This is a pre print version of the following article:

Thermal effects of pyroxenites on mantle melting below mid-ocean ridges / Brunelli, Daniele; Cipriani, Anna; Bonatti, Enrico. - In: NATURE GEOSCIENCE. - ISSN 1752-0908. - 11:7(2018), pp. 520-525. [10.1038/s41561-018-0139-z]

Terms of use:

The terms and conditions for the reuse of this version of the manuscript are specified in the publishing policy. For all terms of use and more information see the publisher's website.

24/12/2024 19:31

1 Melting below Mid Ocean Ridges: thermal effects of pyroxenites in the peridotitic

Daniele Brunelli^{1,2*}, Anna Cipriani^{1,3*}, Enrico Bonatti^{2,3}

- 2 mantle
- 3

4

1 Dipartimento di Scienze Chimiche e Geologiche, Università di Modena e Reggio 5 6 Emilia, Via Campi 103, 41125 Modena, Italy. 2 Istituto di Scienze Marine, CNR, Via Gobetti 101, 40129 Bologna, Italy. 7 3 Lamont Doherty Earth Observatory, Columbia University, Palisades, New York 10964, 8 9 USA. 10 11 * Corresponding authors: daniele.brunelli@unimore.it; anna.cipriani@unimore.it 12 13 After travelling in the Earth's interior for up to billions of years, recycled material once 14 injected at subduction zones can reach a subridge melting region as pyroxenite dispersed 15 in the host peridotitic mantle. We studied genetically related crustal basalts and mantle peridotites sampled along an uplifted lithospheric section created at a segment of the Mid 16 Atlantic Ridge through a time interval of 26 Ma. The arrival of low-solidus material into 17 the melting region forces the elemental and isotopic imprint of the residual peridotites and 18 19 of the basalts to diverge with time. We show that a pyroxenite-bearing source entering the subridge melting region induces undercooling of the host peridotitic mantle, due to 20 21 subtraction of latent heat by melting of the low-T solidus pyroxenite. Mantle undercooling 22 in turn lowers the thermal boundary layer leading to a deeper cessation of melting. A 23 consequence is to decrease the total amount of extracted melt, hence magmatic crustal 24 thickness. The degree of melting undergone by a homogeneous peridotitic mantle is higher 25 than the degree of melting of the same peridotite but veined by pyroxenites. This effect, thermodynamically predicted for a marble-cake type peridotite-pyroxenite mixed source, 26 27 implies incomplete homogenisation of recycled material in the convective mantle.

30 Mantle rising beneath the 60,000 km long Mid Oceanic Ridge system contains, as in a 31 slow-motion movie, a record of ancient upwelling and melting events and of interaction 32 with subduction or hot spot-derived components. It is difficult to reconstruct temporal 33 records of these ancient events due to lack of suitable samples; however, we were given the opportunity to explore the temporal evolution of the oceanic lithosphere composition 34 35 and structure at 11°N along the Mid Atlantic Ridge (MAR) where an uplifted > 300 km long sliver of lithosphere exposes a basal mantle peridotite unit, lower crustal gabbros, a 36 dyke complex and erupted basalts¹⁻³. This lithospheric section (Vema Lithospheric Section 37 38 or VLS) was generated at an 80 km long segment of the MAR (EMAR segment, Supplementary Fig. S1) during a 26 Ma time interval^{1,2,4–6}. Both crustal basalts and their 39 mantle peridotite parents have been densely sampled at the VLS along a seafloor spreading 40 flow line⁴ allowing comparisons of their isotopic and elemental composition throughout 41 the 26 Ma time interval^{1,2,4-6} (Fig. 1). 42

Surprisingly, temporal variations of mantle degree of melting estimated from basalt Na^{7,8} 43 anti-correlate with the degree of melting derived from spinel Cr# of the peridotites^{9,10}. 44 45 although the two curves converge to a common value in the youngest 3 Ma stretch of the VLS (Fig. 1). Older, isotopically enriched basalts display the lower Na₈ values of the entire 46 VLS, suggesting they were generated by a higher degree of melting of their mantle source; 47 in contrast, the genetically associated mantle peridotites record a relatively low extent of 48 49 melting, in agreement with a thinner crust recorded by geophysical data¹. This anticorrelation contrasts with what is inferred to be the "normal" signature of partial melting at 50 51 mid-ocean ridges.

52 We offer a solution to this conundrum by suggesting that a subridge variably veined 53 mantle hosts chemically enriched, fertile, low-T melting components, i.e. pyroxenites. 54 Thermodynamic-based studies predict dramatic effects when pyroxenites are present in the mantle source and partially melt along a decompressive path^{11–15}. Low-T solidus 55 components lower the extent of melting of the host peridotite due to subtraction of latent 56 heat of fusion^{13–15}. Pyroxenites melt preferentially, generating isotopically enriched, low 57 Na₈ melts and cooling the host mantle peridotites, thereby lowering the degree of melting 58 of the peridotite mantle in proportion to its pyroxenite content¹³. In this work we account 59 for variable extents of the melting column by assuming that different pyroxenitic contents 60

61 result in variable extent of undercooling before the ambient peridotite starts melting. This 62 situation mimics varying the potential temperature of the mantle resulting in changes in the 63 length of the melting column. 64 65 Temporal variability of crustal thickness and mantle degree of melting 66 67 Basalt Nd, Sr and Pb isotopes vary coherently along the 26 Ma-long VLS section, 68 showing a decrease in isotopic enrichment towards younger ages that hints at temporal 69 variations of composition and thermal state of the rising mantle⁸. We represent these 70 variations as discrete steps (Fig. 1a), defining three time domains: 0-2 Ma, 2-13 Ma and 71 72 13-26 Ma (Supplementary Tables S1-S3). 73 The basalts major element composition also varies with age, the older samples being poorer in sodium than the younger ones. Na_8 , an inverse proxy of the degree of melting 74 experienced by the mantle column^{7,8} (Supplementary Table S2), is on average lower in the 75 VLS older basalts; thus, they were apparently produced by a degree of melting higher than 76 the younger basalts (Supplementary Fig. S1a). However, Na₈ has been defined for a 77 homogeneous lherzolitic source⁸. A heterogeneous source generates complex melt mixing 78 patterns depending on the relative extent of melting, homogenisation and enrichment of 79 each component $^{16-18}$. For this reason we adopt here the expression "apparent" degree of 80 melting. 81 82 The proxy equivalent (but reverse) to basalt Na₈ is in peridotites the Cr# (Cr # = Cr/(Cr + Al)) of spinels and pyroxenes^{9,10}. During the last 26 Ma, peridotite spinel 83 Cr# increased along the VLS on average from 22 to 37 (Supplementary Fig S1c) 84 suggesting that the amount of magma delivered at ridge axis increased through time, in 85 agreement with gravity profiles running along spreading-flow-lines (Supplementary Fig. 86 S1c), revealing that crustal thickness increased from 4.8±0.2 km in the 22-27 Ma interval 87 to 5.4 ± 0.2 km between 0-5 Ma^{1,4}. 88 Based on calibrations of Warren, 2016^{19} , the degree of melting (F_{max}) of the VLS 89 peridotites increased from 8.0 to 14.2 F% toward younger crustal ages (average 10.8, Fig. 90 2). MORB glasses Na₈ increased with time along the VLS from 2.6 to 3.0 on average 91 (Supplementary Fig. S1a). F_{max} in the basalts can be estimated according to 7 and compared 92 to the F_{max} of the mantle peridotites. Comparing temporal sections of mantle residua and of 93 their melt products must take into account a time-delay in the emplacement of the mantle 94

peridotites in the oceanic crust. According to^{1,4} we corrected the crustal ages of the mantle
rocks relative to that of basalts by a relative time lag of 2.2 Ma (see online Methods: Age
Correction).

The calculated apparent F_{max} of MORB glasses vary little during the 26 Ma-long VLS stretch (Fig. 1b) with values ranging from 18.0 to 15.8 F% (ave. 16.7), significantly higher than those estimated from mantle residual peridotites (Fig. 1b). A striking feature of the Na₈ degree of melting curve is the decrease of the apparent F_{max} through time that countertrends with both the associated mantle peridotites degree of melting curve and the gravity-inferred crustal thickness (Fig. 1b; Supplementary Fig. S1c).

104

105 Significance of the decoupling

106

107 The degrees of melting estimated from the mantle peridotites and from the basalts can 108 be generated by variations of mantle potential temperature, mantle composition and 109 spreading rate. Changes in mantle temperature or source fertility will result in coherent 110 changes of the degrees of melting estimated from basalts and from peridotites. Similarly, 111 changes in spreading rate cannot decouple the behaviour of residual mantle and extracted basalts, because, in a passive upwelling scenario, decreasing the spreading rate lowers the 112 thermal state of the entire melting region, and vice versa²⁰. During the last 26 Ma the half 113 spreading rate at the EMAR segment decreased from 17.2 mm/a (Chron 6) to 16.9 mm/a 114 (Chron 5) to present-day 13.6 mm/ $a^{21,22}$ (Supplementary Fig. S1b). Such decrease of 115 spreading rate toward younger ages should lower the mantle degree of melting by about 116 1%²⁰; thus, the increase in degree of melting recorded by the VLS mantle peridotites must 117 be caused by processes other than changes in spreading rate, mantle temperature or 118 119 fertility.

120 We consider now a heterogeneous mantle source. Thermodynamic modelling of 121 melting a two-component mantle source predicts that when a fertile heterogeneity, i.e. 122 pyroxenite, starts melting, the temperature of the whole mantle parcel is lowered due to the latent heat of melting¹⁵. If the heterogeneity is less than a few kilometres, some heat is 123 124 transferred from the peridotite into the melting heterogeneity increasing its melt productivity while cooling the surrounding mantle^{13–15}. Accordingly, the vertical interval 125 where only pyroxenites undergo melting represents an undercooling region whose extent is 126 127 proportional to the amount of pyroxenites (Fig. 2). It follows that, for a given P-T 128 decompression path, the degree of melting undergone by a homogeneous peridotitic

mantle is higher than the degree of melting of the same peridotite but veined bypyroxenites.

131 A lithologically homogeneous mantle source, resulting in coherent estimates of the 132 degree of melting between peridotites and basalt proxies, is approximated in the younger 133 (< 5 Ma) portion of the VLS where both basalt- and peridotite-derived F% converge 134 toward a common value. We assume that the present-day subridge mantle (Vema 135 Unveined Mantle or VUM) contains negligible amounts of pyroxenites, not sufficient to perturb thermally the melting process of the host mantle peridotite. Thus, for this region 136 the Na₈-derived degree of melting is in line with its original interpretation^{7,8,23}. 137 In contrast, in a veined mantle scenario, degrees of melting estimated from peridotites 138 139 and from basalts differ strongly. While the Cr# records the true F_{max} of the ambient peridotite, the pooled melts aggregate the compositional signal of both (low F) peridotitic 140 and (high F) pyroxenitic melts¹⁸. We propose that the low degree of melting of the older 141 portion of the VLS peridotites is due to heat consumption during preferential melting of a 142 143 pyroxenitic component at nearly constant mantle potential temperature. Along the VLS we 144 have decreasing quantities of pyroxenites injected into the melting region, with consequent 145 decrease of the undercooling effect and expansion of the anhydrous peridotite melting 146 region.

We tested this hypothesis by modelling the decompressive adiabatic melting of a mixed 147 source based on the experimental-parameterized algorithm Melt-PX²⁴. Mantle potential 148 temperatures have been constrained using the passive flow temperature field model of 149 Bonatti et al., $(2003)^1$ giving a mantle Tp = 1350 °C. For this temperature and a lherzolitic 150 151 source containing 15% clinopyroxene, Melt-PX calculations overestimate crustal thickness 152 and mantle degrees of melting observed at the EMAR segment (Fig. 3). These calculations assume that melting ceases at the base of the crust, a boundary condition acceptable for 153 high mantle Tp settings as in fast spreading ridges or hotspots^{24,25}. They represent the 154 model maximum allowed thickness at a given thermal setting (Fig. 3). Mantle flow 155 models^{1,26} predict the end of melting to occur at $P_f \approx 0.7$ GPa, well below the base of the 156 crust. This condition applies to low-spreading ridges due to heat conduction to the surface 157 resulting in a deep transition from the conductive to the convective thermal region^{20,26–28}. 158 As low-melting component we adopted the silica deficient pyroxenite $M7-16^{29}$ for 159 reasons defined in the next section. We observe that an increase in the fraction X_p of 160 161 pyroxenite in the mantle is paralleled by a decrease of degree of melting of the host

162 peridotite (F_{π}) (Fig. 3) depending also on the final pressure of melting (varying in the

163 range 0.3-1.1 GPa, Fig. 3).

164 Integration of the melt productivity of the host peridotite and of the pyroxenite along an adiabatic path, weighted by their relative abundance, allows estimating magmatic crustal 165 thickness. Lambart et al., $(2016)^{24}$ show that the total magmatic productivity increases 166 proportionally to the amount of pyroxenite in the source. This observation apparently is in 167 168 contrast with the increase toward younger ages along the VLS of gravity-inferred crustal 169 thickness, paralleled by a decrease of the estimated amount of pyroxenites dispersed within 170 the mantle (Fig. 2, Supplementary Fig. S1c). This contradiction is solved considering that 171 increasing the amount of low-melting lithologies enhances the undercooling of the host peridotitic mantle due to heat diffusion into the melting pyroxenite¹³. Undercooling 172 estimated by Melt-PX calculations can reach up to 40 °C for adiabatic melting under the 173 174 assumed conditions. Reduced undercooling due to a decrease of the mantle pyroxenite 175 fraction during melting results in shallowing the final pressure of melting from ≈ 1.1 to 0.7 GPa going from the oldest to the youngest VLS sectors (Fig. 3, right panel). 176 177 These observations and numerical experiments reveal that in slow-spreading ridges, at constant mantle potential temperature, the arrival of a pulse of pyroxenites in the mantle 178 179 source region will cause a reduction of crustal thickness. The countertrend of crustal 180 thickness and degree of mantle melting with spreading rate along the VLS is a positive test 181 of our hypothesis.

182

183

184 Composition of the low-solidus component and effects on Na8

185

The effect of pyroxenite-derived melts on the final composition of the pooled MORB 186 depends upon the nature of the heterogeneities and on their dilution in the peridotite-187 derived melt^{17,30–32}. In mid-ocean ridge settings most pyroxenites produce melts with 188 major-element composition similar to those derived from peridotite³³. Hence, little 189 190 reactivity is expected when pyroxenite-derived melts mix with mantle peridotite-derived melts³⁴. We thus explore the possible composition of pyroxenites dispersed in the VLS 191 192 mantle by considering mixing of silica-deficient (SD) and silica-enriched (SE) pyroxenitederived melts with peridotite-derived melts. In a Na₂O versus MgO diagram, young VLS 193

194 lavas plot at higher Na₂O content than the older ones (Supplementary Fig. S2). We assume 195 that the youngest VLS Na-rich lavas, i.e. those showing a degree of melting similar to that 196 of the associated peridotites, derive from melting of the VUM source defining a peridotite 197 primitive melt composition that matches the VUM average Na_8 and F% (Supplementary 198 Table S2). We then calculated mixing lines between the VUM primitive melt and 199 pyroxenitic-derived melts obtained experimentally at variable degrees of melting from 200 different sources (Supplementary Fig. S2-S3). Melt mixing affects the estimated Na₈, and 201 consequently the estimated apparent degree of melting, depending on the absolute Na 202 content and Mg/Na ratio of the added melt fraction (Supplementary Fig. S3). Inferred Na₈ 203 and apparent F of the mixed compositions show that SE-derived melts do not reproduce 204 the observed variability for reasonable fractions and degrees of melting of the pyroxenitic-205 derived components (Supplementary Fig. S3). Among the SD pyroxenites only those 206 having high Mg/Na ratios, as M7-16, match the VLS observed variability. It is worth noting that the mixed melts matching the VLS data are those obtained at high F (F=65%), 207 a value close to those predicted by thermodynamics $^{13-15}$. Based on these calculation the 208 209 VLS variability can be approximated by linear mixing of a VUM primitive melt with ca. 210 30% M7-16 type pyroxenite-derived melt.

211

212

213 Size and nature of mantle domains

214

An important result of thermodynamic modelling^{13,14} is that the undercooling inferred 215 216 from F% decoupling occurs only for a composite source where a lower-T solidus component is finely dispersed in a high-T-solidus host to ensure efficient heat diffusion. 217 Adopting the calibration of ¹³ for tabular heterogeneities limits their size to be < 1 km, a 218 dimension close to those estimated from seismic scatter (<10 km)³⁵. Cryptic stripes of 219 comparable size (4 km) have been described at the SEIR³⁶ and modelled based on Nd-Hf 220 MORB variability by ³⁷. The compositional trend observed along the VLS suggests a 221 222 decreasing decoupling of the measured parameters. The lateral extension of the melting region reaches 300 km in the spreading direction, ca. 70 km along axis²⁶. A single large 223 224 heterogeneity in the older mantle section would have measured tens of km in width, 225 excluding efficient heat diffusion within the heterogeneity itself. We deduce that the older 226 mantle section contained a cluster of small, tabular, low-T solidus components as in Figure 227 2, decreasing in time from ca. 15% to 0% of the volume.

VLS basalts ¹⁴³Nd/¹⁴⁴Nd versus ²⁰⁸Pb/²⁰⁶Pb ratios duplicate one of the mixing trends 228 recognized in South Atlantic basalt suites^{38,39} (Supplementary Fig. S4), suggesting that 229 those endmembers are ubiquitous in the sub-Atlantic mantle. 230 VLS glasses ¹⁴³Nd/¹⁴⁴Nd and ⁸⁷Sr/⁸⁶Sr ratios vary in a restricted range (0.51295-231 0.51317 and 0.70258-0.70351 respectively, Fig. 1, S5, Online Methods); in contrast, 232 mantle peridotite clinopyroxenes display a large scatter (¹⁴³Nd/¹⁴⁴Nd: 0.512024-0.513616; 233 ⁸⁷Sr/⁸⁶Sr: 0.702220-0.705508, age corrected values). This different compositional scatter 234 can be generated by chromatographic dispersion in the melting column⁴⁰ or through time 235 by reactive melt infiltration and veining 41,42 . 236 The VLS oldest basalts show the highest apparent degree of melting and the most 237 238 enriched Sr-Nd-Pb isotopic signature (Supplementary Fig. S4-S5). We suggest that their 239 compositions reflect a larger contribution of pyroxenite-derived melts. As a result, the 240 peridotites of the older domain are less affected by decompression melting, and record lower degrees of melting, possibly preserving their original DMM isotopic fingerprint. In 241 242 contrast, the VLS younger basalts received a negligible contribution of pyroxenite-derived melts. Unfortunately, we do not have enough data on the mantle peridotites of this young 243 244 VLS stretch because they are still buried below the sea floor; however the few available samples indicate that this parcel of peridotitic mantle underwent high degree of melting. 245 246 247 248 249 Distribution of pyroxenites along Mid Ocean Ridges 250 251 We attempt now to extend our findings to other portions of the mid ocean ridge system and interpret the chemistry of genetically related basalt/peridotite in terms of the 252

proportion of pyroxenite dispersed in the mantle source. Only two stretches of the global

254 MOR system have basalt-peridotite pairs sampled densely enough to allow first order

observations: the northern Mid Atlantic and the Southwest Indian Ridges^{19,43}. In both cases

along axis mantle peridotites record an extent of melting systematically lower than thatrecorded by the associated basalts (Fig. 4).

In light of our findings we propose that pyroxenites are widely distributed in subridge mantle sources proportionally to $\Delta F_{\pi}^{\beta} = F_{\beta}^{app} - F_{\pi}$ the difference between the degree of melting derived from basalts and that derived from peridotites (see Online Methods). This

261	interpretation, if correct, should be confirmed by a correlation between the extent of ΔF_{π}^{β}
262	and chemical indicators of the presence of pyroxenite in the source, e.g. the isotopic ratios
263	of radiogenic elements, expected to be enriched in recycled materials. A broad negative
264	correlation appears between the measured ΔF_{π}^{β} and the basalt ¹⁴³ Nd/ ¹⁴⁴ Nd ratios (Fig. 5,
265	Supplementary Table S4), suggesting the dependence of the Nd isotopic composition on
266	ΔF_{π}^{β} (r ² =0.53) and revealing similar enriching mechanisms in the two ridge systems.
267	Spreading rate and mantle potential temperature may not be the leading factors
268	affecting the composition of the extracted basalts and of the residual mantle: the relative
269	proportion of pyroxenites versus peridotites in the mantle source maybe more important. A
270	major implication is that at constant temperature a pulse of low-melting pyroxenite
271	entering the melting region may not lead to a pulse of magmatism because the increased
272	undercooling of the mantle shrinks the peridotitic melting region contrasting the increase
273	of instantaneous pyroxenite melt production.
274	Our results show that low-T melting heterogeneities dispersed in the mantle source
275	affect not only the composition of the extracted basaltic melts, but also the total extent of
276	melting, the volume of extracted melts, and consequently crustal thickness.
277	
278	
279	Acknowledgments
280	This work has been supported by Italian-PRIN prot. 2015C5LN35 and by the U.S.
281	National Science Foundation under grant no. OCE-05-51288. We are also grateful for the
282	support of the Deep Energy community of the Carbon Observatory funded by Alfred P.
283	Sloan Foundation. We thank Charlie Langmuir, Henry Dick, Jessica Warren and Monique
284	Seyler, for stimulating insightful discussions and critical reading of an early version of the
285	work. We are grateful to Marco Ligi for his support on geophysics and Sarah Lambart for
286	helping on Melt-PX. We also thank S. Lambart, A. Stracke and an anonymous reviewer
287	for their constructive reviews that greatly improved the manuscript. We are grateful to A.
288	Whitchurch for the editorial assistance. This is Lamont-Doherty contribution number xxx.
289	
290	Author contributions
291	D.B. performed the modelling. A.C. analysed the samples. D.B. and A.C. processed the

292 geochemical data and wrote jointly the paper. E.B. provided the opportunity and support

for sea-expeditions and work. All the authors discussed the results and the interpretations.

294	
295	

298 References

300	1.	Bonatti, E. et al. Mantle thermal pulses below the Mid-Atlantic Ridge and temporal variations in the
301		formation of oceanic lithosphere. Nature 423, 499-505 (2003).
302	2.	Brunelli, D., Seyler, M., Cipriani, A., Ottolini, L. & Bonatti, E. Discontinuous Melt Extraction and
303		Weak Refertilization of Mantle Peridotites at the Vema Lithospheric Section (Mid-Atlantic Ridge).
304		J. Petrol. 47, 745–771 (2006).
305	3.	Bonatti, E. et al. Flexural uplift of a lithospheric slab near the Vema transform (Central Atlantic):
306		Timing and mechanisms. Earth Planet. Sci. Lett. 240, 642-655 (2005).
307	4.	Cipriani, A., Bonatti, E., Brunelli, D. & Ligi, M. 26 million years of mantle upwelling below a
308		segment of the Mid Atlantic Ridge: The Vema Lithospheric Section revisited. Earth Planet. Sci. Lett.
309		285, 87–95 (2009).
310	5.	Cipriani, A., Brueckner, H. K., Bonatti, E. & Brunelli, D. Oceanic crust generated by elusive parents:
311		Sr and Nd isotopes in basalt-peridotite pairs from the Mid-Atlantic Ridge. Geology 32, 657-660
312		(2004).
313	6.	Cipriani, A. et al. A 19 to 17 Ma amagmatic extension event at the Mid-Atlantic Ridge: Ultramafic
314		mylonites from the Vema Lithospheric Section. Geochemistry Geophys. Geosystems 10, (2009).
315	7.	Plank, T. & Langmuir, C. H. Effects of the melting regime on the composition of the oceanic crust. J.
316		Geophys. Res. 97, 19749–19770 (1992).
317	8.	Klein, E. M. & Langmuir, C. H. Global correlations of ocean ridge basalt chemistry with axial depth
318		and crustal thickness. J. Geophys. Res. 92, 8089 (1987).
319	9.	Dick, H. J. B. & Bullen, T. Chromian spinel as a petrogenetic indicator in abyssal and alpine-type
320		peridotites and spatially associated lavas. Contrib. to Mineral. Petrol. 86, 54-76 (1984).
321	10.	Michael, P. J. & Bonatti, E. Peridotite composition from the North Atlantic: regional and tectonic
322		variations and implications for partial melting. Earth Planet. Sci. Lett. 73, 91-104 (1985).
323	11.	Katz, R. F. & Weatherley, S. M. Consequences of mantle heterogeneity for melt extraction at mid-
324		ocean ridges. Earth Planet. Sci. Lett. 335-336, 226-237 (2012).
325	12.	Weatherley, S. M. & Katz, R. F. Melting and channelized magmatic flow in chemically
326		heterogeneous, upwelling mantle. Geochemistry Geophys. Geosystems 13, Q0AC18 (2012).
327	13.	Katz, R. F. & Rudge, J. F. The energetics of melting fertile heterogeneities within the depleted
328		mantle. Geochemistry Geophys. Geosystems 12, 1-22 (2011).
329	14.	Phipps Morgan, J. Thermodynamics of pressure release melting of a veined plum pudding mantle.
330		Geochemistry Geophys. Geosystems 2, (2001).
331	15.	Sleep, N. H. Tapping of Magmas from Ubiquitous Mantle Heterogeneities : An alternative to Mantle
332		plumes? J. Geophys. Res. 89, 10029-10041 (1984).
333	16.	Ito, G. & Mahoney, J. J. Flow and melting of a heterogeneous mantle: 1. Method and importance to
334		the geochemistry of ocean island and mid-ocean ridge basalts. Earth Planet. Sci. Lett. 230, 29-46
335		(2005).

336	17.	Shorttle, O. Geochemical variability in MORB controlled by concurrent mixing and crystallisation.
337		Earth Planet. Sci. Lett. 424 , 1–14 (2015).
338	18.	Rudge, J. F., Maclennan, J. & Stracke, A. The geochemical consequences of mixing melts from a
339		heterogeneous mantle. Geochim. Cosmochim. Acta 114, 112-143 (2013).
340	19.	Warren, J. M. Global Variations in Abyssal Peridotite Compositions. Lithos 248-251, 193-219
341		(2016).
342	20.	Bown, J. W. & White, R. S. Variation with spreading rate of oceanic crustal thickness and
343		geochemistry. Earth Planet. Sci. Lett. 121, 435-449 (1994).
344	21.	Cande, S. C., LaBrecque, J. L. & Haxby, W. F. Plate kinematics of the South Atlantic: Chron C34 To
345		Present. J. Geophys. Res. Solid Earth 93, 13479–13492 (1988).
346	22.	Cande, S. C. & Kent, D. V. Revised calibration of the geomagnetic polarity timescale for the Late
347		Cretaceous and Cenozoic. J. Geophys. Res. Solid Earth 100, 6093-6095 (1995).
348	23.	Langmuir, C. H., Klein, E. M. & Plank, T. in Mantle Flow and Melt Generation at Mid-Ocean
349		Ridges (ed. Morgan, J. P.) 183-280 (American Geophysical Union, 1992).
350	24.	Lambart, S., Baker, M. B. & Stolper, E. M. The role of pyroxenite in basalt genesis: Melt-PX, a
351		melting parameterization for mantle pyroxenites between 0.9 and 5 GPa. J. Geophys. Res. Solid
352		<i>Earth</i> 121 , 0–28 (2016).
353	25.	Shorttle, O. & Maclennan, J. Compositional trends of Icelandic basalts: Implications for short-length
354		scale lithological heterogeneity in mantle plumes. Geochemistry, Geophys. Geosystems 12, (2011).
355	26.	Ligi, M., Cuffaro, M., Chierici, F. & Calafato, A. Three-dimensional passive mantle flow beneath
356		mid-ocean ridges: an analytical approach. Geophys. J. Int. 175, 783-805 (2008).
357	27.	Mckenzie, D. & Bickle, M. J. The volume and composition of melt generated by extension of the
358		lithosphere. J. Petrol. 29, 625-679 (1988).
359	28.	Shen, Y. & Forsyth, D. W. Geochemical constraints on initial and final depths of melting beneath
360		mid-ocean ridges. J. Geophys. Res. 100, 2211–2237 (1995).
361	29.	Lambart, S., Laporte, D. & Schiano, P. Markers of the pyroxenite contribution in the major-element
362		compositions of oceanic basalts: Review of the experimental constraints. Lithos 160-161, 14-36
363		(2013).
364	30.	Stracke, A., Bourdon, B. & McKenzie, D. Melt extraction in the Earth's mantle: Constraints from U-
365		Th-Pa-Ra studies in oceanic basalts. Earth Planet. Sci. Lett. 244, 97-112 (2006).
366	31.	Stracke, A. & Bourdon, B. The importance of melt extraction for tracing mantle heterogeneity.
367		Geochim. Cosmochim. Acta 73, 218–238 (2009).
368	32.	Rubin, K. H., Sinton, J. M., Maclennan, J. & Hellebrand, E. Magmatic filtering of mantle
369		compositions at mid-ocean-ridge volcanoes. Nat. Geosci. 2, 321-328 (2009).
370	33.	Lambart, S., Laporte, D. & Schiano, P. An experimental study of pyroxenite partial melts at 1 and
371		1.5GPa: Implications for the major-element composition of Mid-Ocean Ridge Basalts. Earth Planet.
372		Sci. Lett. 288, 335–347 (2009).
373	34.	Lambart, S., Laporte, D., Provost, a. & Schiano, P. Fate of Pyroxenite-derived Melts in the
374		Peridotitic Mantle: Thermodynamic and Experimental Constraints. J. Petrol. 53, 451–476 (2012).
375	35.	Helffrich, G. R. & Wood, B. J. The Earth's mantle. Nature 412, 501-7 (2001).

376	36.	Graham, D. W., Blichert-Toft, J., Russo, C. J., Rubin, K. H. & Albarede, F. Cryptic striations in the
377		upper mantle revealed by hafnium isotopes in southeast Indian ridge basalts. Nature 440, 199-202
378		(2006).
379	37.	Liu, B. & Liang, Y. The prevalence of kilometer-scale heterogeneity in the source region of MORB
380		upper mantle. 1–8 (2017).
381	38.	Hoernle, K. et al. On- and off-axis chemical heterogeneities along the South Atlantic Mid-Ocean-
382		Ridge (5-11°S): Shallow or deep recycling of ocean crust and/or intraplate volcanism? <i>Earth Planet</i> .
383		Sci. Lett. 306, 86–97 (2011).
384	39.	Paulick, H., Münker, C. & Schuth, S. The influence of small-scale mantle heterogeneities on Mid-
385		Ocean Ridge volcanism: Evidence from the southern Mid-Atlantic Ridge (7°30'S to 11°30'S) and
386		Ascension Island. Earth Planet. Sci. Lett. 296, 299-310 (2010).
387	40.	Liang, Y. Simple models for dynamic melting in an upwelling heterogeneous mantle column:
388		Analytical solutions. Geochim. Cosmochim. Acta 72, 3804-3821 (2008).
389	41.	Borghini, G. et al. Meter-scale Nd isotopic heterogeneity in pyroxenite-bearing Ligurian peridotites
390		encompasses global-scale upper mantle variability. Geology 41, 1055-1058 (2013).
391	42.	Borghini, G. et al. Pyroxenite Layers in the Northern Apennines' Upper Mantle (Italy)-Generation
392		by Pyroxenite Melting and Melt Infiltration. J. Petrol. 57, 625-653 (2016).
393	43.	Gale, A., Langmuir, C. H. & Dalton, C. A. The global systematics of ocean ridge basalts and their
394		origin. J. Petrol. 55, 1051–1082 (2014).
395		
396		

398 Figure captions

399

Figure 1: Figure 1. a) Temporal variation of the VLS basaltic glasses ¹⁴³Nd/¹⁴⁴Nd 400 401 isotopic ratios. Solid circles define three domains (average Nd isotopic ratio of each sector 402 is indicated). Dashed line is average of oldest sector without one enriched sample. 403 b) Temporal variation of the degree of melting as inferred by mantle peridotite residues¹⁹ and erupted MORBs⁷. Each point represents a dredge average. Thick bold lines 404 405 are linear regressions; thin lines show 95% confidence bands. The age of mantle rocks is 406 corrected for the time lag between their arrival at the seafloor and the arrival of the basaltic melts they produced according to 1,4 (see Methods). 407 408 409 410 Figure 2: Interpretative sketch of the upwelling mantle column below the Vema 411 Lithospheric Section. At constant mantle potential temperature the presence of pyroxenites 412 causes a contraction of the melting region. Total degree of decompressive adiabatic melting is computed based on Melt-PX algorithm²⁴. In the older VLS sectors, the onset of 413 melting of the mantle peridotite is delayed and its degree of melting reduced (F_{max}=8). The 414 415 associated pyroxenite melts more (F_{max} =53) and contributes to the higher apparent degree 416 of melting in the pooled MORBs. Undercooling of the mantle peridotite causes deepening 417 of the end of the melting column estimated to shallow by 0.4 GPa from the older to the 418 younger sector. 419 420

Figure 3: Melt-PX²⁴ numerical experiments for adiabatic melting of a two-component mantle source: lherzolite plus SD pyroxenite (M7-16²⁹). The thick black line represents the model limit value for melting ceasing at the base of the crust.

Left Panel: the degree of melting of the host peridotite is lowered by adding up to 40%

425 pyroxenite in the source. Variable extents of the melting column are computed assuming $P_{\rm f}$

from 1.1 to 0.3 GPa. Red dashed lines correspond to the VLS average melting interval

427 from old (F_{max} =8.0) to young (F_{max} =14.2) sectors.

Panel B: Variation of the aggregated crustal thickness as function of pyroxenite fraction
in the source and final depth of melting. Average values for the VLS extremes are plotted
as red symbols and 1σ standard deviation

431

432 Figure 4: Variation of the degree of melting estimated from mantle peridotite (blue 433 dots) and associated basalts (red dots) along the Southwest Indian Ridge (upper) and the 434 Mid Atlantic Ridge from the Equator to the Azores hotspot region (lower). Degrees of melting are calculated based on ^{19,23,43} on data compiled from PetDB 435 436 (www.earthchem.org/petdb). Variations of the amount of low-T melting heterogeneities 437 (pyroxenite) in the source result in larger differences in the estimated degree of melting (ΔF_{π}^{β}) , a proxy for the along axis pyroxenite vol% content of the source. 438 439 440 Figure 5: Difference of degree of melting estimated from genetically related basalts and 441 peridotites (ΔF) versus the Nd isotopic composition of basalt. The VLS sectors are plotted 442 as large red circles; delta F increases from sector 1 to 3 (young to old). Black diamonds 443 represent SWIR, blue circles MAR. Regression lines are calculated for the whole 444 population (red solid line), the SWIR (black solid line) and the MAR (blue solid line). 445 Data and parameters in supplementary Table S4; 95% confidence bands are plotted in 446 Supplementary Fig. S6. Our interpretation is that the ΔF between basalt and peridotite is a 447 proxy of the amount of low-T solidus pyroxenites in the source. 448

450 METHODS

451

452 Analytical Methods

453 Major elements

Major elements on mineral phases were collected with the electron probe (Cameca SX100)
at the American Museum of Natural History (NY) using 15kV acceleration voltage, 20nA
beam, a 10µm diameter beam and 30 s counting times. Sodium, potassium and chlorine

- 456 beam, a topin diameter beam and 50 s counting times. Solidin, potassium and chlorine
- were run under different conditions to attain a higher precision and monitor their mobility,
 with a 5nA beam and counting times of 80 s. A subset of samples has been analyses with a
- 459 Cameca X-Five microprobe at the CAMPARIS micro-analytical center (University of
- 460 Paris VI), following procedures detailed in ⁴⁴. A number of primary mineral standards
- 461 were used, as well as the MORB JDF-D2 standard.
- 462 Isotope ratios

463 For isotopic determinations 50 to 250 mg of basaltic glass and clinopyroxene separate were prepared by grinding, sieving and handpicking under a binocular microscope. Glass 464 chips were leached in 8N HNO₃. Clinopyroxenes were treated with three leachates to 465 eliminate the effects of seawater alteration^{5,45}. Pb was separated using AG1-X8 anion 466 resin, Sr was separated using Eichrom Sr resin and Nd was separated in a two-column 467 procedure using Eichrom TRU-spec resin to separate the rare-earth elements, followed by 468 α -hydroxy isobutyric acid. Isotopes were measured on a VG Sector 54 multicollector mass 469 470 spectrometer housed at the Lamont Doherty Earth Observatory of Columbia University. Sr and Nd isotopes were measured in multidynamic mode. The mass fractionation corrections 471 were based on 86 Sr/ 88 Sr = 0.1194 and 146 Nd/ 144 Nd = 0.7219. Over the period of analytical 472 work, repeated analyses yielded a 87 Sr/ 86 Sr ratio of 0.710271 ± 0.000015 for the NBS-987 473 Sr standard (2σ external reproducibility, n>22) and a ¹⁴³Nd/¹⁴⁴Nd ratio of 0.512096 ± 474 475 0.000023 for the JNdi-1 (2σ external reproducibility, n>38). Total blanks for Sr and Nd did 476 not exceed 80pg. Pb data on basaltic glasses were collected in static mode, using the 477 double spike technique with the calibrated 207/204 spike. Replicate analyses of the Pb isotope standard NBS981 gave an average of 16.9317±0.0022 and 15.4912±0.0027 and 478 36.7060±0.0066 for ²⁰⁶Pb/²⁰⁴Pb, ²⁰⁷Pb/²⁰⁴Pb, and ²⁰⁸Pb/²⁰⁴Pb, respectively. These measured 479 Pb isotope ratios were corrected to the values defined by ⁴⁶ of 16.9356, 15.4891, and 480 36.7006, respectively, for NBS 981. Reproducibility for NBS981 is 130, 174, and 181 ppm 481 $(2\sigma, N=47)$, for ²⁰⁶Pb/²⁰⁴Pb, ²⁰⁷Pb/²⁰⁴Pb, and ²⁰⁸Pb/²⁰⁴Pb ratios, respectively. Pb blanks 482 483 measured were below 100pg and thus negligible relative to the amount of sample analysed.

484

485 Estimate of the ΔF_{π}^{β} and ¹⁴³Nd/¹⁴⁴Nd of the associated basalts

Figure 4 of the main text reports the correlation between ΔF_{π}^{β} , as the differential in degree of melting between basalt and peridotites, and the Nd isotopic composition of basalts of several portions of the Mid Ocean Ridge system where both basalts and peridotites have 489 been sampled. Among all the explored ridge segments, only few localities report basalts 490 and mantle peridotites sampled in the same dredge haul or site. Basaltic rocks are generally more abundant and present a much denser lateral sampling than mantle peridotites. Basalt 491 492 chemistry and isotopic ratios appear to vary systematically over variable length scale defining domains in which they show little variability or monotonic changes along the 493 ridge axis (e.g. ^{43, 47-48} among others). Domains characterized by reduced variability of the 494 chemical character of the basalts are usually bounded by major transform faults, which 495 also act as thermal barriers^{47,49-51}. Therefore, in Figure 4 (main text), we have chosen to 496 integrate the dataset of the sites where peridotites and basalts were sampled together with 497 sites where only mantle rocks were recovered, but for which is possible to infer the 498 499 isotopic composition of the associated basalts from the regional variability. As a 500 conservative approach, we only considered those domains in which lateral isotopic and compositional variability is very low or described by simple monotonic trends. 501 The degree of melting of mantle-peridotites can be affected by Cr# fluctuations due to 502 melt/rock interaction that modify spinel⁹ and pyroxene compositions⁵². Therefore we 503 filtered spinel composition and applied a threshold of $TiO_2 < 0.15$ wt% as discussed in ^{2,19}. 504 The supplementary Table S4, reports the inferred values showing the measured and 505 506 calculated value for each basalt-peridotite couple. The "regional regression" data are 507 calculated considering sets of neighboring peridotites and basalts, whereas the "local average" set of data refers to basalts and peridotites sampled from the same site. $\pm \sigma$ on 508 ΔF_{π}^{β} are estimated by error propagation. 509

510

511 Age correction

Basalts from the VLS were erupted over a time range of 26 Ma. We applied, hence, an age 512 correction for radiogenic ingrowth since the closure of the system to allow comparisons of 513 514 their initial isotopic composition, which is controlled only by the source. The correction 515 time should be calculated since the closure of the system, represented by the moment of 516 separation between the source and the melt at depth, assuming there was no significant 517 melt-rock interaction thereafter. This is attested by mantle residual rocks from the VLS 518 being all equilibrated in the spinel field showing no late interaction with melts. The only report of plagioclase-equilibrated mantle rocks concerns the strain-driven formation of 519 plagioclase in fertile lherzolites during mylonitization⁵³. We identify the melt-source 520 521 separation at the estimated upper limit of melting as inferred by modelling with Melt-PX 522 (see main text).

523 Based on the estimation of melting a composite source and varying the position of the end

of the melting column between 1.2 and 0.3 GPa, it appears that the end of the melting

column can be constrained based on the correlation with the measured crustal thickness

and degree of melting of the residual mantle. For the time stretch relative to the VLS the

end of the melting column can be set at 1.1 GPa for the older domain and 0.7 GPa for the

528 younger domain. Based on Africa-South America Euler vectors of ²¹ and the geomagnetic

time scale of 22 , the spreading rate at the EMAR axis can be estimated through time. As

- shown in Figure 1 of the main text, the spreading rate decreased steadily in the last 30 Ma.
- 531 The absolute value decreases from 17.2 to 16.9 mm/y at Chron 6 (half spreading rate) and

- from 16.9 to 13.6 mm/y at Chron 5. Crustal ages can be calculated accordingly during this
- time stretch assuming basalts erupted in the axial region.
- 534 Times of extraction for the mantle residue and for the basalts are, however, very different.
- Ascent rates for the basaltic liquids are estimated in the range of m/y^{54-56} . Setting the
- melt/source separation at 1.1 and 0.7 GPa and upwelling rates in the range 1-5 m/y 56 gives
- upwelling times ranging 7-36 ka for the older VLS domain and 5-23 ka for the younger
- 538 VLS domain. Such delays are uninfluential in the age correction of long-time decay
- systems as those here discussed (Sm-Nd; Rb-Sr; U-Pb); however, we considered this
- contribution for the total age correction when discussing age corrected values in Figs 1Band S1.
- 542 Upwelling of the mantle lasts a significant amount of time and can sensibly modify the
- 543 isotopic relationships. The time necessary for a mantle parcel to join the crust from the end
- of melting depth is 2.1 Ma for the older VLS domain and 1.7 Ma for the younger VLS
- 545 domain.
- 546
- 547
- 548

551 References

550

- 44. Seyler, M. & Brunelli, D. Sodium chromium covariation in residual clinopyroxenes from abyssal
 peridotites sampled in the 43°-46°E region of the Southwest Indian Ridge. *Lithos* 302-303, 142-157
 (2018).
- 45. Cipriani, A., Bonatti, E. & Carlson, R. W. Nonchondritic ¹⁴²Nd in suboceanic mantle peridotites.
 Geochemistry, Geophys. Geosystems 12, 1–8 (2011).
- Todt, W., Cliff, R., Hanser, A. & Hofmann, A. W. Evaluation of a 202Pb–205Pb double spike for high precision lead isotope analysis. *Geophys. Monogr. Ser.* 95, 429–437 (1996).
- 47. Meyzen, C. M. *et al.* New insights into the origin and distribution of the DUPAL isotope anomaly in the Indian Ocean mantle from MORB of the Southwest Indian Ridge. *Geochem. Geophys. Geosyst.*562 6, Q11K11 (2005).
- 48. Meyzen, C. M., Toplis, M. J., Humler, E., Ludden, J. N. & Mevel, C. A discontinuity in mantle composition beneath the southwest Indian ridge. *Nature* 421, 731–733 (2003).
- 49. Cannat, M., Rommevaux-Jestin, C., Sauter, D., Deplus, C. & Mendel, V. Formation of the axial relief at the very slow spreading Southwest Indian Ridge (49° to 69°E). *J. Geophys. Res.* 104, 22825–22843 (1999).
- 568 50. Seyler, M., Brunelli, D., Toplis, M. J. & Mével, C. Multiscale chemical heterogeneities beneath the
 669 eastern Southwest Indian Ridge (52°E-68°E): Trace element compositions of along-axis dredged
 570 peridotites. *Geochemistry, Geophys. Geosystems* 12, (2012).
- 51. Paquet, M., Cannat, M., Brunelli, D., Hamelin, C. & Humler, E. Effect of melt/mantle interactions on
 MORB chemistry at the easternmost Southwest Indian Ridge (61°–67°E). *Geochemistry, Geophys. Geosystems* 17, (2016).
- 574 52. Brunelli, D., Paganelli, E. & Seyler, M. Percolation of enriched melts during incremental open575 system melting in the spinel field: A REE approach to abyssal peridotites from the Southwest Indian
 576 Ridge. *Geochim. Cosmochim. Acta* 127, 190–203 (2014).
- 577 53. Cannat, M. & Seyler, M. Transform tectonics, metamorphic plagioclase and amphibolitization in ultramafic rocks of the Vema transform fault (Atlantic Ocean). *Earth Planet. Sci. Lett.* 133, 283–298 (1995).
- 580 54. Spiegelman, M. & Kenyon, P. The requirements for chemical disequilibrium during magma migration. *Earth Planet. Sci. Lett.* 109, 611–620 (1992).
- 582 55. Spiegelman, M. & Elliott, T. Consequences of melt transport for uranium series disequilibrium in young lavas. *Earth Planet. Sci. Lett.* 118, 1–20 (1993).
- 584 56. Lundstrom, C. C., Gill, J., Williams, Q. & Perfit, M. R. Mantle Melting and Basalt Extraction by Equilibrium Porous Flow. *Science (80-.).* 270, 1958 LP-1961 (1995).
- 586
- 587
- 588



Fig. 1





Figure 3_last



Figure 4-last



Figure 5 - last