

Article

Petrogenesis of Lava from Christmas Island, Northeast Indian Ocean: Implications for the Nature of Recycled Components in Non-plume Intraplate Settings

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Supplementary Discussion

1. Geology and Regional Setting

Christmas Island is a flat-topped, cliff-fringed, roughly T-shaped island with an area of about 140 km², built of a pile of flat-lying Tertiary limestone-rich sedimentary rocks with intercalations of lavas and fragmental volcanic horizons (Figs. S2–S5). Classified as an "uplifted, composite, reef carbonate island" or "carbonate Cover Island", the present island is the tip of a submerged seamount that rises 4.5 km from the ocean floor. The present coastal environment is an exposed sea cliff with an erosional bench 2–5 m below sea level [201]. Much of the surface of the island is a heavily forested plateau standing at about 180–240 m above sea level, covered with a thick blanket of phosphate deposits overlying a karst topography of deeply dissected limestone [202–205]. Outcrop is therefore relatively good along the coasts but poor inland.

The volcanic rocks on Christmas Island consist of an Eocene shield-building stage (Lower Volcanic Series, LVS; ~37–44 Ma; [10]) and a younger Pliocene volcanic event (Upper Volcanic Series, UVS, ~4.5 Ma; [10]). These ages are younger than associated Cretaceous ages of seamounts from the Vening-Meinesz Volcanic sub-province (64–96 Ma; [10]), especially seamounts dated just to the southwest of Christmas Island (81–85 Ma; [10]). It is possible that the Eocene and Pliocene volcanic series were erupted on and overlie an older Cretaceous edifice, as suggested by some earlier workers [206]. However, dredging of the underwater slopes of Christmas Island by the RV Sonne between 3626–1891 m (SO199 CHRISP voyage; [10]) and the RV Franklin from 1700–1900 m (voyage FR 9_87, Table S1) only recovered rocks similar in age and geochemistry to the lower and upper volcanic series rocks exposed on Christmas Island.

Our primary aim during sampling was to obtain material suitable for geochemistry, and we therefore sampled float as well as outcrop (Table S2). In consequence float material was dated in preference to less suitable material from nearby outcrop. Samples were also collected by rock dredging during voyage FR 9_87 of the RV Franklin (Table S1, Fig. S6)

as well as from two seamounts of the VMP southwest of Christmas Island, termed the "1341m" and "1763m" seamounts for the purposes of this paper.

2. Osmium Analytical Techniques

All samples were measured for Re, Os and $^{187}\text{Os}/^{188}\text{Os}$ at the Macquarie GeoAnalytical (MQGA), Macquarie University. Whole rock powders (2–5 g), prepared in agate ball mills, were spiked for Re and Os and digested in reverse aqua-regia (double Teflon distilled reagents) for 3 days at 220 °C. Os and Re were separated by solvent extraction following the method of [207,208]. Osmium was analysed by negative-thermal ion mass spectrometry (N-TIMS) in dynamic mode on the electron multiplier (SEM) of the Thermo-Scientific Triton in MQGA. Rhenium was measured on an Agilent 7500cs inductively coupled plasma mass spectrometer (ICP-MS). All data were blank corrected using the total procedural blanks (TPB) processed with the samples analysed. Os TPB was 2.7–6.2 pg Os with an $^{187}\text{Os}/^{188}\text{Os}$ ratio of 0.126–0.182 throughout the analytical campaign, with the appropriate blank applied to individual samples. This corresponds to a maximum correction of 4% for CH7B with the remaining samples <2%. Re TPBs were 2.16–2.82pg corresponding to corrections of <1% for all samples. Whilst ^{185}Re was monitored during analysis, no within-run Re correction was applied to the measured $^{187}\text{Os}/^{188}\text{Os}$ as the ^{187}Re signal comprised <0.05% of the total counts. Measurements of 5ng loads of in-house Os standard solution JMC-2 during the analytical sessions gave an $^{187}\text{Os}/^{188}\text{Os}$ of 0.18338 ± 0.00015 (2SE, $n = 4$) which is in agreement with the long term mean of 0.183414 ± 0.000336 (2SE, $n = 207$) obtained on the MQGA Triton [209]. Three digestions of WPR-1 standard (~0.1g), corresponding to ~1.5 ng Os loads to match the amount of Os in the samples, yielded $^{187}\text{Os}/^{188}\text{Os}$ of 0.14475 ± 0.00046 (2SE $n = 3$), Os concentrations of 16.02 ± 0.71 ppb, and Re concentrations of 10.3 ± 0.33 ppb, respectively. These values are in very good agreement with the compiled mean values of [210] for WPR-1: $^{187}\text{Os}/^{188}\text{Os} = 0.1449 \pm 0.0013$, Os = 16.6 ± 2 ppb and Re = 10.9 ± 1 ppb and represent a measure of the external reproducibility of the Os chemistry. Three digestions of WPR-1 standard (~0.1g), corresponding to ~1.5 ng Os loads to match the amount of Os in the samples, yielded $^{187}\text{Os}/^{188}\text{Os}$ of 0.14475 ± 0.00046 (2SE $n = 3$), Os concentrations of 16.02 ± 0.71 ppb, and Re concentrations of 10.3 ± 0.33 ppb, respectively. These values are in very good agreement with the compiled mean values of [210] for WPR-1: $^{187}\text{Os}/^{188}\text{Os} = 0.1449 \pm 0.0013$, Os = 16.6 ± 2 ppb and Re = 10.9 ± 1 ppb and represent a measure of the external reproducibility of the Os chemistry.

3. Petit-spot volcanism

Machida et al. [162] determined the experimental phase relations for two petit-spot parental magmas from the Hokkaido Rise (northwestern Pacific plate; [27]). The parental magmas have between ~14–15 wt% MgO in equilibrium with olivine Mg# 90 [162]. Machida et al. [162] conducted experiments with a $\text{CO}_2\text{:H}_2\text{O}$ ratio of ~2.6:1 and demonstrated multiple saturation in olivine and orthopyroxene at pressures of ~1.8–2.1GPa (Fig. S11; [162]). As these pressures are significantly lower than expected for the LAB beneath the northwestern Pacific plate (~2.5GPa, 82.5km; [162]), Machida et al. [162] proposed a mid-lithospheric origin for petit-spot volcanism. However, as can be seen from Figure 17, the calculated parental magmas of Machida et al. [162] for the Hokkaido Rise plot at pressures ~3GPa consistent with a model of magma genesis at depths greater than the LAB in contradiction to the interpretation of [162]. We can reconcile these differences by the fact that multiple saturation in olivine and orthopyroxene in the experiments of [162] has occurred by crystallization at temperatures of between ~25–75°C below the liquidus resulting in liquids with MgO contents of ~11–12 wt% in equilibrium with relatively low Mg# olivine ~84–85 (Fig. S11; [162]). However, these lower MgO experimental liquids are invaluable in defining an ol+opx+1 cotectic at ~2GPa for high $\text{CO}_2\text{/H}_2\text{O}$ values (Figure 17). As outlined in [211] the appropriate experimental test for multiple saturation is that when a parental magma composition of interest is reacted with a peridotite mineralogy at its liquidus at a given pressure and temperature its composition does not change. These experiments have not been performed by [162] and need to be performed to demonstrate

potential melting conditions in the mantle. However, compared to other experimental data the parental magma compositions of [162] are good candidates for melt equilibrium with the mantle at pressures $>2.5\text{GPa}$ and temperatures $>1340\text{ }^{\circ}\text{C}$ (Figs. S11, 17).