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# Spatial variation in Late Ordovician glacioeustatic sea-level change

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## ABSTRACT

Mass extinction of Late Ordovician marine fauna closely coincided with southern hemisphere glaciation. The sequence stratigraphic architecture of shallow marine deposits informs estimates of glacioeustatic sea-level change at sites both proximal and distal to the reconstructed Ordovician ice sheet(s) and contemporaneous changes in ice volume. A recent correlation framework for the stratigraphic architectures of one near and one far field Late Ordovician margin concluded that the Late Ordovician glaciation encompassed multiple long-term cycles of ice volume growth and retreat with superimposed higher frequency cycles. Here we posit that—similar to Cenozoic glacial cycles—glacial isostatic adjustment can preclude synchronous and similar magnitude (or directional) changes in Late Ordovician sea level between ice proximal and ice distal locations and, hence, distort a globally correlative sequence stratigraphy. We explored whether long-duration (i.e., million year) Late Ordovician glacial cycles should produce a globally coherent, eustatic record of sea-level change between ice proximal and ice distal margins using a gravitationally self-consistent theory that accounts for the deformational, gravitational and rotational perturbations to sea level on a viscoelastic Earth model. We adopted a Late Ordovician paleogeography and a synthetic continental ice-sheet distribution and volume informed by the areal extent of glaciogenic deposits and geochemical records, respectively. We demonstrate that modeled million year Late Ordovician glacial cycles produce sea-level histories on near and far field margins that differ from eustasy, and from one another, due primarily to elastic flexure and associated gravitational effects. While predicted far-field sea-level histories faithfully preserve the temporal structure of modeled glacioeustasy, their amplitude may differ from eustasy by as much as 30–40%. The impact of glacial isostatic adjustment is largest at the margins of glaciated continents, and these effects can be of the same order of magnitude as the eustatic, and even induce a local sea-level rise during an episode of ice growth and eustatic sea-level fall, and vice versa. In this regard, stratal surfaces of maximum regression and flooding expressed at near-field margins need not reflect global ('eustatic') trends in ice sheet growth and decay, respectively, and thus may not provide chronostratigraphic horizons for correlation with far-field sequence stratigraphic architectures.

## 1. Introduction

Continental ice sheets expanded across southern Gondwana during the Late Ordovician, and the attendant ocean–atmosphere cooling and glacioeustatic sea-level fall likely initiated the Late Ordovician Mass Extinction (Hallam and Wignall, 1999; Sheehan, 2001; Finnegan et al., 2012). Compelling sedimentological, stratigraphic and geochemical evidence for glaciation appears in sedimentary basins both proximal and distal to reconstructed Ordovician ice centers, yet these local records produce contrasting and, at times, conflicting reconstructions of the duration, areal extent, and volume of the Ordovician glaciation (Brenchley, 1994).

The absence of pre-Hirnantian glaciogenic deposits contributes to the view that a short-lived glaciation began and ended within the Hirnantian Stage (445.2 ± 1.4–443.8 ± 1.5 Ma; Brenchley, 1994; Finney et al., 1999; Sutcliffe et al., 2000, 2001; Loi et al., 2010), or persisted locally into the Silurian Period (Landovery Stage: 443.8 ± 1.5–433.4 ± 0.8 Ma; Hambrey, 1985; Grahn and Caputo, 1992; Díaz-Martínez and Grahn, 2007; Le Heron and Craig, 2008). Nested surfaces of glacial erosion intercalated with peri-Gondwana marine strata evidence dynamic intra-glacial ice advance and retreat and delimit the maximum areal extent of Gondwanan ice, reveal-

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ing that, locally, the grounding line reached the continental shelf–slope break (Hambrey, 1985; Sutcliffe et al., 2000; Ghienne, 2003; Le Heron et al., 2007; Le Heron and Craig, 2008).

In contrast to the short-lived glaciation deduced from ice-proximal, glaciogenic strata, hierarchical stratigraphic cycles that extend across non-glaciated, ice proximal and far-field continental margins of Darriwilian–Hirnantian age (467.3 ± 1.1–443.8 ± 1.5 Ma) most parsimoniously reflect glacioeustatic sea-level change induced by frequent expansions and contractions of Gondwanan ice sheets with inferred Milankovitch frequencies (e.g., Saltzman and Young, 2005; Desrochers et al., 2010; Loi et al., 2010; Turner et al., 2012; Elrick et al., 2013; Ghienne et al., 2014; Dabard et al., 2015). The characteristically condensed Hirnantian stratigraphic records from far-field successions typically encompass an erosion surface (sequence boundary) onlapped by transgressive lithofacies; ostensibly, these features reflect a single episode of glacial advance, maximum, and retreat, though these surfaces could conceal a more nuanced glacioeustatic history during glacial maximum (Ghienne et al., 2014).

Recently revised, high-resolution sequence stratigraphic frameworks for archetypal near-field (glaciated) and far-field (non-glaciated) locations in the Anti-Atlas Mountains of Morocco and Anticosti Island, Canada, respectively, appear to resolve discrepancies between ice proximal and ice distal stratigraphies and instead reveal a coherent, global glacioeustatic sea-level history (Desrochers et al., 2010; Ghienne et al., 2014). Ghienne et al. (2014) sequentially correlated the bounding surfaces of three latest Katian–Hirnantian low-order genetic stratigraphic sequences—and a handful of subordinate, higher order and lower significance maximum regressive and maximum flooding surfaces—between the two locations. While this method allows for diachroneity on surfaces at a temporal resolution below that afforded by biostratigraphy, it assumes that fluctuations in global ice volume produce glacioeustatic sea-level rise or fall everywhere the same on the Ordovician paleoglobe, unless modulated by tectonic/geodynamic changes in base level and/or local sediment supply. For sites unaffected or similarly affected by these confounding factors, or for sites in which backstripping procedures removed these signals, the (glacio)eustatic conceptual model only considers correlation of equivalent stratal surfaces valid; for instance, under no circumstance would a maximum flooding surface at a near field location correspond temporally to the maximum regressive surface at a far field site because that would imply that global ice-volume change could simultaneously produce glacioeustatic sea-level rise at one location and glacioeustatic sea-level fall at the other.

However, a variety of physical markers for past sea level during Cenozoic glaciations and ongoing geodetic observations demonstrate that viscoelastic deformation and local ice gravitation—physical processes collectively described as glacial isostatic adjustment (GIA)—produce site-specific time-histories of sea-level change that may differ substantially from the eustatic, or global mean, sea-level curve produced by the melting of ice sheets (e.g., Milne and Mitrovica, 2008; Raymo et al., 2011; Stocchi et al., 2013). For instance, the post-glacial uplift and emergence of shelves surrounding formerly glaciated regions, like Hudson Bay (Andrews, 1970), contrasts with the prolonged submergence of far-field sites like Barbados (Peltier and Fairbanks, 2006), though both occurred during late Pleistocene–Holocene 'glacioeustatic' sea-level rise. Hence, local differences in relative sea level, and concomitant opposing trends in the creation and destruction of accommodation space, can characterize glacioeustasy. Thus, for certain Cenozoic glacial scenarios, corresponding stratal surfaces at near and far field locations—for instance, sequence boundaries or maximum flooding surfaces—neither correlate globally nor carry chronostratigraphic significance. Could this also be true for the Late Ordovician? We sought to explore the circumstances in which ice proximal and ice distal stratigraphies provide a unified and accurate reconstruction of Late Ordovician glacioeustasy.

Determining whether and how stratigraphic inferences of Late Ordovician local sea level differ from eustasy depends on robust constraints on numerous factors, including the temporal history of the volume and location of Ordovician ice; the rheological properties of the solid Earth; the location of paleocontinents; the shelf bathymetry, shoreline geometry, and topography of these continents; and the temporal changes in sediment supply to each margin. Uncertainties in the Ordovician-relevant values for these parameters preclude numerical predictions of site-specific sea-level change of sufficient accuracy to fit inferences determined from careful sequence stratigraphic analysis. Such models can, however, provide qualitative, physical insight into questions about ancient ice configuration, volume, and melt history (e.g., Creveling and Mitrovica, 2014). To this end, this study explores the spatial and temporal variation in sea level induced by the glaciation and deglaciation of a modeled Late Ordovician ice sheet covering southern Gondwana using a theory that accounts for the deformational, gravitational and rotational perturbations to sea level on a viscoelastic Earth model (Mitrovica and Milne, 2003; Kendall et al., 2005). Here we demonstrate that (i) the histories of sea-level change along continental margins both near- and far afield of the Late Ordovician ice sheet can differ substantially between locations, as well as deviate from the glacioeustatic curve; (ii) reconstructions of glacioeustasy from far-field margins may not faithfully reflect the magnitude of glacioeustasy; and, (iii) by inference, the stratal surfaces of transgression and regression developed at near-field margins may, counter-intuitively, result from ice sheet growth and melt, respectively, and thus may not serve as chronostratigraphic horizons for correlation to far-field stratigraphies.

## 2. A model Late Ordovician glaciation

### 2.1. Paleogeography and ice volume history

Paleomagnetic reconstructions of Late Ordovician paleogeography similarly place Gondwana in a south polar position and distribute three large landmasses—Laurentia, Baltica, and Siberia—across the equatorial latitudinal band (Killian et al., 2016; Torsvik and Cocks, 2017; Blakey, 2008), though models differ in the exact paleolatitude and the position of minor landmasses and island arc terranes. Here we adapt the 450 Ma paleogeography of Torsvik and Cocks (2017) with a revised ∼10° northeastward shift of Laurentia following Swanson-Hysell and Macdonald (2017) (Fig. 1A).

In detail, the paleotopography and paleobathymetry of Ordovician continents are not well resolved. Coupled climate–ice sheet models parameterized for the Ordovician reveal an insensitivity of the areal extent of ice to modeled continental topography (Pohl et al., 2016). Thus, we followed Creveling and Mitrovica (2014) and prescribed an initial paleotopography consistent with modern mean elevations. Modeled continental interiors have an elevation of 850 m that linearly tapers to sea level (0 m) within 350 km of any shoreline; oceanward of the shoreline, the modeled continental shelf deepens to −150 m across a distance of 80 km, then to −2000 m over the next 30 km (the continental slope), and to −3800 m over the next 300 km (the continental rise) to the depth of the modeled abyssal plain (Fig. 1B).

The time history of Ordovician–Silurian ice volume adopted here follows the reconstruction of Finnegan et al. (2011) who leveraged clumped isotope paleothermometry to deconvolve the trend in Ordovician $\delta^{18}O_{carb}$ imparted by continental ice growth from the signal of coeval seawater temperature change. This ice history, expressed in units of globally uniform sea level equivalent (SLE), expands from ice free conditions (0 m SLE) at 449 Ma to a Hirnantian glacial maximum (henceforth, HGM) at 444.5 Ma