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A climate-driven model and development of a floating point time scale for the entire Middle Devonian Givetian Stage: A test using magnetostratigraphy susceptibility as a climate proxy

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ABSTRACT

Here we propose an approach to establish a preliminary age chronology for complete stages within the Phanerozoic by applying cyclostratigraphic methods that employ high-resolution data sets. This requires use of geochemical or geophysical data known to serve as a cyclic climate proxy. To demonstrate the method, we use the magnetostratigraphic susceptibility technique as the basis for fitting a climate model to the Givetian Stage of the Middle Devonian System. We show a Milankovitch eccentricity climate zonation for the Givetian that is pinned to time-series analyses from outcrop samples from its upper (Givetian/Frasnian, France) and lower (Eifelian/Givetian, Morocco) stage boundaries. Using these data sets we construct a uniform cyclicity model designed to conform to a ~405 kyr cyclicity, with a duration corresponding to the published duration for the Givetian of ~4.4 myr (Kaufmann, 2006). To this model we fit two well-established conodont zonation schemes, thus allowing time estimates for conodont ranges for the Givetian, indicating a range from ~1.8 myr to ~100 kyr before extinction of an individual conodont species. We then test and adjust the model using independent data sets from the eastern United States. Adjustments to the initial model yield a duration of ~28 climate half-cycles (zones) for the Givetian Stage and an increased age to ~5.6 myr. These zones allow high correlation among sections to better resolve timing of major bio-events, and provide a Floating Point Time Scale to which absolute ages can be applied.

1. Introduction

One of the major objectives in stratigraphy is the development of a high-resolution time scale for the entire Phanerozoic. Our current geologic time scale is based on a biostratigraphic framework/skeleton that roughly defines geologic time with resolution of a million years or so. For the Cenozoic resolution is quite good and comes from isotopic (mainly oxygen) and magnetostratigraphic polarity studies that are tied into the existing biostratigraphic framework. However, high-resolution time scales are especially difficult for the Paleozoic because paleomagnetic and isotopic data sets are not reliable and, few good radiometric ages are available. This paper is a contribution to IGCP Project 499 "Devonian land–sea interaction: Evolution of ecosystems and climate" (DEVEC).

Isotopic studies for Cenozoic marine sediments/rocks rely on the assumption that isotopic (and cyclic lithologic) changes are a proxy for climatic cycles that are assumed to be global (i.e., Dinarès-Turell et al., 2007; Imbrie et al., 1984). Tests of these hypotheses have shown that in general these basic assumptions are correct, and that these data sets can provide a much higher resolution for time scales than are available using biostratigraphic information alone. Such data sets have not been documented for most of the Phanerozoic, however, because stratigraphic sequences are imperfect recorders of time due to erosion, non-deposition or alteration. As a consequence of these processes, short-term Milankovitch bands (Earth's obliquity and precession) are not as well developed in older rocks as they are in younger sequences. It is therefore expected that longer-term climate cycles are more readily identified in older rock sequences, and that the

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~405 kyr eccentricity cycle has a robust, long-term paleoclimatic stratigraphic signal that should be recorded (Laskar et al., 2004; Shackleton et al., 1999a). This band has been observed for Triassic lacustrine (Olsen and Kent, 1995) and Middle Carboniferous marine sediments (Ellwood et al., 2007b), Triassic lacustrine sediments (Olsen and Kent, 1995) and Jurassic marine sediments (Boulila et al., 2008). Given that longer-term climate cycles are preserved in the sedimentary record, any robust method that can track these changes should provide useful proxies for climate.

One such method that is now well established uses low-field magnetic susceptibility (MS) data sets in both unlithified and lithified marine sediments to track climate cyclicity. As such, the cyclostratigraphy recorded in these sequences can be used for astronomical calibration of geologic time scales (Crick et al., 2001; Hartl et al., 1995; Mead et al., 1986; Shackleton et al., 1999b; Weedon et al., 1997, 1999). In addition to its utility in paleoclimatic studies, magnetostratigraphic susceptibility can be used for high-resolution correlation among marine sedimentary rocks of broadly differing facies with regional and global extent (Crick et al., 1997, 2000; Ellwood et al. 1999, 2000, 2007a, b; Whalen and Day, 2008). MS is a correlation method that provides a robust data set to independently evaluate and adjust stratigraphic position among geological sequences. It requires reasonable biostratigraphic control to initially develop a chronostratigraphic framework where distinctive MS zones can be directly correlated with high precision among sections, even when biostratigraphic uncertainties or slight unconformities are known to exist within sections (Ellwood et al., 2006; 2007a). The method is particularly useful for independent age control because it can extract data from sections that are not amenable to other magnetostratigraphic techniques, such as remanent magnetization (Berggren et al., 1995; Gradstein et al., 2004), as it does not require that the rock or sediment analyzed be oriented. MS works as a climate proxy because regional and global processes that drive erosion, including climate and eustasy, bring the detrital components responsible for the MS signature into the marine environment where its stratigraphy is preserved (Ellwood et al., 2000).

Here we develop and test a method to establish high-resolution time scales for any geological stage in the Phanerozoic for which the upper and lower bounding Global Boundary Stratotype section and Point (GSSP) has been defined. To do this we show a Milankovitch eccentricity climate zonation for the Middle Devonian Givetian Stage that is pinned to time-series analysis from its upper (Givetian/Frasnian) and lower (Eifelian/Givetian) stage boundaries. By using time-series analysis of these data we construct a uniform cyclicity model that conforms to a ~405 kyr cyclicity, with a duration corresponding to the published duration for the Givetian of ~4.4 myr (Kaufmann, 2006). We then fit the best available biostratigraphic zonation to this model, and test and revise the age model using MS as an independent data set. It is important to note that this approach can also be applied using geochemical or other geophysical methods.

2. Previous work

Our understanding of the timing of events in Earth history is seriously hampered by age uncertainties for most of geologic time. This problem becomes critically important in resolving timing of significant events. It is possible that age uncertainties have actually ‘created’ distinctive changes in Earth history, or the importance of some changes have been completely missed because we have not realized that abrupt changes identified within globally distributed stratigraphic sequences, thought to be age independent, are in fact coeval.

In the literature for example, the proposed ‘accepted absolute’ age for the Givetian/Frasnian GSSP, defining the base of the Upper Devonian, has varied from 359 Ma in 1964, to its currently used values of 382.5 (Tucker et al., 1998), 383.7 (Kaufmann, 2006), and 385.3 Ma (Gradstein et al., 2004; Ogg et al., 2008), a change of more than 20 myr. The Eifelian/Givetian boundary age has fluctuated from 366 Ma to the present values of 387.5 (Tucker et al., 1998), 388.1 (Kaufmann, 2006) and 391.8 Ma (Gradstein et al., 2004; Ogg et al., 2008), also >20 myr. This has pushed the age for the base of the Givetian back more than 20 million years and dropped its duration from 7 Ma to current estimates of 4 to 6.5 Ma, plus the error estimates for these numbers that are a bit greater than ± 2 myr. These variations mean that papers not using current or converted time scales report ages that can vary significantly from present age estimates and can include large uncertainties just due to age precision. Therefore, work synthesizing long-term changes in the geologic record, such as estimates of mass extinctions (Sepkoski, 1996) or atmospheric CO_2 concentration (Berner, 1990, 2001), must now not only have excellent biostratigraphic control, but also adjust each age reference to some base level for overall age-control estimates. This requires knowing the specific time scale that was used in each reference. If age uncertainties are not resolved, uncertainties for geological properties reported rise dramatically. For example, Berner's work (1990, 2001) examining CO_2 content in the atmosphere for the Devonian uses estimates published over the last 20 years that have uncertainties in timing that are greater than 20 million years just for the age of the Middle Devonian. Given that the Devonian is one of the best studied Systems in the Phanerozoic, it is expected that age uncertainties for other geologic time intervals may be even greater. Failing to correct for the geologic time scale used can lead to either a much larger estimate for CO_2 concentration (data sets with different ages might be merged) or a much lower estimate (data sets with the same ages might be dispersed). Given that during the Devonian there were rapid changes in CO_2 concentration, due to terrestrialization and increasing diversity in land plant populations, the uncertainties produced could have a serious impact on estimates for timing of significant global events.

In an effort to establish better biostratigraphic precision and reduce age uncertainties, the International Union of Geological Sciences (IUGS), International Commission on Stratigraphy (ICS) has been working toward establishing standards representing geologic time, defining a system of GSSPs for all geologic stage boundaries within the Phanerozoic. These GSSPs are well-studied stratigraphic sequences that provide geologic standards to which other sections of equivalent age can be compared. Once geologic stage boundaries have been established, the bounded stage can then be modeled using non-traditional data sets that can be tied directly to the bounding GSSPs, thus providing an age framework that can eventually link both marine and non-marine sequences all over the world. As part of the ICS mandated work, it is being stressed that abiotic methods be used in conjunction with biostratigraphy for boundary correlation purposes. MS is one such abiotic method that has great potential for reducing age uncertainties. The method can also be calibrated against other stratigraphic data sets.

3. Methods

3.1. A model for developing a high-resolution time scale

Our high-resolution time scale model is based on the premise that climate cyclicity reflects Milankovitch fluctuations that are effectively global in character, and these can potentially be identified for any geologic Stage using geophysical or geochemical proxies. Our approach is essentially a six step process. After selecting the Stage of interest, (Step 1) aduration for the stage is chosen from published estimates (Step 2). A standard reference zonation (SRZ) is then established by fitting a ~405 kyr cyclicity to the duration estimated for the stage. This SRZ then is graphically tied to a standard biostratigraphic zonation for the stage that has been developed using graphic correlation (Shaw, 1964) or other methods (Step 3). The bounding GSSP localities are then identified, and those GSSPs are sampled at close intervals. In Step 4 this model is initially tested using the samples collected through the bounding GSSP sequences. This is done in two steps, (Step 4.1) measurement of the geochemical or geophysical climate proxy of choice, and (Step 4.2) calculating the cyclicity, using techniques like the Fourier Transform (FT) method, to evaluate if a ~405 kyr cyclicity is present in the data set. (Step 5) The determined cyclicity in the bounding GSSPs can then be graphically compared to the SRZ to test general linearity in sediment accumulation rates and to establish an initial zonation tied directly to the physical property measured. (Step 6) The SRZ can then be tested using an independent sequence for which some biostratigraphic zonation exists. The test requires comparing cyclicities from this new sequence to the SRZ, by constraining the cyclicity and biostratigraphic position from the new sequence to the standard cyclicity (SRZ) and biostratigraphic zonation for the Stage. (Step 7) Finally, if the test shows more cycles than are consistent with the initial SRZ, then the SRZ can be adjusted, expanded or contracted, to fit the new data set. This model is applied here to the Givetian Stage using MS data sets.

3.2. Magnetostratigraphic susceptibility: General comments

All materials are “susceptible” to becoming magnetized in the presence of an external magnetic field, and initial low-field bulk magnetic susceptibility or MS is an indicator of the strength of this transient magnetism. MS is very different from remanent magnetism (RM), the intrinsic magnetization that accounts for the magnetostratigraphic polarity of materials. MS in marine stratigraphic sequences is generally considered to be an indicator of detrital iron-containing paramagnetic and ferrimagnetic grains, mainly ferromagnesian and clay minerals (da Silva and Boulvain, 2002; Ellwood et al., 2000, 2008b), and can be quickly and easily measured on small samples. In the very low inducing magnetic fields that are generally applied, MS is largely a function of the concentration and composition of the magnetizable material in a sample. MS can be measured on small, irregular lithic fragments and on highly friable material that is difficult to sample for RM measurement.

3.3. MS sampling and measurement used in building the model

3.3.1. Conodont biostratigraphy

In Step 1, we begin by assigning a ~4.4 myr duration to the Givetian Stage (Kaufmann, 2006). While any time scale for the Givetian could be used here, we use that of Kaufmann (2006) because it is relatively recent. In Step 2, we employ two conodont biostratigraphic zonations (left in Fig. 1, work by Weddige et al., 2005; right in Fig. 1, work by Bultynck, 2007 based on work by Gouwy and Bultynck, 2002, 2003), to

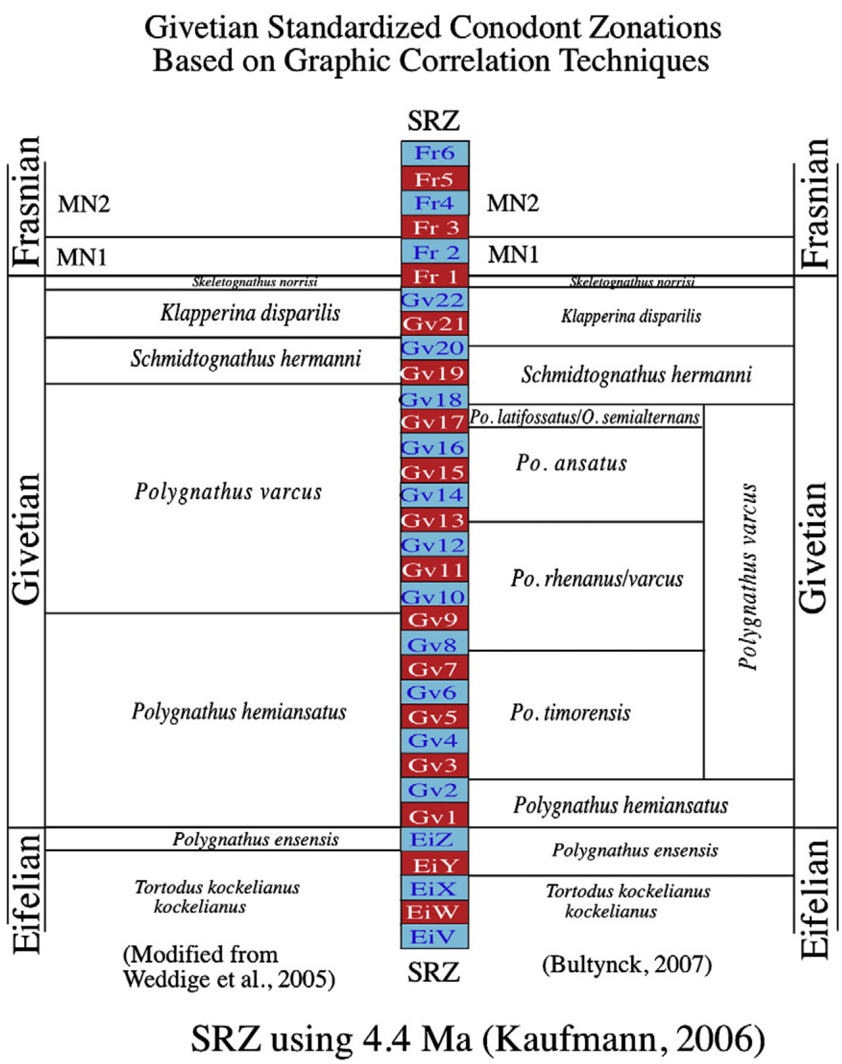

Fig. 1. Two separate conodont biozonations for the Middle Devonian Givetian Stage, modified from (1) Weddige et al. (2005) and (2) based on work by Bultynck (2007) and Gouwy and Bultynck (2002, 2003), compared to a standardized cyclic zonation representing ~405 kyr cyclicity over 4.4 myr estimated by Kaufmann (2006) as the duration for the Givetian. Cycles are labeled using a scheme representing Eifelian (EiV to EiZ), Givetian (Gv1 to Gv22) and Frasnian (Fr1 to Fr6), each 200 kyr half cycles a ~405 kyr cyclicity. Note that the labeling scheme allows Eifelian and Frasnian cycles to be added as new data become available (see discussion in Section 3.3.1 regarding apparent discrepancies between the correlation of the two biozonation schemes used).

establish a zonation relative to time and separated from the physical stratigraphy associated with the sections from which samples were collected. Also given in Fig. 1 is a SRZ that assumes an initial ~4.4 myr estimate for the duration of the Givetian (Kaufmann, 2006). This SRZ is represented as ~22 uniform 200 kyr half-cycles and is based on the assumption that the robust ~405 kyr Milankovitch eccentricity band can be used as a climate proxy for this model.

It is important to note here that the biozones in Fig. 1 represent only relative time units because no radiometric data are available that are directly linked to Givetian conodont zones. Therefore the duration of Givetian conodont zones can only be estimated by indirect means. The estimated duration of the conodont zones for the two Givetian zonation schemes used herein is based on two different methods. The method used in Weddige et al. (2005), pp. 64–67—absolute age assignments based on tie points to uniformly constrain the length of the Lower, Middle and Upper Devonian as published by Weddige (1996) differs from the method in Bultynck (2007) (composite standard units—CSU—based on the graphic correlation method [Shaw, 1964]). As a result the duration of the zones is different in the two schemes. The reader should be aware that the apparent discrepancies between the two zonation schemes in Fig. 1 are not due to a different paleontological content of zones having the same name, but rather to differences in the two methods used for estimating duration of each zone.

3.3.2. Field sampling

For Step 3 of the model, we sampled the two bounding GSSPs (localities E/G and G/F, Fig. 2), both biostratigraphically well-studied sections; (1) the Eifelian/Givetian GSSP (Walliser et al., 1995) at Mech Irdane, in the Anti-Atlas region, Tafilalt Basin, SE Morocco; and (2) the Givetian/Frasnian GSSP (Klapper et al., 1987) exposed at Col du Puech de la Suque in the Montagne Noire region, southern France (sampled localities for Middle Devonian time are given in Fig. 2). Samples were collected for MS measurement at ~5 cm intervals and returned to the laboratory for study.

3.3.3. Laboratory measurement

MS measurements reported in this paper were performed using the susceptibility bridge at LSU, calibrated relative to mass using standard salts reported by Swartzendruber (1992) and CRC Tables. We report MS in terms of sample mass because it is much easier and faster to measure with high precision than is volume, and is now standard for MS measurement.

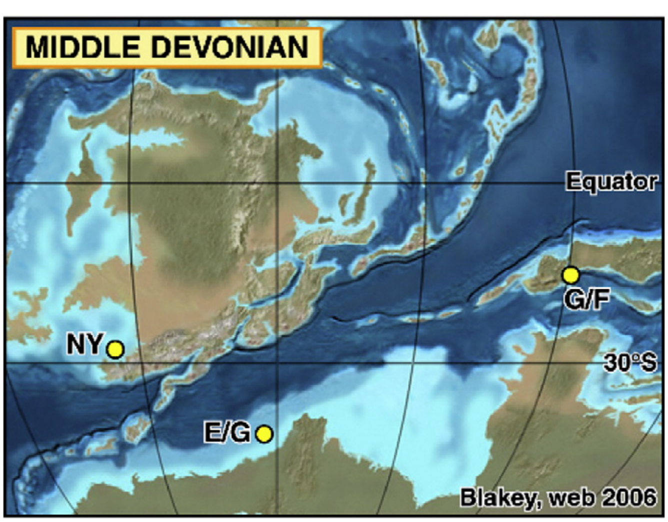

Fig. 2. Map showing continental and site locations of the Eifelian/Givetian GSSP, Morocco (E/G), the Givetian/Frasnian GSSP, southern France (G/F), and test AKZO core and Tully and Geneseo Formation outcrop locations, New York (NY) during middle Givetian time (modified from Blakey, 2006).

3.4. Presentation of MS data

Magnetic susceptibility data presented in diagrams in this paper are represented as δMS, where

$$\delta MS = (MS_{measured} - MS_{marine\ standard}) / MS_{marine\ standard}$$

and $MS_{marine\ standard} = 5.5 \times 10^{-8}$—the median value for ~11,000 lithified marine sedimentary rocks, including siltstone, limestone, marl and shale samples. Thus, δMS is dimensionless and allows direct comparison to other MS data sets. A δMS value of zero is coincident with the $MS_{marine\ standard}$, while negative values are lower and positive values are higher. For presentation purposes and inter data-set comparisons, the bar-log format, similar to that previously established for magnetostratigraphic polarity data presentations, is used here. Bar logs are constructed from smoothed δMS data and are accompanied by both raw and smoothed δMS data sets. Here, raw δMS data (Fig. 3 illustrating data from the Eifelian/Givetian GSSP at Mech Irdane, Morocco, is an example: figure modified from Ellwood et al., 2003) are smoothed using splines to hold data points in stratigraphic position (solid data curve in Fig. 3; splines were calculated using the JMP statistical software package from the SAS Institute Inc.). Splines vary depending on the number of samples in each data set being smoothed, and therefore using splines

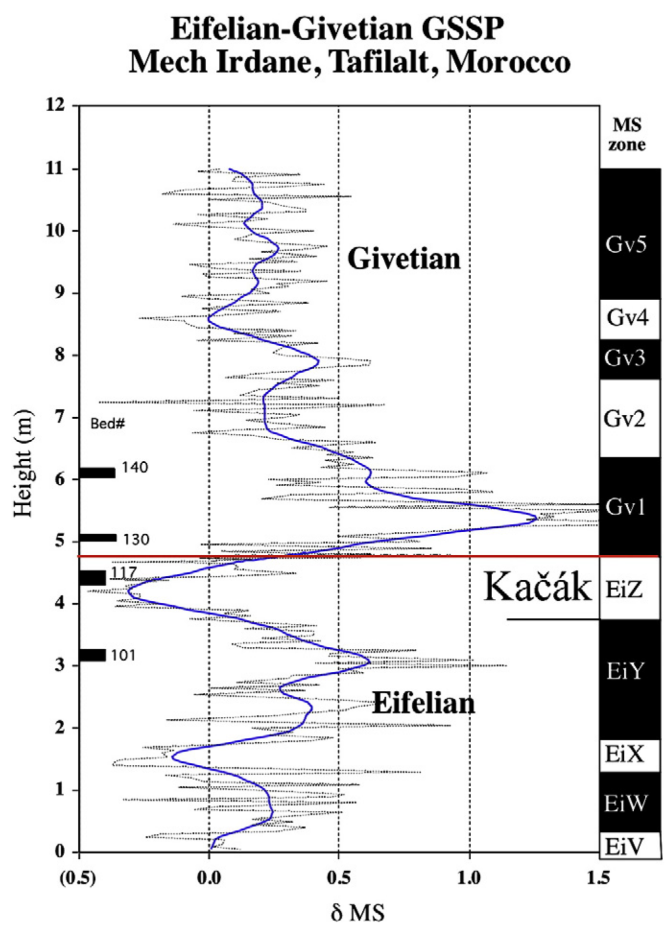

Fig. 3. δMS data (see text for explanation of how δMS is calculated) for the Eifelian/Givetian GSSP at Mech Irdane, Tafilat, Morocco (Walliser et al., 1995; some of their prominent bed numbers are given). Figure modified from Ellwood et al. (2003). Bar-logs (filled—high δMS; open—low δMS constructed from smoothed δMS data using splines–solid data curve; methods discussed in text); raw δMS data are shown as dotted curve. δMS data are dimensionless. MS zones labeled are: Gv1 corresponding to MS Zone Mech Irdane of Crick et al. (2000); Gv2 corresponding to the complete MS Zone Rissani (Crick et al., 2000), and Gv3 to Gv5 are assigned to the other increasingly younger MS zones. Within the Eifelian stage at Mech Irdane, MS zones are labeled in increasing age from EiZ immediately below the boundary to EiV at the base of the section presented.

is somewhat subjective, as are other smoothing techniques. Splines applied were adjusted in increments of 10 to produce an MS zonation that conforms to the desired FT cyclicity. For example, in Fig. 3 the chosen spline produces a bar log representing a cyclicity of ~405 kyr (discussed below). Finer splines represent shorter cycles.

Because δMS data are cyclic, for the purpose of correlating among geologic sequences we use a bar-log plotting convention, such that if a δMS cyclic trend is represented by two or more data points, then this trend is assumed to be significant and the highs and lows associated with these cycles are differentiated by black (high δMS values) or white (low δMS values) bar-logs shown in Fig. 3. This method is best employed when high-resolution data sets are being analyzed (large numbers of closely spaced samples). High-resolution data sets help resolve MS variations associated with anomalous samples. Such variations may be due to weathering effects, secondary alteration and metamorphism, to longer-term trends due to factors such as eustacy (Ellwood et al., 2008a), as opposed to shorter term climate cycles (Ellwood et al. 2007b), or event sequences such as impacts (Ellwood et al., 2003), and to other factors. In addition, variations in detrital input between localities or a change in detrital sediment source is resolved by developing and comparing bar-logs between different localities.

4. Results

4.1. MS for GSSP sequences bounding the Givetian Stage: Step 4.1

4.1.1. Eifelian/Givetian GSSP

The Mid-Devonian, Eifelian/Givetian GSSP, which defines the base of the Givetian Stage, was established at Mech Irdane, near the town of Rissani in SE Morocco (Walliser et al., 1995; Fig. 1). We collected ~11 m of the published section for MS (220 samples), and the results include the δMS data (raw and smoothed data; Fig. 3 modified from Ellwood et al., 2003). Critical beds are labeled from Walliser et al. (1995). One set of bar logs is reported and corresponds to the ~405 kyr eccentricity band (discussed below).

4.1.2. Givetian/Frasnian GSSP

The Mid-Upper Devonian boundary represented by the Givetian/Frasnian GSSP was sampled at the Col du Puech de la Suque, SE of St. Nazaire-de-Ladarez, in the Montagne Noire region, southern France (Klapper et al., 1987; Fig. 4). We collected ~1.9 m of the published section (41 samples) for analysis and the results include the δMS data (raw and smoothed). The exposed section was truncated top and bottom, severely limiting the exposure, and is structurally overturned. All the beds from Klapper et al. (1987) are labeled. One set of bar logs is reported and corresponds to the ~405 kyr eccentricity band (discussed below).

4.2. Time-series analysis: Fourier Transform analysis: Step 4.2

In building our model, we have performed a time-series analysis of the raw MS data (independent of smoothing) for both sections sampled. First, we assumed that the spacing of samples is linearly related with time, i.e., Δx is proportional to Δt, so that a Fourier method could be used. The less this assumption is true, the more noise that will be produced in the spectral graph. The spectral power of the three MS data sets was obtained with FT analysis. The data were both detrended and subjected to a Hanning window so as to reduce spectral leakage and increase the dynamic range (Jenkins and Watts, 1968). Incidences of statistically significant peaks (at the 95% level) in the resulting spectrum are determined by employing the multi-taper method (Ghil et al., 2002), as calculated with the SSA-MTM toolkit (Dettinger et al., 1995). A null hypothesis of red noise is assumed, with a three taper model in which the harmonic signals were tested against an F-test. This method is prone to producing false positives: the large amount of data examined in this study may produce a spurious 5% signal several times. We therefore restrict the use of statistical significance here to its role in supporting (or not) the position of individual peaks as previously determined. The results are reported in Fig. 5. In general, regions with high spectral power coincide with the presumed Milankovitch bands and with the observed MS zonation periods. This agreement is most visible for the Eifelian/Givetian GSSP, which has two statistically significant peaks in the spectral pattern that can be identified and are associated with Milankovitch eccentricity bands—note the correspondence between spectral power, MS zonation, and the presumed E1 (~405 kyr) and E2 bands. Obliquity appears also to be present. The power spectrum exhibits a region of above-average power where the O1 obliquity peak, recalculated for the Devonian (Berger et al., 1992) to ~31.8 kyr assuming an age of ~391.8 Ma (Gradstein et al., 2004; Ogg et al., 2008) is expected to fall, at ~4 cycles/m (Fig. 5).

The shortness of the Givetian/Frasnian section limits the usefulness of the FT analysis. Nevertheless, the spectral power spectrum of this section provides weak evidence of eccentricity. Although no spectral peaks are statistically significant, the frequencies that correspond with E1 and E2 cyclicity have above-average spectral power. Furthermore, the strongest spectral peak (E1) coincides with the period of the observed MS zonation.

4.2.1. Sediment accumulation ages and rate estimates using FT analysis

The spectral data can be used to make a determination of the age range for each section, due to the fact that climate-change cycles drive fluctuations in erosion. The resulting variation in the accumulating marine sediment composition can then be detected using the MS and other techniques. According to Berger (1978; personal communication) and Shackleton et al. (1999a) frequencies with ~405 kyr periods (the

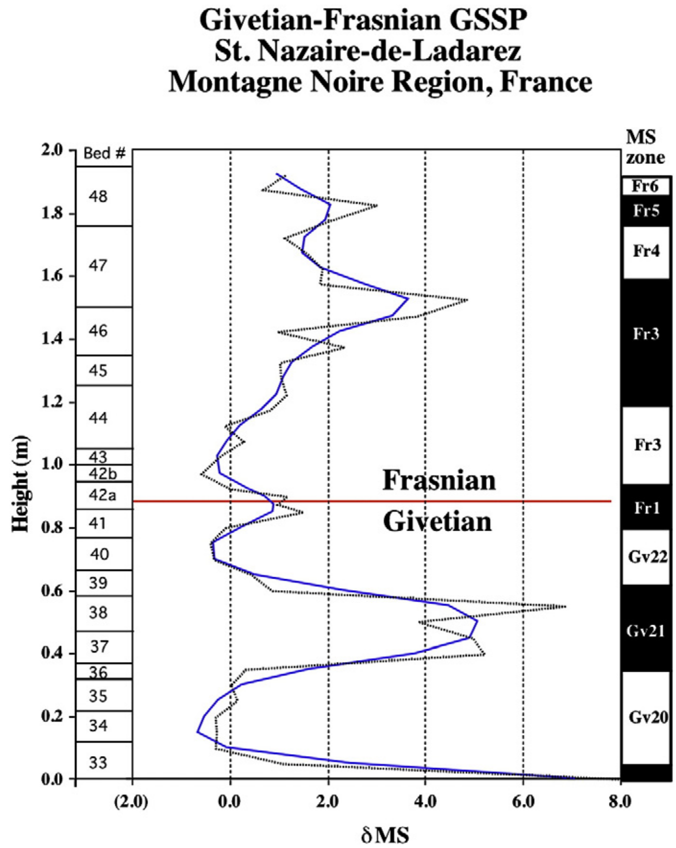

Fig. 4. δMS data for the Givetian/Frasnian GSSP at the Col du Puech de la Suque, SE of St. Nazaire-de-Ladarez, in the Montagne Noire region, southern France (Klapper et al., 1987). δMS data as in Fig. 3. Gv20–Gv22 correspond to the last three MS zones in the Givetian; Fr1 is the MS zone that includes the Givetian/Frasnian boundary Point. MS zones Fr2 to Fr6 are assigned to the bar-log zones representing the 2nd to 5th MS zones in the Frasnian. Bed numbers are from Klapper et al. (1987).

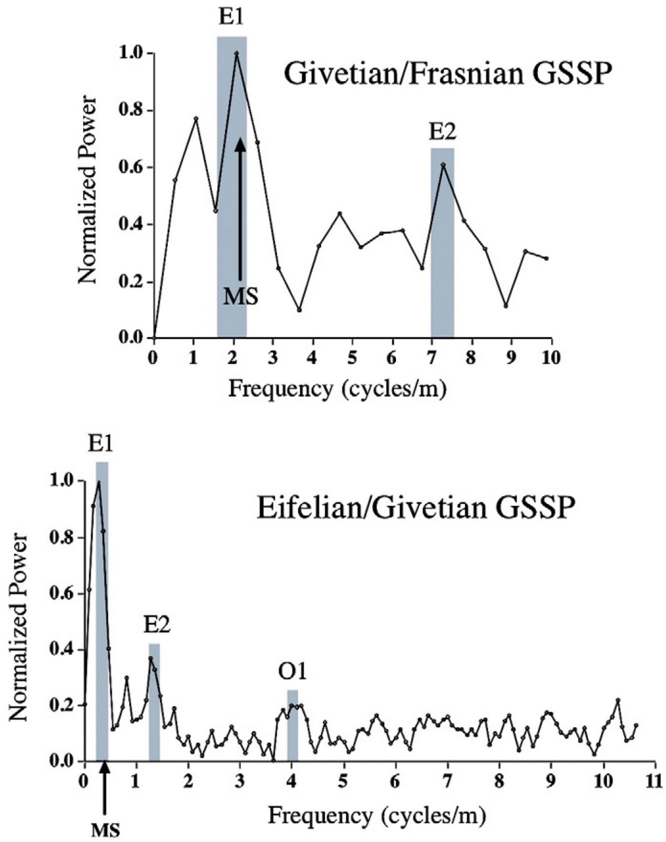

Fig. 5. Spectral power of raw MS values for the Eifelian/Givetian (Fig. 3) and Givetian/Frasnian (Fig. 4) boundary sections, as determined via a Fourier Transform (FT) of the original MS (unsmoothed) data. Frequency in cycles/m. The vertical bars labeled in the diagram indicate the centers of the Milankovitch eccentricity peaks E-1 (~405 kyr) and E-2 (~100 kyr), and an obliquity peak, O1 (~31,850 years; Berger et al., 1992). Both the E1 and E2 peaks in the Eifelian–Givetian GSSP data set are statistically significant at >95% level. The MS bar-log cyclicity for both GSSPs reported here falls within the range of the E-1 eccentricity band.

Milankovitch E1 band) are expected to be found in geological data sets. For the Eifelian/Givetian GSSP, if we assume that the second strongest non-stationary peak (at ~1.3 cycles/m) is ultimately a product of Milankovitch E2 (100 kyr) cyclicity, then we estimate a total age for the ~11 m section at Mech Irdane of ~1.4 Ma. This age, determined by FT analysis of the raw MS data set, is supported by the peak with the most power (~0.3 cycles/m), as it closely corresponds with the ~405 kyr Milankovitch E1 cycle (as noted in Fig. 5). The peak at ~4.0 cycles/m (Fig. 5) then falls at the position where the Milankovitch O1 (obliquity at ~31,850 years; Berger et al., 1992) band should lie.

For the Givetian/Frasnian GSSP, if we assume that the second strongest non-stationary peak (at ~7.2 cycles/m) is ultimately a product of Milankovitch E2 cyclicity (100 kyr), we can estimate a total age range for the ~1.9 m section at Col du Puech de la Suque, and it also indicates ~1.4 Ma for the section. The E1 band then falls where expected, at ~2 cycles/m. This indicates that the sediment accumulation rate (SAR) is much slower at Col du Puech de la Suque (~0.14 cm/kyr) than at Mech Irdane (~0.8 cm/kyr). These results are further discussed later.

5. Discussion

5.1. Building the initial magnetostratigraphic susceptibility standard reference zonation (MS SRZ) for the Middle Devonian, Givetian Stage: Step 5

In building the initial magnetostratigraphic susceptibility SRZ (MS SRZ), we graphically compared the two measured GSSP sequences to the SRZ given in Fig. 1, which we have now labeled as the MS SRZ in Fig. 6. The result is an excellent fit of the MS zones from the two GSSP sections, developed from smoothed δMS data, to the MS SRZ that was based on FT analysis for the unsmoothed MS data set. A single Line-Of-Correlation (LOC) for each GSSP fits the comparison fairly well, although there is a bit more scatter for the Givetian/Frasnian GSSP, where the FT result was not significant, sediment accumulation rate (SAR) was very low, and only 41 samples were analyzed. The comparison of the GSSP MS zones to the MS SRZ allows us to evaluate SAR for each section as a test of the FT data, the assumption being that SARs should be relatively steady. The straight-line LOC segments indicate that SAR, at least on the ~405 kyr time scale, is relatively steady in both GSSP sequences.

5.2. An independent test of the MS SRZ: Constraining the age of the model: Step 6

To test how well other data sets compare to our initial model, we have sampled the Givetian portion of the AKZO Nobel Core #9455, drilled in west central New York (location indicated in Fig. 2). Detailed lithologies are given by Sageman et al. (2003). δMS data for the core are given in Fig. 7. The core includes ~170 m of Givetian section with an unconformity near, but below the Givetian/Frasnian boundary. The missing interval includes the Sheds, Highland Forest and New Lisbon submembers of the Windom Shale (Moscow Formation), and the lower, middle and upper Tully lithologic cycles known to exist in other successions in the region (see Baird and Brett, 2003; Heckel, 1973) and several additional sections have been sampled to include these intervals (Fig. 8). In Fig. 8 we include two splines that we believe record both E1 and E2 eccentricity bands. These are used to illustrate how levels of MS zones can provide high correlation potential.

To test the cyclicity in the AKZO sequence, we applied the FT analysis discussed above to samples collected from the core, above the condensed zone at the base (Sageman et al., 2003), and below the unconformity at the 171 m level (Fig. 7; $N = 647$). The results are striking (Fig. 9), with several well-defined, significant spectral peaks at periods that closely agree with presumed Milankovitch bands: at least three eccentricity peaks (E1 at ~405 kyr; E2 at ~100 kyr; and ~131 kyr), and a distinctive obliquity band (O2 in Fig. 9, representing ~39.3 kyr as extrapolated from the work of Berger et al., 1992). The MS zonation (determined from the data presented in Fig. 7 and marked by the arrow in Fig. 9) agrees closely with the E1 (~405 kyr) band and a region of statistically significant spectral power, and is consistent with the Eifelian/Givetian and Givetian/Frasnian GSSP FT and MS results (Figs. 3–5). The obliquity peak (O2) in Fig. 9 is particularly significant, as it provides an independent check on the inferred length of the section determined from the MS zonation. Furthermore, the ability to resolve a higher frequency signal is a more stringent test of the climate-chronologic method, and it is difficult to hypothesize an alternative forcing that could also produce 80 evenly spaced cycles. In addition, the relatively high frequency of the obliquity cycle minimizes potential problems caused by any low-frequency preservation bias.

5.3. Adjusting the initial model: Step 7—modification of the initial SRZ

Examination of the conodont zonation for the AKZO Core relative to MS zones (Figs. 7 and 8), in comparison with the standard conodont zonation schemes (Fig. 1), requires that the initial SRZ be adjusted by expanding the sequence to account for the additional E1 cycles represented in the full New York Composite data set (Fig. 8), and the conodont zones for the AKZO Core (Fig. 7). This adjustment, including inclusion of samples filling the interval (Fig. 8) represented by the unconformity in the AKZO Core, requires the addition of 2 full ~405 kyr cycles, bringing the duration of the Givetian up to ~5.6 myr (~28, 200 kyr half cycles). This new age falls between the published

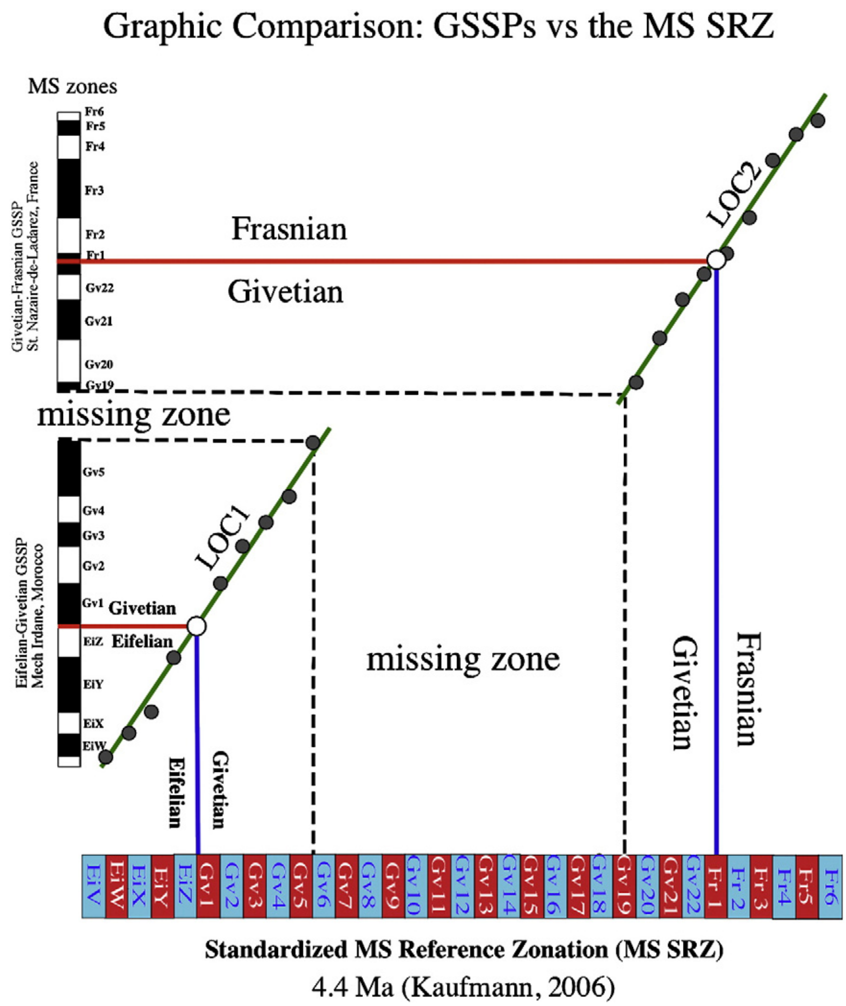

Fig. 6. Graphic comparison (similar to the graphic correction method [Shaw, 1964]) of the Eifelian/Givetian GSSP and the Givetian/Frasnian GSSP with the standardized magnetostratigraphy susceptibility reference zonation (MS SRZ) that assumes a ~405 kyr cyclicity over a period of ~4.4 myr, the duration of the Givetian taken from Kaufmann (2006). Bar-log labels as in Fig. 1. Data points are the intersection of each MS zone top and base top with the corresponding MS SRZ top and base. A Line of Correlation (LOC) is fit through each data set. Missing zone represents a gap in the data that are not represented by GSSP cycles.

results of Tucker et al. (1998), ~5.0 ± >1 myr, and Ogg et al. (2008), ~6.5 ± 2.65 myr for duration of the Givetian.

Following the age adjustment, we graphically compare the New York Composite (merging the data sets represented in Figs. 7 and 8), and both bounding GSSPs (Figs. 3 and 4), with the expanded MS SRZ in Fig. 10. In order to make this comparison and to hold the stratigraphic position of the conodont picks constant in the New York composite, it was necessary to adjust slightly the initial conodont zonation from Bultynck (2007) by compressing the upper portion of the conodont zonation (Fig. 11). For the New York Composite we observe five well-defined, relatively linear LOC segments. These data indicate that the FT result for the AKZO data set is good, and that the composited data presented in Fig. 9 represents a reasonable continuation for the missing section in the AKZO Core. In turn, the New York Composite covers most of the missing portion of the Givetian (missing zones in Fig. 6). It remains to further test the model using additional data sets. Note that the visual LOC slope differences, represented by the different data sets, are simply an artifact of placement of these data sets into the graph (Fig. 10).

SAR values from LOC segments presented in Fig. 10 (circled numbers) for the New York sequences sampled show significantly higher accumulation rates than for the bounding French and Moroccan GSSPs. The AKZO Core SARs, for LOC 2 (~8.30 cm/kyr) and LOC 3 (~12.78 cm/kyr), are quite high, while the New York Outcrop Composite (LOC 4 ~2.26 cm/kyr) gives a value for the Tully Limestone that is much closer to those seen for the carbonate-dominated GSSPs (LOC 1 ~0.8 cm/kyr; LOC 5 ~0.14 cm/kyr).

5.4. MS SRZ, Associated Conodont Zonation and important biozone events

We conclude from our FT data sets (Figs. 5 and 9) and other work (Ellwood et al., 2000, 2008b; Jovane et al., 2006; Weedon et al., 1999; Whalen and Day, 2008) that MS zone cyclicity arises from climate- and/or sea level driven cyclic erosion and deposition of detrital and/or eolian constituents within the sequences analyzed. The FT data also indicate that the driving cyclicity is relatively uniform for those Milankovitch bands identified. We have used this observation in developing a new comparison diagram (Fig. 11) where our conodont zonation scheme (based on the zonation scheme of Bultynck, 2007 and Gouwy and Bultynck, 2002, 2003) is now plotted relative to approximately equal to twenty-eight 200 kyr half-cycle MS SRZ, and with a conodont zone compression in the upper portion of the MS SRZ (Fig. 11). Careful examination of specific MS zones associated with conodont zones identified for the AKZO Core (Fig. 7), when compared with our conodont zonation scheme (Fig. 1), requires the revisions presented in Fig. 11.

Also shown in Fig. 11 are two bio-events, the Kačák (upper Eifelian), and Taghanic events (upper Givetian), discussed for example

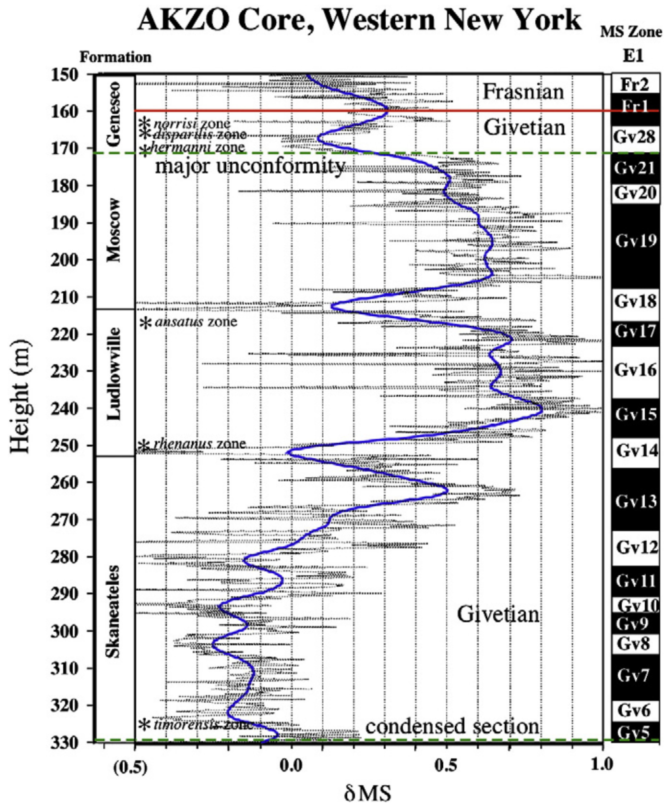

Fig. 7. δMS data for the AKZO Core, sampled in west central New York (location in Fig. 2). δMS data as in Fig. 3. The Givetian/Frasnian boundary is labeled for the sequence (solid horizontal line). An unconformity (dashed horizontal line) has been identified in the upper part of the sequence and we estimate that it represents 2.5 to 3 missing E1 (~405 kyr) cycles. Level of conodont zones within the sequence are label with an '*'. Conodont data indicate that the base of the core (below 330 m) is highly condensed and was not used in this study.

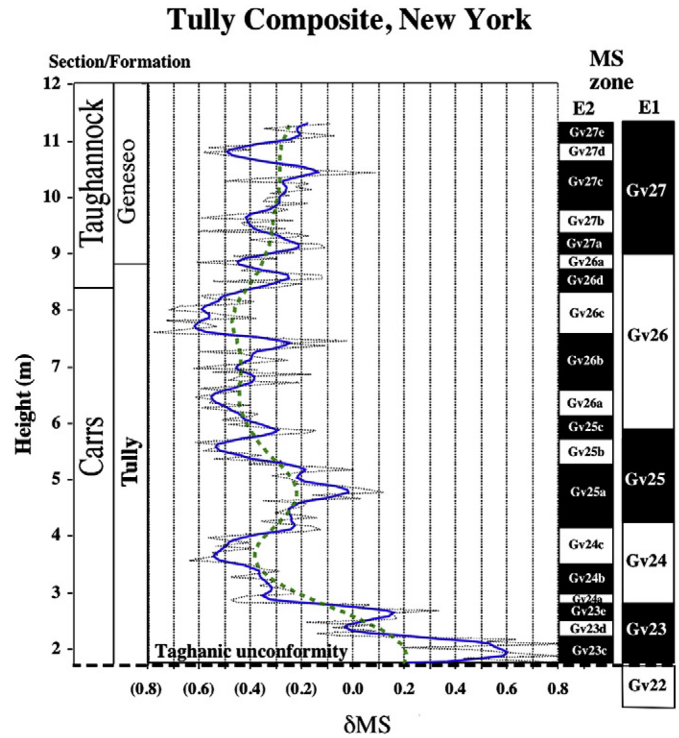

Fig. 8. δMS data composite of samples from two sections exposed in west-central New York, at the Carrs and Taughannock localities, sampled at ~5 cm intervals ($N=229$). These samples fill the missing interval represented by the unconformity in the AKZO core (Fig. 7). Symbols as in Fig. 3. The raw data and two δMS splines are given from which two MS zonation schemes are developed corresponding to time-series work in Fig. 9; E1 ~405 kyr (dashed smoothed curve); E2 100 kyr (solid smoothed curve).

by Walliser (1996). These are correlated to their position within the magnetostratigraphy in Fig. 11 for the revised zonation schemes. These events provide very important bio-markers for the uppermost Eifelian and Givetian, that in turn can be correlated with high precision to globally distributed Middle Devonian sections.

5.4.1. The Kačák bio-event

Summaries dealing with the Kačák bio-event (House, 1985) have been presented by several authors (DeSantis et al., 2007; House, 2002; Schöne, 1997; Walliser, 1990, 1996) and it is clearly defined in the Eifelian/Givetian GSSP (Walliser et al., 1995). This event is associated with transgression and corresponding dysoxic or anoxic bottom waters (House, 2002), and this is reflected in low δMS values for the event in Fig. 3, where its position is represented by MS zone EiZ in the latest Eifelian (Fig. 3). Extinctions identified during this time are attributed to a transgressive anoxic event (Walliser, 1996) that is equivalent to the onset of the stepped T/R cycle If of Johnson et al. (1985) (see also Brett et al., 2011-this volume).

5.4.2. The Taghanic bio-event

The Taghanic bio-event (House, 1985; Walliser, 1996) has been extensively studied by Aboussalam (2003), who reports the stratigraphic position of the event in a number of sections in Europe, North Africa and North America. Timing and magnitude of the event is somewhat ambiguous because of biostratigraphic uncertainties that exist in the literature. Its position is given, within our conodont zonation and MS SRZ scheme, at the MS zone Gv26 level (Fig. 11), generally exhibiting low MS values, indicating a transgressive phase during this interval. This bio-event represents a stepped extinction event that included brachiopods (14 families, discussed by House, 2002), corals (18 rugosan families, discussed by House, 2002), trilobites (1 order, 4 families and 2 sub-families, discussed by Feist, 1991) and stromatoporids, with a rapid radiation of pharciceratid goniatites following these extinctions. It is an important late Devonian bio-event that can be traced globally because it is associated with a

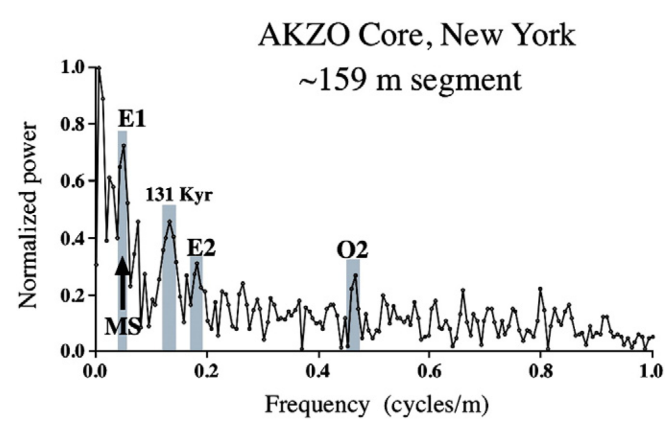

Fig. 9. Spectral power for raw MS values from the AKZO Core—interval from 330 to 171 m in Fig. 7, as determined via a Fourier Transform (FT) of the MS unsmoothed data. Frequency in cycles/m. The vertical bars labeled in the diagram indicate the centers of the Milankovitch eccentricity bands E-1 (~405 kyr), E-2 (~100 kyr), and ~131 kyr, and an obliquity peak, O2 (~39,300 years; Berger et al., 1992). The MS bar-log cyclicity reported here (Fig. 7) falls within the E-1 eccentricity peak (arrow). All shaded peaks are statistically significant at >95% level. There are three other statistically significant peaks (between 1.3 Ma and E-1, at ~0.34 cycles/m and at ~0.51 cycles/m) that represent very low frequency cyclicity not used in this study.

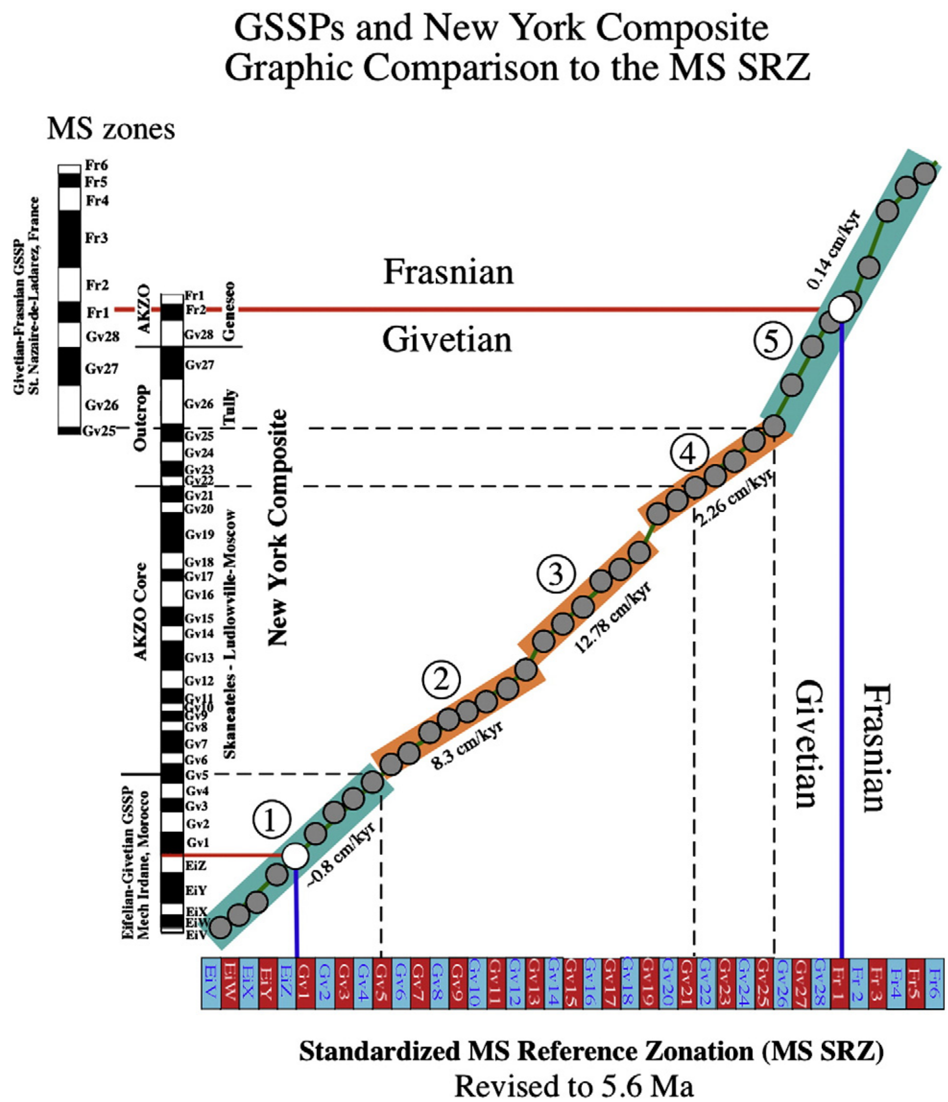

Fig. 10. Graphic comparison of the MS zonation from the New York Composite (core and outcrop sequences reported in Figs. 7 and 8), the Eifelian/Givetian (Fig. 3) and Givetian/Frasnian (Fig. 4) GSSPs, to a standardized MS SRZ for the latest Eifelian through earliest Frasnian. The MS SRZ represents a uniform E1 (~405 kyr) climate cyclicity as identified in the FT data sets (Figs. 5 and 9). Patterned circles represent the intersection of corresponding MS zone tops and bases between the MS zones for the data developed for this study and the MS SRZ; open circles represent the stage boundary points. Lines-of-Correlation (LOCs; sequentially labeled by circled numbers) are fit to segments of these data and bounded by shaded "tunnels". Dashed horizontal lines indicate the composited section intersections. LOC segments are built from the following: EiV through Gv5 from the Eifelian–Givetian GSSP; Gv6 through Gv25 from the New York Composite; Gv26 through Fr5 from the Givetian–Frasnian GSSP. Mean sediment accumulation rates (SARs) for each LOC segment are given in cm/kyr. Deviation of points from each LOC is low, indicating excellent fits and suggesting that sediment accumulation rates (SAR) within each section/core sampled were relatively uniform during most of the time represented by E1 cyclicity in this sequence.

major transgressive pulse at that time (Gv26), argued by House (1985) to be co-eval with the onset of T-R cycle IIa of Johnson et al. (1985). In addition, based on estimates of the extinctions of marine invertebrate families, House (2002) has suggested that the Taghanic event may be the greatest extinction event in the Devonian.

5.5. A Floating Point Time Scale (FPTS)

Because MS zones have been shown to represent Milankovitch climate cyclicity in the ~405 kyr eccentricity band, the MS SRZ presented in Fig. 11 can also be considered as a FPTS, with each MS zone representing ~200 kyr of time (a ~400 kyr half cycle). Then, depending on the absolute time scale used, it is possible to assign specific ages to each MS zone boundary and thus to estimate the timing of the biostratigraphic zonation used (here based on conodonts). For example, the *Polygnathus ansatus* conodont zone lasted for a bit less than ~1.8 myr, the *Polygnathus latifossatus*/*Ozarkodina semialternans* zone slightly more than 200 kyr, and the *Schmidtognathus hermanni* slightly less than 200 kyr (Fig. 11). When correlating between sequences it really does not matter what conodont scheme is used, the FPTS will apply for correlation purposes as long as the same scheme is used in both cases.

To plug into a specific time scale, an age for one of the GSSPs is used. For example, if the time scale of Tucker et al. (1998) is used, they place the beginning of the Givetian at 387.5 Ma. Therefore, the *Polygnathus rhenanus*/*varcus* conodont zone in Fig. 11, would have begun just after the beginning of Gv10 (ten, 200 kyr half cycles), a bit more than 2 myr after the beginning of the Givetian, and therefore at ~385.7 Ma. If the time scale used is different or changes, it is a simple matter to recalculate the new age of the MS zone of interest. Timing of these conodont zones can then be compared on a global scale to other sections using the MS zonation identified for those sequences, with comparison to the MS SRZ to evaluate the global timing and consistency of the biostratigraphic data set in question.

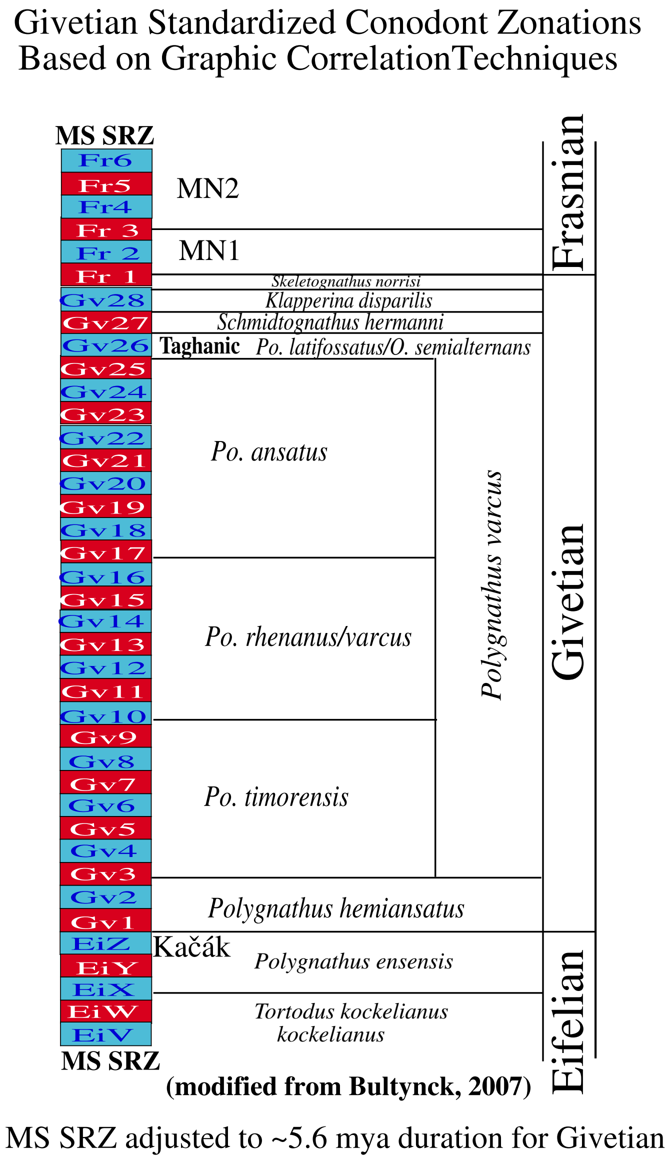

Fig. 11. A revised MS SRZ, based on twenty-eight ~200 kyr half cycles, compared with the adjusted conodont zonation scheme of Bultynck (2007). The MS SRZ reported here is different from that in Fig. 1. Revision is based on the test using the New York composite data set (Fig. 10) and increases the length of the Givetian to ~5.6 myr. Also plotted are the positions of the important Kačák and Taghanic bio-events.

6. Conclusions

Here we establish and test a climate-based age model for the Middle Devonian Givetian Stage, using magnetic susceptibility (MS) as an abiotic, climate-sensitive indicator of cyclicity to develop a robust model yielding a duration for the Givetian of ~5.6 myr, in close agreement with other reported durations for the Givetian. Our approach is to identify a geologic Stage of interest (we chose the Givetian). Then, (1) select an initial age for the duration of the stage from the literature—we chose ~4.4 myr from Kaufmann (2006); and (2) a standard biostratigraphic zonation is fit to a standard reference zonation (SRZ)—we chose a standard conodont zonation adjusted to an expected ~405 kyr MS cyclicity that is fit to the duration estimated for the Stage, ~4.4 myr, yielding 11 climate cycles; (3) identify the bounding Global boundary Stratotype Sections and Points (GSSPs) for that stage (if they have been defined), sample and measure these—we used MS; (4) use time-series analysis of the measured data sets to model dominant climate cyclicity—we determined this to be ~405 kyr; (5) test the initial model by graphically comparing MS zones from the bounding GSSPs—we use the Eifelian/Givetian [in Morocco] and Givetian/Frasnian [in France] GSSPs—and apply this uniform climate zonation to establish a model for the stage—we developed a MS standardized reference zonation (MS SRZ); (6) test this model using one or more independent sequences that cover all or parts of the stage—we used the AKZO Core from the eastern United States: and (7) adjust the model to reflect the new data set. Based on MS, biostratigraphic and FT data, we adjusted the duration of the Givetian Stage to ~5.6 myr, and ~28 MS zones. The process is then completed by plugging the standard biostratigraphic zonation into the uniform climate zonation for the stage (see discussion in Section 3.3.1). This work provides a framework that can then be further modified as additional data become available, ideally with each modification resulting in greater age precision.

Time-series analysis of MS data from the Eifelian/Givetian GSSP sequence in Morocco, and from the Givetian/Frasnian GSSP in France, bounding the Givetian, shows that Milankovitch eccentricity bands are well defined in these data sets. The dominant MS zonation resulting from MS cyclicity in the section falls within the ~405 kyr (E1) eccentricity band, providing a Floating Point Time Scale (FPTS) for the Givetian. Because each MS zone only represents half of the cycle, the MS zonation presented here represents time resolution to ~200 kyr. Graphic comparisons between sections in Morocco and France, using a climate standardized MS SRZ, exhibit excellent correlations, as does the AKZO Core data set used to test the model.

Biostratigraphic zonation tied to the MS SRZ then allows evaluation of significant bio-events that have been described for the Middle Devonian. These are the Kačák and Taghanic extinction bio-events that are both shown to occur in association with transgressive MS cycles, (exhibiting low MS values) in agreement with biostratigraphic and lithologic studies. It has been argued that these events are global. Therefore, the zonation described here can provide a means for precise identification of these events in other regions and the FPTS allows evaluation of relative timing of these events in a global context. Most important is that the method proposed here provides a means for high-resolution correlation on a global basis, using geophysical or geochemical climate-proxy data sets.

Acknowledgements

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