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Shallow lacustrine system of the Permian Pedra de Fogo Formation, Western Gondwana, Parnaíba Basin, Brazil

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ABSTRACT

The Permian Period of the Parnaíba Basin, northern Brazil, represented here by deposits from the Pedra de Fogo Formation, records important events that occurred in Western Gondwana near its boundary with the Mesozoic Era. The analysis of outcrop based facies from the Permian Pedra de Fogo Formation, which is 100 m thick, carried out along the eastern and western borders of the Parnaiba Basin, allowed the identification of eleven sedimentary facies, which were grouped into three distinct facies associations (FA), representative of a shallow lacustrine system associated with mudflats and ephemeral rivers. Bioturbation, desiccation cracks, silcretes and various siliceous concretions characterize the Pedra de Fogo deposits. The FA1 mudflat deposits occur predominantly at the base of the Pedra de Fogo Formation and consist of laminated claystone/mudstone, mudcrack-bearing sandstones/mudstones and sandstones exhibiting cross-lamination, massive and megaripple bedding. Popcorn-like silicified nodules and casts indicate evaporite deposits. Other common features are silica concretions, silicified tepees and silcretes. FA2 represents nearshore deposits and consists of fine-grained sandstones with evenly parallel lamination, climbing ripple cross-lamination, massive and megaripple bedding and mudstone/siltstone showing evenly parallel lamination. FA3 refers to wadi/inundite deposits, generally organized as fining-upward cycles of metric size, composed of conglomerates and medium-grained pebbly sandstones showing massive bedding and cross-stratification, as well as claystone/siltstone showing evenly parallel to undulate lamination. Scour-and-fill features are isolated in predominantly tabular deposits composed of mudstones interbedded with fine to medium-grained sandstones showing planar to slightly undulate lamination. Silicified plant remains previously classified as belonging to the *Psaronius* genus found in the uppermost levels of the Pedra de Fogo Formation, near the contact with the Motuca Formation, are considered here as excellent biostratigraphic markers. Fish remains, ostracods, bryozoans and scolecodonts represent other fossils that are present in the succession. Mudflat deposits developed in an arid and hot climate probably in the Early Permian. Semi-arid conditions prevailed in the Middle Permian allowing the proliferation of fauna and flora in adjacent humid regions and onto the lake margin. The climate variation was responsible for the contraction and expansion phases of the lake, fed by sporadic sheet floods carrying plant remains. The reestablishment of the arid climate, at the end of Permian, marks the final sedimentation of the Pedra de Fogo Formation, linked to the consolidation of the Pangaea Supercontinent. This last event was concomitant with the deposition of the Motuca Formation red beds and the development of extensive ergs related to the Triassic Sambaíba Formation in Western Gondwana.

1. Introduction

The Permian Period is characterized by global climate changes and near its boundary with the Triassic Period there are records of the biggest extinction event that killed 97% of all species on Earth

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(Koeberl et al., 2004; Kiehl and Shields, 2005; Meyer et al., 2008). At the end of the Permian Period, hot and dry conditions prevailed everywhere on Pangaea, and deserts became widespread in several parts of West Gondwana (Scotese et al., 1999; Zharkov and Chumakov, 2001). In South America, climatic changes were associated with tectonic uplift triggered by the Gondwanide Orogeny causing environmental changes within the continent (Caputo, 1984; Zalán, 1991). Uplift of the continental area caused the confining of seas and the development of large lake systems (Scotese et al., 1999). One of the most complete records of the Permian Period in Brazil is the Pedra de Fogo Formation, which is predominantly composed of fine to coarse-grained sandstones, mudstones and subordinately, silicified carbonates and evaporites exposed in an east-west strip in the central part of the Parnaíba Basin. Silex is abundant in Pedra de Fogo deposits, frequently called the "Silex Formation" (Plummer, 1946). Well-preserved and silicified Permian flora have been described by several authors (Coimbra and Mussa, 1984; Mussa and Coimbra, 1987; Martins, 2000; Rößler and Galtier, 2002a, 2002b, 2003; Kurzawe et al., 2013; Tavares et al., 2014).

The Parnaíba Basin is located on the South American platform, in the northeastern portion of Parnaíba Province (Góes, 1995) and covers an area of 600,000 km^2 in northern Brazil. The boundaries of the Parnaíba Basin are the Araguaia Belt to the west, the Ferrer – Urbano Santos Arch, to the north, the Brasilia Fold Belt to the south and the Borborema Province to the east, which is considered to form the basement of the basin. Igneous, metamorphic and sedimentary rocks, with ages ranging from Archean to Ordovician, form the basement where Cambrian-Ordovician precursor grabens were developed (Góes, 1995; Vaz et al., 2007). The lithostratigraphic framework of the Parnaíba Basin has been modified from Small (1914) and was included in different stratigraphic proposals (Góes and Feijó, 1994; Vaz et al., 2007).

The paleoenvironment of the Pedra de Fogo Formation has been interpreted focusing on lithostratigraphic aspects and only in the last decade, this unit was studied using facies analysis (Andrade et al., 2014). In addition, the discontinuous exposures of this unit extending over hundreds of kilometers along the basin make it difficult for continuous stratigraphic correlations. Another problematic issue is the lack of appropriate material in order to determine ages by palynology. Gray to black mudstone is rare in the outcrops and the succession is generally reddish indicating intense oxidization of the lithotypes. Body fossils are scarce, restricted to some intervals and mostly without biostratigraphic significance. In this study, the revisited tentative type section of the Pedra de Fogo Formation is integrated into a new facies framework based on the reinterpretation of well-known outcrops of the western and eastern borders of the Parnaiba Basin. The Pedra de Fogo Formation represents a climate-induced shallow lacustrine system with retreat and expansion phases that influenced not only the sedimentation pattern, but also the fossilization processes responsible for the preservation of the Permian fauna and flora in Western Gondwana.

2. Study area and methods

Outcrop-based facies and stratigraphic analysis of the Permian deposits were carried out along the eastern and western borders of the Parnaíba Basin. The observations were concentrated on the best exposures of these deposits near Pastos Bons and Nova Iorque Cities, State of Maranhão (MA), and in Araguaína and Filadélfia Cities, State of Tocantins (TO), northern Brazil (Fig. 1). In this study, we analyzed the type section of this unit, exposed along the banks of the Pedra de Fogo River, Nova Iorque Region, and integrated it into a new stratigraphic framework. We present a comprehensive facies analysis of three composite stratigraphic sections. Facies analysis involved facies associations (consisting of groups of facies genetically related to one another) which have some environmental significance (Collinson, 1969; Walker, 1992, 2006; Reading and Levell, 1996). The facies description follows the code proposed by Miall (1977), where the first capital letter indicates the main lithology and the second letter represents the main structure of the rock. The cross-bedding sets followed the Mckee and Weir (1953) classification: small (sets less than 0.3 m in height), medium (sets 0.3–3 m long) and large (sets over 3 m in height). Systematic samples were collected from specific beds.

X-ray diffraction (XRD) and scanning electron microscopy (SEM) were used as auxiliary techniques on the petrography of the sandstones, mainly to identify evaporitic minerals and their possible replacements. SEM analysis allowed the acquisition of microphotography of small e fossilized bodies described in the studied succession. In addition, thin sections of carbonate rocks were stained with Alizarin-Red S in order to distinguish calcite from dolomite, as proposed by Adams et al. (1984).

3. Previous work

The Balsas Group consists of clastic-evaporitic rocks that overlie the Canindé Group and is unconformably overlain by the Mosquito, Grajaú, Codó, Itapecuru and Urucuia formations as well as the Mearim Group (Góes and Feijó, 1994). The Balsas Group includes the Piauí, Pedra de Fogo, Motuca and Sambaíba formations (Vaz et al., 2007). The Pedra de Fogo Formation (Plummer, 1946) refers to a succession of sandstones, shales, limestones and mainly silex containing fossilized wood, with its type section being named after the homonymous river, between the Municipalities of Pastos Bons and Nova Iorque, State of Maranhão, Brazil. The unit occurs in the central part of the Parnaiba Basin where it extend for more than 600 km along an E–W trend and reaches thicknesses up to 189 m as determined by sub-surface investigations (Faria Jr. and Truckenbrodt, 1980a; Vaz et al., 2007).

Faria Jr. (1979) divided the Pedra de Fogo Formation in to the Silex Basal, Middle and Upper or "Trisidela" members. Lima and Leite (1978), Faria Jr. and Truckenbrodt (1980b), Mussa and Coimbra (1987) and Góes and Feijó (1994) placed this unit in the Early-Middle Permian, while Cox and Hutchinson (1991) consider a Late Permian age. Dino et al. (2002) have attributed a Late Permian age to the upper part of the Pedra de Fogo Formation based on correlations with palynozones of the Amazon Basin. The unit overlies the Piauí Formation, of Carboniferous age, interpreted as fluvial and aeolian deposits, with small-scale short-termed transgression records according to Caputo (1984), and Lima and Leite (1978). Red bed lake sediments from the Late Permian Motuca Formation and aeolian deposits from the Triassic Sambaíba Formation gradually overlie the Pedra de Fogo Formation in the western Parnaiba Basin (Abrantes and Nogueira, 2013).

The Pedra de Fogo Formation has been interpreted predominantly as transitional fluvio-deltaic deposits (Barbosa and Gomes, 1957; Oliveira, 1961; Moore, 1964; Aguiar, 1964; Cunha, 1964; Northfleet, 1965; Ojeda and Bembom, 1966; Ojeda and Perillo, 1967; Lima and Leite, 1978; Faria Jr. and Truckenbrodt, 1980a; Faria Jr. and Truckenbrodt, 1980b; Coimbra and Mussa, 1984; Caldas et al., 1989). Faria Jr. (1979) interpreted it as an epicontinental shallow marine setting and Góes and Feijó (1994) inferred a shallow neritic to storm-influenced coastal environment associated with sabkha plains. Dino et al. (2002) based on lithological data, the presence of *Psaronius*, abundance of continental palynomorphs and scarcity of marine microplanktons, attributed it to a shallow marine to coastal environment under an arid to semiarid climate.