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Geodynamic Evolution of a Forearc Rift in the Southernmost Mariana Arc

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1 **Geodynamic evolution of a forearc rift in the southernmost Mariana Arc**

2
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25 **Abstract**

26

27 The southernmost Mariana forearc stretched to accommodate opening of the Mariana Trough
28 backarc basin in late Neogene time, erupting basalts now exposed in the SE Mariana Forearc Rift
29 (SEMFR) 3.7 – 2.7 Ma ago. Today, SEMFR is a broad zone of extension that formed on
30 hydrated, forearc lithosphere and overlies the shallow subducting slab (slab depth $\leq 30 - 50$ km).
31 It comprises NW-SE trending subparallel deeps, 3 - 16 km wide, that can be traced $\geq \sim 30$ km
32 from the trench almost to the backarc spreading center, the Malaguana-Gadao Ridge (MGR).
33 While forearcs are usually underlain by serpentinized harzburgites too cold to melt, SEMFR crust
34 is mostly composed of Pliocene, low-K basaltic to basaltic andesite lavas that are compositionally
35 similar to arc lavas and backarc basin (BAB) lavas, and thus defines a forearc region that recently
36 witnessed abundant igneous activity in the form of seafloor spreading. SEMFR igneous rocks
37 have low Na_8 , Ti_8 , and Fe_8 , consistent with extensive melting, at $\sim 23 \pm 6.6$ km depth and $1239 \pm$
38 40°C , by adiabatic decompression of depleted asthenospheric mantle metasomatized by slab-
39 derived fluids. Stretching of pre-existing forearc lithosphere allowed BAB-like mantle to flow
40 along SEMFR and melt, forming new oceanic crust. Melts interacted with preexisting forearc
41 lithosphere during ascent. SEMFR is no longer magmatically active and post-magmatic tectonic
42 activity dominates the rift.

43

44 **KEYWORDS:** forearc rift, seafloor spreading, Mariana arc, subduction zone

45

46 **1. Introduction**

47 Forearcs are cold regions above subduction zones that lie between the trench and the magmatic
48 arc. They can be accretionary or non-accretionary depending on the amount of sediments carried
49 into the trench (Lallemand, 2001, Stern, 2002). Non-accretionary forearcs, such as that of the
50 Marianas, are of special interest as they preserve a record of the first lavas erupted in association
51 with subduction initiation (Ishizuka *et al.*, 2011, Reagan *et al.*, 2010, Stern & Bloomer, 1992).
52 Forearc lithosphere is underlain by the cold, subducting plate that releases its hydrous fluids into
53 the upper mantle wedge, resulting in exceptionally cold (< 400°C; Hulme *et al.*, 2010) and
54 serpentinized mantle lithosphere that rarely melts (Hyndman & Peacock, 2003, Van Keken *et al.*,
55 2002, Wada *et al.*, 2011). The occurrence of cold, serpentinized forearc mantle beneath the
56 Mariana forearc is demonstrated by eruption of serpentinite mud volcanoes (Hulme *et al.*, 2010,
57 Mottl *et al.*, 2004, Savov *et al.*, 2007, Savov *et al.*, 2005, Wheat *et al.*, 2008) and serpentinized
58 peridotite outcroppings on the inner trench slope (Bloomer & Hawkins, 1983, Ohara & Ishii,
59 1998). Serpentinized mantle beneath the forearc has also been imaged by geophysical surveys
60 (Tibi *et al.*, 2008). Ultramafic rocks from the upper mantle wedge found as clasts in mud
61 volcanoes and on the inner trench slope mostly consist of harzburgite, residues of mantle melting
62 (Parkinson & Pearce, 1998, Savov *et al.*, 2007, Savov *et al.*, 2005) that are chemically distinct
63 from the more fertile, backarc basin (BAB) peridotites (Ohara *et al.*, 2002). Such highly depleted,
64 forearc mantle can melt in association with early-arc volcanism to generate boninites (Reagan *et*
65 *al.*, 2010, Stern & Bloomer, 1992). Decompression melting of more fertile mantle to form
66 tholeiitic basalts near the trench also has been documented during the first stage of subduction
67 initiation. These lavas have MORB-like compositions and have been termed forearc basalts

68 (FABs) reflecting their subduction-related origin and location in modern forearcs (Reagan et al.,
69 2010).

70
71 In the Izu-Bonin-Mariana (IBM) intraoceanic system, most forearc lavas are Eocene - Oligocene
72 in age and younger forearc lavas are unusual (Ishizuka et al., 2011, Reagan et al., 2010, Stern &
73 Bloomer, 1992). Here, we document the first record of Pliocene forearc lavas from the
74 southernmost Mariana convergent margin, indicating that the mantle can melt beneath forearcs
75 long after subduction initiation. These low-K lavas are tholeiitic basalts generated from BAB-like
76 asthenospheric mantle during seafloor spreading in the Southeast Mariana Forearc Rift (SEMFR),
77 which is a broad zone of deformation (~ 40 km wide and ~ 60 km long), extending from the
78 trench to the Fina-Nagu arc Volcanic Chain (FNVC). SEMFR today overlies a shallow
79 subducting Pacific slab ($\leq 50 - 100$ km deep; Becker, 2005).

80
81 This paper presents a first report on the geology and tectonic evolution of the SEMFR. We
82 present bathymetry, summarize the results of bottom traverses, and provide petrologic, major
83 element geochemical data and $^{40}\text{Ar}/^{39}\text{Ar}$ ages of igneous rocks sampled during two JAMSTEC
84 research cruises. These data are used to characterize SEMFR lavas and to address when, where,
85 and how SEMFR lavas were generated, and to determine sources of the magmas, and conditions
86 of melting. Addressing these issues helps us better understand how such melts were produced in a
87 cold forearc, and allows us to develop a geodynamic model to constrain the geodynamic
88 evolution of the S. Mariana forearc. In this manuscript, we show that SEMFR lavas have BAB-
89 like geochemical and petrographic features; and opening of the Southernmost Mariana Trough
90 allowed adiabatic decompression melting of BAB-like asthenospheric mantle in the forearc to
91 produce SEMFR lavas 3.7 – 2.7 Ma ago.

93 **2. Geodynamic setting**

94 The Mariana intraoceanic arc system is the southern third of the IBM convergent margin. It is
95 generally associated with a sediment-starved forearc ~ 200 km wide (Fryer *et al.*, 2003, Kato *et*
96 *al.*, 2003), submarine and subaerial volcanoes of the active magmatic arc (Baker *et al.*, 2008), and
97 a BAB with a spreading axis that generally lies ~ 250 – 300 km from the trench (Stern *et al.*,
98 2003). Mariana geodynamic evolution was influenced by collisions with buoyant oceanic
99 plateaus (Ogasawara Plateau in the north and Caroline Ridge in the south). These resisted
100 subduction, stimulating backarc extension to open the Mariana Trough between the collisions
101 (Wallace *et al.*, 2005).

102
103 IBM mostly trends N-S but the southernmost Mariana convergent margin (13°10'N – 11°N)
104 bends to E-W (Fig. 1A ; Bird, 2003). This region is deforming rapidly (Kato *et al.*, 2003,
105 Martinez *et al.*, 2000), accompanied by abundant igneous activity. Here, the Mariana Trench
106 reaches the deepest point on Earth at the Challenger Deep (10994 m; Gardner & Armstrong,
107 2011), and Pacific-Philippine Sea plate convergence is approximately orthogonal to the trench
108 (Bird, 2003). The tectonic evolution of the southernmost Mariana arc began with the Late
109 Miocene collision of the Caroline Ridge, which pinned the Yap arc and allowed the southern
110 Mariana Trough to open, sculpting the southern termination of the arc (Miller *et al.*, 2006b). The
111 southernmost Mariana magmatic arc is poorly developed and entirely submarine, contrasting with
112 the large, often subaerial, arc volcanoes to the north. The arc magmatic front almost intersects the
113 southern end of the BAB spreading center south of 13°N (Fig. 1B; Fryer *et al.*, 2003). These
114 features are about 100 – 150 km from the trench, whereas to the north the BAB spreading axis

115 lies ~250 – 300 km from the trench and is separated from the magmatic arc by 50 - 100 km (Fryer
116 *et al.*, 1998, Stern *et al.*, 2003). The magmatic arc appears to have been reorganized recently, as
117 evidenced by a complex bathymetric high with multiple nested calderas – an inferred paleo-arc
118 (the Fina-Nagu Volcanic Chain in Fig. 1B) where no hydrothermal activity was observed (Baker
119 *et al.*, 2008) and calderas are covered with sediments (Fig. 1C) - SE of and parallel to the modern
120 magmatic arc (e.g. Toto caldera). The southern Mariana Trough has a well-defined spreading
121 ridge, the Malaguana-Gadao Ridge (MGR), with a well-developed magma chamber and several
122 hydrothermal vents (Baker *et al.*, 2008, Becker *et al.*, 2010, Kakegawa *et al.*, 2008). Because the
123 subducted Pacific plate lies ~ 100 km beneath it, the MGR melt source region captures hydrous
124 fluids usually released beneath arc volcanoes, enhancing mantle melting and resulting in an
125 inflated ridge morphology that is unusually robust for the Mariana Trough backarc basin, in spite
126 of an intermediate spreading rate (< 65 mm/yr; Becker *et al.*, 2010, Fryer *et al.*, 1998, Martinez *et*
127 *al.*, 2000). More rapid extension along the MGR might also enhance decompression melting
128 (Becker *et al.*, 2010).

129
130 The southernmost Mariana convergent margin is underthrust by a narrow slab of Pacific plate
131 (traceable to ~ 250 km depth; Gvartzman & Stern, 2004), torn N-S at ~ 144°15'E (Fryer *et al.*,
132 1998, Gvartzman & Stern, 2004). Analogue experiments show that short, narrow subducted slabs
133 trigger toroidal (around the slab edge) and poloidal (underneath the slab tip) asthenospheric
134 mantle flows that generate rapid slab rollback and trench retreat relative to the upper plate
135 (Funiciello *et al.*, 2003, Funiciello *et al.*, 2006, Schellart *et al.*, 2007). These conditions lead to
136 weak coupling of the subducting plate with the overriding plate, stimulating rapid deformation of
137 the overriding plate (i.e., the southern Mariana Trough) and may be responsible for the very

138 narrow forearc that defines the southern Mariana margin west of the W. Santa Rosa Bank Fault
139 (Fig. 1B, Gvirtzman & Stern, 2004). The unusual tectonic situation of the southernmost Mariana
140 convergent margin has also affected magmagenesis. Sub-forearc mantle usually is too cold to
141 melt (Van Keken et al., 2002), so that slab-derived fluids only lead to serpentinization (Hyndman
142 & Peacock, 2003, Wada et al., 2011). Instead, the dynamic tectonic setting of the southern
143 Marianas results in mantle melting much closer to the trench than is normally observed.

144

145 **3. Geology and morphology of the Southeast Mariana Forearc Rift**

146 Most of the IBM convergent margin is underlain by lithosphere that formed after subduction
147 began ~52 Ma (Ishizuka et al., 2011, Reagan et al., 2010). In the southernmost Marianas, Eocene
148 forearc lithosphere was stretched in late Neogene time to accommodate opening of the Mariana
149 Trough BAB; part of this extension is localized along the SEMFR (Martinez & Stern, 2009). The
150 morphological expression of the SEMFR is apparent over a region ~ 40 km wide and at least 60
151 km long (Supporting Information Table S1.2). SEMFR is composed of broad southeast-trending
152 deeps and ridges (Fig. 1B), each 50 to 60 km long and 3 to 16 km wide, which opened nearly
153 parallel to the trench axis. These rifts can be traced from the Mariana Trench almost to the FNVC
154 (Fig. S1.1 in Supporting Information S1). Eastward, the SEMFR is bounded by a N-S fault, the
155 W. Santa Rosa Bank fault (WSRBF, Fig. 1B; Fryer et al., 2003), which separates thick crust of
156 the broad Eocene forearc to the north and east (including that beneath Santa Rosa Bank) from the
157 deeper and narrower forearc of the S. Marianas - including SEMFR - to the west. WSRBF also
158 appears to overlie a tear in the subducted slab (Fryer et al., 2003, Gvirtzman & Stern, 2004). The
159 WSRBF is taken to be the eastern boundary of the SEMFR because it does not have the same

160 NNE-SSW trend as the three SEMFR deeps (Fig. 1B), and the forearc is significantly older to the
161 east (Reagan et al., 2010). SEMFR overlies the shallow part of the slab ($\leq 30 - 100$ km deep,
162 Becker, 2005) and is situated in a region with numerous shallow (crustal) earthquakes, (Martinez
163 & Stern, 2009) signifying active deformation.

164
165 We studied SEMFR by interpreting swathmapped bathymetry and previously published HMR-1
166 sonar backscatter imagery (Martinez et al., 2000). The region is characterized by high sonar
167 backscatter, indicating little sedimentary cover (Fig. 1C). This was confirmed by Shinkai 6500
168 manned submersible and YKDT deep-tow camera / dredge seafloor studies. Table S1.1 in
169 Supporting Information S1 summarizes the position and lithologies encountered during these
170 dives (Fig. 1B). Most dives recovered basalt. In addition, deeper crustal and upper mantle
171 lithologies, e.g. diabase, fine-grained gabbros and deformed peridotites, were recovered near the
172 WSRBF (Supporting Information Fig. S1.7 and S1.8). Similar lithologies are also reported by
173 previous studies of the area (Bloomer & Hawkins, 1983, Fryer, 1993, Michibayashi *et al.*, 2009,
174 Sato & Ishii, 2011). Based on relief, the SEMFR can be subdivided along strike into NW, central,
175 and SE sectors. SEMFR relief is ruggedest in the SE sector near the trench, where it is intensely
176 faulted and affected by landsliding, with abundant talus slopes of fragmented basaltic lavas (Fig.
177 2A, C, D and Fig. S1.5 to S1.8 in Supporting Information). The central SEMFR is less faulted,
178 with more outcrops and less talus, but still has many steep talus slopes and faulted lava flows
179 (Fig. S1.9 - S1.10 in Supporting Information). The NW SEMFR, nearest the MGR, has gentler
180 relief, with better-preserved pillow lava outcrops (Fig. 2B, E and Fig. S1.11 - S1.13 in Supporting
181 Information). We did not recover samples of Paleogene forearc crust in the SEMFR, although this
182 is common to the NE and west, indicating that SEMFR is floored by young, tectonized oceanic

183 crust. Our bottom observations along with the absence of parallel magnetic fabrics in the SEMFR
184 (Martinez et al., 2000) suggest that the SEMFR is no longer a site of active volcanism.

185
186 Toto caldera and part of the MGR near the NW limit of the SEMFR were studied during ROV
187 Kaiko Dives 163 and 164 (R/V Kairei cruise KR00-03 Leg 2, Fig. 1B). Toto caldera, which may
188 be part of the immature magmatic arc, is mostly covered by talus of fresh lava fragments with a
189 whitish coating, perhaps bacteria or sulfur-rich precipitate (Supporting Information Fig. S1.14),
190 derived from the active Nakayama hydrothermal site (Gamo *et al.*, 2004, Kakegawa et al., 2008).
191 The MGR seafloor is mostly composed of fresh, well-preserved pillow lavas alternating with aa
192 and solidified lava lake (Becker et al., 2010), along with active hydrothermal vents (Supporting
193 Information Fig. S1.15) indicating ongoing magmatic activity. Fig. 1C shows high sonar
194 backscatter for Toto caldera and around the MGR, indicating hard rock (fresh lava) exposures and
195 thin sediments, consistent with seafloor seen in dive videos.

196

197 **4. Methods**

198 Igneous rock samples were collected during two cruises YK08-08 Leg 2 (Shinkai 6500 manned
199 submersible dive 1096) in 2008 and YK10-12 (Shinkai 6500 dives 1230, 1235 and Yokosuka
200 deep-tow camera dredge (YKDT) 85, 86, and 88) in 2010. Representative, fresh samples were
201 selected onboard for petrographic and geochemical studies. Information from Kaiko ROV dives
202 163 and 164 (R/V Kairei cruise KR00-03 Leg 2 in 2000) is also included. High-resolution videos
203 of the seafloor generated during dives were reviewed during and after the cruises (see Supporting
204 Information S1 for more details). GMT (Smith & Wessel, 1990, Wessel & Smith, 1995b, Wessel
205 & Smith, 1998, Wessel & Smith, 1995a) was used to compile SEMFR bathymetric data,

206 including swathmapping results from these cruises and those of Gardner (2006), Gardner (2007)
207 and Gardner (2010). Maps were imported into ArcGIS to generate bathymetric cross sections
208 perpendicular to the strike of SEMFR (Fig. S1.1 in Supporting Information).

209
210 Igneous rock samples were analyzed, using procedures reported in Supporting Information S2.
211 For major element analyses, fresh sample chips containing as few phenocrysts as possible were
212 hand-picked and powdered in an alumina ball mill. Whole rock chemical analyses for Shinkai
213 dive 1096 samples were carried out on Philips PW1404 X-Ray fluorescence (XRF) spectrometer
214 at the Geological Survey of Japan/AIST. External errors and accuracy are $< 2\%$. Whole rock
215 chemical analyses for other samples were performed at University of Rhode Island by fusion –
216 dissolution of glass beads; and analyses were conducted using a Ultima-C Jobin Yvon Horiba
217 Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) at Boston University.
218 Glass beads were generated by melting 400 ± 5 mg of lithium metaborate (LiBO_4) flux with 100
219 ± 5 mg of ignited sample powder at 1050°C for 10 min. Molten beads were dissolved in 5% nitric
220 acid to achieve a final dilution factor of ~ 4000 (Kelley *et al.*, 2003). Calibration curves for ICP-
221 AES data yield $r^2 \geq 0.999$, reproducibility of replicate analyses are $\leq 3\%$ rsd for each element,
222 and major element oxides sum to 99 ± 1 wt%. Replicates of samples analyzed by ICP-AES and
223 XRF yield averaged reproducibility $< 4\%$ rsd for each element. Results are reported in Table 1.
224 For mineralogical chemistry analyses, polished thin sections were prepared for 16 samples. These
225 were analyzed using the Cameca SX-50 electron microprobe at University of Texas at El Paso.
226 Multiple point analyses give a mean value with 1σ precision ≤ 1 wt% for each selected mineral.

227

228 Four samples were dated by step-heating ^{40}Ar - ^{39}Ar at the Geological Survey of Japan/AIST on a
229 VG Isotech VG3600 noble gas mass spectrometer fitted with a BALZERS electron multiplier.
230 Further details of procedures are reported in Supporting Information S2.

231

232 **5. Results**

233 *5.1. Rock description:*

234 Here we outline the principal petrographic and mineralogical features of igneous rocks sampled
235 from the SEMFR, Toto caldera and MGR. Method for sample description is reported in
236 Supporting Information S3 and detailed sample descriptions are in Supporting Information S4.
237 SEMFR lavas are mostly aphyric (< 1% phenocrysts) and sparsely phyric (1 – 5% phenocrysts)
238 basalts and basaltic andesites, indicating eruption at near-liquidus temperatures. These are
239 microporphyritic pillows or massive flows, with thin, microcrystallite-rich glassy rims (1 – 11mm
240 of fresh, translucent to dark brown glass), thin (≤ 1 mm) Mn coat, and negligible alteration (Fig.
241 3). Pillow lavas are vesicular despite being collected at ~ 6000 – 3000 m, indicating that these
242 magmas contained significant volatiles. In contrast, basalt massive lava flows are more crystalline
243 and less vesicular. Embayed phenocrysts indicate disequilibrium, perhaps due to magma mixing.
244 Pillowed lavas sampled in the NW (YKDT-88) contain larger crystals (≥ 0.5 mm) of
245 clinopyroxene and olivine set in a finely microcrystalline olivine-rich groundmass (Fig. 3C).
246 Similar olivine-rich lavas were not sampled elsewhere in the SEMFR. Diabase and fine-grained
247 gabbros were also recovered near the WSRB fault (Shinkai 6500 dive 1235; Fig. 3B, D). These
248 might represent the lower crust of SEMFR (dike complex and gabbro layer). Pillow lavas from
249 MGR are very fresh, with translucent glassy rinds. Lavas are vesicular, cryptocrystalline
250 andesites with a glassy groundmass and <1% plagioclase microlites. Lava flows from Toto

251 caldera are vesicular, sparsely phyric to aphyric, fine-grained to cryptocrystalline basaltic
252 andesites.

253

254 *5.2. Major element and mineral compositions:*

255 SEMFR lavas are fresh basalts and basaltic andesites, with 50.4 to 57.0 wt% SiO₂ (data reported
256 are adjusted to 100% total on an anhydrous basis, Fig. 4A). In terms of normative compositions,
257 all lavas are quartz tholeiites. These define a low-K to medium-K suite, with K₂O < 1 wt%. Lava
258 compositions cluster along the tholeiitic – calc-alkaline boundary on a plot of FeO*/MgO vs.
259 SiO₂ (Fig. 4B; Miyashiro, 1974), or along the medium-Fe / low-Fe boundary (Arculus, 2003).
260 Lavas recovered during Shinkai 6500 dive 1096 and 1230 and YKDT-86 and -88 are relatively
261 primitive, with whole-rock Mg# (= atomic Mg * 100 / (Mg + Fe)) > 60, Fig. 4C). Other SEMFR
262 samples are significantly more fractionated, with Mg# = 41 - 60. Composition of SEMFR lavas is
263 reported in Table 1. MGR and Toto caldera lavas are mostly andesites (SiO₂ = 55.1 – 61.7 wt%,
264 with K₂O < 0.5 wt% and Mg# = 33 – 53). None of the studied lavas are boninitic (MgO > 8 wt%,
265 SiO₂ > 52 wt%, TiO₂ < 0.5 wt%; Le Bas, 2000). Toto caldera lavas plot within the compositional
266 field of southernmost Mariana volcanic arc lavas (SMA: 13°10'N – 11°N, Kakegawa et al., 2008,
267 Stern *et al.*, 2013), suggesting that Toto caldera belongs to the S. Mariana arc volcanoes (SMA).
268 Toto caldera samples also cluster along the tholeiitic – calc-alkaline boundary. In contrast, MGR
269 lavas are tholeiitic (medium-Fe to high-Fe) basaltic andesites and andesites (Kakegawa et al.,
270 2008, Pearce *et al.*, 2005 ; Fig. 4A, B). The Fe enrichment of the MGR lavas (Fig. 4B) suggests
271 that their parental magmas contain less water, inhibiting early crystallization of Fe-oxides. In Fig.
272 4A, MGR lavas do not plot along the SEMFR fractionation trend, and their similar K₂O content
273 suggests that MGR and SEMFR lavas interacted with similar arc-like slab-derived fluids. FABs

274 (Reagan et al., 2010) are low-K to medium-K basalt to basaltic andesites that plot within the
275 tholeiitic and calc-alkaline fields (Fig. 4B, C); and SEMFR plot along the FAB fractional trend
276 (Fig. 4C, D). All lavas from the southernmost Marianas suggest fractionation controlled by
277 plagioclase, clinopyroxene \pm olivine crystallization trend (Fig. 4C, F).

278
279 SEMFR basalts and basaltic andesites contain olivine, clinopyroxene, and plagioclase. Results for
280 representative mineral composition are listed in Supporting Information Tables S4.1 to S4.4 and
281 summarized in Table 2. Mineral compositions correlate with whole rock chemical compositions
282 (Fig. 5A, B and Supporting Information S5). Near-primitive ($Mg\# > 60$), olivine-rich SEMFR
283 lavas (Shinkai dive 1096, upper series and YKDT-88) contain Mg-rich olivines (Fo_{86-88}) in
284 equilibrium with Mg-rich clinopyroxene ($Mg\# = 83 - 91$) and anorthitic plagioclase ($An \geq 80$). In
285 contrast, fractionated ($Mg\# \leq 60$) lavas have Fe-rich olivine (Fe_{75-84}) coexisting with two kinds of
286 clinopyroxene (endiopside – diopside with $Mg \# \geq 80$ and augite with $Mg\# < 80$) and plagioclase
287 ($An \geq 80$ and $An < 80$). Reverse and oscillatory zoning is only observed in more fractionated
288 plagioclase ($An < 80$ in the core), suggesting magma mixing perhaps in a magmatic reservoir.
289 Fine-grained gabbro and diabase have Mg-rich clinopyroxenes ($Mg\# \geq 60$) coexisting with more
290 albitic plagioclase ($An \leq 70$). The mineral composition of Toto caldera lavas and MGR lavas are
291 within the compositional range of SEMFR lavas. Occurrence of two mineral compositional
292 groups in Toto and MGR lavas, without significant compositional overlap, strongly suggests
293 magma mixing (Supporting Information S4.2 and Fig. S4.1).

294
295 Olivine xenocrysts (≥ 0.5 mm) enclosing chromium spinel are common in primitive lavas (Fig.
296 3C, 5E). Olivine xenocrysts have higher Fo contents (Fe_{89-92} core and Fe_{87-97} rim) than do the
297 olivine phenocrysts (Fe_{86-88} , Table S4.3 and Fig. S4.1 in Supporting Information) in their host

298 basalts. Olivine xenocrysts host chromium spinel with $Cr\# (= 100 \times Cr / (Cr+Al)) = 47 - 73$. The
299 olivine – spinel assemblages plot in the mantle array of Arai (1994) and they are similar to those
300 of the SE Mariana forearc mantle peridotite ($Cr\# > 50$ and Fo_{90-92} , Ohara & Ishii, 1998),
301 suggesting that these xenocrysts are samples of forearc mantle (Fig. 5C).

302

303 5.3. ^{40}Ar - ^{39}Ar ages:

304 Four SEMFR samples (2 samples from Shinkai 6500 dive 1096, 1 sample each from Shinkai
305 6500 dive 1230 and YKDT-88) were dated by step-heating ^{40}Ar - ^{39}Ar (Fig. 6 and Table 1). Initial
306 $^{40}Ar/^{36}Ar$ for these samples (290 - 295) is nearly atmospheric ($^{40}Ar/^{36}Ar_{atmosphere} = 298.6$),
307 indicating that negligible radiogenic ^{40}Ar was inherited. Dated samples from dive 1096 samples
308 include one from each of the lower (1096-R2) and upper series (1096-R16) lavas. These gave
309 indistinguishable plateau ages of 3.5 ± 0.4 Ma (lower series 1096-R2) and 3.7 ± 0.3 Ma (upper
310 series 1096-R16). Shinkai dive 1230 and YKDT-88 gave slightly younger ages, respectively of
311 2.8 ± 0.5 Ma and 2.7 ± 0.3 Ma. SEMFR ^{40}Ar - ^{39}Ar ages indicate that seafloor spreading occurred
312 in Pliocene time (Fig. 1B), and suggests that SEMFR seafloor youngs toward the MGR.

313

314 6. Discussion

315 6.1. Genesis of SEMFR lavas:

316 Compositions of lavas and their minerals record the conditions of magma genesis and evolution;
317 and from this, important tectonic information can be gleaned (e.g. Klein & Langmuir, 1987).
318 Incompatible elements such as K_2O , Na_2O and TiO_2 are concentrated in the melt as mantle
319 melting or crystal fractionation proceeds. The first melt fraction is enriched in these elements and

320 so concentrations anti-correlate with fraction of melting, or “F” (Kelley *et al.*, 2006, Kelley *et*
321 *al.*, 2010, Klein & Langmuir, 1987, Taylor & Martinez, 2003). In addition, K₂O contents in
322 convergent margin magma sources are strongly affected by subduction-related metasomatism
323 (e.g. K-h relationship, Dickinson, 1975, Kimura & Stern, 2008), therefore this element is
324 generally not used to monitor F. FeO contents in basalts also contain petrogenetic information. In
325 basaltic systems, deeper melts are progressively enriched in iron (Klein & Langmuir, 1987).
326 Therefore, the Na₂O, TiO₂ and FeO contents of lavas are good proxies for the degree and depth of
327 melting. However, estimating the extent and depth of partial melting requires primitive lavas with
328 compositions in equilibrium with their mantle source; consequently, Na₂O, TiO₂ and FeO
329 contents are commonly corrected for olivine fractionation in order to infer their Na₈, Ti₈ and Fe₈
330 contents (Na₂O, TiO₂ and FeO contents calculated at MgO = 8 wt%). The Na₈ of N-MORBs anti-
331 correlates with Fe₈, indicating that melting is greater if it begins deeper (Fig. 7A; Arevalo Jr. &
332 McDonough, 2010, Klein & Langmuir, 1987). Subduction-related melting is somewhat different
333 because melting extents are enhanced by water (Gribble *et al.*, 1996, Kelley *et al.*, 2006, Taylor &
334 Martinez, 2003). BAB magma sources often are affected by subducted water and are
335 characterized by more melting at shallower depth than MORBs, so that Na₈ increases with Fe₈
336 (Fig. 7A; Kelley *et al.*, 2006, Taylor & Martinez, 2003). BAB and arc lavas have distinct
337 geochemical signatures (Fig. 7), resulting from elements dissolved in fluids derived from the
338 subducting slab that are involved in magma genesis. Arc lavas have lower Na₈ and Ti₈ contents at
339 higher K₂O/TiO₂ and Fe₈ content because they formed by high degrees of melting at greater
340 depths in the presence of slab-derived fluids. In contrast, BAB lavas have higher Na₈ and Ti₈
341 contents at lower K₂O/TiO₂ and Fe₈ content, as they were generated at shallower depth by
342 adiabatic mantle decompression, with less involvement of slab-derived fluids.
343

344 To investigate SEMFR magmagenesis (i.e. whether SEMFR lavas were produced in a BAB-like
345 and / or in a arc-like magmagenetic settings), we calculated Na₈, Ti₈ and Fe₈ contents for these
346 lavas. Plots of Al₂O₃, CaO and FeO* against MgO (Fig. 4D-F) show that the kinks in Al₂O₃ and
347 CaO, indicating the beginning of plagioclase and clinopyroxene crystallization, are respectively
348 observed at MgO = 6 wt% and at MgO ~ 7 wt%. Therefore, data were filtered to exclude highly
349 fractionated samples with MgO < 7 wt% that crystallized olivine, clinopyroxene and plagioclase
350 on their LLD (Fig. 4D-F), following the method described in Kelley et al. (2006) and Kelley et al.
351 (2010). The least fractionated samples with 7 - 8 wt% MgO, which fractionated olivine only (Fig.
352 4D-F), were then corrected to MgO = 8 wt% using the equations of Klein and Langmuir (1987)
353 for Na₈ and Fe₈, and Taylor and Martinez (2003) for Ti₈. These are listed in Table 1 (mean
354 SEMFR Na₈ = 1.99 ± 0.40 wt% (1 std. dev.); mean Ti₈ = 0.60 ± 0.11 wt%;. mean Fe₈ = 6.91 ±
355 0.54 wt%). The Na₈, Fe₈ and Ti₈ contents of SEMFR lavas are slightly lower than those
356 observed for N-MORBs (Arevalo Jr. & McDonough, 2010), indicating higher degrees of mantle
357 melting produced shallower. SEMFR lavas have similar Ti₈ and Na₈ contents at lower Fe₈ than
358 FABs; and they plot in the compositional overlap between Mariana arc lavas and the Mariana
359 BAB lavas, with homogeneous, low Na₈ and Ti₈ contents varying little with Fe₈ content (Fig. 7A
360 - B), suggesting a roughly constant degree and depth of mantle melting. These lavas were
361 produced by extensive melting (≥ 15%) of shallow mantle (~ 25 ± 6.6 km, see section 6.2). The
362 K₂O/TiO₂ (proxy for the total subduction input; Shen & Forsyth, 1995) of SEMFR lavas is higher
363 than that of FABs and plot between the arc – BAB compositional fields (Fig. 7C - D), well above N-
364 MORBs, further demonstrating a subduction component in SEMFR magma genesis. Only lavas
365 from YKDT-88, collected closest to the FNVC (Fig. 1B), do not plot on the SEMFR
366 compositional field (Fig. 7A-C), with lower Na₈ and Ti₈ at similar Fe₈ contents. Their Ti₈ and Na₈
367 values are lower than those of Mariana arc lavas (Fig. 7A-C), suggesting that YKDT-88 lavas

368 were produced by more mantle melting and / or melting of a more depleted mantle source at
369 similar depth compared to other SEMFR magmas.

370
371 The above inference that SEMFR lavas are similar to back-arc basin basalts (BABB) can be
372 checked by examining mineral compositions, because arc basalts and BABBs have distinct An-Fo
373 relationships (Stern, 2010). Arc basalts contain more Fe-rich olivine with more An-rich
374 plagioclase compared to BABB, MORB, and OIB (Ocean Island Basalt, Fig. 8A) because higher
375 water contents in arc magmas delay plagioclase but not olivine crystallization (Kelley et al., 2010,
376 Stern, 2010), resulting in higher CaO and FeO contents in the melt when plagioclase starts
377 crystallizing. In contrast, BABBs, formed largely by adiabatic decompression mantle melting,
378 have Fo-An relationships essentially indistinguishable from those of MORB and OIB (Fig. 8A).
379 Accordingly, we can discriminate arc basalts from BABBs based on An and Fo contents of the
380 plagioclase – olivine assemblages. Fig. 8A shows that most SEMFR lavas plot within the BABB
381 compositional field, consistent with observations from Na₈, Ti₈, and Fe₈ discussed in the previous
382 section. Some samples also plot within the arc compositional field, strongly suggesting that BAB-
383 like (i.e. adiabatic decompression melting) and arc-like (i.e. wet mantle melting) conditions of
384 magmagenesis coexisted beneath SEMFR. We propose that SEMFR magmas formed by adiabatic
385 decompression of fertile asthenospheric mantle (BAB-like mantle) metasomatized by slab-
386 derived fluids, enriching the melt in water and sometimes delaying plagioclase fractionation.
387

388 *6.2. Pressure and temperature of mantle melting:*

389 The P-T conditions of mantle melting, recorded by primary melts in equilibrium with the mantle
390 beneath SEMFR, were calculated from major element compositions of primitive basalts with

391 MgO \geq 7 wt% (Kelley et al., 2010; Fig. 4D-F) by using the geothermobarometer of Lee *et al.*
392 (2009), based on Si, Mg and water contents of primitive magmas. The estimated P-T conditions
393 are those of the last melt in equilibrium with the mantle or a mean value of the P-T conditions of
394 polybaric, fractional pooled melts recorded along a melting column (Kelley et al., 2010). SEMFR
395 lavas are compositionally similar to BABBs, we therefore used BAB-like oxidation state
396 ($\text{Fe}^{3+}/\text{Fe}_T = 0.17$) and averaged Mariana BAB water content (1.31 wt%; Gribble et al., 1996,
397 Kelley & Cottrell, 2009) for SEMFR lavas, $\text{Fe}^{3+}/\text{Fe}_T = 0.17$ for Mariana Trough lavas and
398 $\text{Fe}^{3+}/\text{Fe}_T = 0.25$ for Mariana arc magmas (Kelley & Cottrell, 2009). We also used lherzolithic
399 BAB-like mantle source (Fo_{90} ; Kelley et al., 2006) to estimate the P-T conditions of SEMFR
400 mantle melting. Primitive lavas of the Mariana Trough and the Mariana arc with analyzed water
401 were filtered for MgO \geq 7 wt % as SEMFR lavas for consistency. SEMFR whole rock
402 compositions indicate melting pressures of 0.5 – 0.9 GPa (\pm 0.2 GPa) and temperatures of 1217 –
403 1269°C (\pm 40°C), with a mean of 0.7 ± 0.2 GPa (\sim 23 \pm 6.6 km) and $1239 \pm 40^\circ\text{C}$ (Fig. 8B). This
404 is consistent with melting just above the present subducting slab (\leq 30 – 100 km depth), although
405 we do not know the position of the subducting slab at 2.7 – 3.7 Ma, when SEMFR melts were
406 generated. Mariana Trough BABBs (Gribble et al., 1996, Kelley & Cottrell, 2009) have similar P-
407 T conditions of mantle melting ($0.7 - 1.5 \pm 0.2$ GPa, $1214 - 1359 \pm 40^\circ\text{C}$; mean melting depth \sim
408 33 ± 6.6 km). In contrast, Mariana arc lavas (Kelley et al., 2010, Shaw et al., 2008) show higher
409 P-T conditions of mantle melting ($1.1 - 3.0 \pm 0.2$ GPa, $1240 - 1522 \pm 40^\circ\text{C}$). These results
410 suggest that SEMFR lavas and Mariana Trough BABBs were similarly generated by adiabatic
411 decompression of shallow asthenospheric mantle (\sim 25 – 30 \pm 6.6 km). In contrast, arc lavas
412 (Kelley & Cottrell, 2009, Kelley et al., 2010, Shaw *et al.*, 2008) recorded deeper (mean melting
413 depth \sim 51 \pm 6.6 km).and hotter mantle melting conditions (Kelley et al., 2010). This leads to the
414 further deduction that SEMFR lavas formed by BABB-like seafloor spreading at 2.7 to 3.7 Ma.

415

416 *6.3. Geodynamic evolution of the Southeastern Mariana Forearc Rift:*

417 Investigations of the petrography and geochemistry of SEMFR lavas reveal that i) SEMFR lavas
418 are petrographically and compositionally similar to Mariana Trough BABBs; ii) SEMFR melts
419 interacted with the pre-existing forearc lithosphere and picked up some forearc mantle olivines,
420 indicating rapid ascent; iii) magmatic activity (2.7 – 3.7 Ma) formed SEMFR oceanic crust by
421 seafloor spreading (no Eocene forearc basement has been recovered from the SEMFR); iv)
422 SEMFR primitive basalts formed by decompression melting at ~ 23 km depth and 1239°C, like
423 that associated with the Mariana Trough backarc basin, suggesting similar formation; and v) lack
424 of evidence for recent igneous and hydrothermal activity, except near MGR and Toto caldera,
425 indicates that the presently-observed NNW-SSE trending relief formed during post-magmatic
426 rifting (< 2.7 Ma).

427

428 SEMFR is a rift with no morphological expression of large arc-like volcanoes, like those of the
429 Mariana arc. SEMFR lavas are vesicular with K₂O contents (Fig. 4A) and K₂O/TiO₂ ratios that
430 are similar to MGR and other Mariana Trough BAB lavas (Fig. 7C, D). They also have similar P-
431 T conditions of magma genesis, demonstrating that they formed by adiabatic decompression of
432 BAB-like mantle metasomatized by slab-derived fluids. These observations raise a fundamental
433 question: were SEMFR lavas produced by seafloor spreading in the backarc basin or in the
434 forearc? The southernmost Mariana convergent margin has reorganized rapidly since its collision
435 with the Caroline Ridge, suggesting that SEMFR lavas were produced by different geological
436 settings that what exists today. From the location of SEMFR adjacent to the trench, it is clear that
437 these lavas formed in the forearc. We propose a geodynamic model for the southernmost Mariana

438 arc, in which SEMFR formed to accommodate opening of the southernmost Mariana Trough
439 (Fig. 9A, B and Fig. 10A-C). Rupturing the forearc lithosphere allowed asthenospheric mantle to
440 flow into the forearc and to melt by adiabatic decompression under hydrous conditions 2.7 – 3.7
441 Ma ago; and origin of SEMFR mantle (i.e. from the backarc basin, the arc or a slab window) is
442 still under investigation. Some SEMFR melts picked up fragments of pre-existing forearc mantle
443 during ascent, demonstrating that SEMFR lavas formed long after subduction initiation. Post-
444 magmatic activity (< 2.7 Ma ago) shapes the S. Mariana forearc lithosphere (Fig. 9C) and formed
445 the NNW-SSE trending rifts of SEMFR, as we know it today (Fig. 9D and Fig. 10D).

446

447 **7. Conclusions**

448 Two important conclusions can be drawn from this study: i) SEMFR magmas formed by
449 adiabatic decompression in the southernmost IBM forearc, usually underlain by cold,
450 serpentinized harzburgitic mantle that rarely melts (Reagan et al., 2010); and ii) SEMFR lavas
451 were produced by melting of fertile asthenospheric mantle metasomatized by slab-derived fluids,
452 long after subduction initiation, allowing development of a forearc lithosphere. Our results show
453 that the southernmost Mariana forearc stretched to accommodate opening of the Mariana Trough
454 to form the SEMFR, allowing hydrated, asthenospheric mantle to flow into the forearc and to
455 produce new oceanic crust ~ 2.7 – 3.7 Ma ago. SEMFR lavas formed by adiabatic decompression
456 of depleted backarc mantle at $\sim 30 \pm 6.6$ km depth and $1224 \pm 40^\circ\text{C}$. SEMFR at 2.7-3.7 Ma was
457 likely a ridge-like spreading center, where the slab-derived fluids enhanced mantle melting
458 beneath the forearc. Today, SEMFR is no longer magmatically active and amagmatic extension
459 shapes its morphology.

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692 South Chamorro Seamount, an active serpentinite mud volcano in the Mariana forearc.
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694

695 **Tables**

696 Table 1: Major (wt%) element compositions of SEMFR lavas. Mg# [= atomic ($Mg^{2+} * 100$) /
697 ($Mg^{2+} + Fe^{2+}$)] was calculated assuming all the iron is Fe^{2+} on anhydrous basis. Primitive samples
698 with $7 \text{ wt\%} \leq MgO < 8 \text{ wt\%}$ were corrected on anhydrous basis by using the equations of Klein
699 and Langmuir (1987) for Na_8 and Fe_8 , and Taylor and Martinez (2003) for Ti_8 . See text for
700 details. Sample numbers with * have no major element data reported; minor element data will be
701 reported elsewhere. fg: fine-grained, ol: olivine, pl: plagioclase, cpx: clinopyroxene.

702
703 Table 2: Overview of mean mineral compositions in basalts from each dive in the SEMFR. n: is
704 the total number of analyses performed in one sample, s: is the number of minerals analyzed in
705 each sample, c: core, m : mantle, st : sieve texture, r : rim, gr: groundmass, * : minerals in 1235-
706 R12 observed in the microcrystallized basalt, while the other 1235-R12 analyses refer to minerals
707 in the diabasic xenolith. Numbers in italics represent reverse zoning. Bold numbers represent
708 minerals with oscillatory zoning. NA: Not analyzed. MGR: Malaguana-Gadao Ridge, SEMFR:
709 S.E. Mariana Forearc Rift.

710 **Figure Captions**

711 Fig. 1: Locality maps. A) Izu-Bonin-Mariana intraoceanic arc system. The IBM magmatic arc
712 generally lies ~ 200 km from the trench and the Mariana Trough backarc basin spreading center
713 generally lies ~ 300 km from the trench. The arrows represent Pacific-Mariana convergence
714 vectors from Kato *et al.* (2003). Yellow box shows the area of B. B) Bathymetric map of the
715 southernmost Mariana arc-backarc basin system. Southward, the magmatic arc (white line)

716 approaches the Malaguana-Gadao spreading ridge, both of which lie unusually close (~ 110 km)
717 to the trench. Location of the Malaguana-Gadao spreading ridge is from Martinez et al. (2000).
718 Filled colored circles show locations of YK06-12, YK08-08 Leg 2 and YK10-12 Shinkai dives
719 and YK08-08 Leg 2 YKDT deep-tow cameras; the small circles show the locations of dredge site
720 D27 (Bloomer & Hawkins, 1983), Shinkai 6500 dives 158 and 159 (Fryer, 1993) and dredge sites
721 KH98-1D1 and KH98-1D2 (Sato & Ishii, 2011); triangles show the locations of KR00-03 Leg 2
722 Kaiko dives in Toto caldera and Malaguana-Gadao Ridge. Note that Kaiko dive 164 is near the
723 magma chamber (MC) identified by Becker et al. (2010). The white box shows the approximate
724 region encompassed by SEMFR. The dashed white line shows the position of the W. Santa Rosa
725 Bank (WSRB) Fault which separates older rocks of the Santa Rosa Bank (SRB) from the SEMFR
726 younger rocks. The red numbers are $^{40}\text{Ar} - ^{39}\text{Ar}$ radiometric ages. Map generated with GMT
727 (Smith & Wessel, 1990, Wessel & Smith, 1995b, Wessel & Smith, 1998, Wessel & Smith,
728 1995a) by using a compilation from the University of New Hampshire / Center for Coastal and
729 Ocean Mapping / Joint Hydrographic Center (Gardner, 2006, Gardner, 2007, Gardner, 2010). C)
730 Sidescan sonar (HMR1) image of the S. Mariana convergent margin (Fryer et al., 2003) with the
731 location of traverses by JAMSTEC submersibles during YK06-12, YK08-08 Leg 2, YK10-12 and
732 KR00-03 Leg 2 cruises. Dark areas have high backscatter, whitish corresponds to low
733 backscatter. The SEMFR, the Malaguana-Gadao Ridge (MGR) and Toto caldera are dominated
734 by high backscatter, indicating that the oceanic crust or lightly sedimented basement is exposed.
735 White dashed line denotes SEMFR axial deeps, ridges lie between the valleys. Black arrows
736 show the opening of SEMFR (Martinez & Stern, 2009). FNVC (Fina-Nagu Volcanic Chain)
737 represents extinct arc volcanoes.

738
739 Fig. 2: Typical bottom profiles of SEMFR encountered during seafloor traverses. A) near the
740 trench axis (Shinkai 6500 dive 1230) and B) near the Fina-Nagu Volcanic Chain (YKDT-87).
741 Near the trench, SEMFR flanks are dominated by steep talus slopes of lava fragments with few
742 exposures of tilted and faulted lava flows. Talus and outcrops are covered by thin pelagic
743 sediment. Near the Fina-Nagu Volcanic Chain (FNVC), SEMFR relief is smoother with better-
744 preserved pillow lava outcrops covered by thin sediment. Photographs of the typical seafloor
745 observed near the trench (C, D) and near the FNVC (E). Black star in B) shows the beginning of
746 YKDT deep-tow camera dredging.

747
748 Fig. 3: Photomicrographs of SEMFR lavas and fine gabbro. A) Typical microporphyritic olivine
749 – clinopyroxene basalt (sample 1230-R2) with microlitic groundmass and microphenocrysts of
750 plagioclase (pl) and clinopyroxene (cpx). B) Fine-grained diabase xenolith (sample 1235-12)
751 hosted by microcrystalline basalt (finer grained part to left). The diabase contains Mg-rich olivine
752 (Fo_{89}), Mg-rich clinopyroxene ($\text{Mg}\# \geq 80$) and normally zoned Ca-rich plagioclase (≥ 0.1 mm).
753 In contrast, the basaltic host is more fractionated, with Fe-rich olivine (Fo_{85-86}) and Mg-rich
754 clinopyroxene microphenocrysts (≥ 0.1 mm). Clinopyroxene in the groundmass (< 0.1 mm) are
755 Mg-poor and coexist with Ca-poor plagioclase microlites. Clinopyroxenes in the diabase exhibit
756 oscillatory and reverse zoning. The boundary between the two textural realms is straight,
757 suggesting that basalt magma picked up solidified diabase. See Supporting Information S4 for
758 more details. C) Olivine – clinopyroxene basalt from YKDT-88 containing large olivine
759 xenocrysts surrounded by olivine-rich groundmass. D) Photomicrograph of cryptocrystalline
760 plagioclase basalt from Shinkai dive 1235 (sample 1235-R8) hosting an amphibole gabbro
761 xenolith (chl: chlorite, amph: amphibole). The contact between gabbro and basalt is an irregular
762 chilled margin, suggesting that the basalt picked up solid pieces of gabbro. A second chilled

763 margin is observed inside the basalt, suggesting multiple magmatic injections in the basalt. E)
764 Photomicrograph of plagioclase (pl) xenocryst observed in the Shinkai dive 1230 (sample 1230-
765 R17). The core of the plagioclase is well-preserved and exhibits An₉₁₋₉₂ content. The mantle
766 exhibits An₈₀₋₈₉ and is mostly resorbed (sieve-texture) due to the interaction plagioclase – melt.
767 The rim is well-preserved and is An₈₃₋₈₈. Plagioclase microlites have lower An content (An < 80
768 %). Larger, Mg-rich clinopyroxenes (cpx) occur near the An-rich plagioclase xenocrysts (Mg # =
769 86 – 88), while the clinopyroxenes microlites exhibit higher range in Mg# (74 – 88). Such An-
770 rich plagioclases are observed in the arc crust. See Supporting Information S4 for details.
771

772 Fig. 4: Major element compositional characteristics of SEMFR, MGR, Eocene forearc basalts
773 (FABs; Reagan et al., 2010), S. Mariana Arc lavas (SMArc: 13°10'N – 11°N) which include Toto
774 caldera lavas. All data recalculated to 100% anhydrous. A) Potash-silica diagram (Peccerillo &
775 Taylor, 1976), showing that SEMFR lavas are low-K basalts to medium-K basaltic andesites. The
776 grey field represents Mariana Trough BAB lavas (Gribble et al., 1996, Hawkins *et al.*, 1990,
777 Kelley & Cottrell, 2009, Pearce et al., 2005) and the hatched field represents Mariana Arc lavas
778 (Kelley & Cottrell, 2009, Kelley et al., 2010, Pearce et al., 2005, Shaw et al., 2008, Stern *et al.*,
779 2006, Wade *et al.*, 2005). The small grey triangles are Malaguana-Gadao Ridge (MGR) data from
780 Kakegawa et al. (2008) and Pearce et al. (2005). The small black triangles are data from SMA
781 volcanoes (Kakegawa et al., 2008, Stern et al., 2013). Larger grey triangles denote MGR and
782 larger black triangles denote Toto samples reported in this manuscript. The field for boninites is
783 from Reagan et al. (2010). Note that SEMFR lavas mostly plot in field of Mariana Trough BAB
784 lavas. B) FeO*/MgO vs SiO₂ diagram for medium-Fe, medium-Fe, high-Fe discrimination
785 (Arculus, 2003); green line discriminates between tholeiitic and calc-alkaline lavas (Miyashiro,
786 1974). C) Mg# vs SiO₂ and D) CaO, E) Al₂O₃, F) FeO* plotted against MgO for SEMFR, MGR,
787 and Toto caldera. When plagioclase starts crystallizing, it produces a hinge in the liquid line of
788 descent (LLD) of Al₂O₃. The hinge in Al₂O₃ is observed at MgO = 6 wt%; and the kink in CaO
789 and FeO* is observed at MgO ~ 7 wt%. Therefore, primitive lavas are identified with MgO ≥ 7
790 wt%, following the method of Kelley et al. (2010). Arrows represent fractionation trends. Ol :
791 olivine, pl : plagioclase, cpx : clinopyroxene. We used the same method as for SEMFR lavas
792 (MgO ≥ 7 wt%) to filter the Mariana arc and Mariana Trough lavas.
793

794 Fig. 5: Variation of A) olivine Fo and B) clinopyroxene Mg# composition with whole rock Mg#.
795 C) Variation of An content of plagioclase core with whole rock CaO (wt%) content. Olivine,
796 clinopyroxene and plagioclase are mostly in equilibrium with their host rock. Fractional
797 crystallization (grey arrow) removes Mg-rich minerals from the residual melt which precipitates
798 increasingly Fe-rich minerals. The olivine-liquid equilibrium line is calculated from experimental
799 data of Roeder and Emslie (1970) with K_D olivine – melt = 0.3 and Fe³⁺/Fe_T = 0.17 (Kelley &
800 Cottrell, 2009). D) Olivine – Spinel Mantle Array (OSMA) diagram of Arai (1994). Cr# of spinel
801 inclusions and Fo content of host olivine xenocrysts in Shinkai dive 1096 upper series (blue star)
802 and in YKDT-88 lavas (pink stars) plot within OSMA. Cr# are means for each spinel inclusion
803 and reported with the Fo content of their olivine host. Their Cr# ≥ 50 is similar to that of the
804 southern Mariana forearc peridotite (Ohara & Ishii, 1998); whereas BAB peridotites have Cr# <
805 30 (Ohara et al., 2002). SEMFR peridotites (Michibayashi et al., 2009, Sato & Ishii, 2011) have
806 Cr# and Fo contents intermediate between southern Mariana forearc peridotites and Mariana
807 Trough BAB peridotites (Ohara et al., 2002). E) Large xenocryst of anhedral olivine (ol) with
808 Fo₉₀₋₉₂ hosting chromium spinel (sp) and melt inclusions (MI) from sample YKDT88-R2.
809

810 Fig. 6: The $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra with $^{36}\text{Ar}/^{40}\text{Ar}$ vs $^{39}\text{Ar}/^{40}\text{Ar}$ plot for samples from the SEMFR.
811 Percentage of ^{39}Ar released during analysis is also reported.

812
813 Fig. 7: Diagrams showing variations in A) Na_8 , B) Ti_8 , D) $\text{K}_2\text{O}/\text{TiO}_2$ versus Fe_8 and C) $\text{K}_2\text{O}/\text{TiO}_2$
814 versus Ti_8 . Na_8 and Ti_8 are proxies for the fraction of mantle that is melted, Fe_8 is a proxy for the
815 depth of mantle melting (Klein & Langmuir, 1987, Pearce et al., 2005), and $\text{K}_2\text{O}/\text{TiO}_2$ is a proxy
816 for the subduction input. The grey field represents Mariana Trough BAB lavas (Gribble et al.,
817 1996, Hawkins et al., 1990, Kelley & Cottrell, 2009, Pearce et al., 2005) and the hatched field
818 represents Mariana arc lavas (Kelley & Cottrell, 2009, Kelley et al., 2010, Pearce et al., 2005,
819 Shaw et al., 2008, Stern et al., 2006, Wade et al., 2005). Primitive lavas from the Mariana Trough
820 and the Mariana arc were filtered as SEMFR lavas ($\text{MgO} \geq 7$ wt%) for consistency. The FABs
821 field is from Reagan et al. (2010). The negative correlation of Na_8 with Fe_8 of N-MORBs (grey
822 arrow; Arevalo Jr. & McDonough, 2010) shows that more magma is produced when melting
823 begins deeper; while in subduction-related lavas, more melting is produced shallower. SEMFR
824 lavas have Na_8 and Ti_8 contents slightly varying with Fe_8 content, indicating homogeneous
825 degree of mantle melting.

826
827 Fig. 8: A) Composition ranges for coexisting olivine Fo – plagioclase An in intraoceanic arc lavas
828 (blue field) and BABB (red outline) after Stern et al. (2006). Arc basalts have more calcic
829 plagioclase in equilibrium with more Fe-rich olivine compared to MORB (short dashed outline),
830 OIB (long dashed outline), and BABB. The plagioclase-olivine relationships of SEMFR lavas
831 generally plot in the overlap between the BABB and the arc composition fields. The black
832 triangle denotes a Toto caldera sample. B) P-T conditions of mantle-melt equilibration estimated
833 by using the procedure of Lee et al. (2009) for SEMFR primitive lavas with $\text{MgO} \geq 7$ wt%. Also
834 shown are Mariana Trough basaltic glasses (Gribble et al., 1996, Kelley & Cottrell, 2009), and
835 the Mariana arc melt inclusions with analyzed water contents (Kelley et al., 2010, Shaw et al.,
836 2008). The solidus is from Katz *et al.* (2003). We used $\text{Fe}^{3+}/\text{Fe}^{\text{total}} = 0.17$ for SEMFR and Mariana
837 Trough BABBs, $\text{Fe}^{3+}/\text{Fe}^{\text{total}} = 0.25$ for Mariana arc lavas (Kelley & Cottrell, 2009) and Fo_{90} for the
838 equilibrium mantle. We used the same method as for SEMFR lavas ($\text{MgO} \geq 7$ wt%) to filter the
839 Mariana arc and Mariana Trough glass for consistency. The pink field represents the slab depth
840 beneath SEMFR (≤ 30 km – 100 km depth; Becker et al., 2005).

841
842 Fig. 9: Geodynamic evolution of SEMFR. A) The Mariana Trough is opening ~ 5 Ma ago. B)
843 Spreading of the Mariana Trough rifts the arc lithosphere (in orange) and forms SEMFR by
844 stretching the forearc crust (in yellow) ~ 2.7 – 3.7 Ma ago. We speculate that SEMFR is a
845 spreading center with intense magmatic activity. C) Post-magmatic deformation of SEMFR
846 occurred < 2.7 Ma ago, and intensely deformed the Eocene forearc crust. D) Today, SEMFR is no
847 longer magmatically active and amagmatic extension dominates the rift. Eocene forearc is eroded
848 with opening of the S. Mariana Trough; and actual position of the forearc is based on R/V
849 Yokosuka YK08-08 Leg 2 and YK10-12 cruise reports (Ohara *et al.*, 2010, Ohara *et al.*, 2008).
850 The red box highlights the area of Fig. 10.

851
852 Fig. 10: 3D model of geodynamic evolution of the SEMFR drawn after the SE Mariana
853 lithospheric section of Gvirtzman & Stern (2004) and the tomographic images of Miller *et al.*
854 (2006a). The cross section is drawn from the area highlighted by a red box in Fig. 9. BAB lithos.:
855 backarc basin lithosphere. A) Opening of the S. Mariana Trough, the Malaguana-Gadao Ridge
856 (MGR), stretches the pre-existing Eocene forearc lithosphere ~ 5 Ma ago. B) Rupturing of the

857 forearc allow mantle melting, creating new SEMFR oceanic crust ~ 2.7 – 3.7 Ma ago. The red
858 line shows the location of the cross section of SEMFR shown in C. C) Continuous dehydration
859 of the shallow downgoing slab controlled SEMFR magmatic activity, and SEMFR had ridge
860 morphology ~ 2.7 – 3.7 Ma ago. D) Today, post-magmatic rifting dominates SEMFR.
861

862 **Supporting Information:**

863 Supporting Information S1: Description of the dives

864 Fig. S1.1: Cross-sections of SEMFR rifts 1, 2 and 3 from the trench

865 Fig. S1.2: Dive tracks of Shinkai dives 1096, 1230 and 1235 and deep tow camera 82

866 Fig. S1.3: Dive tracks of YKDT 85, 86, 87 and 88.

867 Fig. S1.4: Dive tracks of Shinkai dive 973 from YK06-12 cruise report and Kaiko dive 163 from
868 KR00-03 Leg 2 cruise report

869 Fig. S1.5: Interpreted bathymetric profile of the eastern flank of rift 1 traversed during Shinkai
870 dive 1096

871 Fig. S1.6: Interpreted bathymetric profile of the eastern flank of rift 2 traversed during Shinkai
872 dive 1230

873 Fig. S1.7: Interpreted bathymetric profile of the eastern flank of rift 3 traversed during Shinkai
874 dive 1235.

875 Fig. S1.8: Interpreted bathymetric profile of the eastern flank of rift 1 traversed during Shinkai
876 dive 973

877 Fig. S1.9: Interpreted bathymetric profile of the summit of ridge on the eastern side of rift 3
878 traversed during YKDT-85

879 Fig. S1.10: Interpreted bathymetric profile of the eastern flank of ridge of rift 3 (central part of
880 SEMFR) traversed during YKDT-86

881 Fig. S1.11: Interpreted bathymetric profile of YKDT-82, performed on the summit of a ridge
882 between rifts 2 and 3

883 Fig. S1.12: Interpreted bathymetric profile of the axial valley of rift 3 traversed during YKDT-87

884 Fig. S1.13: Interpreted bathymetric profile of the eastern flank of ridge of rift 2 performed during
885 YKDT-88

886 Fig. S1.14: Interpreted bathymetric profile of Toto caldera performed during Kaiko dive 163

887 Fig. S1.15: Interpreted bathymetric profile along the Malaguana-Gadao Ridge performed during
888 Kaiko dive 164, near the 13°N magmatic chamber

889 Table S1.1: Longitude and latitude of the dives in the SEMFR, MGR and Toto caldera with their
890 depth and trench distance

891 Table S1.2: Variation of the width and depth (km) of the three SEMFR rifts along axis.
892

893 Supporting Information S2: Sample selection and analytical techniques

894 Fig. S2.1: Location of the analyzed samples, for major elements during this study, on the
895 bathymetric profiles of the Shinkai dives 1096, 1230 and 1235

896
897 Supporting Information S3: Method for describing the samples
898

899 Supporting Information S4: Petrographic description and mineralogy of the samples

900 Fig. S4.1: SEMFR mineral compositions in clinopyroxene, plagioclase and olivine

901 Table S4.1: Representative mean clinopyroxene composition

902 Table S4.2: Representative mean plagioclase composition

903 Table S4.3: Representative mean olivine composition

904 Table S4.4: Representative mean spinel composition

905

906 Supporting Information S5: Correlation between mineral abundances and whole rock chemistry

907 Fig. S5.1: Plot showing the correlation between mineral abundances and whole rock composition.

908 A) The olivine proportions are positively correlated to the whole-rock Mg#

909

910 Supporting Information S6: Effects of the variations of the Fo content on the P-T conditions of

911 SEMFR mantle melting

912