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Recurrent tectonic activity in northeastern Brazil during Pangea breakup: Constraints from U-Pb carbonate dating

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ABSTRACT

Carbonate U-Pb dating of samples from rift-bounding faults of intracontinental basins in the Borborema province, northeastern Brazil, indicate recurrent tectonic activity during Pangea breakup lasting for >150 m.y. from the Late Triassic to the Paleocene, reactivating inherited strike-slip Neoproterozoic–Cambrian shear zones. Triassic ages indicate that brittle deformation started some 80 m.y. before previously known, most likely related to rifting along the incipient Central Atlantic. The subsequent Cretaceous opening of the South Atlantic caused renewed fault activity during rifting and basin development. Furthermore, recurrent Cenozoic tectonic activity along the rift-bounding faults is indicated, suggesting that structural inheritance of the Neoproterozoic–Cambrian continental-scale Borborema shear zone system has been responsible for accommodation of recurrent tectonic stress from Mesozoic rifting to the present day.

INTRODUCTION

The Atlantic Ocean is still widening today, but its birth during Pangea breakup was diachronous, with rifting of the central and southern branches during the Triassic and Cretaceous periods, respectively (e.g., Müller et al., 2019). Tectonic inheritance at a range of scales is a fundamental aspect of deformation during continental breakup (Tommasi and Vauchez, 2001; Manatschal et al., 2015). In northeastern Brazil, intracontinental basins related to the southern branch of the Atlantic rift system developed over the Precambrian basement of the Borborema province (e.g., de Matos, 2000, 2021). These basins are invariably bordered and controlled by faults that reactivated older Neoproterozoic shear zones (Fig. 1A), providing direct evidence that Precambrian tectonic inheritance played a role in Atlantic rift development.

Border fault zones accommodate significant extensional strain in the brittle crust (Accardo et al., 2018). Faults related to the intracontinental basins of the Borborema province reactivated heterogeneous mylonitic gneissic rocks and have achieved fault lengths of >90 km (Fig. 1). The main sedimentary infilling of these basins occurred during the Early Cretaceous (e.g., Costa et al., 2007; Rapozo et al., 2021) and is related to the opening of the South Atlantic. However, absolute dating of the controlling structures is lacking. Due to their position in the basement, basin-border fault systems can record several reactivation events. Absolute chronology of reactivation events is challenging, but thanks to recent developments in dating phases with low U concentration, U-Pb dating of carbonates can now be used to date brittle deformation (Ring and Gerdes, 2016; Roberts and Walker, 2016; Nuriel et al., 2017; Hansman et al., 2018; Roberts et al., 2020).

We report U-Pb carbonate dating of brittle structures associated with border fault zones of three intracontinental basins (Rio do Peixe, Araripe, and Jatobá) of the northeastern Brazil rift system (Figs. 1B–1D; see Table S1 in the Supplemental Material[1]). Our data suggest a period of ~150 m.y. of recurrent episodes of brittle deformation, providing the first direct evidence of Triassic tectonic activity possibly related to the Central Atlantic rift system in northeastern Brazil, as foreseen by some researchers in local and global models (e.g., de Matos, 2000; Müller et al., 2019).

GEOLOGICAL SETTING AND SAMPLES

The northeastern Brazil rift system is a wide rift that encompasses several intracontinental basins and has been interpreted as a result of diffuse continental extension during the Early Cretaceous (de Matos, 1992). Regional extensional deformation then developed into South Atlantic spreading and separation of South America and Africa. The rift system was built in part upon the Borborema province Precambrian basement, which displays a well-developed structural fabric characterized by a continental-scale strike-slip shear zone system. This is known as the Borborema shear zone system, developed during the Neoproterozoic–Cambrian West Gondwana assembly (Vauchez et al., 1995; Ganade et al., 2021). In its central portion, this shear zone system displays a sigmoidal shape with major east-west–striking shear zones 500 km long connected to subsidiary (100–200 km long) northeast-trending shear zones (Fig. 1A). The

[1]Supplemental Material. Detailed analytical procedures and U-Pb geochronology dataset. Please visit https://doi.org/10.1130/GEOL.S.19669284 to access the supplemental material, and contact editing@geosociety.org with any questions.

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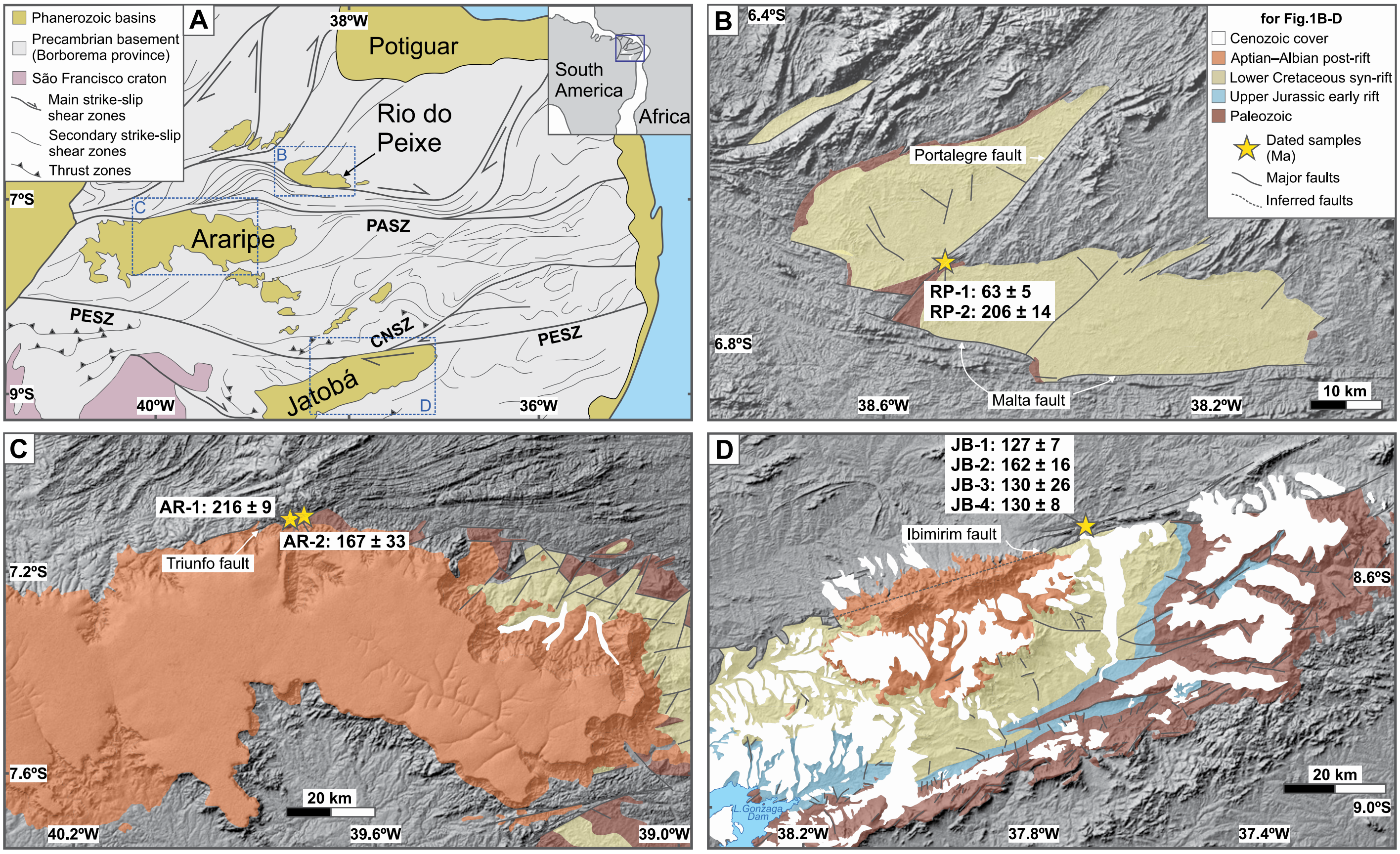

Figure 1. (A) The Borborema province in northeastern Brazil and its structural fabric. PASZ—Patos shear zone; PESZ—Pernambuco shear zone; CNSZ—Cruzeiro do Nordeste shear zone. (B–D) Maps and sample locations from the Rio do Peixe (B), Araripe (C), and Jatobá (D) Basins; based on Vasconcelos et al. (2021), Assine (2007), and Rocha and Leite (1999), respectively. Digital elevation models are based on ALOS PALSAR images (https://search.asf.alaska.edu/).

shear zones are interpreted to have been reactivated under the brittle regime during a Cretaceous extensional event, exerting strong influence on the development of the intracontinental rift basins (Figs. 1B–1D) (de Matos, 1992, 2021; de Castro, 2012; Miranda et al., 2020).

The Rio do Peixe Basin (Fig. 1B) comprises half-grabens bounded by north- to northwest-dipping normal faults related to brittle reactivation of east-west– and northeast-southwest–striking shear zones in the Precambrian basement (Nogueira et al., 2015; Rapozo et al., 2021). The sedimentary infill of the Rio do Peixe Basin consists of (1) restricted pre-rift Devonian sequences, and (2) syn-rift sedimentary sequences as much as 3 km thick deposited during the Early Cretaceous. The two samples reported here (RP-1 and RP-2) come from the footwall of the northeast-trending Portalegre normal fault zone that bounds the northernmost half-graben of the Rio do Peixe Basin (Fig. 1B). Both samples are carbonate cement from hydraulic breccias within Precambrian mylonitic orthogneisses (Figs. 2A and 2B).

The Araripe Basin (Fig. 1C) is bounded on the north by the Patos shear zone, a major east-west–striking dextral shear zone in the Precambrian basement. The basin comprises Paleozoic deposits (Ordovician–Silurian), Upper Jurassic early-rift sequences, Lower Cretaceous rift sequences, and Aptian–Cenomanian post-rift formations (Assine, 2007). The carbonate samples investigated were collected within orthogneisses in the footwall damage zone of the SSE-dipping Triunfo border fault zone (Fig. 1C), which displays normal movement (Celestino et al., 2020) and is interpreted as a brittle reactivation of the Neoproterozoic Patos shear zone. Sample AR-1 is a carbonate-vein within cataclasites (Fig. 2E), and sample AR-2 is from breccia cement of a subsidiary normal fault (Figs. 2C and 2D).

The Jatobá Basin (Fig. 1D) is controlled by SSE-dipping normal faults that reactivated major ENE-trending Neoproterozoic shear zones (Miranda et al., 2020) on its northern border. The basin comprises Paleozoic (Silurian–Devonian) pre-rift sedimentary sequences, Upper Jurassic formations interpreted to be related to an early stage of rifting, Lower Cretaceous sequences related to the rifting climax, and Aptian–Albian post-rift sequences (Costa et al., 2007). The carbonate samples were collected from mylonitic orthogneisses in the footwall of the normal fault zone that bounds the northern border of the basin (Fig. 1D). This fault zone represents the brittle reactivation of the Brasiliano–Pan African ENE-trending Cruzeiro do Nordeste shear zone (Miranda et al., 2020). The samples include carbonate breccia cement sample JB-1 (Fig. 2F) and carbonate slickenfibers related to subsidiary northeast- and northwest-trending faults (samples JB-2, JB-3, and JB-4; Figs. 2G–2I). These subsidiary faults display strike-slip movement (Figs. 2F–2I) that could be related to reactivation of the normal fault zone (e.g., Nogueira et al., 2015).

METHODS

U-Pb isotopic data of eight carbonate samples from the border faults of the Rio do Peixe, Araripe, and Jatobá Basins (Figs. 1B–1D) were obtained by laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) at the Geochronology and Tracers Facility Nottingham, British Geological Survey, and at the Department of Earth Sciences, ETH Zürich. Refer to the Supplemental Material for information on laboratory procedures and the data set. The data were plotted in Tera-Wasserburg diagrams and lower intercept ages were calculated with IsoplotR (Vermeesch, 2018) (Fig. 3). The acquired U-Pb ages range from 216 ± 9 Ma to 63 ± 5 Ma (Fig. 3; Table S1). Uncertainties

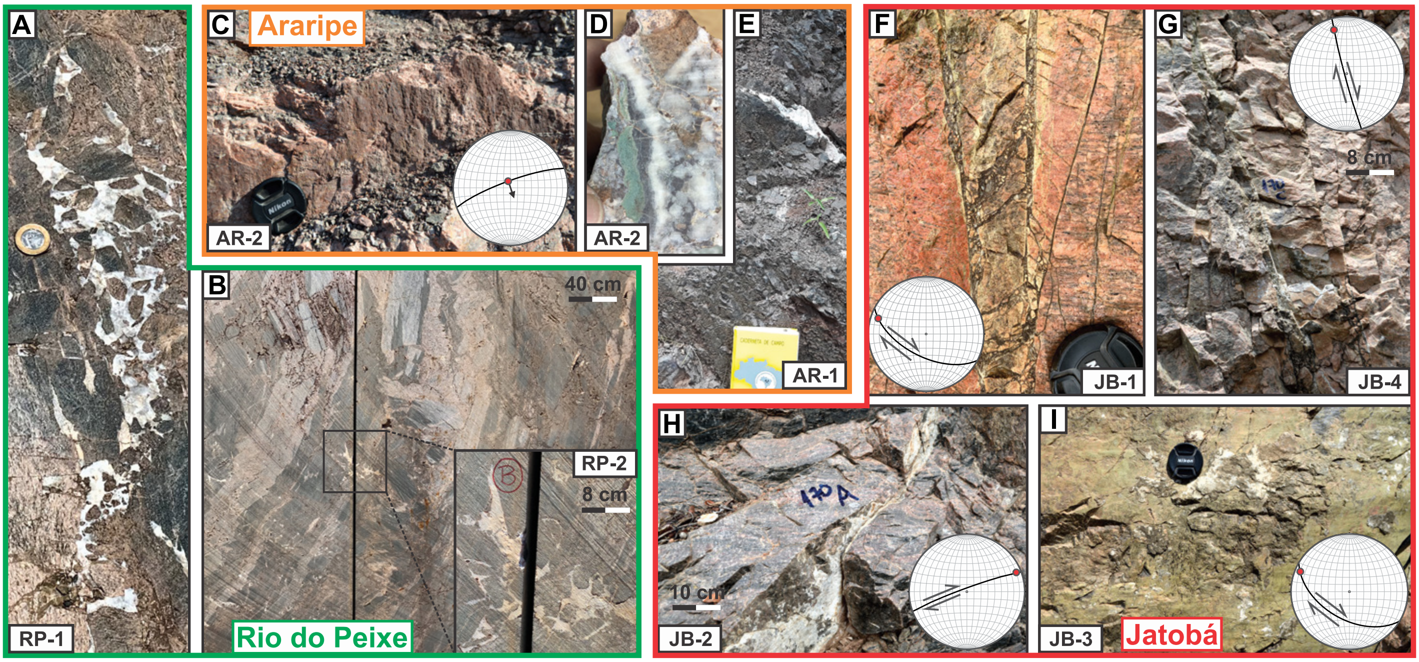

Figure 2. Analyzed carbonate samples from the Borborema province in northeastern Brazil (see Fig. 1 for sampling locations). (A,B) Carbonate cement from breccias in footwall of the northeast-trending Portalegre normal fault zone that bounds the Rio do Peixe Basin. (C,D) Breccia cements of a normal fault that defines the northern border of the Araripe Basin. (E) Carbonate vein from the same fault zone as in C and D. (F) Carbonate breccia cement from the Jatobá Basin. (G–I) Carbonate slickenfibers from the Jatobá Basin. Lower-hemisphere stereonet projections indicate the orientation of fault planes and slickenlines.

are 95% confidence levels with overdispersion and with excess long-term variance propagated.

RESULTS

The two carbonate samples from the Portalegre border fault of the Rio do Peixe Basin (Figs. 1B, 2A, and 2B) yielded U-Pb ages of 206 ± 14 Ma (sample RP-2) and 63 ± 5 Ma (sample RP-1) (Figs. 3A and 3B). The two samples from the northern border of the Araripe Basin (AR-1 and AR-2; Figs. 1B and 2C–2E) yielded U-Pb ages of 216 ± 9 Ma and 167 ± 33 Ma, respectively (Figs. 3C and 3D). The carbonates from these four samples display homogeneous features in photomicrographs and cathodoluminescence (CL) images (Fig. 3), and with the exception of a few analytical spots (see Table S1), the entire data set obtained from each sample defines single age populations (Figs. 3A–3D).

The four samples from the northern border of the Jatobá Basin display complex textural features in CL images and photomicrographs (Fig. 3). In CL images, sample JB-2 displays high-luminescence carbonate blades (0.5–1 mm long) embedded in a mixture of fine-grained blades and isotropic low-luminescence carbonate material. Analyses of the large blades yield an age of 162 ± 16 Ma (Fig. 3F), while data from the fine-grained blades and the low-luminescence material have open-system behavior (empty ellipses in Fig. 3F) and no age could be derived. The other three samples (JB-1, JB-3, and JB-4) display dark-gray rounded carbonate clasts with low luminescence in CL images embedded in light-gray carbonate material. Analyses of the clasts yield ages of 130 ± 8 Ma and 127 ± 7 Ma for samples JB-4 and JB-1, respectively (Figs. 3E and 3H), while data from the light-gray matrix display open-system behavior (empty ellipses in Figs. 3E and 3H). Clasts and matrix of sample JB-3 provide similar U-Pb data and together yield a high–mean squared weighted deviation (9.1) date of 130 ± 26 Ma (Fig. 3G) that should be interpreted with caution.

DISCUSSION AND CONCLUSION

Research in the South Atlantic rift (Conceição et al., 1988; de Matos, 2000) has suggested that Pangea breakup could have started before the Cretaceous, in the Triassic–Jurassic. This hypothesis is based mostly on the occurrence of Triassic–Jurassic magmatism in the northern South American continent related to the Central Atlantic magmatic province (CAMP) (e.g., Marzoli et al., 2018). Additionally, low-temperature thermochronology suggests basement exhumation in the vicinity of the Rio do Peixe Basin since the Triassic, with significant fault activity during the Jurassic-Cretaceous transition (da Nóbrega et al., 2005). Far-field propagation of compressional stress from the western margin of South America as a cause for this early Mesozoic tectonism in northeastern Brazil is discarded because the ages do not match: the main orogenic cycles are either Paleozoic (Pampean, Famatinian, and Gondwanide) or Late Cretaceous–Cenozoic (Andean) (e.g., Ramos, 2009).

Our results are the first direct evidence of tectonic activity on the northeastern South American platform during the Triassic–Jurassic. Cement of the breccia from the Rio do Peixe Basin margin (Fig. 2B) yields a U-Pb carbonate age of ca. 206 Ma (Fig. 3B), and the carbonate vein within cataclasites (Fig. 2E) in the northern border of the Araripe Basin yields an age of ca. 216 Ma (Fig. 3C). These Triassic carbonates constrain the minimum age for brittle reactivation of the inherited basement structures (i.e., the Patos shear zone). The carbonate ages overlap within uncertainty with the Central Atlantic rift system (e.g., Olsen, 1997) and the CAMP magmatic activity ages (e.g., Davies et al., 2017) (Fig. 4). Even though there are no reported Triassic sedimentary sequences within the basins of the northeastern Brazilian rift system, the Triassic carbonate ages support the notion that the opening of the Central Atlantic reactivated older shear zones in the northeastern South American platform.

Our data also indicate an important period of tectonic activity at ca. 130 Ma (Fig. 4) in the ENE-trending fault zone that defines the northern border of the Jatobá Basin (Fig. 1D). The ages were derived from carbonates associated with northwest- and northeast-trending subsidiary strike-slip faults, including fault breccia cement (Fig. 2F) and slickenfibers (Figs. 2G–2I). These ages were obtained from carbonate clasts that occur within fine-grained carbonate matrix

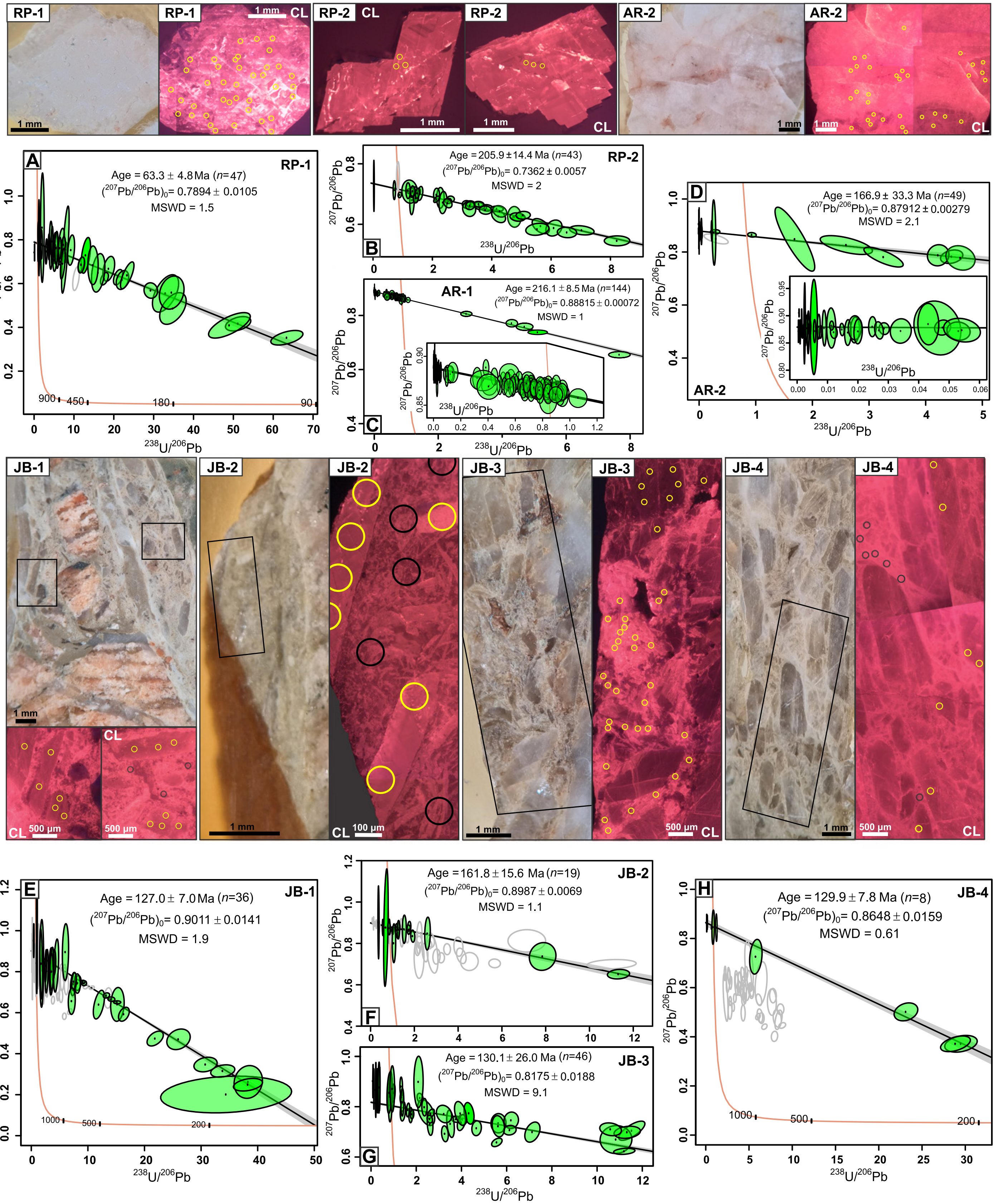

Figure 3. Photomicrographs, cathodoluminescence (CL) images, and U-Pb Tera-Wasserburg plots for the analyzed carbonate samples from the Borborema province in northeastern Brazil (see Fig. 1 for sampling locations). Yellow circles in the CL images represent spots used in age calculations; black circles are spots omitted due to open-system behavior. Green-filled ellipses in the U-Pb data plots are analytical spots used in the age calculations; empty ellipses are spots omitted. Ellipses are 95% confidence level. Red lines are concordia curves. ($^{207}Pb/^{206}Pb)_0$ = initial $^{207}Pb/^{206}Pb$ ratio. MSWD—mean squared weighted deviation.

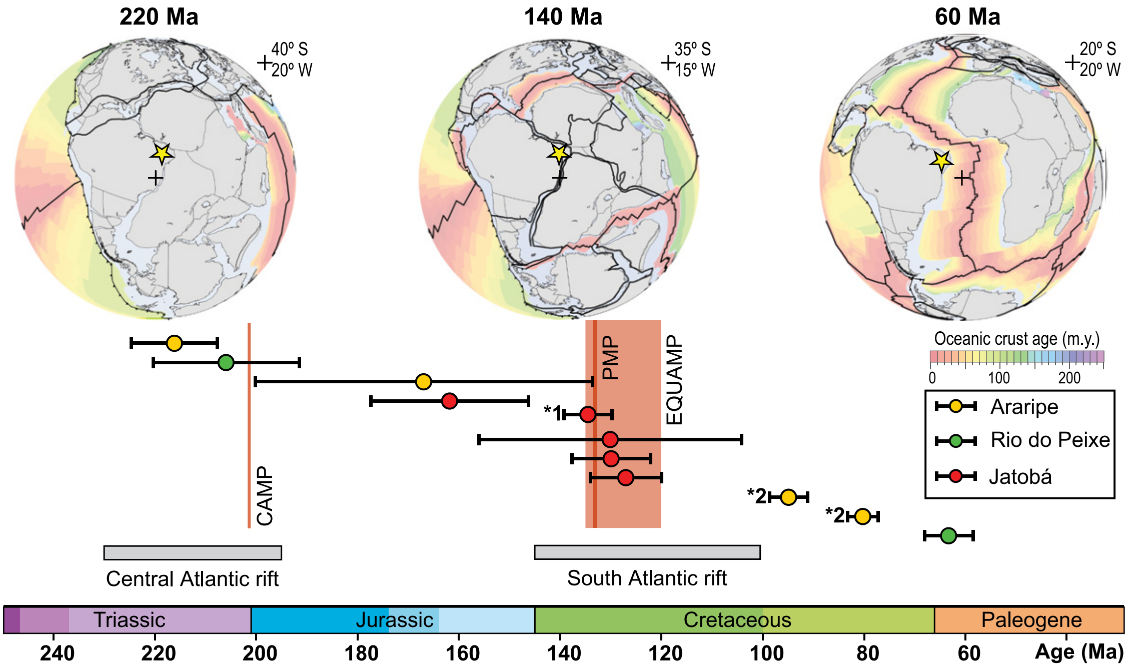

Figure 4. Carbonate U-Pb ages from the Araripe, Rio do Peixe, and Jatobá Basins in the Borborema province (yellow star) in northeastern Brazil and their correlation to events during Pangea breakup. Top row displays plate configuration in three key moments of Atlantic rifting (after Müller et al., 2019), made with GPlates 2.3 (Müller et al., 2018), with the location of the Borborema province and coordinates of the center of each globe (cross). Continents are in gray, present-day submerged areas are in light blue, and plate boundaries are shown as black lines. Bottom row shows carbonate U-Pb ages with uncertainty bars (representing 95% confidence levels with overdispersion and with excess long-term variance propagated), including ages from Miranda et al. (2020) (*1) and Celestino et al. (2021) (*2). Central and South Atlantic rift ages are from Olsen (1997) and de Matos (2021), respectively. Magmatic event ages are from Davies et al. (2017) for the Central Atlantic magmatic province (CAMP), Rocha et al. (2020) for the Paraná magmatic province (PMP), and Hollanda et al. (2019) for the Equatorial Atlantic magmatic province (EQUAMP).

(Fig. 3). The clast ages are most likely related to deformation events older than the strike-slip reactivation. The fine-grained carbonate matrix is interpreted as a product of deformation during reactivation but displays open-system U-Pb behavior, and no ages could be derived. The Cretaceous ages are aligned with expectations for rifting based on Cretaceous rift infill and overlap within analytical uncertainty with the age of the South Atlantic rift event (de Matos, 2021) as well as with the ages of two Cretaceous large igneous provinces of South America, the Equatorial Atlantic and Paraná magmatic provinces (Hollanda et al., 2019; Rocha et al., 2020) (Fig. 4). These results support the hypothesis of extensive brittle reactivation of inherited structures during the Early Cretaceous extensional event that culminated in the separation of South America and Africa.

Two carbonate samples yielded Jurassic dates of ca. 167 and 162 Ma. The former has a large uncertainty, overlapping with both Triassic and Cretaceous ages (Fig. 4). It is difficult to interpret the meaning of this date because it could have resulted from mixing between Triassic and Cretaceous carbonate age populations. The age of ca. 162 Ma was obtained from the footwall of the fault zone that defines the northern border of the Jatobá Basin and is interpreted as an early record of tectonic activity within this fault zone that experienced a climax of tectonic activity during the Early Cretaceous.

Recurrent tectonic reactivation after Pangea's breakup is also recorded by the U-Pb carbonate data. Two carbonate veins associated with breccia pipes within the fault zone that defines the Araripe Basin northern border were dated at ca. 95 and 80 Ma by Celestino et al. (2021) (Fig. 4) and were interpreted as products of brittle reactivation of the Triunfo fault zone during the Late Cretaceous. We have not reproduced such ages, but we report a younger age of ca. 63 Ma (Fig. 3A) from the Rio do Peixe Basin border fault, which we interpret as related to tectonic reactivation of the fault zone during the Cenozoic. Currently active faults also exploit some of these basement structures (i.e., mylonitic foliations, brittle-ductile faults), making the Borborema province among the most seismically active portions of the South American platform (Bezerra et al., 2011).

In conclusion, our U-Pb carbonate data, together with those reported in the literature (Miranda et al., 2020; Celestino et al., 2021), indicate recurrent periods of tectonic activity within the Borborema province basement. Faulting at basin margins had started already in the Triassic, possibly in response to the opening of the Central Atlantic, and span >150 m.y. These faults reactivate Neoproterozoic–Cambrian strike-slip shear zones, which controlled the development of rift-related basins and are still being reactivated today.

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