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Modeling Ordovician ice sheet and the sea-level fingerprint of its collapse: toward a consistent picture of the Ordovician glaciation

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The Ordovician glaciation (∼445 Ma) represents the acme of one of only three major icehouse periods in Earth's Phanerozoic history. The ensuing deglaciation and associated transgression deeply affected depositional environments and critically impacted marine living communities, contributing to the Late Ordovician Mass Extinction. Nevertheless, the geometry of the Ordovician ice sheet remains crudely constrained and, in the absence of a better model, the major transgressive event that followed the collapse of the ice sheet is usually considered to be a uniform (i.e. eustatic) rise in sea level, which may lead to erroneous interpretations of the geological record. Here, using an Earth system model with an innovative coupling method between ocean, atmosphere and land-ice accounting for climate and ice-sheet feedback processes, we report simulations portraying the detailed evolution of the Ordovician ice sheet. We subsequently use the simulated ice sheet to force a gravitationally self-consistent model of sea-level change, allowing us to propose the first numerical simulation of spatially varying late Hirnantian sea-level rise.

1. Simulating Ordovician land ice

We show that the emergence of the ice sheet happened in two discrete phases. The continental ice sheet first appeared in a warm climate (pCO_2: 3360 ppm, global temperature: 24 °C), suddenly extending from the South Pole to the mid-latitudes. The land-ice front subsequently stabilized at these latitudes until CO_2 fell to 840 ppm. At this point, the abrupt spread of sea-ice to the mid-latitudes induced a global climate cooling by 10 °C, and the continental ice-front further advanced to the tropical latitudes.
The comparison with abundant sedimentological, geochemical and micropaleontological data suggests that glacial onset may have occurred as early as the Mid Ordovician Darriwilian (∼460 Ma), in agreement with recent studies reporting third-order glacio-eustatic cycles during the same period. The second step in ice-sheet growth, typified by a sudden drop in tropical sea-surface temperatures by ∼8 °C and the further extension of a single, continental-scale ice sheet over Gondwana, marked the onset of the Hirnantian glacial maximum.

2. Simulating the sea-level fingerprint of Late Ordovician ice-sheet collapse

We demonstrate major departures from eustasy and compare our modeling results to key sedimentary sections. We show that previously enigmatic opposite sea-level trends (i.e. transgressive vs. regressive) documented in the geological record are predicted by the model. Such sections may thus reflect patterns of sea-level change more complex than the eustatic approximation considered so far, rather than erroneous correlations. Our simulations also predict the locations where sea-level changes are closest to the eustatic rise and hence most representative of the volume of the ice sheet that collapsed over the South Pole. We identify these regions as preferential loci for future fieldwork investigating the ice volume during the Hirnantian glacial peak.