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Integration of elemental and isotope data supports a Neoproterozoic Adamastor Ocean realm

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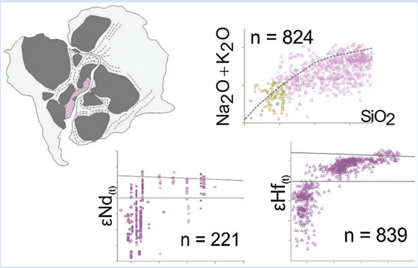
Abstract



A robust elemental and isotopic dataset from Neoproterozoic igneous rocks discloses protracted consumption of oceanic lithosphere in the 3,000 km long orogenic system of southeastern South America. Time dependent isotopic variation trends suggest that Tonian-Cryogenian magmatic rocks formed in intra-oceanic supra-subduction settings, followed by Ediacaran magmatic arc building along Andean-type continental margins. Tectonic slices of basic-ultrabasic rocks associated with deep sea and exhalative rocks are interpreted as remnants of obducted oceanic lithosphere. Protracted closure of the oceanic realm resulted in a Himalayas-sized orogenic belt during Ediacaran-Cambrian collision, as recorded by voluminous aluminum-rich syn-collisional granites followed by post-collisional intrusions. The duration and rates of crust forming processes in island arc, continental margins and collisional settings imply that a vast Adamastor oceanic realm was consumed to form western Gondwana.

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Introduction

The Cretaceous breakup of Gondwana in the South Atlantic region produced an asymmetric division of the Neoproterozoic Brasiliano/Pan-African Orogen (Fig. 1a,b) (Cordani *et al.*, 2003). A large part of the orogen remained in South America as the 3,000 km long and 100–500 km wide Mantiqueira Province (Almeida *et al.*, 1981) (Fig. 1a).

Early postulations of tectonic evolution of the Mantiqueira Province emphasised intra-continental models (*e.g.*, Torquato and Cordani, 1981; Porada *et al.*, 1989), an interpretation that received renewed attention in recent years (Cavalcante *et al.*, 2019; Meira *et al.*, 2019; Fossen *et al.*, 2020; Konopásek *et al.*, 2020). However, a wealth of field, geochemical and geochronological data produced in recent decades progressively prompted interpretations involving distinct stages of typical Wilson cycle processes involved in the closure of the Adamastor Ocean (originally defined by Hartnady *et al.*, 1985). Besides reworked Archean-Palaeoproterozoic basement, Neoproterozoic continental rift and passive margin successions, ocean floor assemblages and syn-orogenic basins were described. Those are intruded by large volumes of Cryogenian to Cambrian plutonic rocks typical of pre-collisional, collisional, and post-collisional stages (Fig. 1a), with temporal and spatial ordering leading to the present unraveling of a simple and reliable interpretation of a complete rift-drift-subduction-collision plate tectonic cycle. The archetypical examples of intracontinental orogens (Raimondo *et al.*, 2014), as proposed in the last century and recently revived, lack many of the tectonic components recognised in the last decades in the Mantiqueira Province.

Here we provide a new interpretation for a comprehensive database of 1,583 Hf-in-zircon (839 from Neoproterozoic, 744 from Archean-Palaeoproterozoic basement), 358 Sm-Nd isotope (221 and 137) and 824 bulk rock elemental geochemistry determinations of Neoproterozoic plutonic and volcanic rocks of the Mantiqueira Province (Supplementary Information), and demonstrate that these rocks are a testimony to an oceanic realm that was consumed to generate a Himalayas-sized orogen.

Tonian-Cryogenian assemblages with Volcanic Arc Signatures

Tonian-Cryogenian tonalite-granodiorite orthogneisses with dioritic to mafic enclaves represent an expanded series of calc-alkaline, magnesian, metaluminous, I-type magmas along tholeiitic basalt (Fig. 1c–f). The 835–860 Ma Serra da Prata Complex of the central province has whole rock $\varepsilon Nd_{(t)}$ from +6.4 to +0.9

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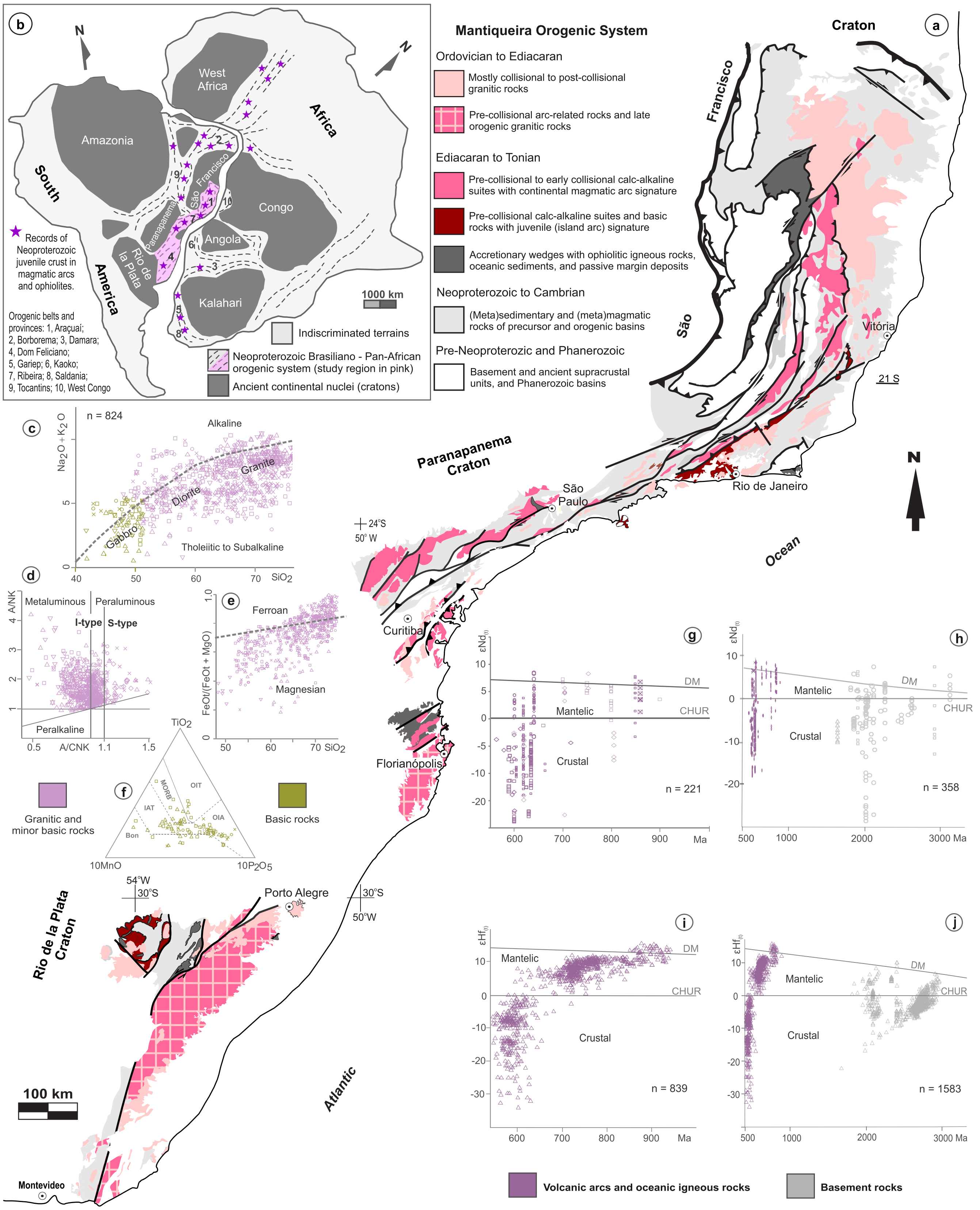

Figure 1 **(a)** Geological map of the Mantiqueira Province of southeastern South America in the context of **(b)** West Gondwana, with **(c-f)** elemental and **(g-j)** isotopic data from basic to felsic plutonic rocks and mafic-ultramafic bodies (see Supplementary Information for sources and references).

with T_{DM} Nd of 860–1,200 Ma, $^{87}Sr/^{86}Sr_i < 0.7035$, zircon $\varepsilon Hf_{(t)}$ from +14 to +10, and T_{DM} Hf of 840–1,010 Ma (Peixoto *et al.*, 2017; Heilbron *et al.*, 2020; Santiago *et al.*, 2020). The Rio Negro Complex comprises intermediate to felsic plutonic rocks (620–790 Ma) with $\varepsilon Nd_{(t)}$ from +5 to −3 and $^{87}Sr/^{86}Sr < 0.705$, as well as high K calc-alkaline to shoshonitic felsic rocks

(605–620 Ma) with $\varepsilon Nd_{(t)} = -3$ to -14 and $^{87}Sr/^{86}Sr = 0.7050$–0.7100 (Tupinambá *et al.*, 2012).

The São Gabriel terrane in the southern region (Fig. 1a) yielded U-Pb zircon ages of 800–860 Ma and 680–770 Ma (Babinski *et al.*, 1996; Saalmann *et al.*, 2005). Sm-Nd T_{DM} are at 800–1,000 Ma with $\varepsilon Nd_{(t)}$ on the depleted mantle curve (up to +8, Babinski *et al.*, 1996; Saalmann *et al.*, 2005) and zircon $\varepsilon Hf_{(t)}$ from +14 to +8 (Cerva-Alves *et al.*, 2020).

Ediacaran Assemblages with Volcanic Arc Signatures

Widespread Ediacaran (mainly *ca.* 580–630 Ma) magmatic rocks represent an expanded series of medium to high K calc-alkaline, magnesian, metaluminous, I-type tonalites to granodiorites rich in dioritic to mafic enclaves, with minor gabbro (Fig. 1a) (Tedeschi *et al.*, 2016; Basei *et al.*, 2018; Corrales *et al.*, 2020). The Rio Doce plutonic and volcanic rocks show $\varepsilon Nd_{(t)}$ of −2.9 to −13.6 with T_{DM}Nd of 1,190–2,030 Ma, $^{87}Sr/^{86}Sr$ of 0.7059–0.7165 and zircon $\varepsilon Hf_{(t)}$ of +2.3 to −11.7 (Tedeschi *et al.*, 2016; Degler *et al.*, 2017; Novo *et al.*, 2018; Araújo *et al.*, 2020; Corrales *et al.*, 2020). The Pelotas-Florianópolis-Aiguá batholith forms a multi-intrusion geological structure consisting of granite, gabbro and diorite with $^{87}Sr/^{86}Sr_i$ ratios of *ca.* 0.712, εNd of −3.6 to −22.2 and T_{DM}Nd of 1,200–2,400 Ma (Babinski *et al.*, 1997; Koester *et al.*, 2016).

Neoproterozoic Basic-Ultrabasic Assemblages

Accretionary mélanges of the northern province (Fig. 1a) include MORB chemistry metabasalt, banded metadolerite, metagabbro and meta-ultramafic rocks, with $\varepsilon Nd_{(t)}$ up to + 6.3 (Pedrosa-Soares *et al.*, 1998; Amaral *et al.*, 2020). Rootless plagiogranite veins hosted by a banded metadolerite are dated at 645 ± 10 Ma (Amaral *et al.*, 2020).

Mafic-ultramafic rock associations in the central sector include dunite cumulates, MORB- and IAT-like gabbro, metabasic rocks with sheeted dikes, pillow lavas and chert, emplaced at *ca.* 630 Ma (Tassinari *et al.*, 2001; Passarelli *et al.*, 2018).

The 715–920 Ma MORB chemistry mafic-ultramafic assemblages in the southern sector have zircon $\varepsilon Hf_{(t)}$ up to +15 and mantle-like trace element signatures (Arena *et al.*, 2017, 2018; Hartmann *et al.*, 2019). Dravite in altered oceanic crust has typical ocean floor $\delta^{11}B$ up to +1.8 (Hartmann *et al.*, 2019). The southernmost ophiolites show whole rock $\varepsilon Nd_{(t)}$ up to +8.5 (Peel *et al.*, 2018; Ramos *et al.*, 2020) (Fig. 1a).

Discussion

The time dependent variation of isotopic trends (Fig. 1g–j) is interpreted as a shift from Tonian-Cryogenian juvenile settings fingerprinting intra-oceanic arcs to Ediacaran settings with magmas formed by mixing of mantle wedge melts and anatectic melts from both the Tonian-Cryogenian rocks and the Archean-Palaeoproterozoic basement. The resulting mixed melts intruded active continental margin settings similar to Andean volcanic arcs. The protracted consumption of oceanic lithosphere is required, and this is attested by the associated ophiolites along the entire length of the Mantiqueira Province.

Recently revisited models of intracontinental orogeny focused on a "space problem" for the development of an Adamastor oceanic realm based on estimates of maximum oceanic width using modern spreading and subduction rates (Fossen *et al.*, 2020; Konopásek *et al.*, 2020). However, those estimates are contingent and cannot be used as hard proof against mobilistic models, because: 1) the ocean was probably fragmented in smaller sub-domains such as in the present day western Pacific and also connected to a much large Neoproterozoic oceanic system (Cordani *et al.*, 2003) (Fig. 1b); 2) the Neoproterozoic upper mantle was warmer, leading to distinct spreading and subduction rates and dynamics (Brown, 2014); 3) intense wrench tectonics with thousands-of-km long shear zones obliterated former low angle surfaces and displaced allochthonous units far from their original position; 4) age, size and time span of an ocean have little significance in determining whether subduction is feasible or not (Hall, 2019), while lithospheric weaknesses such as magma-rich rift systems present in the orogen precursor basins (Tack *et al.*, 2001; Basei *et al.*, 2008) might play a major role in subduction initiation (Stern and Gerya, 2018); 5) those calculations use a palinspastic incorrect pre-drift reconstruction, ignoring at least *ca.* 280 km of restored continental crust now stretched in the Brazilian and African passive margins (Aslanian *et al.*, 2009); 6) the termination of the orogen in a gulf partially enclosed by continental crust implies much lower convergence rates; and 7) non-Euclidean geometry implies the diachronous along strike opening and closure of oceanic basins. Thus, calculations of former oceanic width are interesting hypothetical exercises, but the field, petrographic, isotopic, elemental and geochronological data sets cannot be considered as subordinated to it.

The striking coherence of evidence from various geological disciplines (detailed field, petrographic and structural studies, bulk rock chemistry, isotope geochemistry, quantitative geothermobarometry and petrology) support a solid interpretation for the tectonic units and their arrangement in time and space to be explained better through the development and consumption of an oceanic realm in the Mantiqueira Province. The evidence provided here suggests that the main ocean was located to the west of the arc rocks, where recently paired HP-HT metamorphic belts were described (Ricardo *et al.*, 2020). The original proposition of Hartnady *et al.* (1985) would correspond to the Marmora back-arc basin in the African counterparts, east of the Pelotas arc (Frimmel *et al.*, 2011; Basei *et al.*, 2018).

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Additional Information

Supplementary Information accompanies this letter at https://www.geochemicalperspectivesletters.org/article2106.

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