Origin of isolated seamounts in the Canary Basin (East Atlantic): The role of plume material in the origin of seamounts not associated with hotspot tracks

Xiaojun Long1 | Jörg Geldmacher1 | Kaj Hoernle1,2 | Folkmar Hauff1 | Jo-Anne Wartho1 | C.-Dieter Garbe-Schönberg2

1GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel, Germany
2Institute of Geosciences, Kiel University, Kiel, Germany

Correspondence
Xiaojun Long, GEOMAR Helmholtz Centre for Ocean Research Kiel, Wischhofstrasse 1-3, 24148 Kiel, Germany.
Email: xlong@geomar.de

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Abstract
In contrast to seamount chains, small solitary seamounts/seamount groups have rarely been sampled despite their large number and therefore their origins remain enigmatic. Here we present new 40Ar/39Ar, trace element and Nd-Hf-Pb isotope data from the solitary Demenitskoy Seamount, the isolated Tolkien seamount group and the Krylov Seamount and Ridge in the Canary Basin, Central Atlantic Ocean. Their chemical compositions range from intraplate ocean-island-basalt (Demenitskoy) to mid-ocean-ridge-basalt (Tolkien and Krylov) types. Lavas from all three seamount groups, however, show geochemical evidence for involvement of enriched Canary/Cape Verde plume material. Seismic tomography shows that large areas around these mantle plumes consist of dispersed low-velocity material, which could represent diffusely-upwelling plume mantle. Melts from such upwelling mantle could form isolated seamounts. Diffuse upwelling of plume material is likely to be extremely widespread but has been poorly studied to date.

Significance Statement: A fundamental question concerns the origin of the hundreds of thousands of solitary seamounts and small isolated clusters of such seamounts on the seafloor of the world’s ocean basins. Most of them do not fit into any currently accepted models (e.g. they are not associated with a linear hotspot track or plate boundary processes). Their formation could therefore represent a new kind of intraplate volcanism that in fact could be extremely widespread but has been thus far largely neglected. In this manuscript, we report geochemical data from three isolated seamount sites in the Canary Basin and propose a provocative model for their formation that can also be applied to isolated seamounts elsewhere. Our study is therefore also a plea for the long overdue systematic investigation of small seamount volcanism in the world’s ocean basins.

I hereby confirm that all the data and interpretations are new and have not been published elsewhere. All co-authors have been actively involved in this work, have approved the manuscript and agreed to this submission.
1 | INTRODUCTION

Linear chains of intraplate volcanic islands and seamounts in the ocean basins are generally attributed either to mantle plumes (e.g. Morgan, 1971, 1972; Wilson, 1963) or to shallow tectonically driven processes (e.g. Hieronymus & Bercovici, 2000; Koppers, Staudigel, Pringle, & Wijbrans, 2003; Natland & Winterer, 2005). The earth’s ocean floor, however, is dotted with hundreds of thousands of solitary seamounts/seamount clusters with heights of >1 km (Wessel, Sandwell, & Kim, 2010), which are not directly associated with age-progressive hotspot tracks and thus their origins remain enigmatic. In this study, we present 40Ar/39Ar age, trace element and Nd-Hf-Pb isotope data of dredged rock samples from isolated seamounts at three locations in the Canary Basin (Figure 1). Their origin does not fit any currently accepted models and could represent a new kind of intraplate volcanism that in fact could be very common in the world’s ocean basins but has not been extensively researched thus far.

2 | GEOLOGICAL BACKGROUND AND SAMPLING

The Canary Basin in the central East Atlantic Ocean is bordered by the Canary Islands to the northeast, the Azores Archipelago to the northwest and the Cape Verde Islands to the southeast (Figure 1). Seismic tomography studies show that broad (up to 800 km across) low-velocity anomalies beneath the Canary, Cape Verde and Azores Islands can be traced into the deep mantle, where they coalesce (Montelli, Nolet, Dahlen, & Masters, 2006; Saki, Thomas, Nippress, & Lessing, 2015). Primitive (high) $^3$He/$^4$He ratios detected in phenocrysts of lavas from the Cape Verde Islands provide further support for the presence of lower mantle material brought to the base of the lithosphere by a mantle plume (Doucelance, Escrig, Moreira, Gariépy, & Kurz, 2003), as does an age progression for the Canary Islands and associated seamounts to the northeast (Geldmacher, Hoernle, Bogaard, Duggen, & Werner, 2005).

The abyssal plain of the Canary Basin hosts several small and medium-sized isolated seamounts or small clusters of seamounts (Figure 1), which do not directly relate to any known hotspot tracks. The solitary Demenitskoy Seamount rises ~3,200 m from the sea floor and is located ~800 km to the southwest of the Canary Islands on ~110 Ma old oceanic crust (Müller et al., 2016). Bathymetric profiles indicate that Demenitskoy Seamount is a guyot (see Figure S1) and thus appears to have once formed an ocean island that was eroded to wave base. The Tolkien Seamount cluster consists of six unnamed seamounts located ~670 km southwest of Demenitskoy Seamount and ~750 km northwest of the Cape Verde Islands (Figure 1) on ~95 Ma old crust (Müller et al., 2016). The largest seamount “Tolkien” (Duggen, 2009) in the cluster rises to a height of ~2,750 metres-below-sea-level (m.b.s.l.). Krylov system is located ~300 km west of the Cape Verde Islands (Figure 1). Multi-beam mapping revealed a roundish ~960 m high cone, abutting a 15–20 km long E-W oriented ridge (Figure S1), that are named Krylov Seamount and Krylov Ridge respectively (Duggen, 2009). Krylov Ridge is oriented perpendicular to the MAR axis, subparallel to the prevailing strike of the fracture zones in the Canary Basin. The age of the oceanic crust beneath Krylov is ~95 Ma (Müller et al., 2016).

Since the ages and geochemical compositions of these seamounts are unknown, it is unclear if these volcanic edifices originally formed near the MAR, along fracture zones, or in an intraplate setting. During cruise POS379/1, volcanic rocks were dredged from the solitary Demenitskoy Seamount, the Tolkien Seamount cluster and the Krylov Seamount and Ridge (Duggen, 2009). Dredging information are summarized in Table S1.

FIGURE 1 (a) Bathymetric map of the Canary Basin with the location of solitary seamounts and isolated small seamount clusters sampled for this study. *Working name Tolkien was given to a nameless seamount by the POS379/1 scientific party (Duggen, 2009). White seafloor basement isochrons (in Ma) are based on Müller et al. (2016). Map created using GeoMapApp. The inset (b) shows the location of (a) within the central Atlantic Ocean. [Colour figure can be viewed at wileyonlinelibrary.com]
3 | RESULTS

3.1 | \(^{40}\text{Ar}^{39}\text{Ar}\) age determinations

Only a single sample each from Demenitskoy and the Krylov seamounts were considered fresh enough to attempt age determination, but unfortunately neither of the samples yielded statistically valid plateau ages (Figure 2). Replicate analyses of sample DR5-1 from Demenitskoy Seamount yielded a complex age spectra and inverse isochrons that suggest \(^{39}\text{Ar}\) recoil, a problem commonly encountered in Cretaceous altered seafloor basalts (e.g., Koppers, Staudeigel, & Wijbrans, 2000). Total fusion ages from the two splits were 87.31 ± 0.35 and 91.07 ± 0.39 Ma (all ages are quoted with 2\(\sigma\) external uncertainties, unless otherwise stated), which are similar but do not overlap within errors. Applying the method of Fleck, Hagstrum, Calvert, Evarts, and Conrey (2014), 50\% Ar recoil model ages were determined for these two replicated analyses, giving ages of 86.8 ± 2.8 and 89.6 ± 3.6 Ma (see Table S2 for more details). Combining these recoil model ages, we obtained an age of 87.8 ± 2.2 Ma, which is the best age estimate for this Demenitskoy Seamount sample.

Replicate analyses of basaltic groundmass sample DR9-3 from Krylov Seamount yielded a similarly complex age spectra, with old low-temperature ages that were influenced by high levels of atmospheric \(^{36}\text{Ar}\), and some suppression of the \(^{39}\text{Ar}\) isotope signals by high Cl levels. The old low-temperature ages may be due to either \(^{39}\text{Ar}\) recoil or excess \(^{40}\text{Ar}\). The \(^{36}\text{Ar}/^{39}\text{Ar}\) Alteration Index (AI) values indicate the presence of fresh material for some of the high-temperature steps (Table S2) and the replicate analyses did yield overlapping high-temperature weighted mean (HT-WM) ages of 68.46 ± 0.69 and 69.55 ± 0.76 Ma (Figure 2) consistent with inverse isochron ages of 68.54 ± 0.69 and 62.4 ± 7.8 Ma. Combining the HT-WM ages from these two samples yielded a weighted mean age of 69.02 ± 0.56 Ma (2\(\sigma\) uncertainties), which we interpret to be the best age estimate for this Krylov Seamount sample.

3.2 | Trace element and isotopic variations

Thin section examination shows considerable submarine alteration. Therefore, we restrict this study to largely alteration-resistant immobile trace elements (Table S3) and to the Nd-Hf-Pb isotope systems (Table S4). A description of sample petrography, standard analytical methods and data quality information is given in the Supplemental Material.

Immobile trace element data are shown in Figures 3 and 4. Lavas from Demenitskoy Seamount show patterns with an overall enrichment of more over less incompatible elements and depletion in the heavy rare earth elements (HREE), characteristic of alkali ocean-island basalts (OIBs). The steep HREE patterns can be explained by the presence of residual garnet in the source. In contrast, Tolkien Seamount lavas display relatively flat patterns without significant HREE depletion, overlapping normal mid-ocean-ridge basalts (N-MORBs). Krylov Seamount and Ridge lavas, on the other hand, have intermediate, i.e., enriched (E-) MORB-type, compositions. Many lavas show an enrichment in \(^{43}\text{Y}\) relative to Dy and Ho coupled with a marked depletion in Ce indicating secondary alteration such as phosphatization (Hein et al., 2016). To assess this effect, we use the deviation of \(^{43}\text{Y}\) from HREEs with similar partition coefficients (Dy and Ho) as a filter (\(\text{Y}^* = (2\times(\text{Y})_n/((\text{Dy})_n+2(\text{Ho})_n))\)). Only lavas with \(\text{Y}^*\)
values of $1 \pm 0.1$ are considered to be “relatively unaltered” and are shown with coloured (filled) symbols in Figures 3-5, whereas “more altered” samples are denoted by open symbols.

Ocean-island-basalt-like Demenitskoy lavas possess the most enriched Pb, Hf and Nd isotopic ratios (Figure 5), overlapping or plotting close to the compositional fields of the Canary and Cape Verde Islands (Figure 5). In contrast, Tolkien and Krylov Seamount lavas have less enriched Pb, Nd and Hf isotope ratios, overlapping or plotting close to the enriched end of the regional (16–30°N) present-day and late Mesozoic MORB composition. In summary, all seamount lavas plot between OIBs from the nearby Canary/Cape Verde Islands and the regional depleted upper mantle sampled by MORBs and thus could be derived from sources generated by mixing of these sources.

4 | DISCUSSION

4.1 | Origin of the seamounts

The age difference between the seamounts and the underlying oceanic crust can tell whether the seamounts were formed near a spreading ridge or in an intraplate setting. Subtracting the Demenitskoy Seamount $^{40}$Ar/$^{39}$Ar age of 88 Ma from the ~110 Ma old underlying lithospheric age (Müller et al., 2016), the lava erupted on ~22 Ma old crust, indicating an intraplate origin for this seamount consistent
FIGURE 5 Initial Nd-Pb-Hf isotope ratios of investigated seamount lavas shown in comparison to nearby MORB and OIB fields. Lavas that are potentially affected by secondary alteration (see main text for assessment) are shown with open symbols. Note that no significant difference in isotope compositions (all samples were acid-leached, see Supplemental Material) can be observed for potentially altered versus relatively unaltered lavas. The fields denoted by the black solid and black dashed lines indicate MORBs from the northern MAR (16–30°N; data were obtained from PetDB; http://www.earthchem.org/petdb) and central Atlantic Mesozoic ocean crust (with ages varying between 80 and 120 Ma from Janney and Castillo (2001)) respectively. Sources for Nd-Pb-Hf isotope data of lavas from the Canary, Cape Verde and Azores archipelagoes are listed in the Supplemental Material. For a better comparison, the present-day Canary, Cape Verde and Azores isotope data were corrected to 90 Ma for radiogenic ingrowth using the following assumed source parent and daughter element concentrations for Primitive Mantle (Rb = 0.635, Sr = 21.100, Sm = 0.444, Nd = 1.354, U = 0.021, Th = 0.0850, Pb = 0.1850, Lu = 0.074 and Hf = 0.309; Sun & McDonough, 1989). The MORB data were also corrected to 90 Ma for radiogenic ingrowth using the Depleted Mantle (DM) parent and daughter element concentrations (Rb = 0.050, Sr = 7.664, Sm = 0.239, Nd = 0.581, U = 0.003, Th = 0.008, Pb = 0.018, Lu = 0.058 and Hf = 0.157; Workman & Hart, 2005). Enriched mantle I and II (EMI and EMII) and HIMU isotope end member compositions are from Zindler and Hart (1986). [Colour figure can be viewed at wileyonlinelibrary.com]
with its OIB-like incompatible-element composition. Oceanic crust of this age has a lithosphere thickness of ~50 km (Stein & Stein, 1992), restricting asthenospheric melting to this depth. The fractionated HREEs (Figure 4) either require initiation of melting in the garnet peridotite stability field at >70–80 km or derivation from garnet pyroxenite/eclogite, stable at depths of ≥50 km. Elevated temperature and deeper initiation of melting are consistent with a mantle plume source. In addition, the isotopic compositions of the Demenitskoy lavas are similar to those from the Canary/Cape Verde Islands, for which a mantle plume origin is generally accepted (e.g. French & Romanowicz, 2015; Hoernle, Tilton, & Schmincke, 1991; Montelli et al., 2006).

In contrast to Demenitskoy Seamount, the flat HREE patterns of the N-MORB-like lavas from Tolkien Seamount point to shallow melting predominately within the spinel stability field. In the absence of any radiometric age data, formation of the Tolkien Seamount at the MAR and subsequent passive drifting to its present position are therefore considered as the most likely origin for this seamount. Tolkien Seamount lavas show slightly enriched isotopic compositions plotting between the fields for Mesozoic MORBs and the Canary/Cape Verde plume lavas (Figure 5).

A limestone sample dredged during Russian cruise R/V Akademic N. Strakhov (1985) from the summit of Krylov Seamount (at 2,000 m.b.s.l.) contained an assemblage of Maestrichtian coccoliths (Il’in, 2000). A Maestrichtian (72.1–66.0 Ma; Cohen, Finney, Gibbard, & Fan, 2019) minimum age for the underlying seamount volcanism is consistent with the combined high-temperature weighted mean 40Ar/39Ar age of 69.02 ± 0.56 Ma determined from a Krylov Seamount sample that was dredged from a similar depth. Therefore, the seamount must have formed on ~25 Ma old crust (at ~600 km distance from the spreading center) indicating an intraplate setting. The elongated sub-latitudinal orientation of the Krylov Seamount and Ridge on an extension of a fracture zone (Figure 1) suggests formation along a leaky fracture zone (Il’in, 2000), probably associated with local small-scale upwellings due to lithospheric extension. The E-MORB incompatible-element and slightly enriched (towards Canary/Cape Verde) isotopic compositions are consistent with the additional presence of plume-type mantle in the source. Waters, Sims, Perfit, Blichert-Toft, and Blusztajn (2011) have demonstrated that mixing of deeply generated pyroxenitic melts with shallowly generated spinel peridotite melts can generate E-MORB at fracture zones.

4.2 | Common source material: Could non-hotspot-track seamounts also be derived from plume material?

The isotopic compositions of all investigated seamounts plot between enriched Canary/Cape Verde plume and depleted upper mantle compositions (late Mesozoic MORB), suggesting mixing
of plume mantle with depleted upper mantle (Figure 5). None of
the seamounts, however, were formed closer than ~700 km to the
nearest hotspot (using reconstruction parameters from Matthews
et al., 2016 in GPlates software). Seismic tomographic models (e.g.
French & Romanowicz, 2015; Montelli et al., 2006; Nolet, Allen, &
Zhao, 2007), however, show that zones of slower seismic velocity
are not restricted to narrow conduits beneath the respective active
hotspots, but instead form large, irregularly-shaped zones in the
lower mantle and isolated, discontinuous patches within the sur-
rounding upper mantle (Figure 6a). Low-velocity anomalies beneath
the Canary/Cape Verde hotspots appear to pond at mid-mantle
depths at ~1,000 km below the spinel-perovskite plus magnesio-
wüstitie phase transition. This is an endothermic phase transition
with a negative Clapeyron slope, impeding the passage of material
wüstite phase transition. This is an endothermic phase transition
rounding upper mantle (Figure 6a). Low-velocity anomalies beneath
many other hotspots (e.g. Hawaii, Iceland and St. Helena) and
low-velocity anomalies that can be traced above this transition
seem to shift laterally, branch out or appear to meander through
the upper mantle (French & Romanowicz, 2015). Therefore, it ap-
pears that upwelling plume material pollutes large areas of the
upper mantle around the main plume conduits (1,000 km or more
from the active hotspots) and melting of this diffusely upwelling
plume material could generate small isolated seamounts/seamount
clusters.

It is also possible that small, secondary “plumelets” rise from the
thermal boundary layer at the top of ponded, larger-scale anomalies
(Courtillot, Davaille, Besse, & Stock, 2003). Such plumelets would be
too small to be resolved by most global seismic tomographic models,
but recently tomographic evidence has been found of several small
upper-mantle upwellings (plumelets) rising several 100 km apart from
each other through the transition zone below the northern East-
African Rift system (Civiero, Armitage, Goes, & Hammond, 2019).

Slower seismic velocities are generally interpreted to reflect
hotter or more fertile lithologies (e.g. Bijwaard & Spakman, 1999).
Accordingly, upwelling hot and/or more fertile plume material would undergo decompression melting upon arrival at
shallow mantle depths, regardless of whether the upwelling resulted
from higher buoyancy of the plume material, small-scale upper-
mantle convection (e.g. Ballmer, van Hunen, Tackley, & Bianco, 2008),
extension in the overriding ocean plate (e.g. along a fracture zone) or
by upwelling related to seafloor spreading near a MOR. Melts from
small isolated plumelets or from upwelling blobs of plume-type man-
tle would not create long-lasting hotspot tracks, although possibly
form short clusters of volcanoes (Tolkien and Krylov) and isolated
seamounts (Demenitskoy).

Many of the small, isolated seamounts that populate the ocean
basins could potentially be related to such processes. Seamounts
near the East Pacific Rise (5–15°N), for example, show enriched
isotopic compositions that are different from N-MORB (e.g., Graham
et al., 1988; Niu, Regelous, Wendt, Batiza, & O’Hara, 2002). Other
examples include the Pacific Pukapuka and Rano Rahi seamounts
which show similar isotopic ranges (Hall, Mahoney, Sinton, &
Duncan, 2006; Janney, Macdougall, Natland, & Lynch, 2000). The
occurrence of isotopically enriched E-MORBs or OIBs far from any
hotspot track attests to the ubiquitous presence of chemically-en-
riched lithologies in the upper/mid mantle (e.g. Waters et al., 2011).
In summary, our study suggests a common source for hotspot vol-
canoes and many of the isolated volcanic seamounts on the sea-
floor that are not directly related to age-progressive hotspot tracks.
Clearly more studies of non-hotspot track seamounts are necessary
to test the applicability of our model on a global scale.

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DATA AVAILABILITY STATEMENT
The data that support the findings of this study are provided in the
supplementary material.

ORCID
Xiaojun Long https://orcid.org/0000-0002-7331-7493

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section.

**Figure S1.** Bathymetric maps of investigated isolated seamounts/seamount clusters.

**Table S1.** Sampling sites.

**Table S2.** Demenitskoy and Krylov Seamounts $^{40}$Ar/$^{39}$Ar basaltic groundmass ages.

**Table S3.** Trace element concentrations.$^a$

**Table S4.** Nd-Pb-Hf isotope ratios.$^a$

**Supplementary Material.** Analytical methods and citations of reference fields in Figure 5.

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