Revised geochronology, correlation, and dinosaur stratigraphic ranges of the Santonian-Maastrichtian (Late Cretaceous) formations of the Western Interior of North America

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Abstract

Interbasinal stratigraphic correlation provides the foundation for all consequent continental-scale geological and paleontological analyses. Correlation requires synthesis of lithostratigraphic, biostratigraphic and geochronologic data, and must be periodically updated to accord with advances in dating techniques, changing standards for radiometric dates, new stratigraphic concepts, hypotheses, fossil specimens, and field data. Outdated or incorrect correlation exposes geological and paleontological analyses to potential error.

The current work presents a high-resolution stratigraphic chart for terrestrial Late Cretaceous units of North America, combining published chronostratigraphic, lithostratigraphic, and biostratigraphic data. ^{40}Ar / ^{39}Ar radiometric dates are newly recalibrated to both current standard and decay constant pairings. 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 recalibration corrections in particular affect the relative age positions of the Belly River Group, Alberta; Judith River Formation, Montana; Kaiparowits Formation, Utah; and Fruitland and Kirtland formations, New Mexico.

The stratigraphic ranges of selected clades of dinosaur species are plotted on the chronostratigraphic framework, with some clades comprising short-duration species that do not overlap stratigraphically with preceding or succeeding forms. This is the expected pattern that is produced by an anagenetic mode of evolution, suggesting that true branching (speciation) events were rare and may have geographic significance. The recent hypothesis of intracontinental latitudinal provinciality of dinosaurs is shown to be affected by previous stratigraphic miscorrelation. Rapid stepwise acquisition of display characters in many dinosaur clades, in particular chasmosaurine ceratopsids, suggests that they may be useful for high resolution biostratigraphy.

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 enormously useful for making stratigraphic comparisons between units and similar style diagrams have become commonplace in the geological literature. Recent, broad-scale correlations akin to that of Cobban and Reeside (1952) are less common, but examples include Krystinik and DeJarnett (1995), Sullivan and Lucas (2003; 2006); Miall et al. (2008), and Roberts et al., (2013). Construction of these kinds of correlation charts is built upon a great wealth of literature; the product of dedicated work by generations of stratigraphers working in the Western Interior. Individual papers doubtless number in the thousands, and there are far too many to mention directly here, although many are cited in the supporting information (see S1 Table and S1 Text).

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 and Loewen, 2010; Sampson et al., 2010; Campione and Evans, 2011; 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 is assessment of whether two sister taxa are contemporaneous (thereby inferring a genuine speciation event), or whether they form a succession of stratigraphically separated morphologies (potentially supportive of anagenesis; e.g. Horner et al., 1992; Campione and Evans, 2011; Scannella et al., 2014; Freedman Fowler and Horner, 2015). 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 (Horner et al., 1992; Sampson et al., 2010), 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 Upper Cretaceous deposits of the North American Western Interior represent a rare 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 a vast literature detailing over a century's worth of research and an ever increasing collection of fossils. However, despite the large amount of data available, some problems persist that 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 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 citation of incorrect or unknown stratigraphic data or unknowingly mismatching old outdated stratigraphic data with new interpretations or calibrations (see Discussion for detailed explanation of examples). 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. Depositional hiatuses are not depicted

The normal method of illustrating stratigraphic columns often does not include illustration of the depositional hiatuses (lacunae) that exist within formations, and this can affect the perception of unit duration, conformability, and magnetostratigraphic

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relationships. For example, under conventional lithostratigraphic practice, prominent sandstones are sometimes chosen as uppermost units for formational contacts (e.g. the Capping Sandstone Member, Wahweap Formation, Utah; Eaton, 1991). However, under the conventional sequence stratigraphic model, amalgamated channel sandstones often form the basalmost unit of depositional cycles, resting upon a surface of erosion or depositional hiatus; i.e., the basal bed of a conformable cycle might simultaneously be considered the uppermost unit of a lithostratigraphic formation. For this and other reasons, formation members and the lacunae between them should be plotted on correlation charts where possible.

3. Radiometric dates may be incorrect or incomparable

Many currently cited radiometric dates are not properly comparable, because from the early 1980's to the current day radiometric analyses have used a variety of standards, decay constants, or different methods. In order to rectify this, historical dates have been recalibrated by previous workers (e.g. for the Western Interior, Eberth, 2005; Kuiper et al., 2008; Schmitz, 2012; Roberts et al., 2013; Sageman et al., 2014; Freedman Fowler and Horner, 2015). There is also an emerging issue that analyses performed in different laboratories under slightly different methodologies produce slightly different results, and this is being investigated internally by those labs

This current work presents a comprehensive stratigraphic correlation chart comprising the major terrestrial geological formations of the Santonian through Maastrichtian of the North American Western Interior (S1 Table). The chart is plotted based on extensive reference to the stratigraphic literature on each formation (which is reviewed and cited in detailed notes for each unit), and on the recalibration of ^{40}Ar / ^{39}Ar radiometric dates. Over 200 recalibrated radiometric dates are presented as a separate excel sheet (S2 Table), and are recalibrated to both currently accepted ^{40}Ar / ^{39}Ar standards and decay constant pairings (Kuiper et al., 2008, combined with the decay constant values of Min et al., 2000; and Renne et al., 2011). The resultant stratigraphic framework is used in combination with locality data for individual dinosaur specimens to plot the stratigraphic ranges for dinosaur taxa (currently restricted to Neoceratopsia, Sauropoda, Pachycephalosauridae, and Hadrosauridae). This replotting of dinosaur taxa is discussed with regard 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. thousand years; c.z., coal zone; FCT, Fish Canyon Tuff; TCR, Taylor Creek Rhyolite.

Display format - excel sheets

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

S1 Table - Stratigraphic correlation chart

The stratigraphic correlation chart is arranged as an Excel spreadsheet (S1 Table), 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 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).

S2 Table - Recalibration sheet

The recalibration sheet (S2 Table) is also made available in the form of an Excel sheet. This is due to its large size, but also benefits from the pop-up note function, 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.

The recalibration sheet is adapted from the EARTHTIME excel recalculation sheet kindly provided by Noah McLean at the earthtime.org website. Unfortunately, the main homepage of the earthtime.org website is currently listed as "under construction"; however, the direct link to the recalibration spreadsheet and instructions download page is still active as of Jan 30th 2017: http://www.earth-time.org/ar-ar.html Note that a similar recalibration sheet was provided by Paul Renne (pers. comm. 2012)

The original recalibration formulae were duplicated across into S2 Table such that this is a "live" document that independently recalculates dates based on the input data on each line of the sheet. The source lines for each recalculation have been adapted from the original EARTHTIME recalulation sheet such that in S2 Table 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.

There is an issue 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 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 in which the new error cannot be directly computed, the original error has been multiplied by the % change output factor; errors 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 (S1 Table). 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 (S1 Table)

Construction of the chart is complex and depends upon many different stratigraphic methods. The following text explains the underlying definitions that provide the base framework for the chart, and highlight some of the issues surrounding its construction.

Definitions: stage and substages, magnetostratigraphy, and ammonite biostratigraphy

The chart follows 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 that use the ^{40}Ar /^{39}Ar standard and decay constant pairing of Kuiper et al. (2008) and Min et al. (2000), which are also 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 pop-up notes in the respective parts of the chart.

In some places it is necessary 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; Lerbekmo, 2002; Eberth and Braman, 2012). In such cases, the pop-up note text boxes provide explanation of the problem, and references.

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. For example, if we know a taxon occurs in a given formation, but not the precise stratigraphic position within that formation (or if the age of the formation itself is only roughly known), then the block arrow would show the possible range being equivalent to the full duration of the formation. A combination of a solid cell and block arrow may be used if a taxon or geological unit comprises some specimens or horizons for which stratigraphic position is precisely known (depicted by the solid cell) and some specimens or horizons for which stratigraphic position is unknown (block arrows). Periods of non-material time (lacunae) are represented by blank spaces. In the aforementioned cases, explanation for the plotting of geological units, lacunae, and taxa is given in the corresponding note 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). The ranges and boundaries of each taxon or geological unit are discussed on a case-by-case basis in S1 Table.

Issues with lithostratigraphy

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

Limitation of scope & future versions

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

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The chart 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 Formation, New Mexico; Straight Cliffs Formation, Utah), 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, and overlying or underlying units with chronostratigraphic marker beds).

Dinosaurian fossils are limited to Neoceratopsia, Pachycephalosauridae, Sauropoda, and Hadrosauridae. This is partly to limit the amount of data in this first published version of the chart. Thus, the chosen clades represent the most abundant taxa, and also include taxa considered biostratigraphically informative by previous workers (e.g., Cobban and Reeside, 1952; Lawson, 1976; Sullivan and Lucas, 2003; 2006; Lucas et al., 2012).

Future versions of the chart are intended to extend the stratigraphic range down to the Jurassic-Cretaceous boundary. However, the plans for the first expansion concern inclusion of more Upper 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), crocodylians, and mammals, with the intent of eventually incorporating all useful taxa if possible.

Institutional abbreviations

A list of institutional abbreviations used in the correlation chart are provided in a separate tab of the correlation chart Excel sheet (S1 Table) 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 the arrangement follows 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).

Magnetostratigraphy

The conventional methodology used for delineating magnetostratigraphic chron boundaries can create problems. 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 can arise if 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 cycles 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 on either side of the unsampled sandstone, then the chron boundary would be drawn halfway, within the sandstone, whereas it might be more likely to occur at the base of the sandstone, as this is where the hiatus occurs. This would 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 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 actuality, all magnetostratigraphic samples recovered by Hicks et al. from the Laramie are normal, and it might therefore be entirely C31n. The effects of this issue are best examined on a case by case basis; the reader is referred to the stratigraphic chart (S1 Table) where more examples are highlighted in pop-up text boxes. It should be noted that this issue is purely an artifact of conventional methodology, not any mistake by a given researcher. 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 recalibrates nearly 200 radiometric dates (S2 Table), most of which are ^{40}Ar / ^{39}Ar dates that have been recalibrated to the standard and decay constant pairing of Kuiper et al. (2008), and Min et al. (2000). It is not the intention here to provide a thorough review of all radiometric dating methods (see Villeneuve, 2004); however, given the large number of ^{40}Ar / ^{39}Ar dates used here, and given discrepancies in past recalibrations, a cursory overview is given to the method. This text is also included (and expanded) in the chart itself (S1 Table).

U-Pb and K-Ar

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 that 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; and Chemical Abrasion Thermal Ionization Mass Spectrometry, CA TIMS) 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% accuracy (Villeneuve, 2004).

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 large number of possible datable minerals (due to the common occurrence of potassium in many rock-forming minerals), but among its 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 and Harrison, 1999; Renne et al., 2010). 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 secondary 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 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 and 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 an age comparable to the unknown sample (Renne et al., 1998). Hence, for Upper 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 (e.g., Samson and Alexander, 1987; Renne et al., 1994; 1998).

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 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.

When applied to Upper 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 Ma 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, a difference of 1.28 m.y. from the originally published date.

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 and Gale, 1969). The value of the decay constant λT (and its components) has historically been subject to fewer changes than the standards listed above, but has come under increased scrutiny since the late 1990's. The currently (2014) accepted standard is 5.463 E-10/y (Min et al., 2000), although alternatives are available, and refinement of this figure is the subject of active research (see S1 Table).

The decay constant used for an analysis is not always reported, although it has much less effect on the final calculated age than variations in fluence monitor mineral ages. For example, the difference between using 5.543 E-10/y (Steiger & Jaeger, 1977) and 5.463 E-10/y (Min et al., 2000) is 0.02%, equating to a difference of 0.013 Ma for a sample from the late Campanian (~75 Ma). It should be noted that different values of λT have been used historically by geochronologists compared to physicists and chemists; this is pointed out by Renne et al., (1998) who note that (for example) Endt (1990) used a λT value of 5.428 +/- 0.032 E^{-10}/y which "is more than 2% different from the values recommended by Steiger and Jaeger (1977)". Thus, there is no guarantee that, unless otherwise stated, a lab that performed an ^{40}Ar / ^{39}Ar analysis in the 1990's will be using the λT of 5.543 E^{-10}/y of Steiger and Jaeger (1977), although all dates recalibrated here use either this, Min et al. (2000), or Renne et al. (2011). Further details and a history of decay constant values can be found in the corresponding note within S1 Table .

Recalibration & current standards

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 must be entered, as the formula only uses FCT.

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 range of a radiometric date.

There are two current 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), $\lambda T = 5.463$ +/- 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 (S1 Table) are calibrated to the Kuiper et al. (2008) standard, paired with the Min et al. (2000) decay constant. This is not a reflection on the reliability of one method over another; rather it is out of convenience, because 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; however, plagioclase and biotite dates are quite common in literature from the 1990's. Here these non-sanidine dates are recalibrated, and they are comparable to each other (i.e., 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

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, FCT is 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 the 95% confidence interval 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 personal communication, 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 and systematic error.

As such, it is not possible to make the error consistent between each recalibration (although the effects are relatively minor). Where possible, recalibrated error is reported to 1σ analytical error, but generally the original reported error is simply processed through the recalibration spreadsheet, noting wherever possible all 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 and 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%"

It should be noted (Renne et al., 1998; Villeneuve, 2004), that when comparing dates within the same system (i.e., ^{40}Ar / ^{39}Ar compared to ^{40}Ar / ^{39}Ar; and U-Pb dates compared to other U-Pb dates) then it is accepted practice to not include internal error (such as data uncertainties in K-Ar, decay constants, and intercalibration factors; Renne et al., 1998) as both dates are subject to the same uncertainty, effectively canceling it out. However, when directly comparing dates derived from different systems (i.e., ^{40}Ar / ^{39}Ar dates with U-Pb dates), then internal error should be included. An example from Renne et al. (1998) showed that when reported separately, and therefore without internal error, the age of a biotite-derived ^{40}Ar / ^{39}Ar date for the Permo-Triassic Siberian Trap basalt was 250.0 +/- 0.1 Ma , whereas a zircon and baddeleyite U-Pb date from the same intrusion was 251.2 +/- 0.2 Ma. When properly compared with the internal error included, the ^{40}Ar / ^{39}Ar dates became 250.0 +/- 2.3 Ma, whereas the U-Pb date was recalculated as 251.2 +/- 0.3 Ma, such that the error ranges of the dates now overlap. In the case of this current work, only three U-Pb dates are plotted in S1 Table, all of which are from the Javelina and Aguja formations of Texas. The reader should therefore take care when comparing these units directly with other units based on ^{40}Ar / ^{39}Ar geochronology.

Other general comments

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

In previous publications, a number of radiometric dates are reported as personal communication or featured only in abstracts. Such references typically lack any analytical data, 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 that carried out the analysis (if known; see individual notes for details of sleuthing).

Results

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

Notes on recalibrations by other authors

Various analyses published by J. D. Obradovich

Many critical ^{40}Ar / ^{39}Ar dates have been published by J. D. Obradovich (United States Geological Survey, Colorado), not the least of which his 1993 work, "a Cretaceous time scale" which presented over 30 ^{40}Ar / ^{39}Ar dates for many key horizons or ammonite biozones, establishing a robust framework for the Late Cretaceous of the U.S. Western Interior. As such, recalibration of Obradovich radiometric dates is of great importance, but requires special caution due to the particular methodology of Obradovich during the 1990's (and possibly early 2000's), which differs slightly from what might be expected. During this time, Obradovich typically used the TCR as the standard for his analyses, 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 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. New Mexico Institute of Mining and 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 $\lambda T = 5.543$ 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 and 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 and 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 an FCT equivalent of 28.03 Ma (as calculated by Obradovich; see above; Hicks et al., 2002; 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 a selection of dates from Obradovich (1993), and Hicks et al. (1995, 1999) using a legacy FCT age of 28.00

Ma (not stated, but retrocalculated here). 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 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 and Hinnov, 2012)

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, producing dates that are incorrect by up to a million years.

For recalibrated dates of the Judith River Formation (originally published by Goodwin and Deino, 1989), the study (Roberts et al., 2013) utilizes 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 and Alexander, 1987; see Renne et al., 1998). This produces recalibrations for the Judith River Formation that are nearly half a million years different from the corrected recalibrations calculated in the current article. 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 recalibration offered in the current work (see S1 and S2 Tables) is 79.22 Ma.

The same error was made for recalibrations from the Bearpaw, Dinosaur Park, and Oldman formations as the Renne et al. (1998) FCT date of 28.02 was also input as the legacy FCT for dates originally published by Eberth and Hamblin (1993) and Eberth and Deino (1992); i.e. before the 1998 paper was published. The correct legacy standard to be used for these recalibrations is again, FCT = 27.84 Ma (Samson and Alexander, 1987; confirmed by Eberth, pers. comm., 2017; in prep.)

When recalibrating ^{40}Ar / ^{39}Ar dates for the Fruitland and Kirtland formations, New Mexico (originally published by Fassett and Steiner, 1997), incorrect values are input for the original (legacy) decay constant (λ) and standard (Roberts et al., 2013). First, the legacy λ used (Roberts et al., 2013) is 4.962E-10/y, which was presumably copied from the bottom of the chart on p. 243 of Fassett and Steiner (1997), where it is labeled as the value of λβ (ie. the probability of β- decay of 40K to 40Ca), and is printed below the value of λε (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 and Jaeger, 1977), which is the total (λT) of λβ plus λε. Second, Roberts et al. (2013) correctly state that the legacy standard used by Fassett and Steiner (1997) for fluence monitoring was the TCR at 28.32 Ma; however, this number is then input directly into the recalibration formula with 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 S1 Table; above note on Obradovich), both of which produce recalibrated ages ~1 million years older than the dates presented by Roberts et al. (2013). The resultant misrecalibrated dates are actually younger than the original legacy dates, which should have been more difficult to overlook as the standards for ^{40}Ar / ^{39}Ar dating have been getting progressively older, 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 EARTHTIME institute.

Seven recalibrations were performed correctly; four from the Kaiparowits Formation, Utah, one from the Wahweap Formation, Utah, and two from the Two Medicine Formation, Montana. All other recalibrated dates are incorrect and should be discarded.

Discussion

It is beyond the scope of this short work to summarize the implications of everything in the stratigraphic chart; only some enduring issues and important changes that might affect geological or paleontological interpretation are discussed here, as examples of potential uses of this chart's correlations.

Geology

Judith River Formation

The Judith River Formation is a middle to (possibly) upper Campanian terrestrial unit exposed across north and central Montana. It has been studied since the mid-19th century (Stanton and Hatcher, 1905; Bowen, 1915; Sahni, 1972; Gill and Cobban, 1973), but many aspects of its stratigraphy remain unresolved, especially regional correlation (Rogers et al., 2016). This is in part due to the Judith River Formation being a clastic wedge that thins west to east such that its upper and lower contacts change geographically, and in part due to the uneven geographic distribution of published measured sections. The stratigraphy of some areas of outcrop is well documented, such as the type area in central Montana (Sahni, 1972; Rogers, 1993; Rogers et al. 2016) and near Rudyard in northernmost Montana (e.g., Goodwin and Deino, 1989; Freedman Fowler and Horner, 2015). However, few measured sections have been published for many other equally excellent exposures. For example, despite the recovery of many fine fossil specimens from near the north-central Montana town of Malta (e.g., Prieto-Marquez, 2005), the only measured sections available for this area are in unpublished MS theses (Malik, 1990; LaRock, 2000).

The Judith River Formation in the type area (central Montana; Sahni, 1972) 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 in subsurface Spontaneous Potential (SP) logs by a distinctive "kick" named the Mid Judith Discontinuity (Rogers et al., 2016). However, despite the naming of these members for the type section in central Montana, it is not clear how they might be applied to exposures of the Judith River Formation in northernmost Montana along the U.S.-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 U.S.-Canada border are already recognized as direct lithostratigraphic equivalents to parts of the Belly River Group of Alberta (formerly called the Judith River Formation or Group; Jerzykiewicz and Norris, 1994; Hamblin and Abrahamson, 1996). Specifically, subdivisions of the Foremost and Oldman formations of Alberta (Taber Coal Zone, Herronton Sandstone Zone, Unit 1, Unit 2, and Unit 3; Eberth, 2005) have been identified in outcrop in northernmost Montana (Eberth, 2005; Schott et al., 2009; Ryan et al., 2010; Freedman Fowler and Horner, 2015).

The distinctive well-log "kick" that defines the boundary between the McClelland Ferry and Coal Ridge members is present in the subsurface in northernmost Montana (near Havre) and through into southern Canada (Rogers et al., 2016). Therefore, the discontinuity should occur among the defined subunits of the Belly River Group already identified in this part of southern Canada and their equivalents in the U.S. (Eberth, 2005; Schott et al., 2009; Ryan et al., 2010; Freedman Fowler and Horner, 2015). However, only the subsurface data is referenced for this area by Rogers et al. (2016), so it is not explicitly clear in which Canadian unit the Mid Judith Discontinuity occurs. Rogers et al. (2016) state that it occurs higher in section than the exposures in Kennedy Coulee, near Rudyard, Montana, which comprise direct lithostratigraphic equivalents of the Foremost Formation (Taber Coal Zone and Herronton Sandstone Zone) and the lower part of the Oldman Formation (Unit 1 and the leached zone; *sensu* Eberth, 2005; Schott et al., 2009; Ryan et al., 2010; Freedman Fowler and Horner, 2015; Evans, pers. comm.). As such, the "kick" must therefore occur stratigraphically higher than Unit 1 of the Oldman Formation, possibly correlating with the top of the Comrey Sandstone Zone (Unit 2, middle of the Oldman Formation; Evans. pers. comm. 2016; see S1 Table). The only suggestion in Rogers et al. (2016, p. 126) states, "the Oldman Formation [is an ...] approximate age equivalent to the McClelland Ferry Member [... and ...] the overlying Dinosaur Park Formation [is an ...] approximate age equivalent to the Coal Ridge Member". However, ^{40}Ar / ^{39}Ar dates from immediately below the discontinuity (76.24 and 76.17 Ma; Rogers et al., 2016) are younger than an ^{40}Ar / ^{39}Ar date from the middle of the Dinosaur Park Formation (76.39 Ma; Eberth, pers. comm.; see individual entry in S1 Table). This would make the suggested correlation unlikely, and would also exclude the possibility of the Mid Judith Discontinuity correlating with the top of the Comrey Sandstone Zone. However, 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.

A potential opportunity to correlate the type section of the Judith River Formation with exposures in northern Montana and the equivalent units in southern Alberta is provided by biostratigraphy of rhinobatid rays, the teeth of which are a common component of microsites in Late Cretaceous units of the Western Interior. In Alberta, ray teeth recovered from the Foremost Formation, and Unit 1 of the overlying lower Oldman Formation pertain to the smooth-sided form *Pseudomyledaphus* sp., whereas the overlying Comrey Sandstone Zone (Unit 2) and successively overlying units of the upper Oldman Formation bear only *Myledaphus bipartitus* (Peng et al., 2001; Brinkman et al., 2004; Kirkland et al., 2013). This biostratigraphic pattern was used to corroborate lithostratigraphic correlation of exposures of the Judith River Formation north of Rudyard, Montana, with the upper Foremost and lower Oldman formations, and also that the lowermost exposures of the Judith River Formation near Malta, Montana, correlate with the Comrey Sandstone Zone of the Oldman Formation (Freedman Fowler and Horner, 2015). The large number of microsites recorded in the type section of the Judith

River Formation (Rogers and Kidwell, 2000), and indeed potentially elsewhere in similarly aged units in the Western Interior (e.g. Mesa Verde Group, Wyoming and Colorado; Aguja Formation, Texas), mean that this biostratigraphic change may be easily detectable from existing collections and useful for correlation.

In summary, lack of a defined correlation or lithostratigraphic definition for the Mid Judith Discontinuity in U.S.-Canada border exposures of the Judith River Formation mean that the newly defined members are currently of limited use for surficial regional correlation beyond the type area. Furthermore, as the McClelland Ferry Member is equivalent to at least the combined Foremost Formation and Units 1-2 (and possibly 3) of the Oldman Formation, it offers reduced stratigraphic resolution than simply using the Canadian terminology when referring to these equivalent units for Judith River Formation exposures along the U.S.-Canada border sections where correlations are readily apparent. Due to these limitations, use of the newly defined members outside of the type area of the Judith River Formation is problematic.

A final remaining issue is that the lower part of the Judith River Formation as currently defined is strongly variable in age, being ~80 Ma in the area north of the town of Rudyard (where it is equivalent to the Foremost Formation, Alberta; Godwin and Deino, 1989; Eberth, 2005; Schott et al., 2009; Ryan et al., 2010; Freedman Fowler and Horner, 2015), but perhaps as young as 77.5 Ma ~200km to the east near the town of Malta (where it is equivalent to the Comrey Sandstone, Oldman Formation, Alberta; Freedman Fowler and Horner, 2015). This is mostly an artifact of the lack of subdivision.

A 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 and members that have direct correlates in Canada. In order to maintain the resolution offered by the Canadian terms, here the lower-Oldman Formation (Herronton Sandstone and Unit 1; Eberth, 2005) equivalent of the Judith River Formation is referred to 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.

Age of the Aguja Formation, Texas

The Aguja Formation of southwest Texas is subdivided into Lower and Upper Shale Members, which are separated by a marine tongue (Rowe et al., 1992; Sankey and Gose, 2001). The Upper Shale Member has yielded important vertebrate fossils (Lehman, 1989; Wagner and Lehman, 2009) and is often considered as an upper Campanian or even Maastrichtian aged unit (e.g., Longrich et al., 2010; Sankey, 2010) based on interpretation of magnetostratigraphy (Sankey and Gose, 2001), phreatomagmatic volcanism (Longrich et al., 2010), and chemostratigraphic correlation (Nordt et al., 2003). Magnetostratigraphic analysis by Sankey and Gose (2001) shows that the base of the Upper Shale Member is of reversed polarity, and is overlain by a short normal polarity interval, another reversed interval, then another normal interval. The uppermost part of the Upper Shale Member is shown as normal polarity by Lehman (1990). Sankey and Gose (2001) correlate the basal part of the Upper Shale Member with C32r (74.309 -

73.649 Ma; Ogg, 2012), asserting a late Campanian age. Using chemostratigraphic and magnetostratigraphic data, Nordt et al. (2003) and Sankey (2010) placed the upper part of the Upper Shale Member as early Maastrichtian in age, ~69-68 Ma. However, more recently published stratigraphic evidence is supportive of a middle Campanian age for the Upper Shale Member.

Ammonites and radiometric dates constrain the age of the Upper Shale Member as between ~80.2 and 76.9 Ma. Ammonite remains (Rowe et al., 1992; Lehman and Tomlinson, 2004) from the marine tongue that separates the Lower and Upper Shale members indicate that the Lower Shale Member should be no younger than the earliest middle Campanian *Baculites mclearni* zone (80.67 - 80. 21 Ma; Ogg and Hinnov, 2012), and the Upper Shale Member should be no older than this. A U-Pb 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 part of the Upper Shale Member of the Aguja Formation is unlikely to be any younger than this. Similarly, phreatomagmatic volcanic deposits occur within the Upper Shale Member, and are U-Pb dated at 76.9 +/- 1.2 Ma (Befus et al., 2008) and 72.6 +/- 1.5 Ma (Breyer et al., 2007). In which case the base of the Upper Shale Member should not be any younger than 76.9 +/- 1.2 Ma.

Further refinement of the age of the Upper Shale Member is problematic. Befus et al. (2008; p. 262) proposed a formational model where the phreatomagmatic volcanic deposits were emplaced into a crater formed within Aguja Formation sediment; i.e., the 76.9 Ma volcanic unit must have been deposited after deposition of the Upper Shale

Member (see Fig. 22 in Befus et al., 2008). As such the Upper Shale Member should not itself be considered as 76.9 Ma in age. Sankey and Gose's (2001) assignment of the base of the Upper Shale Member to magnetochron C32r (shown above to no longer be possible) was based in part on the lack of short-duration polarity fluctuations below C32r in the accepted magnetostratigraphic record (then represented by Gradstein et al., 1995). However, a number of short duration 'cryptochron' reversals were detected at the base of C33n by Montgomery et al. (1998). Although these are not yet officially accepted (i.e. in GTS 2012; Ogg, 2012), if these short reversal cryptochrons are considered valid (as in many publications by J. F. Lerbekmo; see S1 Table) then the base of the Upper Shale Member might be more precisely correlated within the lower part of C33n, which would be consistent with the constraints of radiometric dates, ammonite biostratigraphy, and the assertion of Wagner and Lehman (2009). However, this is only speculative, and more data is needed.

Age of the Javelina Formation, Texas

The age of 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 late Maastrichtian, even latest 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

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Javelina Formation. Assuming it is accurate, this plots in the lowermost part of the late Maastrichtian (69.1 - 66.0 Ma; Ogg and Hinnov, 2012). The Javelina Formation is often considered to 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, though not impossible. Alternatively, considerable hiatuses (up to 2 m.y.) are suggested to occur within the Javelina Formation by Nordt et al. (2003). This is important regarding regional correlation and warrants further consideration.

Paleontology

Thinking about taxa as lineages

There has been a recent re-emergence of study regarding the mode of evolution of dinosaurs. Many analyses have found that dinosaur sister taxa form (typically) short-duration species that do not overlap stratigraphically; a pattern especially common within single depositional basins (e.g., Mateer, 1981; Horner et al., 1992; Holmes et al., 2001, although see; Ryan and Russell, 2005; Campione and Evans, 2011; Evans et al., 2011; Mallon et al., 2012; Gates et al., 2013; Scannella et al., 2014; Freedman Fowler and Horner, 2015; Fowler, 2016). In some cases, it has been suggested that this may represent anagenesis (or the synonym, 'phyletic evolution'; Horner et al., 1992; Campione and Evans, 2011; Scannella et al., 2014; Freedman Fowler and Horner, 2015; Fowler, 2016), the evolutionary mode whereupon lineages or populations transform morphologically through time without branching into multiple contemporaneous species (cladogenesis; also technically, speciation; sensu Cook, 1906).

The stratigraphic correlations and taxonomic plots presented here (S1 Table) facilitate more broad investigations of the mode of evolution in Western Interior dinosaurs. One of the striking results of the replotting of both geological formations and dinosaur taxa is that many dinosaur clades form columns of short-duration species (or perhaps more accurately, metaspecies; Archibald, 1994; Lee, 1995) which do not overlap stratigraphically, a pattern which, if real, fails to reject the hypothesis of anagenesis. This suggests that in Western Interior dinosaurs, much of the morphological change that we observe through time might not all be related to the multiplication of species. If cladogenesis was the most important driver of morphological change (Eldredge and Gould, 1972), then we would expect to see stratigraphic overlap between different morphologies. Although this does occur, it is not ubiquitous, and anagenesis should be equally considered alongside cladogenesis as a valid hypothesis explaining morphological change. Further support for anagenesis 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 (Kaiparowits Formation, Utah; Fruitland and Kirtland

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formations, New Mexico), and brachylophosaurin hadrosaurines of the middle Campanian (Freedman Fowler and Horner, 2015).

It could be noted that if the error associated with radiometric dates is included, then for some species it may not be possible to determine with total confidence whether or not they were contemporaneous with their sister taxon (which would falsify anagenesis). This criticism however, applies equally to any evolutionary hypothesis that depends upon precise stratigraphic data for closely related taxa that are stratigraphically similar ages, including the hypothesis of cladogenesis (the alternative to anagenesis), and even biogeographic hypotheses (e.g., Sampson et al., 2010; 2013). It also could be argued that a lack of stratigraphic overlap of sister taxa is simply an artifact of inadequate sampling. These might well be true, but it does not mean that hypotheses should not be formed and tested. In some examples where large datasets have been accumulated (Scannella et al., 2014) the pattern has still been one of stratigraphic replacement rather than overlap, with an increased number of stratigraphically intermediate specimens exhibiting more intermediate morphologies. Increased sampling is evidently the best way to test all hypotheses of anagenesis, cladogenesis, and biogeography in Western Interior dinosaurs, but it would be " pusillanimous to avoid making our best efforts today because they may appear inadequate tomorrow" (Simpson, 1944; p. xviii).

North-south biogeography and intracontinental faunal endemism

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It has been proposed that during the Campanian, the Western Interior of North America was divided into relatively small latitudinally arrayed faunal provinces, each with a unique fauna (Sampson et al., 2010; 2013). 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, review of the data used in the original publication (Sampson et al., 2010) and recalibrations performed here reduce support for this hypothesis.

In 2005, Roberts et al. presented a thorough stratigraphic and sedimentological description of the Kaiparowits Formation, including three ^{40}Ar / ^{39}Ar dates (75.96 Ma; 75.02 Ma; and 74.21 Ma) from a series of volcanic ashes throughout the unit. This provided a welcome opportunity to more precisely correlate the Kaiparowits Formation with similarly aged units in the Western Interior, permitting the testing of paleontological hypotheses regarding the biogeography, phylogeny, and mode of evolution of their dinosaur fauna.

These themes were later explored by the hypothesis of 'intracontinental faunal endemism' (Sampson et al., 2010; 2013), which proposed that taxonomic differences among the dinosaurs of the Kaiparowits Formation, Dinosaur Park Formation, (Alberta); Two Medicine Formation (Montana) and Fruitland and Kirtland formations (New Mexico) were representative of different species being endemic to small geographic ranges. Key evidence for this hypothesis was the presentation and discussion of the stratigraphic ranges of chasmosaurine ceratopsid dinosaurs, of which many taxa were shown to have overlapped (Sampson et al., 2010). This would mean that these taxa were contemporaneous, but apparently segregated geographically, thereby forming key support for intracontinental faunal endemism (Sampson et al., 2010).

However, the chronostratigraphic data used to plot the stratigraphic ranges of chasmosaurine taxa (Sampson et al., 2010) contained an unexplained inconsistency related to the mixed use of unrecalibrated and recalibrated ^{40}Ar / ^{39}Ar dates. The stratigraphic ranges of chasmosaurines from the Kaiparowits Formation (*Utahceratops* and *Kosmoceratops*) were plotted as occurring from 76.3 to 75.5 Ma, and regarding the duration of the formation itself, Sampson et al. (2010, p.6) state "Laser-fusion 40Ar/39Ar ages indicate a late Campanian range for the formation, spanning 76.6–74.5 Ma and corresponding to the Judithian land vertebrate age (Fig. 7)", and cite Roberts et al. (2005) as the source for these ages. However, as shown above, the dates in Roberts et al. (2005) range from 75.96 to 74.21 Ma, i.e. the youngest date given by Roberts et al. (2005), 74.21 Ma, is younger than the upper age limit of the entire formation (74.5 Ma) given by Sampson et al. (2010), which is clearly impossible. Furthermore, Roberts et al. (2005, p. 312) explicitly state that "utilizing an average rock accumulation rate of 41 cm/ka, the ca. 860-m-thick Kaiparowits Formation accumulated for ca. 2.1 Ma, from ca. 76.1 - 74.0 Ma". This is therefore inconsistent with the taxon and formational ranges of Sampson et al. (2010; 76.6-74.5 Ma), and at the time of publication the origin of these dates remained unexplained

More information was later provided in a generalized stratigraphic column of the Kaiparowits Formation (Zanno et al., 2011), which presented four ^{40}Ar / ^{39}Ar dates (76.46 Ma; 75.97 Ma; 75.51 Ma; and again 75.51 Ma), three of which corresponded stratigraphically with the same horizons dated by Roberts et al. (2005), but with different numerical ages. Zanno et al. (2011) do not state that these are recalibrated dates, and instead cite Roberts (2007) as their source for three of these dates, but the dates in Roberts (2007), are the same as in Roberts et al. (2005), and do not correspond with the numbers given by Zanno et al. (2011). It is notable that the dates given by Zanno et al. (2011) are consistent with the age range given by Sampson et al. (2010), i.e. that they probably had the same, unexplained source.

The source of the new dates was only officially published in 2013, when Roberts et al. published a series of dates from the Kaiparowits Formation that were recalibrated (using the FCT standard and decay constant pairing of Kuiper et al., 2008; 28.2 Ma; and Min et al., 2000) from those published by Roberts et al. (2005; which used the 28.02 Ma age for the FCT standard; Renne et al., 1998). That the Sampson et al. (2010) Kaiparowits dates are indeed recalibrated is confirmed by Roberts et al. (2013; p.85) who state, "recalibration of Kaiparowits Formation ash beds demonstrates that the formation is approximately half a million years older than previously suggested, deposited ~76.6–74.5 Ma.", i.e., exactly the same age duration as given by Sampson et al. (2010).

This demonstrates unequivocally that Sampson et al. (2010) used a mixture of ^{40}Ar / ^{39}Ar dates calibrated to different standards to plot the stratigraphic occurrence of chasmosaurine taxa, creating the illusion that certain ataxa overlapped. *Utahceratops* and *Kosmoceratops* from the Kaiparowits Formation were the only taxa that were plotted based on radiometric dates recalibrated to the current standard (Kuiper et al., 2008). Other taxa from different units (Dinosaur Park Formation, Alberta; Fruitland and Kirtland formations, New Mexico) were plotted based on unrecalibrated dates which used previous standards, mostly that of Samson and Alexander (1987). This results in taxa from the Kaiparowits Formation being shown ~0.5 m.y. relatively older (Roberts et al., 2013) than they would have been if they had been plotted to the same standard as the taxa from the other units.

When all the available dates are recalibrated to the same standards (as in the current work), the stratigraphic overlap between key taxa is no longer recovered. Only the lower part of the Kaiparowits Formation stratigraphically overlaps with the fossiliferous portion of the Dinosaur Park Formation (see S1 Table). 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). Here it is considered more likely that differences between dinosaur species found in the Dinosaur Park Formation and middle Kaiparowits Formation are mostly an artifact of sampling different stratigraphic levels, rather than biogeographic segregation (also see Lucas et al., 2016). 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 formations being slightly younger than the middle Kaiparowits Formation (Sullivan and Lucas, 2006; Lucas et al., 2016). Moreover, the recent identification of purportedly southern *Pentaceratops*-lineage chasmosaurines within the Dinosaur Park Formation, Alberta (Longrich, 2014; Fowler, 2016), demonstrates that this lineage was able to move between northern and southern regions in the middle Campanian.

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 Campanian and Maastrichtian units of the United States (Lawson, 1976; Lehman 1987, 2001; Sullivan, 2003), and were utilized by Sullivan and Lucas (2003, 2006) in their definition of the “Kirtlandian”: an additional LVA roughly equivalent to the early deposition of the Bearpaw Shale and positioned in the gap between the Judithian and Edmontonian identified by Russell (1964; 1975). Dinosaurs were also strongly utilised for biostratigraphy in the definition or redefinition of 10 vertebrate biochrons for the Cretaceous of the Western Interior (Lucas et al., 2012).

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The demonstration that individual dinosaur species form stratigraphically stacked sequences of non-overlapping taxa could make them useful for biostratigraphy. This might be seen as controversial, since generally dinosaur taxa are known from relatively few specimens and are arguably less abundant than mammals or other groups typically used in terrestrial biostratigraphy. However, at least some clades of dinosaurs would seem ideal for biostratigraphic correlation, especially if current hypotheses of rapid evolution are correct (e.g. Horner et al., 1992; Holmes et al., 2001; Scannella et al., 2014; Fowler, 2016). For example, the chasmosaurine dinosaur *Triceratops* has been demonstrated to evolve at least three different metaspecies through the duration of the Hell Creek Formation in Montana (Scannella et al., 2014). Although the duration of the Hell Creek Formation is not precisely known, two stratigraphically separated metaspecies of *Triceratops* (*T. prorsus* and *T.* sp.; Scannella et al., 2014) are recorded from the uppermost 30m, which has been recently demonstrated by Ar / Ar dates as representing ~300 k.y. of deposition (Sprain et al., 2014; see S1 Table). If we are able to understand the stratigraphic distribution and ontogenetic variation of dinosaurs well enough, then conceivably many more clades may be biostratigraphically informative at resolutions of ~300Ka (or less; see S1 Table).

Conclusions

Understanding the paleobiology of extinct organisms requires explicit knowledge of their relative positions in time. In turn, this depends upon the accurate correlation of the geological formations from which fossil remains are recovered.

Here, recalibrated radiometric dates are combined with existing stratigraphic data to create a comprehensive stratigraphic correlation chart for terrestrial units of the U.S Western Interior. This revised stratigraphic framework is intended to be a tool for use by other researchers to investigate dinosaur evolution. Recalibration of radiometric dates to the same standard should remove artifacts of miscorrelation, permitting a clearer search for evolutionary patterns. Conflicts between different kinds of stratigraphic data are highlighted, particularly where they may affect paleontological understanding.

Future expansions of the chart will increase the geographic scope of formations covered, and include additional 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.

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).

S2 Text. Comment Boxes for Stratigraphic Chart. This text file provides transcripts of all the pop-up comment boxes featured in the stratigraphic chart (Table S1). This file should be of use to readers who prefer the text in this larger format.

S1 Figure. Stratigraphic Chart, graphic version. This is a image file version of the stratigraphic chart (S1 Table). It is an image only, provided for quick reference, and does not have embedded pop-up comments.

S2 Figure. Geographic Location of Stratigraphic Sections featured on Stratigraphic Chart Table S1. This map shows the geographic location of the different stratigraphic sections shown in stratigraphic chart Table S1.

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