Discussion and reply: Ages of the Steens and Columbia River flood basalts and their relationship to extension related calc-alkalic volcanism in eastern Oregon

Discussion

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Hooper et al. (2002) present stratigraphic, chemical, and field relationships for Tertiary volcanic rocks of eastern Oregon and conclude that (1) the Imnaha Basalt are ~15.5 m.y. old and (2) the Steens Basalt (ca. 16.6 Ma) represents the earliest eruptions of the Columbia River Basalt flood-basalt province. Critical scrutiny of published geochronological data (Baksi, 1989; Baksi and Farrar, 1990) indicates the Imnaha Basalt ca. 17.5 Ma is older than the Steens Basalt and the latter is equivalent in age to lower sections of the Grande Ronde Basalt. Herein, $^{40}Ar/^{39}Ar$ ages are reported relative to the calibrations of Renne et al. (1998) and all errors are quoted at the 1σ level. I shall refer to the magnetostratigraphic units seen in the Columbia River Basalt; the main sections, consisting of the Imnaha Basalt and the Grande Ronde Basalt, were formed in five magnetic chrons. Magnetostratigraphic units are, in order of decreasing age, N_0 for the Imnaha Basalt, and R_1, N_1, R_2, and N_2 for the Grande Ronde Basalt (Reidel et al., 1989; Tolan et al., 1989).

For the Imnaha Basalt, Hooper et al. (2002) list $^{40}Ar/^{39}Ar$ ages of 15.4 ± 0.2 and 15.5 ± 0.2 Ma; no details are available as to whether these are plateau or total fusion ages. The Imnaha Basalt is considerably older than ca. 15.5 Ma. $^{40}Ar/^{39}Ar$ incremental heating results (Baksi and Farrar, 1990) yield an age of 17.5 ± 0.3 Ma. One of the authors whose work is discussed herein (P.R. Hooper) previously quoted an unpublished $^{40}Ar/^{39}Ar$ age of 17.5 ± 0.3 Ma for the Imnaha Basalt (Reidel et al., 1989, p. 25). Hooper et al.'s (2002) new $^{40}Ar/^{39}Ar$ ages (ca. 15.5 Ma) are in agreement with K-Ar results obtained thirty years ago (Baksi and Watkins, 1973). These latter dates are known to be ~10% too young (Baksi, 1989) based on evaluation of their alteration state. K-Ar dating of young (<10 Ma) whole-rock basalts generally leads to ages that are 5%–7% younger than $^{40}Ar/^{39}Ar$ plateau ages (Baksi et al., 1993; Baksi, 1995). Minor alteration, undetectable on thin section examination, leads to ~5%–7% loss of $^{40}Ar^*$, lowering K-Ar dates an equivalent amount (Baksi, 1995). Hooper et al. (2002) reject McKee et al.'s (1981) K-Ar date of 17.2 ± 0.2 Ma for the Imnaha Basalt. This work involved crushed material that had been treated with dilute hydrofluoric acid, a procedure that is not recommended for whole-rock basalts (Dalrymple and Lanphere, 1969). However, there is no evidence that this technique produces dates that are too old. In the case of the McKee et al. (1981) work, if an age of ca. 15.5 Ma is correct, ~10% loss of K would have had to occur with no concomitant loss of $^{40}Ar^*$—an unlikely scenario. This author's unpublished data show that K-Ar work on HF-treated Tertiary whole-rock basalts generally results in dates that are too young.

Steens Basalt, collected from the type section on Steens Mountain, gives $^{40}Ar/^{39}Ar$ ages of 16.5–16.6 Ma. This is based on incremental heating studies on whole-rock material (Baksi and Farrar, 1990) and total fusion analysis of plagioclase separates (Swisher et al., 1990). This section shows a geomagnetic polarity transition from reversed to normal polarity (Watkins, 1965). Baksi and Farrar (1990) suggested that this is equivalent to the R_1 to N_1 transition seen in the Grande Ronde Basalt. The Imnaha Basalt was formed during an older normal (magnetic) chron.

Hooper et al. (2002) state that the Grande Ronde Basalt is between 16 and 15 Ma, quoting ages from an internal report (Long and Duncan, 1982). A copy of the detailed results was obtained from Robert Duncan. Critical scrutiny shows that none of the ages cited for the Grande Ronde Basalt meets the statistical requirements of plateau and/or isochron ages (cf. Baksi, 1999). Recent $^{40}Ar/^{39}Ar$ ages for the Grande Ronde Basalt are said to fall in the range of 16.1 to 15.5 Ma (Hooper et al., 2002). Sections of the Grande Ronde Basalt appear to be considerably older than this. A flow from the bottom of the N_1 magnetostratigraphic horizon gave a $^{40}Ar/^{39}Ar$ plateau age of 16.5 ± 0.1 Ma (Baksi and Farrar, 1990). Since the R_1 magnetostratigraphic unit lies below this horizon, extrusion of the Grande Ronde Basalt commenced ca. 17.0 Ma. The older Imnaha Basalt must then be >17 Ma in age. Hooper et al. (2002) appear to suggest that the Imnaha Basalt (ca. 15.5 Ma) is younger than their oldest Grande Ronde Basalt (ca. 16.1 Ma). This contradicts field evidence that shows that the Grande Ronde Basalt overlies the Imnaha Basalt (McKee et al., 1981; Reidel et al., 1989; Tolan et al., 1989).

I conclude by noting that $^{40}Ar/^{39}Ar$ ages on whole-rock material that meet all the statistical requirements of a plateau value (Baksi, 1999, 2002) may yield values younger than the crystallization age. Thus, Sutter and Smith (1979) reported plateau ages of 175 and 189 Ma on the Gettysburg Sill, northeastern United States, whereas the correct age is 201 Ma (Dunning and Hodych, 1990; Baksi, 2002). The alteration state of samples must be evaluated by monitoring the atmospheric argon content of the gas released in $^{40}Ar/^{39}Ar$ incremental heating studies. If these are relatively high, the sites from which the $^{40}Ar^*$ is derived show considerable alteration and yield incor-

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rect low step ages (Baksi, 1999, 2002). Numerous $^{40}Ar/^{39}Ar$ analyses on the Imnaha Basalt appear to reflect this situation. The $^{40}Ar/^{39}Ar$ ages of ca. 15.5–15.7 Ma (Hooper et al., 2002) and K-Ar dates on altered whole-rock material (Baksi and Watkins, 1973) are ~10% younger than the crystallization value.

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Reply

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Baksi questions the ages of the various units presented in Hooper et al. (2002) and reiterates his belief that Imnaha basalt flows on the main Columbia Plateau are older than the Steens Basalt. In particular he questions two new $^{40}Ar/^{39}Ar$ ages of Imnaha basalt flows from R.A. Duncan's laboratory at Oregon State University that are based on multiple step plateaus comprising >50% of gas released, concordant with isochron ages. In support of this position he quotes his own $^{40}Ar/^{39}Ar$ ages (Baksi and Farmer, 1990). In part this is a disagreement between specialized dating laboratories and the best absolute dates must eventually be resolved between those laboratories. The relative ages, as opposed to the absolute ages, are the more important in the present context because they have a direct bearing on the evolution of the Columbia River flood-basalt province and hence the tectonic setting in which those massive eruptions occurred.

Baksi misleads his readers in stating that Hooper et al. (2002) "conclude that the Imnaha Basalt is ~15.5 m.y. old" and again that "Hooper et al. (2002) appear to suggest that the Imnaha Basalt (ca. 15.5 Ma) is younger than their oldest Grande Ronde Basalt (ca. 16.1 Ma)." Hooper et al. (2002, p. 46) actually said "we concur with R.A. Duncan (1999, personal commun.) that all Imnaha and Grande Ronde Basalt flows (>90% of the Columbia River Basalt Group on the Columbia Plateau) were erupted between 16.1 and 15.0 Ma." Obviously the stratigraphically older Imnaha Basalt flows lie at the older end of this range.

The evidence for the Steens Basalt being older than the Imnaha Basalt is based on both field stratigraphy and on the $^{40}Ar/^{39}Ar$ ages from three laboratories (Berkeley, Oregon State, and the Open University, UK) as opposed to ages from Baksi's single laboratory. In eastern Oregon the field stratigraphy is unequivocal (see also Camp et al., 2003); Lower Steens Basalt flows can be traced north from Steens Mountain to the Malheur Gorge where they are overlain conformably by the Upper Pole Creek basalt that correlates chemically and petrographically with the Imnaha Basalt, which has been traced south from the main Columbia Plateau to Farewell Bend on the Snake River and thence southwest to Malheur Gorge. Similarly, the Upper Pole Creek (Imnaha Basalt) of the Malheur Gorge is overlain conformably by the Birch Creek basalts that are the chemical and petrographic equivalents of the Grande Ronde Basalt, which has also been mapped south from the Columbia Plateau to Farewell Bend and then across to Malheur Gorge.

Aware of the discrepancies in ages from different laboratories and our own long-standing suspicions of the early K-Ar age for the Imnaha Basalt (16.9 Ma) in McKee et al. (1981), whose original results were widely scattered, we wished to verify the new data from the Open University with another laboratory. Hence R.A. Duncan kindly duplicated analyses already dated by the Open University and also dated two new samples from the original Imnaha sections to correlate the Imnaha from the Columbia Plateau with his own earlier dates of the Grande Ronde Basalt from the same area. These were all 5–7 step incremental heating experiments that produced statistically significant plateaus (3 or more concordant step ages comprising >50% of total gas) and concordant isochrons. The new ages from Oregon State University agreed closely with those from the Open University (see Table 1 of Hooper et al., 2002, corrected in July 2002; Table 1 provided here with details of plateau and isochron ages, calculated using data reduction software ArArCALC [Koppers, 2002], relative to FCT-3 biotite monitor age of 28.03 ± 0.16 Ma [Renne et al., 1998]). The measured plateau ages for the Imnaha on the Columbia Plateau proved compatible with the older Oregon State University $^{40}Ar/^{39}Ar$ ages of the Grande Ronde Basalt and ages for the Steens Basalt from Berkeley (Table 1; Swisher et al., 1990).

The further suggestion by Baksi that the magnetic reversal in the famous Steens Mountain section is equivalent to the R_1/N_1 reversal in the middle of the Grande Ronde Basalt sequence is equally unacceptable. The magnet-

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TABLE 1. $^{40}AR/^{39}AR$ RADIOMETRIC AGES FOR STEENS AND COLUMBIA RIVER BASALTS

Sample	Material	Total fusion age (Ma)	1σ error	N (steps)	Plateau age (Ma)	1σ error	MSWD	Isochron age (Ma)	1σ error	MSWD	$^{40}Ar/^{36}Ar$ initial	1σ error	J
Eastern Oregon													
MP050	Whole rock	12.92	0.18	4	12.75	0.17	0.32	12.48	0.35	0.09	301.3	6.7	0.001612
BB080	Whole rock	13.47	0.23	6	13.87	0.19	1.60	12.77	0.69	0.28	306.4	7.1	0.001300
MP028	Whole rock	13.99	0.16	4	13.61	0.16	0.85	13.36	0.34	1.01	299.4	5.0	0.001496
WB104	Whole rock	15.41	0.28	6	15.29	0.29	1.41	14.47	0.99	1.49	300.3	5.7	0.001380
WB134	Whole rock	15.76	0.15	6	15.39	0.09	2.07	15.26	0.11	1.25	315.3	11.7	0.001392
SK078	Whole rock	15.76	0.15	5	15.82	0.15	1.54	16.01	0.31	1.8	291.5	5.2	0.001483
Imnaha, Columbia Plateau													
BUK-1	Whole rock	16.26	0.44	6	16.31	0.28	0.70	15.85	0.71	0.73	302.4	9.7	0.001496
BUK-5	Whole rock	17.07	0.94	3	15.38	0.91	0.58	11.90	3.91	0.27	307.9	12.5	0.001616
BUK-7	Whole rock	15.99	0.27	3	15.61	0.16	0.06	15.51	0.43	0.05	300.2	17.9	0.001616

Note: Ages calculated using biotite monitor FCT-3 (28.02 ± 0.16 Ma) and the following decay constants; lambda epsilon = 0.581E-10/yr, lambda beta = 4.963E-10/yr. Table kindly provided by R.A. Duncan (2003, personal commun.).

ically reversed lower Steens Basalt as exposed at both Steens Mountain and Malheur Gorge is petrographically unusual in that it contains significantly more and larger phenocrysts than the overlying Imnaha Basalt. The reversed-to-normal magnetic break recorded by Taubeneck at the base of the Imnaha Basalt along the southern margin of the Wallowa Mountains (Carlson, 1984) and the similar magnetic break at the base of Imnaha flows at Squaw Creek, north of Boise, Idaho, are associated with the same petrographic and chemical changes as those between the Steens and Upper Pole Creek flows at Malheur Gorge. Clearly, the Steens Mountain magnetic transition correlates with the Steens Basalt/Imnaha (R_0/N_0) magnetic, petrographic, and chemical break to the north and east.

There can be little room for doubt about the relative ages of the various basalt units involved. Simple superposition of these units as mapped in the field dictates that Lower Steens Basalt is overlain conformably by, first, Imnaha and then Grande Ronde Basalt, the center of effusive activity moving rapidly north from Steens Mountain where the eruptions began immediately above the supposed position of the hotspot. Absolute ages from three laboratories appear entirely compatible with this conclusion, emphasizing that >90% of the Columbia River Basalt erupted in the very short period between 16.6 and 15.0 Ma and that this sudden and massive tholeiitic effusion was superimposed on the long-standing (Eocene to present) calc-alkaline to alkaline eruptions that attended the equally long-lived east-west extension of the lithosphere in eastern Oregon and Washington.

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