Deep Pacific ventilation ages during the last deglaciation: Evaluating the influence of diffusive mixing and source region reservoir age

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The rise in atmospheric carbon dioxide during the last deglaciation may have been driven by the release of carbon sequestered in the deep ocean. If this was the case, it would imply that deep Pacific ventilation ages should have A) been greater than today during the LGM and B) decreased during the deglaciation. Yet recent results based on the projection age method suggest Pacific ventilation ages during the LGM were similar to today and increased during the deglaciation, opposite the expected pattern [1]. Because the projection age method does not account for tracer diffusion [2] it can potentially yield spurious results and therefore requires validation with alternative techniques.

Here we determine ventilation ages using the transit-time distribution (TTD) method that explicitly accounts for diffusive mixing in the ocean interior [3]. To estimate TTD ages, we assumed an initial TTD width of 600 years, an equilibration-time distribution (ETD) mean of 900 years, and an ETD width of 1600 years. The ETD mean is equivalent to the average surface water reservoir age for the deep water formation region in the Southern Ocean [3]. We used five separate Monte Carlo chains with prior mean TTD values of 1000, 1500, 2000, 2500, and 3000 years. In each case, the chains were run 2000 times to ensure they had converged on a common ventilation age.

Both the TTD and projection age methods imply the ventilation age of the deep Pacific increased by ~1000 years during Heinrich Stadial 1 (H1) and ~500 years during the Younger Dryas (YD). Thus, explicitly accounting for mixing has little impact on the key features of the deep Pacific ventilation history. The similar results are due in part to the projection age error analysis in [1] that fully accounts for the uncertainty in calendar ages and benthic Δ^{14}C estimates. The resulting projection age distributions are similar to the transit time distributions produced by diffusive mixing in the TTD method.

Our ventilation age results imply that either: 1) the ventilation rate of the deep Pacific decreased during the deglaciation, 2) the surface water reservoir age in the Southern Ocean increased, or 3) there was an influx of ^{14}C-depleted carbon from another source into the deep Pacific. The first scenario would likely increase the residence time of deep water in the Pacific basin and promote oceanic sequestration of respired carbon. Although we cannot rule out this possibility, it seems unlikely given that atmospheric CO$_2$ increased during both H1 and the YD [4]. Alternatively, an increase in surface water reservoir age in the deep water formation region may have driven the ventilation age signal, but the timing of the required increase is inconsistent with upwelling proxies from the Southern Ocean [5]. Results from a simple geochemical box also show that a 2x increase in Southern Ocean mixing yields negligible changes in deep Pacific Δ^{14}C. Turning off North Atlantic Deep Water formation reduces the quantity of ^{14}C-enriched carbon entering the deep Atlantic but increases the flux of atmospheric ^{14}C into the surface ocean in general, resulting in little net change in Pacific Δ^{14}C. The lack of an obvious oceanographic mechanism implies that input of old carbon from another reservoir may have responsible for the deglacial ventilation age anomalies in the deep Pacific.

[1] Lund, Mix & Southon (2011) *Nature Geoscience* **4**, 771-774. [2] Adkins and Boyle (1997) *Paleoceanography* **12**, 337-344. [3] DeVries and Primeau (2010) *Earth and Planetary Science Letters* **295**, 367-378. [4] Monnin et al. (2001) *Science* **291**, 112-114. [5] Anderson et al. (2009) *Science* **323**, 1443-1448.

Non-traditional isotope ratios in the Sonju Lake layered mafic intrusion: insight into magma differentiation

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The Sonju Lake Intrusion (SLI) is a 1200 m thick layered mafic intrusion that directly underlies the equal volume Finland Granite (FG). These intrusions, part of the Proterozoic Keweenaw rift, provide a puzzle to standard models of igneous petrogenesis: examination of mineral modes, mineral compositions and even incompatible trace element ratios grade systematically between the two bodies as if the two intrusions were genetically related while U-Pb ages overlap. Yet, simple volume relationships argue against any fractional crystallization-like process linking the intrusions.

Despite expectations of minimal fractionation in igneous rocks, non-traditional isotope ratios show signficant variations with differentiation index in many igneous suites. Thus, examination of non-traditional systems may provide insight into the differentiation process and the SLI-FG genetic relationship. The sample set analyzed here provides a complete top to bottom transect; 10 samples come from the bottom of the SLI (the SNA drill core reaches the bottom contact); 8 come from the AC-1 drill core through the Finland Granite (these show the granite to be heterogeneous, possibly reflecting sill accumulation); another 20 field-collected samples span the SLI and SLI-FG contact zone. Results of MC-ICPMS analysis show clear distinction in ^{87}Sr/^{86}Sr testifying to the FG and SLI coming from different sources. δ^{56}Fe changes with stratigraphic height. The basal SNA drill core samples average -0.01 but have values as low as -0.2. The middle SLI samples average around the mean mafic earth but show systematic oscillations. The FG samples vary in δ^{56}Fe with heaviest values (0.35) in the most silicic samples.

The correlation of non-traditional isotope ratios with differentiation could reflect: 1) effects of fractional crystallization; 2) effects of fluid loss; 3) crustal contamination processes; 4) a temperature gradient effect. With regard to #1, the peak in Fe-Ti oxides in the SLI shows no relationship to the variations in δ^{56}Fe; as magnetite tends to enrich in heavy Fe isotopes, the lack of correlation does not support control by FC. Although heavy δ^{56}Fe occurs in silicic FG samples (which have more radiogenic ^{87}Sr/^{86}Sr), the relationship between Sr and Fe isotopes within each intrusion argues against crustal contamination (#2). Loss of a fluid (#3) is more difficult to assess but appears inconsistent because FG samples which are most fluid rich have the highest δ^{56}Fe. A model of thermal migration zone refining shows that SLI modes and compositional trends are reproduced by a top down sill injection process; differentiation of a uniform composition basalt occurs by temperature gradient based diffusion-reaction above the sill [2]. The δ^{56}Fe pattern observed is generally consistent with the "S" shaped pattern with depth predicted by #4. If so, the FG could reflect a ripening effect of a basaltic sill system (the SLI) cooking an already existing rhyolite flow or dome into the Finland Granophyre.

[1] Shahar et al. (2008) *EPSL* **268**, 330-338.
[2] Lundstrom et al. (2011) *Intl Geol. Rev.* **53** 377-405.