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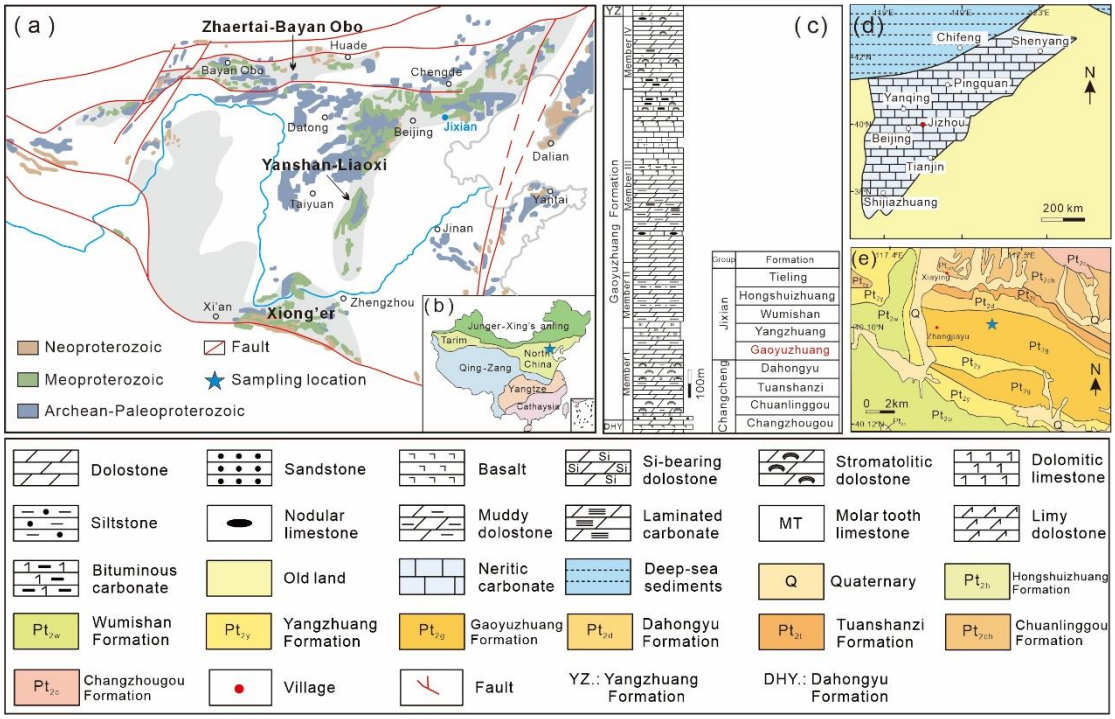

Figure 1. Geological framework of the study areas and sampling sites. (a) Schematic map of the North China Craton showing Mesoproterozoic strata (modified after Zhai and Liu, 2003; Zhao and Zhai, 2013); (b) Simplified map of the tectonic units of China; (c) General stratigraphic column showing the Changcheng and Jixian groups, and a more detailed stratigraphic column for the Gaoyuzhuang Formation; (d) Simplified paleogeographic map of North China during the early Mesoproterozoic, showing the location of the study area (modified after Xie et al., 2024); (e) Simplified geological map of the Jixian area, north of Tianjin (modified after Xie et al., 2024). Samples in this study are from Member I to the bottom segment of Member IV in the Gaoyuzhuang Formation (modified after Luo et al., 2021).

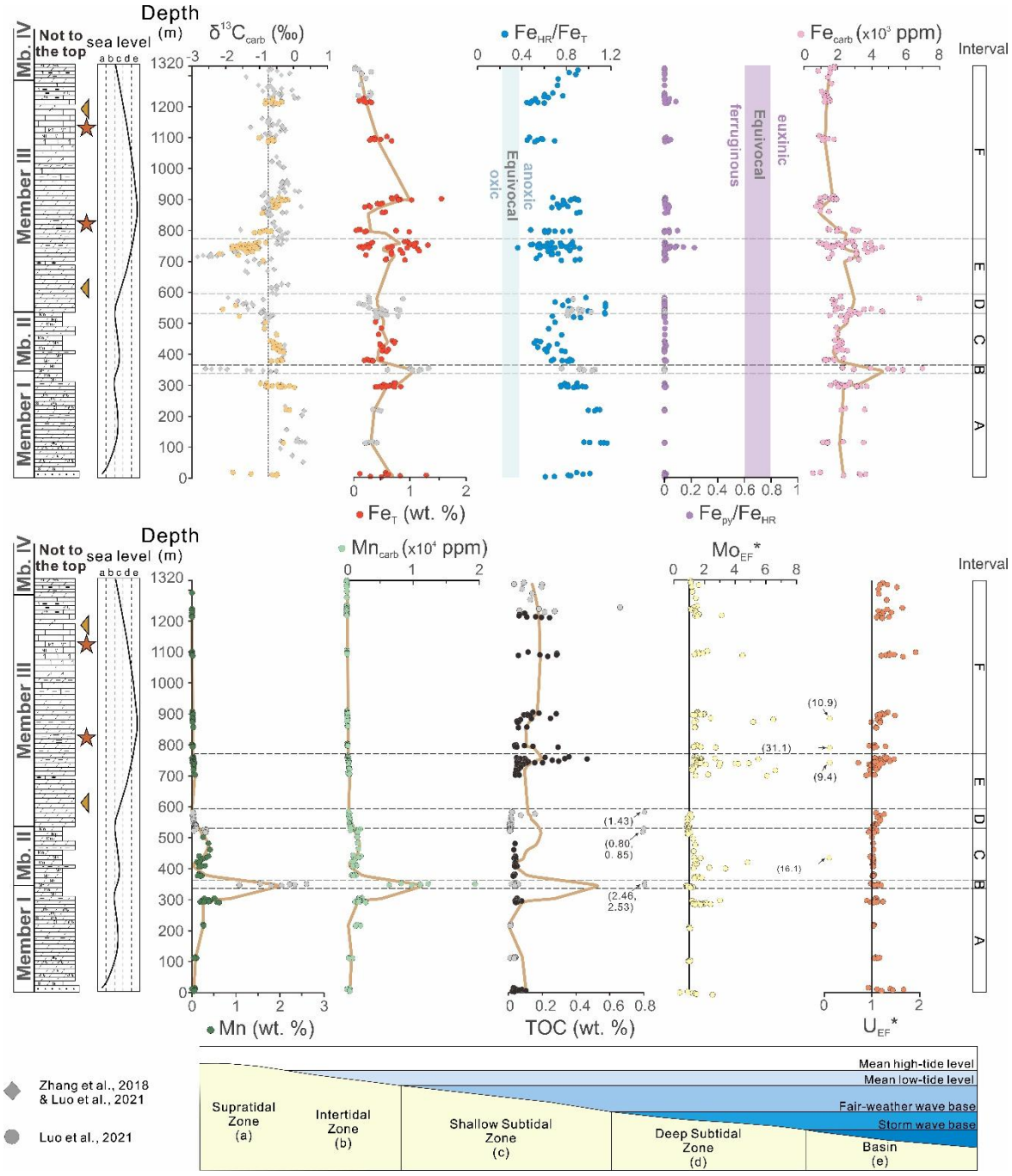

Figure 2. Geochemical profiles through the Gaoyuzhuang Formation in the Jixian sections. The geochemical data comprises $\delta^{13}C_{carb}$, Fe_{HR}/Fe_T, Fe_{py}/Fe_{HR}, total Fe and Mn, Fe and Mn in carbonate phases (determined via sequential leaching), TOC, Mo_{EF}^* and U_{EF}^* values. Published $\delta^{13}C_{carb}$ data (shown as grey symbols) for the Jixian section are from Zhang et al. (2018) and Luo et al. (2021), while data from the current study are shown in yellow symbols. Grey circles on other plots are data from Luo et al. (2021). The vertical dashed line on the $\delta^{13}C_{carb}$ plot represents the average value of the Jixian section. Solid black lines on the Mo_{EF}^* and U_{EF}^* plots represent an enrichment factor of 1, with values above this representing element enrichment. The brown stars represent

the approximate position of the Gaoyuzhuang fossils (Zhu et al., 2016; Chen et al., 2023). Triangles represent the tuff horizons, which gave ages of 1582 ± 12 Ma in the lower part of Member III (Tian et al., 2020), and 1588.8 ± 6.5 Ma at the top of Member III (Chen et al., 2024). The brown curves on the total Fe, Fe and Mn in carbonate phases, and TOC plots represent estimated scatterplot smoothing lines (LOESS, 0.2). The relative sea level curve is from Luo et al. (2021).

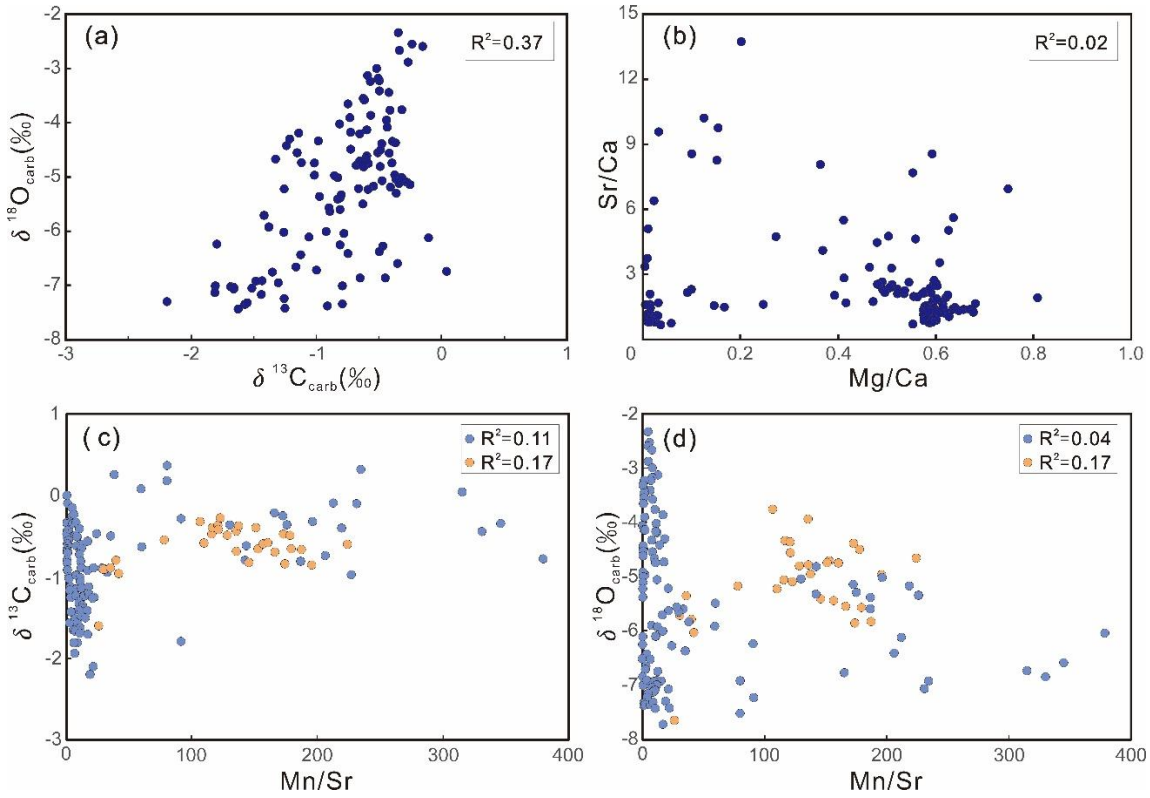

Figure 3. Cross-plots of (a) $\delta^{13}C_{carb}$ values versus $\delta^{18}O$, (b) Sr/Ca versus Mg/Ca, (c) Mn/Sr versus $\delta^{13}C_{carb}$, and (d) Mn/Sr versus $\delta^{18}O$, to examine the potential influence of diagenesis on the studied samples. Both data plots show no correlation. Sr, Mg and Ca contents in (a) and (b) represent total analyses of the bulk-rocks, while Mn and Sr contents in (c) and (d) represent analyses of the extracted leaching carbonate-phase. The blue circles in (c) and (d) represent the samples from non-Mn-rich horizons, while yellow circles in (c) and (d) represent the samples from Mn-rich horizons.

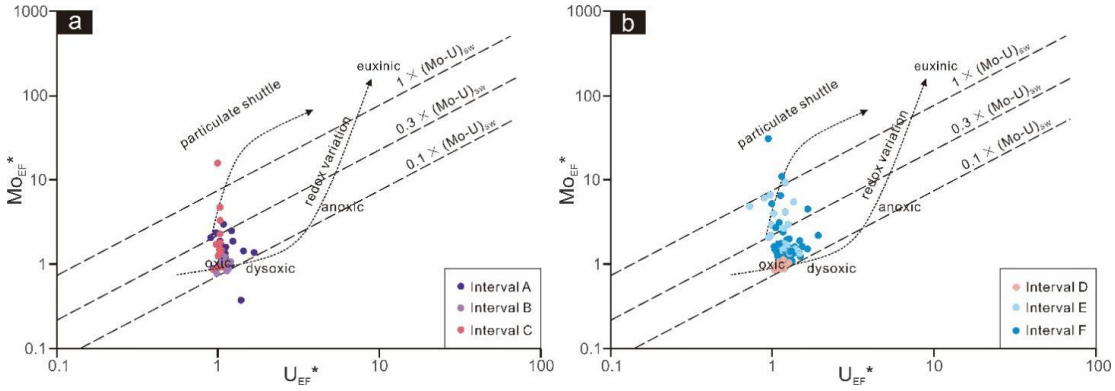

Figure 4. Mo_{EF}^{*}–U_{EF}^{*} covariation for different stratigraphic intervals through the Jixian section. The diagonal dashed lines represent proportions of the seawater (SW) Mo/U molar ratio. The dashed arrows illustrate different Mo accumulation pathways. The *particulate shuttle* represents uptake of Mo during the water column precipitation of Fe–Mn (oxyhydr)oxides, and the *redox variation* trajectory tracks oxic, dysoxic, anoxic, and euxinic water column conditions (modified after Algeo and Tribovillard, 2009 and Li et al., 2025).