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The Late Devonian (Frasnian/Famenian) mass extinction: a proposed test of the glaciation hypothesis

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In this paper it is agued that Late Frasnian global cooling was the first step in the onset of the Late Paleozoic Ice Age, and that a Late Frasnian glaciation existed that was analogous to the early Oligocene (Oi-1) glaciation that took place in the first step of global cooling in the onset of the Cenozoic Ice Age. It is here proposed that definitive sedimentological evidence for the existence of Late Frasnian glaciation, like the Oi-1 glaciation, would be the discovery of ice-rafted debris in marine sediments of Late Frasnian age similar to the ice-rafted debris found in Oi-1 marine sediments (Zachos et al., 1992; Ehrmann and Mackensen, 1992). Rather than metre- to decimetre-sized ice-rafted debris, a search should be initiated for the presence of sand-sized (>250 m) ice-rafted debris in Frasnian marine strata located offshore from the main Gondwana landmass, and dated to the Late *rhenana* Conodont Zone and/or to the *linguiformis*–Early *triangularis* conodont zonal interval where the extinctions and sharp drops in sea-surface temperature occurred (Joachimski and Buggisch, 2002).

Key words: mass extinction, glaciation, Late Paleozoic Ice Age, Cenozoic Ice Age.

INTRODUCTION

The cause of the Late Devonian (Frasnian/Famennian) extinction 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 extinction (Table 1). However, the cause of global cooling in the Late Frasnian remains unproved. Catastrophic causal hypotheses have included asteroid impacts (McGhee, 2001, 2005) and mantle-plume volcanism (Racki, 1998; Courtillot and Renne, 2003; Courtillot et al., 2010). Non-catastrophic, longer-term causal hypotheses have included global cooling produced by atmospheric carbon-dioxide downdraw by biological weathering processes (Algeo et al., 2001) or by the chemical weathering of tectonically-active mountain ranges (Averbuch et al., 2005).

Global-cooling produced glaciation has long been proposed to have been a trigger for the Frasnian/Famennian extinction (for an extensive discussion of proposed causes of the Late Devonian extinction see McGhee, 1996, 2013). However, decades of searching on a world-wide basis has failed to uncover hard physical evidence for glaciation in the Late Frasnian.

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Only two icehouse intervals exist in the Phanerozoic in which glaciation persisted for tens of millions of years: the Late Paleozoic Ice Age and the Cenozoic Ice Age (Fielding et al., 2008). It is well established that the development of the glaciations of the Cenozoic Ice Age took place in three steps in geologic time: the Early Oligocene, Middle Miocene, and Late Pliocene (Lewis et al., 2008). It has recently been proposed that the onset of the Late Paleozoic Ice Age also took place in three steps: the Late Frasnian, Late Famennian, and Late Visean–Serpukhovian (Barham et al., 2012; McGhee, 2013). Such a scenario requires glaciation in the Late Frasnian, and the object of the present paper is to propose a definitive test of the hypothesis of Late Frasnian glaciation.

A COMPARISON OF CENOZOIC AND LATE PALEOZOIC GLOBAL COOLING

The development of the glaciations of the Cenozoic Ice Age took place in three steps in geologic time: the Early Oligocene, Middle Miocene, and Late Pliocene (Lewis et al., 2008). The first step in the Cenozoic Ice Age, the Early Oligocene Oi-1 glacial pulse (Miller et al., 1991), took place between 34 and 33 Ma and lasted for 400,000 years. The onset of the Early Oligocene glaciations coincided with two separate pulses of extinction that occurred in the oceans at about 33 Ma, and a third pulse of extinction that occurred on land at about 32 Ma (Prothero, 1994; McGhee, 2001; Prothero et al., 2003). The Oi-1 glacial pulse initiated the formation of ice sheets in eastern Antarctica, glaciers

Table 1

Empirical biological observations in marine and terrestrial ecosystems that have been used to argue for global cooling in the Late Frasnian and Early Famennian

A. MARINE ECOSYSTEMS:

1. Differential survival of high-latitude marine faunas:
   - Brachiopods (Copper, 1977, 1986, 1998)
   - Microbial reef biota (Copper, 2002)
2. Differential survival of deep-water marine faunas:
   - Glass sponges (McGhee, 1996)
   - Rugose corals (Oliver and Pedder, 1994)
   - Tornoceratid ammonoids (House, 1988)
3. Migration of deep-water marine faunas into shallow-waters:
   - Glass sponges (McGhee, 1996)
   - Tornoceratid ammonoids (House, 1988)
4. Blooms in cold-water plankton:
   - Prasinophytes (Streel et al., 2000b)
   - Radiolarians (Racki, 1998, 1999; Copper, 2002)
   - Chitinozoans (Paris et al., 1996; Streel et al., 2000b; Grahn and Paris, 2011)
5. Differential survival of fresh-water versus marine species:
   - Acanthodian fishes (Dennison, 1979)
   - Placoderm fishes (Dennison, 1978; Long, 1993)
6. Latitudinal contraction of geographic range in surviving equatorial marine faunas:
   - Foraminifera (Kalvoda, 1990)
   - Stromatoporoid and coral reefs (Stern, 1987; Copper, 2002)
   - Tentaculitoids (Wei et al., 2012)
   - Trilobites (Morzadec, 1992)

B. TERRESTRIAL ECOSYSTEMS:

1. Differential survival of high-latitude terrestrial biota:
   - Land plants (Streel et al., 2000a)
2. Latitudinal contraction of geographic range in surviving equatorial terrestrial biota:
   - Land plants (Streel et al., 2000a)
   - Tetrapod vertebrates (McGhee, 2013)

that persisted for about eight million years (Zachos et al., 2001) before retreating during a warming trend that began in the Late Oligocene and extended into the Miocene.

The second step in the Cenozoic Ice Age was initiated by a second glacial pulse, the Mi-1, that took place in the Early Miocene and lasted for 200,000 years (Zachos et al., 2001). The Mi-1 glacial pulse initiated a series of brief and smaller glaciations in Antarctica and then the Earth began to cool rapidly in the Middle Miocene. The onset of the major expansion of the East Antarctic Ice Sheet between 14 and 13 Ma (Flower and Kennett, 1995) triggered pulses of extinction in both the marine and terrestrial realms during this interval of time (Sepkoski, 1996; Lewis et al., 2008). By 12 Ma massive ice sheets had formed in eastern Antarctica that persist to the present day.

The third step in the Cenozoic Ice Age took place in the Late Pliocene when glaciation became bipolar, with formation of persistent ice sheets in the northern hemisphere of the Earth in addition to those in the southern hemisphere (Zachos et al., 2001). The onset of glaciation in the northern hemisphere coincided with additional extinction pulses first in the marine realm (Hayward, 2002) and then later in the terrestrial realm (Barnes et al., 1996).

It has recently been proposed that the onset of the Late Paleozoic Ice Age also took place in three steps: the Late Frasnian, Late Famennian, and Late Visean–Serpukhovian (Barham et al., 2012; McGhee, 2013). The proposed first step in the Late Paleozoic Ice Age, Late Frasnian cooling, took place in two pulses: the first pulse took place at about 376 Ma, is dated to the Late *rhenana* Conodont Zone in the Lower Kellwasser stratigraphic horizon (Walliser, 1996; Joachimski and Buggisch, 2002). The second cooling pulse took place at about 375 Ma in the latest Frasnian, is dated to the *linguiformis* Conodont Zone at the Upper Kellwasser stratigraphic horizon (Walliser, 1996; Joachimski and Buggisch, 2002). Both of the Kellwasser stratigraphic horizons are also associated with extinction pulses: extinctions dated to the Late *rhenana* Conodont Zone occurred in both the marine and terrestrial realms (Raymond and Metz, 1995; McGhee, 1996), and further extinctions dated to the *linguiformis* Conodont Zone occurred in the marine realm (Schindler, 1993; McGhee, 1996).

The proposed second step in the Late Paleozoic Ice Age, Late Famennian cooling, is evidenced by glacial sediments in Gondwana that have been dated to the VCo spore zone on land, and correlated to the Late *postera* Conodont Zone in the sea (Isaacson et al., 2008). The glaciers in Gondwana reached their maximum expansion phase in the latest Famennian, dated to the LE–LN spore zonal interval on land (Streel et al., 2000a; Caputo et al., 2008), and correlated to the Middle–Late *praesulcata* conodont zonal interval in the sea (Isaacson et al., 2008). At the same stratigraphic horizon ice-rafted glacial debris, in some cases metre-sized dropstones (Brezinski et al., 2010: fig. 10G), are found in offshore marine deposits of the Cleveland Shale in Kentucky (Ettensohn et al., 2007). This ice-rafted debris apparently came from continental glaciers in the Appalachian mountains to the east, a region that was as close to the equator as 30°S and thus is evidence of the intensity of the Late Famennian glacial cooling (Brezinski et al., 2009, 2010). Extinctions associated with the maximum expansion phase of the Famennian glaciation took place in two pulses: the first pulse occurred in the marine realm at about 360 Ma in the Late Famennian, is dated to the Middle *praesulcata* Conodont Zone at the Hangenberg Black Shale horizon (Kaiser et al., 2006). The second pulse of extinction occurred in the terrestrial realm and took place at about 359 Ma in the latest Famennian, is dated to the Late *praeculcata* Conodont Zone, and coincides with the maximum expansion of the ice sheets on land in Gondwana (Streel et al., 2000a).

The proposed third step in the Late Paleozoic Ice Age took place in the Late Visean–Serpukhovian (Early Carboniferous) when glaciation became bipolar and the ice age entered its main phase (Stanley and Powell, 2003; Barham et al., 2012). This third step in global cooling coincided with further biodiversity losses and major ecological disruption in the marine realm and, similar to the Late Frasnian, the biodiversity loss was triggered primarily by speciation suppression (Stanley and Powell, 2003; McGhee et al., 2012).

Last, the timing of the biological events that took place during the stepwise onset of the Cenozoic Ice Age and during the proposed stepwise onset of the Late Paleozoic Ice Age in the Late Devonian are very similar. In the onset of the Cenozoic Ice Age the time interval between the Oligocene and Miocene extinction pulses was 19 million years, and in the proposed onset of the Late Paleozoic Ice Age the time interval between the Frasnian and Famennian extinction pulses was 16 million years.

If the Earth cooled at a similar rate in the Cenozoic and in the Late Devonian, then the similar temporal spacing and patterns of extinctions during these two time intervals may not be accidental, they may reflect the timing of the step-wise glaciation of the planet. A similar cooling rate further suggests a similarity in the forcing mechanisms, and hypothesized causes of the onset of the Cenozoic Ice Age in the Oi-1 glaciation and the proposed onset of the Late Paleozoic Ice Age in the Late Frasnian are the same: (1) CO_2-downdraw due to the weathering of silicates in geographically extensive, tectonically-uplifted mountain ranges and plateaus, (2) falling temperatures, triggered by the decline of the greenhouse-gas CO_2 below threshold values in the atmosphere, further triggering the sudden growth of continental ice sheets, and (3) the subsequent expansion and contraction of these early ice sheets being paced by Milankovitch orbital variations in heat from the sun (Raymo and Ruddiman, 1992; Zachos et al., 2001; Filer, 2002; DeConto and Pollard, 2003; Pagani et al., 2005; Averbuch et al., 2005; Berner, 2006; Bowen, 2007; for an extensive discussion see McGhee, 2013).

SEDIMENTARY EVIDENCE FOR GLACIATION IN THE OLIGOCENE AND FRASNIAN?

Evidence for the existence of glaciers in the second and third steps of the Cenozoic Ice Age, the Miocene and Late Pliocene, is undisputed (Lewis et al., 2008). Evidence for glaciation in the first step, the Early Oligocene Oi-1 glaciation, is much more tenuous.

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 m, 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: fig. 8) reported the presence of gravel-sized 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).

Ehrmann and Mackensen (1992) and Robert et al. (2002) also argued that changes in clay mineralogy in marine sediments that take place at the Oi-1 stratigraphic horizon, such as a shift from smectite-dominated clays to illite- and chlorite-dominated clays, evidence a shift to weathering in cooler climates in Antarctica and hence can be taken as further evidence of glaciation. Evidence of climatic cooling is not unequivocal evidence of glacier formation, however, thus the best physical sedimentological evidence for Oi-1 glaciation remains the ice-rafted debris (Ehrmann and Mackensen, 1992; Zachos et al., 1992).

Likewise, evidence for the existence of glaciers in the proposed second and third steps of the Late Paleozoic Ice Age, the Late Famennian and Late Visean–Serpukhovian, is undisputed (Fielding et al., 2008; Barham et al., 2012). Sedimentological evidence for glaciation in the first proposed step, a Late Frasnian glaciation, does not exist at present.

Analogous to the Oi-1 glaciation at the onset of the Cenozoic Ice Age, it is here argued that glacial sediments of Late Frasnian age at the onset of the Late Paleozoic Ice Age probably never will be discovered on land as they will have been removed by the erosive action of the subsequent much larger ice sheet that formed in Gondwana in the Late Famennian. The minimum size of the second step Late Famennian glaciers has been measured to have been 16 10^6 km^2 in western Gondwana (Isaacson et al., 2008). I here propose that glaciers approximately 50 to 71% the size of the Famennian ice sheet, or 8–11 10^6 km^2, were present in western Gondwana in the Late Frasnian. 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 Ice Age, 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 Late Paleozoic Ice Age. 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, thus sedimentological evidence for Late Frasnian glaciation must be sought for in marine sediments offshore from the Gondwana landmass.

The large Late Famennian glaciers produced metre-sized ice-rafted dropstones (Brezinski et al., 2010: fig. 10G). The proposed smaller Late Frasnian glaciers, like the smaller Oi-1 glaciers, potentially produced sand-sized (> 250 m) ice-rafted debris similar to the ice-rafted debris found in Oi-1 marine sediments (Zachos et al., 1992; Ehrmann and Mackensen, 1992). 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 marine strata dated to the Late *rhenana* Conodont Zone and/or to the *linguiformis*–Early *triangularis* conodont zonal interval where the extinctions and sharp drops in sea-surface temperature occurred (Joachimski and Buggisch, 2002).

Are there any anomalous occurrences of gravel or clastic grains larger than 250 m in any of the offshore-marine black-shale strata of the Lower or Upper Kellwasser horizons? Absence of evidence is not evidence of absence, as even in the Oi-1 glaciation ice-rafted debris is not universally found in the stratigraphic 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 even the discovery of 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.

SUMMARY AND CONCLUSIONS

The oldest glaciation usually associated with the onset of the Late Paleozoic Ice Age is the formation of the Late Famennian (Late Devonian) ice sheet in Gondwana (Isaacson et al., 2008; Caputo et al., 2008). However, it has been argued that an older glacial phase existed in the Late Frasnian (Late Devonian), and that it is from this glacial phase that the onset of the Late Paleozoic Ice Age should be measured (McGhee, 2013: 203–212). If the Late Frasnian is taken as the first step in the onset of the Late Paleozoic Ice Age, and the Late Famennian glaciation is taken as the second step, then the timing of the proposed onset of the Late Paleozoic Ice Age becomes strikingly similar to the first two steps in the onset of the Cenozoic Ice Age. Last, the hypothesized causes of the onset of the Cenozoic Ice Age in the Oi-1 glaciation and the proposed onset of the Late Paleozoic Ice Age in the Late Frasnian are the same: (1) CO_2-downdraw due to the weathering of silicates in geographically extensive, tectonically-uplifted mountain ranges and plateaus, (2) falling temperatures, triggered by the decline of the greenhouse-gas CO_2 below threshold values in the atmosphere, further triggering the sudden growth of continental ice sheets, and (3) the subsequent expansion and contraction of these early ice sheets being paced by Milankovitch orbital variations in heat from the sun (Raymo and Ruddiman, 1992; Zachos et al., 2001; Filer, 2002; DeConto and Pollard, 2003; Averbuch et al., 2005; Pagani et al., 2005; Berner, 2006; Bowen, 2007).

Actual Oi-1 glacial sediments on land in Antarctica have been removed by the erosive action of the larger middle Miocene glaciers and subsequent glaciers, and thus the best sedimentary evidence for the existence of the Oi-1 glaciation is glacially-derived, ice-rafted debris in marine sediments (Ehrmann and Mackensen, 1992; Zachos et al., 1992). Analogous to the Oi-1 glaciation, it is argued that glacial sediments of Late Frasnian age probably never will be discovered on land as they will have been removed by the erosive action of the subsequent much larger ice sheet that formed in Gondwana in the Late Famennian.

In conclusion, to test the hypothesis that glaciers formed in the Late Frasnian a search should be initiated for the presence of sand-sized (>250 m) ice-rafted debris present in Frasnian marine strata located offshore from the main Gondwana landmass, and dated to the Late *rhenana* Conodont Zone and/or to the *linguiformis*–Early *triangularis* conodont zonal interval where the extinctions and sharp drops in sea-surface temperature occurred (Joachimski and Buggisch, 2002).

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