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Abstract: The São Francisco Basin contains a spectacular archive of Neoproterozoic strata. Its hydrocarbon-bearing strata are receiving increasing attention as global oil and gas exploration targets progressively deeper and older rocks. New Re-Os geochronology for the Paracatú Slate Formation of the Canastra Group, Brazil yields a depositional age of 1002 ± 45 Ma. This age represents the first successful application of the Re-Os system to rocks of this group and indicates excellent agreement with previous published U-Pb detrital zircon age (Rodrigues et al., 2010). Together with TOC values ~2 wt.% preserved even after green-schist metamorphism, it might be argued that the São Francisco Basin has had the potential for hydrocarbon generation since Tonian times. We also report an imprecise Re-Os age (1304 ± 210 Ma) for the Serra do Garrote Formation, a further potential source rock of the Vazante Group. We suggest, based on petrological evidence that Re-Os systematics may have been disturbed by post-depositional fluid flow associated with the Vazante hydrothermal alteration. An attempt to determine a Re-Os date for the Sete Lagoas Formation, a putative post-Sturtian cap carbonate, is precluded owing to low Re presence. Major environmental changes in the aftermath of the Jequitaí glaciation, particularly the development of palaeotopography such as subglacial tunnel valleys, may account for the apparent random distribution of TOC enrichment in these Cryogenian post-glacial deposits. This scenario might thus have major implications for the hydrocarbon prospectivity of this post-glacial succession.

Cover letter

Maria Emilia Bertoni
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London, 20th of November, 2013

Dear Editor,

I am pleased to submit an original research manuscript entitled "*Neoproterozoic Re-Os systematics of organic-rich rocks in the São Francisco Basin, Brazil and implications for hydrocarbon exploration*". In this article we study three potential source rocks of the São Francisco Basin in order to date them using Re-Os geochronology. The study of Neoproterozoic strata as components of potential petroleum systems is a new and exciting frontier, and one that we feel is entirely appropriate for Precambrian Research. We provide the first depositional isochron for the Canastra Group, and explain the complexities and issues surrounding the application of the technique to other units. We offer a simple model to explain the low TOC values in the Sete Lagoas Formation- a unit representing a cap carbonate above the Sturtian glacial and which was expected to have far higher TOC values than measured. Demonstration of "successful" isochron acquisition is especially important, as in the authors' experience there has been a general resistance to using this technique in Brazil more generally. The article does not include detailed sedimentological investigations, as the outcrops are almost universally low lying and patchily exposed- and weathered! Thus, samples are limited to cores.

We would suggest the following individuals as potential reviewers: Dr Jonathan Craig (jonathan.craig@eni.com), Dr Robert Creaser (Robert.Creaser@ualberta.ca), Dr Alan Collins (alan.collins@adelaide.edu.au), Dr Sebastian Luening (sebastian.luening@galpenergia.com). We confirm that the manuscript has not been published and is not under consideration for publication elsewhere, and look forward to hearing from you in due course.

Yours sincerely,

Maria Emilia Bertoni

Postgraduate research student
Department of Earth Sciences
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***Highlights (for review)**

- We assess three formations using the rhenium–osmium (Re–Os) geochronometer
- A depositional age of 1002 ± 45 Ma was obtained for the Paracatú Fm.
- Fluid flow is suggested responsible for imprecise ages in the Serra do Garrote Fm.
- Dating of the Sete Lagoas Formation was precluded due to low Rhenium presence
- The São Francisco Basin may have petroleum potential since Tonian times

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Neoproterozoic Re-Os systematics of organic-rich rocks in the São Francisco Basin, Brazil and implications for hydrocarbon exploration

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Abstract

The São Francisco Basin contains a spectacular archive of Neoproterozoic strata. Its hydrocarbon-bearing strata are receiving increasing attention as global oil and gas exploration targets progressively deeper and older rocks. New Re–Os geochronology for the Paracatú Slate Formation of the Canastra Group, Brazil yields a depositional age of 1002 ± 45 Ma. This age represents the first successful application of the Re–Os system to rocks of this group and indicates excellent agreement with previous published U–Pb detrital zircon age (Rodrigues et al., 2010). Together with TOC values ~2 wt.% preserved even after green-schist metamorphism, it might be argued that the São Francisco Basin has had the potential for hydrocarbon generation since Tonian times. We also report an imprecise Re–Os age (1304 ± 210 Ma) for the Serra do Garrote Formation, a further potential source rock of the Vazante Group. We suggest, based on petrological evidence that Re–Os systematics may have been disturbed by post-depositional fluid flow associated with the Vazante hydrothermal alteration. An attempt to determine a Re-Os date for the Sete Lagoas Formation, a putative post-Sturtian cap carbonate, is precluded owing to low Re presence. Major environmental changes in the aftermath of the Jequitaí glaciation, particularly the development of palaeotopography such as subglacial tunnel valleys, may account for the apparent random distribution of TOC enrichment in these Cryogenian post-glacial deposits. This scenario might thus have major implications for the hydrocarbon

prospectivity of this post-glacial succession.

Keywords: Re–Os, Neoproterozoic, Canastra, Vazante, Bambuí, source rock

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1.Introduction

The rhenium–osmium (Re–Os) geochronometer is an increasingly recognized tool for determining depositional ages of organic-rich rocks (Ravizza and Turekian, 1989; Cohen et al., 1999; Selby and Creaser, 2005a; Georgiev et al., 2011) and hydrocarbon deposits (Selby et al, 2005; Selby and Creaser, 2005b). Although the method has yielded absolute dates for Neoproterozoic strata with precision approaching 1% uncertainty (2σ) in units up to greenschist facies (Kendall et al., 2004; Rooney et al., in press), their concordance with those obtained by conventional, geochronological techniques remains controversial in some Proterozoic intervals (Kendall et al., 2006; Kendall et al., 2009a; Mahan et al., 2010).

In the São Francisco Basin of Brazil (**Fig. 1, A**) the Re-Os radioisotope system has been used to provide Meso-Neoproterozoic depositional ages for the Lapa and Serra do Garrote Formations of the Vazante Group (Geboy, 2006; Azmy et al., 2008). However, the lack of accurate geochronological data throughout the stratigraphy severely hinders attempts to develop a chronological framework for the São Francisco Basin. This is a critical problem for two reasons. First, the São Francisco Basin and its surrounding belts contains a magnificent stratigraphic archive of Proterozoic time, extending at least from the Statherian (1750 Ma) to the Ediacaran (610 Ma) (Alkmim and Martins-Neto, 2012), of wider interest to the Precambrian research community. For example, it exposes, over a wide area, diamictites and associated cap carbonates attributable to Marinoan (Caxito et al., 2012), plus evidence of intra-Cryogenian photosynthetic communities (Olcott et al., 2005). Second, the São Francisco Basin has multiple gas shows, which are probably sourced from Meso-Neoproterozoic organic-rich rocks (Craig et al., 2012 and refs therein). The São Francisco is a frontier basin for hydrocarbon exploration: the origins of these hydrocarbons, the timing of their migration, and mechanism of entrapment, remain unknown. Placing proper geochronological constraints on organic-rich horizons is key to understanding of the nature of the depositional environment and fossil hydrocarbon system in this vast basin.

The aims of the present paper are threefold: 1) to constrain the depositional age of the organic-rich strata using Re-Os geochronology; 2) to improve radiometric calibration of the Brazilian Proterozoic rock record and contribute to a better understanding of the geological evolution of the Brasília Belt and São Francisco Basin; 3) to establish whether key intervals are enriched in total organic carbon, and hence potential hydrocarbon source rocks. A more detailed sedimentological description of the strata will be presented elsewhere.

2. Geological setting and existing chronostratigraphy

The São Francisco craton (**Fig. 1A**), as one of the oldest portions of the Precambrian nucleus of the South American continent, hosts sedimentary successions deposited between the Neoarchean (~2800 Ma) and Late Neoproterozoic (580 Ma) (Almeida et al., 2000). Together with other cratons of South America, it represents the internal portions of the plates involved in the assembly of West Gondwana by the end of the Proterozoic Era (Alkmim and Martins-Neto, 2012). The Neoproterozoic Brasiliano-Pan Africano orogenic belts, on the other hand, encompass the margin of those plates and the intervening accretionary material (Alkmim et al., 2001; Alkmim and Martins-Neto, 2012; Almeida et al., 2000). The Brasilia Belt, which flanks the São Francisco Basin to the west, exhibits a fundamentally complex tectonic character and variable metamorphic grade. Therefore, it is essential to briefly outline the structural character, the stratigraphy, and present geochronology of both the Brasília belt and the São Francisco basin.

"Insert Supplementary Figure 1 here"

2.1 The Brasilia Belt and São Francisco basin

The Brasilia Belt, located on the western margin of the São Francisco Craton (**Fig. 1B**), is the product of a collision between the Amazon, São Francisco-Congo and Paranapanema paleocontinents during the amalgamation of Gondwana (Li et al., 2008; Pimentel et al., 2011; Rodrigues et al., 2012). This belt is composed of thrust sheets verging eastward towards the São Francisco platform (**Fig. 1B**). Metamorphic grade increases progressively westward, reaching granulite facies conditions in the central part of the belt (Dardenne, 2000).

The southern Brasília Belt, focused in this paper, involves sedimentary rocks grouped into several lithostratigraphic units (**Fig. 1B**): the Araxá, Paranoá, Canastra, and Ibiá groups (Pimentel et al., 2011). Intense deformation, the lack of intercalated volcanics, and the absence of biostratigraphic controls results in multiple possible interpretations for this supracrustal succession (Dardenne, 2000; Valeriano et al., 2008; and references therein). Provenance studies suggest that the Paranoá and Canastra groups are passive margin deposits of the São Francisco paleocontinent, while the Araxá, and Ibiá–groups are synorogenic (fore- or back-arc) basin fill (Pimentel et al. 2001; Rodrigues et al. 2010; Pimentel et al., 2011).

The São Francisco basin occupies the ca. 800 km-long NS-trending lobe of the São Francisco craton (Alkmim and Martins-Neto, 2012) (Fig.1). Bounded to the west and to the east by emergent thrust of the adjacent Brasília and Araçuaí orogenic belts respectively, the basin is filled by Paleo/Mesoproterozoic units (Paranoá Group and Espinhaço Supergroup), and Neoproterzoic strata of the Vazante Group, Jequitaí Formation, and Bambuí Group (Fig. 1).

Below, we briefly summarise the characteristics of the Canastra, Vazante and Bambuí groups, as well as the Jequitaí Formation, which are the focus of the present paper.

2.2 Canastra Group

The Canastra Group, mainly present in the southern portion of the eastern Brasilia orogen (**Fig. 1B**), comprises phyllite and quartzite with common carbonate beds. These have experienced lower greenschist (chlorite) facies metamorphism (Dardenne, 2000). The lithostratigraphy is difficult to unravel owing to numerous thrust faults (Rodrigues et al., 2010) (**Fig. 2**), especially for the basal Serra do Landim Formation (chlorite-rich calc-phyllite and calcschist) and the upper units (Paracatú and the Chapada dos Pilões formations). The Paracatú comprises slope turbidites and basinal, carbonaceous phyllites rich in diagenetic pyrite, whereas the Chapada dos Pilões comprise shallow marine wave and storm-modulated clastics (Pereira et al., 1994). The coarsening upward succession in the upper Canastra Group thus records a regressive, continental platform megasequence (Pereira et al., 1994).

Pimentel et al., (2001) obtained TDM model ages for Canastra rhythmites from Sm-Nd systematics ranging from 1.9 to 2.3 Ga, suggesting a Paleoproterozoic source from the São Francisco-Congo craton. The youngest detrital zircons are ca. 1040 Ma (Valeriano et al., 2004; Rodrigues et al., 2010) (**Fig. 2**), indicative of a passive margin association within the Brasília Belt (Pimentel et al., 2001, 2011; Rodrigues et al., 2010). Ore-hosting carbonaceous phyllites of the Morro do Ouro Member of the Paracatú Formation are estimated at 1000 to 1300 Ma, an assumed diagenetic age range based on Rb-Sr, K-Ar chlorite and Pb-Pb on galena (Freitas-Silva, 1996). Metamorphism and gold enrichment of this unit is related to the Brasiliano event at ca. 680 Ma (Freitas-Silva, 1996).

Thrust contacts characterize the boundaries between the Canastra and lower grade metamorphic strata of the Vazante, Paranoá and Bambuí groups (Pereira et al., 1994). It has been suggested that the Canastra Group is a lateral equivalent of the Paranoá Group (Dardenne, 2000; Pimentel et al., 2011).

"Insert Supplementary Figure 2 here"

2.3 The Vazante Group

The Vazante Group is divided into seven formations (**Fig. 3**). Broadly, these comprise thick pelitic-dolomitic deposits of marine origin. The formations are metamorphosed to greenschist facies, and are exposed in the eastern Brasilia Belt (**Fig. 1B**). Brasiliano-Pan African thrusts and nappes obscure many sedimentary contacts (Dardenne, 2000), particularly with the Canastra Group to the west and the Bambuí Group to the east (Rodrigues et al., 2012). Intense deformation in the outcrop area in the southern segment of the Brasilia belt raises major uncertainties about the internal stratigraphy and lateral correlation of the units.

In this paper, we analyzed the Serra do Garrote Formation (**Fig. 3**). This formation is dominantly carbonaceous and pyrite-bearing slate, intercalated with fine quartzite beds, representing an open marine succession deposited below storm wave base (Madalosso, 1980; Madalosso and Valle, 1978). The Serra do Poço Verde lies conformably over the non-carbonate deposits of the Serra do Garrote Formation and is dominantly dolomitic. It also includes slate, carbonaceous phyllite with pyrite and marls (Babinski et al., 2005): glendonite pseudomorphs after ikaite, and dropstones in slates, suggesting paraglacial depositional conditions (Olcott et al., 2005). The Serra do Poço Verde Formation is conformably overlain by the Morro do Calcário Formation – a carbonate-dominated succession including stromatolitic bioherms and biostromes (Dardenne, 2000). This formation is truncated by an unconformity at the base of the overlying Lapa Formation (Misi et al., 2005). The Lapa Formation contains organic-rich shale, which taken together with a $\delta^{13}C$ negative excursion is interpreted to record the resumption of primary productivity in the aftermath of the Serra de Poço Verde glaciation (Azmy et al., 2006).

Based on C and Sr isotope curves (Azmy et al., 2006), the Lapa Formation is correlated with the "Sturtian" glacial event (ca. 715 Ma; Macdonald et al., 2010). Globally, the chronometry of the Sturtian glaciation is considered to encompass a ~60 Myr window, based on U-Pb zircon and Re-Os geochronology of syn- and postglacial deposits associated with the Rapitan glacials in north western Canada (Macdonald et al., 2010; Rooney et al., in press). Previous Re-Os analyses have yielded depositional ages for organic rich shales of the Serra do Garrote (1353 ± 69 Ma) and Serra do Poço Verde (1126 ± 47 Ma) formations, respectively (**Fig. 3**; Geboy, 2006). The same technique together with U-Pb measurements on detrital zircons of the Lapa Formation (Azmy et al, 2008) indicated that deposition occurred ca. 1000–1100 Ma. Thus, a late Mesoproterozoic age, rather than a Sturtian assignment, is currently preferred (Azmy et al, 2008). Finally, U–Pb detrital zircon analyses using SHRIMP (Rodrigues et al., 2012) sampled five formations of the Vazante Group. This work identified the youngest population (ca. 930 Ma) at the base of the group, and older populations (ranging ca. 1200-1000 Ma) toward the top (**Fig. 3**). This suggests either that the Neoproterozoic source was isolated or covered during the evolution of the basin, or that tectonic discontinuities led to tectonic inversion of part of the lithostratigraphic units of the group.

Despite the complex history of this group, the detrital zircon age pattern of the Serra do Garrote Formation (~1.29 Ga, Rodrigues et al., 2012) is coherent with the isochron Re-Os age (~1.35 Ga, Geboy, 2006) obtained for the same formation. However, the Re-Os isochron (1353 ± 69 Ma) is associated with high MSWD value (26) and the interval of deposition remains quite broad. This raises the possibility that the detrital zircon age is even younger than the Re-Os isochron. Therefore, further provision of radiometric ages is clearly necessary, and motivates our attempts to date the formation.

"Insert Supplementary Figure 3 here"

2.4 Neoproterozoic glacials and the Jequitaí Formation

Evidence for glaciation in the Jequitaí Formation and its correlatives, the Bebedouro Formation and Macaúbas Group, exposed respectively in the northern São Francisco craton and Araçuaí belt (Fig.1), is compelling (e.g. Cukrov et al., 2005; Uhlein et al., 2007; Chaves et al., 2010). The preceding authors have cited a striated pavement cut into the Espinhaço Supergroup in the northeastern portion of the São Francisco basin, together with abundant diamictites with exotic lonestones, some of which are well stratified and exhibit unequivocal impact structures implying ice-rafted debris. Furthermore, Martins-Ferreira et al. (2013) describe a ca. 4km-wide valley carved in the sandstones of the Paranoá Group and filled by a package of sandstones, diamictites and tillite of the Jequitaí Formation. These glaciogenic rocks are in turn covered by cap dolomites that mark the base of the Bambuí Group in the western portion of the São Francisco basin. With the exception of the striated pavement, each of these facies are recognised in proprietary cores across the subsurface of the basin. Thus, clear evidence for glacial sedimentary processes at outcrop guides subsurface interpretations.

Zircons extracted from the Jequitaí Formation and the correlative Macaúbas Group yielded maximum deposition ages of 880Ma and 864Ma, respectively (Pedrosa-Soares et al., 2000; Rodrigues et al., 2008).

Regional seismic sections across the São Francisco Basin (**Fig. 4**) reveal the presence of major incisions that cut through the top of the Espinhaço II sequence (Alkmim and Martins-Neto, 2012) on the eastern margin of the basin. The dimensions of these valleys range from ~1.5 to ~4 km width and ~100m to ~500 m depth. Their morphology is variable, including forms with flat bottoms and steep sides, and others with a characteristic “v” profile. Almost universally, deformation at the valley margins, in the form of downwarped strata below the incisions, is recognized (**Fig. 4**). Within the valleys, transparent seismofacies are characteristic. The scale of the palaeovalleys is exactly analogous to Sturtian incisions observed elsewhere, such as in Namibia (Le Heron et al., 2012) and in Oman (Van der Vegt et al., 2012).

Whilst further work is clearly required, we tentatively interpret the palaeovalleys as subglacial tunnel valleys. Their dimensions are analogous to Pleistocene examples of such incisions (Lonergan et al., 2006; Stewart and Lonergan, 2011), which are cut under hydrostatically elevated conditions beneath a retreating ice mass. Their dimensions bear a close resemblance to Sturtian examples previously interpreted as such (Le Heron et al., 2012). Furthermore, the downwarped strata at the valley margins are typical of subglacial incisions, with the deformation resulting from ice loading the substrate. The style of fill is presently uncertain, as the palaeovalleys are undrilled, although the seismic transparency of the fill may imply coarse (e.g. diamictite) fill. Assuming a stratigraphic position beneath the Bambuí, it is likely that the incisions are related to the Jequitaí glaciation. Even if the thickness of the Macaúbas Group where the palaeovalleys are imaged (**Fig. 4**) is not compatible with the average thickness of the Jequitaí Formation exposed in adjacent areas (~200 m, F. Alkmim pers. comm.), this unit tends to thinner to the centre of the basin (**Fig. 4**). Therefore, if there were palaeovalleys further inland, these would have been probably infilled with the Jequitaí and basal portion of the Sete Lagoas Formation (as in Martins-Ferreira et al., (2013)). Thus, these incisions are suggested to record the retreat of Jequitaí ice sheets (880 Ma, Rodrigues 2008), which took place during the late rift stage of the Macaúbas basin.

"Insert Supplementary Figure 4 here"

2.5 Bambuí Group

These epicontinental deposits, of alternating siliciclastics and carbonates are the most widely distributed unit in the São Francisco basin (**Fig. 1**), draping the Jequitaí diamictites and sandstones. They form a shallowing upwards sequence (Dardenne, 2000; Santos et al., 2000), divisible into three coarsening upward megacycles (**Fig. 5**;

Dardenne, 2000) clearly observed in seismic profile in the cratonic area of the São Francisco basin (Martins-Neto, 2009) **Fig. 6**. The first megacycle is represented by the Sete Lagoas Formation, the second includes the Serra de Santa Helena and Lagoa do Jacaré formations and the last cycle comprises the Serra da Saudade and Três Marias formations (Martins and Lemos, 2007).

"Insert Supplementary Figure 5 here"
"Insert Supplementary Figure 6 here"

The Sete Lagoas Formation, for which we present data in this paper, comprises a succession of pelitic-calcareous sediments, grading upwards into microcrystalline limestones and lately to dolostones. Its upper section contains the most extensive shallow water carbonates of the basin with laminated and columnar *Gymnosolenide* stromatolites (Dardenne, 1978) and evidence for subaerial exposure (Martins and Lemos 2007). Its basal contact is characterized by an unconformity: the formation rests on granite-gneiss basement, on the glaciogenic Jequitaí Formation, or on conglomerates of the Carrancas Formation, exposed along the southern border of basin (Dardenne, 2000, Alkmin and Martins-Neto, 2001, Vieira et al. 2007).

The absence of volcanic ash horizons throughout the Bambuí, in addition to hampering geochronology, has stimulated discussion regarding the tectonic setting for this group (e.g. Alkmim and Martins-Neto, 2001; Zalán and Silva, 2007) and its relationship with the Jequitaí diamictites (Babinski et al. 2007, 2012; Misi et al., 2011; Caxito et al., 2012). A large suite of isotopic and chemostratigraphic data are available (e.g. Iyer et al, 1995; Babinski et al 1999, D'Agrella-Filho et al., 2000; Santos et al., 2000; Misi et al, 2007; Vieira et al. 2007), yet its depositional age remains unknown. A Pb-Pb age of 740 ± 22 Ma (**Fig. 5**) from basal carbonates of the Sete Lagoas Formation (Babinski et al. 2007) is the only published estimate for its depositional age. In tandem with stable isotope analysis, this date led Babinski et al. (2007) and Vieira et al. (2007) to propose that the Sete Lagoas is a post-Sturtian cap carbonate. These interpretations contrast sharply with maximum depositional ages from U-Pb detrital zircons in the upper Sete Lagoas pelites (610 Ma) (**Fig. 5**), and from the overlying Serra de Santa Helena (650 Ma) and Serra da Saudade (612 Ma) respectively (Rodrigues, 2008).

Detrital zircons from the underlying Jequitaí Formation yield a maximum depositional age of 880 Ma (Rodrigues, 2008), loosely supporting potential correlation with the Sturtian glaciation, even if the depositional age of the Bambuí Group, and specifically the Sete Lagoas Formation, remains highly contentious. The different ages suggest a substantial hiatus. On the other hand, identical typically Ediacaran $^{87}Sr/^{86}Sr$ values (0.7074-0.7076) are obtained both below and above the unconformity thus arguing against a long hiatus (Caxito et al., 2012). The latter authors thus interpret most of the Sete Lagoas as Ediacaran in age, with its basal strata a cap carbonate deposited following the end-Cryogenian (Marinoan) glaciation.

From the above, it is clear that despite the importance in regional and global studies of the Proterozoic, the understanding of the Sete Lagoas Formation sequence still suffers from a lack of precise and accurate radiometric ages.

3. Geochemistry and Re-Os geochronology methodology

3.1 Sampling

Samples of the 3 formations in this study were collected from proprietary drill cores (**Fig. 1**). The Paracatú and Serra do Garrote formations cores were provided by Votorantim Mine, and a mine company from the Arcos region supplied the Sete Lagoas Formation samples. In the MASW03 (Paracatú) core (**Fig. 7**) the sampled interval spans 47.10 to 55.70 m (MD) and include dark grey to black slates, with sporadic quartz as thin veins together with pyrite. VZCF001 (Serra do Garrote) core samples (**Fig. 8**) extend from 280.10 to 292.65 m and include black slates, with considerable carbonaceous material (staining). Pyrite is present, both as lamina-parallel mineralization, and as crosscutting veins and framboid nodules. Finally, LMR1009 (Sete Lagoas) core samples (**Fig. 9**) were obtained from four intervals; 1, from 36-47 m (microbial dolomite and mudstones); 2, from 111-118 m (laminated limestones with carbonaceous seams); 3, from 144-157 m (clay-rich limestones); 4, from 158-165 m (argillites). Following Kendall et al. (2009a), ~100g samples were collected at 1 m intervals in each core. Sub-sampling at further 0.4 m intervals was undertaken to detect further changes in Re and Os abundance and isotope composition. Care was taken to avoid zones of hydrothermal alteration and mineralization.

3.2 Total organic carbon (TOC)

TOC values for the all samples were determined at the School of Civil Engineering and Geoscience of Newcastle University, UK. An accurately weighed 0.1 g of powdered rock was digested in hot (60-70°C) hydrochloric acid (4 mol/L) to remove the inorganic (carbonate) carbon. The decarbonated and washed samples (in deionised water) were then dried overnight in an oven at 65°C. The organic carbon in the decarbonated samples was determined using a Leco CS230 Carbon-Sulphur analyser (previously calibrated on standard samples), which combusted the sample in pure oxygen. Any carbon present was fully oxidized and converted to CO_2 and the gaseous phase was passed into an infrared detector, which measures the mass of CO_2 present and converts it to percent carbon based on the dry sample weight.

3.3 Re-Os geochronology

For Re-Os analysis, the core samples were polished to eliminate any metal contamination (e.g. cutting and drilling marks). Each sample was dried at 60 °C for 24h and then crushed to a powder (c. 30 μm) in a zirconium dish using an automated shatterbox. Rhenium and Os isotope analyses were carried out at Durham University's TOTAL laboratory for source rock geochronology and geochemistry at the Northern Centre for Isotopic and Elemental Tracing (NCIET) using methods outlined in Selby and Creaser (2003) and Selby (2007). Between 0.2 and 0.4 g of each sample was digested and equilibrated in a borosilicate carius tube in 8 ml of Cr^{VI}–H_2SO_4 together with a mixed tracer (spike) solution of ^{190}Os and ^{185}Re at 220 °C for 48 h. The Cr^{VI}–H_2SO_4 solution was used to liberate hydrogenous Re and Os, restricting the incorporation of non-hydrogenous Re and Os (Kendall et al., 2004). Solvent extraction ($CHCl_3$) for Re and Os purification, micro-distillation and anion chromatography methods were employed as outlined by Cumming et al., (2013). The purified Re and Os fractions were loaded onto Ni and Pt filaments, respectively (Selby, 2007), with the isotopic measurements determined by Negative Thermal Ionization Mass Spectrometry using a Thermo Electron TRITON mass spectrometer via static Faraday collection for Re and ion-counting using a secondary electron multiplier in peak-hopping mode for Os. Total procedural blanks during this study were 14.6 ± 0.16 pg and 0.05 ± 0.01 pg (1σ S.D., n = 3) for Re and Os, respectively, with an average $^{187}Os/^{188}Os$ value of 0.61 ± 0.03 (n = 3). Uncertainties for $^{187}Re/^{188}Os$

and $^{187}Os/^{188}Os$ were determined by error propagation of uncertainties in Re and Os mass spectrometer measurements, blank abundances and isotopic compositions, spike calibrations and reproducibility of standard Re and Os isotopic values. The Re–Os isotopic data including the 2σ calculated uncertainties for $^{187}Re/^{188}Os$ and $^{187}Os/^{188}Os$ and the associated error correlation function (rho) were regressed to yield a Re–Os date using Isoplot V. 4.0 and the λ ^{187}Re constant of 1.666 × 10-11a-1 (Smoliar et al., 1996; Ludwig, 2003). The age uncertainty including the uncertainty of 0.35 % in the ^{187}Re decay constant only affects the third decimal place (Smoliar et al., 1996; Selby, 2007).

To evaluate mass spectrometry reproducibility, two in-house Re and Os (Durham Romil Osmium Standard = DROsS) solution standards were analyzed. The Re solution standard yields an average $^{185}Re/^{187}Re$ ratio of 0.598071 ± 0.001510 (1 S.D., n = 67), which is in agreement with the value reported for the AB-1 standard (Rooney et al., 2010). The measured difference in $^{185}Re/^{187}Re$ values for the Re standard solution and the accepted $^{185}Re/^{187}Re$ value (0.5974; Gramlich et al., 1973) is used to correct the measured sample Re isotope composition. The Os isotope reference solution (DROsS) gave an $^{187}Os/^{188}Os$ ratio of 0.160892 ± 0.000559 (1 S.D., n = 67), which is in agreement with previous studies (Rooney et al., 2010).

4. Results

4.1 TOC

The TOC results for all samples are presented in **Table 1** and **Fig. 7, 8** and **9**. The Sete Lagoas Formation has the lowest TOC of the 3 analyzed cores (<0.01 to 0.49 wt%), while the Serra do Garrote and Paracatú formations possess the highest TOC values (0.75 to 2.12% and 0.07 to 2.15 wt% respectively). According to these samples, the basin possesses fair quality as a potential hydrocarbon source rock, both in carbonates and shales (c.f. Craig et al., 2012). As Re-Os geochronology has been applied successfully to rocks with 0.5% TOC (Kendall et al. (2004), this cut off was used to select the samples for Re-Os analysis. Whole rock Rock-Eval pyrolysis (Espitalié et al., 1977) permits rapid evaluation of the organic matter type, quantity and maturity, however a minimum amount of organic matter is needed to obtain reliable results. As only the samples from the Paracatú and Serra do Garrote formations provided ≥1wt% TOC (**Fig. 7** and **8**), in low-grade metamorphic rocks, maturation analyses (Rock Eval) were not performed.

"Insert Supplementary Figure 7 here"
"Insert Supplementary Figure 8 here"
"Insert Supplementary Figure 9 here"
"Insert Supplementary Table 1 here"

4.2 Paracatú Slate Formation: Re-Os data

The Paracatú Slate samples have Re (0.3 – 4.1 ppb) and Os (53 – 297 ppt) abundances (**Table 2**) that are close to or less than that of average continental crustal values of 1 ppb and 50 ppt, respectively (Esser and Turekian, 1993; Peucker-Ehrenbrink and Jahn, 2001; Hattori et al., 2003). The $^{187}Re/^{188}Os$ ratios display a limited range from 24.2 to 79.6 and present-day $^{187}Os/^{188}Os$ ratios range from 0.667 to 1.593 (**Table 2**). Regression of the Re–Os isotope data yield a Re–Os age of 1002 ± 45 Ma (2σ, n=4, Model 1, Mean Square of Weighted Deviates [MSWD] = 1.2, initial $^{187}Os/^{188}Os$ = 0.25 ± 0.04; **Fig. 10**).

"Insert Supplementary Table 2 here"
"Insert Supplementary Figure 10 here"

4.3 Serra do Garrote Formation: Re-Os data

The Serra do Garrote slates are enriched in Re (4 – 28 ppb) and Os (137 – 585 ppt; **Table 2**) and present a large spread in $^{187}Re/^{188}Os$ ratios (205.1 - 601.2) and $^{187}Os/^{188}Os$ ratios (3.628 - 12.207) (**Fig. 10**). Replicate analysis of one Serra do Garrote sample (VZCF-6r) show good reproducibility in Re and Os abundances and $^{187}Re/^{188}Os$ and $^{187}Os/^{188}Os$ ratios. Contrary to the Paracatú Formation, the regression of the isotope data for the Serra do Garrote Formation yields an imprecise, Model 3 age of 1304 ± 210 Ma with a negative initial Os isotope composition of -1.0 ± 1.4 and an MSWD = 96.

4.4 Sete Lagoas Formation: Re-Os data

The samples of the Sete Lagoas Formation are strongly depleted in Re, with abundances <100 ppt, which are lower than estimated average (present-day) upper continental crust and were not investigated further.

5. Discussion

5.1 Paracatú Formation

New Re–Os geochronology for the Paracatú Formation yields a depositional age of 1002 ± 45 Ma, which is in agreement, within uncertainty, of U–Pb geochronology (detrital zircons ca. 1040 Ma; Valeriano et al. 2004; Rodrigues et al., 2010). This relatively precise age represents the first successful application of the Re–Os system in samples of this Group and the first direct depositional age geochronometer. The new Re–Os geochronology data adds credence to previous studies that suggest that there is no significant disturbance in the Re-Os systematics of carbonaceous organic-rich rocks which have experienced low degree of metamorphism (Kendall et al., 2004; Rooney et al., 2011).

Based on our Re-Os data, the Canastra Group was deposited at or around the Meso-Neoproterozoic boundary. This endorses tectonostratigraphic models of a passive margin sequence, deposited along the SW margin of the São Francisco-Congo paleocontinent (Pimentel et al., 2001, 2011; Rodrigues et al., 2010). The dates place the Canastra Group as considerably younger than the early Mesoproterozoic Paranoá Group (Matteini et al., 2012), with which it has been previously correlated.

The Osi value for seawater at the time of deposition of the Paracatú Formation (0.25) is much less radiogenic than the present day value (~1.06; Levasseur et al., 1998) indicating that the dominant input of Os to seawater was unradiogenic. This Osi value is consistent with marine Os budget dominated by extraterrestrial and ultramafic-mafic magmatic / hydrothermal inputs with minor contribution of dissolved radiogenic crustal Os, as has been demonstrated for Mesoproterozoic seawater Os isotope composition (Kendall et al., 2009a; Rooney et al., 2010). Additionally, there is a close similarity in Osi values from the Paracatú Formation with the Lapa deposits (0.33 ± 0.30; Azmy et al. 2008). The Paracatú Formation Osi provides an important additional datapoint to that available for Precambrian seawater, indicating that the change in global patterns of oxidative weathering and Os influx was of little importance, at least until the Tonian.

Considering the amount of organic matter preserved even after maturation, it is likely that the Paracatú Formation of the Canastra Group constituted an extensive hydrocarbon source rock. Despite no remaining potential for further hydrocarbon generation, it is not implausible that between deposition (~1000 Ma) and prior to the last tectono-metamorphic event recognised in the Brasília Belt (ca. 600 Ma; Pimentel et al., 1999), the rock expelled hydrocarbons. However, the data available is insufficient to determine the precise timing of generation / migration, as the intense deformation during the Brasiliano-Pan African events and the posthumous erosion has obliterated true stratigraphic thicknesses and has conditioned seismic imaging.

5.2 Serra do Garrote Formation

Although the Paracatú Formation experienced regional metamorphism, these samples yield a nominally precise depositional age with a low degree of scatter about the linear regression of the Re–Os data (1002 ± 45 Ma, MSWD = 1.2). In contrast, the Serra do Garrote Formation which has also experienced regional Brasiliano metamorphic event (Dardenne, 2000) show a large scatter about the Re–Os regression line (Model 3, 1304 ± 210, MSWD = 96) together with a negative initial Os isotope composition (-1.0 ± 1.4) suggestive of disturbances to the Re–Os systematics. This imprecise age may result from either depositional and/or post-depositional processes. The presence of detrital Os with variable initial $^{187}Os/^{188}Os$ composition, which tends to induce imprecise and geologically meaningless ages (Kendall et al., 2004, 2009a), is considered unlikely because the Cr^{VI}-H_2SO_4 digestion technique used in this study has successfully allowed the generation of Model 1 ages for organic-rich rocks containing low Re and Os abundances (Kendall et al., 2004, 2006, 2009a; Rooney et al., 2011). Another feasible cause of geological uncertainty for the Re-Os systematics can be represented by variations in seawater Os isotope compositions during deposition (Selby and Creaser, 2003). In order to avoid heterogeneity in the contemporaneous seawater Os isotope composition, short stratigraphic sampling intervals (~0.6 m) were used. Os isotope composition, however, show variations that span far beyond those expected from temporal evolution in seawater (unless sedimentation rates were anomalously low). Thus, these variations may not fully account for the complex Re–Os systematics in the Serra do Garrote Formation.

Weathering and metamorphism are unlikely explanations for the scattered Re-

Os isotope systematics because drill core samples were used for the analysis. Additionally, metamorphic conditions of the Serra do Garrote Formation related to the Brasiliano-Pan African Orogeny did not exceed greenschist facies (Dardenne, 2000; Misi et al., 2005, 2007). Petrologic evidence (coarse pyrite aggregates, quartz veinlets and pervasive faulting and fracturing) suggests the Serra do Garrote Formation has been affected by hydrothermal fluid flow. Although we avoided sampling material with abundant quartz veins, the scatter in the Re–Os regressions for the Serra do Garrote Formation and the Osi signature of the samples is indicative of a hydrothermal alteration origin, implying that there might have been some mobilization of Re and Os by fluid flow. Similar Re-Os behavior has been observed by Rooney et al., (2011) for the Leny Limestone and by Kendall et al., (2009b) for the Wollogorang Formation. Although the Vazante Ore deposit is located in the overlying Serra do Poço Verde Formation (Soares Monteiro et al., 2006), we do not discount the possibility that the same mineralizing and oxidant fluids may have affected the unit under study due to the proximity of well VZCF001 to brecciated metadolomites and epigenetic willemitic ore bodies along the Vazante Shear Zone (**Fig. 1B**). Therefore, it is possible that the high-temperature (> 250°C), oxidizing and moderate saline (~ 15 wt. % NaCl equiv.) brines that leached base metals from the basement and ascended to finally interact with the host dolostones of the Serra do Poço Verde (Monteiro et al., 2003; Misi et al., 2005) have hydrated the Serra do Garrote slates, resulting in disturbance of the Re–Os geochronometer.

It is likely that the extensive hydrothermal activity recorded in the Vazante Group, and associated with the abundant Zn deposits (Soares Monteiro et al., 2006) had intrinsic relation with hydrocarbon generation, possibly sourced by the Serra do Garrote Formation. Pyrobitumen has been observed within hydrothermal veins in the carbonates of the overlying Morro do Calcário Formation (Rubo and Soares Monteiro, 2010; Tonietto, 2011) and hydrocarbon inclusions were described in sulfides of the Vazante ore deposit (L. Soares Monteiro pers. comm.). Future dating of these hydrocarbon products with the ^{187}Re-^{187}Os radioisotope system (e.g., Selby and Creaser, 2005b) could help constraining the timing of emplacement, the source of migrated hydrocarbons and the temporal relation of the mineralization and hydrocarbon accumulation.

5.3 Sete Lagoas Formation

The lack of Re in the carbonate of the Sete Lagoas could be intrinsically associated with the low TOC observed for the unit. Re and Os are organophilic and redox-sensitive, therefore in reducing pore waters Re is removed at the sediment–water interface, remaining physically associated with organic matter (Selby & Creaser 2003, Kendall et al., 2004, 2009a and refs therein). If the sediments lacked enough organic matter and / or if the environment of deposition was neither euxinic nor anoxic, it is likely that hydrogenous Os was not incorporated into the sediments. On the other hand, the observed low organic content can also be related to thermal maturation (Peters and Cassa, 1994) which may cause as a loss of 30-50% of the assumed original amount of TOC (Buchardt et al., 1986). With the intention of accounting for the effects of maturation, biomarkers studies were performed by the author. However, results proved inconclusive likely due to low volumes of organic matter analysed.

Several isotopic studies have demonstrated negative excursion of $\delta^{13}C$ and ^{18}O for the base of the Sete Lagoas Formation (Alvarenga et al., 2007; Kuchenbecker, 2011). This behaviour, together with its stratigraphic position, sitting on top of the Jequitaí diamictite deposits, led to interpretations of a typical postglacial cap carbonate sequence related either to Sturtian (Babinski et al. 2007; Babinski and Kaufman, 2003) or Marinoan (Caxito et al., 2012) deglaciation.

The recognition of palaeovalleys on seismic and outcrop data (Martins-Ferreira et al. 2013) and information of their infill with the Jequitaí Diamictites and Bambuí dolomites has important implications. Bechstädt et al. (2009) provided TOC data from the Maieberg Formation in northern Namibia, a laminated cap dolostone sitting on top of the Ghaub Formation diamictite, and which corresponds to a late Cryogenian ("Marinoan") glacial deposit. Noting that there is local enrichment of TOC in the dololaminites, Bechstädt et al. (2009) draw on analogues of deglaciation from the Lower Palaeozoic of North Africa to explain this phenomenon. Deglaciation from the Hirnantian ice age left behind a complex, glacially sculpted topography produced by a combination of subglacial abrasion and meltwater. Accumulation of organic material, with primary productivity stimulated by meltwater release and aeolian dust (Gabbott et al. 2010), occurred. During transgression, however, palaeovalleys were flooded first. Initially, these were disconnected from one another, and thus euxinic to anoxic conditions developed. Later during the transgression, organic-lean shales were deposited as circulation resumed and palaeovalleys were overspilled (Lüning et al., 2000). The presence of lingering ice sheets lowered the preservation potential of organic material, because oxygen-rich brines released during sea ice production diminish euxinia at the sea floor (Le Heron et al., 2013). Thus, by analogy, the distribution of TOC enrichment in Cryogenian post-glacial deposits has been hard to predict (Bechstädt et al. 2009). If the base of the Sete Lagoas Formation was deposited under these circumstances, some of the complex factors linked to restricted / open circulation within / out palaeovalleys may explain oxidizing versus anoxic conditions for organic preservation and associated Rhenium complexation. The lack of diamictites underlying the carbonates of the Sete Lagoas Formation in well LMR1009 (opposed to other cores of the region; F. Pimenta pers. comm.) could indicate its position away from a paleodepression (**Fig. 11**), justifying the low TOC values observed in this particular location. This interpretation can only be tentative, however, because the location of the well used for this analysis is not imaged in seismic section. Nevertheless, considering that post-glacial shales in North Africa, have charged more than 50 major oil and gas fields (Lu□ning et al., 2000), and that enrichment of up to ~6%TOC has been reported in other parts of the basin for the Sete Lagoas Formation (Iyer et al., 1995), it is likely that post-Jequitaí sediments might represent a hydrocarbon source rock interval.

"Insert Supplementary Figure 11 here"

6. Conclusions

- New Re–Os geochronology for the Paracatú Formation yields a depositional age of 1002 ± 45 Ma and is in agreement, within uncertainty, of U–Pb detrital geochronology. This relatively precise age coupled with the excellent linear fit of the Re–Os isotope data provides a more precise chronostratigraphic framework for understanding the tectonic evolution of the Canastra Group and the onset of sedimentation within the basin.

- Disturbance of Re–Os systematics in the Serra do Garrote Formation is evident by a very imprecise and inaccurate age along with a negative value for the Osi value. These factors together with petrological evidence strongly suggest that the Re–Os system was disturbed in response to hydrothermal fluid flow, possibly associated with the mineralized bodies of the Vazante ore deposits. The circulation of fluids through the Vazante Group is suggested to be the cause for the gain of Re and Os and loss of reliable depositional age information. Care is consequently necessary when applying the Re–Os deposition-age geochronometer to sedimentary rocks subject to tectonic deformation and affected by hydrothermal fluids.

- The lack of Rhenium enrichment in the base of the Sete Lagoas Formation could be explained by the control on the distribution of the organically enrich facies which, similarly to the Early Silurian deglacial shales (Lu□ning et al., 2000), was inherited from glacial topography, and is directly related to incisions cut during ice advance and ice retreat.

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Figure Captions

Figure 1: Location and geology of the study area. A – São Francisco Craton, São Francisco Basin and surrounding belts (BFB=Brasilia Fold belt; Araçuaí Fold Belt). B - Simplified geological map of the Brasília Belt (after Dardenne, 2000).

Figure 2: Lithostratigraphic column of the Canastra Group (modified from Dardenne, 2000). Youngest concordant age interpreted as maximum depositional age ([1] Rodrigues et al., 2010).

Figure 3: Lithostratigraphic column of the Vazante Group (modified from Dardenne, 2000). Youngest concordant age interpreted as maximum depositional age ([1] Rodrigues et al., 2012) and Re-Os isochron interpreted as depositional age ([2]Geboy, 2006; [3]Azmy et al., 2008).

Figure 4: Seismic interpretation of the São Francisco Basin, with tunnel valleys and downwarped strata developed on the Espinhaço II Sequence.

Figure 5: Lithostratigraphic column of the Bambuí Group (modified from Dardenne, 2000). Youngest concordant age interpreted as maximum depositional age ([1] Rodrigues, 2008) and Pb-Pb isochron interpreted as depositional age ([2]Babinski et al.,2007).

Figure 6: Seismic profile in the cratonic area of the São Francisco basin showing the expression of the three shallowing-upward 2nd order sequences of the Bambuí 1st order sequence (based on Martins-Neto, 2009)

Figure 7: Stratigraphic levels of the Paracatú slate samples used for TOC and Re–Os measurements.

Figure 8: Stratigraphic levels of the Serra do Garrote slate samples used for TOC and Re–Os measurements.

Figure 9: Stratigraphic levels of the Sete Lagoas samples used for TOC and Re–Os measurements.

Figure 10: Re–Os isochron diagram for the Paracatú Formation organic-rich slates, drillhole MASW03.

Figure 11: Tentative explanation for variance of depositional TOC across the basal Sete Lagoas Formation. Core A would represent well LMR1009.

Tables

Table 1: TOC content for the Canastra, Vazante and Bambuí groups.

Table 2: Re-Os isotope data for the Paracatú and Serra do Garrote formations. *Rho is the associated error correlation at 2σ (Ludwig, 1980). [§]Osi is the initial $^{187}Os/^{188}Os$ isotope ratio calculated at 1002 Ma for the Paracatú Formation and 1300 Ma for the Serra do Garrote Formation. VZCF-6r is a repeat analysis and was not included in the

regression

Table

Formation	Sample	Depth [m]	TOC [wt%]
Serra do Garrote	VZCF001-1	280.23	0.85
	VZCF001-2	281.33	1.53
	VZCF001-3	281.55	0.07
	VZCF001-4	281.78	2.15
	VZCF001-5	282.00	0.87
	VZCF001-6	282.23	2.10
	VZCF001-7	285.78	0.72
	VZCF001-8	286.63	0.20
	VZCF001-9	287.78	0.93
	VZCF001-10	288.43	1.48
	VZCF001-11	288.98	0.62
	VZCF001-12	289.15	1.98
	VZCF001-13	289.60	1.50
	VZCF001-14	289.98	1.38
	VZCF001-15	292.55	1.89
Paracatú	MASW03-33	47.6	2.12
	MASW03-34	48.0	1.76
	MASW03-35	48.3	1.75
	MASW03-36	48.6	1.56
	MASW03-37	49.9	1.48
	MASW03-38	50.4	1.03
	MASW03-39	50.7	1.42
	MASW03-40	51.0	0.92
	MASW03-41	52.3	1.23
	MASW03-42	52.6	1.19
	MASW03-43	52.9	1.16
	MASW03-44	53.2	0.99
	MASW03-45	53.5	1.59
	MASW03-46	55.6	0.75
	MASW03-47	55.9	1.13
Sete Lagoas	LIMR1009-U4S15	35.85	0.08
	LIMR1009-U4S14	36.85	0.17
	LIMR1009-U4S13	37.85	0.03
	LIMR1009-U4S12	38.85	0.05
	LIMR1009-U4S11	39.85	0.02
	LIMR1009-U4S10	40.85	0.04
	LIMR1009-U4S9	41.85	0.02
	LIMR1009-U4S8	42.85	0.04
	LIMR1009-U4S7	43.85	0.10
	LIMR1009-U4S6	44.85	0.03
	LIMR1009-U4S5	45.85	0.04
	LIMR1009-U4S4	46.25	0.02
	LIMR1009-U4S3	46.65	0.01
	LIMR1009-U4S2	47.05	0.02
	LIMR1009-U4S1	47.57	0.01
	LIMR1009-U3S8	112.34	0.01
	LIMR1009-U3S7	113.34	0.01
	LIMR1009-U3S6	114.34	0.02
	LIMR1009-U3S5	115.34	0.08
	LIMR1009-U3S4	116.34	0.01
	LIMR1009-U3S3	116.74	0.04
	LIMR1009-U3S2	117.14	0.03
	LIMR1009-U3S1	117.54	0.02
	LIMR1009-U2S15	145.75	0.00
	LIMR1009-U2S14	146.75	0.00
	LIMR1009-U2S13	147.75	0.00
	LIMR1009-U2S12	148.75	0.02
	LIMR1009-U2S11	149.75	0.00
	LIMR1009-U2S10	150.75	0.02
	LIMR1009-U2S9	151.75	0.08
	LIMR1009-U2S8	152.75	0.00

	LIMR1009-U2S7	153.75	0.01
	LIMR1009-U2S6	154.75	0.01
	LIMR1009-U2S5	155.75	0.00
	LIMR1009-U2S4	156.15	0.01
	LIMR1009-U2S3	156.55	0.06
	LIMR1009-U2S2	156.95	0.02
	LIMR1009-U2S1	157.35	0.13
	LIMR1009-U1S1	158.15	0.32
	LIMR1009-U1S2	158.55	0.22
	LIMR1009-U1S3	158.95	0.24
	LIMR1009-U1S4	159.35	0.24
	LIMR1009-U1S5	159.75	0.22
	LIMR1009-U1S6	160.75	0.06
	LIMR1009-U1S7	161.75	0.36
	LIMR1009-U1S8	162.75	0.14
	LIMR1009-U1S9	163.75	0.49
	LIMR1009-U1S10	164.75	0.33

Table

Sample	Re (ppb)	±	Os	±	$^{187}Re/^{188}Os$	±	$^{187}Os/^{188}Os$	±	Rho*	Osi§
Paracatú										
MASW03-36	0.30	0.001	64.8	1.2	24.2	0.3	0.667	0.038	0.705	0.260
MASW03-38	0.36	0.001	52.7	1.0	36.1	0.7	0.847	0.030	0.705	0.239
MASW03-40	4.11	0.013	296.5	2.1	79.6	0.8	1.593	0.040	0.656	0.253
MASW03-42	1.31	0.004	175.1	1.0	39.8	0.6	0.934	0.030	0.654	0.264
Serra do Garrote										
VZCF-6	18.7	0.06	507.2	5.2	317.9	2.8	6.167	0.070	0.656	-0.793
VZCF-6r	18.9	0.06	515.7	9.3	314.3	6.4	6.136	0.174	0.698	-0.746
VZCF-11	9.2	0.03	260.2	2.5	269.9	2.4	4.654	0.053	0.657	-1.255
VZCF-13	28.3	0.09	584.6	7.0	601.2	5.2	12.207	0.139	0.656	-0.956
VZCF-3B	4.0	0.01	136.8	2.2	205.1	4.2	3.628	0.103	0.699	-0.862

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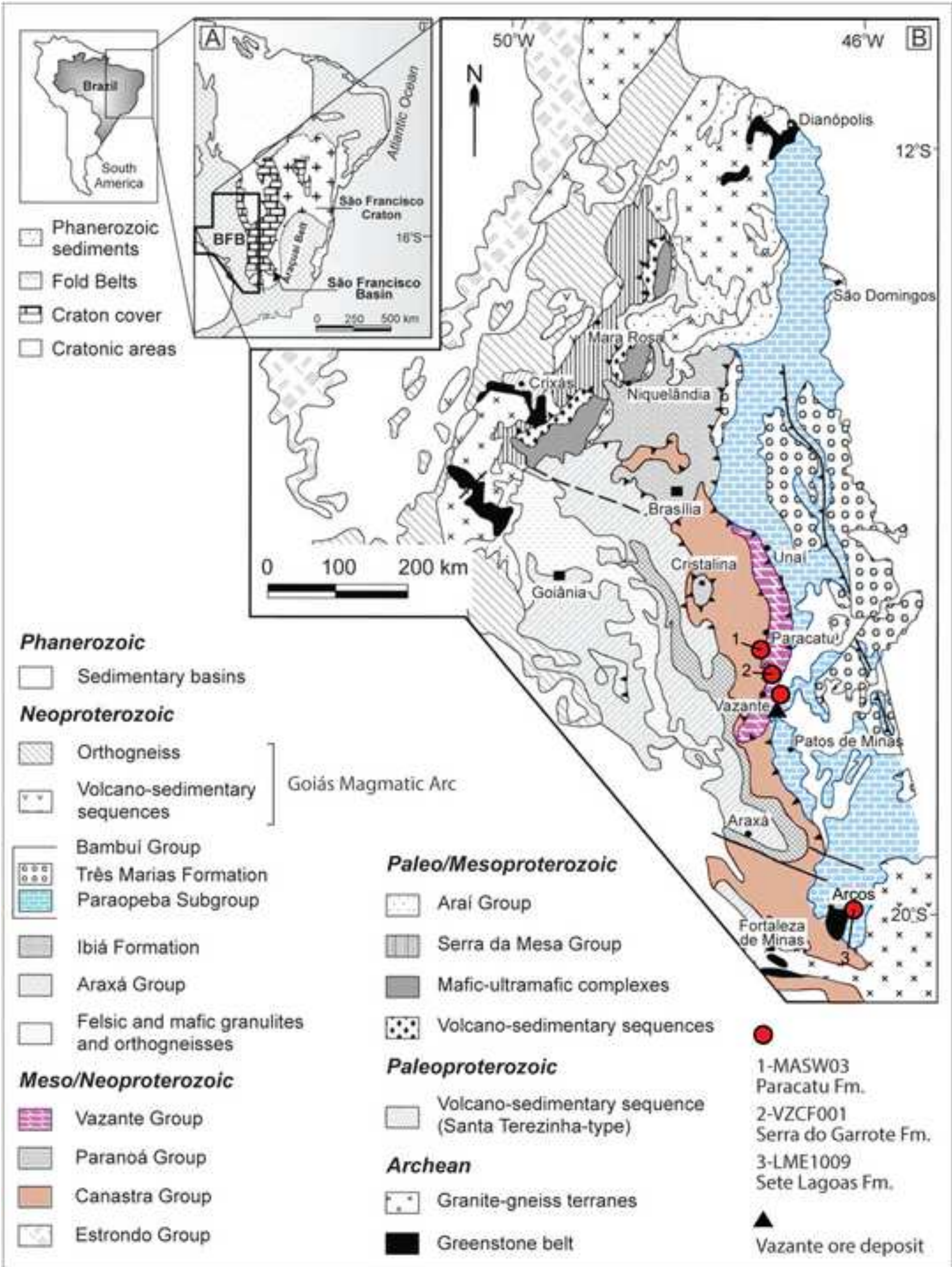

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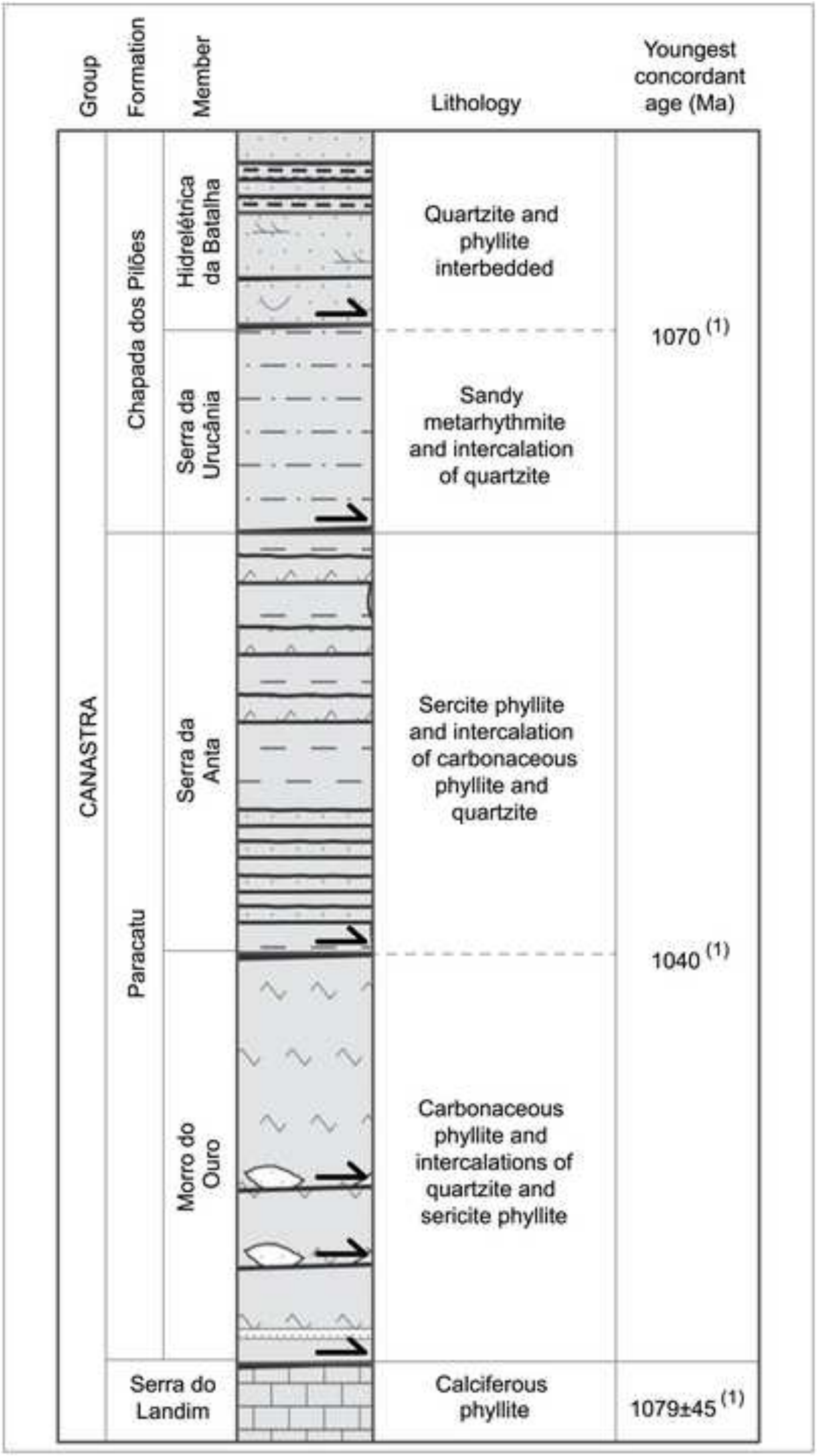

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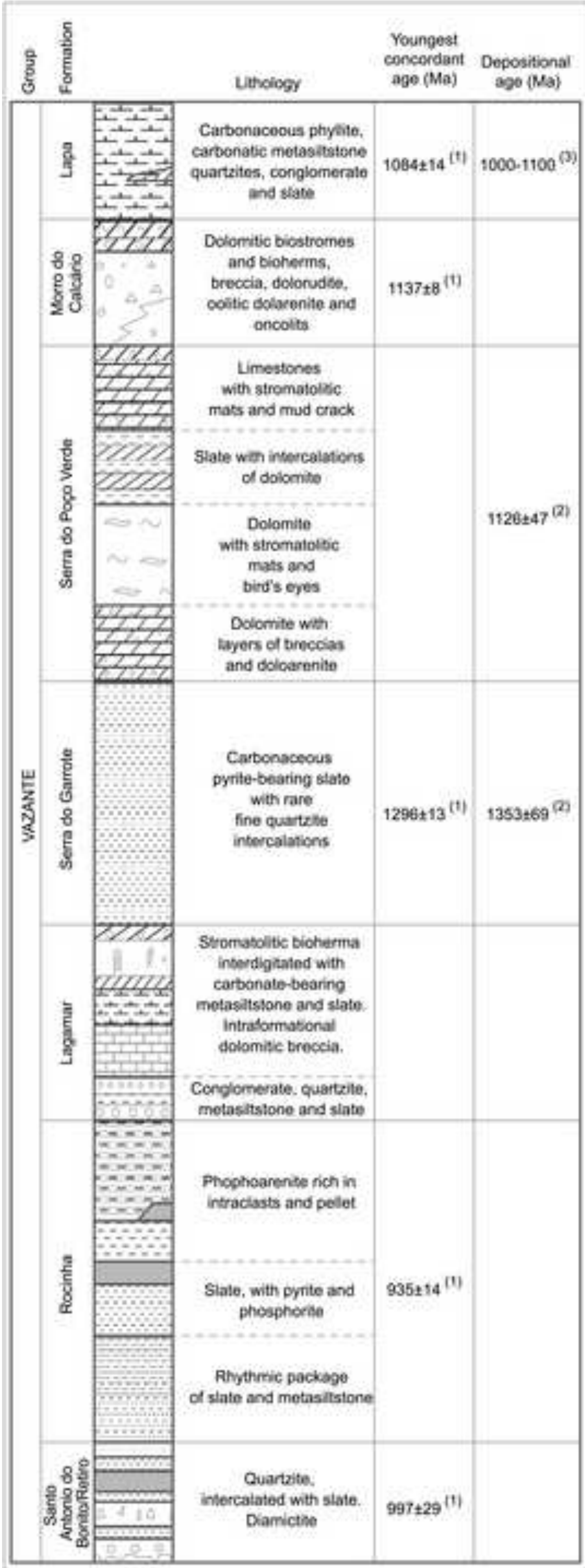

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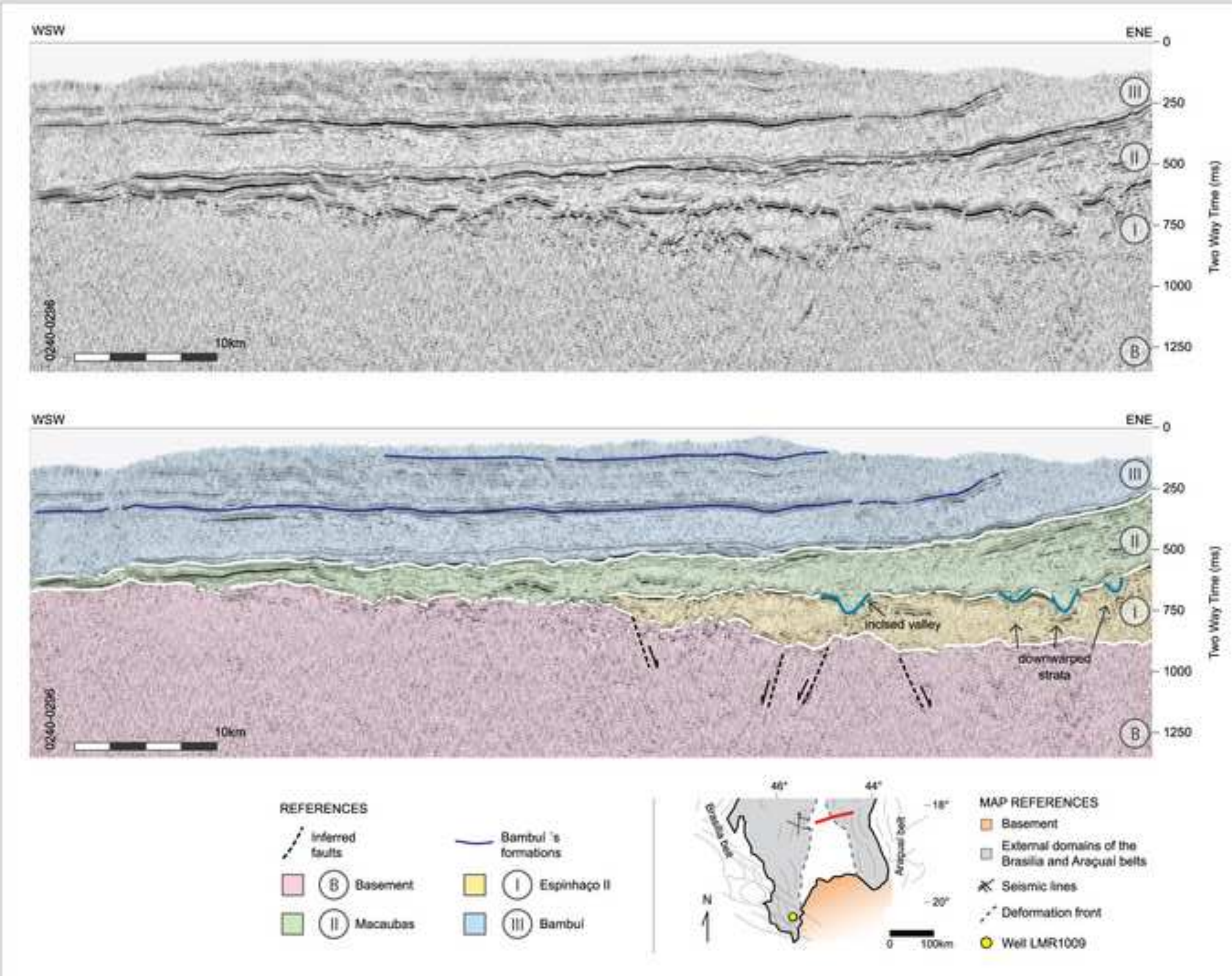

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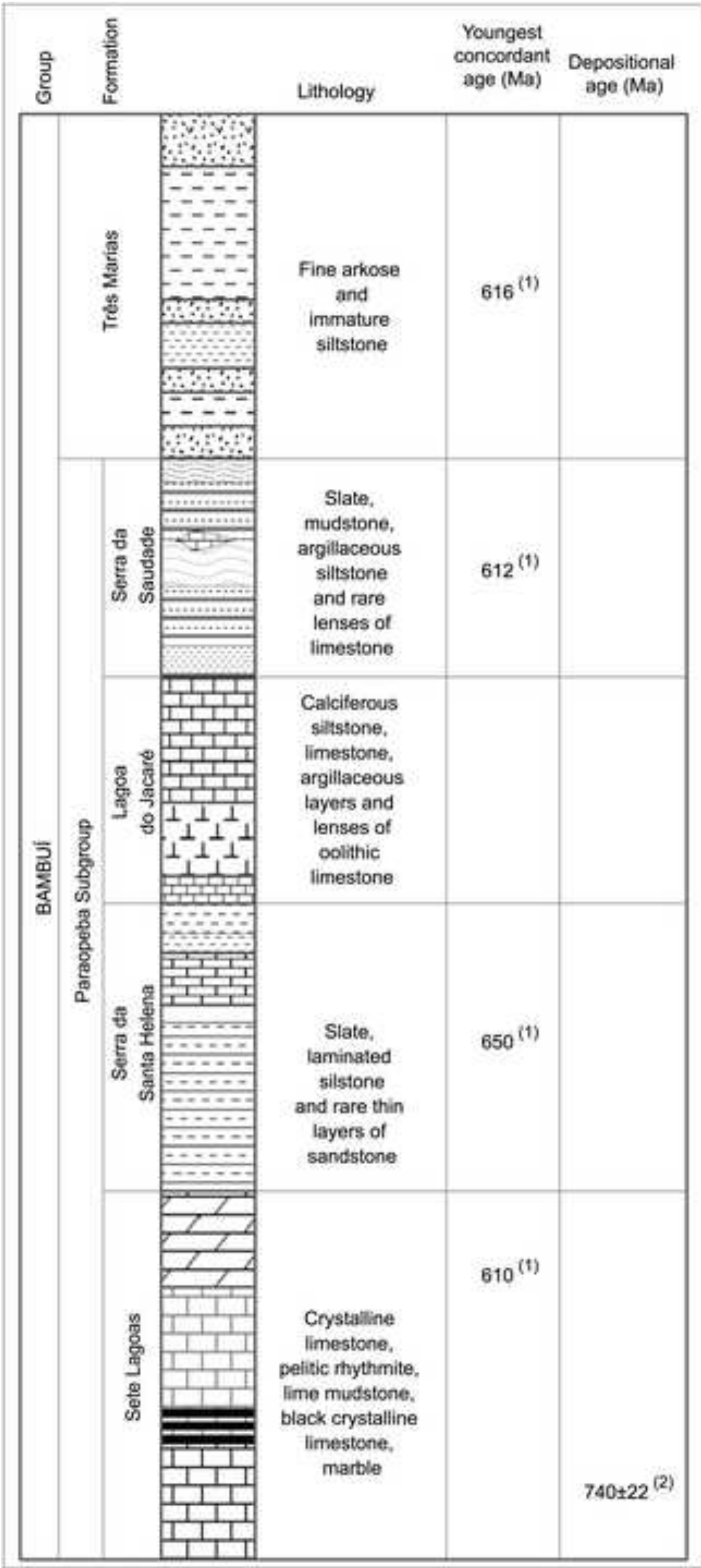

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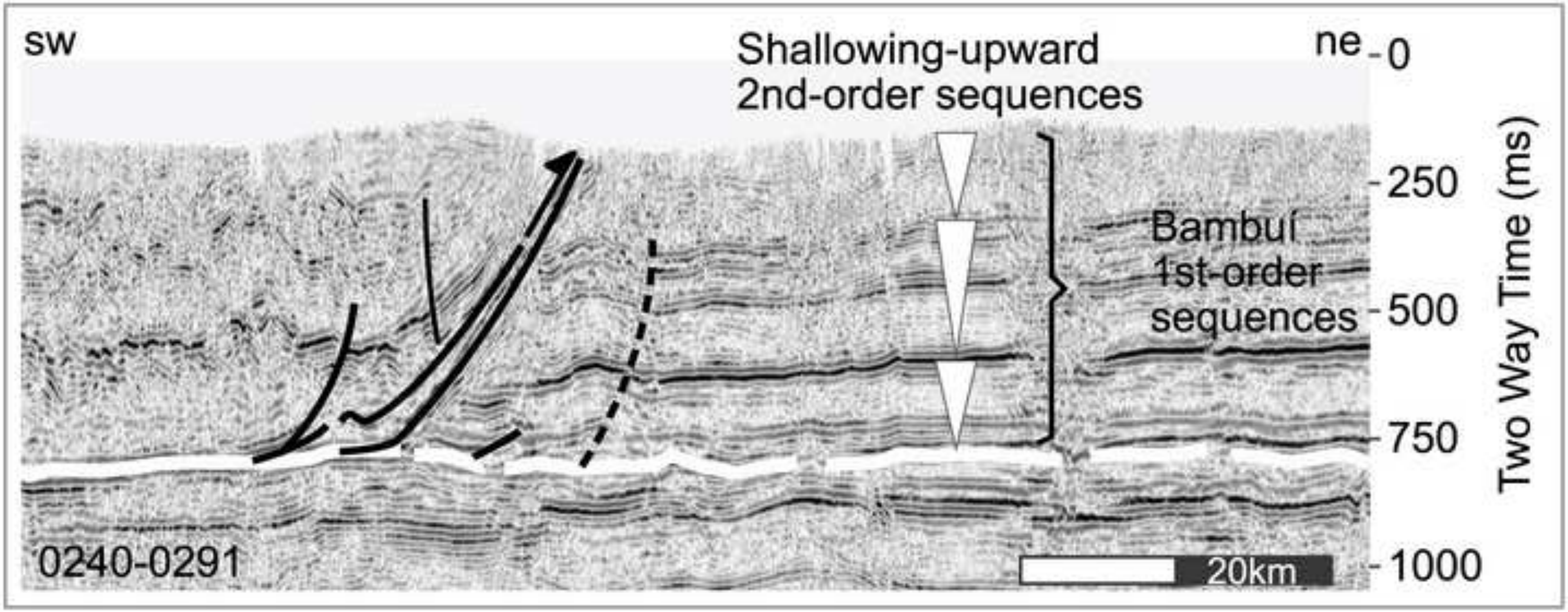

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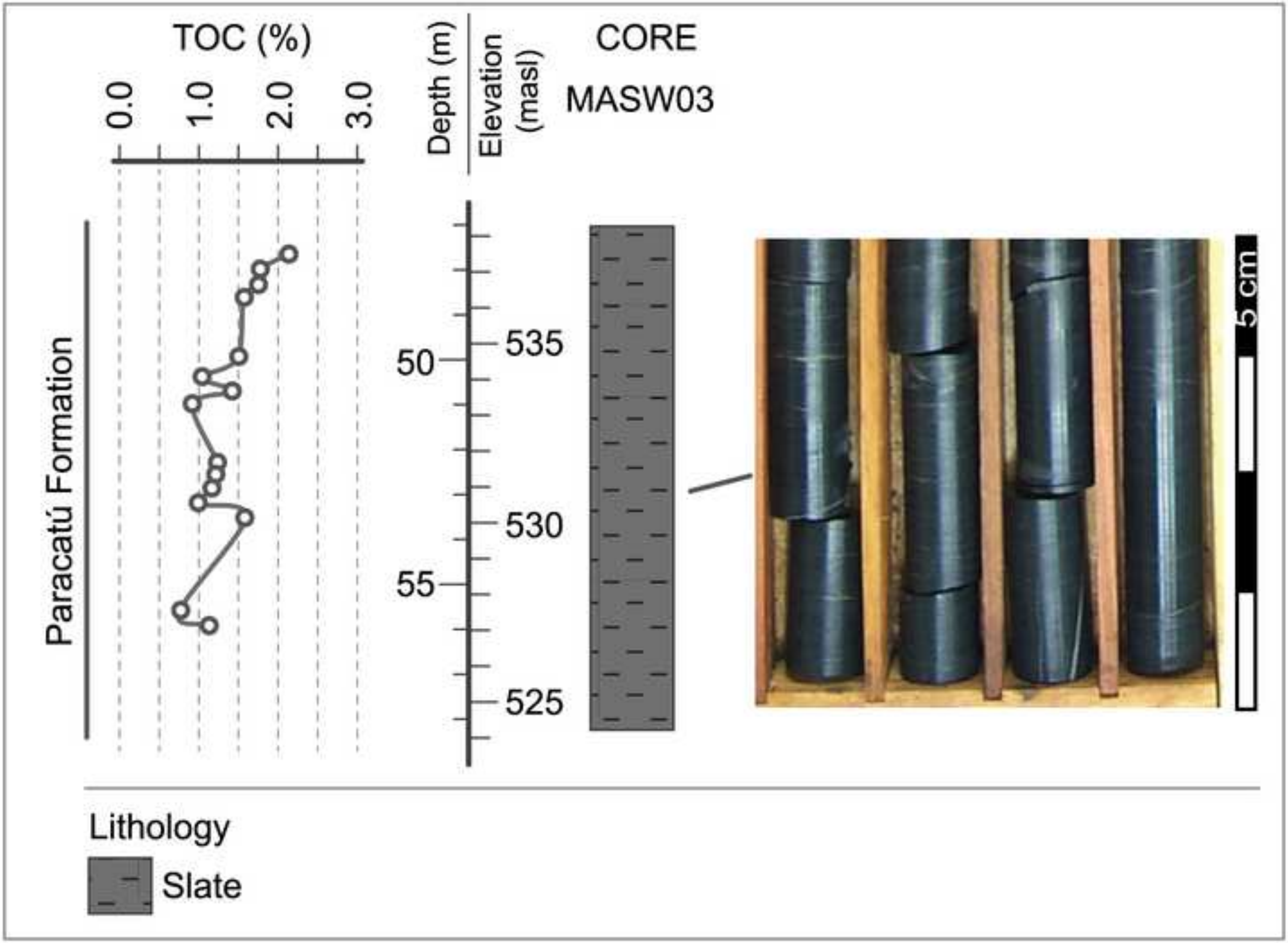

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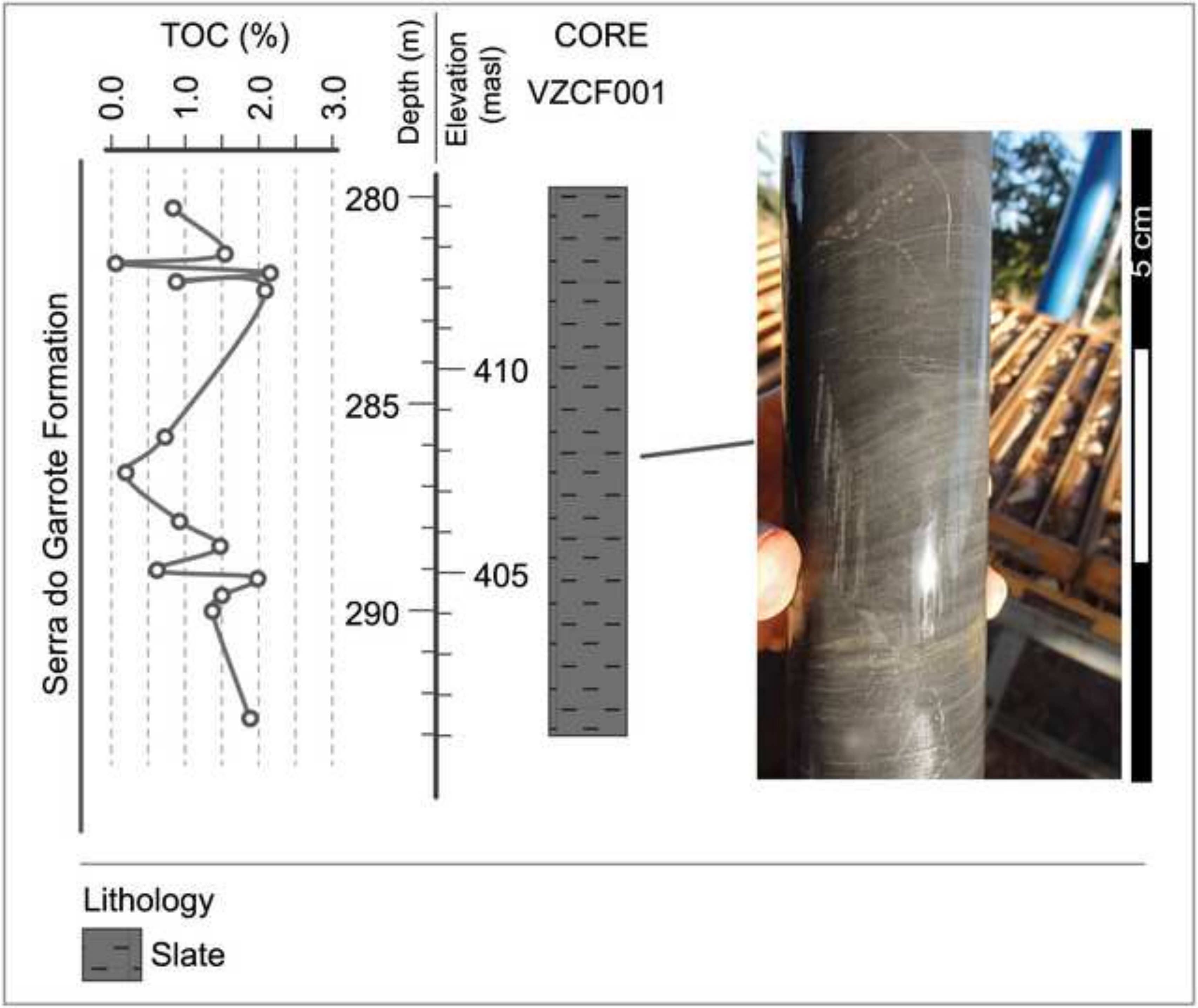

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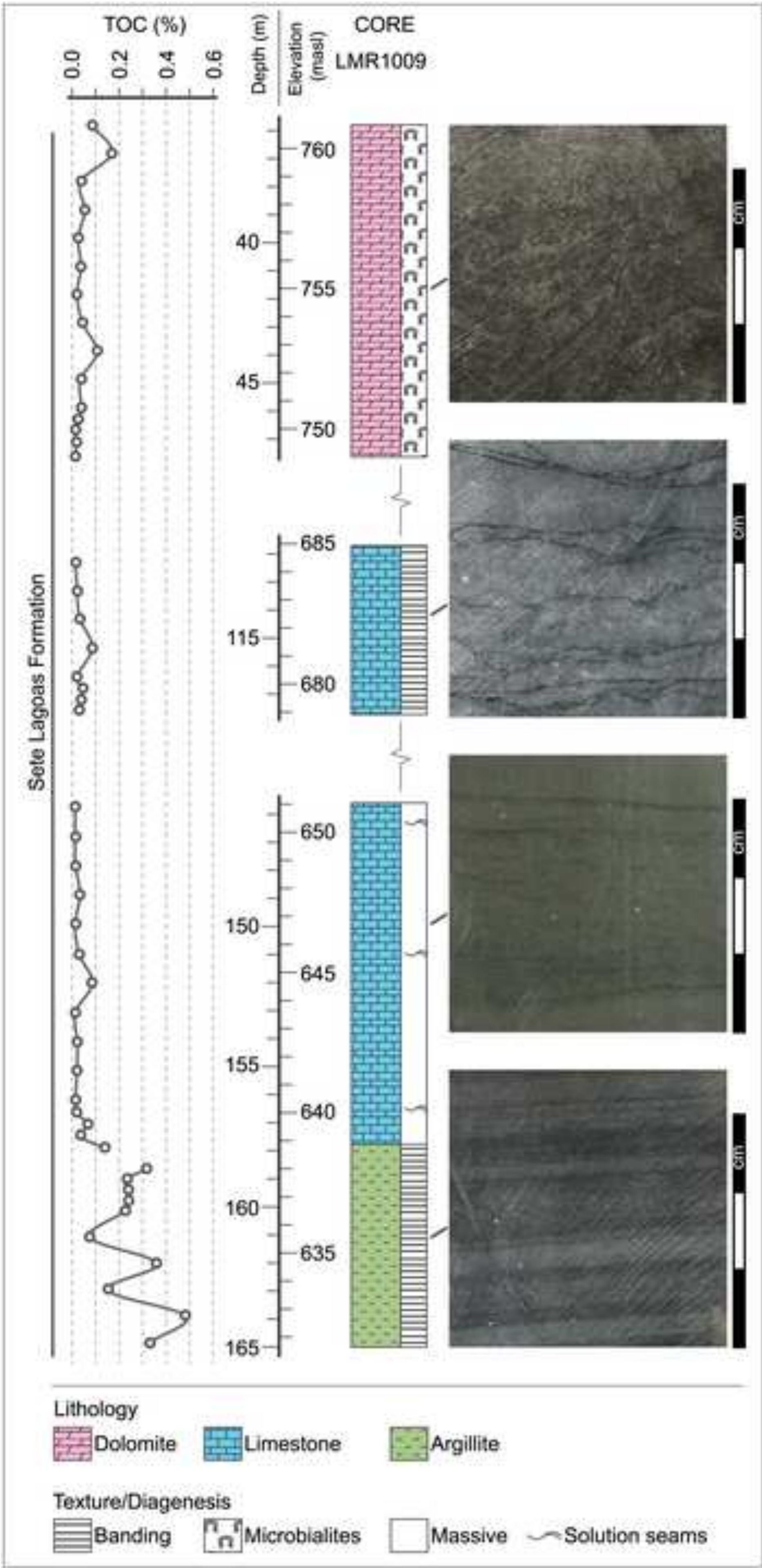

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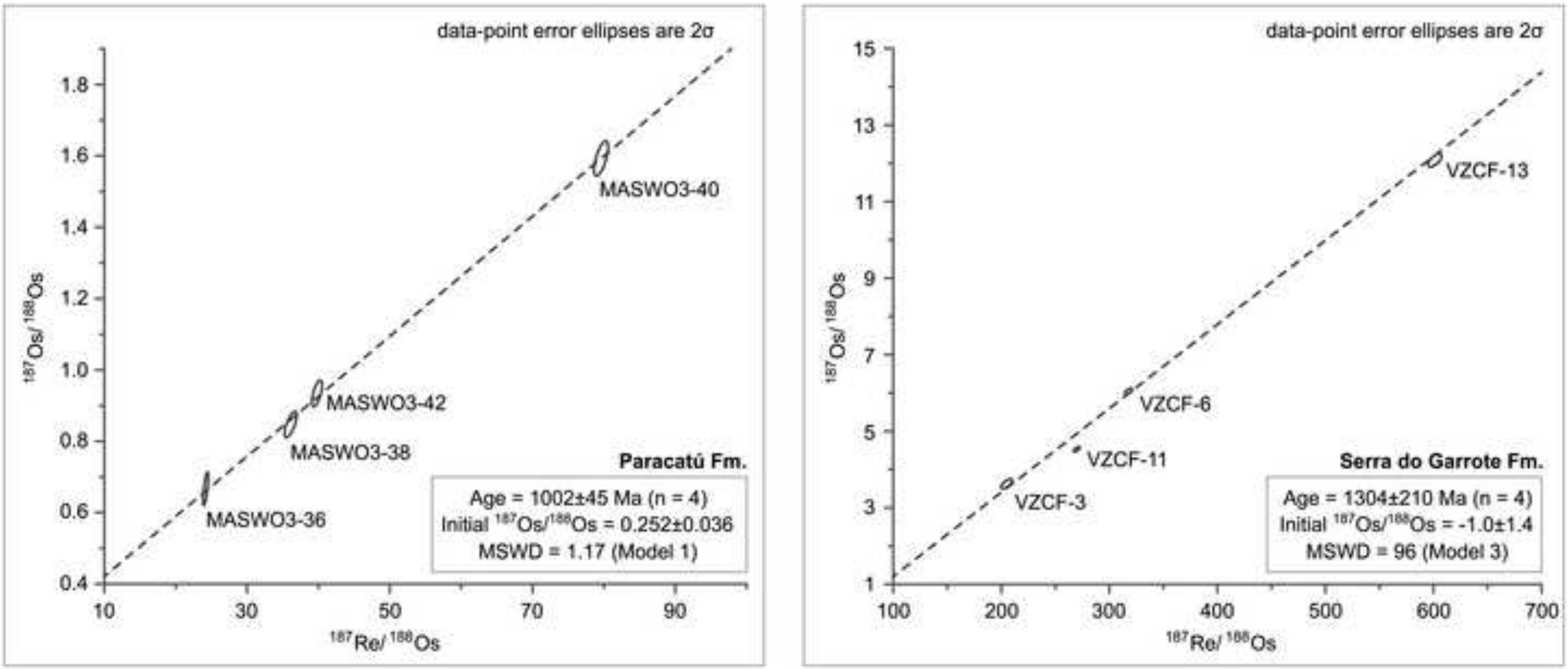

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