geosciences

MDPI

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 Figures

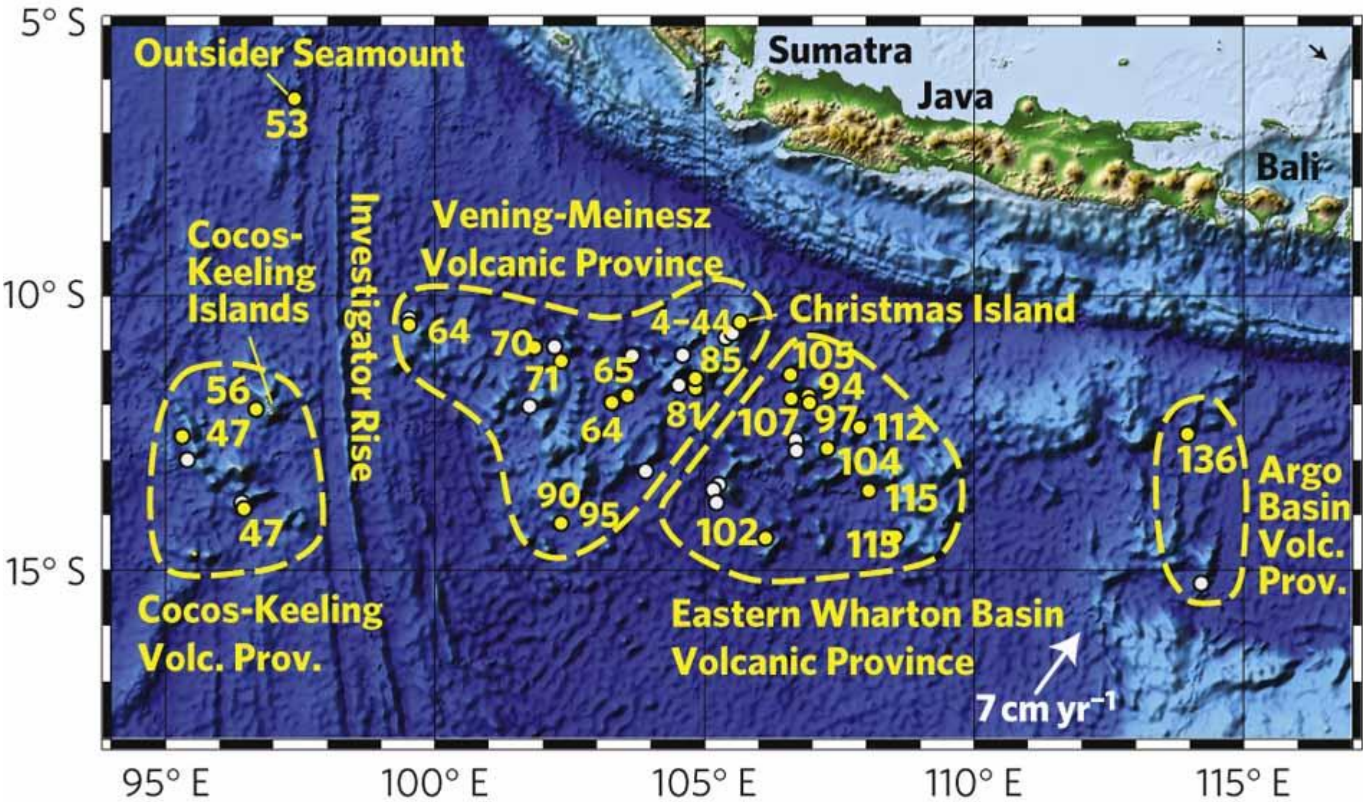


Figure S1. Bathymetric map [212] of the Christmas Island Seamount Province (CHRISP) summarizing seafloor morphology and Ar/Ar ages in millions of years. The CHRISP forms a diffuse volcanic belt with an E–W length of ~1,800 km and a N–S width of ~600 km and is divided into four sub-provinces: (1) Argo Basin (136 Myr), (2) Eastern Wharton Basin (94–115 Myr), (3) Vening-Meinesz

(64–95 Myr; Christmas Island 37–44 and 4 Myr), and (4) the Cocos/Keeling (47–56 Myr) volcanic provinces. Also shown is Outsider Seamount (53 Myr). Plate motion vector and rate from UNAVCO model (http://www.unavco.org). Figure taken from Figure 1 in [10].

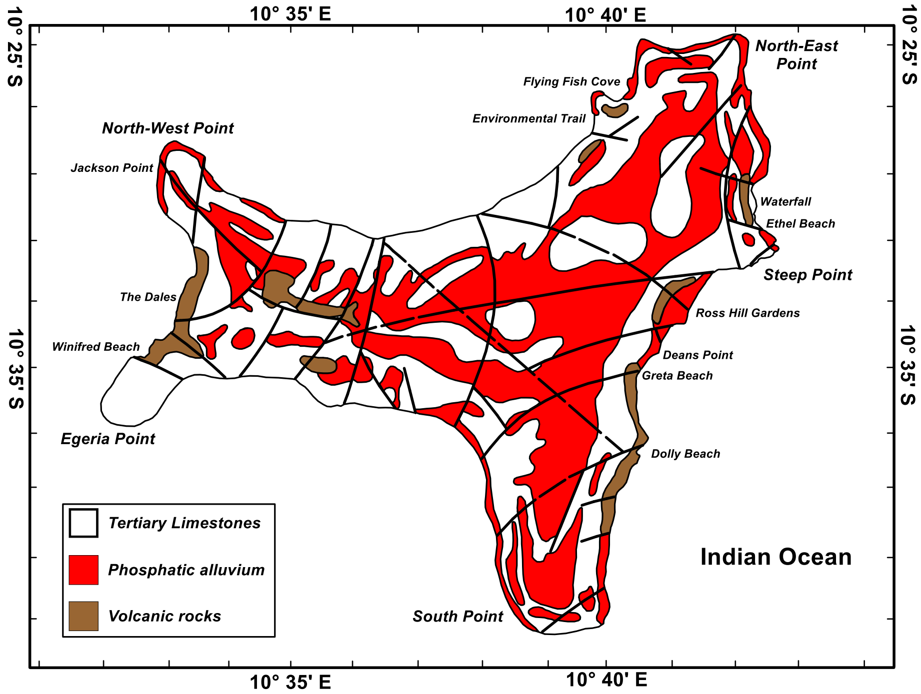


Figure S2. A simplified geological map of Christmas Island adapted from [205]). Polak [206] based on geophysical evidence suggests that Christmas Island consists of a central volcanic caldera with three major rifts dividing the island into four blocks. The outline of the major headlands and embayments of Christmas Island appears to be not the result of modern coast erosion, nor of major landslides into deep water but reflects the under-water topography of a submerged three-armed volcanic structure [206]. Heavy black lines – faults.

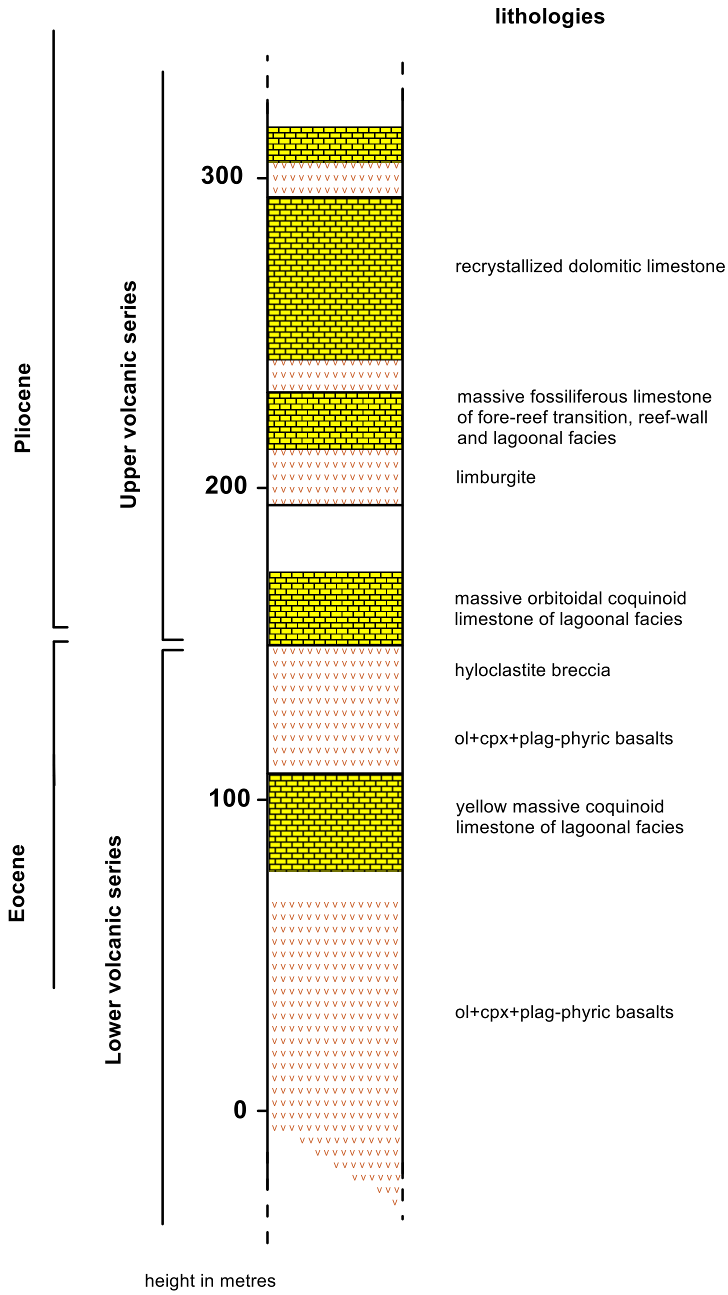


Figure S3. A simplified stratigraphic column for exposed rocks on Christmas Island based on the palaeontologic and stratigraphic studies of [203-205,213-215]. The oldest exposed sedimentary rocks are upper Eocene foraminiferal limestones, termed the Lower Carbonate Series by [204]. The limestones may have been deposited in a warm, shallow, lagoonal environment, and are interbedded with layers of cherty carbonate containing much volcanic debris. Eocene limestones of the Lower Carbonate Series overlie volcanic rocks at sea-level at Flying Fish Cove and Sydney's Dale. These volcanics, which include basaltic, trachybasaltic, and trachytic types, are therefore of Eocene or pre-Eocene age and are termed the Lower Volcanic Series (LVS; [10,52,203]). They are the oldest rocks known on Christmas Island and their base is nowhere seen. The Upper Carbonate Series makes up most of the Christmas Island sedimentary succession, which is generally flat-lying but disturbed by faulting (arcuate tension faults according to [205] – Figure S2) that has thrown Eocene volcanics and sedimentary rocks against younger rocks in the Flying Fish Cove area [204,215]. The greater part of the Upper Carbonate Series succession is made up of foraminiferal and algal debris in a matrix of carbonate mud [204,215]. The faunal, textural and mineralogical characteristics of these rocks were interpreted by [204] to be characteristic of deposition in reef-wall, fore-reef, and lagoonal settings. According to [215] the foraminifera range in age from late Oligocene to middle Miocene. In the southwest of the island, volcanic rocks are interbedded with aragonitic limestones on the Egeria Point peninsula. The limestones are of unknown age, but apparently occur high in the succession. The interbedded volcanic rocks are of Pliocene age [10] and term them the Upper Volcanic Series

(UVS). They occur as volcanic flows interbedded with limestones, as pillow lavas, and as fragmental deposits. One outcrop exposes pillow lava that pass vertically into broken pillows and laterally into well-bedded carbonates which drape the volcanic rocks (Figure S5). Although the volcanics are poorly exposed in-situ outcrops clearly demonstrate eruption in a marine environment which is consistent with evidence from paleo-karsts on Christmas Island (Figure S4; [202]). The younger rocks on the island include Quaternary reef limestones on uplifted shore terraces, and phosphate deposits on the upper plateau, on terraces, in fissures, and on fossil beaches.

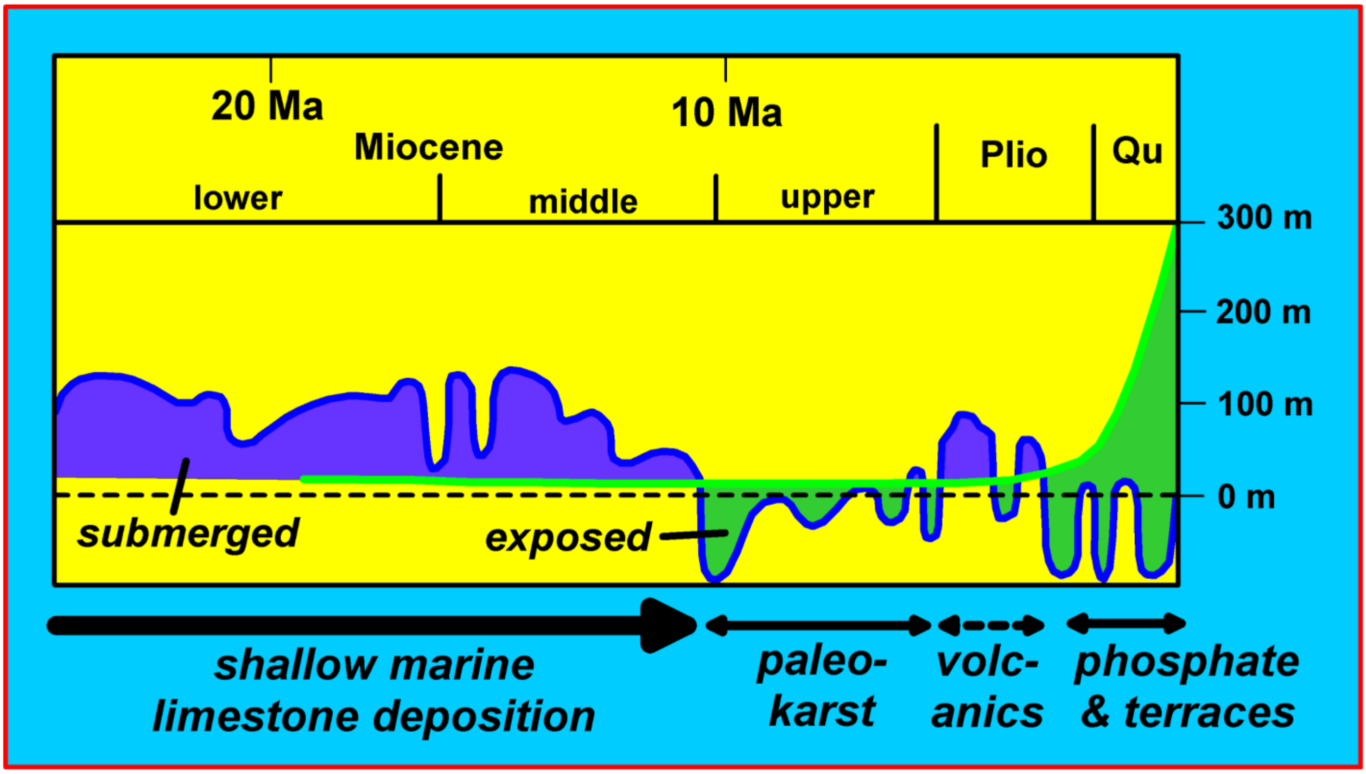


Figure S4. Schematic figure adapted from [202] showing the sea-level curve of [216] (blue line). The green line is an extrapolated uplift rate, based on the work of [217] indicating that uplift of over 361m occurred over a time period of 2-3Ma [202]. Note that during the Pliocene – Christmas Island was submerged – consistent with the nature of the UVS lavas outcrops (see Figure S5).

(**a**)

(**b**)

Figure S5. Pillow lavas (A) and hyloclastite breccia and broken pillows (B) of the Pliocene-aged Upper Volcanic Series – exposed in the Egeria Point Peninsula of Christmas Island (Figure S2)

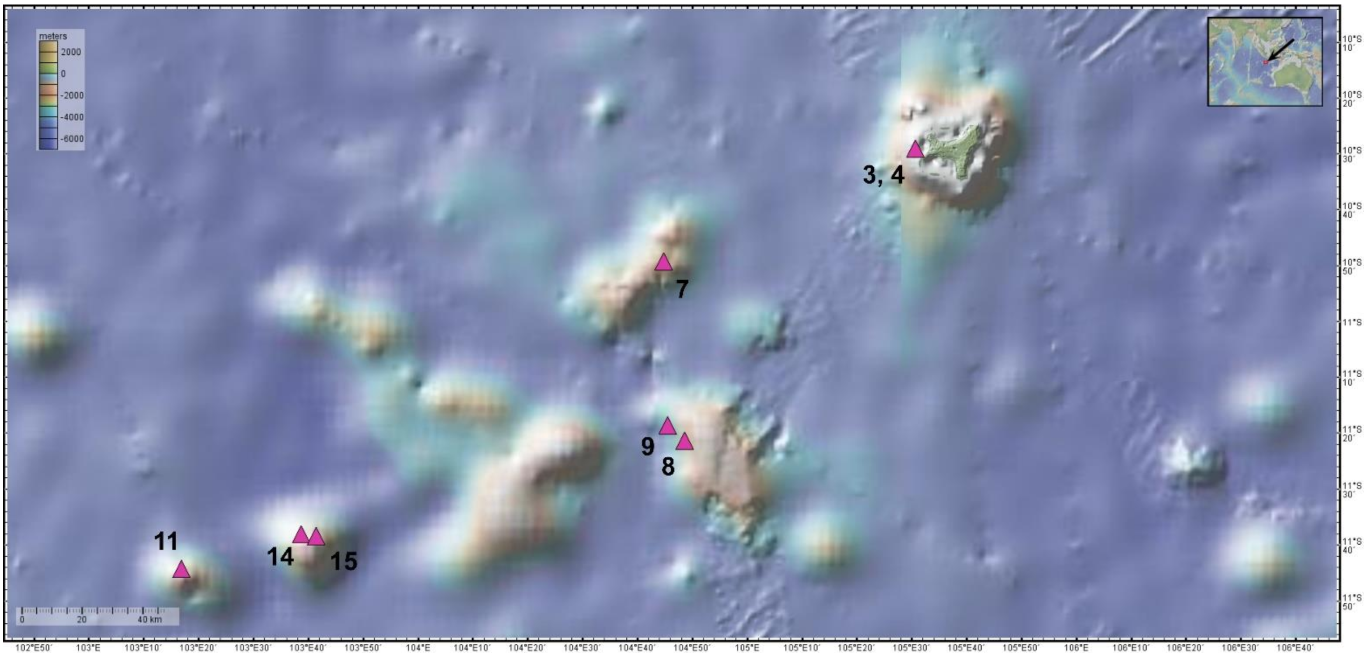


Figure S6. Bathymetric map of the area Southwest of Christmas Island showing the location of dredge stations during voyage FR9_87 of the RV Franklin (Table S2). Map created using GeoMapApp [17].

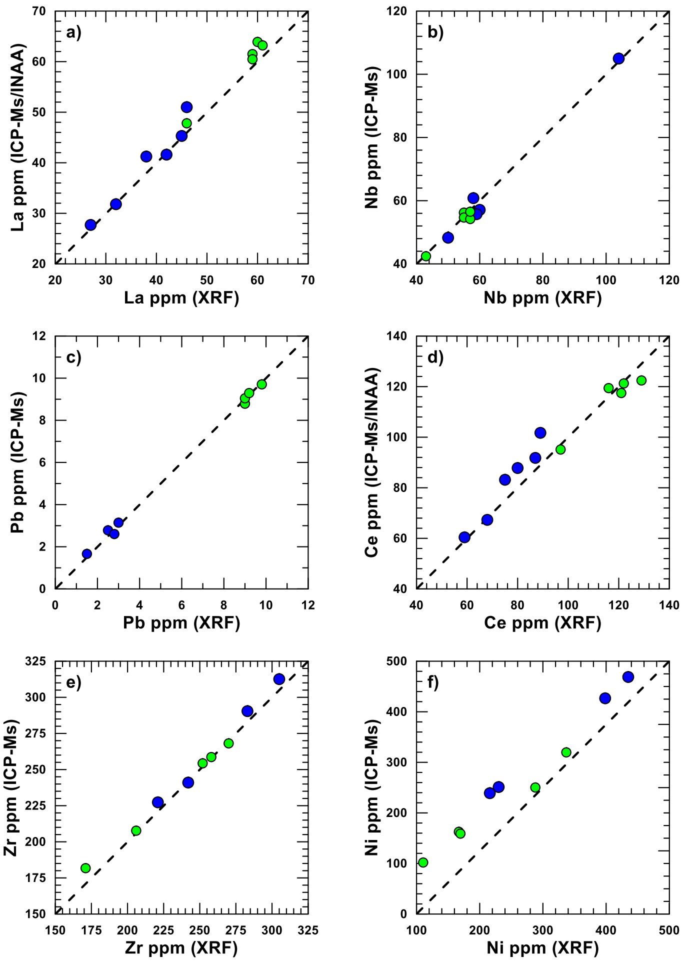


Figure S7. A comparison of trace element abundances in Christmas Island lava series as determined by XRF versus ICPMS/INAA methods.

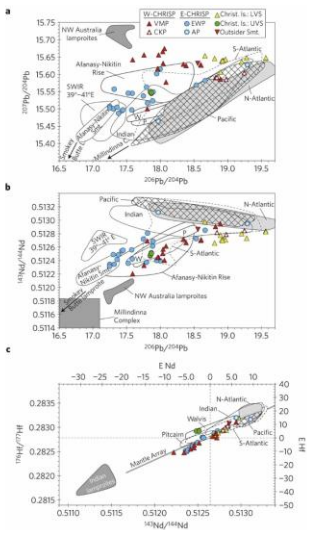
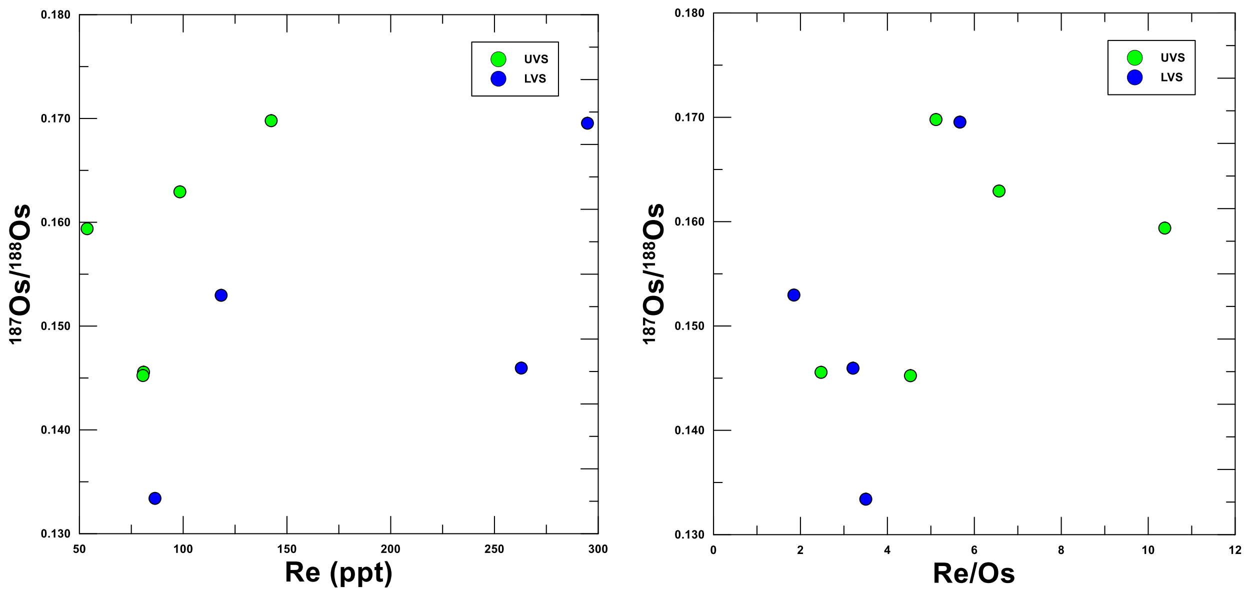


Figure S8. The CHRISP volcanism displays a large range in isotopic composition. a–c, Isotope diagrams illustrate that mixing of MORB (fields from PetDB: http://www.petdb.org) with NW Australian [73] and Indian lamproites [71] and the NW Australian mafic–ultramafic-layered Millindinna Complex [218] can generate the CHRISP, SWIR (39–41E), Walvis Ridge (W), Pitcairn (P) and Afanasy–Nikitin Rise and Seamount compositions [190,219-221]. Abbreviations: Argo Basin

Province (AP), Eastern Wharton Basin Province (EWP), Vening-Meinesz Province (VMP), Cocos–Keeling Province (CKP), Christmas Island (Christ. Is.), Lower and Upper Volcanic Series (LVS and UVS respectively). Figure taken from Figure 2 in [10].



(a) (b)

Figure S9. The $^{187}Os/^{188}Os$ values of the Christmas Island lava series versus a) Re (ppt) and b) Re/Os values.

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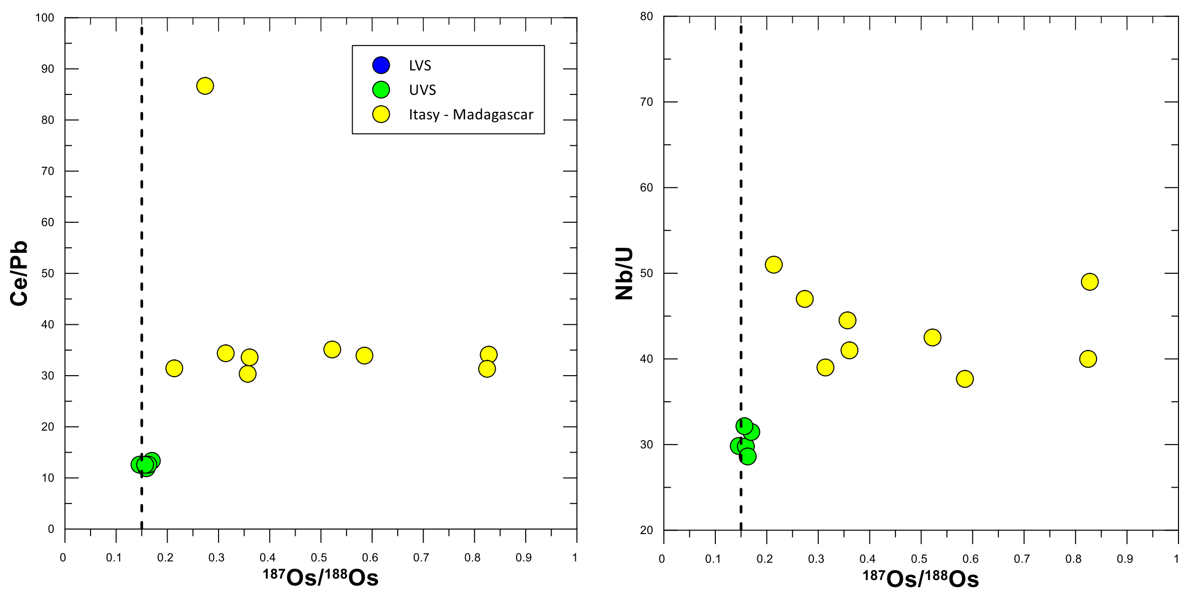
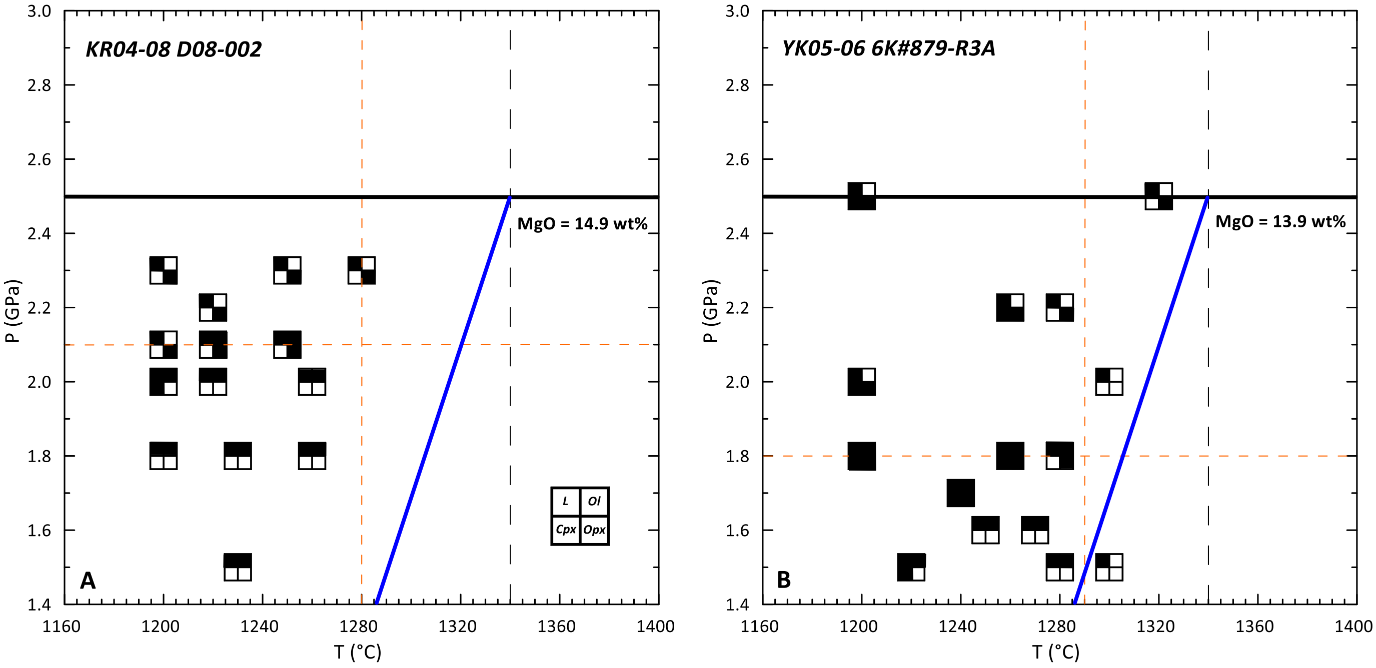


(a) (b)

Figure S10. The Ce/Pb (a) and Nb/U (b) versus $^{187}Os/^{188}Os$ values for the Christmas Island lava series. For comparison are alkaline lavas from Itasy [74]. Dotted line represents the $^{187}Os/^{188}Os$ value of 0.15 which is considered to be a limiting value for uncontaminated mantle derived magmas [90].



(a) (b)

Figure S11. Pressure (GPa) and Temperature (°C) for parental petit-spot magmas from the Hokkaido Rise, northwestern Pacific [162]; a) sample KR04-08 D08-002 and b) sample YK05-06 6K#879-R3A. The black solid horizontal line in both a) and b) is the inferred depth of the LAB beneath the northwestern Pacific oceanic plate (~2.5GPa, 82.5km; [162]). The blue solid line is the olivine liquidus inferred from the experimental results on sample YK05-06 6K#879-R3A and an olivine liquidus slope of ~5°C/0.1GPa [157] as the olivine liquidus has not been determined for composition KR04-08 D08-002, we use the same olivine liquidus determined for YK05-06 6K#879-R3A in a). MgO refers to the MgO content of the respective parental magmas (wt%; [162]). The orange dashed lines represent the pressure and temperature of melt segregation inferred by [162]. The dashed black line is the inferred minimum temperature of melt segregation (>1340°C; see supplementary discussion) which is defined by the intersection of the olivine liquidus line (blue) and the inferred depth of the LAB (black). A filled black square indicates the indicated phase is present (see legend in Fig.S11a).

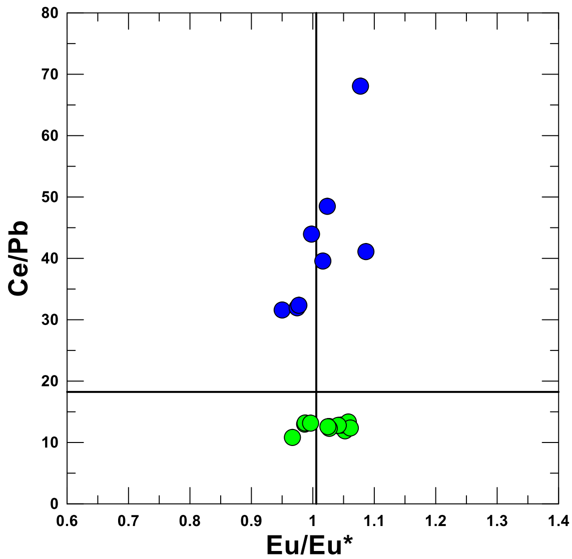


Figure S12. Ce/Pb vs Eu/Eu* values of the Christmas Island lava series (LVS, blue filled circles; UVS, green filled circles). All plotted compositions have >9 wt% MgO (Table S5). The solid black horizontal and vertical line represent the Ce/Pb (horizontal) and Eu/Eu* (vertical) values of D-DMM [76]. $Eu/Eu^* = Eu_N/(Sm_N+Gd_N)$, N refers to chondrite normalised values.