A model for the preferential degassing of the upper mantle

CRITICAL to the model of the depletion of the mantle presented by Hart *et al.*[1] is the assumption that 3.2×10^{-6} ml g^{-1} is an upper limit to the concentration of ^{40}Ar in the mantle source of submarine basalts. This value was obtained from the maximum slope of the upper envelope of data on a plot of $^{40}Ar/^{36}Ar$ against $1/^{36}Ar$. This interpretation ignores the probable significant depletion of initial magma Ar by strong partitioning into CO_2 bubbles and their loss before and during emplacement of magma[2–4]. Further, it has been demonstrated that natural cracks as well as those produced during sample preparation will probably release a considerable part of the CO_2 in vesicles, whose existence has been recently confirmed[5]. Superimposed on this alteration of mantle ^{40}Ar is the variable contamination with atmospheric Ar[3]. Thus the simple interpretation based on the upper envelope of scattered points seems to be invalid. Further, a basic contradiction follows if we apply their value to a limiting model requiring coherency of ^{40}Ar with K transfer; this coherency must apply in their model to the formation of oceanic crust at the ridges as this is the source of the degassed Ar as well as the transfer of K to the sialic crust (see Fig. 1 of Hart *et al.*[1]). Their derived maximum ^{40}Ar concentration of the mantle source of submarine basalts is a factor of 0.04 lower than the coherent ^{40}Ar concentration computed assuming a K concentration of 0.1%. The coherent concentration represents the ^{40}Ar produced from this K concentration in 4,550 Myr. As I pointed out previously[2], this does not require a single-stage mantle history, only coherent degassing at each melting event. Self-consistency demands use of a computed ^{40}Ar concentration of about 8×10^{-5} ml g^{-1} for the initial magma in a limiting coherent model. Correcting for enrichment on partial melting gives an ^{40}Ar concentration of 2×10^{-5} ml g^{-1} for the depleted upper mantle source. Application of this to an estimate of the K concentration of the non-depleted mantle (their Fig. 3) leads to values of >300 p.p.m. even for very high extent of depletion of the mantle. Their other arguments are not qualitatively changed.

D. W. SCHWARTZMAN

Department of Geology and Geography, Howard University, Washington, DC 20059

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HART ET AL. REPLY—The concentration of ^{40}Ar in submarine basalts is not critical to the principal observation made in our model calculation of preferential mantle degassing[1]. The main point we stress is the similarity in the $^{40}Ar/^{36}Ar$ ratio of the atmosphere and non-depleted lower mantle if the atmosphere and sialic crust formed preferentially as a coherent system from the upper mantle. We chose to estimate the ^{40}Ar content of the depleted upper mantle from the ^{40}Ar content of submarine basalts rather than to calculate it indirectly from the K content of the sialic crust and mantle because these values are not well established.

Schwartzman's value of 2×10^{-5} ml g^{-1} for the ^{40}Ar argon content of the mantle is only slightly different from our value of 4.5×10^{-5} ml g^{-1} calculated for the non-depleted lower mantle. Adoption of his calculated value would enhance the similarity in the $^{40}Ar/^{36}Ar$ ratios of the atmosphere and non-depleted mantle. The concentration of ^{40}Ar measured in submarine basalts is at least an order of magnitude lower than these calculated values. We suggest that this is evidence for an upper mantle depleted in ^{40}Ar relative to the deep mantle and is consistent with the well-established depletion of K in the mantle source of ridge basalt.

There is no evidence that Schwartzman's 'probable significant' degassing of the basalt magma under oceanic ridges by CO_2 bubble transfer is more significant than degassing by basalt–seawater interactions after magma emplacement or than degassing during partial melting and metamorphism in subduction zones and within continental cratons. Because Si and Ca are not partitioned into residual phases or CO_2 bubbles during magmatic processes, the high flux of these elements and ^3He observed in geothermal plumes from the Galápagos Spreading Center[2] suggests basalt–seawater interactions rather than bubble transfer are the dominant mechanism for degassing noble gases in ridge basalts today.

We have extensively discussed the effects of atmospheric contamination and degassing on the concentration of ^{40}Ar in submarine basalts and suggest that the surprisingly uniform concentration rules out significant degassing by CO_2 bubble transfer before magma emplacement[3,4]. The ^{40}Ar contents of basalts recovered from depths of over 5,000 m in the Cayman Trough are very similar to those of typical ridge basalts suggesting the ridge basalts have not degassed more than basalts extruded in deep trenches. Basalts with well developed vesicles that have obviously undergone extensive degassing by bubble transfer have been dredged from shallower portions of the ocean and have ^{40}Ar contents up to an order of magnitude lower than the maximum of 3.2×10^{-6} ml g^{-1} we adopted for our model.

ROGER HART
JACK DYMOND
LEWIS HOGAN

School of Oceanography, Oregon State University, Corvallis, Oregon 97331

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The late-Würm Arctic ice sheet

I HAVE recently realised that we did not give Dr John Mercer full credit for his earlier contributions when we wrote our paper *Was there a late-Würm Arctic Ice Sheet?*[1]. In our reference to Mercer's paper *A former ice sheet in the Arctic Ocean?*[2] we should have noted that he was the first to make a mass balance calculation for Arctic ice shelves based on present snowfall over the Arctic Ocean and present iceberg calving rates of Antarctic ice shelves; he had also postulated that late-Würm Arctic ice shelves may have occupied the northern Norwegian Sea; and he had also commented on the evidence for ice from the Arctic Ocean moving southward onto the north slope of Alaska. Mercer's (1970) comments on an ice shelf in the Norwegian Sea were a summary of ideas he had developed more fully previously[3].

Our 1977 paper in *Nature* differed from Mercer's (1969 and 1970) papers in that it developed the idea that ice shelves in the Arctic Ocean, Norwegian, Greenland, and Labrador Seas, and Baffin Bay would have been components of a late Würm Arctic Ice Sheet that also included the Laurentide, Innuition, Greenland, Barents-Kara Sea, British, Scandinavian, and possibly East Siberian Sea grounded ice sheets. This connection is implicit, but not explicit, in Mercer's work. We treated the grounded and floating ice complex as a single, unified dynamic system. As a result, our mass balance calculation included not only the Arctic Ocean (which Mercer treated), but also snowfall over the portions of these fringing ice sheets which drained into the Arctic Ocean and its adjacent seas and bays, and distributed that input along an ice-shelf calving front much further south than Mercer's.

TERENCE J. HUGHES

Institute for Quaternary Studies, University of Maine, Orono, Maine 04473

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