Discussion and reply: $^{40}$Ar/$^{39}$Ar geochronology of the Eocene Green River Formation, Wyoming Discussion

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Smith et al. (2003, hereafter referred to as Smith et al.) present seven new isotopic ages from the Green River Formation in the greater Green River Basin. These data provide welcome new information in the ongoing effort to develop a coherent and reliable geochronological framework for this large and stratigraphically complex basin. Several of their main conclusions are based on a revised age estimate for the Wasatchian-Bridgerian North American Land Mammal Age boundary. For instance, Smith et al. use the revised age estimate for the Wasatchian-Bridgerian boundary to argue that the onset of maximum temperatures during the early Eocene climate optimum (EECO) could not have caused the faunal turnover that marks the boundary. Since no vertebrate fossils are known from the stratigraphic sections presented in Smith et al., these important conclusions rest entirely on their reinterpretation of a magnetostratigraphic correlation presented in Clyde et al. (2001, hereafter referred to as Clyde et al.). Unfortunately, the authors overlook several important stratigraphic observations in their efforts to reinterpret this record.

Smith et al. argue that the uppermost normal polarity zone from Clyde et al. (zone F+) correlates to Chron C21n instead of Chron C22n. We rejected this interpretation because that normal polarity zone lies within Bridger “A” lithologies and is associated with a well-characterized Bridgerian Br1b (= early Blacksforkian) mammalian fauna (Fig. 4 in Clyde et al.), both of which are known to be older than Chron C21n (see below). This Bridgerian Br1b fauna contains many biostratigraphically diagnostic taxa such as Anaptomorphus westi, Notharctus robinsoni, Smilodectes mcgrewei, and Palaeoscyllia fontinalis (Gunnell and Bartels, 2001).

Murphey et al. (1999) report an isotopic age of 47.96 ± 0.13 Ma for the Church Butte Tuff, which lies within Bridger “B” lithologies (i.e., above the Bridger “A” beds of polarity zone F+) and is closely associated with a Bridgerian Br2 fauna (i.e., above the Bridgerian Br1b fauna of polarity zone F+). Smith et al. deem this age determination to be reliable but recalculate it to 48.65 ± 0.30 Ma using the standard ages of Renne et al. (1998). They also recalculate the beginning of Chron C22n to be 48.1 Ma as opposed to 47.9 Ma as originally reported in Cande and Kent (1995). Basic stratigraphic principles thus indicate that polarity zone F+ must be considerably older than ca. 48.6 Ma according to the recalculated Murphey et al. (1999) age, yet the Smith et al. interpretation would have it younger than ca. 48 Ma (Fig. 1). The youngest normal Chron in the Geomagnetic Polarity Time Scale (GPTS) that is older than ca. 48.6 Ma is Chron C22n, which is the one to which Clyde et al. correlated polarity zone F+ in their original study.

The Green River Basin is characterized by a particularly complex array of lateral facies changes that make it difficult to apply standard lithostratigraphic correlation across the basin. For instance, the new isotopic ages come from locations near the center of the basin where the lacustrine Green River Formation is dominant and there is little or no development of the fluvial Wasatch Formation. The magnetostratigraphic and biostratigraphic data of Clyde et al. (1997, 2001) come from marginal basin localities where the Wasatch Formation is prominent and precise stratigraphic relationships between it and members of the Green River Formation have been established, but no isotopic age framework exists. Smith et al. correlate between these distant locations using a presumed model of lateral facies associations that is rather imprecise for the purposes of creating a robust chronostratigraphic framework.

Unfortunately, the present array of stratigraphic and radiometric information from the greater Green River Basin remains inconsistent, making it impossible at present to construct a reliable basinwide chronostratigraphic framework for the Green River Basin. Part of
the problem may be due to stratigraphic and analytical uncertainty associated with the calibration points for the early Eocene part of the current GPTS (Berggren et al., 1995; Berggren and Aubry, 1998). In any case, resolution of these inconsistencies will require yet more work, particularly in areas where basin-margin and basin-center deposits can be precisely lithostratigraphically correlated and biostratigraphic and magnetostratigraphic data can be combined directly with isotopic age determinations.

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Reply

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In their comment, Clyde et al. point out an important discrepancy between our 40Ar/39Ar-based age model (Smith et al., 2003), paleomagnetic stratigraphy (Clyde et al., 1997; 2001), and an 40Ar/39Ar age from Murphey et al. (1999). Specifically, Clyde et al. conclude that the F+ chron within the Bridger Formation at the top of their South Pass section (Clyde et al., 2001) correlates to C22n instead of C21n, implying that the entire Green River Formation is contained between C23r and C22r. Their interpretation is based largely on the age for the Church Butte tuff given by Murphey et al. (1999). However, we suspect that this age is too old and may reflect detrital or xenocrystic contamination. Adopting the Murphey et al. (1999) age for the Church Butte tuff as valid requires one or more of the following:

1. Rejection of well-documented basinwide correlations.
2. Abandonment of seven fully documented, stratigraphically consistent age determinations by Smith et al. (2003).
3. Acceptance of unreasonably high depositional rates for the Laney Member and Bridger Formations between the Analcite and Wilkins Peak Member.

Herein, we present an amended version of our age model that rejects the age of Murphey et al. (1999) for the Church Butte tuff, thereby eliminating the contradiction noted by Clyde et al. (Fig. 1).

1. We acknowledge that lateral facies changes are pronounced in the Greater Green River Basin but observe that certain units, most notably the Tipton and Laney members, can be confidently correlated basinwide (Bradley, 1964; Roehler, 1992b; Clyde et al., 2001; Pietras et al., 2003). Contrary to Clyde et al.’s concern that the “particularly complex array of lateral facies changes... make it difficult to apply standard lithostratigraphic correlation across the basin,” considerable lithostratigraphic and biostratigraphic continuity exists regarding the basinwide correlation of these units, which both record major expansions of Lake Gosiute (e.g., Bradley, 1964; Roehler, 1992b). In fact, Clyde et al. (1997, 2001) correlate the base of the Laney Member of the Green River Formation between two sections (Opal and South Pass) that are separated by more than 140 km, and in both indicate it to be stratigraphically coincident with the Gardnerbuttean-Blacksforkian (Br1a-Br1b) boundary and just above a characteristic normal magnetic chron. Clyde et al. also argue that the ages of several biostratigraphic boundaries in Smith et al. (2003) rest entirely upon reinterpretation of the basin margin magnetostratigraphy and biostratigraphy of Clyde et al. (1997, 2001). However, our ages for the Lostcabinian-Gardnerbuttean (Wa7-Br0) and Gardnerbuttean-Blacksforkian (Br1a-Br1b) boundaries integrate several biostratigraphic studies from multiple localities throughout the basin (Wood et al., 1941; McGrew and Roehler, 1960; Morris, 1954; Bradley, 1964; Gazin, 1965; West and Dawson, 1973; Krishtalaka et al., 1987; Honey, 1988; Holroyd and Smith, 2000) in addition to the more recent contributions from the Opal (Roehler, 1989; Zonneveld, 2000; Clyde et al., 1997) and South Pass (Clyde et al., 2001; Gunnell and Bartels, 2001) sections. Despite recent complications with Gardnerbuttean index taxa (Smith and Holroyd, 2003), biostratigraphers have consistently placed the Wasatchian-Bridgerian (Lostcabinian-Gardnerbuttean) boundary in the lower part of the Cathedral Bluffs Tongue of the Wasatch Formation and equivalent Wilkins Peak Member. Likewise, in their Opal section in the SW corner of the Greater Green River Basin, Clyde et al. (1997) and Zonneveld et al. (2000) located the Wasatchian-Bridgerian boundary in the lower part of the Wilkins Peak Member, above laminated mudstones of the Tipton Member (Roehler, 1989).

2. Inheritance of Xenocrysts or Detrital Grains can introduce significant error into the radiotisopic ages of Tuff Beds when Large Samples are Dated. We propose that an inherited contaminant best explains the apparent contradiction. Owing to the grossly different radiogenic argon contents, a single Precambrian detrital grain or partially outgassed xenocryst of feldspar or biotite incorporated into a population of 1000 crystals erupted 47 Ma could easily elevate the apparent age of the bulk sample by 1%–2% over its depositional age. Our 2003 study recognized this and took pains to exclude analyses potentially biased by detrital or xenocrystic contamination. Analyses of small (1–10 grain) aliquots of sandine and biotite from Green River Formation tuff beds reveal subtle xenocrystic or detrital con-
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tamination that can only be detected and excluded if sufficiently small aliquots (<10 grains) are used (Smith et al., 2003). Nearly half the biotite analyses from the Main tuff fall outside the 95% confidence limits about the mean age of 50.01 ± 0.21 Ma and were excluded from its calculation. Inclusion of these outliers shifts the age 1% to 50.56 Ma. In contrast, sanidine from the Main tuff was free of outliers, giving an age of 49.96 ± 0.16 Ma that independently confirms the validity of excluding the biotite outliers.

To further illustrate the sample size problem, we re-dated sanidine from an upper Willwood Formation ash bed from the Bighorn Basin (bed B; Rohrer, 1964; Wing et al., 1991), located at the base of chron 24n.1 and coincident with the Lystitean-Lostcabinian (Wa6-Wa7) North American land mammal age (NALMA) substage boundary. Sanidine from this ash was ⁴⁰Ar/³⁹Ar dated at 53.09 ± 0.34 Ma by incrementally heating a 100 mg sample (Wing et al., 1991). Smith et al. (2003) utilized this age to recalibrate the Eocene Geomagnetic Polarity Timescale (GPTS) to the standard ages of Renne et al. (1998) and constrain the Wa6-Wa7 boundary, which is found in the upper part of the Luman Tongue of the Green River Formation (McGrew and Roehler, 1960; Gazin, 1965; Holroyd and Smith, 2000). However, we suspected the Wing et al. (1991) age to be too old because of the large sample size used.

We conducted sixteen laser-fusion and four 5-step laser incremental heating analyses of one to three crystal aliquots of large, optically clear ~10 microgram sanidine crystals that give a weighted mean age of 52.59 ± 0.12 Ma for the Willwood ash bed (2σ analytical uncertainties; ± 0.19 m.y. with intercalibration uncertainties; Fig. 2). Thus, Wing et al.’s (1991) age determination likely overestimates the age of the Willwood ash by ~0.5 m.y. due to the inclusion of xenocrystic or detrital grains in their ~10,000 grain aliquot (Fig. 2). Use of this new age to recalibrate the GPTS gives chron boundary ages that are more similar to those of Cande and Kent (1995) than recent recalibrations by Wing et al. (2000) and Smith et al. (2003).

Although not fully reported in their ab-
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Figure 2. Incremental heating and single-crystal laser-fusion $^{40}$Ar/$^{39}$Ar experiments on sanidine from the upper Willwood Formation ash. Shading indicates 2σ envelope of analytical uncertainty. Ages shown between plots reflect intercalibration uncertainties relative to the standard ages of Renne et al. (1998). Note the shift to a younger, more precise age from the original determination by Wing et al. (1991).

Figure 1. Upper Willwood Formation ash sanidine
Combined weighted mean age: 52.59 ± 0.12 Ma, n = 35, MSWD = 0.72

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The alluvial and lacustrine sediments contained within Laramide basins represent one of the world’s foremost archives of Eocene climate, evolution, and paleography. In the Greater Green River Basin, as elsewhere, the construction of an internally consistent and accurate age model is crucial and should not rely on individual published ages. An accurate integrated age model must account for lithostratigraphic correlations, magnetostratigraphy, and well-documented geochronology—including uncertainties—from multiple ashes. Like the commenting authors, we strongly support future efforts to obtain higher resolution stratigraphic correlations and age determinations throughout the basin. Specifically, we suggest that re-dating small aliquots of sanidine from Bridger Formation ashes as well as performing magnetostratigraphy on Bridger Formation strata on the east side of the Bridger Basin hold the most promise for resolving outstanding problems. We also encourage future investigations to more fully address the nature of paleomagnetic remanence acquisition and secondary overprinting in these facies.

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