A new correlation of the Cretaceous formations of the Western Interior of the United States, I: Santonian-Maastrichtian formations and dinosaur biostratigraphy

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Abstract

Late Cretaceous deposits of the North American Western Interior represent the best, if not only, opportunity to construct a high-resolution chronostratigraphic framework within which to conduct continental-scale geological and paleontological analyses. This is due to the serendipitous combination of large areas of outcrop, interfingering marine units with biostratigraphically informative fossils, and a consistent scattering of radiometric dates due to synorogenic volcanic activity. Accurate correlation is essential for testing a large number of current geological and paleobiological hypotheses; however, despite the large amount of data available, many published correlations suffer from inaccuracies or are simply based on outdated information.

Here I present a comprehensive high-resolution stratigraphic chart for terrestrial Late Cretaceous units of North America, combining published chronostratigraphic, lithostratigraphic, and biostratigraphic data. For the first time, nearly two hundred ^{40}Ar / ^{39}Ar radiometric dates are recalibrated to both current standard and decay constant pairings, correcting errors in previous recalibrations. Revisions to the stratigraphic placement of most units are slight, but important changes are made to the proposed correlations of the Aguja and Javelina Formations, Texas, and miscalculations in recently published analyses are corrected which in particular affects the relative age positions of the Belly River Group, Alberta; Judith River Group, Montana, Kaiparowits Formation, Utah, and Fruitland and Kirtland Formations, New Mexico.

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This work represents the most extensive and accurate interbasinal correlation currently available for the North American Western Interior and should replace all previously published similar works and diagrams.

The stratigraphic ranges of selected dinosaur clades are plotted on the chronostratigraphic framework, typically forming stacks of short-duration species which do not overlap stratigraphically with preceding or succeeding forms. This is the expected pattern which is produced by an anagenetic mode of evolution, suggesting that true branching (speciation) events were rare and may have geographic significance. Purported north-south provinciality of dinosaurs is shown to be mostly an artifact of stratigraphic miscorrelation. Rapid stepwise acquisition of display characters in many dinosaur clades, in particular chasmosaurine ceratopsids, suggests that they may represent the highest resolution biostratigraphic markers to be used where radiometric dates are not available.

Introduction

In 1952, Cobban and Reeside published a grand correlation of Cretaceous rocks of the Western Interior of central and southern North America, including both marine and terrestrial units, and biostratigraphic ranges for a variety of invertebrates and vertebrates. Such interbasinal correlation diagrams are useful for making stratigraphic comparisons between units and similar style diagrams have become commonplace in the geological literature, albeit few with such broad geographical scope. The interbasinal correlation

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chart of Cobban and Reeside (1952) was important in its day, but it has been superceded by the advent of advanced chronostratigraphic methods which offer current workers much greater precision and accuracy in placing stratigraphic boundaries. However, most recently published correlations are fairly local in scale, aligning units within the same or adjacent basins, and thus limiting applicability. An exception was presented by Krystinik and DeJarnett (1995) that was specifically intended to show sequence stratigraphic correlations (and lack of correlations) between Western Interior units. This progressive work incorporated sea-level curves and radiometric dates, yet is itself now largely outdated with changes to many of the depicted unit ages and especially their durations. Another analysis (Miall et al., 2008) was similarly broad in geographic scope, but not particularly detailed (although this was not their main intent).

Interbasinal correlation charts are not just of use to geologists; more frequently than ever, paleontologists are using high-resolution chronostratigraphic data to formulate and test evolutionary hypotheses. A simple example is that of time-calibrated phylogenies, where the stratigraphic positions of individual taxa are superimposed on phylogenetic trees. These are becoming much more prominent in the dinosaur literature (e.g. Sampson et al., 2010; Evans et al., 2013), and are used to deduce the timing of important phylogenetic branching events, infer ghost ranges, and potentially to calculate rates of evolution. A more nuanced application that is especially important to my research is assessing whether two sister taxa are contemporaneous (thereby inferring a genuine speciation event), or whether they form a succession of stratigraphically separated morphologies (supportive of anagenesis; e.g. Horner et al, 1992; Scannella et al., 2014).

The value of such analyses is inherently dependent upon the accuracy of the plotted taxa, which in turn depend upon the accuracy of the stratigraphic correlations of the formations from which their fossils were recovered. Herein lies the problem. Precise dating of geological formations is especially critical for testing anagenesis or cladogenesis in dinosaurs, but when specimens are very similar in age, imprecision of only a few hundred thousand years is often enough to completely reverse paleobiological interpretation.

The Late Cretaceous deposits of the North American Western Interior represent the best, if not only, opportunity to make a high-resolution chronostratigraphic framework within which to study dinosaur evolution. This is due to the serendipitous combination of large areas of outcrop, interfingering marine units with biostratigraphically informative fossils, and a consistent scattering of radiometric dates due to synorogenic volcanic activity, not to mention the vast literature detailing over a century's worth of research. However, despite the large amount of data available, many published correlations suffer from inaccuracies that inevitably strongly affect paleobiological interpretations:

1. It is difficult to find the reasoning behind some correlations

In paleontological papers especially, correlation charts are typically presented as a series of geological columns, and rarely contain clear or detailed justifications for the stratigraphic positions of the depicted horizons. Usually a few citations are given for stratigraphic position, and radiometric dates may be marked (also including citations), but important details may be lacking. This can create many problems, including circular

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citation of incorrect or unknown stratigraphic data (e.g. the age of the '*Alamosaurus* fauna'; Lehman 2001) or unknowingly mismatching old outdated stratigraphic data with new interpretations or calibrations (e.g. the changing correlations and calibrations of radiometric dates from the Kaiparowits Formation Utah; Roberts et al., 2005; 2013; Sampson et al., 2010; Zanno et al., 2011). Admittedly, justifying every boundary or horizon in a stratigraphic column is an arduous task, but without detailed work like this, precise stratigraphic placement of taxa can be either impossible or plotted incorrectly.

2. Lacunae are not depicted

Geological columns often do not emphasize the lacunae that exist within formations. For example, a historical problem in terrestrial lithostratigraphy is that laterally consistent resistant sandstones are often used as uppermost units for formational contacts; e.g. the Capping Sandstone Member, Wahweap Formation, Utah (Eaton, 1991). This is a problem as amalgamated channel sandstones typically form the basalmost unit of depositional sequences; it happens that the uppermost unit of the Wahweap Formation (Capping Sandstone) is actually the basal amalgamated channel complex of the overlying sequence that comprises the Kaiparowits Formation (Lawton et al., 2003). Hence, the Wahweap and Kaiparowits Formations can appear to represent a more conformable succession than what occurs in actuality, and the therefore technically correct cited durations for each of the formations are misinformative. For this and other reasons, formation members and the lacunae between them should be plotted on correlation charts and explained where possible.

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3. Radiometric dates may be incorrect or incomparable

Many currently cited radiometric dates are not properly comparable as from the early 1980's through to the current day, radiometric analyses have used a variety of standards, decay constants, or different methods. There is also an emerging issue that analyses performed in different laboratories produce slightly different results, and this is being investigated internally by those labs (Renne., pers. comm.).

Here I present a comprehensive stratigraphic correlation chart comprising the major terrestrial geological formations of the North American Western Interior (Table S1). The chart is plotted based on extensive review of the pertinent stratigraphic literature on each formation, and on the recalibration of nearly 200 ^{40}Ar / ^{39}Ar radiometric dates. Recalibrated radiometric dates are presented both on the chart itself, and as a separate excel sheet (Table S2), and are recalibrated to both currently accepted ^{40}Ar / ^{39}Ar standards (Kuiper et al., 2008, combined with the decay constant values of Min et al., 2000; and Renne et al., 2011). The recalibrations correct minor and major errors in previous works (e.g. Kuiper et al., 2008; Schmitz, 2012; Roberts et al., 2013). This new work represents the most precise and comprehensive correlation currently available for terrestrial geological formations of the North American Western Interior. This is used in combination with locality data for individual dinosaur specimens to plot the stratigraphic ranges for dinosaur taxa (currently restricted to Neoceratopsia, Sauropoda, and Hadrosauridae). This replotting of dinosaur taxa is discussed with regards to current hypotheses of dinosaur biogeography and evolution.

Methods

Abbreviations used

Gp, Group; Fm, Formation; Mbr, Member. Ma, millions of years ago; Ka thousands of years ago; m.y. million years; k.y. thousands of years; c.z., coal zone; FCT, Fish Canyon Tuff; TCR, Taylor Creek Rhyolite.

Display format - excel sheets

The recalibration sheet and stratigraphic correlation chart are offered as two separate excel files (Tables S1 and S2). They are kept separate for ease of cross referencing.

Table S1 - Stratigraphic correlation chart

The stratigraphic correlation chart is arranged as an excel spreadsheet (Table S1), and is intended to be used directly in this format as it offers a number of advantages over a graphic embedded within a PDF or printed page. The grid of cells naturally permit precise plotting of stratigraphic boundaries, with each vertical cell height representing 0.1 m.y.. Most usefully, each cell, (or group of cells) can be tagged with a pop-up note that is activated by simply hovering the mouse cursor over any cell with a red triangle in the

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upper right corner. These pop-up notes comprise the bulk of the results of this study, providing the information that supports each depicted stratigraphic position or boundary of the geologic unit or taxon, along with introductory text. For ideal formatting, the reader is advised to view the chart in native resolution, at 22% zoom level.

Some disadvantages of the excel format include the limited range of line styles and orientations, such that (for example) it is not possible to represent unconformities by a wavy line, and cell borders necessarily are straight. Due to the need to keep font size small (to increase available space), taxon names are not produced in italics as it makes them much less readable. The reader is advised that under some levels of zoom, a note box might not be fully readable; if so, right click and select edit note, then either read the note in place, or resize the note box such that all the text is visible.

References used in the construction of the chart are available as a separate document (Text S1).

Table S2 - Recalibration sheet

The recalibration sheet (Table S2) is also made available in the form of an excel sheet. This is due to its large size, but also enjoys the benefit of the pop-up notes, providing additional information on radiometric dates and the original publications. Maintaining the recalibrations as an excel sheet also permits the retention of the active formulae used to calculate the new dates.

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The recalibration sheet is adapted from the EARTHTIME excel recalculation sheet provided by Noah McLean at the earthtime.org website. This is the same source as for the recalibrations performed by Roberts et al. (2013), cited as: http://www .earth-time.org/ar-ar.html, by those authors. Unfortunately, the earthtime.org website is currently listed as "under construction", and so I have not been able to relocate the original download location.

The original recalibration formulae were duplicated across into my Table S2 such that this is a "live" document which independently recalculates dates based on the input data on each line of the sheet. I have also adapted the source lines for each recalculation such that all the original input data (standards, decay constant, etc.) are visible for each recalculation. This way the sheet shows all the "working" for all of the 200 recalculations, and each can be properly independently assessed (by comparison, the original sheet provided by McLean and EARTHTIME only had space for a few recalculations at a time). This is a direct response to the lack of such data provided in previous recalculation publications (e.g. Roberts et al., 2013), requiring therefore that the reader must replicate the result for themselves in order to check that the recalibration was performed correctly (see results section for discussion of errors encountered in previous recalibrations).

There is a problem with the recalculation of error in the original formulae present in the McLean EARTHTIME sheet. This has the result that for some recalibrations, the excel sheet will only produce a "!VALUE" statement for the recalibrated

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uncertainty/error (caused by the formula attempting to divide by zero). As a result, the uncertainty/error for many recalibrations cannot be computed (an additional problem is the lack of J-value data in most analyses). To overcome this, for analyses where the new error cannot be directly computed, I have multiplied the original error by the % change output factor; error calculated by this method are shown in red (normally calculated error values are shown in black). Comparison to normally calculated error values show that this method produces comparable results such that the new stated error values are not significantly different from what would be calculated if J-values (etc) were known.

There are two tabs of recalibrations. The first, labeled "Kuiper et al 2008", recalibrates all the dates to the Kuiper et al. (2008) FCT standard, coupled with the Min et al. (2000) decay constant. Dates from this first tab are plotted on the stratigraphic chart (Table S1). The second tab, labeled "Renne et al 2011", recalibrates all dates to the standard and decay constant pairing of Renne et al. (2011). This second set of recalibrations is provided for comparison. Both tables of recalibrations have the same formatting for ease of comparison.

Stratigraphic chart (Table S1)

Construction of the chart is complex and depends upon many different stratigraphic methods. Here I explain the underlying definitions which provide the base framework for the chart, and highlight some of the issues surrounding its construction.

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Definitions: stage and substages, magnetostratigraphy, and ammonite biostratigraphy

Here I follow The Geological Time Scale 2012 (GTS2012; Gradstein et al., 2012) for definitions of stage and substage boundaries (Ogg and Hinnov, 2012), magnetostratigraphic boundaries (Ogg, 2012), and ammonite biostratigraphy (Ogg and Hinnov, 2012). Although more recent revisions of these definitions are available, GTS2012 integrates all these defined units with chronostratigraphic dates which use the ^{40}Ar /^{39}Ar standard and decay constant pairing of Kuiper et al. (2008) and Min et al. (2000), which are used here. A second magnetostratigraphic column is also offered containing some revised chron boundaries and includes many of the very short duration cryptochrons that have not yet been officially recognised, but are often named in magnetostratigraphic analyses (e.g. Lerbekmo and Braman, 2002). Individual definitions and discussion (where appropriate) can be found in the popup notes in the respective parts of the chart.

In some places I have been forced to provide a compromise in stratigraphic placement, generally where a magnetostratigraphic assertion does not match, say, the ammonite zonation (e.g. age of the Dorothy bentonite in the Drumheller Member, Horseshoe Canyon Formation, Alberta). In such cases, text boxes provide explanation of the problem, and references.

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Positioning of geological units and dinosaur taxa

The stratigraphic ranges of geological units and fossil taxa are plotted as a solid bordered white cell with the lower and upper borders representing the lower and upper contacts of the geological unit, or first and last documented taxon occurrences (respectively). If stratigraphic position is not sufficiently documented, the possible or likely stratigraphic range is illustrated as a block arrow. A combination of a solid cell and block arrow may be used if a taxon comprises some specimens for which stratigraphic position is precisely known (depicted by the solid cell) and some specimens for which stratigraphic position is unknown (block arrows). Periods of non-material time (lacunae) are represented by blank spaces. A graded block arrow is used for units which may continue for a long time below the period of interest (typically used for thick marine shales).

Sequence Stratigraphy and lithostratigraphy

Some features of typical lithostratigraphic units are not possible to properly depict on the stratigraphic chart format. In the Western Interior, many terrestrial packages form clastic wedges thinning basinwardly. I have attempted to represent this in the chart where possible, although for the most part depicted stratigraphic sections are based on single well-sampled sections, cores, or geographic areas, and so the wedge-shaped overall geometry might not be visible.

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Limitation of scope & future versions

There are some limitations of scope for this initial version of the correlation chart.

Stratigraphic age is currently mostly limited to units of Santonian age (86.3 Ma) up to the K-Pg boundary (66.0 Ma). There are a few exceptions (e.g. Moreno Hill Fm, NM; Straight Cliffs Fm, UT) which are included because they have yielded important specimens, or provide stratigraphic context for overlying units.

Geological units featured in the correlation chart are currently limited to those for which dinosaurian material has been collected, or which provide contextual information for surrounding units (e.g. intertonguing marine units with biostratigraphically informative fauna; overlying or underlying units with chronostratigraphic marker beds).

Dinosaurian fossils are limited to Neoceratopsia, Sauropoda, and Hadrosauridae as these are the most abundant and biostratigraphically informative taxa.

Future versions of the chart are intended to extend stratigraphic range down to the Jurassic-Cretaceous boundary (eventually). However, the plans for the first expansion concern inclusion of more Late Cretaceous formations from North America, and also similarly aged deposits in Asia. Initial work on expanding faunal coverage has already begun concerning the addition of all remaining dinosaur taxa (including birds),

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crocodilians, and mammals, with the intent of eventually incorporating all useful taxa if possible (although coauthors will be sought for this).

Institutional abbreviations

A list of institutional abbreviations used in the correlation chart are provided in a separate tab of the correlation chart excel sheet (Table S1) labeled "repository codes".

Taxa display format- phylogenies and lineages

It is not the intention of this project to make significant comment on phylogenies *per se*. However, precise stratigraphic placement of taxa permits testing of speciation hypotheses (see discussion) and so the arrangement of taxa on the chart should reflect up-to-date phylogenies or other hypotheses of descent. In this current version, this only affects Ceratopsidae and Hadrosauridae. For ceratopsids, the general arrangement follows the chasmosaurine phylogeny from Fowler (2016), and for centrosaurines I follow the phylogeny of Evans and Ryan (2015). For hadrosaurids, the general arrangement of hadrosaurines follows Freedman Fowler and Horner (2015), and lambeosaurines follows Evans and Reisz (2007). An important difference with the arrangement of taxa in the strat chart is that unless they are contemporaneous, taxa are arranged as lineages of stratigraphically separated "species".

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Magnetostratigraphy

In magnetostratigraphic analysis, if two stratigraphically adjacent sample points yield opposite polarities (i.e. they are recognisable as different chrons), then it is convention to draw the chron boundary stratigraphically halfway between the two points. However an issue arises when these lower and upper sample points are separated by a sandstone from which it is difficult or impossible to extract a magnetostratigraphic signal. In terrestrial floodplain deposition (typical of the units studied in this work), the bases of depositional sequences are characterized by a surface of non-deposition or erosion, overlain by a low accommodation systems tract, typically comprising an amalgamated channel sandstone. The combination of the depositional hiatus at the base of the sandstone, and the sandstone itself, means that there may be a considerable time gap (up to millions of years) between the last sampled horizon immediately below the sandstone, and the first sampled horizon immediately above the sandstone. If opposite polarities are recorded for the two sampled horizons either side of the unsampled sandstone, then the chron boundary would be drawn halfway, within the sandstone, whereas it is more likely to occur at the base of the sandstone, as this is where the hiatus occurs. This can have the effect of making a unit appear older or younger than it really is. For example, the mudstone immediately beneath the Apex sandstone (basal unit of the upper Hell Creek Formation, Montana; Hartman et al., 2014) is of normal polarity, assigned to C30n, whereas the mudstone immediately above the Apex Sandstone is of reversed polarity (assigned to C29r; LeCain et al., 2014). The C30n-C29r boundary is therefore drawn within the Apex Sandstone, whereas it is more likely that it occurs at the hiatus at the

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base of the sandstone. A more significant case arises with the contact between the Laramie Formation and overlying D1 sequence in central Colorado: here, because of the halfway convention, the uppermost part of the Laramie is drawn as being within the lowermost C31r zone (Hicks et al., 2003), whereas in reality, all magnetostratigraphic samples from the Laramie are normal, and it is probably entirely C31n. These are just two examples, and more are highlighted as notes in the chart. So long as the reader is careful and remains cautious of this issue, then mistaken correlation and / or artificial age extension can be avoided.

Radiometric dating

This analysis reports nearly 200 radiometric dates (Table S2), most of which are ^{40}Ar / ^{39}Ar dates which have been recalibrated to the standard and decay constant pairing of Kuiper et al. (2008), and Min et al. (2000). It is not my intention to provide a thorough review of all radiometric dating methods (see Villeneuve, 2004), nor is this my personal research specialisation. However, given the large number of ^{40}Ar / ^{39}Ar dates used here, and given discrepancies in past recalibrations, I give a cursory overview to the method. This text is also included (and expanded) in the chart itself (Table S1).

U-Pb and K-Ar

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Most radiometric dates reported for Upper Cretaceous units use either U-Pb, K-Ar, or ^{40}Ar / ^{39}Ar dating methods. U-Pb and K-Ar are primary dating methods, which directly determine the age of a sample and do not require recalibration (unless decay constants change, which is rare); whereas relative or secondary methods (such as ^{40}Ar / ^{39}Ar dating) require use of a monitor mineral of known or presumed age ("standard"). It is the recent changes to the recognized age of these standards which has been the cause of changing ^{40}Ar / ^{39}Ar dates.

U-Pb dating actually analyses two decay series (^{235}U decay to ^{207}Pb, and ^{238}U decay to ^{206}Pb), such that there are two independent measures of age, the overlap of which is the concordant age of the sample (Villeneuve, 2004). Recent improvements in analytical techniques (High-Resolution–Secondary Ion Mass Spectrometry: SHRIMP) have brought greater precision and accuracy to U-Pb dating and it remains one of the best methodologies currently available (Villeneuve, 2004). The decay constant for U-Pb analysis is well established (Steiger and Jaeger, 1977), and known to better than 0.07% (Villeneuve, 2004). It is noted however (Villeneuve, 2004) that uncertainty in the U-Pb decay constant is not typically included in cited final ages; this is not an issue when comparing among U-Pb dates, but should be properly included when comparing (say) U-Pb to ^{40}Ar / ^{39}Ar dates.

K-Ar dating is an older method of radiometric dating that was commonplace up until the end of the 1980's when it was essentially replaced by the more precise and accurate ^{40}Ar / ^{39}Ar method (Villeneuve, 2004). K-Ar had a range of benefits, including a

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large number of possible datable minerals (due to the common occurrence of potassium in many rock-forming minerals), but among its many drawbacks was a relative lack of precision, largely due to the requirement to run two separate analyses per sample for K and ^{40}Ar. As such, analytical precision was never better than 0.5%, and with the development of new technologies K-Ar dating was quickly replaced by ^{40}Ar / ^{39}Ar in the early 1990's (Villeneuve, 2004). Even so, some K-Ar dates are still the only dates available for a given unit, and so are included in the chart. K-Ar dates typically have error in the region of 1-2 m.y for Upper Cretaceous units, so are useful indicators as to a general age range for a unit, but not for precise correlation.

^{40}Ar / ^{39}Ar

Detailed reviews of ^{40}Ar / ^{39}Ar dating have been published elsewhere (e.g. McDougall & Harrison, 1999). Notes given here are for the purpose of aiding the reader in understanding the recalculation of radiometric dates reported in this work, how ^{40}Ar / ^{39}Ar dates are affected by changing standards and decay constants, and comparability of radiometric dates recovered by different methods (e.g. ^{40}Ar / ^{39}Ar vs U-Pb).

Standards (neutron fluence monitor)

As ^{40}Ar / ^{39}Ar dating is a relative dating method, every unknown sample needs to be analysed alongside a sample of known age: a standard. Primary standards are minerals from specific rock samples that have been directly dated by ^{40}K / ^{40}Ar dating or another method; whereas secondary standards are based on ^{40}Ar / ^{39}Ar intercalibration with a

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primary standard (Renne et al., 1998). The following list includes (but is not limited to) some of the more popular standards that have been used historically (see McDougall & Harrison, 1999, for a more complete list):

MMhb-1	McClure Mountain hornblende, primary standard: ~420 Ma
GA-1550	Biotite, monazite, NSW, Australia, primary standard: ~98 Ma
TCR	Taylor Creek Rhyolite (or sanidine, TCs), secondary standard: ~28 Ma
FCT	Fish Canyon Tuff (or sandine, FCs), secondary standard: ~28 Ma
ACR	Alder Creek Rhyolite (or sanidine, ACs), secondary or tertiary standard: ~1 Ma

Standards are chosen depending on availability, and should be of comparable age to the unknown sample (Renne et al., 1998). Hence, for Late Cretaceous deposits, usually the secondary standards TCR or FCT have been used, typically themselves being calibrated against a primary standard (historically, the MMhb-1 is commonly used, although this depends on the preference of the particular laboratory). Many historically popular standards are no longer used as repeated calibration studies have found the original sample to give inconsistent dates; for example, Baksi et al. (1996) found the widely used MMhb-1 primary standard to be inhomogenous, making its use as a standard no longer tenable. Further, intercalibration studies have continually honed and refined the ages of standards (especially the more widely used secondary standards), with the result that radiometric dates published years apart are typically not precisely comparable without recalibration.

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For ^{40}Ar / ^{39}Ar analysis, a significant issue concerns the changing age of the Fish Canyon Tuff (FCT: the relative standard used for most ^{40}Ar / ^{39}Ar analyses of Cretaceous rocks), and to a lesser extent, the associated decay constants (λβ: β- decay of 40K to 40Ca; and λε: electron capture or β+ of 40K to 40Ar; which combined are referred to as λT or λtotal; Beckinsale and Gale, 1969).

Cebula et al. (1986) first proposed an age of 27.79 Ma for the Fish Canyon Tuff. This was quickly refined to 27.84 Ma by Samson and Alexander (1987), which remained the standard used by ^{40}Ar / ^{39}Ar analyses published up to the mid 1990's (e.g. Rogers et al., 1993). Renne et al. (1994) revised the FCT to 27.95 Ma (although this new figure was not commonly used at the time). The next major update was that of Renne et al. (1998) whereupon the FCT was revised to 28.02 Ma, which was widely accepted up to 2008 when Kuiper et al. published the current standard of 28.201 Ma. This also brought ^{40}Ar / ^{39}Ar dates into line with U-Pb dates, unifying these two major chronostratigraphic dating systems (Kuiper et al., 2008). Two further revisions have been offered by Renne et al. in 2010 and 2011, of 28.305 Ma, and 28.294 Ma (respectively). Rivera et al. (2011), Meyers et al. (2012), Singer et al. (2012), and Sageman et al. (2014) all found independent support for Kuiper et al. (2008)'s 28.201 Ma age for the Fish Canyon Sanidine (and therefore rejected Renne et al.'s (2010) further revised 28.305 Ma standard as too old). These three analyses also used three methods (^{40}Ar / ^{39}Ar, U-Pb, cyclostratigraphy) to reach consensus, confirming alignment of U-Pb and ^{40}Ar / ^{39}Ar dates.

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When applied to Late Cretaceous units, a ~0.2 m.y. difference between the age of two different standards corresponds to ~0.4 - 0.5 m.y. difference in the ^{40}Ar / ^{39}Ar age of the analysed sample, and this is exacerbated if the standards used were further apart. For example, using the 27.84 standard of Samson and Alexander (1987), Rogers et al., 1993 published an ^{40}Ar / ^{39}Ar date of 74.076 Ma for a bentonite at the top of the Two Medicine Formation, MT. This becomes 75.038 Ma if using the current Kuiper et al. (2008) standard, and 75.271 Ma under the less commonly used Renne et al. (2011) standard. This difference of 1.28 m.y. between 1987 and 2008 standards highlights why it is important to know which standards were used for an analysis, especially since only a few hundred thousand years make critical differences in paleobiological interpretation.

Decay constants

The ^{40}Ar / ^{39}Ar method depends upon the β- decay of ^{40}K to ^{40}Ca (λβ), and electron capture or β+ of ^{40}K to ^{40}Ar (λε), which combined are referred to as λT or λtotal (Beckinsale & Gale, 1969). The value of the decay constant λT (and its components) have historically been subject to fewer changes than the standards listed above, but have come under increased scrutiny since the late 1990's. It is also notable that different values of λT have been used historically by geochronologists compared to physicists and chemists (further details and a history of decay constant values can be found in the corresponding note within the chart).

Recalibration & current standards

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In order to compare ^{40}Ar / ^{39}Ar dates, it is essential to ensure that the same standards and decay constants were used in their calculation, which may require recalibration. If the standards used are different (for example, if an old analysis used the TCR standard, and a more recent one used the FCT), then it will be necessary to find what the equivalent FCT value was to the TCR used in the original analysis. This is usually achieved by referencing either the original publication of the standard, or the relevant published intercalibration analysis (e.g. Renne et al. 1994). It is critical to understand that recalculation cannot simply be performed by entering the original standard used (e.g. TCR = 28.32 Ma) into the equation provided on the recalculation sheet from McLean and EARTHTIME (or the adapted spreadsheet used here); the equivalent FCT value is what is entered as the formula only uses FCT. This might seem obvious, but this error was the cause of numerous miscalculations in Roberts et al. (2013; see later).

The decay constant absolute value has only a small effect on the absolute age of a sample, but decay constants contribute a greater amount to the error of a radiometric date.

There are two currently prominently used pairings of standard and decay constant: Kuiper et al. (2008) combined an FCT standard age of 28.201 +/-0.023 Ma, with the decay constant of Min et al. (2000), λT = 5.463 +/- 0.214 E-10/y. Renne et al. (2011) use an FCT standard age of 28.294 +/- 0.036 Ma, with a λT of 5.5305 E-10/y. The dates used here in the correlation chart (Table S1) are calibrated to the Kuiper et al. (2008) standard, paired with the Min et al. (2000) decay constant. This is not a judgment on the reliability of one method over another; rather it is out of convenience, since the various ammonite biozones and magnetochrons detailed in The Geological Time Scale 2012 (Gradstein et al., 2012; upon which this chart is based) use the Kuiper et al. (2008) FCT standard, and Min et al. (2000) decay constant.

Choice of mineral

Direct comparisons between ^{40}Ar / ^{39}Ar dates require not only the same standard and decay constant pairing, but also that the subject mineral is the same. Although it is theoretically possible that a date obtained from biotite crystals might be comparable with one from sanidine, in practice the difference in closure temperature (the temperature at which the mineral no longer loses any products of radioactive decay; Villeneuve, 2004) and other factors such as recoil effects (Obradovich, 1993) mean that (for example) biotite dates are typically ~0.3% older than sanidine dates (e.g. see Rogers et al., 1993). The current "gold standard" mineral for ^{40}Ar / ^{39}Ar dating is sanidine, and most modern analyses use this mineral exclusively (where possible), however plagioclase and biotite dates are quite common in literature from the 1990's. I recalibrate these non-sanidine dates, and they are comparable to each other (ie. biotite dates can be directly compared with other biotite dates), but caution is advised when comparing non-sanidine dates with those of sanidine (although this is sometimes unavoidable).

Reporting of uncertainty / error

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Reporting of error associated with ^{40}Ar / ^{39}Ar derived ages is not standardized and varies in the inclusiveness of sources of error, the statistical method used to calculate error, the type of error, and in the amount of analytical information provided.

Sources of error in ^{40}Ar / ^{39}Ar analyses include analytical error (e.g. J-value), uncertainty in the standard used (e.g. age of the Fish Canyon Tuff, FCTis 28.201 +/- 0.23 Ma at 1σ; Kuiper et al., 2008), uncertainty in the decay constant (e.g. λ_T of 5.463 +/- 0.214 E-10/y; Min et al., 2000), and geological processes that may lead to post-crystallization alteration of isotope ratios (Villeneuve, 2004). Most older publications do not explicitly state what is included in the reported error, but newer studies (e.g. Sprain et al., 2014) report both analytical and systematic error.

The statistical method used to report error is not standardized, and is typically given in one of three forms; some authors report 1 or 2 standard deviations (σ); Standard Error is also commonly reported (especially for population means); finally, some authors report 95% confidence intervals for the population mean, which is roughly equivalent to 2σ (=95.45% confidence interval).

It is common for published radiometric dates to lack associated details of the analysis, by either the date being given as a pers. comm., or simply the omission of analytical details. Consequently, it is sometimes unclear as to whether (for example) a stated error of +/- 0.15 Ma refers to 1σ, 2σ, Standard Error, or whether it includes analytical an systematic error.

As such, it is not possible to make the error consistent between each recalibration (although the effects are relatively minor). Where possible, I have reported recalibrated error to 1σ analytical error, but generally I have simply taken the original reported error and processed it through the recalibration spreadsheet, noting wherever possible all possible details and any issues that may arise. Direct comparison of error between dates (both recalibrated and unrecalibrated) should therefore be approached with caution.

Agreement of ^{40}Ar / ^{39}Ar dates with U-Pb dates

^{40}Ar / ^{39}Ar dates have historically tended to be younger than U-Pb dates by about 1% (Schoene et al., 2006), equating to ~750 k.y. difference in a 75 m.y. old sample (i.e. the approximate age of the units studied here). Possible explanations include longer zircon magma residence times prior to an eruption (Villeneuve, 2004), error in the ^{40}K decay constant (Schmitz & Bowring, 2001), or interlaboratory bias and geological complexities (Kuiper et al., 2008). Recent revisions of standards and decay constants for ^{40}Ar / ^{39}Ar dating have closed the gap to within ~0.3% (Kuiper et al., 2008; Renne et al., 2011). This led Kuiper et al. (2008) to suggest that ^{40}Ar / ^{39}Ar dating has improved "absolute uncertainty from ~2.5% to 0.25%"

Other general comments

The number of decimal places for reported dates and error are left in their original published form where possible.

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In previous publications, a large number of radiometric dates are reported as pers. comm. or featured only in abstracts. Such references typically lack any analytical data and so original standards (etc) must be assumed based on the year in which the analysis was (likely) conducted, and any details of the typical standards used by the scientist and laboratory which carried out the analysis (if known; see individual notes for details of sleuthing).

Results

An early version of this chart was presented by Fowler (2006), small parts of which were published elsewhere without my knowledge. This prior version was not finalized, contains taxonomic misplots, and is based on unrecalibrated radiometric dates and stratigraphic boundary definitions from the previous version of A Geologic Time Scale (Gradstein et al., 2004; as opposed to Gradstein et al., 2012). As such, the previous data presented in Fowler (2006) and elsewhere should be disregarded and replaced by this new version.

The results of this study are presented as separate documents in the Supporting Information; the stratigraphic chart (Table S1), and the recalibration sheet (Table S2). These documents contain a large amount of information in the various pop up notes, most of which is not repeated here.

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Notes on recalibrations by other authors

Various analyses published by J. D. Obradovich (~1990 until at least 2002)

Recalibration of radiometric dates from analyses by J. D. Obradovich (USGS, Colorado) conducted in the 1990's (and possibly early 2000's) requires special caution due to the particular methodology of Obradovich during this time, which differs slightly from what might be expected. Obradovich typically uses the TCR as the standard for his analysis, but the equivalent age of the FCT (required for recalibration) is not typical. Indication of this is noted by Hicks et al. (2002, p.43) who state:

"The TCR (Duffield & Dalrymple, 1990) has been used exclusively since 1990 by one of us (Obradovich) with an assigned age of 28.32 Ma normalized to an age of 520.4 Ma for MMhb-1 (Samson & Alexander, 1987). This age differs from that of 27.92 Ma assigned by Sarna-Wojcicki and Pringle (1992). The choice of 28.32 Ma was entirely pragmatic because this monitor age provided the best comparison with ages delivered by Obradovich and Cobban (1975). In an intercalibration study [...] Renne et al. (1998) obtained ages of 28.34 Ma for TCR and 28.02 Ma for FCT when calibrated against GA1550 biotite as their primary standard with an age of 98.79 Ma. This value of 28.02 agrees quite well with [..] 28.03 Ma obtained through calibration based on the

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astronomical time scale (Renne et al., 1994). On the basis of unpublished data, one of us (Obradovich) obtained an age of 28.03 Ma for the FCT [...] of W, McIntosh (Geoscience Dept. NM Institute Mining * Technology, Socorro), calibrated against an age of 28.32 Ma for TCR."

However, Obradovich-published analyses from this time do not exclusively use the TCR at 28.32 Ma, as Izzett and Obradovich (1994) state that they use FCT sanidine at 27.55 Ma, and TCR sanidine at 27.92 Ma, both relative to MMhb-1 at 513.9 Ma (in conjunction with λT = 5.543 E-10/y). They note that the 513.9 Ma age of MMhb-1 differs from the then standardized age of 520.4 Ma (Samson & Alexander, 1987) as the former age was calibrated in the lab where their current samples were analysed (Lanphere et al., 1990; Dalrymple et al., 1993).

This creates a problem when recalibrating ^{40}Ar / ^{39}Ar ages that used TCR as the fluence monitor (standard). The "official" TCR age of 27.92 Ma has a corresponding FCT age of 27.84 Ma (Samson & Alexander, 1987; Renne et al., 1998). However, since most analyses by Obradovich use TCR at 28.32 Ma, then the question remains as to what number to use for the equivalent FCT when performing recalibrations. Renne et al. (1998) provide an intercalibration factor for FCT : TCR of 1 : 1.00112 +/- 0.0010, which simply calculated is FCT = 28.32 / 1.100112 = 28.006 Ma. This agrees well with the calculated FCT equivalent of 28.03 Ma (Hicks et al., 2002; above; Obradovich, 2002) and a value of 28.02 Ma of Renne et al. (1998). In the Geological Time Scale 2012 (Gradstein et al., 2012), Schmitz (2012) recalibrates dates from Obradovich (1993), and Hicks et al. (1995,

1999) using a legacy FCT age of 28.00 Ma (not stated, but retrocalculated by DF). Sageman et al. (2014; cited as Siewert et al., in press, by Schmitz, 2012) recalibrate Obradovich's older dates using a legacy FCT age of 28.02 Ma (thereby agreeing with Renne et al., 1998).

In this analysis, when recalibrating an ^{40}Ar / ^{39}Ar date that was calculated by Obradovich using a TCR = 28.32, I use an FCT value of 28.03, as this is the equivalent FCT explicitly stated by Obradovich (2002). This is a very close value to 28.02 (Renne et al., 1998; where the TCR equivalent is 28.34 +/- 0.16 Ma; 1σ, ignoring decay error) so confusion between the two should be avoided, although the difference between ages calculated using 28.03 or 28.02 Ma standards would correspond to only 0.02 to 0.04 m.y. for ages in the Late Cretaceous (100.5 - 66 Ma; Ogg & Hinnov, 2012)

Kuiper et al. (2008)

In their presentation of the new standard and decay constant pairing for the FCT, Kuiper et al. (2008) recalibrate some radiometric dates which are of general interest. One of these dates (the K-Pg boundary dates of Swisher et al., 1993) is used in my current stratigraphic chart, but I found that my own recalibration (66.06 Ma) did not agree with that presented by Kuiper et al. (2008; 65.99 Ma). Through retrocalculation, I determined that Kuiper et al. (2008) had not accounted for the fact that Swisher et al. (1993) had used the Steiger and Jaeger (1977) decay constant; Kuiper et al. (2008) had only accounted for change in the standards used (thereby assuming that Swisher et al., 1993, had used the

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decay constant of Min et al., 2000, which was clearly impossible). The difference between the two dates is only 0.07 Ma, but I feel that it is worth highlighting in case this discrepancy is of greater significance to other works.

Schmitz (2012)

As mentioned above, recalibrations of Obradovich dates (Obradovich, 1993; Hicks et al., 1995; 1999) that use the 28.32 TCR standard are recalibrated using an FCT equivalent of 28.00 by Schmitz (2012). Schmitz's recalibrated dates form the basis of the spline fits (etc) of the Geological Time Scale of Gradstein et al. (2012), and so any slight changes might be important. The correct date to use for the FCT equivalent would be either 28.03 Ma (used by me; see above note), or 28.02 Ma (based on Renne et al., 1994).

Roberts et al. (2013)

Roberts et al. (2013) present a table of recalibrated radiometric dates from a selection of important dinosaur-bearing formations of the North American Western Interior. Unfortunately, 11 out of 18 dates are incorrectly recalibrated, with different kinds of errors in different recalibrations, producing dates that are incorrect by up to a million years.

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Roberts et al. (2013) recalibrate the dates for the Judith River Formation (originally published by Goodwin and Deino, 1989), however they input an incorrect original (legacy) FCT standard of 28.02 Ma (i.e. from Renne et al., 1998, published after the original 1989 analysis). For the recalibration to be correct, the legacy standard must be the value of FCT that was equivalent to the MMhb-1 at 420.4 Ma, which is FCT = 27.84 Ma (Samson & Alexander, 1987; see Renne et al., 1998). As it stands, the Roberts et al. (2013) recalibrations for the Judith River Formation are incorrect by nearly half a million years. For example, the sample 84MG8-3-4 was originally published as 78.2 Ma (Goodwin and Deino, 1989), Roberts et al. (2013) recalibrate it as 78.71 Ma, whereas the correct recalibration (see Table S1 and S2) is 79.22 Ma, a difference of half a million years, which can have serious implications for correlation.

It is likely that the same error is made for the Bearpaw, Dinosaur Park, and Oldman Formations as Roberts et al. (2013) also use the Renne et al. (1998) FCT date of 28.02 as their legacy FCT for dates originally published by Eberth and Hamblin (1993) and Eberth and Deino (1992); i.e. before the 1998 paper was published.

When recalibrating ^{40}Ar / ^{39}Ar dates for the Fruitland and Kirtland Formations, New Mexico (originally published by Fassett & Steiner, 1997), Roberts et al. (2013) input the incorrect original (legacy) decay constant (λ) and standard, producing recalibrated dates that are incorrect by nearly a million years. First, the legacy λ used by Roberts et al. (2013) is 4.962E-10/y, which was presumably copied from the bottom of the chart on p. 243 of Fassett & Steiner (1997), where it is clearly referred to as the value

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of $\lambda\beta$ (ie. the probability of β- decay of 40K to 40Ca), and which is printed below the value $\lambda\varepsilon$ (0.581 E-10/y; probability of electron capture or β+ of 40Kto 40Ar). In this case, the correct λ value to use for recalibration is 5.543 E-10/y (Steiger & Jaeger, 1977), which is the total (λT) of $\lambda\beta$ plus $\lambda\varepsilon$. Second, Roberts et al. (2013) correctly state that the legacy standard used by Fassett & Steiner (1997) for fluence monitoring was the TCR at 28.32 Ma; however Roberts et al. (2013) then use this number directly for their recalibration to the new FCT standard (28.201; Kuiper et al., 2008). This is incorrect as recalculation must use the same standard mineral (e.g. FCT) for both legacy and recalibrated dates. For the recalculation to be correct, the legacy standard must therefore be the value of FCT that was equivalent to the TCR at 28.32 at the time of the 1997 analysis, which is either FCT = 27.84 Ma or ~28.03 (see Table S1; above note on Obradovich), both of which produce recalibrated ages ~1 million years older than the dates presented by Roberts et al. (2013). This miscalibration is all the more surprising as the newly recalibrated dates of Roberts et al. (2013) are actually younger than the original dates, which should have been obviously incorrect as the standards for ^{40}Ar / ^{39}Ar dating have been getting progressively older, and so all recalibrations should produce older dates.

The recalibrated dates of Roberts et al. (2013) were replicated (therefore confirmed) by rerunning the legacy values through the recalibration spreadsheet provided by the Earth-Time institute.

Roberts et al. (2013) correctly recalibrated only seven out of eighteen ^{40}Ar / ^{39}Ar dates, notably five from the Kaiparowits Formation, Utah, and two from the Two Medicine Formation, Montana. All other dates published in their recalibration chart are incorrect and should be discarded.

Discussion

Here I discuss some of the implications of this stratigraphic reassessment. It is beyond the scope of this short work to summarize the implications of everything in the stratigraphic chart, so here I will highlight some of the important changes which might affect geological or paleontological interpretation.

Geology

Judith River Formation -further subdivision required

The Judith River Formation is a Middle to Upper Campanian terrestrial unit exposed across north and central Montana. It has been studied since the mid-19th century, but its upper and lower contacts are still not well documented nor understood, although some details are offered for specific sections by Goodwin & Deino (1989), Rogers (1993), and Rogers et al. (2016).

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The Judith River Formation in the type area has recently been formally subdivided into a series of members (Rogers et al., 2016), notably a sand-dominated basal McClelland Ferry Member and overlying mud-dominated Coal Ridge Member, distinguished by a distinctive "kick" in subsurface SP logs. This "kick" is named the Mid Judith Discontinuity by Rogers et al. (2016) and is thought to be related to the maximum regression of the Claggett seaway. However, despite the naming of these members it is not clear how the type section of the Judith River Formation correlates with exposures of the Judith River Formation along the US-Canada border, from which most of the diagnostic vertebrate fossils have been recovered. In contrast to the type area, exposures of the Judith River Formation close to the US-Canada border are already recognized as direct lithostratigraphic equivalents to the Dinosaur Park (albeit very limited), Oldman, and Foremost Formations (Belly River Group; Eberth, 2005) of southern Alberta and Saskatchewan, and can be readily identified as such in outcrop.

Rogers et al. (2016) state that the distinctive well-log "kick" is detectable in the subsurface near Havre (north-central Montana) and into southern Canada, but there is very little discussion as to which of the well-defined lithostratigraphic boundaries within the Oldman and Dinosaur Park Formations is equivalent to the "kick". Rogers et al. (2016) state that the discontinuity occurs higher in section than the exposures in Kennedy Coulee, near Rudyard, Montana, which comprise direct equivalents of the Foremost Formation through to Unit 1 of the Oldman Formation. As such, the "kick" must therefore be stratigraphically higher than Unit 1 of the Oldman Formation, possibly the top of the

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sandy zone of the overlying Dinosaur Park Formation (Eberth, 2005; see Table S1). In the only statement suggesting possible correlation, Rogers et al. (2016; p. 126) state that "the Oldman Formation [is an ...] approximate age equivalent to the McClelland Ferry Member [... and that ...] the overlying Dinosaur Park Formation [is an ...] approximate age equivalent to the Coal Ridge Member". However, radiometric dates from immediately below the discontinuity (76.24 and 76.17 Ma; Rogers et al., 2016) are younger than a radiometric date from the middle of the Dinosaur Park Fm (76.39 Ma; see individual entry in Table S1). This would make the suggested correlation therefore unlikely. However, I suspect that accuracy or incompatibility of the radiometric dates may be the cause of this issue; as such it is only likely to be resolved if samples from both the Judith River Formation and Canadian units are analysed by the same laboratory under identical conditions.

In summary, lack of a defined correlation or lithostratigraphic definition for the Mid Judith Continuity in US-Canada border exposures of the Judith River Formation mean that the newly defined members are therefore of limited use for surficial regional correlation. Furthermore, as the McLelland Ferry Member is equivalent to the combined Foremost, Units 1-3 of the Oldman Formation, and probably part of the Dinosaur Park Formation, it offers reduced stratigraphic resolution from merely referring to these equivalent units for Judith River Formation exposures along the US-Canada border sections where correlations are readily apparent. Due to these limitations I cannot recommend use of the newly defined members outside of the type area. Instead, here I follow previous workers in referring to the lithostratigraphically correlative Foremost, Oldman, and Dinosaur Park Formations, as defined by Eberth (2005), which offer much greater stratigraphic resolution and whose stratigraphic correlations are well understood and defined.

A final issue which remains unresolved by any current stratigraphic work or revision is that as a result of lack of formal subdivision, the base of the Judith River Formation is strongly diachronous, being ~ 80 Ma in the area north of the town of Rudyard (where it is the base of the Foremost Formation equivalent), but perhaps as young as 77.5 Ma 200km to the east near the town of Malta (base of the upper Oldman Formation equivalent). This is not the same as "true" diachronaeity which occurs at the base of (say) a prograding deltaic deposit (e.g. the Fox Hills Formation), but rather it is mostly an artifact of the lack of subdivision. The solution to this issue would be to follow Canadian stratigraphic definition in raising the Judith River Formation to group status, and subdivide it into constituent formations which have direct correlates in Canada. Formal subdivision of the Judith River Formation is beyond the scope of this work. However, here I informally refer to the lower-Oldman (Herronton Sandstone and Unit 1; Eberth, 2005) equivalent of the Judith River Formation as the "Rudyard beds", and the upper Oldman Formation (Units 2-3; Eberth, 2005) equivalent as the "Malta beds" in reference to the geographic locations where these particular parts of section are well exposed. It is a long term goal to formalize these names.

Age

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A number of radiometric dates help constrain the Judith River Fm, and are particularly useful in dating the contact between the Foremost and Oldman Fm equivalents near the town of Rudyard in northern Montana (see individual entries; Table S1). New radiometric dates from the type area published by Rogers et al. (2016) seem to raise conflicts with previous correlations based on bounding surfaces (Rogers, 1994, 1998).

Age of the Aguja Formation, Texas

The Aguja Formation of southwest Texas is typically considered as an Upper Campanian or even Maastrichtian aged unit (e.g. Longrich et al., 2010; Sankey, 2010) based on interpretation of low resolution magnetostratigraphy (Sankey and Gose, 2001), phreatomagmatic volcanism (Longrich et al., 2010), and chemostratigraphic correlation (Nordt et al., 2003). However, detailed review of more reliable published stratigraphic evidence is not supportive of this view. Ammonite remains from the marine tongue which separates the Lower and Upper Shale Members indicate that the Lower Shale Member can be no younger than the Early Campanian *Baculites mclearni* zone (Rowe et al., 1992; Lehman and Tomlinson, 2004). A recently published radiometric date of 69.0 Ma recovered from the overlying Javelina Formation, ~60 m above the formational contact (Lehman et al., 2006) demonstrates that the Upper Shale Member of the Aguja Formation cannot be any younger than this (i.e. *contra* Sankey et al., 2010). Furthermore, the Upper Shale Member of the Aguja Formation contains phreatomagmatic volcanic deposits dated at 76.9 +/- 1.2 Ma (Befus et al., 2008) and 72.6 +/- 1.5 Ma (Breyer et al., 2007), which by

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the nature of their formational mechanism must have been emplaced after deposition of the Upper Shale Member itself, meaning that it cannot be any younger than 76.9 Ma +/- 1.2 Ma, and is probably much older (i.e. contra Longrich et al., 2010) based on the absence of any obvious lengthy hiatus separating the Upper Shale Member from the underlying Lower Campanian units. Thus it is likely that the Upper Shale Member is probably Middle Campanian, and is shown as such in Table S1 (see included notes for a more detailed account of the evidence). This revision of the age of the Aguja Formation is important as dinosaur taxa from the Upper Shale Member probably represent early, more basal forms of their respective clades (e.g. chasmosaurines), giving key insight into the morphological changes and timing of lineage splitting events (speciation, or true cladogenesis), rather than being regional endemic species (e.g. Sampson et al., 2010).

Age of the Javelina Formation, Texas

The Javelina Formation (and basal part of the overlying Black Peaks Formation, sensu Lehman and Coulson, 2002) of southwest Texas has often been considered as Upper Maastrichtian, even uppermost Maastrichtian (e.g. Lawson, 1976; Lehman and Coulson, 2002; Atchley et al., 2004), and is based on comparison of the Javelina Formation dinosaur fauna with that of the Hell Creek and Lance Formations (Lawson, 1976; Lehman, 2001). From this perspective then, it was perhaps surprising when Lehman et al. (2006) published a U-Pb date of 69.0 +/- 0.9 Ma for the middle of the Javelina Formation. This date plots firmly in the lowermost part of the Late Maastrichtian (69.1 - 66.0 Ma; Ogg and Hinnov, 2012). The Javelina Fm is often considered to

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represent continuous deposition up to and through the K-Pg boundary (e.g. Atchley et al., 2004). If this were the case, then it would mean that the ~90m of deposits overlying the 69 Ma datum (Lehman et al., 2006) represented the 3 m.y. leading up to the K-Pg boundary, and that the ~60 m below might represent 2 m.y. (if average rates of deposition were assumed). This would seem to be an unusually long period of time for such a thin unit, although not impossible. Alternatively, considerable hiatuses (up to 2 m.y.) are suggested to occur within the Javelina Fm (Nordt et al., 2003). This would be consistent with the findings of Fowler (2016) which proposes that the recently named ceratopsid dinosaur *Bravoceratops* (collected from the basalmost part of the Javelina Fm; Wick and Lehman, 2013), is probably Upper Campanian in age, similar to the Fruitland and Kirtland Formations of New Mexico. This is of great importance to regional correlation and warrants further consideration.

Thinking about taxa as lineages

One of the striking results of the accurate replotting of both geological formations and dinosaur taxa, is that dinosaur taxa often from stacked columns of short-duration species which do not overlap stratigraphically. This is the expected pattern produced by anagenesis, the evolutionary mode whereupon lineages or populations transform morphologically through time without branching into multiple contemporaneous species (cladogenesis; also technically, speciation; sensu Cook, 1906). This is an important finding as it suggests that most of the morphological change which we observe through time is probably not related to the multiplication of species. If cladogenesis was the most

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important driver of morphological change, then we would expect to see stratigraphic overlap between different morphologies. Although this does occur, it is much more rare than stratigraphically successive replacement. In itself this is very interesting as it reduces the likely number of genuine lineage splitting events to maybe only three within the best studied group, chasmosaurine ceratopsids. Further support for this interpretation is that many stratigraphically intermediate forms are also intermediate in morphology; this is best shown in chasmosaurine ceratopsids of the Upper Maastrichtian Hell Creek Formation (*Triceratops*; Scannella et al., 2014), but also in the *Pentaceratops* lineage chasmosaurines of the Middle to Upper Campanian, and probably *Chasmosaurus* in the Dinosaur Park Formation, Alberta (Fowler, 2016).

The trouble with "turnover"

Stratigraphic successions of non-overlapping species have previously been referred to as "turnover". Among many examples, Mallon et al. (2012) refer to the rapid succession of different dinosaur species within Dinosaur Provincial Park as turnover; Gates et al. (2013) suggest that a change from *Gryposaurus notablis* in the lower Kaiparowits Formation, Utah, to *G. monumentensis* in the middle Kaiparowits Formation is an example of "intergeneric [sic] faunal turnover" (presumably the authors mean intrageneric). However, if these records are indicative of anagenesis (i.e. non-branching evolution of one form into an another) then they technically cannot be "turnover" by definition. In one of the few publications that attempt a definition of "turnover", Vrba (1985) defines “lineage turnover” as:

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"includes speciation, extinction and migration, all of which change the composition of species in particular areas." (p. 229).

Therefore, "turnover" refers to a point where one species disappears from the fossil record, and is replaced by another; apparently implying stasis followed by turnover. The notable exclusion of anagenesis (or any synonym) from this list suggests that it should therefore not be considered as part of turnover events (Vrba, 1985, includes a definition for "phyletic evolution", a synonym of anagenesis, within the same paper, so she is not using "speciation" in the general sense to mean any change in morphology).

Expanding and clarifying upon the concepts and definitions presented in Vrba (1985), Vrba (1993) specifically notes (her Fig. 1) that she considers the phyletic evolution (anagenesis) of one form into another as representing neither species extinction (of the ancestor) nor origination (of the descendant).

This may seem pedantic, but turnover is an important and precise concept used to explain (for example) the replacement of a native species by non-native immigrants, or the classic example of a "turnover pulse" (Vrba, 1985), where many turnover events occur to multiple lineages simultaneously, indicating a major immigration event. If turnover is merely used as a synonym of anagenesis then explanatory power of the term is lost. Anagenesis is not turnover, and the term should not be used unless it can be shown that a replacement species (or its lineage) is at least partly contemporaneous with

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the species being replaced. Admittedly, this discussion is only a short and simple treatment of a complex subject; a more detailed account is in preparation.

North-south biogeography and extreme faunal endemism

Anagenesis also provides explanatory power challenging the hypothesis of extreme faunal endemism proposed for the Campanian Western Interior. It has been proposed that during the Campanian, the Western Interior of North America was divided into basin-scale faunal provinces, each with a unique fauna (Sampson et al., 2010). This is based primarily on the description of new genera and species of dinosaur collected from the Kaiparowits Formation, Utah (e.g. Gates and Sampson, 2007; Sampson et al., 2010; 2013), and the perception that the Kaiparowits Formation was deposited contemporaneously with other dinosaur-bearing deposits (e.g. the Dinosaur Park Formation, Alberta; Fruitland and Kirtland Formations, New Mexico). However, recalibration here of critical radiometric dates shows that only the lower part of the Kaiparowits Formation stratigraphically overlaps with the fossiliferous portion of the Dinosaur Park Formation (see Table S1). This is important as the lower Kaiparowits Formation does not yield the taxa purportedly endemic to southern Utah, and fragmentary specimens suggest that taxa are shared between the upper part of the Dinosaur Park and lower Kaiparowits Formations (Gates et al., 2013; Fowler, 2016). Here I consider it more likely that differences between dinosaur species found in the Dinosaur Park Formation, and middle Kaiparowits Formation are an artifact of sampling different stratigraphic levels (likely, though not necessarily an anagenetic lineage), rather than biogeographic

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segregation; at the least the anagenetic hypothesis remains unfalsified. Similarly, differences between the middle Kaiparowits taxa, and those of the Fruitland and Kirtland Formations, New Mexico, are also more parsimoniously explained by the slight difference in age of the units, with the Fruitland and Kirtland being slightly younger than the middle Kaiparowits Formation. Moreover, the recent identification of purportedly southern *Pentaceratops*-lineage chasmosaurines within the Dinosaur Park Fm, Alberta (Longrich, 2014; Fowler, 2016), demonstrates that this lineage was able to move between northern and southern regions in the middle Campanian, further falsifying the extreme faunal endemism hypothesis.

Biostratigraphy

Cobban and Reeside (1952) used the ceratopsid dinosaur *Triceratops* as an index taxon of the latest Maastrichtian. Similarly, dinosaurs were part of the original Land Vertebrate Ages (LVA; Aquilian; Judithian; Edmontonian; Lancian) described by Russell (1964) before revision into North American Land Mammal Ages (NALMA; Russell, 1975; Lillegraven & McKenna 1986; Cifelli et al., 2004). More recently, dinosaurs have been used to stratigraphically correlate Maastrichtian units of the Southwestern US (Lawson, 1976; Lehman 1987, 2001) and were utilized by Sullivan and Lucas (2003, 2006) in their definition of the “Kirtlandian”: an additional LVA roughly equivalent to the early part of the Bearpaw Shale and positioned in the gap between the Judithian and Edmontonian identified by Russell (1964; 1975).

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The demonstration here that individual dinosaur species form stratigraphically stacked sequences of non-overlapping taxa should make them ideal for use as biostratigraphic indicators. It is probably not an exaggeration to claim that the single most biostratigraphically informative skeletal element that can be found in the Late Cretaceous of North America is the midline portion of the posterior parietal border from an adult chasmosaurine ceratopsid dinosaur. The use of dinosaurs as biostratigraphic indicators might be seen as controversial, since generally dinosaur taxa are known from relatively few specimens and are arguably less abundant than mammals. However, if current hypotheses of rapid evolution are correct (e.g. Horner et al., 1992; Holmes et al., 2001; Scannella et al., 2014; Fowler, 2016), then at least some clades of dinosaurs would seem ideal for biostratigraphic correlation. If we are able to understand the stratigraphic distribution and ontogenetic variation of dinosaurs well enough, then conceivably they may represent the most biostratigraphically informative taxa that we have for terrestrial sediments, potentially at resolutions of ~200Ka (or less; see Table S1; Mallon et al., 2012), superior to the resolution available using mammals or palynomorphs: the other primary options in terrestrial biostratigraphy.

Conclusions

Precise stratigraphic placement of specimens is critical to understanding paleobiology. Horner et al. (1992) demonstrated that a better understanding of the mode of evolution in dinosaurs can be achieved with careful stratigraphic analysis. However,

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all too often in descriptions of new specimens, stratigraphic and geologic data are ignored, or only poorly described. The value of such data in testing paleobiological hypotheses is incomparable.

Similarly, it is clear that care needs to be taken when recalibrating radiometric dates. Although it is time consuming to intensively search older publications for analytical data, a better approximation for the original standards can be found with careful reading and some knowledge of past procedures. Misinformation in the form of mistakenly recalibrated dates could potentially be a source of significant error in the literature.

Future versions of the chart will include additional stratigraphic units and taxa.

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Supporting Information

S1 Table. Stratigraphic Chart. Stratigraphic correlation of Upper Cretaceous terrestrial strata of the North American Western Interior from the Santonian through to the K-Pg boundary. Dinosaur taxon ranges plotted on to correlated geological units.

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S2 Table. Recalibration Sheet. This sheet shows recalibration calculations for over 200 published Ar / Ar radiometric dates. These are recalibrated to the two current standards (Kuiper et al., 2008; Renne et al., 2011), shown on separate tabs. References are given within pop up notes for the respective recalibrated date(s).

S1 Text. References for Stratigraphic Chart. This text file lists all the references used in construction of the stratigraphic chart (Table S1).

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