The nature of chemical heterogeneities preserved in the deep mantle seen from geochemistry

Maud Boyet

Claudine Israel, Régis Doucelance, Pierre Bonnand, Paul Frossard, Delphine Auclair

Laboratoire Magmas et Volcans, Université Clermont-Auvergne

Global Scale Seismic Imaging and Dynamics of the Earth's Mantle, Paris, 6-7 November, 2021

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

UNIVERSITÉ Clermont Auvergne

Laboratoire Magmas & Volcans

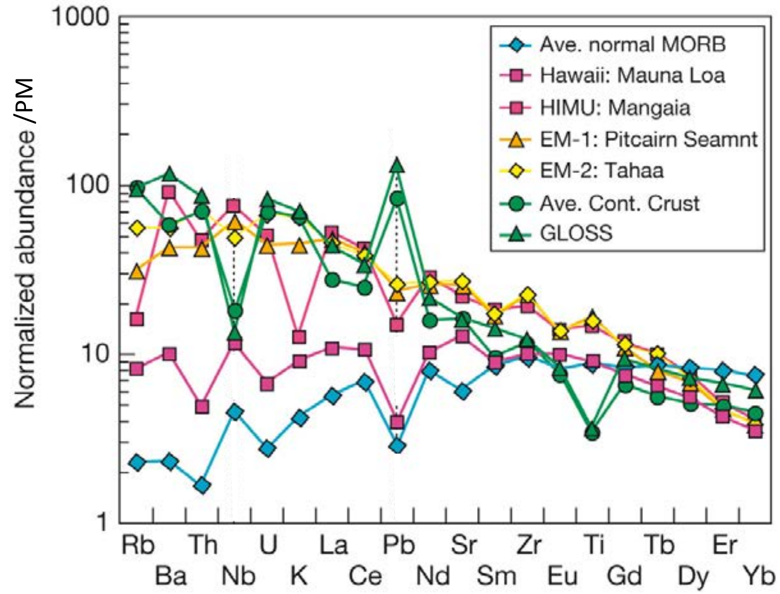
European Research Council

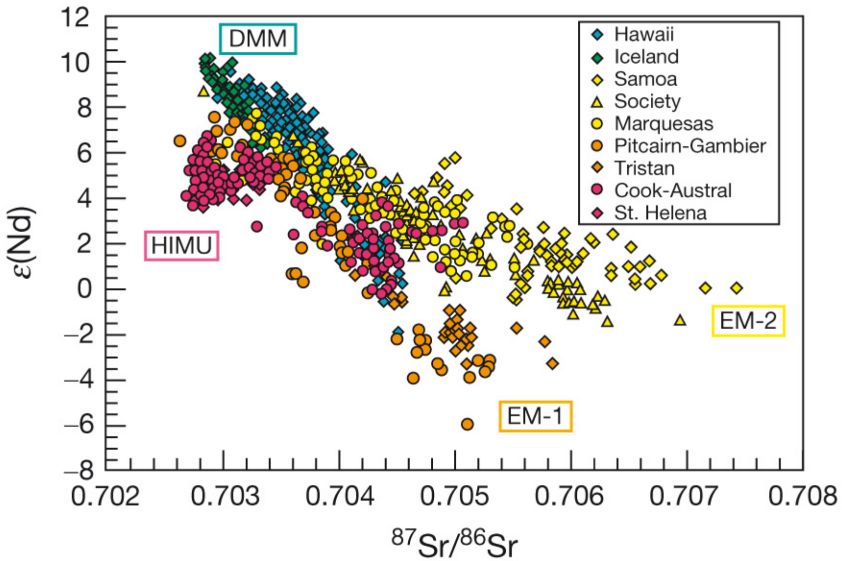
Different geochemical signatures in modern mantle-derived samples:

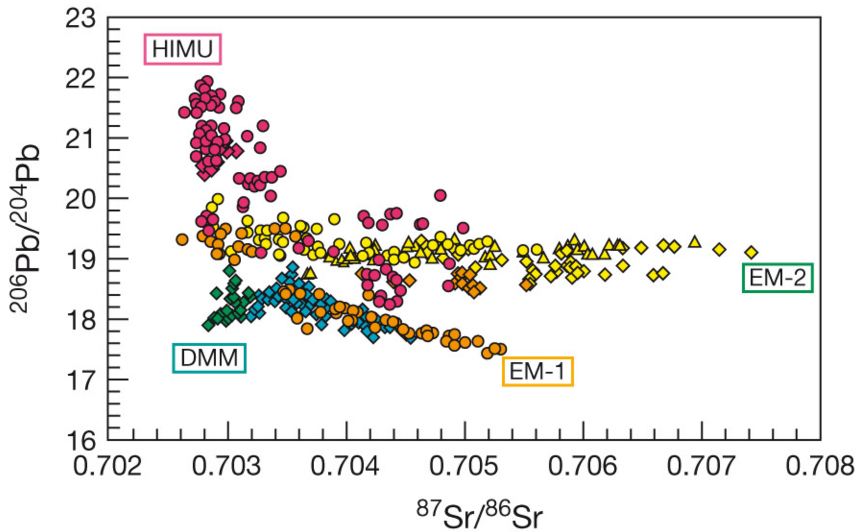
- Trace elements
- Long-lived isotopes systematics

Ocean Island Basalts vs. Mid-Ocean Ridge Basalts:

- Melting at greater depth
- Ancient chemical heterogeneities preserved in the source mantle







Hoffman ToG 2013

Different geochemical signatures in modern mantle-derived samples:

- Trace elements
- Long-lived isotopes systematics

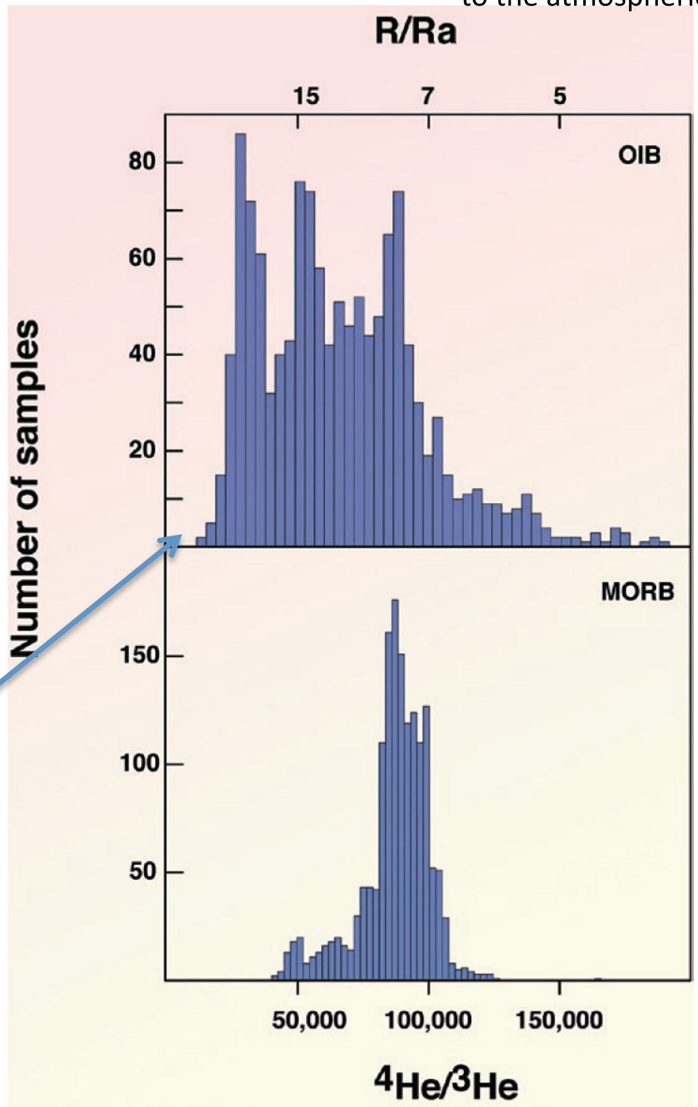
Ocean Island Basalts vs. Mid-Ocean Ridge Basalts:

- Melting at greater depth
- Ancient chemical heterogeneities preserved in the source mantle

Long-lived systematics (noble gas):

- The MORB source represent a well-homogeneised mantle (R/Ra=8).
- OIB shows a large variation and present non-radiogenic ratios (R/Ra up to 50 on Baffin Island picrites): undegassed reservoir
- Hawaii, Iceland and Galapagos hotspots also show primitive helium isotopic ratios.

$^3He/^4He$ ratio normalised to the atmospheric ratio



Moreira Geoch. Persp. 2013

Isotope heterogeneities measured in OIBs

Recycled material *vs.* early-formed reservoirs

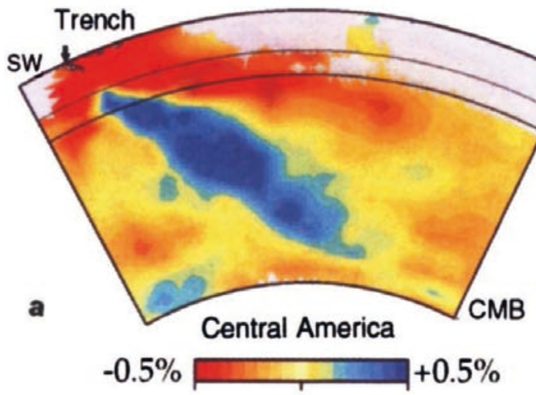
Long-lived systematics:

^{138}La-^{142}Ce systematics

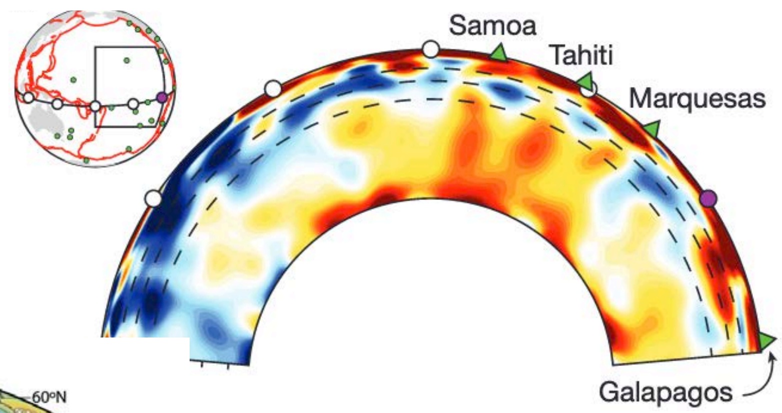
Short-lived systematics:

^{146}Sm-^{142}Nd, ^{182}Hf-^{182}W

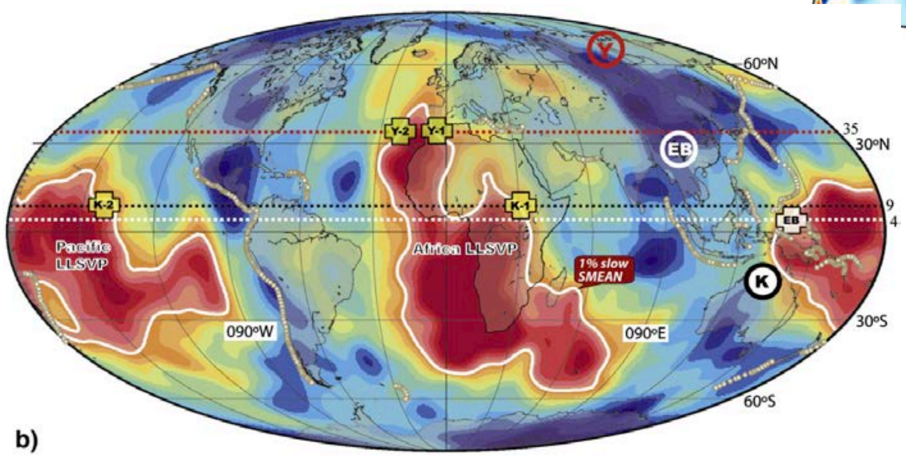
+ noble gas



van der Hilst et al., Nature 1997



French and Romanowicz Nature 2015



Torsvik et al., EPSL 2008

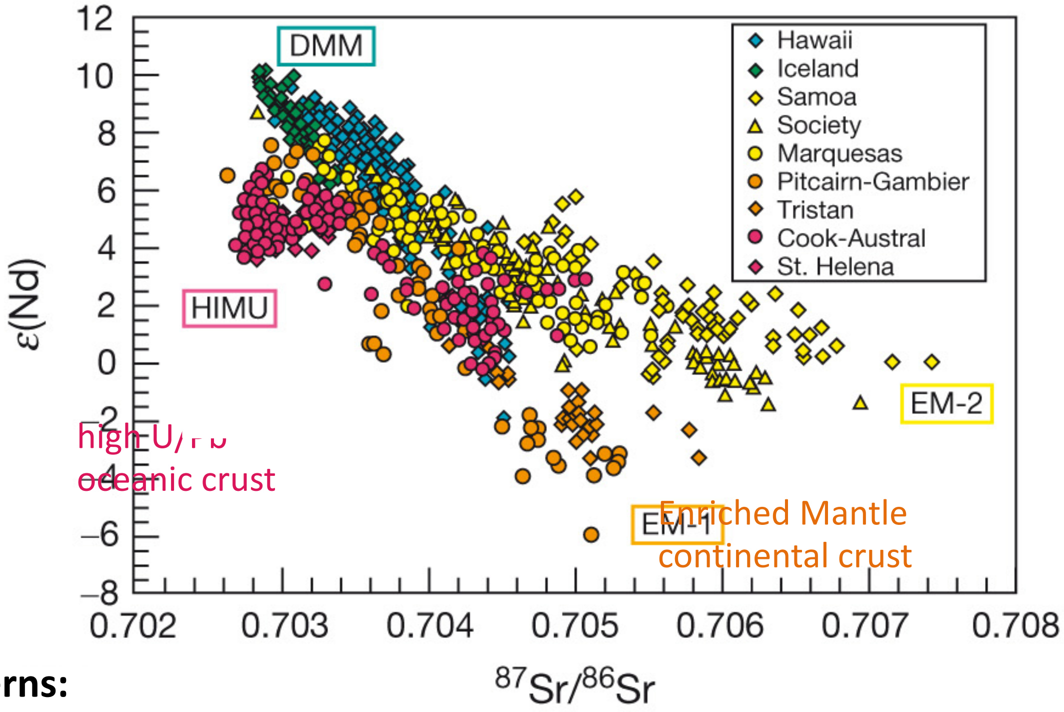
La-Ce systematics:

$^{138}La \longrightarrow {}^{138}Ce$ ($T_{1/2}$= 292.5 Ga)

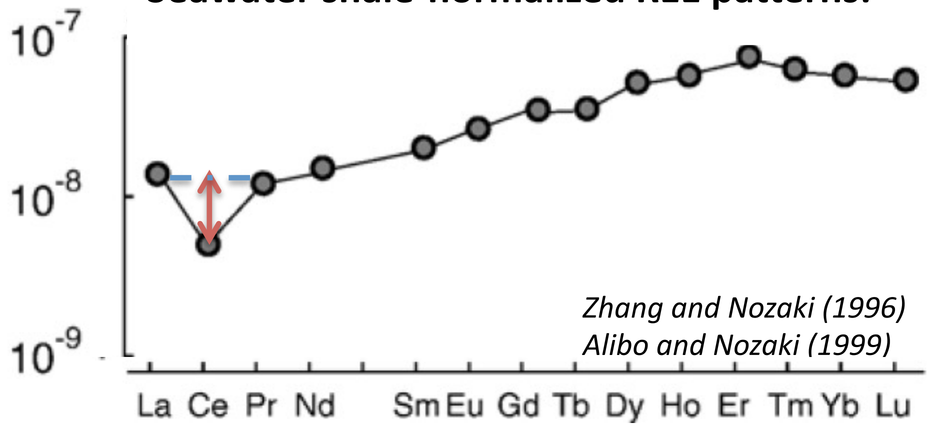
^{138}La decreased by 1% in 4.567 Ga

Two main oxidation states : Ce^{3+}/Ce^{4}

Under current oceanic conditions, Ce is oxidized into insoluble Ce^{4+} and it is subtracted from seawater, resulting in high La/Ce fractionation.



Seawater shale-normalized REE patterns:



Cerium anomaly

$Ce/Ce^* = Ce_N / (La_N^{0.5} \times Pr_N^{0.5})$

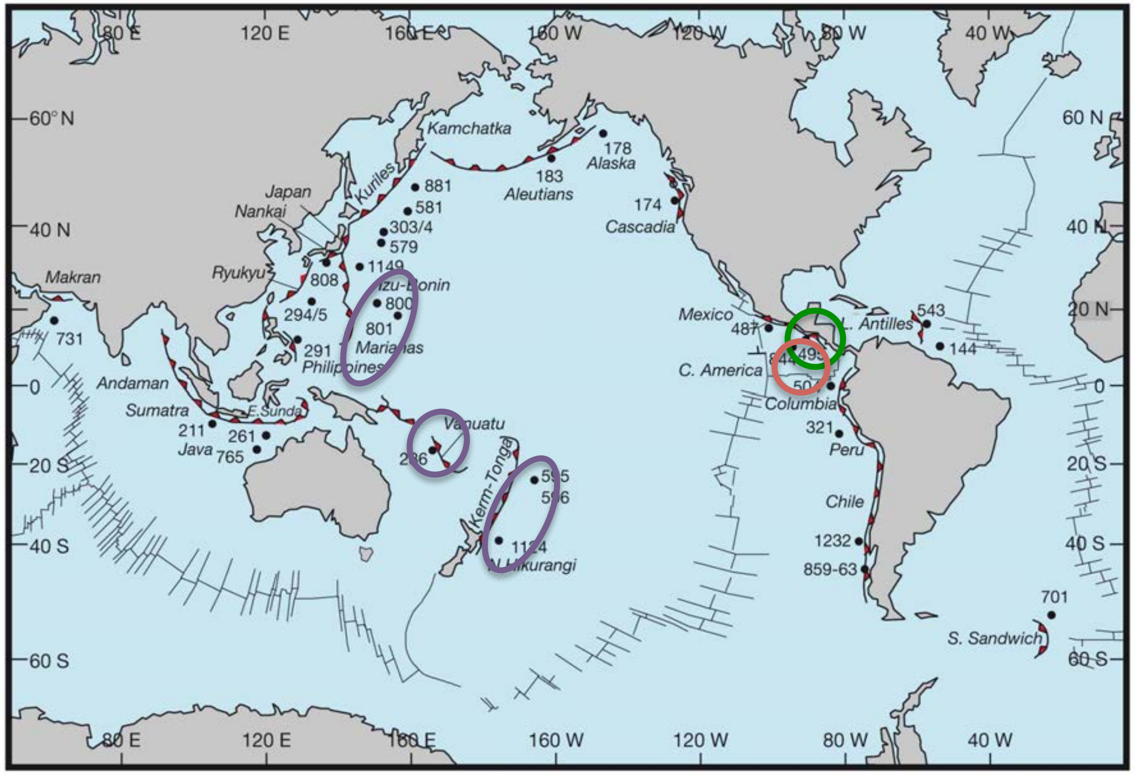
Ce/Ce*<0: Radiogenic Ce isotopic composition with time.

Nature and chemistry of the material currently recycled:

Bulk composition for sediments subducting (25 trenches) called GLOSS: GLobal Subducting Sediment
Plank TOG 2013

GLOSS Ce/Ce*= 0.95

60% of the trenches have negative cerium anomalies up to 0.35

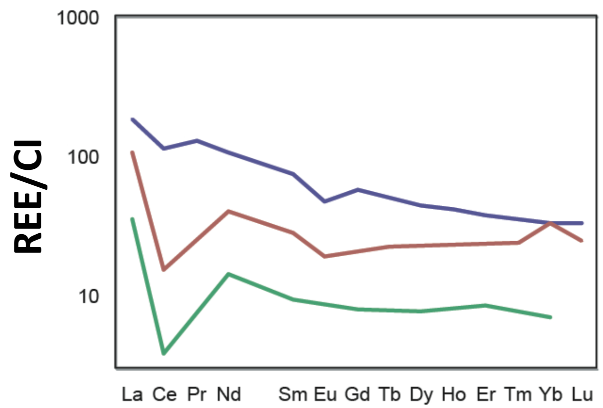


Ce/Ce*
0.14
0.20
0.76

Carbonate sediments from DSDP Site 495 (Cocos Plate)

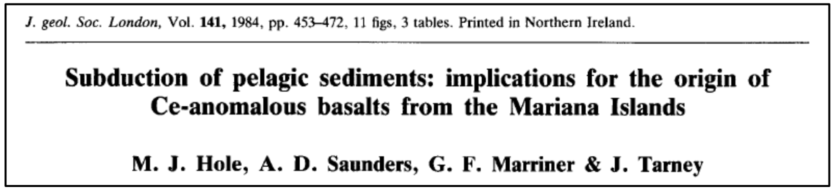
Sequence of pelagic oozes recovered from Nasca Plate (Leg 34- hole 319).

Mean of 5 trenchs (Kermadec, Tonga, Vanuatu, Marianas, Izu-Bonin).



Negative cerium anomalies measured in lavas:

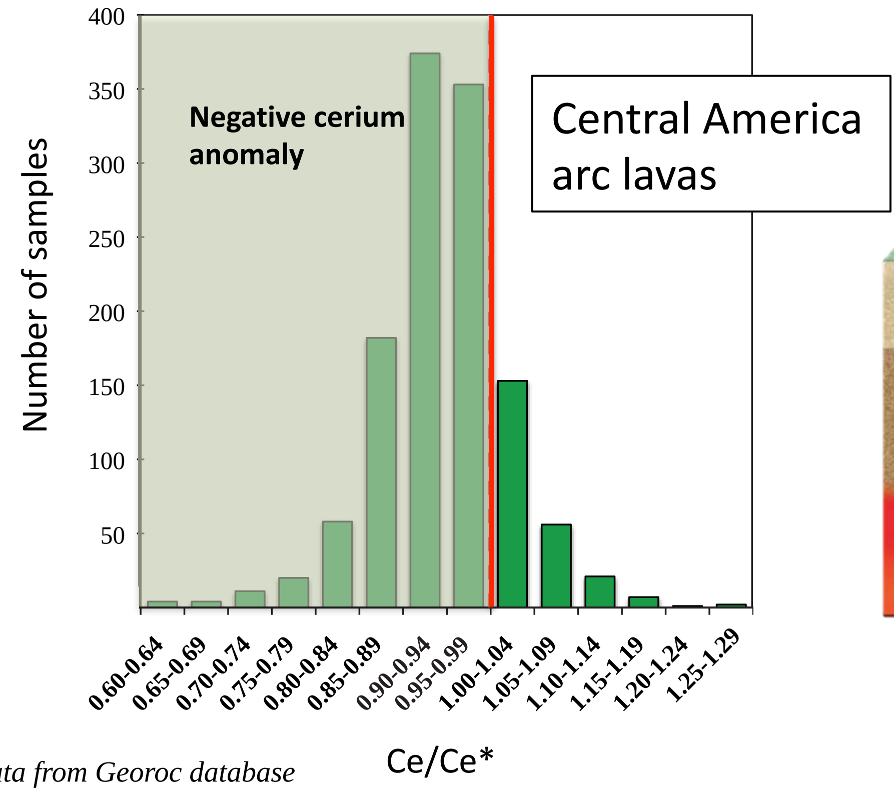
Arc lavas


J. geol. Soc. London, Vol. **141,** 1984, pp. 453–472, 11 figs, 3 tables. Printed in Northern Ireland.

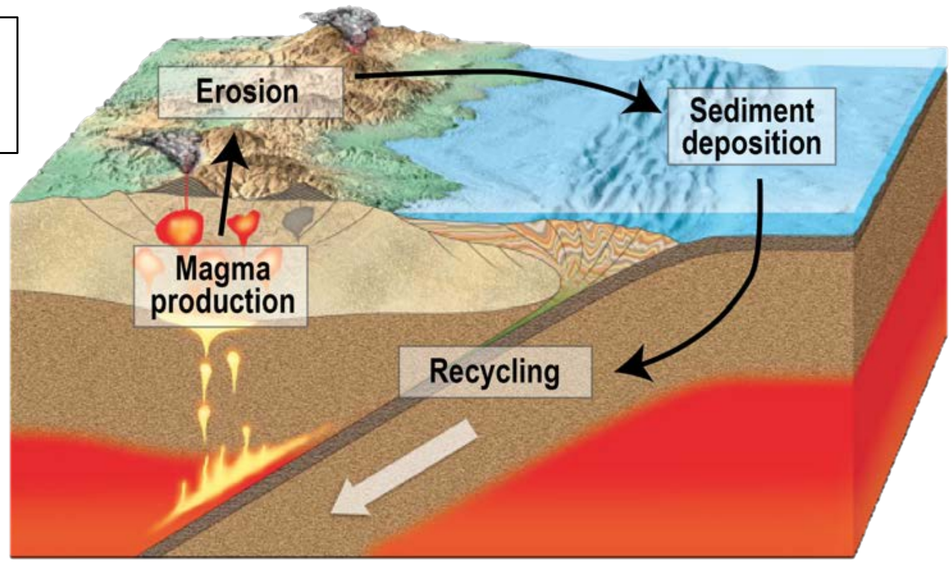
Subduction of pelagic sediments: implications for the origin of Ce-anomalous basalts from the Mariana Islands

M. J. Hole, A. D. Saunders, G. F. Marriner & J. Tarney

Recycled sediments involved in the source of arc lavas (fluid/melting).



Data from Georoc database



Negative cerium anomalies measured in both:

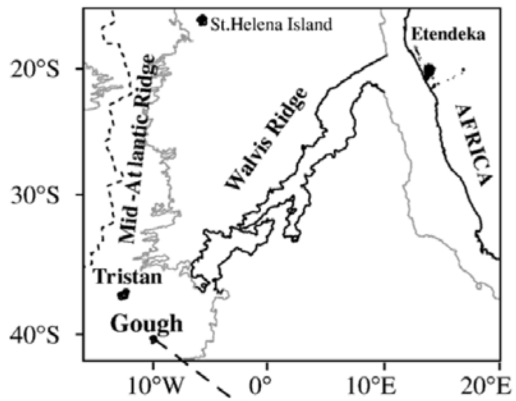
Ocean island lavas

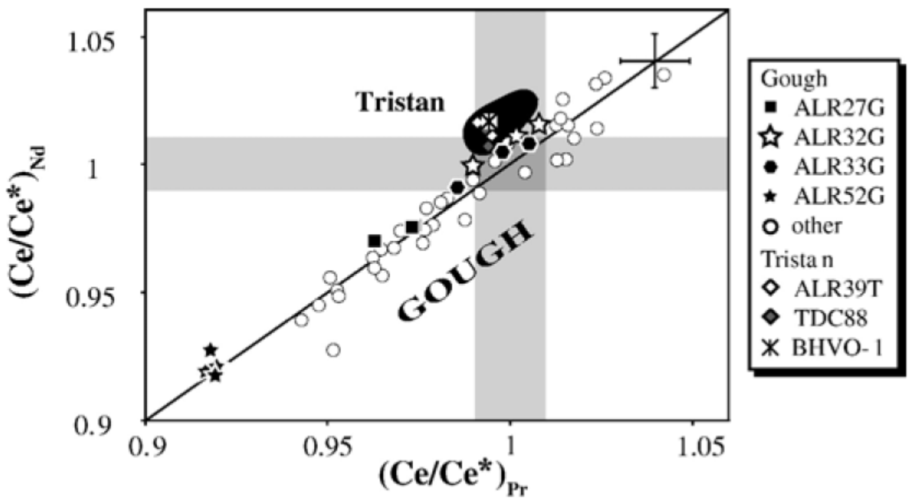
ELSEVIER
Available online at www.sciencedirect.com
ScienceDirect
Earth and Planetary Science Letters 265 (2008) 475–486
EPSL
www.elsevier.com/locate/epsl

Ce anomalies in Gough Island lavas — Trace element characteristics of a recycled sediment component

Cornelia Class [a,*], Anton P. le Roex [b]

Gough Island (EM1)





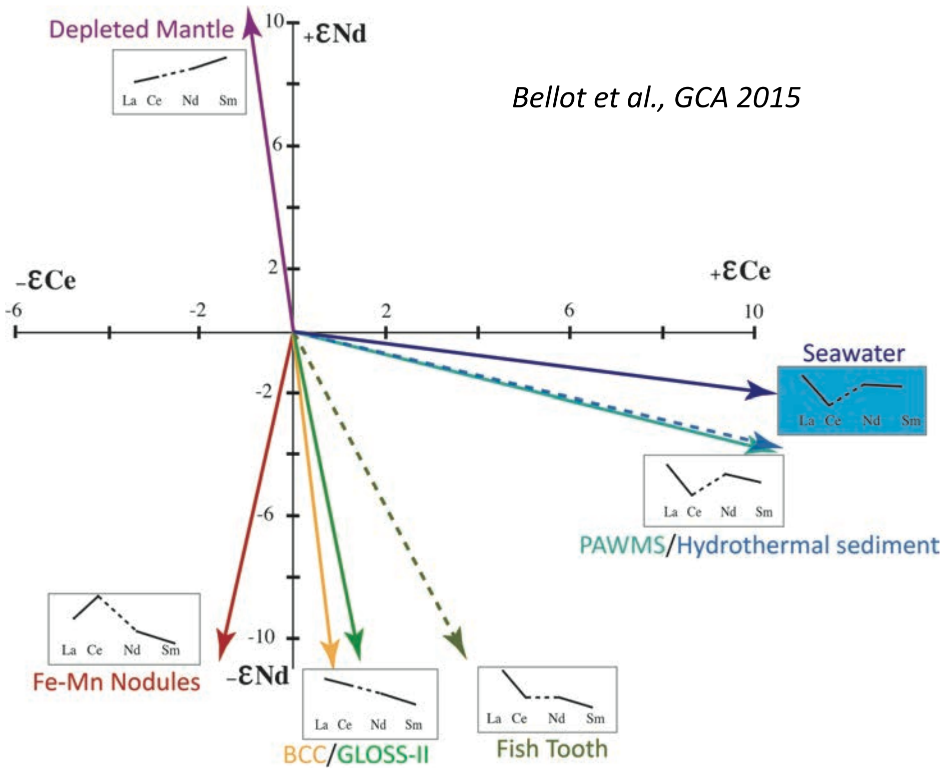
Interpretations:

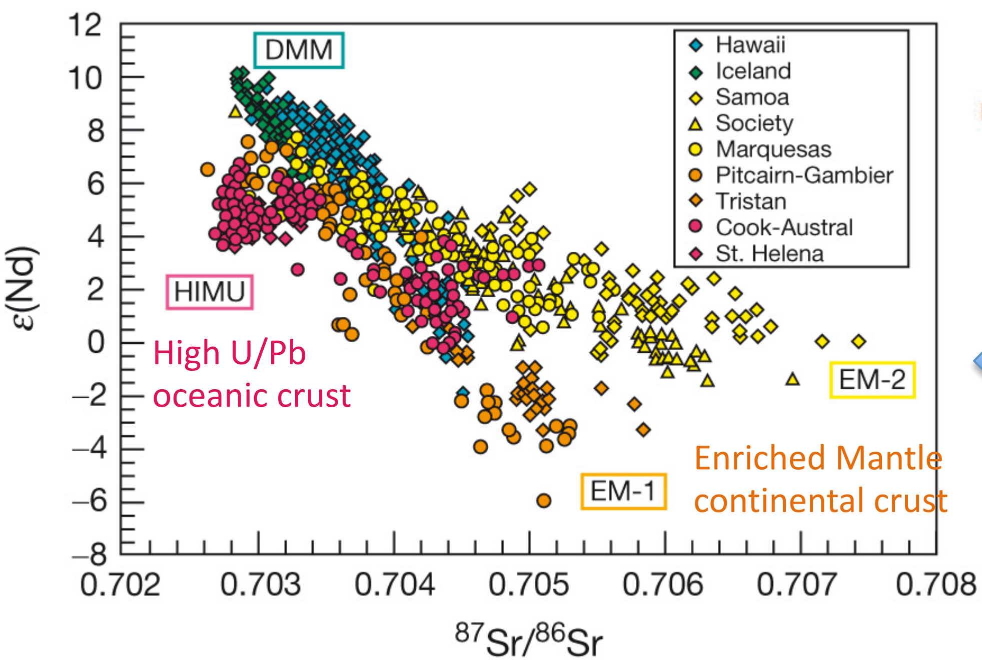
- Shallow-level contamination by local marine sediments.
- Consequence of weathering processes.
- Variable amounts of a sediment component in the mantle plume source.

La-Ce systematics:

$^{138}La \longrightarrow ^{138}Ce$ ($T_{1/2}$= 292.5 Ga)

When combined to ^{147}Sm-^{143}Nd systematics:
1. Define the shape of the Light rare earth element pattern
2. Identify decoupling of the two systematics (cerium anomaly)



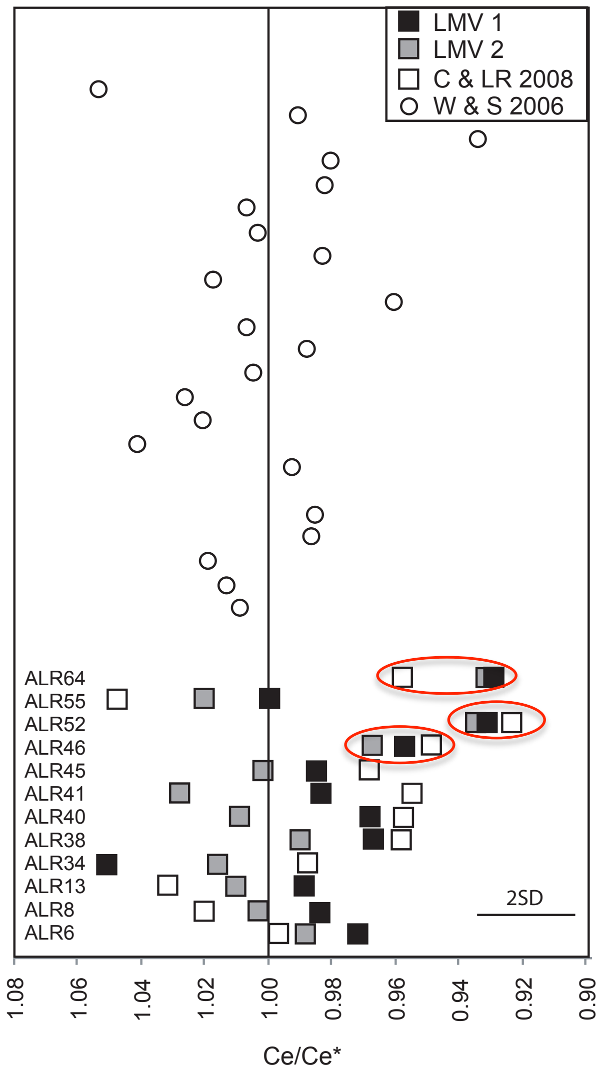


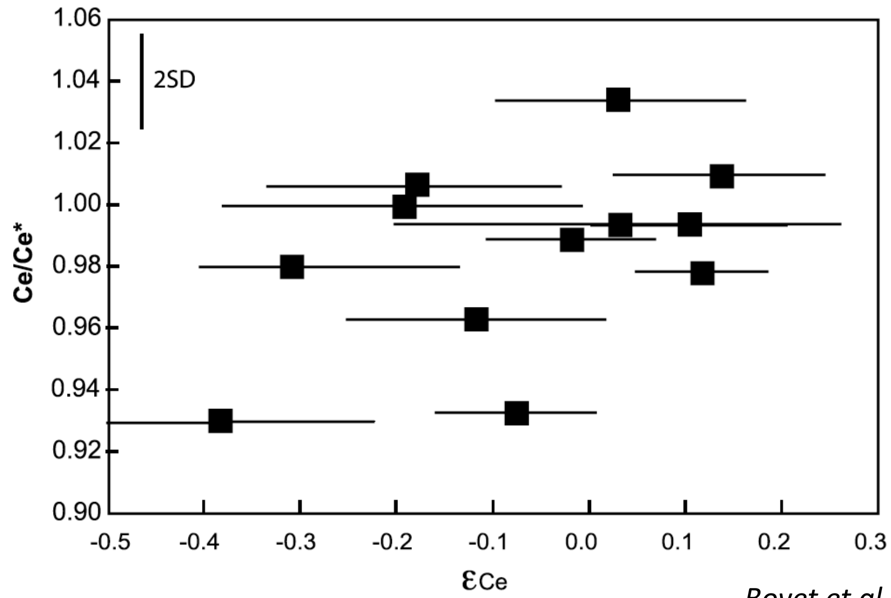
La-Ce systematics may help deciphering the nature of the sediments invloved in the source of OIB.

The chemistry of the sediments have changed through time: no Ce^{4+} before the Great Oxygenation Event (2.3-2.6 Ga)

Ce isotopic composition of Gough Island lavas (EM1):

- Only few samples have resolvable negative cerium anomalies (0.92-0.96)
- Ce/Ce*do not correlate with measured Ce isotope ratios (ε^{138}Ce)



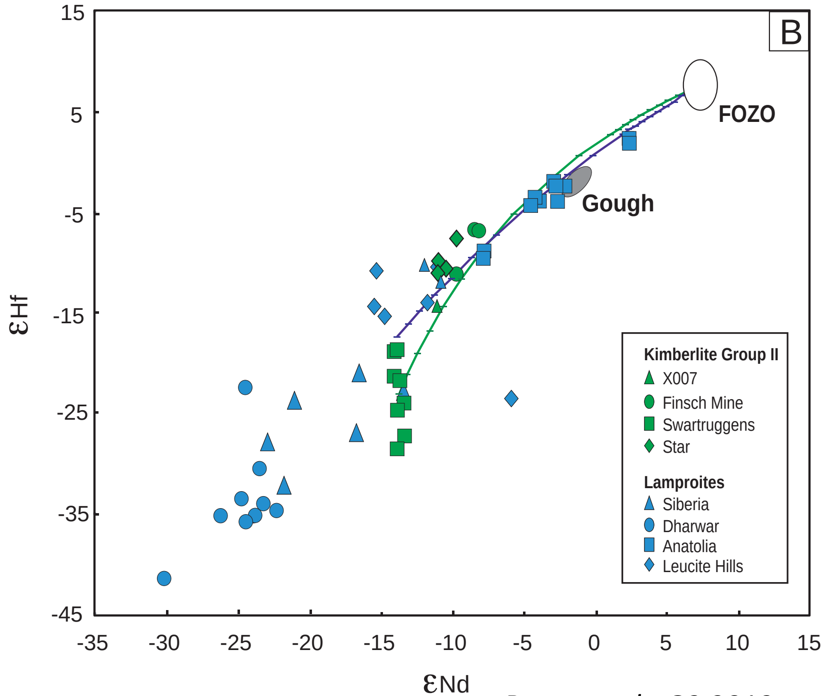


Boyet et al., G3 2019

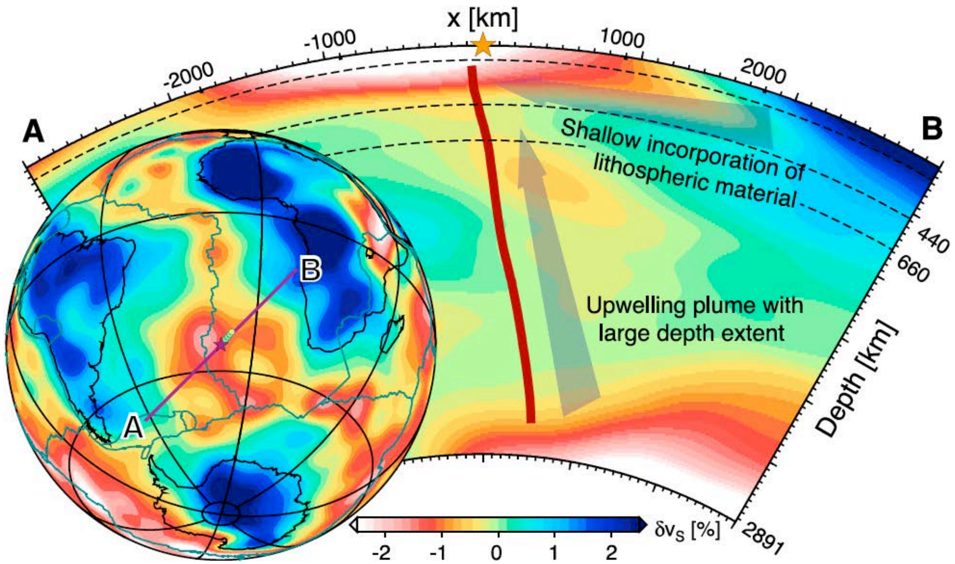
Measured ε^{138}Ce values between −0.39 and 0.15 are too low to give support to the incorporation of recycled pelagic sediments in the mantle source of Gough Island lavas.

Hf-Ce-Nd isotopic compositions of Gough Island lavas (EM1):

- Values are more consistent with the contribution in proportions between 10% and 30% of subcontinental lithospheric material.
- Gough classified as a deep-rooted mantle plume But samples have low $^3He/^4He$ (=MORBs).
- Negative, elemental cerium anomalies are repo-rted in subcontinental lithospheric (kimberlites and lamproites) from different locations.



Boyet et al., G3 2019



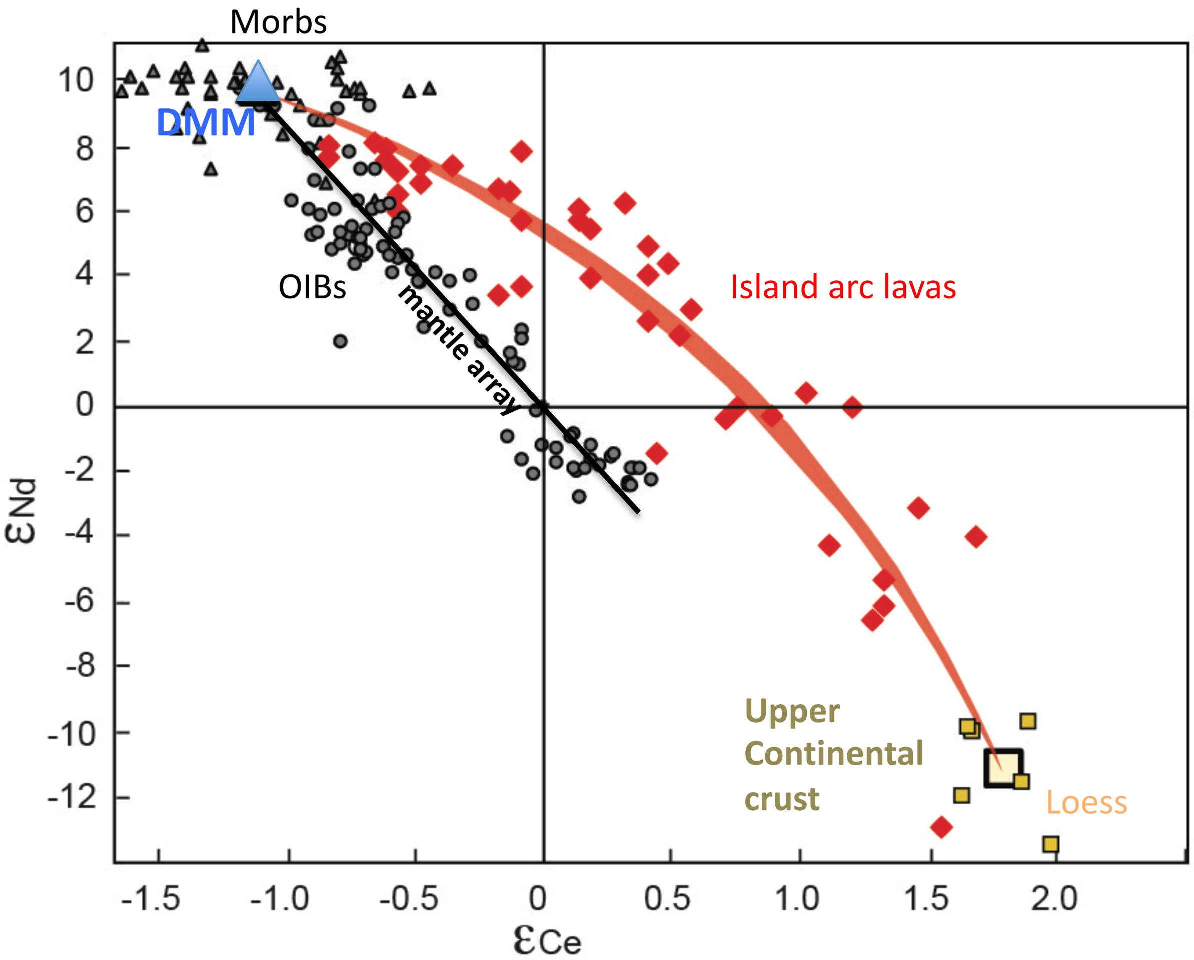
Geochemistry Geophysics Geosystems G3
Published by AGU and the Geochemical Society
Article
Volume 13, Number 1
10 February 2012
Q02004, doi:10.1029/2011GC003923
ISSN: 1525-2027

Shallow lithospheric contribution to mantle plumes revealed by integrating seismic and geochemical data

Jasper G. Konter
Department of Geological Sciences, University of Texas at El Paso, El Paso, Texas 79968, USA (jgkonter@utep.edu)

Thorsten W. Becker
Department of Earth Sciences, University of Southern California, Los Angeles, California 90089, USA

Global picture of the Ce-Nd isotope systematics :



Ce-Nd mantle array (Israel et al., EPSL 2019)
IAB: Lesser Antilles and Mariana (Bellot et al., GCA 2015 and Chem Geol 2018)
Bulk upper continental crust = average of 6 loess samples (Israel et al., EPSL 2019)

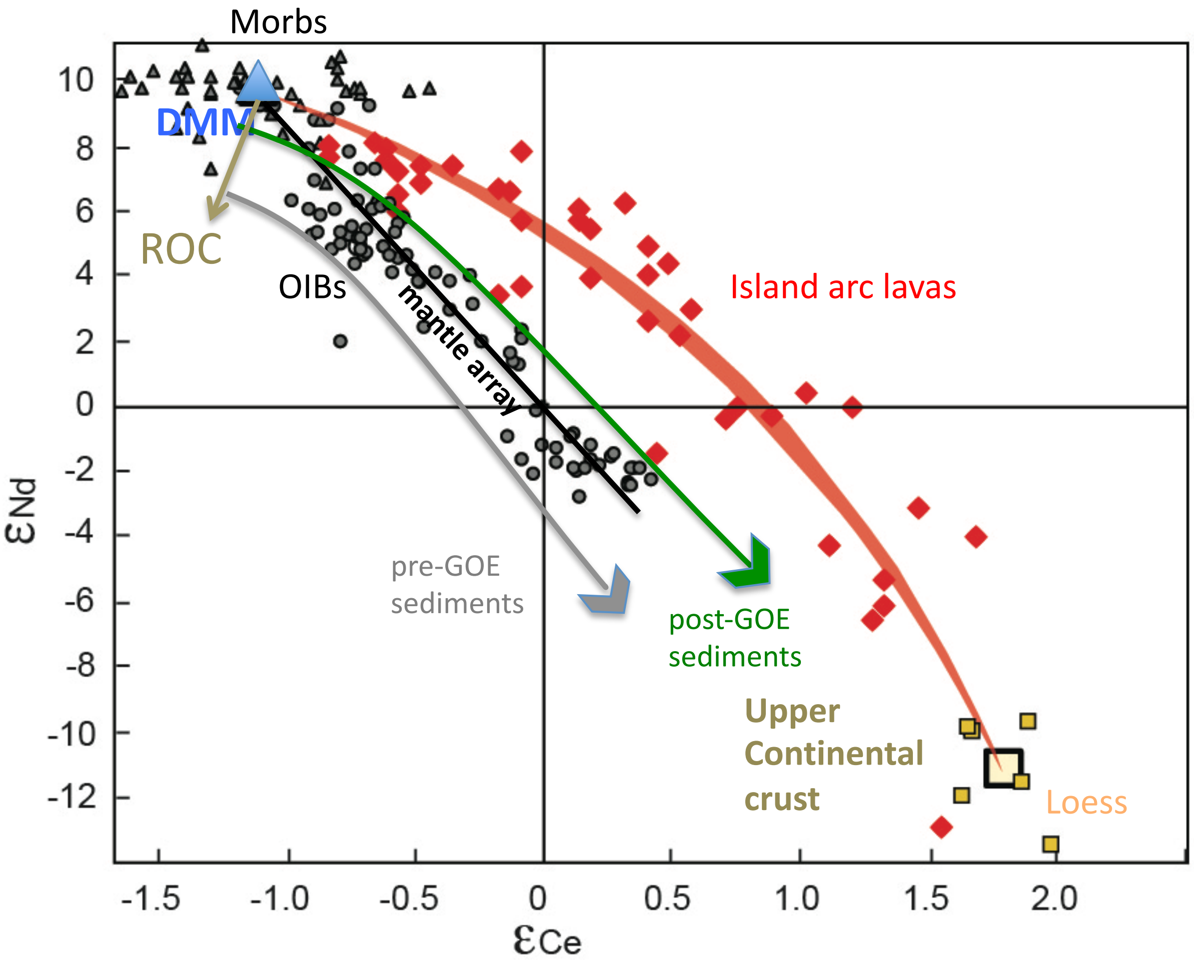
IAB Ce-Nd isotope signature explained by the involvement of sediments in the mantle source → recycling of trench sediments through active subduction.

How to form the mantle array ?

Participation of both oceanic crust and sediments in the mantle through time.

The most extreme EM-like signatures require the involvement of oceanic sediments that formed under reduced conditions before the Great Oxygenation Event at 2.4 Ga, and which are devoid of Ce elemental anomalies.

Global picture of the Ce-Nd isotope systematics :



IAB Ce-Nd isotope signature explained by the involvement of sediments in the mantle source → recycling of trench sediments through active subduction.

How to form the mantle array ?

Participation of both oceanic crust and sediments in the mantle through time.

The most extreme EM-like signatures require the involvement of oceanic sediments that formed under reduced conditions before the Great Oxygenation Event at 2.4 Ga, and which are devoid of Ce elemental anomalies.

Ce-Nd mantle array (Israel et al., EPSL 2019)
IAB: Lesser Antilles and Mariana (Bellot et al., GCA 2015 and Chem Geol 2018)
Bulk upper continental crust = average of 6 loess samples (Israel et al., EPSL 2019)

Isotope heterogeneities measured in OIBs
Recycled material *vs.* early-formed reservoirs

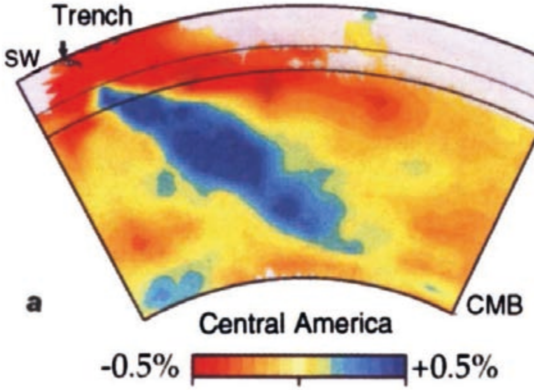
Long-lived systematics:

^{138}La-^{142}Ce systematics

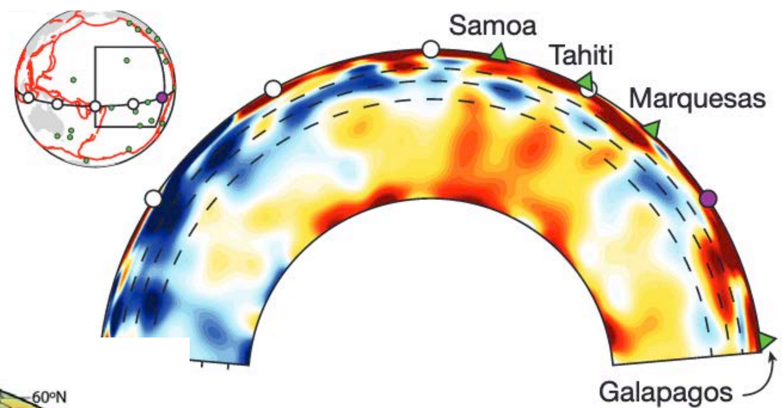
Short-lived systematics:

^{146}Sm-^{142}Nd, ^{182}Hf-^{182}W

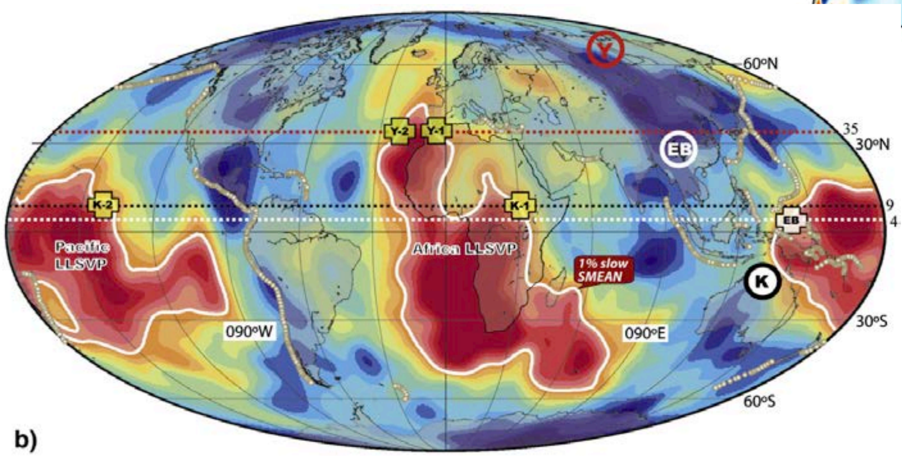
+ noble gas



van der Hilst et al., Nature 1997



French and Romanowicz Nature 2015

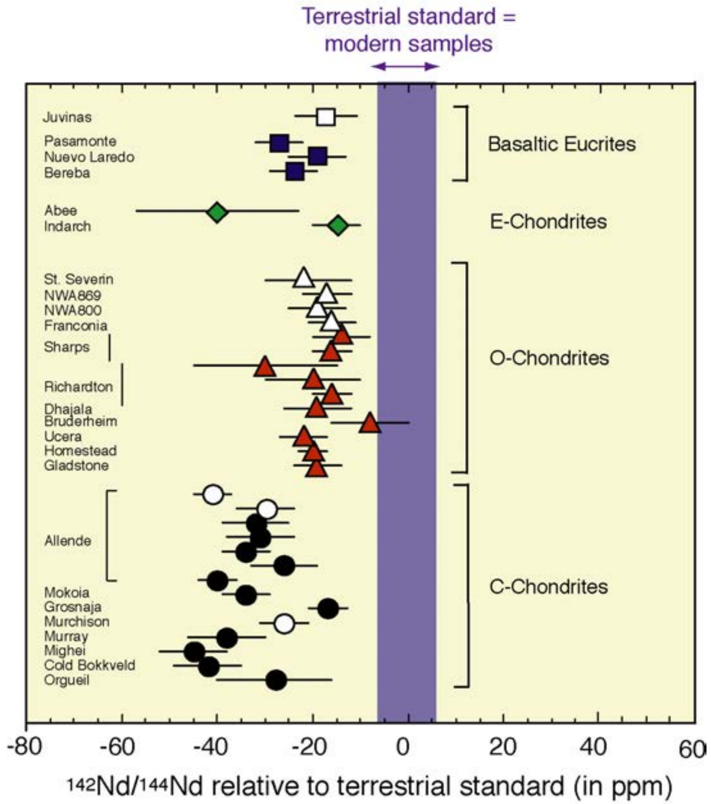


Torsvik et al., EPSL 2008

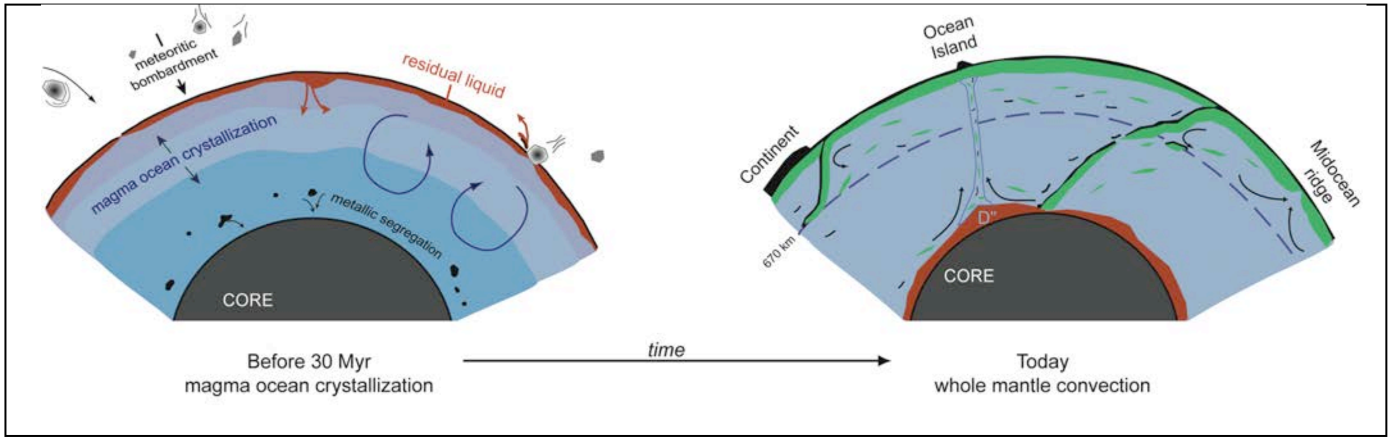
Back to 2005:

The first high-precision ^{146}Sm-^{142}Nd data measured on chondritic meteorites showed that their $^{142}Nd/^{144}Nd$ ratio were 20 ppm lower than that of most terrestrial rocks.

Evidence for a global differentiation of the Earth's mantle (Silicate Earth) within 30-50 million years of Earth's formation.



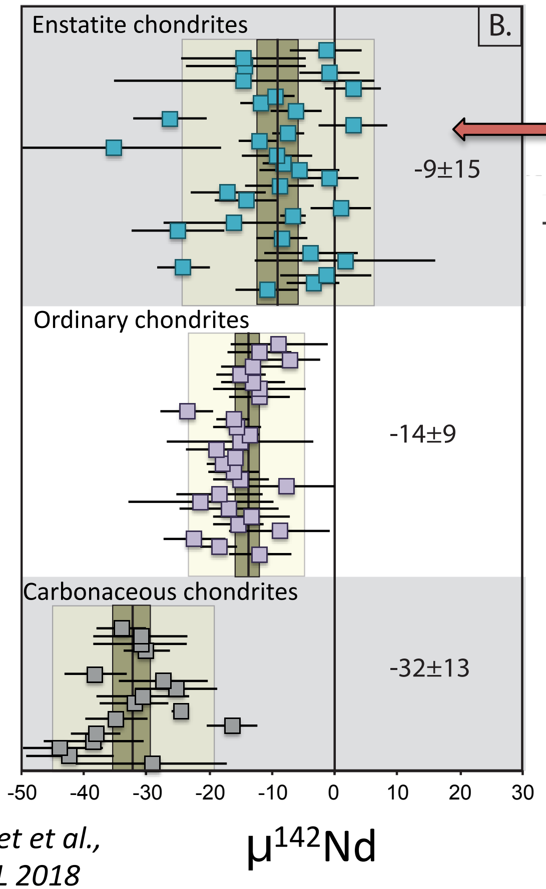
Boyet and Carlson, Science 2005

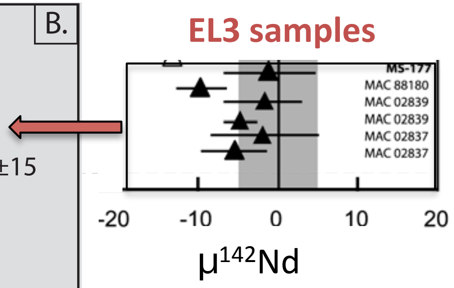


Early formed heterogeneities preserved in the deep mantle.

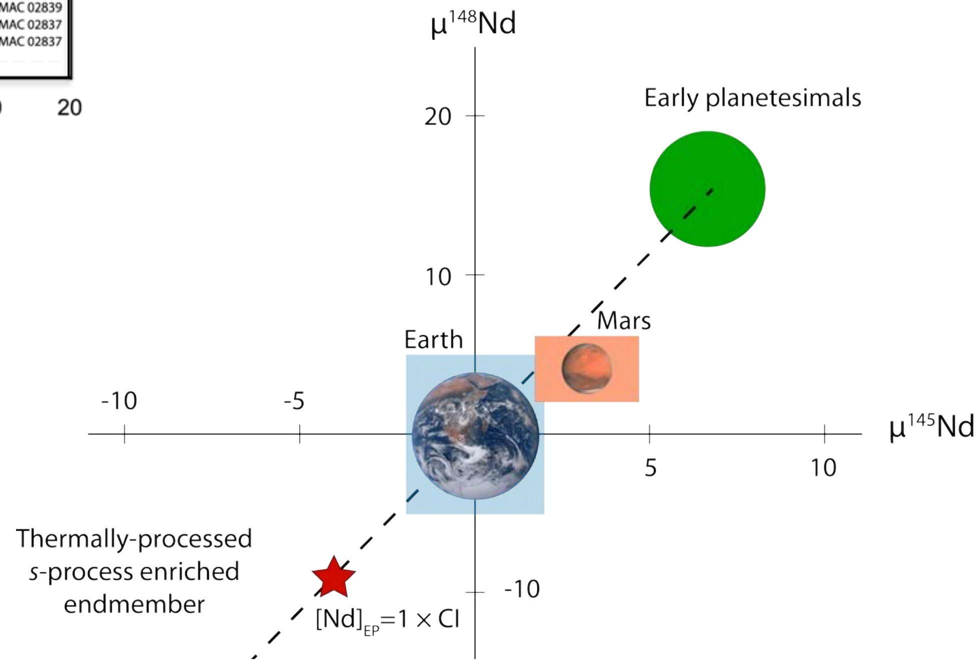
Where are we after 15 years of measurement?

- The different groups of chondrites have different ^{142}Nd signature.
- Enstatite chondrites (EC) have isotope signatures that are the closest to the Earth value.
- Nucleosynthetic anomalies: ^{142}Nd correlated with mass independent Nd isotope ratios (145, 148).





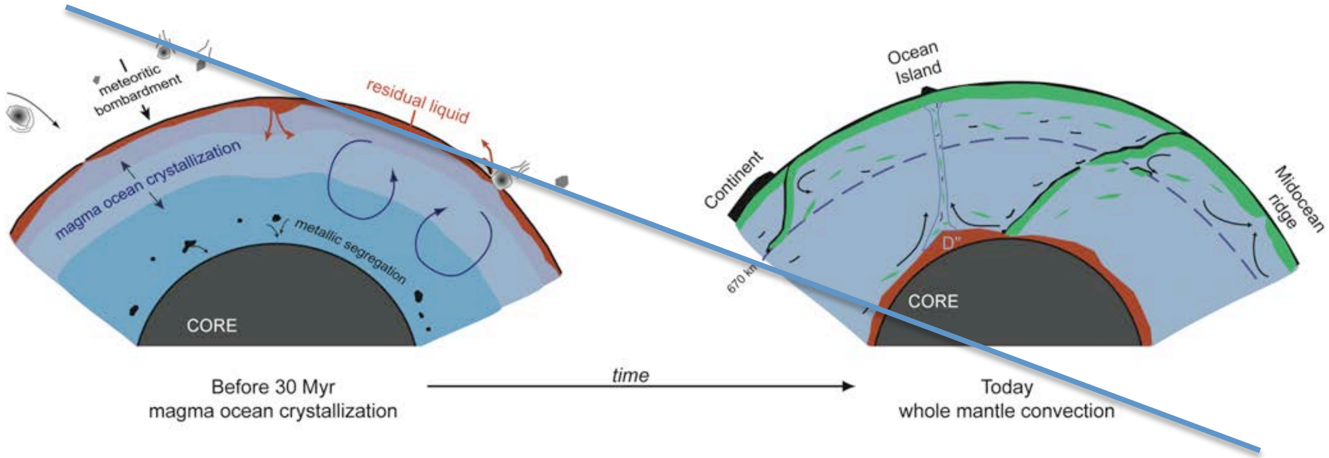
Boyet et al., EPSL 2018



Frossard et al., EPSL 2021

Where are we after 15 years of measurement?

- The different groups of chondrites have different ^{142}Nd signature.
- Enstatite chondrites (EC) have isotope signatures that are the closest to the Earth value.
- Nucleosynthetic anomalies: ^{142}Nd correlated with variations in mass independent Nd isotope ratios (145, 148).



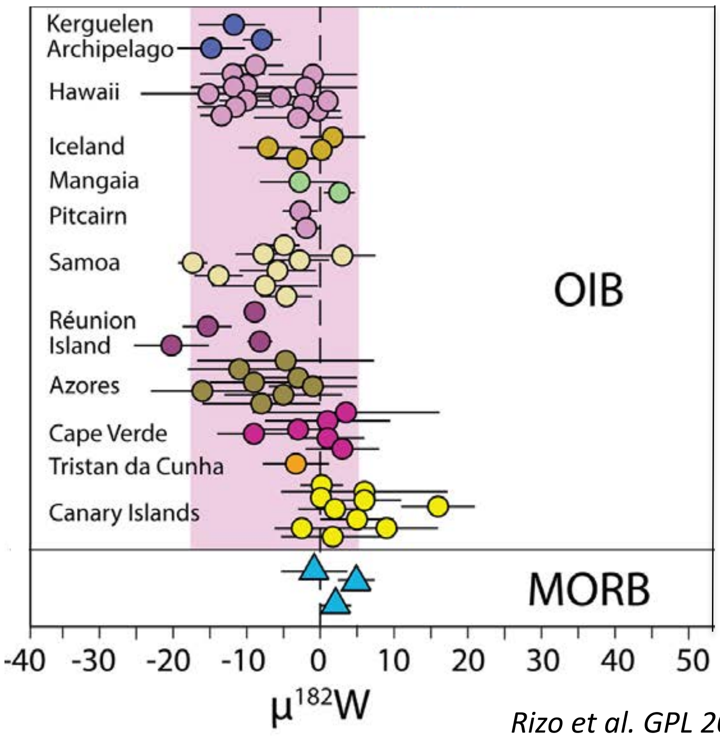
No proof for a **large** early-formed silicate reservoir hidden in the deep mantle and preserved form mantle convection since the Hadean.

→ Can small size heterogeneities be preserved over 4.5 Ga?

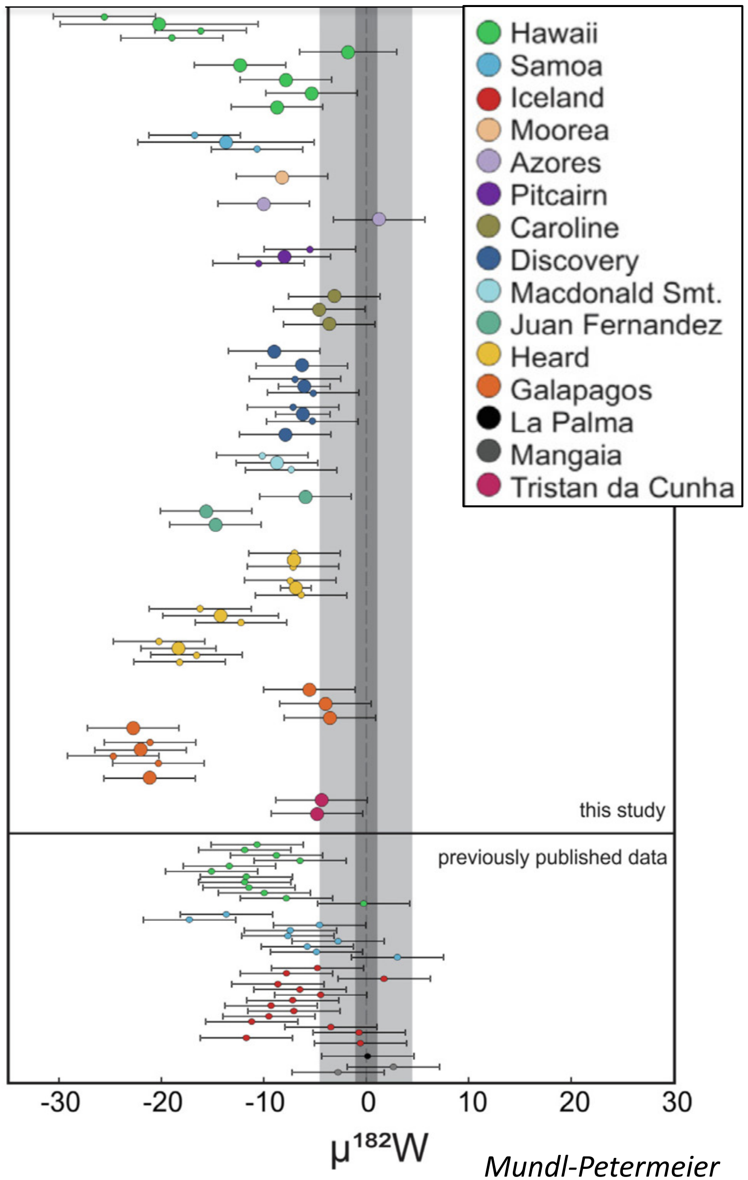
^{182}Hf-^{182}W systematics:

- Negative ^{182}W anomalies measured in OIB.
- Core: reservoir with negative ^{182}W signature (outer core: $\mu^{182}W$=-200)

Do OIB - sample an early-formed mantle reservoir?
- or trace core-mantle exchange?



Rizo et al. GPL 2019



Mundl-Petermeier et al. GCA 2020

^{182}Hf-^{182}W systematics:

- Negative ^{182}W anomalies measured in OIB.
- Core: reservoir with negative 182W signature (outer core: μ^{182}W=-200)

Early-formed mantle reservoir

Are μ^{182}W signatures correlated to μ^{142}Nd?

Easy to decouple:

- They have different lifetime.
- Parent-daughter elements have different chemical properties.

Core-mantle exchange

Are μ^{182}W signatures correlated to Highly Siderophile Element abundances ?

Easy to decouple:

- Unlike W, HSE are not incorporated in the Si-Mg-Fe oxide formed by exolution from the core.
- The siderophile behavior of W change with oxygen fugacities.

Geochemical Perspectives Letters
© 2020 The Authors
Published by the European Association of Geochemistry

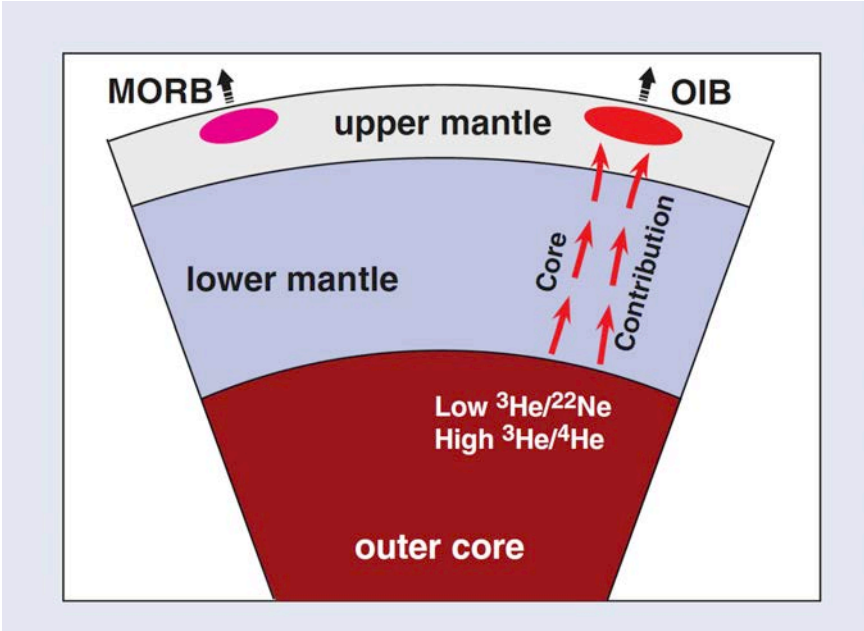
Potential of Earth's core as a reservoir for noble gases: Case for helium and neon

M.A. Bouhifd[1,2*], A.P. Jephcoat[2,3], D. Porcelli[2], S.P. Kelley[4,§], B. Marty[5]

The core is a reservoir that has long been neglected by geochemists.

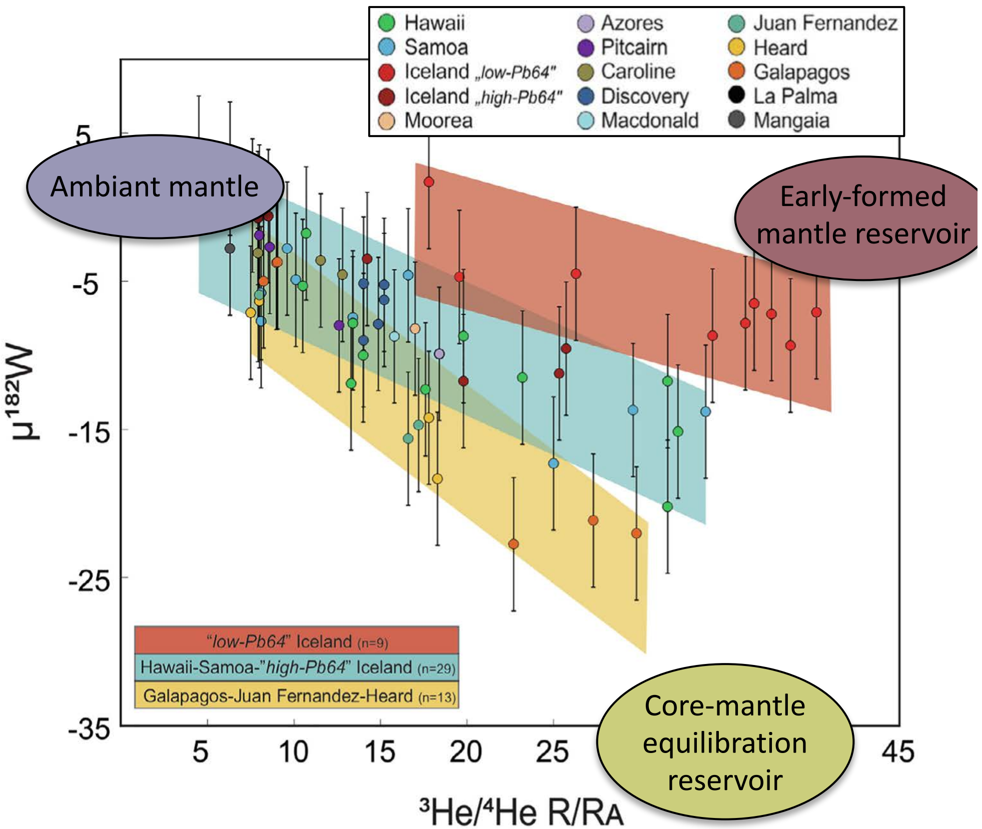
Metal-silicate partition coefficients measured at high P, T conditions show that the core stored **He**, **Ne**, I (^{129}I–^{129}**Xe**).

The measured noble gas signature in some OIBs could be influenced from a small core component.

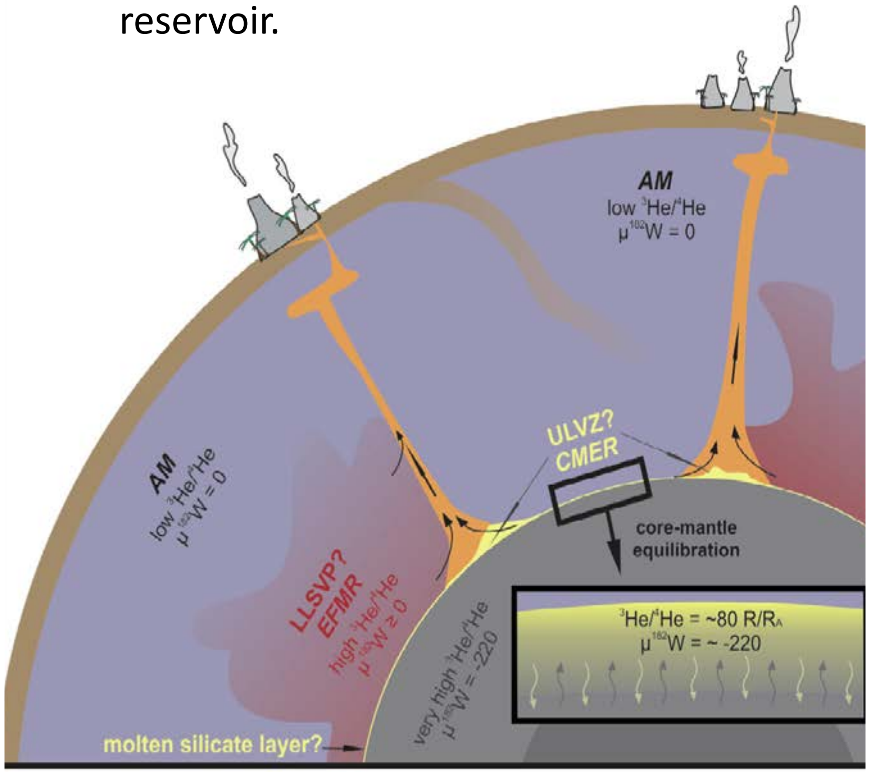


See also:
Armytage et al. EPSL 2013; Bouhifd et al. Nature Geoscience 2013; Jackson; Kurz and; Porcelli and Halliday EPSL 2001

- Differently sloping He-W trends for variable OIB systems.
- Iceland: two separate trends broadly defined by age.
- The most negative ^{182}W values are reproduced with a small (<0.3%) proportion of this core-mantle equilibrated reservoir.



Mundl-Petermeier et al. GCA 2020



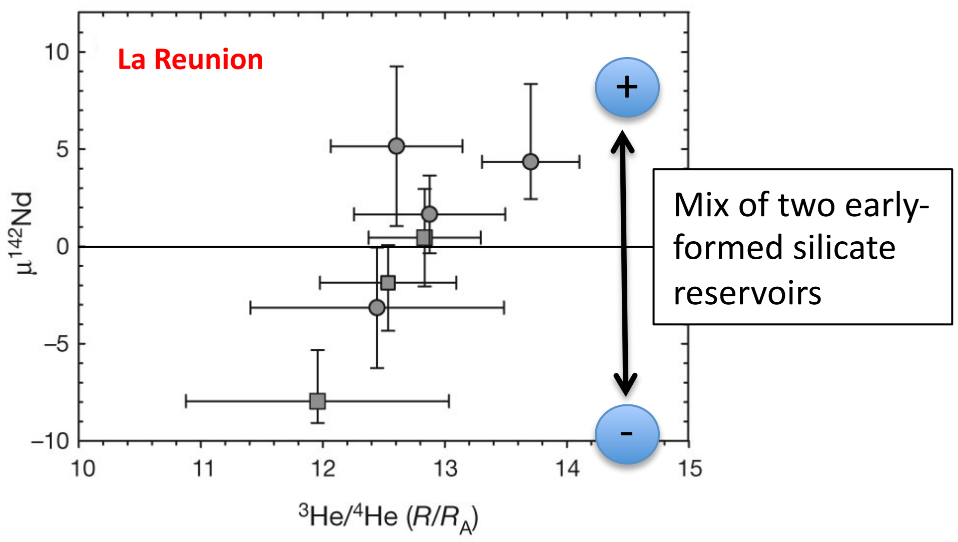
Link with seismic tomography:
LLSVP: Early formed mantle reservoir (dense thermochemical pile).
ULVZ: Partially molten zone that could equilibrate with the outer core.

^{146}Sm-^{142}Nd systematics:

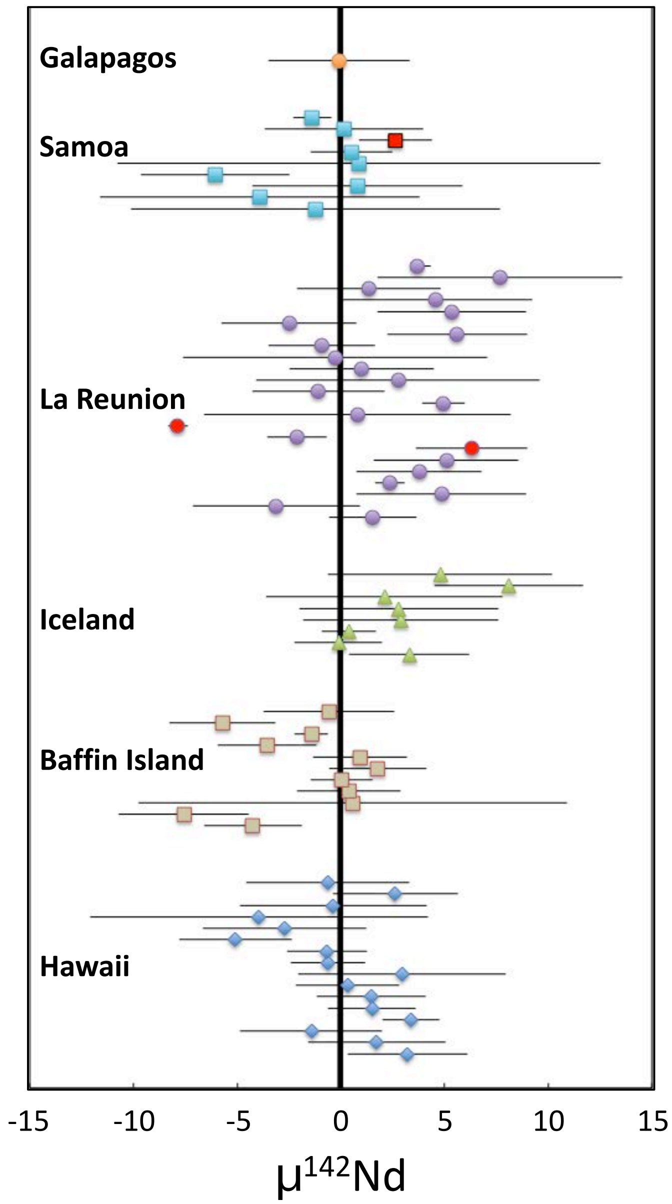
- Track hadean (500 Ma) silicate differentiation processes.
- ^{142}Nd anomalies measured in Archean rocks (Greenland, Canada, South Africa, etc).

^{142}Nd measurements on OIBs:

- Very few samples have resolved ^{142}Nd anomalies (La Reunion, Samoa).
- No global correlation with ^{3}He/^{4}He, ^{182}W.



Data from Andreasen et al 2008; Burkhardt et al. 2016; de Leeuw et al 2017; Garçon et al. 2018; Jackson and Carlson 2012; Horan et al. 2018; Hyung and Jasobsen 2020; Murphy et al 2018; Peters et al 2018; Saji et al. 2016.



Recycling

- Combining La-Ce and Sm-Nd systematics may help deciphering the nature of recycled component in the mantle plume source.

- Pre vs post GOE sediments.

Mass-independent S isotopic fractionations measured in olivine-hosted suggest the recycling of surface materials that existed in a reduced atmosphere before the GOE (Cabral et al., 2013; Delavault et al., 2016).

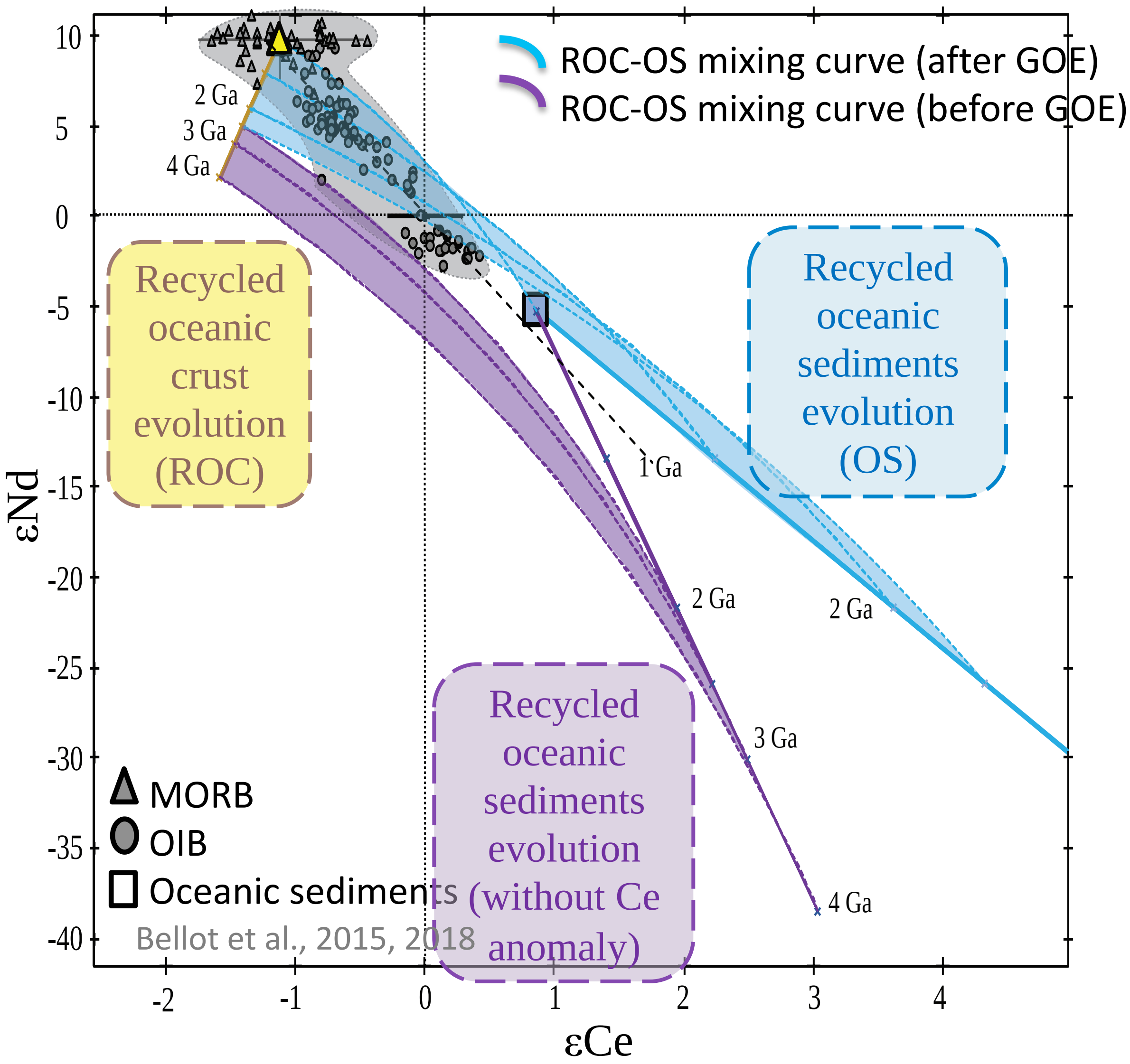
Early-formed

- The chemical signature of the core is detected in OIBs (^{182}W).

- Both depleted and enriched early-formed silicate reservoirs sampled in la Reunion. These reservoirs have survived in the deep Earth for billions of years, despite sustained mantle convection.

- ^{142}Nd anomalies have been resolved only for samples from la Reunion. More high-precision data are necessary.

Recycling of surface material



Modelling Ce-Nd isotopic composition of recycled surface material during the Earth's history :

- Evolution of oceanic crust
- Evolution of oceanic sediments

⚠ Ce^{4+} under oxidised conditions

➔ Before/after GOE (2.4 Ga)

(Holland 2002, GCA)

Following calculations described in Chauvel et al., 2008, Nature Geo