the dominance of a meandering fluvial system, compared with the Upper Member, where there was less accommodation space with a braided fluvial system controlling it. Our findings show that even though paleontological studies are null in this area, there are several options to find terrestrial macrofossil assemblages that will allow us to investigate the possible biological role of global climatic changes and regional tectonics in the Neotropical biomes based on the Amagá Formation.

Keywords: Paleontology; Neotropics; Climate change; Biodiversity.

Resumen

Hemos generado un marco espacial para la búsqueda de macrofósiles basado en las localidades fósiles y las capas con contenido fósil reportadas hasta hoy en la Formación Amagá localizada en los Andes noroccidentales en Colombia. Nuestros resultados muestran veintitrés localidades fósiles y noventa y cinco capas con contenido fósil que se distribuyen a lo largo de esta sucesión sedimentaria. El potencial de conservación es mayor en el Miembro Inferior debido a un mayor espacio de acomodación y al control que ejerce el predominio de un sistema fluvial meandriforme, en comparación con el Miembro Superior donde había menos espacio de acomodación y un sistema fluvial trenzado. Nuestros hallazgos muestran que a pesar de que los estudios paleontológicos son nulos en esta área, existen varias posibilidades para encontrar asociaciones de macrofósiles terrestres que permitirán investigar el posible papel biológico de los cambios climáticos globales y la tectónica regional en los biomas neotropicales de la Formación Amagá.

Palabras claves: Paleontología; Neotropico; Cambio climático; Biodiversidad.

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Introduction

Located between the Central and the Western cordilleras in the northernmost part of the Colombian Andes (**Figure 1**), the Amagá Formation is a late Oligocene to middle Miocene Neotropical fluvial siliciclastic succession deposited in a strike-slip intermontane basin associated with the obliquity interaction between the Farallon and the South American plates (**Figure 1**) (**Lara *et al.***, 2018; **Silva-Tamayo *et al.***, 2020). Stratigraphically, the base of the Amagá Formation is marked by an unconformity atop Pre-Cenozoic continental and oceanic basement, while the upper Miocene Combia Formation rests in unconformity

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atop the strata of the Amagá Formation (**Lara *et al.***, 2018; **Silva-Tamayo *et al.***, 2020). Moreover, the Amagá Formation has been divided into two members. The Lower Member (~294 m) is characterized by a succession of poorly sorted quartzose conglomerates, well-sorted sublitharenites, massive grayish siltstones, and coal seams (**Sierra & Marín-Cerón**, 2011). On the other hand, the Upper Member (~228 m) is determined by a succession of lithic wackes, feldspathic litharenites, and greenish-to-reddish siltstones (**Sierra & Marín-Cerón**, 2011).

In his extensive geological work, **Grosse** (1926) pointed out that the Amagá Formation could potentially have terrestrial macrofossils (i.e., wood, gastropods, and vertebrates). Later, **Schönfeld** (1947) showed that the fossil wood specimens collected by **Grosse** (1926) were critical to understanding the Colombian Neogene floristic biomes. However, after **Schönfeld's** (1947) work, there are no paleontological studies based on the macrofossils of the Amagá Formation. However, under the current global warming scenario, it is worth displaying all possible efforts to find and study fossils in the Amagá Formation, given the geological time interval recorded in its rocks and its ancient Neotropical location.

The Lower and the Upper Members are dated between the Late Oligocene (~28 to ~23 Ma) and the Early-Middle Miocene (~23 to ~11 Ma) (**Lara *et al.***, 2018), so the possible fossils recorded in the Amagá Formation could inform us about the late Oligocene Warming (~26.5 to 24 Ma) (**Pekar *et al.***, 2006), followed by the Middle Miocene climatic optimum (~17 to 14 Ma) (**Ji *et al.***, 2018), and finally, the Middle Miocene climate transition (~14

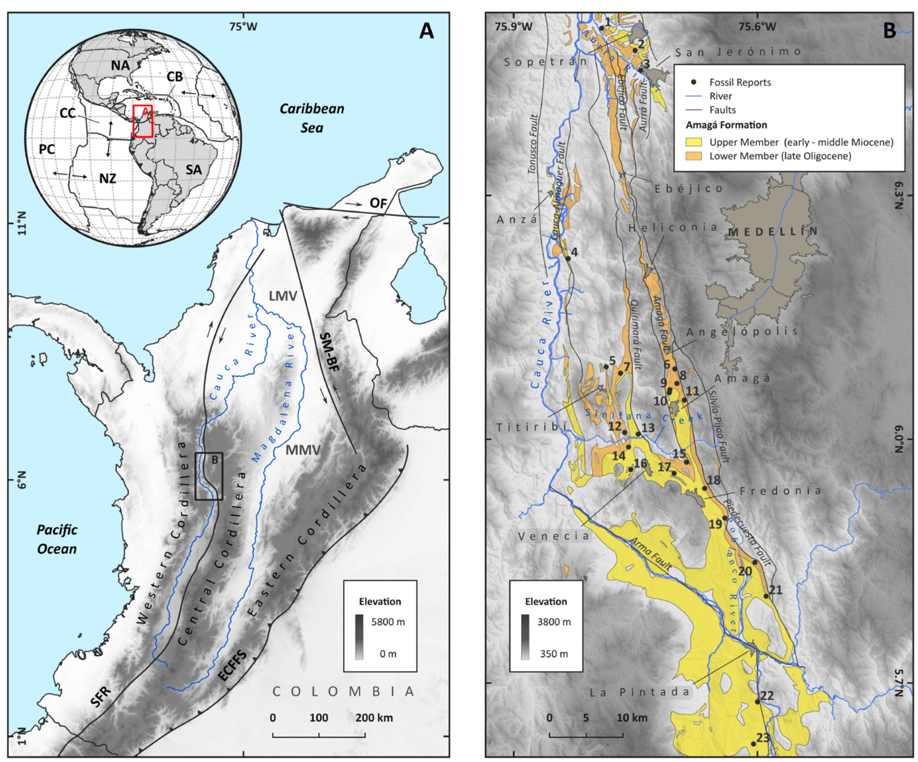

Figure 1. Location of the fossil localities in the Amagá Formation. **A.** General location map of the studied area in America and its major tectonic features (red rectangle in the upper right corner) and in the Colombian Andes and their major structural components (black rectangle in the center of the panel). **B.** Specific location of each fossil locality found in the Amagá Formation. Each number represents a fossil locality (e.g., **1** is fossil locality Schönfeld X1). For all the names of the localities and their respective numbers, please read **table 1**. The ochre color represents the Lower Member of the Amagá Formation and the yellow color represents the Upper Member of the Amagá Formation. The geological distribution of the Amagá Formation is based on **Grosse's** geological map (1926).

Ma) (**Sosdian & Lear**, 2020) in the Neotropic. Besides, given the location in northern South America, these fossils would also allow us to decipher the paleoenvironments of this basin and how they were related to the formation of the Isthmus of Panama (**Montes *et al.***, 2015). In this context, we have compiled all the possible fossil localities and fossil beds reported in the Amagá Formation to develop a spatial framework for paleontologists who want to find and study macrofossils in this sedimentary succession.

Methods

We searched for all written sources, including peer-reviewed papers and undergraduate theses mentioning macrofossils in the Amagá Formation. With this information, we generated a map that includes all the macrofossil sites in the formation's Lower and Upper members (**Figure 1**). Then, using the R (R Core Team 2021) package SDAR (**Ortiz *et al.***, 2020), we digitized all the measured sedimentary successions with macrofossils found in the Amagá Formation: Sinifaná (**Silva-Tamayo *et al.***, 2008), Cinco-Venecia (**Silva-Tamayo *et al.***, 2008), Palomos (**Silva-Tamayo *et al.***, 2008), La Naranjala (**Henao**, 2012), Sabaleticas (**Páez-Acuña**, 2013), Sabaletas (**Páez-Acuña**, 2013), and Palmichala (**Páez-Acuña**, 2013) including the stratigraphic position of their fossil beds (**Figure 2**) (for a more detailed resolution see **Appendix 1,** https://www.raccefyn.co/index.php/raccefyn/article/view/1896/3388). Next, we determined the number of fossil beds in each fossil locality (**Table 1**). In the case of the El Plan locality, given that neither **Grosse** (1926) nor **Schönfeld** (1947) reported sedimentary logs, we counted two fossil beds because specimens were surveyed at two different sandstone beds (**Grosse**, 1926). On the other hand, each macrofossil reported by **Schönfeld** (1947) in the Amagá Formation is located at different coordinates (**Figure 1**); therefore, we assumed that every macrofossil was found in a separate bed. Next, using the sedimentary logs (when available) and the lithological information reported in all the works considered, we assigned the lithology to each fossil bed and recorded the type of fossil found (**Table 2**). Finally, we did a t-test to verify if there was a sampling bias in the number of fossil beds related to the differences in thickness among the used sedimentary logs measured in the Lower and the Upper members of the Amagá Formation.

Results

Reports of fossil beds in the Amagá Formation were found in three papers (**Grosse**, 1926; **Schönfeld**, 1947; **Silva-Tamayo *et al.***, 2008) and two undergraduate theses (**Henao**, 2012; **Páez-Acuña**, 2013). Our results show 23 fossil localities in the Amagá Formation: 14 in the Lower Member and nine in the Upper Member (**Figure 1**, **Table 1**). We found at least 95 fossil beds throughout the Amagá Formation. Specifically, 79 are distributed through 14 fossil localities in the Lower Member. On the other hand, 16 fossil beds along the Upper Member are found in nine fossil localities (**Table 1**).

The fossil beds in the Lower Member are found mainly in three sedimentary successions: La Naranjala (32 fossil beds), Palomos (24 fossil beds), and Sinifaná (12 fossil beds) (**Table 2**). On the other hand, only four localities at the Upper Member have more than one fossil bed: Sabaleticas (5 fossil beds), Cinco-Venecia (2 fossil beds), El Plan (2 fossil beds), and Palmichala (2 fossil beds) (**Table 2**). Based on the sedimentary successions used here, the average thickness of the Lower and Upper member successions are 241.6 m and 249.4 m, respectively (for the thickness of each sedimentary succession, please consult **Appendix 1,** https://www.raccefyn.co/index.php/raccefyn/article/view/1896/3388). Therefore, there is no significant difference in thickness among the members of the Amagá Formation (t = -0.14391, *p-value* = 0.88).

Our results also evidenced that the fossil content in the Amagá Formation is composed of four main terrestrial macrofossil groups (**Table 2**): leaves (73%), wood (24%), gastropods (2%), and vertebrates (1%). Besides, macrofossils were found among three types of lithologies: sandstones (54%), coal beds (26%), and mudstones (20%) (**Table 2**). Fossil leaves were found mainly in sandstones (72%) and minor percentages in mudstones and

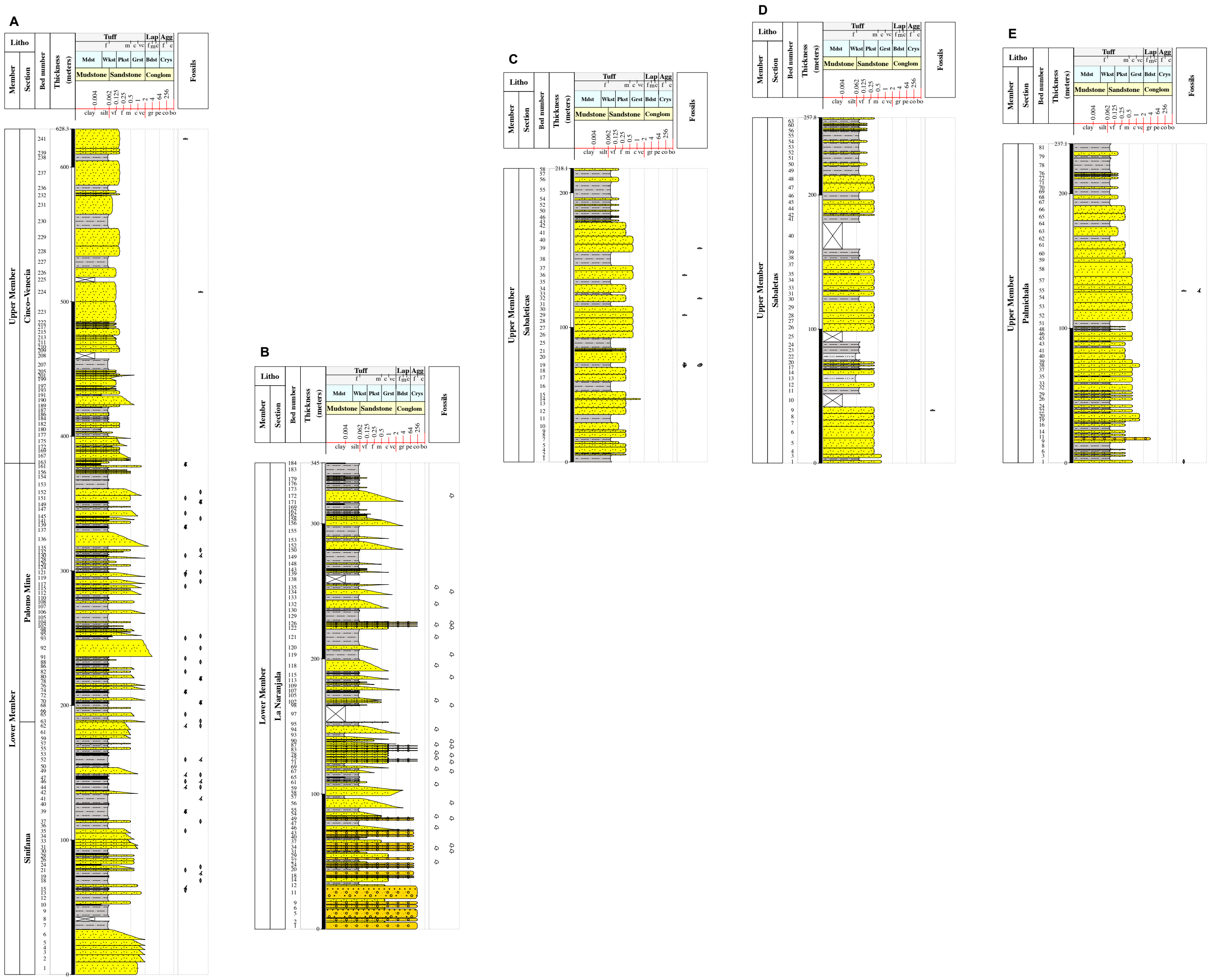

Figure 2. Sedimentary logs of the fossil localities of Sinifaná (**Silva-Tamayo *et al.*** 2008), Palomos (**Silva-Tamayo *et al.*** 2008), Cinco-Venecia (**Silva-Tamayo *et al.*** 2008), La Naranjala (**Henao**, 2012), Sabaleticas (**Paéz-Acuña**, 2013), Sabaletas (**Paéz-Acuña**, 2013), and Palmichala (**Paéz-Acuña**, 2012). The base of the Upper Member of the Amagá Formation was used to correlate the logs. For a detailed sedimentary log of each locality, please read Appendix 1.

coal layers (24% and 14%, respectively) (**Table 2**). Fossil wood was found in coal layers (65%) and sandstones (35%) (**Table 2**), gastropods and vertebrates in sandstones at the El Plan and Sabaleticas localities, and gastropods in mudstones (**Table 2**). Although the number of fossil localities and beds was higher in the Lower Member than in the Upper Member (**Tables 1** and **2**), the percentages of fossils located in the different lithologies among the Lower and the Upper Members were very similar: sandstones, 53% and 56%, respectively; coal layers 27% and 25%, respectively, and mudstones, 20% and 19%, respectively (**Table 2**).

Discussion

Why are there more fossil beds in the Lower Member?

In the Late Oligocene, the Lower Member recorded a depositional change regime among braided to meandering fluvial systems as the accommodation space increased likely caused

Table 1. Geographical and stratigraphical locations of the fossil localities and the fossil beds among the Amagá Formation.

Map code	Fossil locality	Authors	Lat	Long	Stratigraphic position	Fossil beds
1	Schonfeld X 1	Schonfeld (1947)	6.505788	-75.791763	Lower member	1
2	Schonfeld X 2	Schonfeld (1947)	6.478594	-75.750639	Lower member	1
3	Schonfeld X 3	Schonfeld (1947)	6.453942	-75.743829	Lower member	1
4	Schonfeld X 4	Schonfeld (1947)	6.222358	-75.833082	Lower member	1
5	Schonfeld X 5	Schonfeld (1947)	6.089032	-75.786298	Lower member	1
6	Schonfeld X 11	Schonfeld (1947)	6.086504	-75.701756	Lower member	1
7	Schonfeld X 6	Schonfeld (1947)	6.081238	-75.768577	Lower member	1
8	Schonfeld X 12	Schonfeld (1947)	6.068584	-75.699152	Lower member	1
9	Schonfeld X 13	Schonfeld (1947)	6.060974	-75.707914	Upper member	1
10	Schonfeld X 14	Schonfeld (1947)	6.057300	-75.708640	Upper member	1
11	Schonfeld X 15	Schonfeld (1947)	6.048100	-75.689959	Lower member	1
12	Sinifana	Silva-Tamayo *et al.* (2008)	6.008238	-75.763604	Lower member	12
13	Schonfeld X 7	Schonfeld (1947)	6.006255	-75.746909	Upper member	1
14	Schonfeld X 8	Schonfeld (1947)	5.990373	-75.758716	Lower member	1
15	Palomos	Silva-Tamayo *et al.* (2008)	5.971600	-75.687400	Lower member	24
16	Schonfeld X 9	Schonfeld (1947)	5.962603	-75.756019	Upper member	1
17	El cinco - Venecia	Silva-Tamayo *et al.* (2008)	5.958100	-75.702700	Upper member	2
18	El plan	Grosse (1926)	5.939550	-75.665000	Upper member	2
19	La Naranjala	Henao (2012)	5.903012	-75.640209	Lower member	32
20	Schonfeld X 10	Schonfeld (1947)	5.848233	-75.603104	Lower member	1
21	Sabaleticas	Páez-Acuña (2013)	5.806800	-75.589400	Upper member	5
22	Sabaletas	Páez-Acuña (2013)	5.676600	-75.600000	Upper member	1
23	Palmichala	Páez-Acuña (2013)	5.624900	-75.604900	Upper member	2

by the breakup of the Farallon Plate. On the other hand, during the Early-Middle Miocene, the Upper Member evidenced a switch in the depositional pattern from meandering to braided fluvial systems, given the decrease in the accommodation space expected by the Early Miocene change from oblique to orthogonal convergence between the Nazca and South American plates and the docking of the Panamá-Chocó Block to northern South America (**Lara *et al.***, 2018; **Silva-Tamayo *et al.***, 2020). Therefore, the Lower Member had a higher fossil preservation potential considering the high burial capacity due to the combination of the accommodation space, the sediment supply, and a higher frequency of low-energy and low-oxygen environments (e.g., coal swamps, flood plains) developed in a meandering tropical system. Our results agree with the expected pattern, given that the number of fossil beds is five times higher in the Lower Member than in the Upper Member (**Table 2**). Besides, they show that the number of fossil beds is not biased by the thickness of the sedimentary successions since there is no significant difference between the measured extent of the Lower and the Upper members.

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Table 2. Fossil content and lithological information about the fossil beds in each fossil locality.

Fossil locality	Fossiliferous beds	Leaves	Wood	Molluscs	Vertebrates	Sandstone	Coal	Mudstone	Stratigraphic position
Schonfeld X 1	1	0	1	0	0	0	1	0	Lower member
Schonfeld X 2	1	0	1	0	0	0	1	0	Lower member
Schonfeld X 3	1	0	1	0	0	0	1	0	Lower member
Schonfeld X 4	1	0	1	0	0	0	1	0	Lower member
Schonfeld X 5	1	0	1	0	0	0	1	0	Lower member
Schonfeld X 11	1	0	1	0	0	0	1	0	Lower member
Schonfeld X 6	1	0	1	0	0	0	1	0	Lower member
Schonfeld X 12	1	0	1	0	0	0	1	0	Lower member
Schonfeld X 13	1	0	1	0	0	0	1	0	Upper member
Schonfeld X 14	1	0	1	0	0	0	1	0	Upper member
Schonfeld X 15	1	0	1	0	0	0	1	0	Lower member
Sinifana	12	12	0	0	0	5	0	7	Lower member
Schonfeld X 7	1	0	1	0	0	0	1	0	Upper member
Schonfeld X 8	1	0	1	0	0	0	1	0	Lower member
Palomos	24	24	0	0	0	11	10	3	Lower member
Schonfeld X 9	1	0	1	0	0	0	1	0	Upper member
El cinco - Venecia	2	0	2	0	0	2	0	0	Upper member
El plan	2	0	0	1	1	2	0	0	Upper member
La Naranjala	32	32	0	0	0	26	0	6	Lower member
Schonfeld X 10	1	0	1	0	0	0	1	0	Lower member
Sabaleticas	5	0	4	1	0	4	0	1	Upper member
Sabaletas	1	0	1	0	0	1	0	0	Upper member
Palmichala	2	1	1	0	0	2	0	0	Upper member

Where were these fossil beds deposited?

Combining the stratigraphic position of the fossil beds in the Amagá Formation with the facies associations interpreted by **Silva-Tamayo *et al.*** (2008; 2020), it is possible to postulate that the fossil beds accumulated at the Lower Member in a meandering fluvial system are likely situated at crevasse (sandstones) facies associations and humid flood plains (mudstones) in the La Naranjala locality (**Appendix 1,** https://www.raccefyn.co/index.php/raccefyn/article/view/1896/3388). Fossil beds at Sinifaná and Palomos localities are possibly related to crevasse facies associations (thick to very thick fine-medium sandstone with primary sedimentary structure beds), humid flood plains (laminated/massive mudstones), and swamps (coal layers) (**Appendix 1,** https://www.raccefyn.co/index.php/raccefyn/article/view/1896/3388). On the other hand, fossil beds found in the Upper Member (Sabaleticas, Cinco-Venecia, Palmichala, and Sabaletas localities) are likely to be situated at facies associations interpreted as channel braided rivers (thick to very thick massive sandstone beds), crevasse (thick to very thick fine-medium sandstone with primary sedimentary structure beds), and humid floods (laminated/massive mudstones) in a braided fluvial system (**Appendix 1,** https://www.raccefyn.co/index.php/raccefyn/article/view/1896/3388).

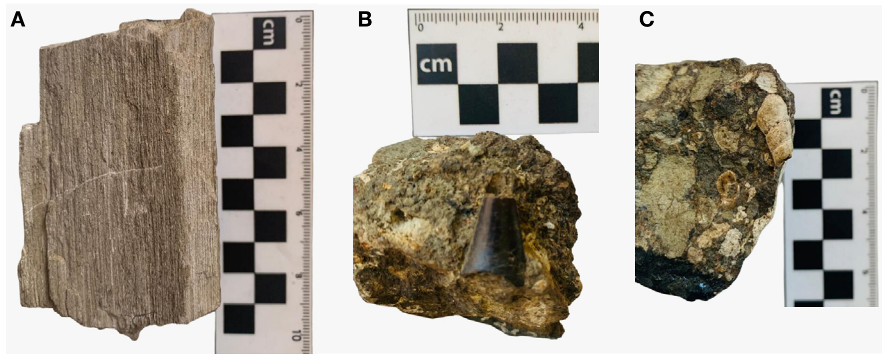

Figure 3. Photographs of some fossils collected by **Grosse** (1926). **A.** Fossil wood. **B.** Crocodile tooth, according to **Grosse** (1926). **C.** *Hemisinus sp.* (terrestrial gastropod) according to G. Steinmann (pers. comm. in **Grosse**, 1926). Not all the fossils collected by Grosse during his extensive fieldwork in Antioquia (**Grosse**, 1926) are taxonomically classified. Their repository is at the *Museo de Geociencias, Facultad de Minas, Universidad Nacional de Colombia, Sede Medellín*.

The localities reported by **Grosse** (1926) and **Schönfeld** (1947) do not have detailed descriptions of the sedimentary successions. Therefore, inferring the depositional characteristics of the fossil beds at the El Plan and Schönfeld-X1 to -X15 localities is impossible.

Why should we care about the fossils of the Amagá Formation?

According to our results, the fossil assemblage at the Amagá Formation comprises leaves, wood, gastropods, and a crocodile tooth, listed from major to minor components.

Fossil leaves, wood, and terrestrial vertebrates have been fundamental to determining the type of forests, paleotemperatures, and CO_2 levels in the Neotropics (e.g. **Wing *et al.***, 2009; **Head *et al.***, 2009; **Carvalho *et al.***, 2011; **Londoño *et al.***, 2018; **Martínez *et al.***, 2021; **Giraldo *et al.***, 2021). Moreover, these empirical fossil data have constrained global and regional climatic models (e.g., **Martínez *et al.***, 2020). Therefore, the systematic study of the fossil content of the Amagá Formation could enhance our knowledge of the floristic and faunistic composition and the biologic and paleoclimatic evolution of the Neotropical biomes during the Late Oligocene (~28 to ~23 Ma; Lower Member) and Early-Middle Miocene (~23 to ~11 Ma; Upper Member). Furthermore, terrestrial gastropods have also been essential for paleoenvironmental reconstructions in the Early Miocene (~18 to 14 Ma; Huesser Horizon) of the Neotropics (**Gómez *et al.,*** 2009). However, in the Amagá Formation, a further use could be to constrain the current uplift hypothesis of the Panamá Isthmus (**Montes *et al.***, 2015). According to **Grosse** (1926) and **Paéz-Acuña** (2013), the gastropods found in the Upper Member of the Amagá Formation (El Plan and Sabaleticas localities, respectively) belong to the genus *Hemisinus* (*Longiverena*). This genus has also been found in the Oligocene of Colombia (Mugrosa Formation in the Middle Magdalena Valley) (**Pilsbry & Olsson**, 1935) and Panamá (Bohio Formation) (**Woodring**, 1957) and in the Miocene of Colombia (Castilletes Formation in the Cocinetas Basin, Guajira Peninsula) (**Hendy *et al.***, 2015).

Conclusions

Although **Schönfeld's** (1947) work has been the only fossil report made by a trained paleontologist based on the Amagá Formation, here we show 23 fossil localities with 95 fossil beds along the Lower and the Upper members of this formation. Therefore, there is a tremendous potential for developing paleontological studies based on these rocks. Moreover, given that the sedimentary succession records an intramontane basin dominated by fluvial systems during the Late Oligocene (~28 to ~23 Ma) and the Early-Middle Miocene (~23 to ~11 Ma) (**Lara *et al.***, 2018; **Silva-Tamayo *et al.***, 2020), its

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fossils could be critical to understanding the terrestrial biologic response of the Neotropics facing global climatic changes (i.e., Middle Miocene Climatic Optimum and the Middle Miocene climate transition) and regional tectonic changes (i.e., the formation of the Panama Isthmus). However, our study is an attention call to tropical paleontologists. It has been a century since **Grosse** (1926) showed that the Amagá Formation has exciting fossils (**Figure 3**), and still, paleontologists have not done the first systematic sampling of its fossil beds. We hope this paper will enhance the paleontological investigation of the Amagá Formation.

Supplementary material

See appendix 1 in https://www.raccefyn.co/index.php/raccefyn/article/view/1896/3388

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Author contributions

A.C. designed and coordinated the research; J.D.G. and D.M. generated the dataset and performed the stratigraphic columns, and A.C. and M.W. led the writing process with the contribution of all co-authors.

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