U-PB AND SM-ND GEOCHRONOLOGICAL CONSTRAINTS ON THE CRUSTAL EVOLUTION AND BASEMENT ARCHITECTURE OF CEARÁ STATE, NW BORBOREMA PROVINCE, NE BRAZIL: IMPLICATIONS FOR THE EXISTENCE OF THE PALEOPROTEROZOIC SUPERCONTINENT "ATLANTICA"

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ABSTRACT Sm-Nd whole-rock and U-Pb zircon geochronological studies of the basement gneisses of Ceará (NW Borborema Province, NE Brazil) have identified two major pulses of Paleoproterozoic crustal growth within the state; the first between ca. 2.35 to 2.30 Ga, and the second from ca. 2.19 to 2.05 Ga. The former was characterized exclusively by juvenile growth and accretion, whereas the latter involved the amalgamation of new juvenile crustal material, reworked or enriched crust, and Archean crustal fragments. It was during this second event, also known as the Transamazonian orogeny (ca. 2.2 to 2.0 Ga), that Ceará's fundamental crustal framework was assembled. Isotopic and geologic data indicate that this assembly involved the fusion of three distinct crustal blocks; the Northwest Ceará (AKA Médio Coreaú) Domain (NCD), the Central Ceará Domain (CCD), and the Rio Grande do Norte Domain (RND). This network of crustal blocks was subsequently affected by an episode of Late Paleoproterozoic intracratonic rifting at around 1.8 Ga. The presence of similar rift sequences of this age in other parts of South America and Africa lend support to the existence of the Paleoproterozoic supercontinental mass Atlantica. Based on the available data, this supercontinent appears to have included the Paleoproterozoic (and older) basement of the Brasiliano/Pan-African provinces in Brazil and West Africa as well as the cratons adjacent to them.

Keywords: Borborema Province, Paleoproterozoic crustal growth, U-Pb zircon and Sm-Nd whole-rock geochronology

INTRODUCTION

Ceará State, of northeastern Brazil, is located in the northwestern part of a Neoproterozoic orogenic belt known as the Borborema Province (BP) (Almeida *et al*. 1981). Although the BP formed at the end of the Precambrian during the assembly of West Gondwana, its crustal framework is made up primarily of older Mesoproterozoic to Archean crustal fragments and domains (Van Schmus *et al*. 1995). Understanding the growth and evolution of these constituent basement blocks is important for reconstructing the precollisional history of the BP and that of West Gondwana. As Ceará encompasses a significant portion of the BP, accurate constraints on the growth and evolution its basement complex are key for unraveling the early growth of the BP.

Pioneering Rb-Sr and K-Ar geochronological studies in Ceará State and the surrounding region, e.g., Brito Neves *et al*. (1975), Brito Neves *et al*. (1978), Torquato *et al*. (1986), and Pessoa *et al*. (1986), provided clues to the antiquity of lithologic units in the region, but the data lacked the necessary accuracy and precision to resolve age differences between different rock units and crustal domains. Furthermore, the susceptibility of the Rb-Sr and K-Ar systems to metamorphic resetting left some doubt as to whether the data represented original or reset ages, e.g. Caby and Arthaud (1986). In recent years, however, U-Pb zircon and Sm-Nd whole-rock studies, e.g., Van Schmus *et al*. (1995, 1997), Dantas *et al*. (1995, 1998) and Fetter *et al*. (1995, 1997), have provided precise and accurate constraints on the formation ages and crustal histories of different blocks within the BP.

In this paper, we report Sm-Nd whole-rock and U-Pb zircon geochronological data obtained from Ceará's basement complex, and discuss the interpretation of these results with respect to the early growth and assembly of Ceará's crustal domains, as well as their implications for the greater tectonic setting during the Middle to Late Paleoproterozoic.

GEOLOGIC SETTING

Ceará State occupies the western part of the Borborema Province's Northern Tectonic Domain (Van Schmus *et al*. 1997), i.e. the region of the BP north of the Patos lineament (Fig. 1). Two continental-scale shear zones, the Transbrasiliano and Senador Pompeu lineaments, subdivide the Northern Tectonic Domain into three major crustal blocks; the Northwest Ceará Domain, the Central Ceará Domain and the Rio Grande do Norte Domain (Fig. 1). The Northwest Ceará and Central Ceará domains are located exclusively in Ceará State, whereas only the western part of the Rio Grande do Norte Domain extends into Ceará. The basement rocks in these blocks consist of variably metamorphosed and migmatized orthogneisses, paragneisses and schists, along with some localized greenstone-gneiss assemblages. Gray orthogneisses, which constitute a greater part of the basement lithologies, are mainly derived from tonalites and granodiorites and have been classified as TTG (tonalite-tronjhemite-granodiorite) suites (Caby and Arthaud 1986, Hackspacher *et al.* 1990, Silva *et al.* 1995, Torquato 1995). Paragneisses and schists, making up a lesser part of the basement were transformed from psammitic and pelitic sedimentary protoliths. Overlying parts of the basement complex are a series of supracrustal sequences ranging from Middle Paleoproterozoic to Late Neoproterozoic in age (Van Schmus *et al*. 1995, 1997, Fetter 1999). Both basement complex and supracrustal rocks are intruded by abundant alkaline and calcalkaline plutons and plutonic complexes that were generated during Brasiliano orogenesis (Almeida *et al.* 1981).

Preliminary U-Pb and Sm-Nd geochronological studies of the Northern Tectonic Domain (NTD), e.g., Hackspacher *et al*. (1990), Van Schmus *et al*. (1993, 1995), Dantas *et al*. (1995), and Fetter *et al*. (1995, 1997), showed its basement architecture to be composed primarily of Paleoproterozoic gneisses, with smaller Archean crustal fragments or nuclei constituting only a minor part of the framework (Fig. 1). Furthermore, differences in ages and Nd isotopic signatures between crustal blocks in this northern portion of the BP, suggested that each of the major crustal blocks grew separately prior to their amalgamation into the composite NTD. U-Pb and Sm-Nd investigations of the Archean enclaves in the NTD; the São José do Campestre massif (Dantas 1997, Dantas *et al*. 1998), the Tróia massif (Fetter *et al*. 1997, Fetter 1999), and the Granjeiro complex (Da Silva *et al*. 1995, Fetter 1999), indicated that they were unrelated exotic fragments which probably became entrained in the network of younger gneisses during Paleoproterozoic accretionary growth. The São José do Campestre massif is a composite block of 3.45 Ga reworked crust and 3.2 Ga juvenile crust, which is intruded by 2.7 Ga alkali plutons (Dantas *et al*. 1998). The Tróia Massif is also a composite block, but notably younger; consisting of 2.86 to 2.79 Ga reworked gneisses and a juvenile 2.78 Ga greenstone-gneiss association, intruded by 2.68 Ga plutons (Fetter 1999). The Grajeiro Complex is the youngest fragment, with an age of 2.54 Ga (Da Silva *et al*. 1995), and appears to be composed entirely of juvenile crust (Fetter 1999). Although these Archean blocks constitute a small fraction of the basement architecture, Nd signatures from the surrounding Paleoproterozoic gneisses indicate that Archean crustal material may have played a role in their genesis.

To place better constraints on the growth histories of the individual crustal domains within Ceará and evaluate differences between the eastern and western portions of the Rio Grande do Norte domain, additional U-Pb zircon and Sm-Nd whole-rock investigations of Ceará

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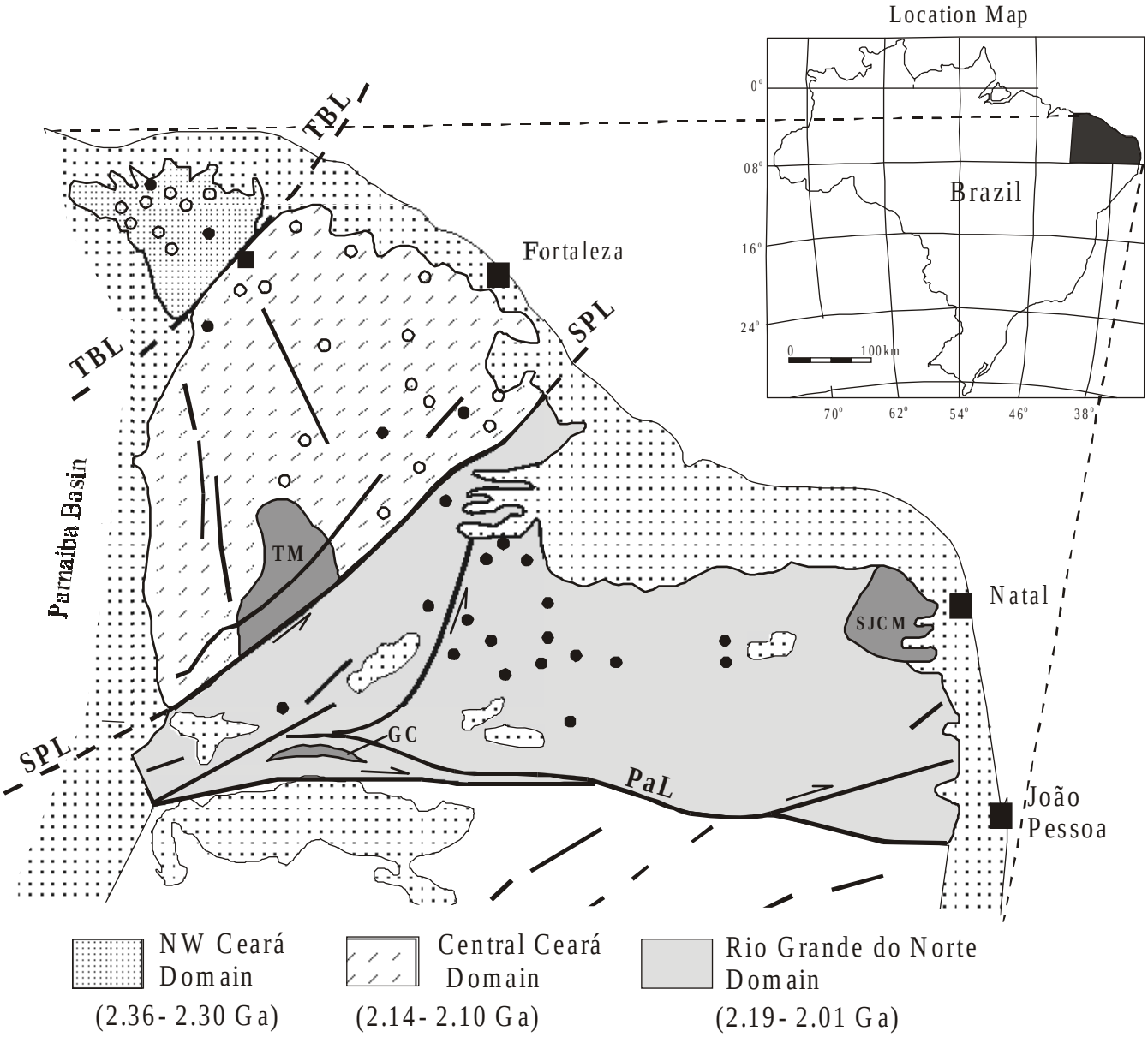

Figure 1 - Schematic map showing the subdivision of major crustal blocks in the Northern Tectonic Domain of the Borborema Province. For simplicity, geologic detail is omitted, except to differentiate between Precambrian rocks and Phanerozoic sediments. TM = Tróia Massif, GC = Granjeiro Complex, SJCM = São Jose do Campestre Massif, TBL = Transbrasiliano Lineament, SPL = Senador Pompeu Lineament, PaL = Patos Lineament. The circles represent U-Pb and Sm-Nd sample locations (open circles represent juvenile crust and filled circles represent enriched or "reworked" crust).

State were performed. Sm-Nd analyses were done to obtain preliminary information about the crustal antiquity in different locales and U-Pb zircon methods were used to constrain the crystallization ages of basement protoliths. Samples were selected to ensure comprehensive geographic coverage of the state and provide detailed data coverage in more complex areas.

ANALYTICAL METHODS Analytical data were obtained at the Isotope Geochemistry Laboratory at the University of Kansas (USA). U-Pb zircon samples were prepared using procedures modified after Krogh (1973, 1982) and Parrish (1987). Whereas, Sm-Nd whole-rock samples were prepared using methods modified from Patchett and Ruiz (1987). Owing to space limitations set forth for this special volume of Revista Brasileira de Geociências a complete description of the analytical methods and conditions encountered during the running of samples will not be discussed further in this paper. For a complete summary of the analytical methods used at the KU Isotope Geochemistry Lab, refer to Van Schmus *et al.* (1995) or Dantas *et al*. (1998).

RESULTS Studies of Ceará's basement complex involved the analysis of 44 samples by Sm-Nd whole-rock methods and 13 samples by U-Pb zircon techniques. Because the data tables are quite extensive, they cannot be accommodated in this special edition of RBG. Nonetheless, copies of the data tables can be obtained by contacting the first author. The written summary of results presented below represent only a portion of the geochronological data obtained during the course of this investigation. Additional data bearing on the geologic evolution of Ceará subsequent to the assembly of its basement framework will be presented in additional papers.

The Northwest Ceará Domain Migmatitic tonalitic to granodioritic gneisses constitute the greater portion of this crustal block, with charnockites, kinzingites and enderbites making up a subordinate fraction of the crystalline basement (Nogueira *et al*. 1990). Some previous Rb-Sr data, obtained by Hackspacher *et al*. (1991), had suggested the presence Middle Archean basement in the NCD, but our data do not confirm this. Sm-Nd whole-rock data from 12 basement gneisses in this domain yield T(DM) model ages ranging between 2.38 and 2.61 Ga, with the majority clustering between 2.42 and 2.48 Ga. U-Pb zircon data from four orthogneisses, ranging from tonalitic to granodioritic in composition, yield upper intercept ages between 2.36 and 2.30 Ga (Figs. 2A & 2B). Both the composition of these gneisses

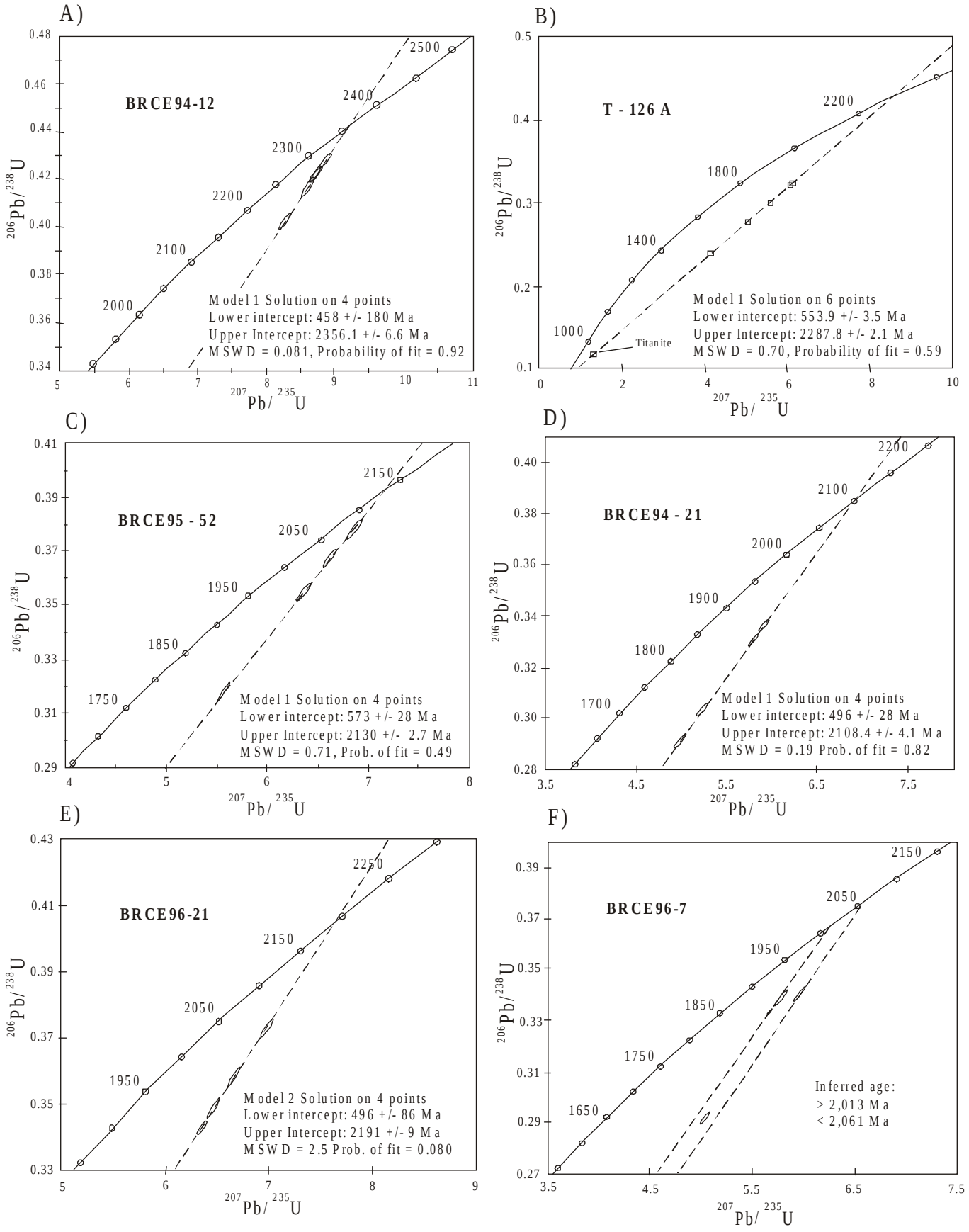

Figure 2 – Representative concordia plots for zircon fractions from tonalitic gneisses of Ceará State's three main crustal blocks. Plots A) and B) show the range of basement ages in the Northwest Ceará Domain; C) and D) show the basement age range in the Central Ceará Domain; and E) and F) show the range of basement ages in the Rio Grande do Norte Domain.

and the morphology of their zircons indicate that these ages represent primary crystallization of the protoliths. Two zircon populations from a granulite-grade metasedimentary rock (a kinzingite), yield two distinct linear arrays, with upper intercept ages of 2.34 and 2.28 Ga. These ages suggest that 1) zircons from this high-grade gneiss are not metamorphic, and 2) detritus for this protolith was derived from the surrounding gneisses. With the exception of two samples, the $å_N$ (t=crystallization age) values for the gneisses of the NCD are positive, and the T(DM) model ages correspond closely to the protolith crystallization ages. These data indicate that this domain is composed of Early Paleoproterozoic juvenile crust, which formed significantly before the 2.2 – 2.0 Ga Transamazonian accretionary-orogenic event.

The Central Ceará Domain The basement complex of the Central Ceará domain is dominated by high-grade felsic orthogneisses and migmatites that are primarily tonalitic to granodioritic in composition. The gneisses of this domain were postulated to represent reworked Archean protoliths (Caby and Arthaud 1986), but subsequent studies, e.g., Fetter *et al*. (1997), showed that only the Tróia Massif within this block was of Archean ancestry. Six U-Pb zircon ages (five from this study and one from Martins *et al*. (1998)) obtained from the surrounding network of orthogneisses confirm a Middle Paleoproterozoic age for this domain (Figs. 2B & 2C). The ages, however, display a pronounced geographical variation. In the northwest part of the CCD, zircon ages cluster tightly at between 2.10 and 2.11 Ga, whereas the basement ages to the southeast are noticeably older, between 2.13 and 2.14 Ga. In contrast, Sm-Nd whole-rock data obtained from 20 basement samples do not follow this geographical variation. T(DM) values range from 1.98 to 2.44, with the majority clustering between 2.23 and 2.37 Ga. $å_{Nd}$ (t=crystallization age) values are positive for most of the samples in domain, indicating that the majority of the crust is juvenile, barring some cryptic enrichment of older crustal material. Strikingly, the gneisses close to the Tróia Massif do not display any particular enrichment. This suggests that the younger gneiss units grew beyond the influence of the Archean block, probably as island-arc terranes in an open ocean environment, as proposed by Martins *et al*. (1998), prior to colliding with it.

The Rio Grande do Norte Domain The basement complex of the Rio Grande do Norte domain in Ceará is dominated by paragneisses and schists, but some tonalitic to granodioritic orthogneisses are present locally. Most of these basement gneisses show variable degrees of migmatization, from small degrees of partial melting to almost complete remelting in some locales. Initial Sm-Nd whole-rock results from orthogneisses in this block suggested the presence of Archean crust, but follow-up zircon analyses showed that only enriched Middle Paleoproterozoic crust is present. Zircons from one sample of tonalitic gneiss (BRCE96-21) yield a precise upper intercept age of 2,191 Ma (Fig. 2D) and is interpreted represent the initial crystallization of the protolith. Zircons from a second sample (BRCE96-7), however, yield highly scattered data unsuitable for classic data regressions. Instead, the $^{207}Pb/^{206}Pb$ ages from the different fractions have been used to place constraints on the possible age of this gneiss, between 2,013 and 2,061 Ma (Fig. 2E). Corresponding Nd T(DM) ages from these two samples are 2.61 and 2.54 Ga, respectively, indicating incorporation of an older crustal component. Nd T(DM) values from other orthogneisses in this domain range from 2.50 to 2.60 Ga demonstrating that the influence of older crust is pervasive in this domain. A similar, but wider range of T(DM) values is reflected by the paragneisses and schists, 2.42 to 2.73 Ga, with the bulk of them clustering between 2.44 and 2.55 Ga. These enriched crustal signatures are not restricted to just this region of the Rio Grande do Norte domain. Farther to the east in this domain an even greater influence of old crust is present. The basement orthogneisses of the Rio Piranhas massif to the east have been dated at between 2.15 and 2.16 Ga by U-Pb zircon methods (Hackspacher *et al*. 1990) and their corresponding Nd T(DM) values are from 2.62 to 2.76 Ga (Van Schmus *et al*. 1995). This apparent progressive Nd enrichment in the RND from east to west suggests that the Archean São Jose do Campestre massif in the eastern part of the RND may have been a possible source of older crustal material during the Paleoproterozoic growth of this domain. The smaller Archean Granjeiro complex, located in the southwestern part of the RND, is also a candidate source of older crustal input.

DISCUSSION AND CONCLUSIONS The U-Pb and Sm-Nd geochronological data presented above reveal the distinctive growth histories of Ceará's major crustal blocks. Despite variations in the evolution of each domain, their development was a Paleoproterozoic, not an Archean, phenomenon. The Paleoproterozoic crustal growth of each block can be summarized as follows: The Northwest Ceará domain (NCD) grew during the Early Paleoproterozoic between ca. 2.36 and 2.30 Ga. Both the juvenile Nd signatures and TTG lithologies in this domain suggest that it probably developed in an isolated island-arc setting distal from older crustal sources. The Central Ceará domain (CCD) grew during the Middle Paleoproterozoic, from ca. 2.14 to 2.10, and like the NCD, it appears to have grown primarily by accretion of juvenile arc terranes. The bimodal clustering of ages in the eastern and western parts of this domain can be explained either by progressive accretion from east to west, or by two distinct pulses of growth within it. Additional data from the central part of this block are needed to answer this question. The presence of some enriched crust in the CCD probably reflects the influence of older Archean crust during its genesis, e.g. the subduction of Archean turbidites during arc-magma genesis. One possible Archean source may have been the Tróia Massif located within CCD. The Rio Grande do Norte domain in Ceará records a crustal genesis between 2.19 and 2.01 Ga, but in contrast to the CCD and NCD, no juvenile crust is present. The pervasive Nd enrichment in both orthogneisses and paragneisses in the RND indicates that the rocks in this block grew under the influence of older Archean sources. Such candidates within the RND include the Archean Granjeiro Complex and the São Jose do Campestre Massif. The progressive younging of Nd T(DM) ages from east to west in the entire RND suggests that the São Jose Campestre Massif may have been the primary source of Nd enrichment in this domain.

All three of the crustal blocks in the Northern Tectonic Domain (NTD) are postulated to have joined during the later stages of the ca. 2.2 to 2.0 Ga Transamazonian orogeny. The presence of Late Paleoproterozoic intracontinental rift sequences (ca. 1.8 to 1.6 Ga) within Ceará (Parente and Arthaud 1995, Sá *et al*. 1995, Fetter 1999) not only suggest the coherence of the NTD, their likeness to other ca. 1.8 to 1.6 Ga rift-related assemblages in other parts of South America (Brito Neves *et al*. 1995) and Africa (Caby and Andreopoulos-Renaud 1983) suggest that the NTD may also have been part the Paleoproterozoic supercontinent Atlantica (Rogers 1996) (Fig. 3). The synchroneity of Late Paleoproterozoic rifting over a wide geographical area is consistent with fragmentation of a large continental mass due to heat buildup (see Condie 1989, Windley 1995, and Brito Neves *et al*. 1995). As such, we propose that the Northern Tectonic Domain of the Borborema Province was a constituent part of the Paleoproterozoic supercontinent Atlantica, which may have included much of Brazil.

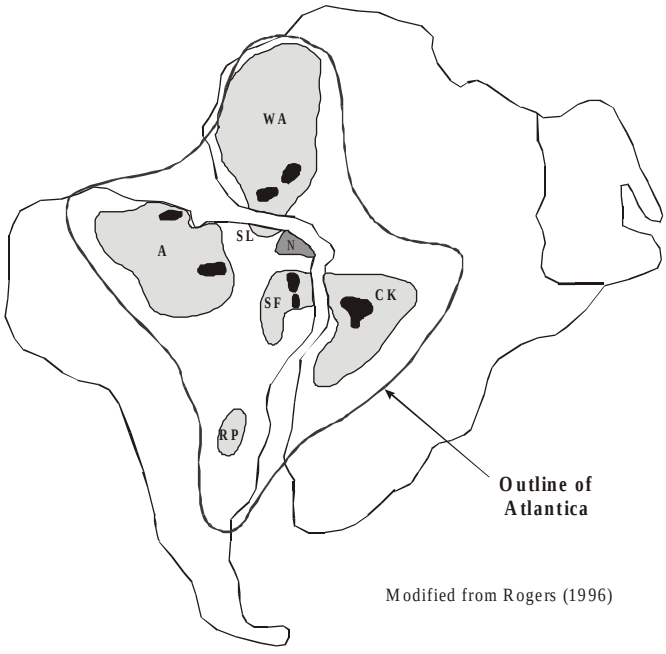

Figure 3 – A schematic reconstruction of the Paleoproterozoic supercontinent "Atlantica" showing the present-day outlines of Africa and South America. N = Northern Tectonic Domain of the Borborema Province, A = Amazon craton, WA = West African craton, SL = São Luis craton, SF = São Francisco craton, CK = Congo/Kasai craton, and RP = Rio de Plata craton. 2.0 Ga fluivo-deltaic deposits shown in black.

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