New $^{40}Ar/^{39}Ar$ dating of the Grande Ronde lavas, Columbia River Basalts, USA: Implications for duration of flood basalt eruption episodes

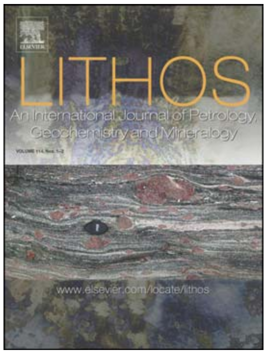
Journal Item

How to cite:

Barry, T. L.; Self, S.; Kelley, S. P.; Reidel, S.; Hooper, P. and Widdowson, M. (2010). New 40Ar/39Ar dating of the Grande Ronde lavas, Columbia River Basalts, USA: Implications for duration of flood basalt eruption episodes. Lithos, 118(3-4) pp. 213–222.

Version: Accepted Manuscript

Link(s) to article on publisher's website:
http://dx.doi.org/doi:10.1016/j.lithos.2010.03.014



New ^{40}Ar/^{39}Ar dating of the Grande Ronde lavas, Columbia River Basalts, USA: Implications for duration of flood basalt eruption episodes

T.L. Barry, S. Self, S.P. Kelley, S. Reidel, P. Hooper, M. Widdowson

PII: S0024-4937(10)00089-7
DOI: doi: 10.1016/j.lithos.2010.03.014
Reference: LITHOS 2224

To appear in: *LITHOS*

Received date: 22 September 2009
Accepted date: 10 March 2010

Please cite this article as: Barry, T.L., Self, S., Kelley, S.P., Reidel, S., Hooper, P., Widdowson, M., New ^{40}Ar/^{39}Ar dating of the Grande Ronde lavas, Columbia River Basalts, USA: Implications for duration of flood basalt eruption episodes, ***LITHOS*** (2010), doi: 10.1016/j.lithos.2010.03.014

New ^{40}Ar/^{39}Ar dating of the Grande Ronde lavas, Columbia River Basalts, USA: implications for duration of flood basalt eruption episodes

T.L. Barry[1], S. Self[1], S.P. Kelley[1], S. Reidel[2], P. Hooper[1], M. Widdowson[1]

[1]Volcano Dynamics Group, CEPSAR, Open University, Walton Hall, Milton Keynes, MK7 6AA, UK.
[2] Washington State University, Tri-Cities Campus, Richland, WA 99354, USA.

ABSTRACT

Grande Ronde Basalt (GRB) lavas represent the most voluminous eruptive pulse of the Columbia River-Snake River-Yellowstone hotspot volcanism. With an estimated eruptive volume of 150,000 km^3, GRB lavas form at least 66% of the total volume of the Columbia River Basalt Group. New ^{40}Ar/^{39}Ar dates for GRB lavas reveal they were emplaced within a maximum period of 0.42 ±0.18 My. A well-documented stratigraphy indicates at least 110 GRB flow fields (or individual eruptions), and on this basis suggests an average inter-eruption hiatus of less than 4,000 years. Isotopic age-dating cannot resolve time gaps between GRB eruptions, and it is difficult to otherwise form a picture of the durations of eruptions because of non-uniform weathering in the top of flow fields and a general paucity of sediments between GR lavas. Where sediment has formed on top of the GRB, it varies in thickness from zero to 20-30 cm of silty to fine-sandy material, with occasional diatomaceous sediment. Individual GRB eruptions varied considerably in volume but many were greater than 1000 km^3 in size. Most probably eruptive events were not equally spaced in time; some eruptions may have followed short periods of volcanic repose (perhaps 10^2 to 10^3 of yrs), whilst others could have been considerably longer (many 1000s to >10^4 yrs). Recent improvements in age-dating for other continental flood basalt (CFB) lava sequences have yielded estimates of total eruptive durations of less than 1 My for high-volume pulses of lava production. The GRB appears to be a similar example, where the main pulse occupied a brief period. Even allowing for moderate to long-duration pahoehoe flow field production, the amount of time the system spends in active lava-producing mode is small – less than *c.* 2.6% (based on eruption durations of approximately 10,000 yrs, as compared to the duration of the entire eruptive pulse of *c.* 420,000 yrs). A review of available ^{40}Ar/^{39}Ar data for the major voluminous phases of the Columbia River Basalt Group suggests that activity of the Steens Basalt-Imnaha Basalt-GRB may have, at times, been simultaneous, with obvious implications for climatic effects. Resolving intervals between successive eruptions during CFB province construction, and durations of main eruptive pulses, remains vital to determining the environmental impact of these huge eruptions.

Keywords: $^{40}Ar/^{39}Ar$ dating; Continental flood basalts; Columbia River Basalt Province; flood basalt volcanism.

1. Introduction

Large igneous provinces and their extrusive components, flood basalt lavas, represent exceptional volcanic events (Eldholm & Coffin, 2000). Highly voluminous large igneous provinces emplaced within geologically short periods of time (e.g., ~1 My; Duncan & Pyle, 1988; Chenet et al., 2008; Reichow and Saunders, 2008) represent huge potential for atmospheric loading by volcanic gases (e.g., S, CO_2; see Self et al., 2006, 2008) and for inundating landscapes with vast volumes of basalt lava. Such events have been linked to mass extinctions (e.g., Wignall, 2001; Courtillot and Renne, 2003; Saunders & Reichow, 2008) and mantle plume activity (e.g., Courtillot et al., 2003 and references therein

Even the most precise radiometric dating, e.g. $^{40}Ar/^{39}Ar$, cannot resolve the length of time between flood basalt eruptions (possibly 100s to 10,000s of years, Jolley et al., 2008) due to analytical uncertainties of no better than ~1%. In order to bridge this gap in our understanding, we have taken a new look at packages (major eruptive pulses) of stratigraphically well-constrained flood basalt lavas. This has involved sampling from the bottom and top of lava formations to estimate the time elapsed between the first and last eruptions (lavas), and hence constrain the time gaps between superposed formations. There are few clues to the potential duration of individual flood basalt-type eruptions, but on the basis of interpretation of chemical and/or physical parameters, estimates of individual eruption durations for the lavas within the Columbia River Basalt Group (CRBG) from the Pacific Northwest region, USA, range from the scale of months (Reidel 2005) to years (Petcovic & Dufek, 2005), and even decades (Thordarson & Self, 1998; Self et al. 2006). Although we cannot resolve the duration of individual eruptions using current techniques for radioisotopic age-determinations, we can examine the length of time taken for the eruption of pulses or packages of lavas.

For this study we chose the Grande Ronde Basalt (GRB) of the CRBG (Fig. 1). GRB lavas are the product of the most voluminous outpouring of basalt lava within the province formed by the Columbia River – Snake River – Yellowstone hotspot system and constitute more than 66% of the total volume of the CRBG [using the latest estimates of total CRB-related lava volume (Camp et al., 2003; Camp & Ross, 2004) compared with 90% of the volume of the CRBG as previously defined by Tolan et al.

(1989)]. The basalt-dominated part of the province is an order of magnitude smaller in scale than large igneous provinces such as the Deccan basalts. However, for this study, we selected the mid-Miocene CRBG over other provinces because the stratigraphy is well defined (e.g., Tolan et al., 1989), the lavas are relatively fresh, and age-date errors would be kept to a minimum. Importantly, the results may be used as an analogue for older flood basalt provinces where such precision is not possible.

---Insert Figure 1---

2. Geological setting and previous age estimates

The CRBG is the Earth's youngest continental flood basalt province with volcanism beginning around 17 Ma. Previous age determinations placed the eruption of the whole province between 17 and 6 Ma (Baksi, 1989; Tolan et al., 1989), with the voluminous GRB lavas estimated to have erupted between ~ 16.0 and ~ 15.0 Ma ago (Long and Duncan 1983; Hooper et al., 2002). The GRB lavas overlie the readily identifiable phenocryst-rich Imnaha Basalt lavas in the south of the province, and immediately underlie the Vantage Sandstone Member which forms part of the Ellensburg Formation (Swanson et al., 1979), that is distributed throughout much of the western CRBG on the Columbia Plateau. In many places throughout the province, the lavas of the Wanapum Basalt lie above the GRB, with or without the Vantage sediments between.

2.1 Imnaha Basalt

One of the oldest CRBG-related formations, the Imnaha Basalt, is coarsely porphyritic with abundant plagioclase feldspars up to approximately 1 cm in size. Ages of the Imnaha lavas have been given as 17.2 ±0.4 Ma (e.g. Baksi, 1989 and references therein), as dated by the K-Ar technique (McKee et al., 1981), with the topmost lavas at 17.5 ±0.4 Ma by extrapolation of an ^{40}Ar/^{39}Ar date of 17.67 ±0.32 Ma (Table 1; Baksi and Farrar, 1990). See footnote about reporting of published age data.[1] However, three

---

[1] Note about reporting of published age data. All K-Ar ages are quoted to one decimal place, whereas higher precision ^{40}Ar/^{39}Ar dates are quoted to two decimal places. Both K-Ar and ^{40}Ar/^{39}Ar published data are quoted here with 2σ errors, and therefore may appear different from more commonly reported 1σ errors in original texts. All published dates and their extrapolations have been re-calculated from that given at the time of publication to the currently accepted age for Fish Canyon Tuff standard of 28.201 (Kuiper et al., 2008). Subsequently, ages are different from those in the original manuscripts. The newly accepted Fish Canyon Tuff age was revised on the basis of a new decay constant for ^{40}K to ^{40}Ar (Min et al., 2000), and for astronomical inter-calibration (Kuiper et al., 2008). Without the original data, which is commonly omitted from references, we are not able to recalculate the K-Ar ages.

younger ^{40}Ar/^{39}Ar dates for Imnaha lava samples have been reported; 15.50 ±0.40 Ma and 15.60 ±0.60 Ma (Hooper et al., 2002), and 15.7 ±0.6 Ma by K-Ar (Watkins and Baksi, 1974), although the latter is recorded as having a high ^{36}Ar content that may suggest a sample with altered mineralogy. Note that this span of ages from previous studies on Imnaha lavas encompasses almost the entire range of published ages for all CRBG lava formations, including those from the Wanapum Basalt above the GRB.

The Imnaha Basalt is best exposed near the Washington - Oregon - Idaho borders. Further south, Imnaha Basalt is not found, but instead the older Steens Basalt successions are exposed. Field relations between Imnaha Basalt and Steens Basalt are not yet well constrained (Camp et al., 2003). However, it is thought that Imnaha Basalt conformably overlies Lower Steens Basalt in the south, but that elsewhere it might be interfingered with Upper Steens Basalt (Hooper et al., 2002; Camp et al., 2003). Unfortunately, evidence for interstratification between Imnaha and Steens Basalts has not been described in outcrop, and its inference is based on supposition (V.E. Camp, pers. comm., 2010). Further, no field evidence has yet been found to suggest a marked hiatus between Imnaha and Steens Basalt. Steens Basalt volcanism and its equivalents in Malheur Gorge have been dated between 16.46 ±0.24 (Baksi and Farrar, 1990) and 17.10 ±1.60 Ma (Hooper et al., 2002). Age data for Steens Basalt and its proposed equivalents are presented in Jarboe et al. (2006 and 2008), Henry et al. (2006), and Brueseke et al. (2007).

---INSERT Table 1---

2.2 Grande Ronde Basalt

The ≤ 500 m (proximally) to almost 4 km thick (in the Pasco Basin; Reidel et al., 1989) succession of GRB lavas rests partly on the upper surface of the Imnaha Basalt with little or no evidence for erosion or extensive weathering between. Elsewhere GRB lavas sit on Tertiary sediments and older basement (e.g. at Granite Point, Washington). The GRB is recognized to span at least four paleomagnetic zones and, on this basis, has been stratigraphically sub-divided into R_1, N_1, R_2 and N_2 units (R = reversed, N = normal; Swanson et al., 1979). Past age determinations are presented in Table 1 and are summarised below.

However, K-Ar ages are only quoted here for completeness and we do not make any inferences or conclusions using them.

Previously determined ages for the lowest lying R_1 lava flow sequence are15.7 ±0.6 and 15.9 ±0.6 Ma (K-Ar; Watkins and Baksi, 1974) and 16.41 ±0.22 Ma ($^{40}Ar/^{39}Ar$; Baksi and Farrar, 1990). On the basis of the latter age, Baksi and Farrar (1990) extrapolated the R_1 to N_1 boundary at 16.48 ±0.20 Ma. A $^{40}Ar/^{39}Ar$ date of 16.32 ±0.20 Ma from near the top of N_1 lavas led Baksi and Farrar (1990) to propose a date of 16.38 ±0.30 Ma for the N_1-R_2 boundary. Further R_2 and N_2 units have been dated at 15.8 ±0.3 Ma (K-Ar; Watkins and Baksi, 1974; Baksi, 1989) and 16.07 ±0.28 (Baksi and Farrar, 1990), respectively. The R_2-N_2 boundary is suggested to be at ~15.97 ±0.30 Ma (Baksi and Farrar, 1990), and the top of the GRB has been placed at 15.79 ±0.40 Ma ($^{40}Ar/^{39}Ar$ on N_2 lava; Long and Duncan, 1983) and should thus date approximately the onset of deposition of the Vantage Sandstone Member interval (see below).

Individual GRB lavas are stacked on each other with little or no intervening sediment, soil or well-developed weathering horizon, suggesting rapid emplacement of the whole succession. Most commonly, chilled lava bases sit directly on the vesicular lava top of the underlying lava with nothing between. Sediments (usually thin sands, silts, and some ash) appear to be very localised and intermittent. In localities where sediment is present, it is typically thin (< 10 cm in thickness) in vent-proximal areas where new lavas frequently re-surfaced the previous flow field. Towards the margins of the province, where fewer lava fields reached, thicker accumulations of sediment can occur (up to 10-15 m; Schmincke, 1964; Smith, 1988; Jolley et al. 2008).

2.3 The Vantage Sandstone Member and the overlying Wanapum Basalt

The Vantage sediments consist of a number of facies spread across mainly the central and western part of the Columbia River province. Its depositional environment was due, in part, to the paleo-Columbia River drainage system and thus includes fluvial sediments, thin plant-rich layers, and lacustrine diatomite deposits. In the east of the province, where the rivers were not depositing, the Vantage sediments are dominated by weathering horizons (i.e. saprolite) developed upon lava, or this time horizon is represented by no sediment or soil at all. Elsewhere, the sediments include stratified sands and gravels, possible debris-flow deposits (Smith, 1988), some containing petrified wood concentrations, e.g., at Ginkgo Petrified Forest State Park (Orsen, 2003). Importantly, perhaps with the possible exception of those developed at the very eastern margins of the CRBG, the sediments of the Vantage Member do not necessarily represent a long period of sediment accumulation.

Overlying the Vantage sediments, the Wanapum Basalt consists of the fairly locally distributed Eckler Mountain lavas, confined to the central part of the province (Tolan et al., 1989), which are overlain in turn by the widely distributed Frenchman Springs, Roza and Priest Rapids Members. These lavas have been previously bracketed between 15.90 ±0.40 Ma, based on a ^{40}Ar/^{39}Ar age for Ginkgo lava near the base of the Frenchman Springs Member (Duncan, 1983, unpublished data), and 14.5 Ma (K-Ar) age for a Lolo lava sample at the top of the Priest Rapids Member (Tolan et al., 1989).

3. Sample selection and analytical techniques

Columbia River Basalt Group lavas are dominantly aphyric, with notable exceptions including the Imnaha Basalt lavas and many of the Wanapum and Saddle Mountains basalts. The aphyric nature of some of the CRBG lavas has hampered past efforts to obtain accurate, high precision Ar dates. Therefore, in order to identify the best material for dating purposes, an initial batch of samples were selected that consisted of (a) feldspar phenocryst separates, (b) fresh glassy whole-rock chips, (c) altered whole-rock chips, and (d) whole-rock chips from lava segregation features from within thick basalt cores (i.e., 'vesicle cylinders' developed during late-stage cooling; Goff, 1996; Hartley & Thordarson, 2009) in the hope of obtaining material with a higher K content (Table 2; Electronic Appendix 1).

Samples were ultrasonically cleaned using methanol and deionized water, wrapped in aluminum foil and irradiated at the McMaster Nuclear Reactor, Canada, together with biotite standard GA1550 (accepted age of 98.79 ±0.96 for FCT=28.02, Renne et al., 1998, recalculated to 99.43 Ma for FCT = 28.201 Ma) to monitor neutron flux. Laser stepped heating was undertaken using a focused CW Nd-YAG infra-red laser scanned over the surface of a single layer of material contained in an aluminium pan in the vacuum system. The released gases were cleaned by Zr-Al getters and Ar isotopes were measured in peak hopping mode on a MAP 215-50 noble gas mass spectrometer. Analytical procedures and corrections follow that of Wolfenden et al. (2005). All errors on step ages, total gas ages and plateau ages are quoted at the 2-sigma level. Final weighted mean ages were calculated using ISOPLOT-Ex after Ludwig (1999).

Samples for the initial experiment revealed the following results. (1) The large single feldspar crystals (up to 1 cm in size) found within the Imnaha, N_2 GRB lava and Roza lava from the Wanapum Basalt, did not give any meaningful geochronological data (e.g. ages of incremental steps from a multi-grain sample of feldspar crystals for Roza sample DF1-2 range between zero age and 8.00 ±2.50 Ma). On the basis of complex zoning patterns and internal disequilibrium features within single grains, and crystal sizes up to 1 cm in an otherwise near-hyalocrystalline matrix, we concur with Ramos et al. (2005) that these crystals appear to be disaggregated cognate crystals recording a complicated magmatic history. As such, it is not clear what effects such a history may have had on the crystals and their K-Ar content. It appears from our preliminary study, that in the units studied here, these crystals are less than reliable for Ar-dating and the data obtained has therefore been excluded from our results. (2) The fresh whole-rock matrix from the segregation features, which are more evolved than the host basalt, did not yield better age plateaus than the glassy matrix from the bulk lava. Most likely this was caused by alteration of the segregation features by higher volatile flux and fluid contents related to late-stage crystallisation, combined with their vesicular nature making them more susceptible to weathering. (3) Data with the lowest errors and lowest ^{36}Ar, suggesting little atmospheric Ar contamination, were obtained from small chips of matrix (including glass) that had been acid-leached prior to irradiation (Fig. 2).

---Insert Table 2---

---Insert Figure 2 –

---Electronic Appendix including plateau diagrams ---

On the basis of these findings further analyses were focussed upon whole-rock fresh matrix (plus glass) samples, rather than feldspar separates or segregation feature material. To address the question of eruptive history of the GRB lavas, we chose samples from the top of the Imnaha Basalt, GRB units R_1 through to N_2, and the base of the Wanapum Basalt (Table 2). Data for laser step-heating Ar experiments are given in Electronic Appendix 2, and a summary of the new dates are presented along with published data in Table 1.

4. Results

4.1 Imnaha Basalt

Four different lava samples were analysed from the Imnaha Basalt. Three of these (CJC-1, -3(1), and -5) were collected from the upper part of the sequence close to the contact with the GRB lavas at Joseph Creek (GR: 46° 01.58’N, 117° 01.30’W), near the confluence of Snake and Grande Ronde rivers. Due to ground water movement along the uppermost surface of the Imnaha Basalt, these topmost Imnaha samples have undergone feldspar seritization and alteration. We note that there is no evidence for erosion of the original lava top, which appears intact but weathered. Relatively large errors on the ages of some of these samples (e.g. 16.08 ±0.67 and 15.89 ±0.60 Ma, CJC-1 and –3(1), respectively; Fig. 3a

& c) are due to small sample size and/or limited number of steps and high atmospheric contents (see Electronic Appendix). Repeat analyses of CJC-1 from two separate irradiations give very similar ages (16.08 ±0.67 and 16.06 ±0.29 Ma; Fig. 3 a & b) and this confirms sample reproducibility despite very different Ca/K ratios for the two aliquots (2 and 11). The reproducible age of CJC-1 is in good agreement with CJC-5 (16.11 ±0.54 Ma; Fig. 3d), which was collected from directly under GRB sample CJC7 (see section below).

Sample MLC-2 was collected from near the top of the Imnaha Basalt sequence at Maloney Creek, Salmon River, Idaho (GR: 46° 2.7’N, 116° 36.6’W), and shows evidence of weathering. MLC-2 yielded two plateau ages of 15.29 ±0.22 Ma and 15.70 ±0.49 Ma (Fig. 3e & f), but the first analysis was less detailed than the repeat with only 5 steps analysed rather than 12 steps, respectively. Due to the increased number of steps to constrain the age plateau in the repeat sample, the second age is accepted as the better age estimate. However, it is important to note that ages for both these samples are within error of each other at the 2□ confidence level.

Insert Figure 3

4.2 Grande Ronde Basalt

Grande Ronde R_1 dike sample (CRB05-030) was collected from Green Gulch Road, Joseph Creek, near the Oregon-Washington border (GR: 46° 01.724’N, 117° 00.923’W) and yielded a plateau age of 15.53 ±0.20 Ma (Fig. 3g). The sample is from a R_1 dike that intrudes Imnaha Basalt. The release spectrum reveals that the plateau age is dominated by two large ^{39}Ar-release steps (Fig. 3g). A second aliquot of the same sample analysed at a higher resolution exhibits much lower radiogenic contents and yielded a decreasing staircase release pattern, with no plateau (Electronic Appendix). Although the initial age for this sample appears sound, we place less emphasis on it since we were not able to reproduce it.

Sample CJC-7, is from the Grande Ronde River-Snake River confluence, from the same location as CJC-5 (Imnaha Basalt). CJC-7 is a basal GRB lava sitting directly on top of Imnaha lava. Sample CJC-7 gave a plateau age of 16.25 ±0.27 Ma (Fig. 3h), within error of the uppermost sample of the underlying Imnaha Basalt.

Sample CRB05-033 of the R_2 group was collected from along the Weissenfels Ridge Road, south-east Washington State (GR: 46° 16.333’N 116° 59.696’W). A plateau age of 15.46 ±0.21 Ma (Fig. 3i) for this sample is in good agreement with the aforementioned R_1 sample, as R_2 lavas lie above R_1 lavas.

For the youngest of the GRB lavas, samples were collected from the uppermost N_2 Basalt of Museum, Sentinel Bluffs Member (Reidel 2005) from near Vantage, Washington (WH-1 samples; GR: 46° 58.24’N, 119° 58.13’W) and Frenchman Springs Coulee (CRB05-106; GR: 47° 01.70’N, 119° 59.65’W). Three ages were obtained from samples WH-1a (fresh whole rock matrix) and WH-1b (segregation matrix), run as part of the initial set-up experiment. The plateau age of 15.48 ±0.22 Ma from whole-rock sample WH-1a (Fig. 3j) is in agreement with those determined for the segregation material (15.71 ±0.26 and 15.55 ±0.32 Ma; Fig. 3k & l, respectively) and also shows correct stratigraphic-age relationship with the previous samples from R_1 and R_2. Sample CRB05-106 produced a plateau age of 15.94 ±0.20 Ma, much older than any of the other GRB dates and it does not fit with stratigraphic constraints (Fig. 3m). We do not have an obvious answer for this result but CRB05-106 is from Frenchman Springs Coulee and has abundant vesicular sheets and pipes present. Although the age plateau from this sample appears at first to be analytically good, we suspect that the K-Ar contents of the rock have been later disturbed.

Between the GRB and the extensive Frenchmans Springs Member of the Wanapum Basalt, there is the restricted Eckler Mountain Member lavas. Eckler Mountain basalts outcrop around the Blue Mountains of southeastern Washington, and sample CRB05-081 was collected from the Dodge lava at Burr Canyon on the Snake River (GR: 46° 30.451’N, 118° 36.969’W). The slightly altered, feldspar-rich Dodge sample gave a plateau age of 15.70 ±0.34 Ma (Fig. 3n), which is within error of the stratigraphically older GRB dates.

To constrain the timing of the Frenchmans Springs Member of the Wanapum Basalt, a sample was selected from the Basalt of Sand Hollow (middle part of the Frenchmans Springs Member). Sample PF7 (GR: 46° 40.094’N, 118° 13.512’W) was collected from a highly vesicular zone at the top of a thick Sand Hollow sheet lobe at Palouse Falls Park. It yielded a plateau age of 15.12 ±0.38 Ma (Fig. 3o), which is within error of a repeat analysis of the same sample (14.70 ±0.21 Ma; Fig. 3p).

5. Discussion

5.1 Duration of the Grande Ronde Basalt

On the basis of the new Ar data, we can assess individual ages for the top and bottom of the GRB lavas and calculate a period in which the GRB erupted. Furthermore, the interval in which the GRB volcanism occurred can be examined by its relationship with the Imnaha Basalt below and the Wanapum Basalt above.

A calculated weighted mean average age for all the previous data (with no exclusions) for the timing of the Imnaha Basalt is 16.61 ±0.28 Ma (MSWD=11.9; Fig. 4). [Weighted mean average ages are calculated using ISOPLOT and include standard error propagation]. The same calculation for our Imnaha Basalt, excluding the poor analysis of MLC-2 (Table 1; electronic online appendix), gives a result of 15.99 ±0.20 Ma (MSWD=0.5; Fig. 4). This latter date is outside of error of the weighted mean average age for all published data for Imnaha Basalt, but is our best estimate for the top of the lava pile. The wide scatter in published ages for the Imnaha Basalt (15.30 ±5.60 to 17.67 ±0.32 Ma; Fig. 4) may be the result of samples representing different parts of the Imnaha lava pile and possible diachroneity within the Imnaha Basalt, as a result of complex volcanic architecture such as overlapping lava lobes of differing ages, rather than a single horizon. In addition, the variation in the results may reflect variable degrees of sample alteration or excess argon in some samples. Regardless of such complexities, we suggest that Imnaha Basalt volcanism in southern Washington State - where GRB was subsequently emplaced - finished at around 16.00 Ma. In the absence of any evidence for a significant hiatus between the Imnaha Basalt and the GRB, it seems likely that the climactic GRB volcanism began shortly thereafter. No field-based evidence for interstratification of Imnaha and GRB lavas has yet been found.

A calculation of all published data (Table 1) for N_2 lavas at the top of the GRB succession reveals a weighted mean average age of 15.62 ±0.37 Ma (MSWD = 1.7; Fig. 4). The same calculation for our new data alone, excluding sample CRB05-106 for reasons given in the Results section, gives a date of 15.57 ±0.15 Ma (MSWD = 0.92; Fig. 4). Clearly, these results are well within error of each other and fit with data for the overlying Wanapum Basalt, e.g. Eckler Mountain Member (15.70 ±0.34 Ma) and basalt of Sand Hollow (15.12 ±0.38 Ma). Between the top of the GRB succession and the Wanapum Basalt are the Vantage sediments. It was once considered that the Vantage sediments were deposited in a 250, 000 year period, but it is likely that they formed in a much shorter interval, given constraints from the new argon data, the lack of any sediment in places, and the lack of evidence of erosion on the top surface of the GRB.

On the basis of this new evidence it would appear that the GRB lava succession started erupting shortly after 15.99 ±0.20 Ma and finished around 15.57 ±0.15 Ma. This suggests a total duration of 0.42 ±0.18 (1□) My, or approximately 420,000 years. Given uncertainties in the timing of the end of the Imnaha volcanism and that dates younger than 16 Ma are reported for the Imnaha (Table 1), the duration of the Grande Ronde volcanism could be considerably less than our estimate.

Insert Figure 4

The possibility that the 150,000 km^3, 1 to 3 km-thick, GRB succession was erupted over a duration time of around 420,000 years has precedence in CFB provinces elsewhere, and is by no means unusual. For example, in Greenland 5.3-6.3 ±2.7 km thickness of flood basalts (total volume unknown) associated with the opening of the Northeast Atlantic Ocean, are thought to have been emplaced in less than 300,000 years atop and synchronous with the Skaergaard intrusion (Larsen and Tegner, 2006). Similarly, Deccan lavas of ~ 800,000 km^3 and over 1 km thick can be constrained to have formed largely within the 833,000 year duration of paleomagnetic chron 29R (Chenet et al., 2008; 2009). The most voluminous part of these, the Wai Sub-group, appears to have formed in about half of that interval (Self et al., 2006).

5.2 Absolute age of the Grande Ronde Basalt

As described by Swanson et al. (1979), the GRB lava pile contains flows that have been demonstrated to have two normal and two reverse magnetizations (R_1-N_1-R_2-N_2). Two full cycles of polarity overturn within 420,000 years is more rapid than generally observed in the geomagnetic record, although similarly rapid overturns are recorded in detailed studies of the Oligocene/Miocene boundary (e.g., Billups et al., 2004).

Using the geomagnetic polarity timescale and Ar data for Steens Basalt and one Imnaha Basalt sample (Table 1), Jarboe et al. (2006) similarly suggest a rapid succession of eruption for these lava formations; they propose that the bulk of the Imnaha and GRB lavas erupted within a 0.75 My period. However, on the basis of Ar data and paleomagnetic results they suggest that the Steens Basalts erupted in geomagnetic chron C5Cr (Fig. 4; 17.235 to 16.721 Ma; Gradstein et al., 2004), and that Imnaha erupted within the chron C5Cn.3n (16.721 to 16.543 Ma; Gradstein et al., 2004). As a consequence of this and the geomagnetic timescale, Jarboe et al. (2008) neatly suggest that rapid reversals C5Cn.2r (16.543 to 16.472 Ma), C5Cn.2n (16.472 to 16.303 Ma), C5Cn.1r (16.303 to 16.268 Ma) and C5Cn.1n (16.268 to 15.974 Ma) are GRB R_1-N_1-R_2-N_2, respectively (Fig. 4). However, they do not have age data directly from the GRB succession to support this.

Chron C5Cn.3n ends at 16.543 Ma, and following Jarboe et al. would imply that Imnaha magmatism did not occur after this time. Yet there are many Ar dates suggesting younger ages than 16.50 Ma for Imnaha Basalt (Table 1; Fig. 4). Similarly with the GRB, chrons C5Cn.2r to C5Cn.1n are between approximately 16.50 and 16.00 Ma, yet almost all available Ar-age data for the GRB are younger than 16.00 Ma (Fig. 4). The spread of available age data for Steens Basalt, Imnaha Basalt and GRB make it difficult to be certain when a particular volcanic phase ended and suggests that activity may have even overlapped at times. However, the overriding evidence from all the available age data is that the GRB erupted after 16 Ma and therefore cannot be constrained to the C5Cn.2r to C5Cn.1n chrons, and that Imnaha Basalt eruption cannot be restricted to have occurred only in chron C5Cn.3n (Fig. 4). It is worth noting that very little paleomagnetic work has been carried out on Imnaha Basalt, and it may yet prove to be more complex than initially thought (V.E. Camp, pers. comm., 2010). The age data even suggest that Imnaha Basalt volcanism could have been occurring for sometime after GRB volcanism had begun. Potential evidence supporting the eruption of highly voluminous lavas such as Imnaha Basalt and GRB at around 16.0 Ma and 15.5 Ma, respectively, are dissolution events recorded in sediments off the coast of Africa. These dissolution events are thought to record climatic disturbances caused by changes in the oxygen and carbon dioxide composition of the atmosphere and would fit well with voluminous basaltic eruptions (Kender et al., 2009). In summary, with the lack of knowledge of the detailed stratigraphy and paleomagnetic signatures of the Imnaha lavas, it is unwise to speculate further on the exact absolute age of the GRB lava succession from their relationship with Imnaha Basalts.

Our age data, along with other published information suggest that GRB lavas most likely erupted within the younger geomagnetic chron C5Br (15.974 to 15.160 Ma; Gradstein et al., 2004; Fig. 4). We recognise that this poses a problem for the significance of the reversals within the GRB; there appears to be a lack of rapid magnetic reversals during C5Br (e.g. Gradstein et al., 2004). We have no solution to this dilemma at present, and can only suggest that either (a) the reversals measured in the GRB are short excursions within the geomagnetic cycle, or b) that rapid reversals C5Cn.2r to C5Cn.1n should be younger than 16 Ma. In support of younger geomagnetic chrons for Imnaha and GRB lavas than suggested by Jarboe et al. (2008) are $^{40}Ar/^{39}Ar$ dates for Steens Basalts that are younger than 16.60 Ma (Fig. 4).

5.3 Average estimates of eruption frequency

The stratigraphy of the 150,000 km^3 GRB lavas has been well constrained and mapped in previous studies (e.g. Reidel et al., 1989). The GRB lavas built up from at least 110 individual eruptions, which over a 420,000 year time span, suggests an average periodicity of one eruption every ~4200 years. Assuming an eruption duration of 10 to 100 years per eruption, that would add up to between 1100 and 11,000 years total eruption time, within the 420,000 year time span. This would suggest that the total amount of time that the system was actively erupting, was no more than 2.6% of the total duration time of formation of the GRB, and quite probably much less than 1% of the time.

In more detail, the individual GRB eruptions have estimated eruption volumes between 90 and as much as 10,000 km^3 (Reidel et al., 1989) – the larger estimates rival the outputs of even the greatest volume explosive rhyolitic super-eruption deposits such as at Yellowstone (c. 2500 km^3; Mason et al., 2004). In reality, the eruptions would most likely have been irregularly distributed through time, possibly in pulses with some eruptions following another after a few 1000 years, while others may have erupted after, possibly, up to 10,000 years of quiescence. With eruptions lasting decades to perhaps centuries, the chances of distinguishing a hiatus that is intra-eruption versus inter-eruption becomes very difficult. Approaches that may be able to contribute to resolving that type of detail may be studies of weathering horizons and palynology of spores between lavas (e.g., Sheldon, 2003; Jolley et al., 2008).

6. Conclusions

New $^{40}Ar/^{39}Ar$ data provide constraints for the duration of time in which the Grande Ronde Basalt, the climactic phase of the Columbia River Basalt Province, erupted. The Grande Ronde Basalt is bracketed by an age of 15.99 ±0.20 Ma for the top of the underlying Imnaha Basalt and by an age of 15.57 ±0.15 Ma for the end of Grande Ronde Basalt volcanism. A duration of approximately 420,000 years implies that, on average, there may have been an eruption every 4000 years. Based on published estimates for single eruption durations, we find that within a 420,000 year period less than 2.6%, and quite possibly less than 1% of that time, would have been volcanically active. A review of all the available $^{40}Ar/^{39}Ar$ data for the Steens Basalt-Imnaha Basalt-GRB suggests that activity of these petrochemically distinct groups may have, at times, been simultaneous, and if confirmed would have significant implications for potential environmental effects.

References

Baksi, A.K., 1989. Reevaluation of the timing and duration of extrusion of the Imnaha, Picture Gorge, and Grande Ronde Basalts, Columbia River basalt group. In: Reidel, S.P., and Hooper, P.R., eds: Geological Society of America Special Paper 239, 105-112.

Baksi, A.K. and Farrar, E., 1990. Evidence for errors in the geomagnetic polarity time-scale at 17-15 Ma: $^{40}Ar/^{39}Ar$ dating of basalt from the Pacific northwest, USA. Geophysical Research Letters 17, 1117-1120.

Baksi, A.K., Hall, C.H., York, D., 1991. Laser probe $^{40}Ar/^{39}Ar$ dating studies on sub-milligram whole-rock basalt samples: the age of the Steens Mountain geomagnetic polarity transition (revisited). Earth and Planetary Science Letters 104, 292-298.

Billups, K., Pälike, H., Channell, J.E.T., Zachos, J.C., Shackleton, N.J., 2004. Astronomic calibration of the late Oligocene through early Miocene geomagnetic polarity time scale. Earth and Planetary Science Letters 224, 33-44.

Brueseke, M.E., Heizler, M.T., Mertzman, S.A., 2007. Distribution and geochronology of Oregon Plateau (USA) flood basalt volcanism: The Steens Basalt revisited. Journal of Volcanology and Geothermal Research 161, 187-214.

Camp, V.E. and Ross, M.E., 2004. Mantle dynamics and genesis of mafic magmatism in the intermontane Pacific northwest. Journal of Geophysical Research 109, B08204, doi:10.1029/2003JB002838.

Camp, V. E., Ross, M.E., Hanson, W.E., 2003. Genesis of flood basalts and basin and range volcanic rocks from Steens mountain to the Malheur River Gorge, Oregon. The Geological Society of America Bulletin 115 (1), 105-128.

Courtillot, V., Jaupart, C., Manighetti, I., Tapponnier, P., Besse, J., 1999. On causal links between flood basalts and continental break-up. Earth and Planetary Science Letters 166, 177-195.

Courtillot, V., Davaille, A., Besse J., Stock., J., 2003. Three distinct types of hotspots in the Earth's mantle. Earth and Planetary Science Letters 205, 295-308.

Courtillot, V.E., Renne, P.R., 2003. On the ages of flood basalt events. C.R.Geoscience 335, 113-140.

Duncan, R.A., Pyle, D.G., 1988. Rapid eruption of the Deccan flood basalts at the Cretaceous/Tertiary boundary. Nature 333, 841-843.

Eldholm and Coffin, M., 2000. Large igneous provinces and plate tectonics. Geophysical Monograph 121, The History and Dynamics of Global Plate Motions 309-326.

Gradstein, F., Ogg, J., Smith, A., 2004. A geologic time scale. 589 pp., Cambridge University Press, Cambridge, UK.

Goff, F., 1996. Vesicle cylinders in vapor-differentiated basalt flows. Journal of Volcanology and Geothermal Research 71, 167-185.

Hartley, M.R. and Thordarson, T, 2009. Melt segregations in a Columbia River Basalt lava flow: a possible mechanism for the formation of highly evolved mafic magmas. Lithos 112, 434-446.

Henry, C. D., Castor, S. B., McIntosh, W. C., Heizler, M. T., Cuney, M., Chemillac, R., 2006. Timing of oldest Steens Basalt magmatism from precise dating of silicic volcanic rocks, McDermitt Caldera and Northwest Nevada volcanic field. Eos Transactions American Geophysical Union 87(52), Fall Meet. Suppl., Abstract V44C-08.

Hooper, P.R., 1984. Physical and chemical constraints on the evolution of the Columbia River basalt. Geology 12, 495-499.

Hooper, P.R., Binger, G.B., Lees, K.R., 2002. Ages of the Steens and Columbia River flood basalts and their relationship to extension-related calc-alkalic volcanism in eastern Oregon. Geological Society of America Bulletin 114, 43-50.

Jarboe, N.A., Coe, R.S., Renne, P.R., Glen, J.M., 2006. ^{40}Ar/^{39}Ar ages of the early Columbia River Basalt Group: determining the Steens Mountain geomagnetic polarity reversal (R_0-N_0) as the top of the C5Cr chron and the Imnaha normal (N_0) as the C5Cn.3n chro.. EOS Transactions, American Geophysical Union 87(52), Fall meeting supplement, Abstract V51D – 1702.

Jarboe, N.A., Coe, R.S., Renne, P.R., Glen, J.M.G., Mankinen,, E.A., 2008. Quickly erupted volcanic sections of the Steens Basalt, Columbia River Basalt Group: secular variation, tectonic rotation, and the Steens Mountain reversal. Geochemistry Geophysics Geosystems 9 (11), Q11010, doi:10.1029/2008GC002067.

Jolley, D.W., Widdowson, M., Self, S., 2008. Volcanogenic nutrient fluxes and plant ecosystems in large igneous provinces: an example from the Columbia River Basalt Group. Journal of the Geological Society, London 165, 955-966.

Kender, S., Peck, V.L., Jones, R.W., Kaminski, M.A., 2009. Middle Miocene oxygen minimum zone expansion offshore West Africa: evidence of global cooling precursor events. Geology 37, 699-702.

Kuiper, K. F., Deino, A., Hilgen, F.J., Krijgsman, W., Renne, P.R., Wijbrans, J.R., 2008. Synchronizing rock clocks of Earth history. Science 320, 500-504.

Larsen, R.B., Tegner, C., 2006. Pressure conditions for the solidification of the Skaergaard intrusion: eruption of East Greenland flood basalts in less than 300,000 years. Lithos 92, 181-197.

Long, P.E., Duncan, R.A., 1983. ^{40}Ar/^{39}Ar ages of the Columbia River Basalt from deep boreholes in south-central Washington [abs], EOS Transactions American Geophysical Union 64, 90.

Ludwig, K.R., 2003. Isoplot 3.13: a geochronological toolkit for Microsoft Excel. Special Publication 4, Berkeley Geochronology Centre, Berkeley, California.

Mason, B.G., Pyle, D.M., Oppenheimer, C., 2004. The size and frequency of the largest explosive eruptions on Earth. Bulletin of Volcanology 66, 735-748, doi: 10.1007/s00445-004-0355-9.

McKee, E.H., Swanson, D.A., Wright, T.L., 1977. Duration and volume of Columbia River basalt volcanism, Washington, Oregon, and Idaho. Geological Society of America Abstracts with Programs 9, 463.

McKee, E.H., Hooper, P.R., Kleck, W.D., 1981. Age of Imnaha Basalt – oldest basalt flows of the Columbia River Basalt Group, northwest United States. Isochron/West 31, 31-33.

Min K., Mundil, R., Renne, P.R., Ludwig, K.R., 2000. A test for systematic errors in ^{40}Ar/^{39}Ar geochronology through comparison with U-Pb analysis of a 1.1 Ga rhyolite. Geochimica et Cosmochimica Acta 64, 73–98.

Orsen, M.J., 2003. Biostratigraphy of Columbia River Basalt Group petrified forests. GSA Abstracts with Programs 35, 551.

Petcovic, H.L., and Dufek, J.D., 2005. Modeling magma flow and cooling in dikes: implications for the emplacement of Columbia River flood basalts. Journal of Geophysical Research 110, B10201, doi:10.1029/2004JB003432.

Ramos, F.C., Wolff, J.A., Tollstrup, D.L., 2005. Sr isotope disequilibrium in Columbia River flood basalts: evidence for rapid shallow-level open-system processes. Geology 33, 457-460.

Reidel, S.P., Tolan, T.L., Hooper, P.R., Beeson, M.H., Fecht, K.R., Bentley, R.D., Anderson, J.L., 1989. The Grande Ronde Basalt, Columbia River Basalt Group; stratigraphic descriptions and correlations in Washington, Oregon, and Idaho. Geological Society of America Special Paper 239, 21-53.

Reidel, S.P., 2005. A lava flow without a source: the Cohassett Flow and its compositional components, Sentinel Bluffs Member, Columbia River Basalt Group. Journal of Geology 113, 1-21.

Renne, P.R., Swisher, C.C., Deino, A.L., Karner, D., Owens, B.T.L., DePaolo, D.J., 1998. Intercalibration of standards, absolute ages and uncertainties in ^{40}Ar/^{39}Ar dating. Chemical Geology 145, 117-152, doi:10.1016/S0009-2541(97) 00159-9.

Schmincke, H. –U., 1964. Petrology, paleocurrents, and stratigraphy of the Ellensburg Formation and interbedded Yakima Basalt flows, south-central Washington. PhD dissertation, John Hopkins University, Baltimore, 426 pp.

Self, S., Widdowson, M., Thordarson, T., Jay, A.E., 2006. Volatile fluxes during flood basalt eruptions and potential effects on the global environment: a Deccan perspective. Earth and Planetary Science Letters 248, 517-531.

Sheldon, N., 2003. Pedogenesis and geochemical alteration of the Picture Gorge sub-group, Columbia River basalt, Oregon. Geological Society of America Bulletin 115, 1377-1387.

Smith, G.A., 1988. Sedimentology of proximal to distal volcaniclastics dispersed across an active foldbelt: Ellensburg Formation (late Miocene), central Washington. Sedimentology 35, 953-977.

Snavely, P.D., Jr., MacLeod, N.S., Wagner, H.C., 1973. Miocene tholeiitic basalts of coastal Oregon and Washington and their relations to coeval basalts of the Columbia Plateau. Geological Society of America Bulletin 84, 387-424.

Swanson, D.A., Wright, T.L., Hooper, P.R., Bentley, R.D., 1979. Revisions in stratigraphic nomenclature of the Columbia River Basalt Group. U.S. Geological Survey Bulletin 1457-G, 59 pp.

Swisher, C.C., Ach, J.A., Hart, W.K., 1990. Laser fusion ^{40}Ar/^{39}Ar dating of the type Steens Mountain Basalt, southeastern Oregon and the age of the Steens geomagnetic polarity transition. EOS Transactions American Geophysical Union 71, 1296.

Thordarson, T., Self, S., 1996. Sulfur, chlorine and fluorine degassing and atmospheric loading by the Roza eruption, Columbia River Basalt Group, Washington, USA. Journal of Volcanology and Geothermal Research 74, 49-73.

Thordarson, T., Self, S., 1998. The Roza Member, Columbia River Basalt Group: a gigantic pahoehoe lava flow field formed by endogenous processes? Journal of Geophysical Research 103, 27411-27445.

Thordarson, T., Self, S., 2003. Atmospheric and environmental effects of the AD1783-84 Laki eruption: a review and reassessment. Journal of Geophysical Research (Atmospheres) 108, doi:1029/2001JD002042.

Thordarson, T., Self, S., Miller, D.J., Larsen, G., Vilmundardottir, E.G., 2003. Sulphur release from flood lava eruptions in Veidivötn, Grímsvötn and Katla volcanic systems, Iceland. In: Oppenheimer, C., Pyle, D.M. and Barclay, J. (eds), Volcanic Degassing. Geological Society Special Publication 213, 103-121.

Tolan, T.L., Reidel, S.P., Beeson, M.H., Anderson, J.L., Fecht, K.R., Swanson, D.A., 1989. Revisions to the estimates of the areal extent and volume of the Columbia River Basalt Group. In: Reidel, S.P. and Hooper, P.R., (eds), Volcanism and tectonism in the Columbia River flood-basalt province, Geological Society of America Special Paper 239, 1-20.

Watkins, N.D., Baksi, A.K., 1974. Magnetostratigraphy and oroclinal folding of the Columbia River, Steens, and Owyhee Basalts in Oregon, Washington, and Idaho. American Journal of Science 274, 148-189.

Wignall, P. B., 2001. Large igneous provinces and mass extinctions. Earth-Science Reviews 53, 1-33.

Wolfenden, E., Ebinger, C., Yirgu, G., Renne, P.R., Kelley, S.P., 2005. Evolution of a volcanic rifted margin: Southern Red Sea, Ethiopia. Geological Society of America Bulletin 117, 846-864.

Table captions

Table 1. Summary of published and new age determinations for the Imnaha Basalt, GRB and the base of the Wanapum Basalt. All new data and published data are reported with 2□ errors. Formations are presented in stratigraphic order, with the oldest at the base. Directly underlying Imnaha Basalt is the Steens Basalt, and directly overlying the Wanapum Basalt is Saddle Mountains Basalt (not shown). Bracketed letters (A) to (H) refer to reference sources: (A) previously unpublished data; details available from S. Reidel; (B) Long and Duncan (1983); (C) Baksi and Farrar (1990); (D) Hooper et al. (2002); (E) Jarboe et al. (2006); (F) Watkins and Baksi (1974); (G) Snavely et al. (1973); and (H) McKee et al. (1977). All previously published data has been corrected to a Fish Canyon Tuff accepted age of 28.201 Ma (Kuiper et al., 2008) and therefore will appear differently from published text. $^{\#}$ indicates samples that are from Malheur Gorge succession, eastern Oregon – Birch Creek Member and Upper Pole Creek Member are lateral equivalent of GR Basalt – R_1 and Imnaha Basalt, respectively (Hooper et al., 2002). Data for other newly analysed samples that did not produce a plateau age are given along with the full data set in an online Electronic Appendix. Abbreviations for material is: gl = glassy; wr = wholerock; alt = altered; seg.ves. = segregation vesicle.

Table 2. Sample numbers and type of material used in initial experiment for testing suitability of datable materials. Analysis results in Electronic Appendix.

Figure captions

Figure 1. Geographic extent of the Grande Ronde Basalt (stippled field) within the wider limits of the whole Columbia River Basalt Group (including Steens Basalts), western USA. Sample location sites are: Vantage (V), Frenchmans Spring Coulee (FC), Wildhorse Monument (WM), Burr Canyon (BC), Palouse Falls Park (PF), Weissenfels Ridge (WR), Joseph Creek (JC), Maloney Creek (MC). Inset map: location of detailed map and the GRB within the USA.

Figure 2. Photomicrograph of a GRB sample showing the glassy matrix (cross polarised light). Scale bar shown.

Figure 3. ^{40}Ar/^{39}Ar plateau age diagrams for dated units from Imnaha Basalt [a – CJC-1; b – CJC-1(rpt); c – CJC-3(1); d – CJC-5; e – MLC-2; f – MLC-2(rpt)], Grande Ronde Basalt [g – R_1 CRB05-030; h – R_1 CJC-7; i – R_2 CRB05-033; j – N_2 WH1a-1; k – N_2 WH1b-1; l – N_2 WH1b-2; m – N_2 CRB05-106] and Wanapum Basalt [n – Eckler Moutain Formation CRB05-081; o – Basalt of Sand

Hollow PF7; p – Basalt of Sand Hollow PF7(rpt)]. Step errors are 2σ. Black boxes are steps included within the plateau, whereas white boxes are those not included in the plateau calculation. MSWD = mean standard weighted deviation. Data for samples that did not produce a plateau age are given along with the full data set in an online Electronic Appendix.

Figure 4. A comparison of available $^{40}Ar/^{39}Ar$ data for Grande Ronde Basalt, and Imnaha and Steens Basalt, plotted against geomagnetic polarity timescale. All $^{40}Ar/^{39}Ar$ errors are plotted here as 1σ, rather than the usual 2σ used throughout the text, to aid clarity of the figure. Data from this study are plotted as solid black squares. Published data are plotted as solid white squares. * refers to silicic units that are interpreted to overlie or interfinger with Steens Basalt. Reference abbreviations: A-E are the same as for Table 1; plus additional data from (F) Henry et al., 2006; (G) Jarboe et al., 2008; (H) Brueseke et al., 2007; (I) Swisher et al., 1990; (J) Baksi et al., 1991. Geomagnetic timescale from Gradstein et al. (2004). For the GRB-N_2 data and for Imnaha Basalt, the weighted mean average age of our data is shown as a heavy dashed line with 1σ errors shown as the upper and lower limits of the light grey box (refer to text for full description). Similar calculations for published data are shown by the dotted line within the dark grey box.

FORMATION **Member**	**Previous K/Ar ages (Ma)**	**Previous $^{40}Ar/^{39}Ar$ ages (Ma)**	**This study: sample number**	**Material analysed**	**Steps on plateau/ Total no. of steps**	**MSWD**	**This study: $^{40}Ar/^{39}Ar$ ages (Ma)**
WANAPUM							
Frenchman Springs							
Basalt of Sand Hollow			PF7	gl matrix	7/7	1.40	14.70 ±0.21
			PF7 (rpt)	gl matrix	6/6	1.50	15.12 ±0.38
Eckler Mountain			CRB05-081	gl matrix	9/16	0.33	15.70 ±0.34
Vantage sediments							
GRANDE							
RONDE	15.0 ±0.4 (F)	15.05 ±0.60 (A)	WH1a-1	gl matrix	6/8	1.80	15.48 ±0.22
N_2 group	16.0 ±1.4	15.36 ±0.60 (A)	WH1b-2	alt.	6/6	0.95	15.55 ±0.32
7 - 10	(G)	15.56 ±0.40 (A)	WH1b-1	matrix	6/8	1.80	15.71 ±0.26
members		15.79 ±0.40 (B)		seg. ves			
		15.87 ±0.40 (A)	CRB05-106	matrix	11/14	0.85	15.94 ±0.20
				alt.			
				matrix			
R_2 group	15.8 ±0.6 (F)	14.95 ±0.60 (A)	CRB05-033	gl matrix	6/9	1.20	15.46 ±0.21
4 - 5 members		16.07 ±0.28 (C)					
		16.32 ±0.20 (C)					
N_1 group	15.7 ±0.6 (F)						
2 - 3 members	15.9 ±0.6 (F)						
R_1 group		$^{\#}$14.49 ±0.80 (D)	CRB05-030	gl matrix	2/8	0.62	15.53 ±0.20
4 - 5 members		$^{\#}$15.20 ±0.60 (D)	CJC-7	gl matrix	11/13	1.05	16.25 ±0.27
($^{\#}$ Birch		$^{\#}$16.00 ±0.20 (D)					
Creek)		16.41 ±0.22 (C)					
IMNAHA	15.7 ±0.6 (F)	$^{\#}$ 15.30 ±5.60 (D)	MLC-2	wr matrix	3/5	1.90	15.29 ±0.22
($^{\#}$ Upper Pole	17.2 ±0.4	15.50 ±0.40 (D)	MLC-2	wr matrix	8/12	0.47	15.70 ±0.49
Creek)	(H)	15.60 ±0.60 (D)	(rpt)	wr matrix	6/9	0.76	15.89 ±0.60
		$^{\#}$ 15.60 ±1.20 (D)	CJC-3(1)	wr matrix	3/8	2.00	16.08 ±0.67
		16.53 ±0.09 (E)	CJC-1	wr matrix	10/14	0.63	16.06 ±0.29
		16.73 ±0.14 (E)	CJC-1 (rpt)	wr matrix	4/10	0.18	16.11 ±0.54
		$^{\#}$ 16.70 ±1.60 (D)	CJC-5				
		$^{\#}$ 16.90 ±0.60 (D)					
		17.60 ±0.60 (A)					

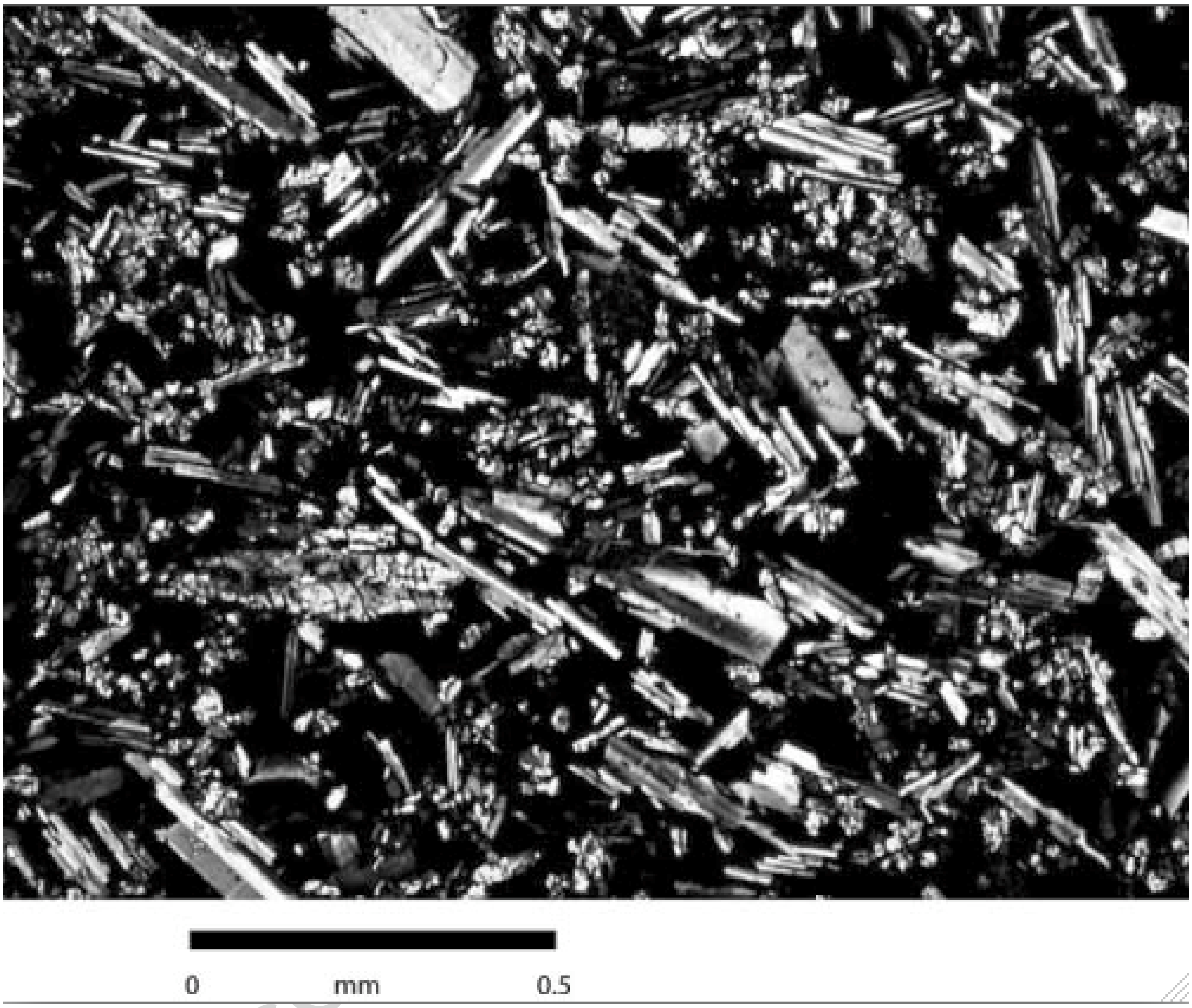
17.67 ±0.32 (C)	

Table 1

Lava Unit Material	*Imnaha*	*Grande Ronde (N_2)*	*Upper part of Wanapum Basalts*
Feldspar separate	CJC3-2	-	DF1-2 and DF3-2 (the latter from a vesicle cylinder)
Fresh wholerock matrix (glassy)	CJC3-1	WH1-a	DF1-1
Altered wholerock matrix	-	WH1b-2 (from segregation vesicle)	-
Freshest possible matrix from vesicle cylinders	-	WH1b-1	DF3-1

Table 2


Canada
Washington
Montana
Areal Extent
of CRBG
FC
V
WM
BC
PF
WR
JC
MC
Idaho
Oregon
0
50
Kilometers
Map Area
Steens and
Imnaha Basalt


0
mm
0.5

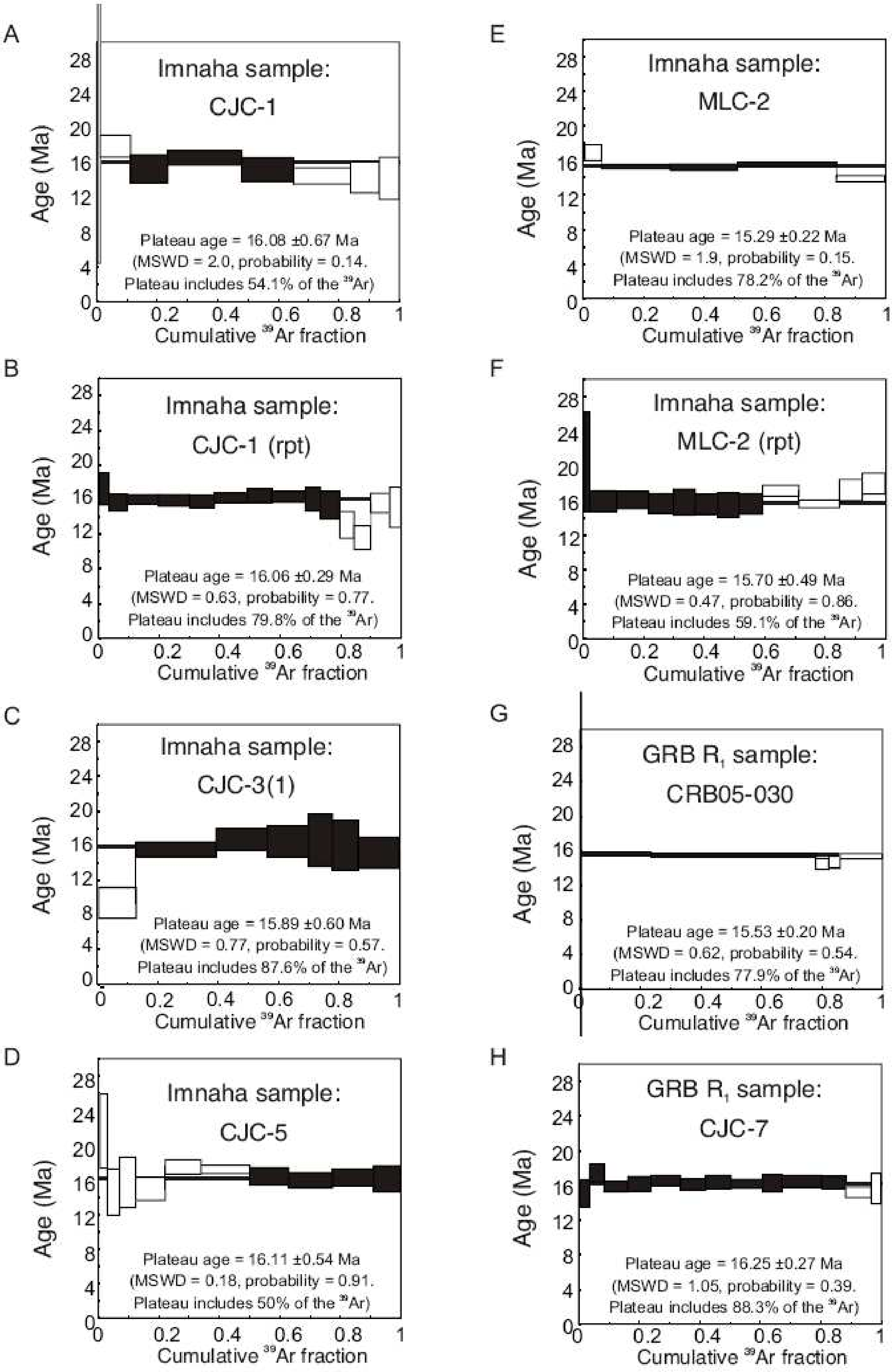

A
Imnaha sample:
CJC-1
Plateau age = 16.08 ±0.67 Ma
(MSWD = 2.0, probability = 0.14.
Plateau includes 54.1% of the 39Ar)
E
Imnaha sample:
MLC-2
Plateau age = 15.29 ±0.22 Ma
(MSWD = 1.9, probability = 0.15.
Plateau includes 78.2% of the 39Ar)
B
Imnaha sample:
CJC-1 (rpt)
Plateau age = 16.06 ±0.29 Ma
(MSWD = 0.63, probability = 0.77.
Plateau includes 79.8% of the 39Ar)
F
Imnaha sample:
MLC-2 (rpt)
Plateau age = 15.70 ±0.49 Ma
(MSWD = 0.47, probability = 0.86.
Plateau includes 59.1% of the 39Ar)
C
Imnaha sample:
CJC-3(1)
Plateau age = 15.89 ±0.60 Ma
(MSWD = 0.77, probability = 0.57.
Plateau includes 87.6% of the 39Ar)
G
GRB R1 sample:
CRB05-030
Plateau age = 15.53 ±0.20 Ma
(MSWD = 0.62, probability = 0.54.
Plateau includes 77.9% of the 39Ar)
D
Imnaha sample:
CJC-5
Plateau age = 16.11 ±0.54 Ma
(MSWD = 0.18, probability = 0.91.
Plateau includes 50% of the 39Ar)
H
GRB R1 sample:
CJC-7
Plateau age = 16.25 ±0.27 Ma
(MSWD = 1.05, probability = 0.39.
Plateau includes 88.3% of the 39Ar)
Age (Ma)
0
4
8
12
16
20
24
28
Cumulative 39Ar fraction
0
0.2
0.4
0.6
0.8
1

Figure 3

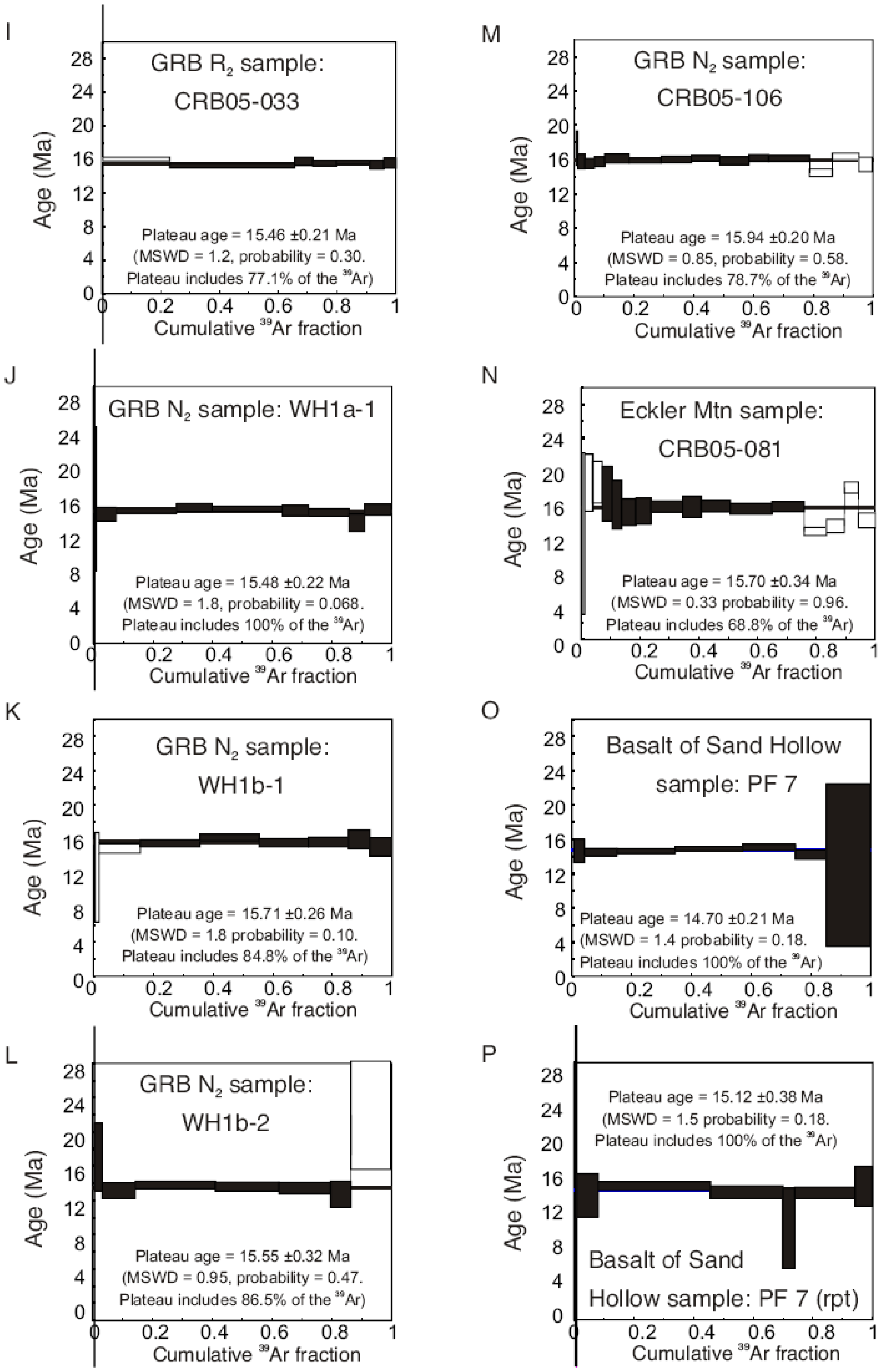


Figure 3 cont.

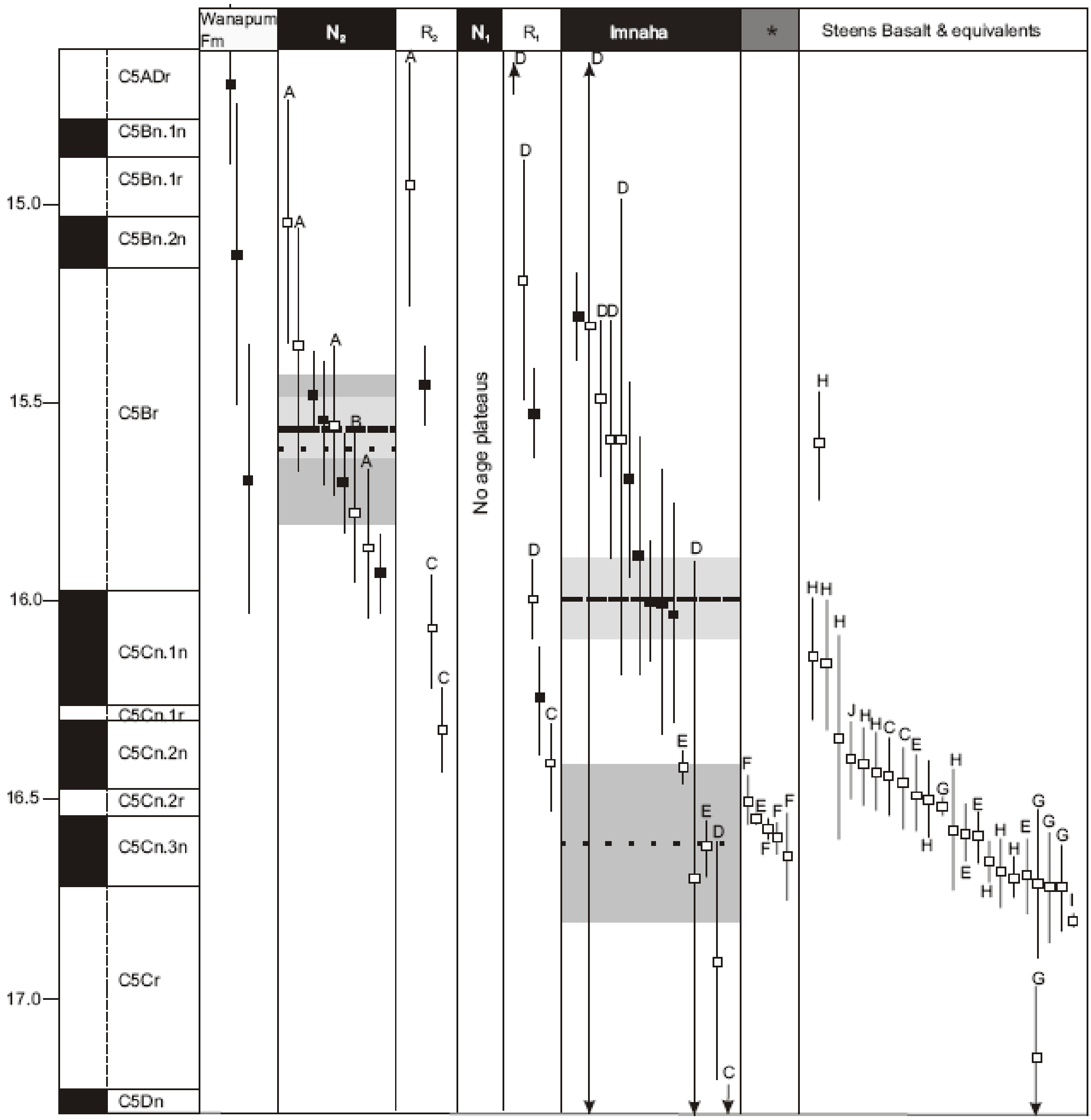

Wanapum Fm
N2
R2
N1
R1
Imnaha
*
Steens Basalt & equivalents
C5ADr
C5Bn.1n
C5Bn.1r
C5Bn.2n
C5Br
C5Cn.1n
C5Cn.1r
C5Cn.2n
C5Cn.2r
C5Cn.3n
C5Cr
C5Dn
15.0
15.5
16.0
16.5
17.0
No age plateaus
A
B
C
D
E
F
G
H
I
J

Figure 4