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Mesozoic paleogeography and paleoclimates – A discussion of the diverse greenhouse and hothouse conditions of an alien world

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ABSTRACT

The Mesozoic was the time of the break-up of Pangaea, with profound consequences not only for the paleocontinental configuration, but also for paleoclimates and for the evolution of life. Cool greenhouse conditions alternated with warm greenhouse and even hothouse conditions, with global average temperatures around 6–9 °C warmer than the present ones. There are only sparse and controversial evidence for polar ice; meanwhile, extensive evaporitic and desertic deposits are well described. Global sea levels were mainly high, and the content of atmospheric O_2 was varying between 15 and 25%. These conditions make the Mesozoic Earth an alien world compared to present-day conditions. Degassing from volcanism linked to the rifting process of Pangaea and methane emissions from reptilian biotas were climate-controlling factors because they enhanced atmospheric CO_2 concentrations up to 16 times compared to present-day levels. The continental break-up modified paleopositions and shoreline configurations of the landmasses, generating huge epicontinental seas and altering profoundly the oceanic circulation. The Mesozoic was also a time of important impact events as probable triggers for "impact winters"; and for the Era at least nine huge (diameter > 20 km) impact structures are known. This paper presents an abridged but updated overview of the Mesozoic paleogeographic and paleoclimatic variations, characterizing each period and sub-period in terms of paleoclimatic state and main tectonic and climatic events, and provides a brief geologic, stratigraphic, paleoclimatic and taphonomic characterization of dinosaur occurrences as recorded in the Brazilian continental basins.

1. Introduction – the Mesozoic – an alien world

The rifting of Pangaea occurred during the Mesozoic, eventually fragmenting this supercontinent into several plates which will form the modern continents. This break-up had profound consequences not only for the paleocontinental configuration, but also for paleoclimates and for the evolution of life; because it significantly modified the paleoposition and shoreline configurations of the land masses, generated huge epicontinental seas and altered profoundly the oceanic circulation.

Due to its unique paleoclimatic conditions, with several times of very high temperatures (mean global temperature >25 °C) alternating with less warmer intervals and even with short-lived ice-ages, the Mesozoic Earth was, in comparison to the present, an "alien world", paraphrasing Sellwood and Valdes (2006).

Fischer (1982) introduced the nowadays widely used terms 'greenhouse' and 'icehouse' to characterize the two major climatic states of the Earth during the Phanerozoic. Kidder and Worsley (2010, 2012) proposed that there are actually three basic states for Earth climate: Icehouse, Greenhouse (subdivided into Cool and Warm states), and Hothouse. The 'Icehouse' (IH) displays polar ice, strong latitudinal temperature gradient (50–60 °C) and alternating glacial–interglacial episodes in response to orbital forcing. This climatic state apparently did not occur during the whole Mesozoic. The 'Cool Greenhouse' (GH-c) shows some polar ice and alpine glaciers, but no ice streams calving icebergs into the ocean. Global average temperatures are thought to range between 21° and 24 °C. Atmospheric CO_2 levels are thought to have been between 2 and 4 times those of today (600–1200 ppmv). The high to low latitude temperature gradient is weaker that in the icehouse (ca. 40 °C). The 'Warm Greenhouse' (GH-w) is devoid of any polar ice. Global average temperatures might have ranged from 24° to 30 °C. Kidder and Worsley (2012) believe that atmospheric CO_2 levels ranged between 4 and 16 times the present ones

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(1200–4800 ppmv) during GH-w stages. Seasonal reversals of the atmospheric pressure systems around the poles should have occurred. The lower latitudinal temperature gradients (<34 °C) thus mean reduced winds, and the warmer ocean would absorb even less oxygen. Isolated basins could become bottom oxygen-depleted. The "Hothouse" (HH) condition is relatively short-lived (<1 to ca. 3 Ma) and results from anomalously large inputs of CO_2 into the atmosphere during the formation of Large Igneous Provinces (LIPs), when atmospheric CO_2 concentrations may rise above 16 times (4800 ppmv).

The Mesozoic Earth had been experiencing the cool greenhouse, warm greenhouse and the hothouse climatic states. Hence, Mesozoic climate was very variable, what is corroborated by several global-scale studies. For instance, Veizer et al. (2000) demonstrated the variability of the Mesozoic global climate relying on a study on atmospheric CO_2 and global tropical sea surface temperatures anomalies (TSSTA), reporting positive anomalies for the Early to Middle Triassic and for the Late Cretaceous, and negative anomalies during Early Jurassic and specially for the Mid-Jurassic, when the mean surface temperatures were 4 °C higher than today.

Global sea levels throughout the Mesozoic were generally much higher than at present, with exceptions for the sea level lowstand in the Early Induan (i.e, the beginning of the Triassic, cf. Haq et al., 1988) and two noticeable lowstands in the early Jurassic (Hettangian/Sinemurian) and in the early Cretaceous (Valanginian) (Haq, 2014).

Mesozoic atmospheric oxygen content was also different when compared to current values. Theoretical calculations, based on both chemical and isotopic composition of sedimentary rocks and admitting a wide margin of error (about ±10%), indicate that atmospheric O_2 had been varying between 15 and 25% (Campbell and Allen, 2008; Royer, 2014). The transition from Permian to Triassic is marked by a huge drop of the atmospheric oxygen content, falling from ~30% to less than 15% according to some authors (e.g. Dudley, 2000; Berner et al., 2003). During Induan/Olenekian (Early Triassic), the O_2 content was about 15%, then it increasing to 20% (i.e. close to the present-day level) until the Early Jurassic and finally to 25% toward the Late Cretaceous (Berner and Canfield, 1989; Berner et al., 2003; Holland, 2006).

Why did the Mesozoic have such a different and overall hotter climate when compared, for instance, to the present day world? The main factors are:

(1) the paleocontinental configuration: the assembling of a supercontinent, forming an almost pole-to-pole continuous land mass, is one of the climate-driving factors. The combination of a gigantic land mass (Pangaea covered an approximate surface of 130 million km^2) and a lower global sea level (associated with reduced rates of tectonic movement) resulted in an arid climate during the Early Mesozoic, as stated by Frakes (1979). Parrish (1993) assigned to the Triassic the maximum development of megamonsoons, due to an almost symmetrical position of Pangaea over the equator. This megamonsoonal regime would have caused the displacement of the arid belt towards the poles, causing a decrease of the precipitation/evaporation rate in the mid-latitudes of Pangaea interiors, where huge semi-arid to arid belts characterized that period. The rifting of the supercontinent began during the Triassic, and the major break-up of Pangaea took place during the Jurassic (when Laurasia rifted from Gondwana and Africa separated from Antarctica/Australia); and continued during the Cretaceous (when Africa and South America rifted apart, and Greenland separated from North America). The break-up and the consequent continental drift modified the paleoposition and shoreline configurations of the land masses, generated huge epicontinental seas, separated land masses by interior sea ways, and altered profoundly the oceanic circulation. These factors helped controlling climate change during Middle and Late Mesozoic.

(2) the degassing process linked to plate tectonics: intense seafloor spreading enhanced greenhouse conditions thanks to degassing of H_2S, CH_4 and CO_2 (Seton et al., 2009; Royer, 2014), and rifting events are frequently linked to flood basalts and to the emplacements of large igneous provinces (LIPs) both continental and oceanic. It is a climate-controlling factor: since during these events the short term cooling is followed by warming induced by CO_2 degassing and enhanced greenhouse effect on climate (e.g. Kidder and Worsley, 2010; Chui and Komp, 2014). During the entire Mesozoic the CO_2 levels were relatively high (1000–2000 ppmv), with transient excursions to even higher values (>2000 ppmv; Retallack, 2001), and extremely elevated CO_2 concentrations at the Triassic/Jurassic boundary (Steinthorsdottir et al., 2011). Times of high atmospheric CO_2 and the consequent warm-wet paleoclimatic conditions led to the so-called "greenhouse crises" (Retallack, 2013), which are believed to have played a role in mass extinctions and long-term evolutionary trends during the entire Phanerozoic (Retallack, 2009). Greenhouse gases would have not only disrupted life on land with warmer and wetter climates, but with spreading tropical pathogens, long-distance plant and animal migrations, sea level rise, low-oxygenated ground water and water acidification. Atmospheric oxygen depleted by massive emissions of CH_4 and H_2S (Berner, 2006) would have challenged animals with pulmonary edema, high elevations might have become uninhabitable, later reducing habitat for many animals (Huey and Ward, 2005), and animals with small–medium body size and short muscular limbs (e.g. Lystrosaurus), would be the evolutionary outcome of such a greenhouse crisis (Retallack et al., 2003).

The evolution of terrestrial vertebrates seemingly was another climate-controlling factor. During Mesozoic, herbivorous vertebrates display an evolutionary trend towards gigantism; hence, methane emissions from that kind of reptilian biotas are also considered a climate-controlling factor: the vast herds of grazing reptiles might have released enhanced methane content in the atmosphere and therefore elevated the warm to hot greenhouse conditions of the Mesozoic world (Wilkinson et al., 2012).

(3) the impact events: the collision of huge asteroids produces a huge amount of ejecta which is smeared through atmospheric circulation over huge areas or even globally, causing the so-called "impact winter" which is a period of prolonged cold weather resulting from blocked sunlight (e.g. Covey et al., 1994; Chapman and Morrison, 1994), hence, inducing severe ecological alterations that could lead to extinction (e.g. Raup, 1992).

The goal of the present paper is twofold.

The first and main goal is to offer an abridged but updated overview of the Mesozoic paleogeographic and paleoclimatic variations, characterizing for each period and sub-period:

- the paleoclimatic state (GH-c, GH-w and HH, sensu Kidder and Worsley, 2010);
- global temperature (e.g. Sun et al., 2012; Veizer et al., 2000; Wang et al., 2012);
- sea surface temperature anomalies (Veizer et al., 2000);
- global CO_2 levels (e.g. Bergman et al., 2004; Retallack, 2013; Royer, 2014);
- global O_2 levels (e.g. Bergman et al., 2004; Berner, 2009);
- rifting events and LIP (large igneous provinces) emplacements, compiled from Prokoph et al. (2013) – only considering LIP's with vol. $> 1000 \times 10^3$ km^3;
- main impact events, with data compiled from Rajmon (2009) and cross-checked with information from the data bank of the Planetary and Space Science Centre of the University of New Brunswick (Canada);