The Search for Sedimentary Evidence of Glaciation during the Frasnian/Famennian (Late Devonian) Biodiversity Crisis

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INTRODUCTION

The cause of the Late Devonian (Frasnian/Famennian) biodiversity crisis remains controversial. Over 36 years of amassed empirical biological data have been used to argue for a causal link between global cooling and the Frasnian/Famennian extinctions (for a review of the data see McGhee 2013, 2014). In particular, glaciation produced by global cooling has long been proposed to have been a trigger for the Frasnian/Famennian extinctions (Caputo and Crowell 1985, Caputo 1985, Streel et al. 2000a, 2000b, Isaacson et al. 2008). However, decades of searching have failed to uncover sedimentary evidence for glaciation in late Frasnian strata on the landmass of Gondwana (in South America and Africa). In this paper I will argue that this is to be expected, and that the continent of Gondwana is the wrong locality to search for such evidence.

SEDIMENTARY EVIDENCE OF LATE DEVONIAN GLACIATION

Late Famennian Evidence: Sedimentary evidence for massive glaciation on Gondwana in the late Famennian, at the end of the Late Devonian, is unequivocal. Biostratigraphically-dated glacial tillites (Fig. 1), glacial striated pavements and clasts (Fig. 2), and ice-rafted dropstones are widespread in western Gondwana (South America and Africa; Caputo et al. 2008, Isaacson et al. 2008) where continental ice sheets covered 16×10^6 km^2 of land at the very minimum, and were probably much larger. In Laurussia, late Famennian glacial tillites produced by lowland glaciers as close as 30°S to the equator are present in the Appalachian basin (Fig. 3), glacioeustatically-produced incised valleys that are 75 m to 90 m deep are present in both North America and Europe, and decimeter- to meter-sized ice-rafted dropstones are present in offshore marine sediments (Brezinski et al. 2010). The depth of the late Famennian incised valleys approaches the valley incision depths of 100 m seen in the Pleistocene glaciations, thus suggesting a late Famennian glacial severity approaching that of the Pleistocene.

Late Frasnian Enigmas: In contrast to the Famennian, the hypothesis that glaciers were present in the late Frasnian world remains highly controversial. However, sedimentary evidence for glaciation and glacioeustacy in the late Frasnian has increased steadily over time. Filer (2002) has demonstrated the existence of numerous sedimentary cycles in late Frasnian subsurface strata that are continuous over 700 km, revealed in the analysis of data from over 600 gamma-ray logs from hydrocarbon test wells in the Appalachian basin, and has argued that these cycles are evidence of glacioeustatic sea-level changes. McClung et al. (2013) have traced 12 of these Frasnian sedimentary cycles from the subsurface to surface outcrops and have argued that the ability to correlate these cycles in both outcrop and subsurface, and both parallel and perpendicular to depositional strike, consistent with the hypothesis that the sedimentary cycles are the product of glacioeustatic sea-level fluctuations. Moreover, McClung et al. (2013) have estimated that these 12 sedimentary cycles had a temporal periodicity around 375 kyr and have measured over 70 smaller-scale sedimentary cycles in outcrop with an estimated periodicity of around 65 kyr, cyclic frequencies that are similar in magnitude to the long-term orbital eccentricity and axial obliquity Milankovitch cycles seen in the Cenozoic glaciations (Zachos et al. 2001). Last, McClung et al. (2013) have also demonstrated the existence of incised-valley fills in outcrop which they argue to have been produced by a sea-level fall of some 35 m to 40 m, a late Frasnian glacioeustatic sea-level fall about half the magnitude of the sea-level fall that produced the incised valleys in the late Famennian.

As yet, evidence for late Frasnian glaciation is found only outside of Gondwana. On Gondwana all efforts to find late-Frasnian-age glacial striated pavements and tillites, similar to those found in the late Famennian, have failed. The western edge of the landmass of Gondwana was positioned over the South Pole in the Frasnian as well as in the Famennian (McGhee 2013, plates 10 and 11)—where then were the Frasnian glaciers? I argue that a closer examination of the pattern of glacial onset seen in the Cenozoic ice age may explain the enigma of the absence of sedimentary evidence of late Frasnian glaciation on the Gondwana landmass.

***Figure 1:** Late Famennian Cumaná outcrop with very large granite and other clasts of various lithologies, Quebrada Chamacani, Peninsula de Copacabana (Díaz-Martínez et al., 1999).*

COMPARATIVE ANALYSIS OF LATE DEVONIAN AND CENOZOIC GLACIAL AND BIOTIC EVENTS

Only two icehouse intervals exist in the Phanerozoic in which glaciation persisted for tens of millions of years: the late Paleozoic and the Cenozoic (see the discussions in Fielding et al. 2008). The onset of the Cenozoic glaciations occurred in two steps: the first step glaciation took place in the early Oligocene, followed by a warming period, and the second step glaciation took place in the middle Miocene (Lewis et al. 2008). If the Late Devonian glaciations also took place in two steps, the late Frasnian and then the late Famennian, then the timing of the onset of proposed glaciation and of associated extinction pulses in the Devonian and the Cenozoic icehouse intervals is striking similar. In the onset of the Cenozoic ice age the time interval between the first step extinctions in the Oligocene (33–32 Ma) and second step extinctions in the Miocene (14–13 Ma) was 19 Myr and in the proposed onset of the Devonian ice age the time interval between the Frasnian (376–375 Ma) and Famennian (360–359 Ma) extinctions was 16 Myr (for detailed discussion see McGhee 2013). The sequential severity of the extinctions was also the same: in the onset of the Cenozoic ice age the first step Oligocene extinctions were much more severe than the second step Miocene (Prothero 1994, Prothero et al. 2003) and in the proposed onset of the Devonian ice age the first step Frasnian extinctions were much more severe than the second step Famennian (McGhee et al. 2013). Last, the Oligocene cooling event triggered continental glaciation that persisted for 8 Myr (Zachos et al. 2001) and the Frasnian cooling event triggered a cold interval, the Famennian Gap, that persisted for 7 Myr (McGhee 2013). If the Earth cooled at a similar rate in the Cenozoic and Devonian then the temporal spacing and magnitudes of extinction seen in these two time intervals may not be coincidental.

In addition, both the Miocene and Famennian glaciations were characterized by positive carbon-isotope anomalies (+0.8‰ $\delta^{13}C$ and +1.2‰ $\delta^{13}C$, respectively; Zachos et al. 2001, Kaiser et al. 2006), oxygen-isotope increases

Figure 2:** Late Famennian large striated sandstone clast in Cumaná Formation diamictite, Hinchaka locality, Peninsula de Copacabana, Bolivia* **altiplano.** ***Photograph courtesy of Dr. Enrique Díaz-Martínez, Instituto Geológico y Minero de España, Madrid.

(0.3–1.0‰ $\delta^{18}O$ and 0.8–1.2‰ $\delta^{18}O$; Flower and Kennett 1995, Kaiser et al. 2006), drops in sea-surface temperature (6–7°C drop in the Miocene and at least a 2–4°C drop in the Famennian, based on partial data; Shevenell et al. 2004, Kaiser et al. 2006), and sea-level falls (55–60 m and 60–90 m; Westerhold et al. 2005, Isaacson et al. 2008, Brezinski et al. 2010). The areal expanse of the Miocene ice sheet has been estimated to have been in the range of 14.0–16.8 × 10^6 km^2 (Westerhold et al. 2005, Wilson and Luyendyk 2009) and the Famennian ice sheet covered at least 16 × 10^6 km^2 (Isaacson et al., 2008). Likewise, both the Oligocene and proposed Frasnian glaciations were characterized by positive carbon-isotope anomalies (+0.8‰ $\delta^{13}C$ and +3.0‰ $\delta^{13}C$, respectively; Zachos et al. 2001, Joachimski and Buggisch 2002), oxygen-isotope increases (0.5–1.0‰ $\delta^{18}O$ and 1.0–1.5‰ $\delta^{18}O$; Pusz et al. 2011, Joachimski and Buggisch 2002), drops in sea-surface temperature (3–4°C drop in the Oligocene, based on partial data, and a 5–7°C drop in the Frasnian; Wade et al. 2012, Joachimski and Buggisch 2002), and sea-level falls (45–90 m and 35–45 m; Pusz et al. 2011, McClung et al. 2013). The areal coverage of land by the Oligocene ice sheet has been estimated to have been in the range of 7.0–11.9 × 10^6 km^2 (Zachos et al. 2001, Pusz et al. 2011) and I have estimated the areal expanse of the potential Frasnian ice sheet to have been in the range of 8–11 × 10^6 km^2 (McGhee 2014).

Sedimentary evidence for the existence of glaciers in the late Famennian is undisputed, it is the existence of glaciers in the proposed first step in the Late Devonian glaciations, the late Frasnian, that remains disputed. Interestingly, this evidential relation between the proposed two steps in the onset of Devonian glaciations is also very similar to that of the two steps in the onset of Cenozoic glaciations: sedimentary evidence for the existence of glaciers in the second step of the Cenozoic glaciations, the middle Miocene, is undisputed (Lewis et al. 2008). However, evidence for glaciation in the first step, the early Oligocene Oi-1 glaciation, is much more tenuous.

Figure 3: Late Famennian Spechty Kopf diamictite, Interstate 81, approximately 3 miles south of Wilkes-Barre, Pennsylvania. Photograph courtesy of Dr. Peter Isaacson, Department of Geological Sciences, University of Idaho.

The problem is that Oi-1 glacial sediments on land in Antarctica have been removed by the erosive action of the larger middle Miocene glaciers, with two possible exceptions (Strand et al. 2003, Ivany et al. 2006). The size of the first step Oi-1 glaciers has been estimated to have been in the range of 7.0–11.9 × 10^6 km^2 (Zachos et al. 2001, Pusz et al. 2011). In contrast, the size of the second step Miocene glaciers has been estimated to have been in the range of 14–16 × 10^6 km^2 (Westerhold et al. 2005, Wilson and Luyendyk 2009), totally covering the expanse of and erasing the trace of the initial Oligocene glaciers on the Antarctic landmass. Thus the best independent sedimentary evidence for the existence of the Oi-1 glaciation is glacially-derived, ice-rafted debris in marine sediments. Zachos et al. (1992) have documented the presence of layers of angular quartz sands and heavy minerals at the Oi-1 stratigraphic level on the Kerguelen Plateau in the southern Indian Ocean. These layers contain over 200 grains per gram of clastic grains that are larger than 250 μm, which are argued to be too large to have been transported offshore from Antarctica by wind and thus must have been transported by ice (Zachos et al. 1992). In addition, Ehrmann and Mackensen (1992) reported the presence of gravels and pebbles at the same stratigraphic horizon containing the ice-rafted sand deposits on the Kerguelen Plateau. The presence of gravel in offshore marine deposits is unequivocal evidence of ice rafting, and the presence of ice-rafted debris as far north as 61°S is argued to be evidence of either a high frequency of icebergs in the area, or of a few large debris-containing icebergs, both of which evidence large-scale continental Oi-1 glaciation rather than small-scale local glaciation in Antarctica (see discussion in Ehrmann and Mackensen 1992).

PREDICTIVE SEDIMENTOLOGY: A FIELDWORK CHALLENGE TO TEST THE LATE FRASNIAN GLACIATION HYPOTHESIS

I suggest that glacial sediments of late Frasnian age never will be discovered

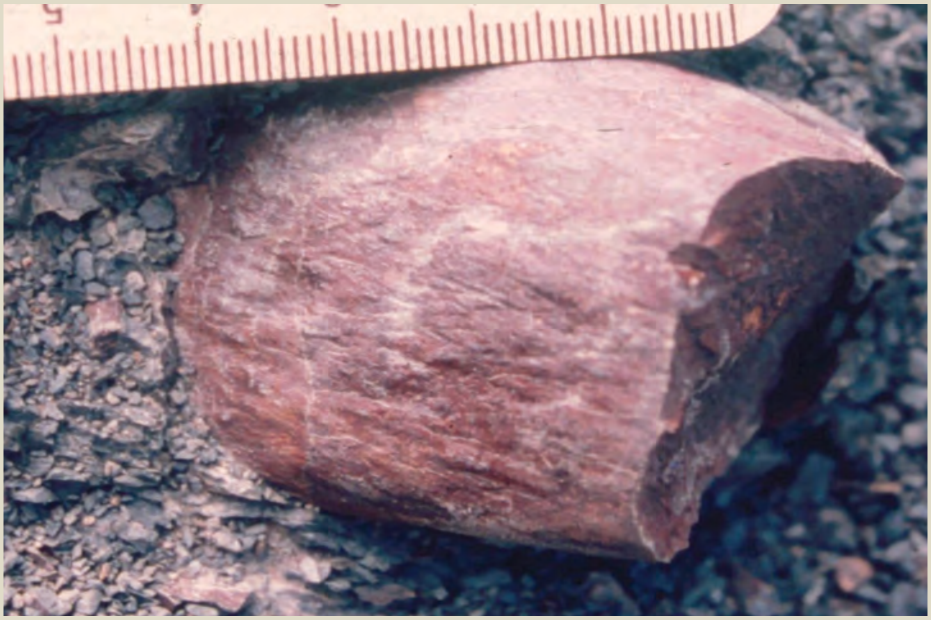

Figure 4: Late Famennian striated dropstone contained within marine shale from the Cumaná Formation, Hinchaka locality, Peninsula de Copacabana, Bolivia **altiplano.** *Photograph courtesy of Dr. Peter Isaacson, Department of Geological Sciences, University of Idaho.*

on the landmass of Gondwana because they were removed by the erosive action of the much larger glacier that formed in the late Famennian, analogous to the removal of Oi-1 glacial sediments on Antarctica by the much larger Miocene glacier. As discussed above, McClung et al. (2013) have demonstrated the existence of Frasnian incised-valley fills that suggest a late Frasnian glacioeustatic sea-level fall about 50% of the sea-level fall that produced the incised valleys in the late Famennian. The minimum areal expanse of the late Famennian glaciers has been measured to have been 16×10^6 km^2 in western Gondwana (Isaacson et al. 2008) and I have proposed that glaciers approximately 50% to 71% the area of the Famennian ice sheet, or $8–11 \times 10^6$ km^2, were present in western Gondwana in the late Frasnian (McGhee 2014). The scaling used to obtain that estimate is based upon the scaling of the size range of the first step Oi-1 glaciers to the size range of the second step Miocene glaciers in the onset of the Cenozoic icehouse interval, and the assumption that that scaling was similar in the size ranges of the first step late Frasnian glaciers to the second step Famennian glaciers in the proposed onset of the Devonian icehouse interval. As in the case of the Oi-1 glaciation in Antarctica, the much larger late Famennian glaciers would have totally covered the expanse of and erased the trace of the initial late Frasnian glaciers on Gondwana. Therefore I suggest that glacial sediments produced by the late Frasnian glaciers will only be found in marine sediments offshore from the Gondwana landmass. However, the possibility always exists that some sedimentary glacial deposits of the hypothesized late Frasnian glaciers remain intact on the continent of Gondwana. If so, I suggest that the search for this sedimentary evidence be focused within the central 50% to 71% of the areal expanse of the Famennian glaciation field.

To test the hypothesis that glaciers formed in the late Frasnian a world-wide search should be initiated for the presence of ice-rafted debris in late Frasnian marine strata deposited offshore from Gondwana. Rather than the meter- to decimeter-sized Famennian ice-rafted debris (Fig. 4), a search should be initiated for the presence of Frasnian ice-rafted debris of medium-sized (> 250 μm) and larger sand grains and gravels with pebbles, similar to the ice-rafted debris found in Oi-1 marine sediments (Zachos et al. 1992, Ehrmann and Mackensen 1992) That search should target Frasnian marine strata correlated to the Lower and/or Upper Kellwasser horizons where late Frasnian extinctions and sharp drops in sea-surface temperature occurred (for discussion see McGhee 2013, 2014). Absence of evidence is not evidence of absence, as even in the Oi-1 glaciation ice-rafted debris is not universally found in the sedimentary record: for example, ice-rafted sand and gravel is present on the Kerguelen Plateau in the Indian Ocean but absent on the Maud Rise in the Atlantic Ocean (Ehrmann and Mackensen, 1992). Yet the discovery of even one site with marine strata containing ice-rafted debris at the same horizon as one of the Lower or Upper Kellwasser horizons would confirm the existence of glaciation in the late Frasnian.

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