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Late Ordovician mass extinction: A new perspective from stratigraphic sections in central Nevada

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ABSTRACT

Integrated sequence stratigraphic, biostratigraphic, and chemostratigraphic analyses of three stratigraphic sections in central Nevada indicate that Late Ordovician glaciation-induced sea-level fall produced diachronous, stepwise faunal turnover in graptolites, conodonts, chitinozoans, and radiolarians, and also triggered a strong, but transient, positive δ^{13}C excursion. This pattern is very different from that described for most mass extinction events.

INTRODUCTION

The Late Ordovician mass extinction, which eliminated 60% of marine genera, was the second greatest of the "Big Five" Phanerozoic mass extinctions (Sepkoski, 1995). As the one mass extinction that can be linked temporally to glaciation and a glacioeustatic sea-level drop (Brenchley et al., 1995; Gibbs et al., 1997), it provides an instructive example of the possible relationships between dramatic biotic changes and Earth systems perturbations.

An exceptional record of the Late Ordovician glacioeustatic event along a basin to mid platform transect is contained within three sedimentary successions in central Nevada: the uppermost Vinini Formation in the Roberts Mountains, and the Hanson Creek Formation in the Monitor Range and at Lone Mountain (Fig. 1). Although many Upper Ordovician stratigraphic sections worldwide were described in discussions of the Ordovician-Silurian boundary (Cocks and Rickards, 1988), most are deficient within the glacioeustatic interval. The Nevada sections, in contrast, are uniquely complete through critical parts of the Upper Ordovician and include: distinct sedimentological signals of sea-level change; abundant graptolites and conodonts, as well as organic- and siliceous-walled microfossils; and well-preserved δ^{13}C profiles. These multiple components provide an unparalleled opportunity to assess linkages between the Late Ordovician glaciation, glacioeustasy, biological extinction, and carbon cycle disruption.

VININI CREEK, ROBERTS MOUNTAINS

An ~30-m-thick section of uppermost Vinini Formation is continuously exposed in a hillside trench at Vinini Creek (Finney et al., 1997). The off-platform to basin strata consist of periplatform and pelagic sediments (Fig. 2). Biostratigraphic records of graptolites, conodonts, and chitinozoans are excellent, in particular through the *N. extraordinarius* graptolite zone, to which the Gondwanan glaciation and Late Ordovician mass extinction are correlated (Brenchley, 1989). The boundary between the *D. ornatus* and *P. pacificus* graptolite zones is within the lower part of a 9-m-thick succession of dark gray to black, organic-rich mudstone (20% total organic carbon) with hydrogen-rich (HI = 400–600) kerogen. The graptolite fauna was at maximum diversity (16 species) and abundance during deposition of these sediments.

In the uppermost *P. pacificus* zone, the dominant lithology changes gradationally over 1.45 m from black, organic-rich, siliceous mudstone to

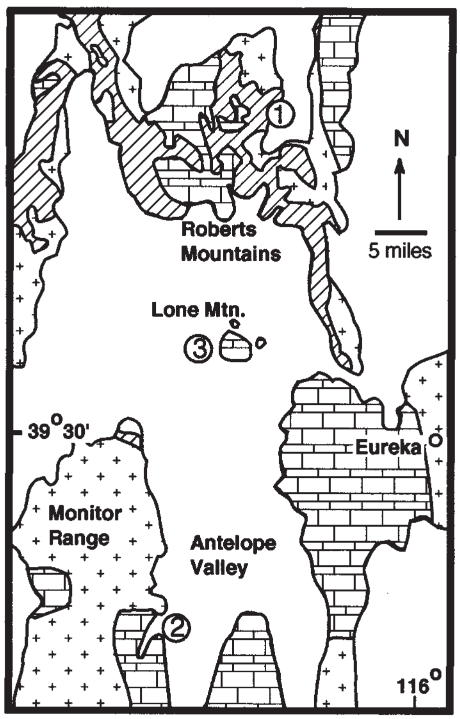

Figure 1. Index map of north-central Nevada showing location of (1) Vinini Creek section in Roberts Mountains, (2) Monitor Range section in Copenhagen Canyon and Martin Ridge area, and (3) Lone Mountain section. Brick pattern represents Cambrian to Devonian mainly carbonate platform rocks of lower plate of Roberts Mountains thrust; diagonal pattern is Roberts Mountains allochthon; cross pattern is Cenozoic volcanic rocks.

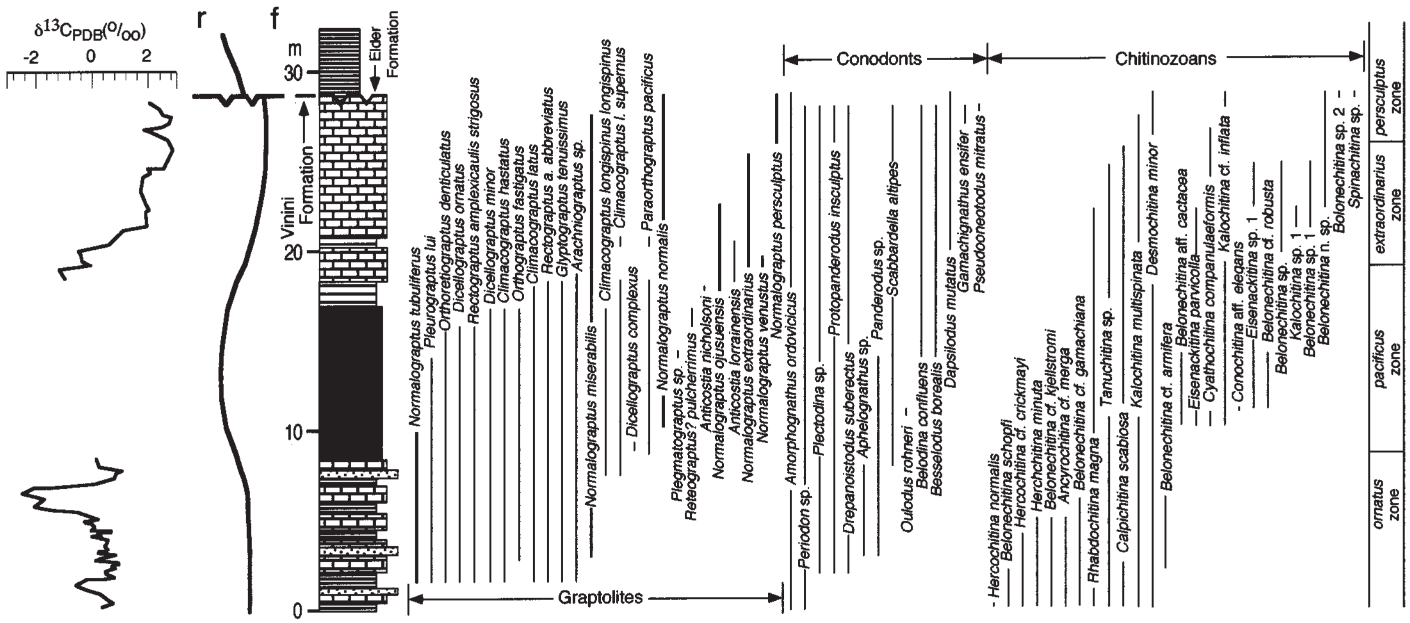

Figure 2. Vinini Creek section showing uppermost 28.75 m of Vinini Formation and lowest 4 m of Elder Formation, curve of rising (r) and falling (f) sea level, δ^{13}C profile, ranges of graptolite, conodont, and chitinozoan species, and graptolite zonation. See Finney et al., (1997) for detailed stratigraphic logs and descriptions. PDB is Peedee belemnite. Thicker range bar for species of *Normalograptus*.

brown mudstone to light gray lime mudstone. This sedimentological record of shallowing is interpreted to signal the eustatic sea-level drawdown triggered by Gondwanan glaciation. It correlates biostratigraphically to distinct sedimentological records of sea-level change worldwide (Brenchley, 1988). Graptolite diversity decreases substantially to 7 species and then 3 species at the base and top, respectively, of the *N. extraordinarius* zone.

This decrease in diversity is the graptolite record of the Late Ordovician mass extinction. It correlates with virtually identical faunal changes in graptolite successions at Mirny Creek, northeast Siberia (Koren et al., 1988), at Dob's Linn, Scotland (Williams, 1983), in the Canadian Arctic Islands (Melchin et al., 1991), and on the Yangtze platform of China (Mu, 1988). At Vinini Creek, as at Mirny Creek, species of the *ornatus-pacificus* zones disappear in a stepwise manner. Graptolite diversity reaches a minimum in the uppermost 9.75 m of the Vinini Formation (Fig. 2) within a succession of lime mudstone that records a sustained sea-level lowstand in the *N. extraordinarius* and early *N. persculptus* zones. Graptolite specimens are common in the lime mudstone, but the fauna includes only three species of the evolving *Normalograptus* lineage. The appearance of *N. persculptus* at 7 m in this uppermost interval heralds the reradiation of graptolites. The disconformable contact with the overlying Elder Formation, which has middle Llandovery (Aeronian, *M. convolutus* zone) graptolites at its base, records the maximum sea-level lowstand.

Conodonts typical of the Upper Ordovician *A. ordovicicus* conodont zone occur relatively unchanged through the *P. pacificus* and *N. extraordinarius* zones and into the lower *N. persculptus* zone. Chitinozoans show the same pattern. Radiolarians are present throughout the section, but are poorly preserved and commonly calcitized. A positive excursion in δ^{13}C values begins near the base of the *N. extraordinarius* zone with values rising from –2‰ to 3+‰ at the overlying disconformity where it is truncated. As with the graptolite extinction, the initiation of the positive excursion coincides stratigraphically with the facies change recording sea-level drawdown.

MONITOR RANGE

The Monitor Range section (Fig. 3) is a composite of the slightly overlapping Martin Ridge and Copenhagen Canyon sections (Finney et al., 1997). It represents deposition in an embayed platform margin and anchors the more oceanward, basinal Vinini Creek section and the more inboard, mid platform Lone Mountain section. Here, the lower half of the Hanson Creek Formation consists of ~125 m of monotonous dark gray to brown-gray, thin-bedded lime mudstone rich in a diverse open-marine fauna that includes graptolites, conodonts, chitinozoans, and radiolarians. The *ornatus-pacificus* graptolite zonal boundary is at the 90 m level in the section. *P. pacificus* zone graptolites disappear at 126 m at the base of a cliff-forming, chert-bearing interval, coincident with a shallowing event expressed by increase in bedding thickness and carbonate. Also, at 126 m, conodonts that inhabited basinal environments are replaced by those of shelf and slope environments.

Graptolites reappear briefly between 146 and 152 m, during a short-lived deepening event recorded by darker gray, more shaley rocks. Above 152 m, *P. pacificus* zone graptolites, conodonts, chitinozoans, and radiolarians disappear coincident with a renewed and dramatic shallowing phase expressed by rapid vertical facies changes that culminate in several meters of light gray, cross-stratified grainstone capped by quartz sandy, oolitic dolograinstone (Finney et al., 1997). The shallowing interval is accompanied by a change in siliceous sponge spicules from deep-water, hexactinellid-dominated assemblages to lithistid-dominated assemblages indicative of shallow subtidal conditions. The oolitic dolograinstone is sharply overlain by 1–6 cm of orange-brown, fine quartz arenite that veneers a corroded, irregular surface at 187 m. This exposure surface, correlated with the lower part of the *N. persculptus* graptolite zone (Fig. 3), signals the maximum sea-level lowstand produced by Late Ordovician glaciation.

Above the quartz arenite is several meters of medium gray wackestone with open-marine fauna and dolomitized burrows. This shallow subtidal facies is followed abruptly by a thick succession of deeper marine, dark gray lime mudstone with abundant chert nodules and stringers. Conodonts, graptolites, and organic-walled microfossils are missing from strata equivalent to the *N. extraordinarius* and lower *N. persculptus* zones, but reappear in the lower part of this upper cherty succession. The sparse graptolite fauna represents the upper part of the *N. persculptus* zone. Conodonts and chitinozoans are considered typical of the Early Silurian.

The carbon isotopic composition of marine carbonates undergoes several rapid changes in the Monitor Range section (Fig. 3). A sharp 2‰ drop in δ^{13}C values occurs at 146 m within the

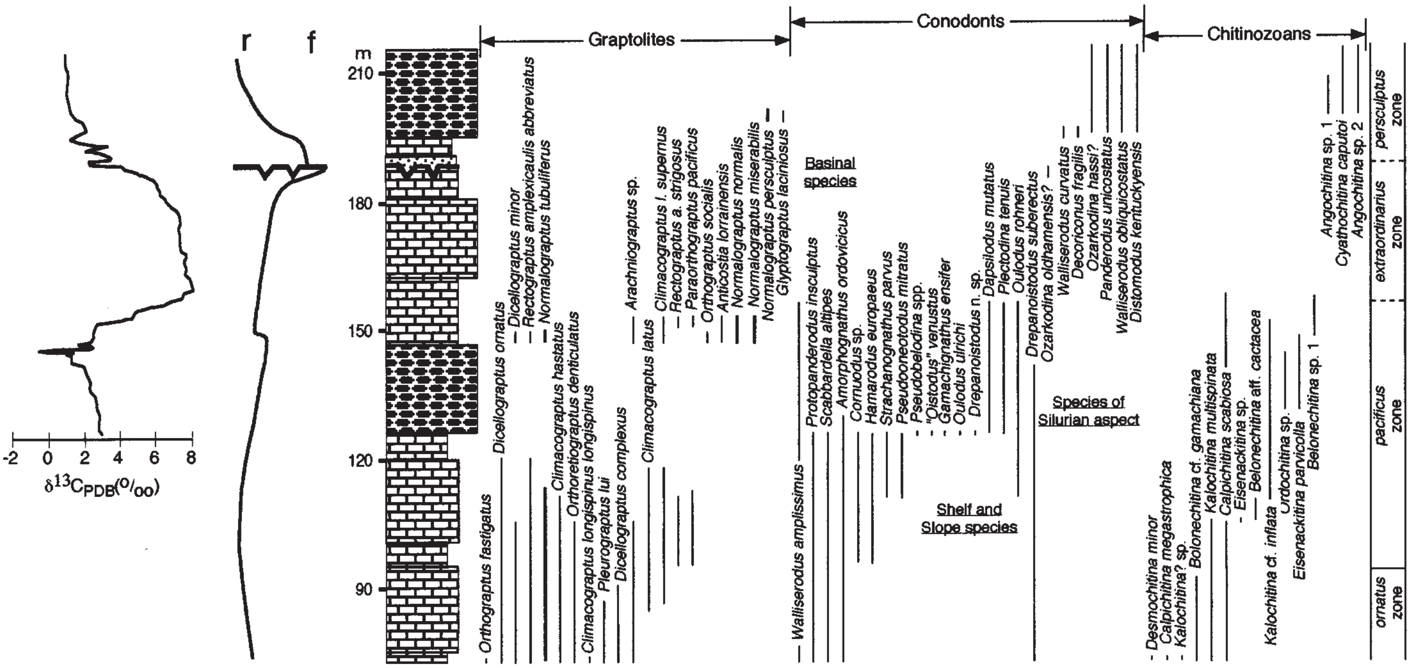

Figure 3. Monitor Range composite section showing stratigraphy of middle part of Hanson Creek Formation, sea-level curve (r—rising, f—falling), $\delta^{13}C$ profile, ranges of graptolite, conodont, and chitinozoan species, and graptolite zonation. See Finney et al., (1997) for detailed stratigraphic logs and descriptions. PDB is Peedee belemnite. Thicker range bar for species of *Normalograptus*.

upper 50 cm of the lower chert-bearing unit. In the shaly rocks between 146 and 152 m, $\delta^{13}C$ values return to previous levels. A major positive excursion in the $\delta^{13}C$ values begins at 152 m. Values rise rapidly to >7‰ and remain above >6‰ through the next 25 m, then decline. Above the exposure surface (187 m), $\delta^{13}C$ values decline more rapidly, coincident with sedimentological evidence for sea-level rise. They vary abruptly through the next 10 m. At 198 m, coincident with the reappearance of abundant chert, $\delta^{13}C$ values return to virtually the same levels of the lower chert-bearing unit.

LONE MOUNTAIN

The Hanson Creek Formation at Lone Mountain (Fig. 1) is developed as a heterogeneous succession of pervasively dolomitized shallow-marine facies (Finney et al., 1997). Graptolites and chitinozoans are absent from this mid platform section, but conodonts are locally abundant (Fig. 4) and were first sampled and described by Leatham (1987). An irregular, oxidized surface at 79 m separates karstified dolograinstone below from a 1 m bed of cross-stratified quartz arenite that grades up into sandy dolostone and contains terra rosa-stained clasts in its basal part (Fig. 4). Conodonts biostratigraphically tied to graptolites in the Monitor Range and Vinini Creek sections suggest that the upper part of the section below the sandstone is equivalent to the lower *N. extraordinarius* zone. Conodonts above the sandstone are clearly Silurian. No positive $\delta^{13}C$ excursion is recognized in this section. Pervasive dolomitization compromises the $\delta^{13}C$ values, and much of the excursion-bearing interval is missing at the unconformity below the sandstone.

DISCUSSION

The prominent surfaces covered by quartz sandstone at 79 m at Lone Mountain and at 187 m at Monitor Range are bracketed by biostratigraphic correlations and represent the same regional erosion event. This platform-wide type-1 sequence boundary, which is mantled by transgressive sand, caps a rapidly shallowing facies succession that signals a sea-level drawdown. The timing is consistent with the sea-level drop accompanying the global Hirnantian glacio-eustatic event (Brenchley et al., 1995). In the Vinini Creek section, the sea-level lowstand is expressed by the disconformity at the top of the uppermost lime mudstone. This surface of omission represents maximum lowstand when the platform was exposed, precluding periplatform sedimentation.

The environmental change driven by sea-level drawdown had a drastic effect on the faunas, but one that produced stepwise extinction. The graptolite extinction and the last occurrence of radiolarians were significantly earlier than the turnover in conodont and chitinozoan faunas. Graptolites were affected first because their shelf-margin upwelling habitat (Finney and Berry, 1997) was sensitive to the initiation of shallowing, and extinction was diachronous across habitats, with faunal change directly linked to the sedimentological record of sea-level drawdown. Inboard habitats and populations over

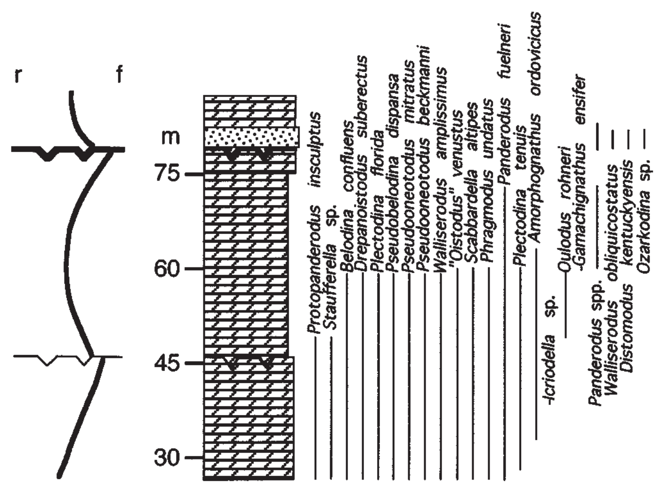

Figure 4. Lone Mountain section showing stratigraphy of middle part of Hanson Creek Formation, sea-level curve (r—rising, f—falling), and ranges of conodont species. See Finney et al., (1997) for detailed stratigraphic logs and descriptions. Conodont data from Leatham (1987).

the outer platform, as represented in the Monitor Range section, were lost first. Outboard habitats and populations over the continental slope, rise, and adjacent basin, represented in the Vinini Creek section, disappeared later and coincide with the global turnover in graptolite faunas.

While graptolite diversity dropped dramatically from the upper *P. pacificus* to the lower *N. extraordinarius* zone, one graptolite genus, *Normalograptus*, evolved and flourished. From its few species the post-extinction morphological radiation would later develop in the *N. persculptus* zone (Melchin and Mitchell, 1991). Diversification of *Normalograptus* indicates that some graptolite habitats were maintained while simultaneously others were lost. The stepwise extinction affected common species that occur regularly through the section. It coincided with rapidly deteriorating environmental conditions that caused rapid habitat migration and loss.

Disappearances of conodonts and chitinozoans from the mid platform Lone Mountain section out to the basinal Vinini Creek section resulted from sequential and diachronous disappearance of favorable environments as evidenced by the replacement of basinal species by shelf and slope species in the Monitor Range section (Fig. 3) and the persistence of basinal species in the Vinini Creek section (Fig. 2) to the time of maximum lowstand. These extinctions lagged behind those of graptolites because the overall platform environmental conditions were maintained longer during the sea-level drawdown; hence, their turnover occurred closer to the time of maximum sea-level lowstand than the initiation of sea-level fall.

Our discovery that faunal changes were diachronous between sections and differed in timing between faunal groups leads us to term the Late Ordovician mass extinction event as the Late Ordovician faunal turnover, a protracted environmental crisis that was driven by sea-level change.

The restriction of anomalously high $\delta^{13}C$ values to an interval bracketed by sedimentological evidence for sea-level fall suggests that changing burial flux relationships within the marine carbon reservoir were driven by sea-level fluctuations. As a result, the inferred sharp increase in the sequestration of isotopically light organic carbon (^{12}C) during the excursion interval was likely the result of glaciation and sea-level fall. A linear trend in carbon isotope values bracketing the excursion (Fig. 3) suggests the increase in sequestration of isotopically light, organic carbon required to drive the excursion was a transient event that only briefly perturbed the marine carbon cycle (Ripperdan et al., 1998). Any apparent, significant relationship between variation in $\delta^{13}C$ values and faunal turnover is most likely fortuitous. Falling sea-level drove both changes independently.

CONCLUSIONS

The central Nevada sections provide a unique perspective for understanding the temporal and causal relationships between glaciation, sea-level change, faunal turnover, and carbon isotope excursions in the Late Ordovician. The Hirnantian glaciation (Gibbs et al., 1997) precipitated a dramatic global sea-level fall and resulted in environmental changes that devastated local ecologies. Graptolites, conodonts, chitinozoans, and radiolarians provide strong evidence for a series of diachronous faunal turnovers, during which some species diversified, rather than the classic single catastrophic annihilation. Strong changes in $\delta^{13}C$ values of marine carbonate are related directly to sea-level change.

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