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Deep time plate configurations and their emerging applications

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Plate tectonic reconstructions have progressed substantially over the last decade, incorporating evolving plate boundaries as well as plate deformation. These technological innovations have spurred the construction of a variety of new regional and global plate models. They are acting as a catalyst for the emergence of a new generation of geodynamic models as well as new approaches for studying the flux of material, including volatiles, from the surface to the deep Earth and vice-versa. Plate models with dynamic plate boundaries have evolved to reach further back in geological time, extending into the Proterozoic. Uncertainties in Proterozoic reconstructions are difficult to quantify, but the availability of the GPlates software accompanied by a variety of open-access data sets has enabled the community to develop alternative models, exploring a range of possible interpretations of available geodata to reconstruct plate motions and plate boundary evolution. The emergence of deep-time plate models has opened numerous opportunities for Earth system analysis, including an improved understanding of the evolution of Earth's mantle structure through time, quantifying solid Earth carbon degassing, and linking biodiversity evolution to plate tectonic and surface processes. Three additional developments are significant in the context of emerging spatio-temporal deep-time data analysis: (1) the availability of large open-access geological, geochemical and geochronological databases; (2) the spread of shared open-source software and workflows aiding data analysis; and (3) the rapid recent rise of open AI tools to extract new knowledge from a complex, hyperdimensional data volume through space and time. The pyGPlates and GPlately python libraries have particularly played an enabling role for allowing the analysis of plate models as well as geodata attached to tectonic plates. Together, these developments are catalysing the emergence of entirely new approaches to study deep time Earth system evolution. The applied drivers of deep-time geodata science are to a large extent tied to rapid climate change, the need to better understand potential future trajectories of Earth's surface environments and to enable a transition to renewable energy generation and an electrified transport sector. This transition demands a significant increase in exploration for and discovery of critical minerals below the well-explored surface. It is estimated that at least 384 new mines for graphite, lithium, nickel and cobalt alone are required to meet demand for battery energy storage by 2035. Deep-time Earth models allow the connection of traditional mineral exploration data to evolving tectonic and surface environments, providing the opportunity to build new approaches for better understanding the emplacement and preservation of mineral deposits. The societal and economic need to rapidly reduce our dependence on fossil fuel and to better understand the complex feedbacks between deep Earth, the hydrosphere, atmosphere and biosphere is invigorating the entire field of geology. I will briefly outline some emerging

applications of deep-time Earth system analysis and provide an outlook for the future.