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Warming or cooling in the Pragian? Sedimentary record and petrophysical logs across the Lochkovian–Pragian boundary in the Spanish Central Pyrenees

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High-resolution petrophysical correlation methods were applied, for the first time, to mid-Paleozoic rocks of the Pyrenees. The methods included magnetic susceptibility measurements (MS), gamma-ray spectrometry (GRS), and alignment of MS logs using the dynamic time-warping (DTW) algorithm. Conodont biostratigraphy provided the basic framework necessary for work with the GRS and MS logs. Despite differences in the sediment patterns and accumulation/erosion rates, the logs from two selected sections in the Spanish Central Pyrenees show a striking symmetry that correlates well with the previously published logs from the Barrandian area in the Czech Republic. The high similarity between the petrophysical records from paleogeographically related but distant areas has the potential to contribute to the current discussions about the eustatic and climatic changes that took place in the overall greenhouse settings, where evidence for any polar ice sheets is still absent. In addition to the extant evidence of a major Lochkovian–Pragian offlap, combined with sea level lowering known from the North America, evidence about a major sea level fall and drastic reconstruction of the climatic system in the Pragian is now expanding over significant parts of the peri-Gondwanan belt. The data from Spain provide many new details about this change, including the phenomenon of a stratigraphically condensed upper Lochkovian, a dramatically different type of sedimentation in the Pragian, and a GRS-Th-and-MS anomalous stratigraphic interval in the middle Pragian. The multifaceted evidence allows us to determine the essential parts of the Pragian as a still "hot and humid" period, even with the strong differences from the possibly "extremely hot" Lochkovian.

1. Introduction

The complex petrophysical characteristics of the biostratigraphically well-constrained Early Devonian strata are urgently needed from many regions in order to provide a more complete image of the impacts of possible global environmental changes. The principal environmental instabilities in the Early Devonian are well expressed, especially by the obvious differences between the classical megasequences that represent traditional hercynian (Bohemian) stages (Lochkovian, Pragian, Zlichovian, and Dalejan). These regional stages are characterized by typical marine successions/formations whose boundaries often differ from the official global GSSP-based subdivision. These may reflect the global or, at least, supra-regional trends in environmental dynamics, and, as they can be very distinctly recognized, may also partly correspond to the "Time Specific Facies" of Walliser (1984). Especially conspicuous on the global scale are the differences between the Lochkovian and the Pragian stages, as they can very distinctively be recognized as turnovers in the marine faunal communities, described from many areas (e.g., Chlupáč et al., 1985; Brett and Baird, 1995; Havlíček and Vaněk, 1998; Koren' et al., 2007; Dupret and Blieck, 2009) as well as by a change in the composition of marine sedimentary rocks, a drastic change of environmental proxies (Małkowski et al., 2009), and the extremely high extinction-speciation rates of land plants (Xiong et al., 2013). According to Chlupáč and Kukal (1986, 1988) as well as House (2002), there was a trend toward a gradual shallowing and increase of water energy, which culminated close to the base of the Pragian, especially during the Basal Pragian Event (Chlupáč and Kukal, 1986, 1988). In the type area (Prague Synform, Barrandian area), the boundary event is connected with a positive shift of δ^{13}C values (Hladíková et al., 1997; Buggisch and Mann, 2004), and with heavily condensed sedimentation around the Lochkovian–Pragian (Lo–Pg) boundary (cf. Slavík et al., 2012). According to Koptíková et al. (2010a, 2010b), the interval close above the boundary is also marked by a change in the delivery of non-carbonate impurities into marine carbonates, with an increased long-distance aeolian input, maybe reflecting a major change of the ocean-atmospheric

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system. Additionally, oxidizing conditions spread down the carbonate slope, also occurring with iron in the relatively deeper water carbonate beds of the Pragian, mostly occurring in the oxides and oxyhydroxides rather than pyrrhotite, which is common in the Lochkovian beds. With the exception of coarse bioclastic deposits at the base, the Pragian sedimentary rocks are often characterized by the presence of highly polydisperse and polymodal mixtures of calcisiltitic materials, and instead of cementation, a tendency to early diagenetic compaction and lithification due to re-crystallization predominates. A tendency toward the increased occurrence of nodular limestones is seen, also having violet- and orange-band color hues, but virtually no cherts. It is most likely that a global climate change could have been a crucial factor and that these rocks may represent the "Time Specific Facies" (cf. summary by Brett et al., 2012). Although the rapid and massive change makes the Pragian sedimentary systems so different, an understanding of the parameters and causation is still a challenge.

Hladil et al. (2008) proposed the Pragian as an interval with extremely low sea level, but a relatively hot and humid climate, based on the petrological/mineralogical characteristics of the terrigenous input, i.e., suggesting a rather unusual coupling of eustatic and climatic parameters. The idea of climatic warming was also supported by Vacek (2011), according to an environmental interpretation of MS vs. GRS measurements. Contrastingly, Buggisch and Joachimski (2006) and Joachimski et al. (2009) suggested a climatic cooling by means of the interpretation of carbon and oxygen isotope data, respectively. This isotopic evidence of cooling can easily explain the sea level fall as well as the observed erosional/non-depositional conditions around the cratons (Sloss, 1963; Ver Straeten, 2009a; Menning et al., 2006), although the evidence of Pragian glaciation in circumpolar areas is slight and may relate instead to early Emsian ages (Rubinstein et al., 2010). On the contrary, the faunas of the very south of the globe diversified in these times (de Carvalho, 2006); the Koněprusy reef at ca. 35°S (Hladil et al., 2011) yields several hundreds of described species, and the faunas of the Pragian are two times richer than those of the Lochkovian in the classic areas of these stratigraphic stages (Chlupáč et al., 1998). Concerning faunas and climate, it is very significant that Pragian siliceous plankton and siliceous sponges were much reduced, cherts are rare or absent, and that the carbonate rocks are often light colored, yellowish-pink, or variegated. This contrasts with the gray and cherty beds of the Lochkovian and "Zlichovian," below and above, respectively (Chlupáč et al., 1998). A general cooling can correspond to the rapid expansion of deltas with quartzites and variegated siltstones (Stets and Schäfer, 2009—Rhenish area; Gutiérrez-Marco et al., 1998—Central Iberian Zone). The presence of quartzites and uranium-depleted aeolian input (Koptíková et al., 2010b—Barrandian area), however, suggest rather a significant degree of chemical weathering in hot climatic conditions.

In general, the global correlation of the Lochkovian–Pragian boundary is still a bit of a complicated issue in Devonian stratigraphy because of the above-mentioned turnovers linked to global fluctuations of sea level (Sloss, 1963; Johnson et al., 1985; vs. Ver Straeten, 2009a; the latter based on the Appalachian Foreland). This has largely affected the composition of the marine faunal communities and their biostratigraphical potential. Due to an overall and frequently manifested sea level fall (Buggisch and Joachimski, 2006; Hladil et al., 2008; Ver Straeten, 2009b), the boundary in many regions is masked by low accumulation rates or even gaps, sometimes even in combination with local tectonic disruptions following the rheological differences between the Lochkovian and Pragian beds (Hladil et al., 2010). This especially applies to the areas of peri-Gondwana, where the Lochkovian–Pragian boundary is typically characterized by a shallowing and stratigraphic condensation, often with the presence of small-scale gaps (e.g., Valenzuela-Ríos, 1994; Suttner, 2007: for the Pyrenees and Carnic Alps, respectively). Also, in the Prague Synform, a marked stratigraphic condensation around the Lo–Pg boundary in the shallow-water sections has been documented due to pelagic faunas and conodont biostratigraphy (Slavík et al., 2012).

The highest precision in the relative dating of Paleozoic marine carbonate successions can be attained by conodont biostratigraphy. The sedimentation rate can also be deduced from a comparison of the integrity of conodont lineages between sections in areas with different environments. In contrast to peri-Gondwana, the conodont record seems to be more complete in more distant and/or less shallowing-affected areas, e.g., Podolia (Drygant and Szaniawski, 2012), Nevada (Murphy, 2005), Australia (NSW, Wilson, 1989; Victoria, Wall et al., 1995), or Arctic Asia (Al'khovik and Baranov, 2001; Baranov et al., 2014). However, in most of these areas, the conodont faunas show a high degree of provincialism. This is the reason why there is no universally applicable biostratigraphic scale for the Pragian stage, despite a long and complex history of research (for a summary, see e.g., Slavík et al., 2007; Becker et al., 2012).This seems to be a particularly serious issue, especially at a time of ongoing discussions on the future subdivision of these stages, and the redefinition of several intra-Devonian boundaries (notably the base of the Emsian stage; Carls et al., 2008).

Although the problem of early Pragian biostratigraphic correlation has largely been solved for the peri-Gondwanan region (cf. Slavík et al., 2007), the details of the biostratigraphic data still remain incomplete in the specific conditions of many sections. Also, the positions and manifestations of lithological change vary locally, so that the boundaries of the sequences (or formally discerned formations) do not always correspond to the biostratigraphic boundary between the stages. Therefore, an additional set of case studies has been initiated to also apply petrophysical and microfacies methods to facilitate a more precise correlation of the Lo–Pg boundary beds. Two instructive Lower Devonian sections in the Spanish Central Pyrenees (Compte-I and Segre 2) have been studied from aspects of their biostratigraphy, combined with magnetic susceptibility (MS) and gamma-ray spectrometric (GRS) logging. This was due to the fact that the biostratigraphic data for a precise delimitation of the boundary are missing in critical narrow boundary intervals, and the correlations need further refinement. The same procedure had previously been applied in the Lower Devonian strata of the Prague Synform (e.g., Hladil et al., 2010; Koptíková et al., 2010b), where the GRS and MS logs were correlated with the established detailed biostratigraphic scales and the position of the Lo–Pg boundary is precisely controlled by conodonts (Slavík, 2004; Slavík et al., 2007). The MS-based refinements of local stratigraphic correlations were also successfully applied between distant areas with high density of biostratigraphic data (Prague Synform to Uzbekistan, Central Asia; Hladil et al., 2011). However, the Spanish Central Pyrenees and the Prague Synform are closely related paleogeographically, and both areas feature biofacies with the presence of cosmopolitan rather than endemic offshore faunas. Together with the Carnic Alps, they represent the key areas of peri-Gondwana for stratigraphical correlation of the early–middle Paleozoic. The primary intention of this study was to enhance the correlation potential at the interregional level in peri-Gondwana. The expected goal of the study, however, exceeds the originally intended refinement of the stratigraphic correlation and aims at understanding of the essential parameters of environmental change at the Lo–Pg boundary.

1.1. Geological setting

Most of the sedimentary Paleozoic rocks of the Axial Zone of the Spanish Central Pyrenees (Fig. 1) underwent varying degrees of metamorphism. The Variscan and subsequent Alpine deformations largely affected the spatial distribution of the Palaeozoic strata. The complex facial distribution of Devonian rocks has led to various interpretations of their relationships, but often without sufficient biostratigraphical information, which is required for the reconstruction of a complete scenario (e.g., Boersma, 1973; for a summary, see Valenzuela-Ríos and Liao, 2006, and some details in Valenzuela-Ríos and Liao, 2012). The sections selected for this study belong to the area with the best biostratigraphical control in the Devonian of the Spanish Central Pyrenees (Valenzuela-