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EARTH'S CLIMATE CHANGE: SCIENCE AND IMPACTS

BOOK OF ABSTRACTS

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The Late Triassic and Early Jurassic Prelude to the Anthropocene?

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Abstract

Introduction

Late Triassic and Early Jurassic (ca. 237-195 Ma) proxy data suggest that atmospheric CO_2 reached levels (~5000-6000 ppm) not seen in at least the last 400 million years comparable to some projections for anthropogenic CO_2 rise by 2400 AD (Foster et al., 2017) (Fig. 1). That part of the Early Mesozoic offers a potential natural experiment for exploring the effects of very high CO_2 on the Earth System, especially because that episode also witnessed one of the largest mass-extinctions of the Phanerozoic, the end-Triassic mass extinction (ETE) at 201.6 Ma. The ETE itself has been attributed to an abrupt input of volcanogenic or thermogenic CO_2 caused by emplacement of the giant Central Atlantic Magmatic Province (CAMP: Marzoli et al., 1999) - a very disturbing linkage, considering we may already be in a mass extinction event. Here we examine the effects of high CO_2 on Milankovitch-cycle-paced climate variability and biotic diversity during this time we call the Early Mesozoic CO_2 Zenith (EMCOZ) (Fig. 1).

Triassic-Jurassic Lacustrine Cyclicity in Eastern North America

Lacustrine strata are sensitive recorders of climate change, and Late Triassic, and Early Jurassic lacustrine strata of Newark Supergroup rift basins of eastern North America, particularly those of the Newark Basin, have been famous for lacustrine Milankovitch-paced sedimentary cycles for over half a century (e.g., Van Houten, 1962). Subsequent work showed that similar cyclicity is characteristic of other eastern North American basins (Olsen, 1986) culminating with the Newark Basin Coring Project (NBCP) that recovered virtually the entire basin section of Triassic age strata (references in Olsen et al., 2011; Kent et al., 2017a). Combined with cores and outcrop data from Early Jurassic sequences of the Newark and adjacent Hartford basin, this record forms the basis for the Newark-Hartford Astrochronostratigraphic Polarity Time Scale (APTS: Kent et al., 2017a) that uses the 405 kyr long eccentricity cycle as the unimodal astronomical metronome for time calibration. This record provided the first empirical calibration of precession-related chaotic evolution of the Solar System (Olsen and Kent, 1999) and a

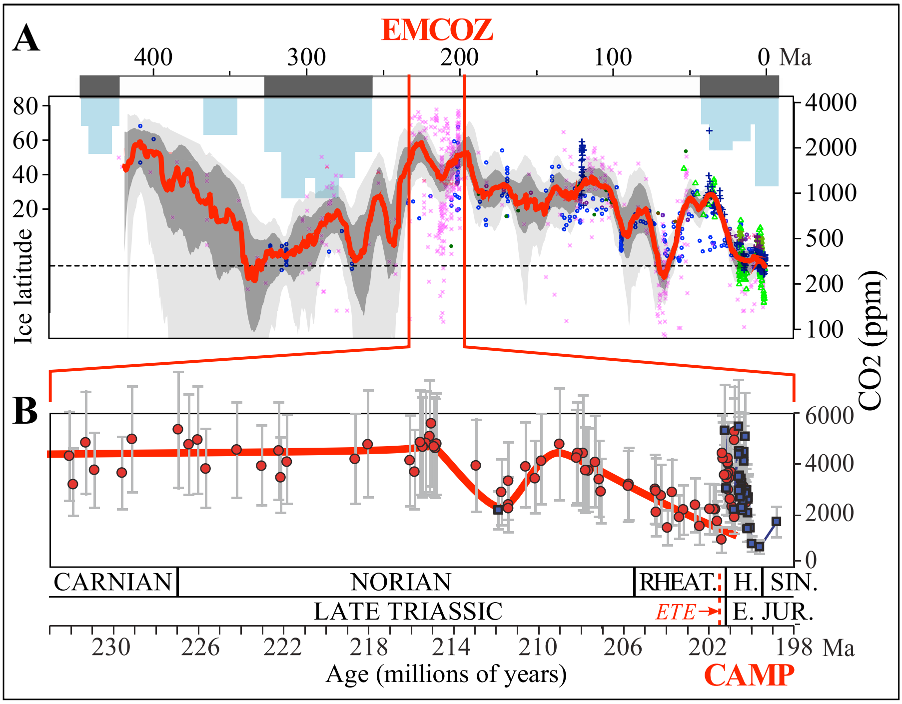

Fig. 1. A, Compilation of CO_2 proxy data and extent of continental ice modified from Foster et al. (2017): Lati-tudinal extent of ice (light blue bars) and ice-house con-ditions (gray bars). Proxy symbols are: leaf stomata (blue open circles); pedogenic carbonate (pink crosses); boron isotopes (green triangles); liverworts (blue filled circles); and alkenones (blue crosses). Red line is fit through the data and 68 and 95% confidence intervals are dark and light grey bands. B, The ECMOZ, based on the pedogenic CO_2 proxy, modified from Schaller et al. (2015). Red circles are from the Newark Basin and blue circles are from the Hartford Basin.

high-resolution record of the continental expression of the ETE (Olsen et al, 2002, 2011).

Lake level cyclicity is very obvious in most of the Newark and Hartford basin sequences, expressing the full spectrum of precession-related tropical climate variability (paleolatitudinal position of 5-21° N (Kent and Tauxe, 2005) (Fig. 2). The average water depth of the lakes was very shallow to dry, and as a consequence most strata are comprised of red playa mudstone sequences with footprints and paleosols. As interpreted within a Milankovitch context, however, intervals deposited during periods of highest precessional variance (times of high eccentricity) are often punctuated by deep-water strata consisting of thin microlaminated black mudstones deposited in chemically stratified lakes with a rich and well-preserved aquatic fauna. Times of intermediate precessional variability have less well-developed gray to black deeper water units and lack fine lamination. Times of low precessional variability (low eccentricity) have only red and purple strata (Fig. 2). The lake-level cyclicity is interpreted as reflecting tropical insolation modulation of African-like monsoonal precipitation and evaporation intensity.

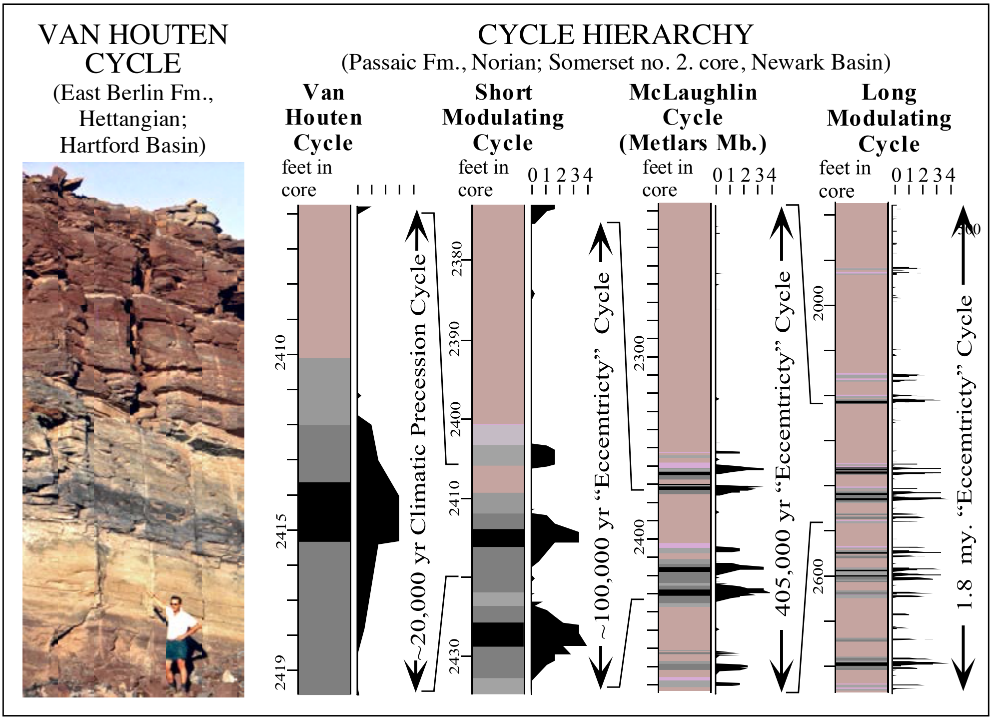

Fig. 2. Hierarchy of lithologic and environmental cyclicity in the Triassic and Early Jurassic of the Newark Basin.

Originally, Van Houten (1962) recognized the smallest, easily recognized sedimentary cycle in these strata as being paced by the ~20 kyr precession cycle and recognized longer cycles of ~100 and 400-500 kyr by counting the number of precession cycles within the larger cycles with a very loosely calibrated time scale. Olsen (1986) and others (references in Olsen et al., 2011; Kent et al., 2017a) used various Fourier spectral analysis methods on a semi-quantitative classification of sedimentary fabrics related to water depth (depth ranks) and color related to redox state to recognize a similar hierarchy of precession-related cycles, again within a relatively weakly constrained, paleontologically-based age model. Assuming the thickest prominent cycle was in fact the 405 kyr cycle, the depth scale could be tuned to time resulting in the Newark-Hartford APTS. Instrumental characterization of the Newark-Hartford cyclicity in geophysical logs, x-ray florescence spectrometry, and laser induced breakdown spectrometry reveals the same basic pattern and Milankovitch hierarchy as does color and depth ranks.

Given the length and importance of this record it has been justifiably criticized as lacking the "necessary first-order time control" (Hilgen et al., 1997), and a variety of different kinds of largely biostratigraphically inferred hiatuses have been asserted to be present in the sections. However, the Milankovitch pacing of the lacustrine cyclicity has been recently tested and corroborated by zircon CA ID-TIMS U-Pb dating of CAMP lavas and related intrusions in Eastern North

America interbedded with the very latest Triassic and Early Jurassic age strata in eastern North America and Morocco. This also resulted in dating the ETE, at the base of the oldest CAMP lavas in these areas at 201.564±0.011 Ma, completely consistent with available slightly lower resolution CA ID-TIMS U-Pb dates from ashes in marine sequences (references in Olsen et al., 2011; Kent et al., 2014a).

Testing of the older and much longer part of the Newark-Hartford APTS has been a major goal of the Colorado Plateau Coring Project, drilling for which was completed in 2013 with the continuous coring of the entire Triassic sequence in Petrified Forest National Park in Arizona (western USA). While fluvial in origin and not expected to reveal much in the way of Milankovitch climate cyclicity, the sequence was known to have a recoverable paleomagnetic reversal stratigraphy and multiple CA ID-TIMS U-Pb datable ashes, potentially allowing correlation with the Newark-Hartford APTS. Analysis of the cores reveals an unambiguous correlation and agreement between the astronomical calibration and the CA ID-TIMS U-Pb dates from the CPCP (Kent et al., 2017b) as well as from marine strata.

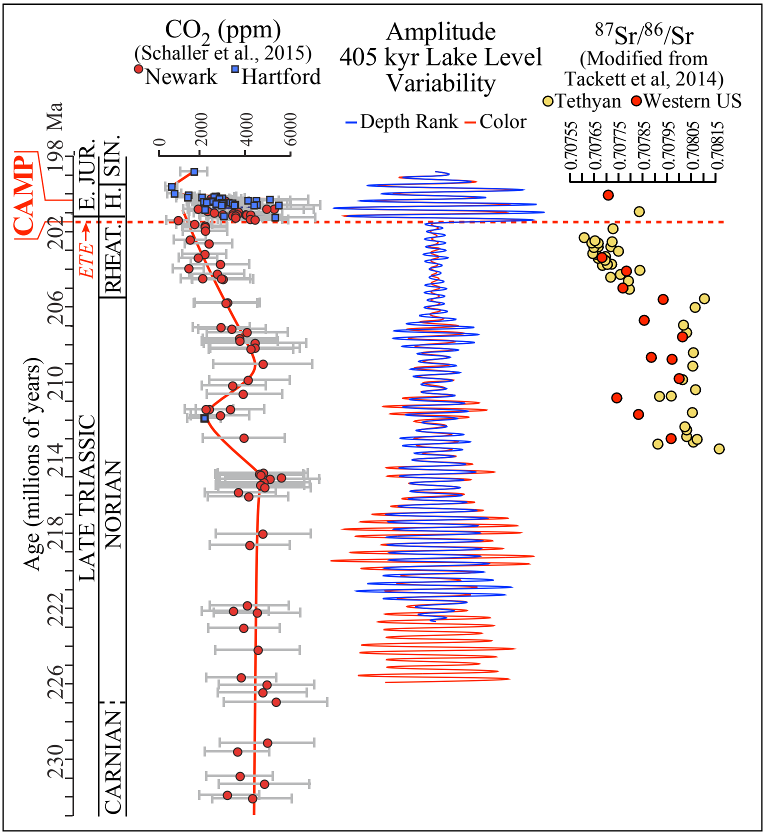

Fig. 3. Paleosol carbonate CO_2 proxy compared to Newark-Hartford lake level variability 87Sr/86Sr from marine strata.

Using the Newark-Hartford APTS as a template, along with independently acquired paleomagnetic polarity stratigraphies, the Milankovitch pattern has been mapped across latitudinal zones, from the equatorial tropics, to the continental subtropics and mid-latitudes in both hemispheres and into marine strata (references in Olsen et al., 2011; Kent et al., 2017a). In lacustrine strata, hemiprecessional along with precessional cyclicity dominates in the equatorial tropics and precessional cyclicity dominates in the arid subtropics although its variability is muted, in the evaporate-bearing and eolian mudrocks. In the subtropical marine strata, precessional cyclicity dominates. The limited high latitudes do not yet have a paleomagnetic polarity stratigraphy or independent radiometric age control, but based on correlation of putative 405 kyr cycles tied to biostratigraphic data significant variability in the obliquity bands are present along with precession-related cycles (Sha et al., 2015).

Central Pangea drifted north over 20° during the Triassic and Early Jurassic and in eastern North America and Morocco predicable large-scale vertical changes in facies and cycle expression occur. Older strata have more humid facies and younger strata display more arid facies. Contemporaneous strata in the mid-latitude basins change in the opposite sense, from arid to humid (Kent and Tauxe, 2005). This is because while the North American basins drifted from more humid into more arid zones, but the higher latitude basins in central Pangean drifted from arid into more humid zones. The widths of the low- to mid-latitude humid and arid zones do not seem to differ greatly from now(Kent and Tauxe, 2005).

Two major deviations from this expected general trend are apparent, however. First, there is a dramatic and abrupt diminution of the amplitude of the precession-related cycles as seen in the lacustrine cyclicity, during the latest Norian through nearly all of the Rhaetian, in continental as well as marine strata (Figs. 3), with the 20 kyr climatic precession-paced cyclicity nearly disappearing in the Rhaetian. This occurs without a concomitant increase in features indicating increased aridity. Second, the amplitude of precession-related cyclicity becomes much greater in the very latest Rhaetian through the Hettangian (Fig. 3), reversing the expected trend anticipated from the northward drift of central Pangea. These deviations are synchronous with changes in atmospheric CO2.

EMCOZ and Climate

Newark and Hartford basin paleosols have yielded a detailed soil carbonate record of atmospheric CO2 (Schaller et al., 2015 and references therein) (Fig. 1, 3) that form the basis for recognizing the EMCOZ (Figs. 1, 3). The proxy records are consistent between correlative core and outcrops and between basins. The soil carbonate proxy records very high CO2 (~5000 ppm) during the preserved duration of the Carnian and nearly all of the Norian. There is a prominent dip at about 212 Ma where it drops to ~2000 ppm and rises again, thereafter dropping to between 1000 and 2000 ppm to the ETE, where it rises abruptly in 4 pulses in strata around and interbedded with the CAMP lavas. Three of the CO_2 pulses occur directly above three pulses of CAMP lavas and are correlative between the Newark and Hartford basins, and the fourth and youngest is not associated directly with a known flow. After the fourth pulse CO_2 drops to levels seen in the Late Rheatian of ~1000-2000 ppm. Leaf stomatal proxy data from Greenland, Sweden, and the UK also record a dramatic increase in CO_2 correlative with CAMP emplacement (see references in Steinthorsdottir et al., 2011), as well, albeit at lower temporal precision and without benefit of superposition with the lavas themselves. The absolute values of the stomatal proxy are lower than the soil carbonate proxy, but the trends are the same.

Associated with the EMCOZ is a lack of any evidence for persistent polar ice caps or glaciers (Frakes and Francis, 1988). High latitude regions supported at least partly deciduous forests and coal-bearing environments even near or at the poles (Pole, 2009; Pole et al., 2016), which is certainly consistent with the paradigmatic relationship between CO_2 and high latitude warmth. However, evidence from lake-ice-rafted debris suggests freezing during winter in at least paleo-high-latitude Asia associated with deciduous forests and coals during at least the Rhaetian and possibly early -Early Jurassic.

EMCOZ and Milankovitch-Paced Cyclicity

A striking correlation exists between the proxy record of CO_2 and the amplitude of sedimentary cyclicity, best seen in the Newark Basin. The filtered 405 kyr cycle based on depth ranks and color shows striking changes synchronous with the larger scale pattern of CO_2 change (Fig. 3). Cyclicity variance is high during times of high CO_2 (~4000 ppm) during most of the Late Triassic, drops precipitously as CO_2 drops below 2500 ppm during most of the Rhaetian, dramatically increases during the huge CO_2 spikes (~5000-6000 ppm) associated with the CAMP and ETE, and again drops as CO_2 drops during the Jurassic to Rhaetian levels (<2000 ppm).

87Sr/86Sr in marine strata apparently tracks CO_2 (Fig. 3) with a dramatic decrease from about 0.70795 to 0.70765 during the Rhaetian (Tackett et al., 2014) suggesting both a mechanistic link though weathering and that the relative changes in the soil carbonate and stomatal proxy data are meaningful, even if the absolute values of the two differ.

Examination of sections from different environments, such as marine strata of Europe (Bristol Chanel and Northwest Germanic Basin), suggest a similar muted cyclicity for most of the Rhaetian, especially compared to the preceding Norian and succeeding latest Rhaetian and Hettangian in the same areas.

These observations are in line with the argument that higher CO_2 amplifies orbital forcing through intensification of the hydrological cycle, at least in terms of climatic precession. IPCC (Stocker et al., 2013) predictions include a lengthening of the monsoon season, increased frequency of extreme events, especially in precipitation, but with both flood and drought frequency increases. While the magnitude of lake level cyclicity could be a reflection of basin tectonics via changing accommodation space, the apparent tracking of variance in cyclicity in far distant marine sequences suggests otherwise.

EMCOZ and the ETE

The dramatic increase in CO_2 at the ETE associated with the emplacement of the CAMP is usefully examined in relation of the otherwise dropping CO_2 of the Rhaetian and rest of the Early Jurassic. This is the only part of the EMCOZ for which there is a plausible cause either through direct volcanic outgassing or thermogenic greenhouse gas generation by CAMP intrusions (Davies et al., 2017 and references therein). While the total CAMP event may have lasted nearly a million years, the individual major pulsed eruptions that caused the CO_2 doublings to triplings may have lasted less than a hundred years, based on paleomagnetic secular variation constraints (Kent et al., 2012), and certainly less than a few thousand years based on the cyclicity. These eruptions could plausibly have caused multiple significant biocalcification crises using the constraints of Hönisch et at. (2012), consistent with the invertebrate extinction pattern (Hautmann, et al., 2008). However on land the situation is more complex.

The Late Triassic was characterized by dramatic continental faunal and floral provinciality, in which all herbivorous dinosaurs were apparently restricted to mid- and high-latitudes, while pseudosuchians dominated the tropics. Plausibly, herbivorous dinosaurs with their high metabolic requirements were excluded from the tropics in the face of competition from pseudosuchians because of the ecosystem instability engendered by the extreme climatic swings and high frequency of extreme events and fire during the times of high CO_2 (Whiteside et al., 2015). As CO_2 declined in the Rhaetian carnivorous dinosaurs became more abundant in the tropics at the expense of the pseudosuchians, but herbivorous dinosaurs did not spread into the low latitudes until the ETE and nearly all pseudosuchians became extinct. This extinction pattern seems inconsistent with a ~3° to ~4° increase in temperature expected of the doubling to tripling of the CO_2, which would seem to favor the uninsulated psedosuchians with lower metabolic requirements, especially in higher latitudes. However, large uninsulated psedosuchians would have had no evolutionary adaptive experience with the extraordinary volcanic winters generated by the gigantic flood basalt eruptions of the CAMP. Primitively insulated dinosaurs (with protofeathers), living at higher latitudes, perhaps already living in areas with freezing winters would be accidently adapted to survive the cold spells. Cold from many short duration volcanic winters, rather than heat from much longer term CO_2 increases is more consistent with the extinction and survival pattern on land.

EMCOZ and The Late Triassic and Early Jurassic Prelude to the Anthropocene

While there is a general consensus that climate models predict that with rising CO_2, wet areas will grow wetter and dry areas drier (Stocker, et al., 2013), and there is some evidence that higher CO_2 amplifies the effects of orbital forcing, including the effects on the monsoon, the relationships between radiative forcing via CO_2 and precipitation are complex. Increases in orbitally forced isolation need not be additive to the warming effects of rising CO_2 because of multiple non-linear effects such as plant transpiration (Steinthorsdottir et al., 2013) and atmospheric water vapor content and, in some locations and various scenarios, even the sign of the change is unclear (Schaller, N. et al., 2013). Comparisons between models and Pleistocene fluctuations in CO_2 have the advantage that CO_2 concentrations are better constrained than any previous time, but they did not exceed present or reach projected levels, limiting their power to test and validate models.

In contrast, during the EMCOZ, CO_2 concentrations reached or exceeded present and most projected levels for protracted periods, and in the case of CAMP eruptions, even the rate of CO_2 increase may have equaled or exceeded anthropogenic fossil fuel additions. While several boundary conditions, such as continental position, ocean currents, ecosystem composition were clearly different than today, the positive correlation of CO_2 and the amplitude of Milankovitch-paced environmental cyclicity at million-year and Milankovitch scales, suggests that Earth System sensitivity to the CO_2 changes were sufficient to strongly modify the translation of insolation variations to climate change. Anthropocene Milankovitch climate variability and with it linked seasonality and associated extreme events would thus be expected to be much amplified over the next 100 kyr or so, even as meridional temperature gradients decrease.

However, EMCOZ CO_2 multiple increases during the CAMP emplacement, associated with the ETE, do not provide a clear parallel with "sixth extinction" scenarios. While offering a plausible example of ocean acidification driving extinction, there were multiple CO_2 increases, separated by relaxations, while there will presumably be only one Anthropocene CO_2 pulse - we do not know if the repetition of the ocean acidifications is what assured extinction or the magnitude, or both. On land, volcanic winters are more consistent with the extinction and survival patterns, than increasing CO_2 and an anthropogenic parallel is not anticipated, unless some Earth System remediation attempt via albedo increase goes badly wrong. Thus while CO_2 increases were temporally associated with continental extinctions, they were correlated but not causative, and that might be the case with other large igneous provinces as well. The EMCOZ, ETE, and CAMP CO_2, are not therefore appropriate natural experiments pertinent to continental biotas, but might very well be for the marine biota and for understanding the effect of intensification of the hydrological cycle during the Anthropocene.

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