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SUPPLEMENTAL MATERIAL

Detailed Geological Setting

The Apula Domain

The Apula Platform developed on the southern margin of the Mediterranean Tethys, and its northern extension crops out in the Majella Mountain (central Apennines, Fig. 1). The Oligo-Miocene succession of the Majella Mountain consists of a homoclinal carbonate ramp (Bolognano Fm), formed by six lithostratigraphic units, three representatives of inner and middle ramp environments alternating with three deeper ones (Brandano et al., 2016). A phosphate-rich hardground crops out in the upper Burdigalian, separating the middle ramp “*Lepidocyclina* calcarenites 2” unit from the outer ramp “Bryozoan calcarenites” unit (Fig. DR1, DR 2A; Mutti and Bernoulli, 2003; Brandano et al., 2016).
The Apula Platform extends southward, where it represents the Apennines and Dinaric foreland (Fig. 1; Bernoulli, 2001). In this succession, Oligo-Miocene shallow-water carbonates crop out in the Salento Peninsula (Southeastern Italy, Fig. 1). The upper Oligocene consists of a carbonate ramp dominated by red algae, Larger Benthic Foraminifera (LBFs) and mesophotic coral mounds (Porto Badisco Calcarenite Fm, (Pomar et al., 2014), overlaid by a fossiliferous 5- to 30-cm thick phosphatic hardground named “*Aturia* Level” (Figs. DR 2B, C; DR3) Bosellini et al., 1999; Föllmi et al., 2015). Above the *Aturia* Level, a lower Messinian reef complex crops out (Novaglie Fm, Bosellini et al., 2002). Therefore, this hardground identifies a long-lasting episode of non-deposition and sediment reworking. In fact, the Sr isotope record of fossils and phosphate nodules of the “*Aturia* Level” clusters around 12 and 10.5 Ma, testifying for very low sedimentations rates and phosphogenesis across the middle to late Miocene (Föllmi et al., 2015). In this work, we analyzed the first phase of phosphogenesis in the Porto Badisco outcrop (Fig. 1), dated at 12 Ma.

The Latium-Abruzzi Domain

The third phosphatic hardground belongs to the Latium-Abruzzi Platform (central Apennines, Fig.1). The Miocene succession here identifies a carbonate ramp (*Lithtothamnion* and Bryozoan Limestone, *L*BL Fm), formed by oligophotic facies dominated by rhodoliths, and aphotic facies dominated by bryozoans, echinoids and mollusks (Brandano et al., 2017). Along the Mesozoic platform margins, the Oligo-Miocene Guadagnolo Fm occurs, documenting the platform-to-basin transition (Civitelli et al., 1986). On top of the *L*BL and the Guadagnolo fms, a 20-cm thick Tortonian (11 Ma) hardground with phosphates and glauconite occurs (Fig. DR2D; DR4; Brandano et al., 2020). For this paper, this-hardground was investigated in the Tornimparte Village section, where it overlays the Guadagnolo Fm (Fig. 1).

Detailed Sample Cleaning and Nd purification

The samples were cleaned with H_2O_2 and observed at an optical microscope to assess their preservation state.
The purification procedure comprises two steps: first the Rare Earth Elements (REEs) purification within chromatographic columns equipped with TRU-Spec resins; secondly the Nd separation from REEs, with Ln-Spec resins.

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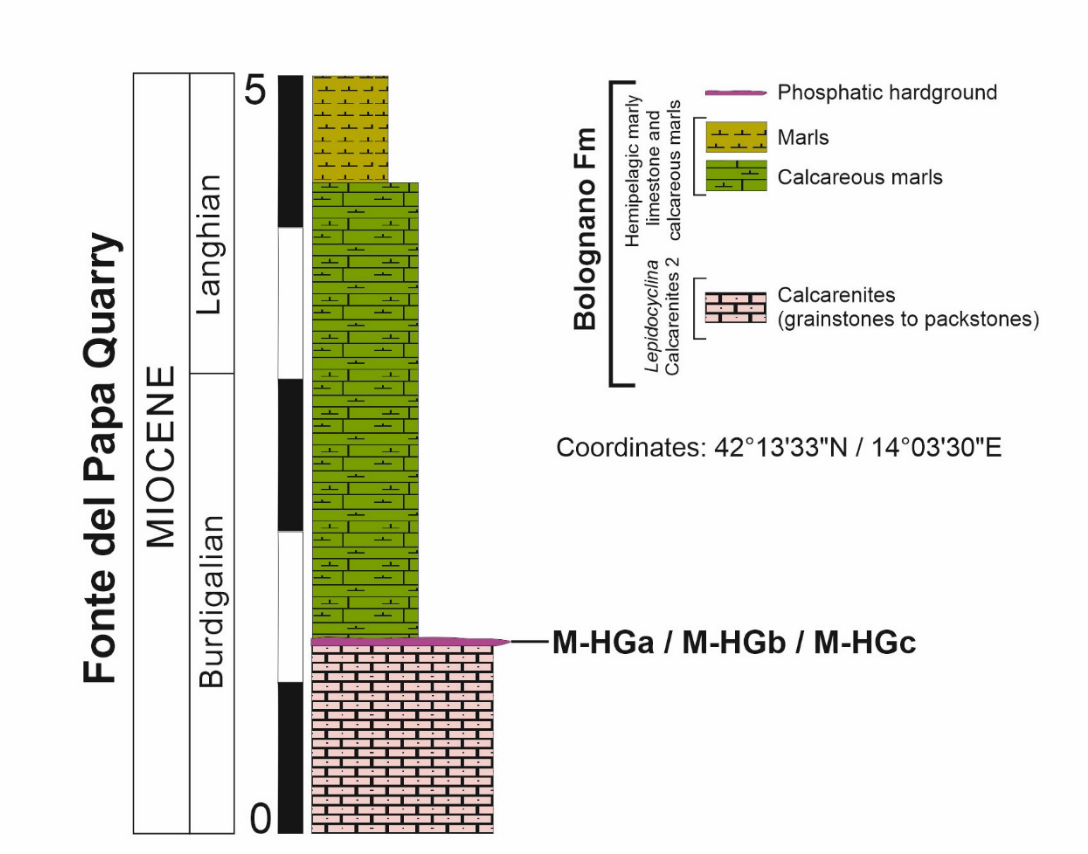

Figure S1: Fonte del Papa Quarry section plotted against stratigraphic depth, with sample positions. Age constraints are referred to Brandano et al. (2016) and based on calcareous nannofossil biostratigraphy.

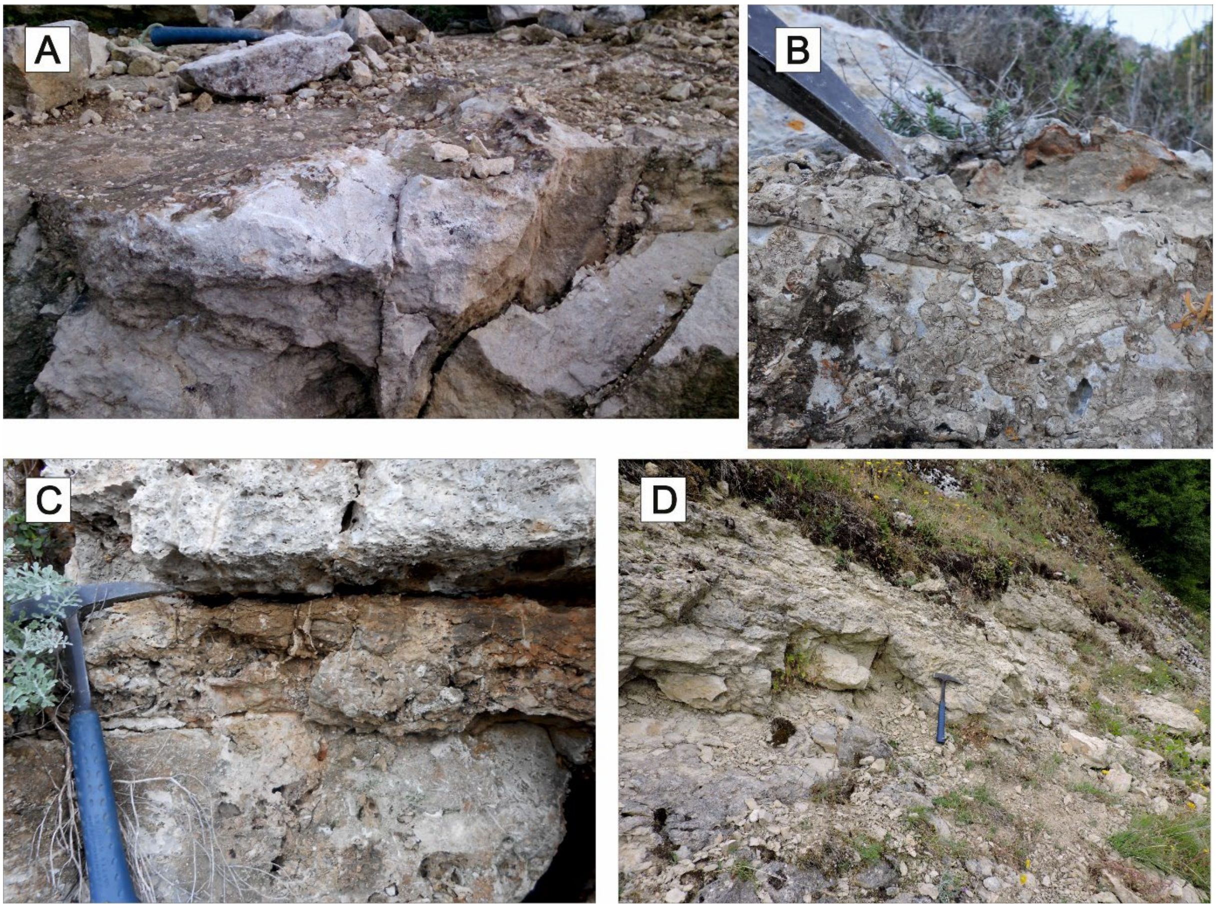

Figure S2: Outcrop photos of the investigated hardgounds. A) Fonte del Papa Quarry hardground surface; B) Phosphatized solitary corals in the Aturia Level; C) Aturia Level phospatic bed at Porto Badisco; D) Tornimparte Village phosphatic bed.

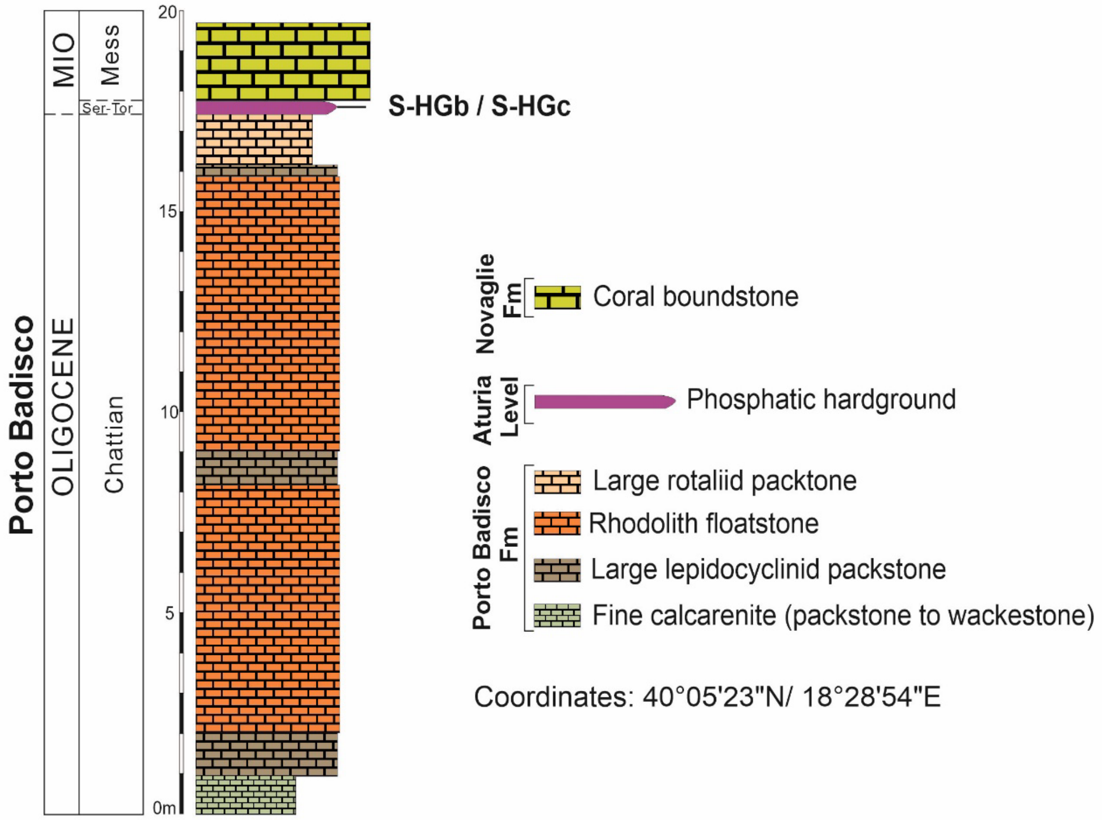

Figure S3: Porto Badisco section plotted against stratigraphic depth, with sample position. The stratigragraphic log is modified and redrawn after Tomassetti et al. (2018). Age constraints are referred to Pomar et al. (2014) for the Porto Badisco Fm, to Föllmi et al. (2015) for the Aturia Level hardground and to Bosellini et al. (2002) for the Novaglie Fm.

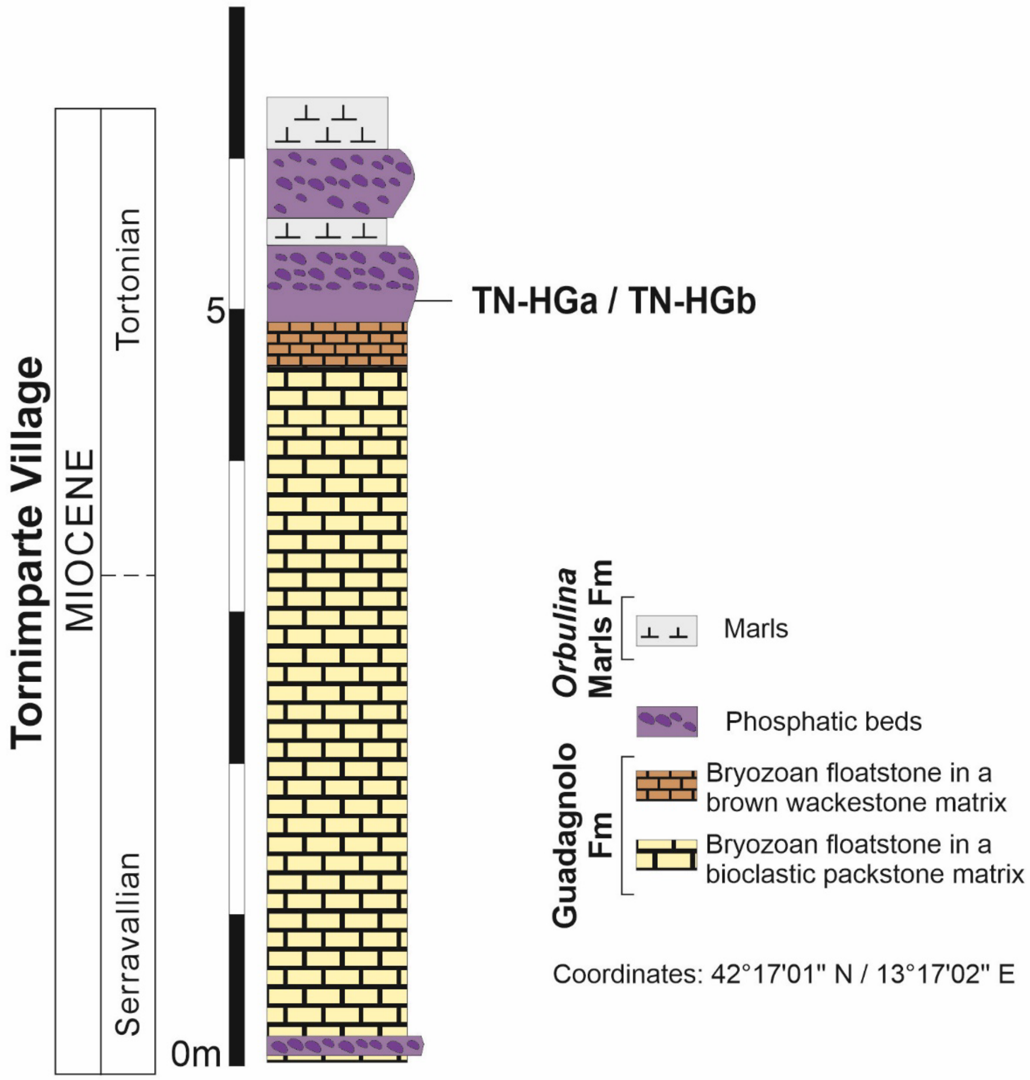

Figure S4: Tornimparte Village section plotted against stratigraphic depth, with sample position. The stratigraphic log is modified and redrawn after Brandano et al. (2020). Age constraints of the hadrgound are referred to Brandano et al. (2020) based on planktonic foraminifera biostratigraphy.