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Melt Inclusions in Plagioclase Macrocrysts at Mount Jourdanne, Southwest Indian Ridge (~64° E): Implications for an Enriched Mantle Source and Shallow Magmatic Processes

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Abstract: Plagioclase ultraphyric basalts (PUBs) with up to 40% millimeter-sized plagioclase crystals, were sampled from the Mount Jourdanne volcanic massif (~64° E) in the Southwest Indian Ridge. The geochemistry of the host glass, the glassy melt inclusions and their host plagioclase macrocrysts (An₆₀₋₆₉) are used to reveal the mantle heterogeneity and to discuss the origin of Mount Jourdanne PUBs. The melt inclusions trapped in plagioclase display low MgO and high SiO₂ contents and show rare earth element (REE) patterns resembling enriched mid-ocean ridge basalts (E-MORB). Together with their positive Sr and Eu anomalies, these features indicate that they were derived from an enriched mantle source, likely a refertilized peridotite or a pyroxenite. In contrast to some 61–67° E basalts, there is a lack of negative Eu anomalies in the PUB host glasses, precluding large amounts of plagioclase crystallization from their parental magma. Petrographic observations and the general chemical similarity between melt inclusions and melts equilibrated with the clinopyroxene cores in regional gabbros and/or troctolites suggest that these plagioclase macrocrysts originate from gabbroic mush within the lower crust. The density contrasts allow the effective segregation of plagioclase prior to their incorporation into the host magma. We propose that these plagioclase macrocrysts were entrained when a new batch of magma passed through the crustal mush zone, and resulted in the formation of the PUB. Eruption of Mount Jourdanne PUBs requires a minimum ascending velocity of 5 m d^{−1} for the host magma, which is not as high as the eruption rate for typical MORB samples. It is likely that the PUB host magma erupts during a period with reduced magma supply, whereas eruption of aphyric lavas correspond to the fast volcanic formation of the Mount Jourdanne massif.

Keywords: basalts; mantle heterogeneity; melt inclusions; plagioclase; Southwest Indian Ridge

1. Introduction

Mid-ocean ridge basalts (MORB) are produced as a consequence of adiabatic decompression melting when the Earth's mantle rises beneath the ridge. The erupted magmas span a wide range of compositions, which are usually classified into two principal groups (i.e., normal MORB (N-MORB) and enriched MORB (E-MORB)) based on their geochemistry. Usually, these magmas undergo mixing, fractionation and/or assimilation at shallow levels before their eruption at the surface [1–3], which obscure the original variability of the MORB magmas. Melt inclusions captured by early crystallizing phase (e.g., olivine) may isolate early liquids and hence provide a great deal of information about

magma at a more primitive stage [4–7]. In contrast, melt inclusions entrained by late-stage crystallized minerals (e.g., plagioclase) could record more evolved compositions and hence unravel the subsequent chemical evolution [8]. Previous studies of melt inclusions in MORB samples show that they span a wide range of compositions [9–12]. The compositional diversity varies with the spreading rate, crustal thickness and mantle temperature. At slow-spreading ridges, where magma supply is episodic and steady-state magma chambers are rare [13–15], the generated melts have fewer opportunities to mix. Therefore, any original diversity in melt composition is likely to be preserved.

Basaltic lavas with abundant calcic plagioclase crystals are common at mid-ocean ridges with intermediate to ultraslow spreading rates [16–23]. These basaltic lavas are noteworthy for their high proportions of plagioclase compared to olivine and/or clinopyroxene. Usually, they contain millimeter-sized plagioclase with phyric to ultraphyric textures, which can be defined as plagioclase ultraphyric basalts (PUBs) following Cullen et al. [16]. Understanding the petrogenesis of PUBs is important as they preserve important information about crustal processes, as well as unique compositions of the primitive magma [24]. So far, the origin of PUBs is still a matter of debate. Existing models for PUB formation include extreme crystallization from high-Al parental liquids [25,26] or the physical accumulation of plagioclase in the melt [16] or mixing of a basaltic liquid with plagioclase cumulates or mush zones [18,20,27].

The easternmost part of Southwest Indian Ridge (SWIR) is among the deepest parts of the oceanic ridge and far from any known hotspot, but E-MORB coexists with N-MORB in its axial region [28–30]. Although the presence of E-MORB has been attributed to a heterogeneous mantle source together with low partial melting degrees [30], the origin of the mantle source heterogeneity has not been well constrained. In addition, being aware that the easternmost part of SWIR represents an extreme melt poor end member for global mid-ocean ridges, we are motivated to investigate the shallow magmatic processes at the slowest end of the spreading-rate spectrum.

In this study, plagioclase macrocrysts and their associated melt inclusions in Mount Jourdanne PUBs from SWIR (~64° E) were analyzed for major and trace element compositions. These data provide important information on the mantle source heterogeneity. In particular, the data demonstrate that the plagioclase-hosted melt inclusions preserve the inherent characteristics of the enriched mantle source, whereas the host magmas preserve the record of the melt/mantle interaction in the axial lithosphere. Because the PUB samples are the first reported in this region, we also discuss the petrogenesis of Mount Jourdanne PUBs, which may provide insights into the axial magma plumbing system beneath the ultra-slow spreading SWIR.

2. Geological Setting

The easternmost part (east of the Melville Fracture Zone) of the ultraslow SWIR (14 mm yr⁻¹ full rate) [31] is an end member of the global ridge system in terms of its very low magma supply (Figure 1). The low melt budget is supported by geophysical observations (e.g., bathymetric, gravity and seismic crustal structure) [32–34] and geochemical data of basaltic lavas [29]. In this region, the model of seafloor spreading is variable along the axis, which is indicated by detailed geophysical observations and sample dredging [33,35]. There are large volcanic centers, where most of the low melt influx to the ridge is focused [36], leaving corridors with almost no magmatic activity (Figure 1a). In the amagmatic corridors, the seafloor exposes wide expanses of partially serpentinized peridotites, with a small proportion of gabbroic rocks and a thin and discontinuous basaltic cover [35].

Figure 1. (a) Bathymetric map of the Southwest Indian Ridge east of Melville fracture zone (FZ), with the location of the Mount Jourdanne volcanic massif and regional basalts from volcanic, and ultramafic seafloor (according to Paquet et al. [30]). Inset shows the study area. (b) High-resolution bathymetry map with an oblique view of the Mount Jourdanne massif with the sample location of aphyric basalt and plagioclase ultraphyric basalts (PUBs) in this study. Samples ED16–1 and ED16–3 are from the literature data [30]. The base map was prepared using Generic Mapping Tools (GMT) [37]. CIR: Central Indian Ridge; SEIR: Southeast Indian Ridge.

Mount Jourdanne is a large volcanic massif [38,39], located at 63°55' E, 27°52' S on segment 11 from SWIR (Figure 1b). This approximately W–E trending volcanic construction has a lenticular shape and extends for several kilometers along the rift axis. The volcanic terrain tapers to the west, indicating that the tip of the axial volcanic ridge (AVR) has propagated westward over the past few million years [40]. The summit of Mount Jourdanne is characterized by a series of extrusive units, principally alternating sheet flows, lobate flows, tubes and pillow basalts, which comprise the main outcrop of the northeastern part of the AVR [41]. Sheet flow patterns predominate on the smoothly dipping flanks to the north, whereas pillow mounds and basaltic rock fragments are more dominant on the uppermost plateau of the summit.

3. Samples and Petrography

Samples in this study were collected from the Mount Jourdanne volcanic massif by television-guided grabs (TVG) on R/V *Dayang Yihao* during DY115–19, DY115–20, DY125–26, DY125–30 and DY135–49 cruises (Figure 1b).

Most of the samples are fresh basaltic pillow lavas and show fine-grained textures with <3 vol % plagioclase crystals. The matrix is mainly composed of microcrystals of clinopyroxene, plagioclase and olivine with interstitial glass. Specifically, two samples (30I–TVG2–1 and 30I–TVG2–2) show typical PUB textures (Figure 2a,b) with abundant plagioclase crystals (up to 40 vol %), but rare (<2 vol %) olivine and spinel microphenocrysts in a glassy to cryptocrystalline matrix (Figure 2c,d). The plagioclase crystals are generally very large, ranging from ~200 μm up to 3 cm in size. Plagioclase crystals larger than 2 mm may be either phenocrysts (grown in situ from the host magma) or antecrysts (derived from a genetically related older magma) [18,27,42]. We use the non-genetic term ‘macrocrysts’ to refer to these crystals following Neave et al. [43]. Many of the plagioclase macrocrysts show patchy and sieve textures (Figure 2e,f) with abundant melt inclusions. In general, the melt inclusions are arranged in the core of plagioclase macrocrysts (Figure 2f), ranging in morphology from small (<10 μm) inclusions to large (up to 300 μm in diameter) inclusions. SEM observations show that the large inclusions are round, elongated or irregular in shape (Figure 2f–h). In general, the large melt inclusions (>10 μm) are glassy, homogeneous and often surrounded by low anorthite haloes, whereas the small-size inclusions (<10 μm) display round shape and contain bubbles (Figure 2h).

Figure 2. (a,b) Photos of the Mount Jourdanne PUBs investigated in this study. Note that the plagioclase (plg) show very large size up to 3 cm. (c,d). Glomerocrysts composed of small plagioclase, olivine and

Fe-Ti oxides in a glassy to slightly cryptocrystalline matrix. (e) An anhedral plagioclase crystal showing evidence of a multi-stage history, with a homogeneous core surrounded by a patchy zone. It also shows resorbed texture, and late microcracks. (f) A plagioclase macrocryst with abundant melt inclusions. (g) A separated plagioclase macrocryst with a glassy melt inclusion large enough for LA-ICP-MS analysis. (h) A large melt inclusion with dark low-anorthite halo. Also note the coexistence of abundant small melt inclusions with bubbles in the same host plagioclase.

4. Analytical Methods

4.1. Electron Microprobe Analysis (EPMA)

The PUB matrix glasses, naturally glassy melt inclusions and the host plagioclase macrocrysts were analyzed for major elements using a JEOL-JXA-8100 electron microprobe at the Second Institute of Oceanography, Ministry of Natural Resources. During quantitative analysis, a 15 kV accelerating voltage and a 20 nA beam current were used, with a focused beam of 1 μm diameter for plagioclase and a defocused beam of 5–10 μm diameter for PUB matrix glasses and melt inclusions. Natural minerals and synthetic oxides were used as standards and the data correction was obtained by a program based on the ZAF procedure. The analytical uncertainty was <1% for elements with concentration >5 wt % and <3 wt % for elements with concentration >1 wt %. Profiles of elemental concentrations in plagioclase macrocrysts were also obtained with the JEOL-JXA-8100 electron microprobe under the same conditions.

4.2. LA-ICP-MS Analyses

Trace element compositions of 5 large melt inclusions trapped in plagioclase macrocrysts and PUB matrix glass were determined by an Agilent 7500 LA-ICP-MS at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geoscience, Wuhan. Detailed operating conditions for the laser ablation system and the ICP-MS instrument and data reduction are the same as described by Liu et al. [44]. Each analysis incorporated a background acquisition of approximately 20–30 s (gas blank) followed by 50 s data acquisition from the sample. The Agilent Chemstation was utilized for the acquisition of each individual analysis. The laser ablation spot was correlated to the nearest EPMA points and the ablation diameter of the spot was set as 44 μm . Element contents were calibrated against multiple-reference materials (BCR-2G, BIR-1G, NIST610 and BHVO-2G) without applying internal standardization [44]. Typical analytical errors were less than 10%.

4.3. Whole Rock Analysis

Prior to whole rock analysis, samples ($\sim 5 \times 5 \times 5 \text{ cm}$) were ultrasonically cleaned in distilled water several times, and then crushed and powdered in an agate mill to less than 200 mesh size. Both major and trace element analyses were performed at the Wuhan Sample Solution Analytical Technology Co., Ltd., Wuhan, China. The major element concentrations were determined on fused glass disks using an X-ray fluorescence spectrometer (XRF) (XRF-8100). These analyses have a precision (relative standard deviation expressed in percentage, RSD) that is better than 1% for most major oxides. The accuracy (expressed in percentage) is better than $\pm 3\%$ for most major elements relative to accepted values, as determined from three geological standard samples (Table S1). Trace element analysis was performed on dissolved sample solutions using an Agilent 7700e ICP-MS instrument. Before analysis, sample powders were digested in acid in Teflon bombs. The details of the sample digestion procedure for ICP-MS analysis were reported by Liu et al. [44]. Analyses of the USGS standards (BCR-2 and BHVO-2) indicated that the accuracy was better than $\pm 10\%$ for most trace elements (Table S2).

5. Results

5.1. Plagioclase Major Element Compositions

The major element data was collected from the plagioclase core and in some case as transects from crystal interior to rim for the plagioclase macrocrysts in Mount Jourdanne PUBs. The analyzed plagioclase cores have An (%) contents varying from 60.6 to 69.5 (Table S3). Most of the plagioclase crystals are remarkably homogeneous with less than 2% intra-grain variations. However, some macrocrysts exhibit reverse zoning and/or oscillatory zoning patterns, making an abrupt compositional discontinuity with the core (see profiles in Table S3 and Figure S1). Plagioclase microlites in the groundmass generally show less-variable compositions, ranging from An₆₂ to An₆₅.

5.2. Whole-Rock and PUB Matrix Glass Compositions

Bulk rock major element compositions of the Mount Jourdanne basalts are given in Table 1. They show a very limited range of major element compositions (Figure 3), with 51.04–51.51 wt % SiO₂, 4.54–7.34 wt % MgO, 4.70–8.96 wt % FeO_t and 10.44–11.89 wt % CaO. The alkali content (Na₂O + K₂O) varies from 4.05 wt % to 4.73 wt %. H₂O contents are low with loss on ignition (LOI) between −0.6 wt % and −0.04 wt %. Most of the Mount Jourdanne basalts (except for two PUB samples) show similar compositions to basaltic lavas from the easternmost part of SWIR [29,30]. The two PUB bulk rocks plotted outside the data field and display lower MgO, FeO and TiO₂, but higher CaO and Al₂O₃ contents (Figure 3), suggesting a plagioclase-accumulative origin for the PUBs. In general, the Mount Jourdanne basalts show a well-defined trend in the major element against MgO diagrams, which can be reproduced by calculated liquid line of descent (LLD) of fractional crystallization (see further discussion in Section 6.1). Finally, the matrix glasses of PUBs show very homogeneous compositions (Table S4), which plot along the fractional trends defined by the Mount Jourdanne basalts (Figure 3).

5.3. Plagioclase-Hosted Melt Inclusions

Major element compositions of the plagioclase-hosted melt inclusions are presented in Table 2. The melt inclusions show moderate degrees of differentiation with Mg# (Mg# = Mg/(Mg + Fe)) of 0.61–0.66, similar to Mount Jourdanne basalts (0.56–0.65). As shown in Figure 3, compositions of these melt inclusions fall within the field defined by the 61–67° E volcanic seafloor basalts, but extend to the low MgO and high SiO₂ end, which is distinct from the LREE depleted volcanic seafloor basalts. In general, these melt inclusions have relatively high K/Ti ratios (defined as K₂O/TiO₂ × 100) (15–39), which can be classified as E-MORB [45]. When compared with PUB host glasses, the melt inclusions are characterized by higher MgO and SiO₂ contents, and lower CaO and Al₂O₃ contents (Figure 3).

Trace element compositions of the plagioclase-hosted melt inclusions are given in Table 2. They have an enriched composition, with (La/Sm)_N and (Sm/Yb)_N varying in the range of 0.86–1.26 and 1.07–1.54, respectively. Zr/Nb varies between 24.8 and 31.3, within the range of Mount Jourdanne basalts (23.3–33.7). The chondrite-normalized rare earth element (REE) patterns for the melt inclusions are plotted in Figure 4a. In general, these melt inclusions display flat to slightly LREE-enriched patterns, resembling typical E-MORB. In addition, absolute REE abundances of the melt inclusions are slightly lower than those of PUB host glasses, indicative of their more primitive nature. However, the PUB bulk rocks show much lower absolute REE abundances partially due to high modal proportions of plagioclase crystals. One of the most striking characteristics for the melt inclusions is their positive Eu anomalies (Eu/Eu* > 1; Table 2 and Figure 4a), similar to the PUB bulk-rocks. In contrast, the 61–67° E basalts show no or even negative Eu anomalies, indicating strong plagioclase fractionation. In the spider diagram (Figure 4b), the plagioclase-hosted melt inclusions are characterized by positive Sr anomalies and strong negative Pb anomalies. Positive Sr anomalies were also observed in PUB bulk rocks and host glasses. Finally, incompatible trace element chemistry of the melt inclusions is similar to that of Mount Jourdanne basalts and the 61–67° E ultramafic seafloor basalts. They show depletion for Rb, Ba, Th, U and Nb compared to LREE, as these elements are more incompatible than LREE.

However, the volcanic seafloor basalts show broadly continuous variations for these elements between the average N-MORB and E-MORB.

Figure 3. Major element compositions (a–e) and K/Ti ratio (f) plotted versus MgO for Mount Jourdanne basalts and plagioclase-hosted melt inclusions in PUBs. Basalts from the easternmost part of Southwest Indian Ridge (SWIR) (61–67° E) are plotted for comparison. The 61–67° E basalts are divided into two parts; i.e., basalts from the volcanic seafloor and from the ultramafic seafloors. The volcanic seafloor basalts with depleted light rare earth elements (LREE) are marked with cross in circles (data from Paquet et al. [30]). The horizontal line at $K_2O/TiO_2 \times 100 = 11$ in (f) separates fields for N-MORB (<11) and E-MORB (>11) [45].

Table 1. Major and trace element compositions of Mount Jourdanne basalts from the Southwest Indian Ridge.

Rock Sample	49I-TVG01	49I-TVG01 ¹	20VII-TVG19-1	26VI-TVG02-1	26VI-TVG03-1	26VI-TVG03-1-2	19III-TVG3-1	30I-TVG2-1	30I-TVG2-2
Longitude(° E)	63.923	63.923	63.923	63.935	63.935	63.935	63.940	63.936	63.936
Latitude(° S)	27.851	27.851	27.851	27.842	27.849	27.849	27.850	27.849	27.849
Depth(m)	2743	2743	2759	-	2936	2936	-	2958	2958
Major element (wt %)									
SiO ₂	51.17	51.06	51.04	51.51	51.42	51.66	51.45	51.16	51.48
TiO ₂	1.14	1.13	1.17	1.58	1.60	1.63	1.62	0.87	0.79
Al ₂ O ₃	17.72	17.76	17.52	15.49	15.36	15.45	15.28	20.81	21.89
Fe ₂ O ₃	7.76	7.76	7.77	9.54	9.86	9.80	9.96	5.81	5.22
FeO	-	-	-	-	-	-	-	-	-
MnO	0.13	0.13	0.13	0.17	0.17	0.17	0.18	0.12	0.09
MgO	7.34	7.28	7.23	6.44	6.43	6.41	6.42	5.09	4.54
CaO	10.97	10.94	10.88	10.63	10.44	10.49	10.41	11.58	11.89
Na ₂ O	3.86	3.92	3.86	4.47	4.39	4.44	4.34	3.95	3.88
K ₂ O	0.20	0.20	0.23	0.26	0.28	0.29	0.27	0.18	0.17
P ₂ O ₅	0.14	0.14	0.14	0.19	0.20	0.20	0.20	0.11	0.10
LOI	-0.41	-0.35	-0.22	-0.40	-0.60	-0.40	-0.39	-0.04	-0.10
Total	100.00	99.96	99.75	99.88	99.56	100.14	99.74	99.64	99.94
K ₂ O/TiO ₂ × 100	17.4	17.5	19.6	16.4	17.5	17.8	16.7	20.4	21.3
Mg#	0.65	0.65	0.65	0.57	0.56	0.56	0.56	0.63	0.63
Trace element (ppm)									
Sc	32.8			42.5	43.3	43.4	43.3	26.3	22.1
V	181			236	244	240	240	147	125
Cr	263			207	174	174	152	223	205
Co	33.2			33.2	34.6	34.2	35.1	132	104
Ni	93.4			43.7	41.3	42.0	41.2	58.4	48.8
Cu	65.8			82.5	82.8	85.0	88.3	60.5	44.9
Zn	68.5			68.7	70.6	72.9	124	42.7	35.3
Rb	1.77			2.16	2.47	2.64	2.36	1.42	1.15
Sr	232			195	195	201	186	271	283
Y	23.4			33.5	35.1	35.5	35.4	18.7	15.7
Zr	101			141	145	149	144	79.4	66.7
Nb	3.00			4.52	4.72	4.91	4.75	3.41	2.70

Table 1. Cont.

Rock Sample	49I-TVG01	49I-TVG01 ¹	20VII-TVG19-1	26VI-TVG02-1	26VI-TVG03-1	26VI-TVG03-1-2	19III-TVG3-1	30I-TVG2-1	30I-TVG2-2
Ba	22.1			26.9	27.0	26.5	26.1	17.9	16.0
La	4.41			6.34	6.49	6.56	6.21	3.60	3.28
Ce	17.8			17.5	18.0	18.2	17.7	10.2	8.85
Pr	1.97			2.56	2.59	2.68	2.76	1.56	1.35
Nd	9.43			12.5	13.3	13.3	12.7	7.66	6.62
Sm	2.65			4.00	4.07	4.10	4.02	2.29	1.87
Eu	1.11			1.36	1.42	1.43	1.45	0.90	0.84
Gd	3.33			5.13	5.02	5.28	5.16	2.72	2.22
Tb	0.63			0.81	0.91	0.91	0.92	0.50	0.43
Dy	4.19			5.45	5.93	5.90	6.01	3.34	2.81
Ho	0.86			1.17	1.19	1.19	1.28	0.68	0.59
Er	2.47			3.48	3.60	3.61	3.63	1.90	1.70
Tm	0.37			0.50	0.54	0.56	0.56	0.29	0.24
Yb	2.31			3.25	3.45	3.23	3.52	1.80	1.54
Lu	0.35			0.48	0.50	0.52	0.53	0.27	0.23
Hf	2.28			2.96	3.11	2.93	3.21	1.93	1.51
Ta	0.22			0.28	0.30	0.32	0.31	0.87	0.49
Pb	0.76			1.20	0.99	0.95	1.17	2.33	5.48
Th	0.26			0.36	0.34	0.36	0.35	0.18	0.16
U	0.079			0.12	0.12	0.21	0.13	0.092	0.064
Eu/Eu*	1.14			0.92	0.96	0.94	0.97	1.11	1.26
(La/Sm) _N	1.07			1.02	1.03	1.03	1.00	1.02	1.13
(Sm/Yb) _N	1.28			1.37	1.31	1.41	1.27	1.41	1.35

Note: Repeat analysis of the sample. LOI is loss weight on ignition. $Eu/Eu^* = Eu_N / (Sm_N \times Gd_N)^{1/2}$, where subscript N denotes chondrite normalization [46]. Subscript PM denotes primitive mantle normalization [47].

Table 2. Major and trace element concentrations for plagioclase-hosted melt inclusions in Mount Jourdanne PUBs.

Sample		30I-TVG2-1													
Rystal	C1-1	C1-2		C1-3			C1-4		C1-6	C1-7					C1-8
MI Inclusions	1-1MI1	1-2MI1	1-2MI2	1-3MI1_1	1-3MI1_2	1-3MI2	1-4MI1	1-4MI2	1-6MI1	1-7MI1	1-7MI2	1-7MI3	1-7MI4	1-7MI5	1-8MI1
Size (µm)	200	80	250	50	80	50	250	75	35	40	40	60	60	40	70
Major elements (wt %)															
SiO ₂	52.73	51.74	52.72	52.06	52.14	52.6	52.58	53.01	52.49	52.3	51.71	51.99	51.8	52.16	53.29
TiO ₂	1.32	1.41	1.34	1.16	1.2	1.27	1.2	1.36	1.24	1.15	1.19	1.46	1.5	1.45	1.05
Al ₂ O ₃	16.01	15.85	15.91	15.26	15.39	15.61	16.06	16	15.65	15.23	15.67	15.56	15.56	15.67	15.33
Cr ₂ O ₃	0.02	0.05	0.11	0.07	0.03	0.01	0.04		0.04	0.05	0.05	0.14	0.08	0.05	0.02
FeO	7.83	7.88	7.89	7.89	7.56	7.28	7.96	7.78	7.59	7.71	7.68	8.02	8	7.84	7.02
MnO	0.13	0.09	0.17	0.15	0.15	0.13	0.15	0.12	0.14	0.07	0.08	0.14	0.14	0.09	0.15
MgO	7	7.04	6.9	7.8	7.91	7.83	7.05	7.09	7.45	7.45	7.25	7.25	7.49	7.62	7.48
CaO	9.69	9.65	9.81	9.72	9.62	9.85	9.76	9.76	9.61	10.35	10.22	10.02	10.22	10.04	9.22
Na ₂ O	4.03	4.27	3.94	3.65	3.67	3.64	4.01	3.91	4.08	3.89	4.05	4.04	3.97	4.03	4.33
K ₂ O	0.31	0.33	0.29	0.36	0.38	0.35	0.3	0.29	0.33	0.25	0.28	0.28	0.26	0.26	0.41
P ₂ O ₅	0.17	0.19	0.16	0.19	0.18	0.21	0.17	0.17	0.16	0.12	0.16	0.17	0.17	0.18	0.1
Total	99.21	98.51	99.23	98.3	98.23	98.79	99.27	99.49	98.78	98.58	98.33	99.08	99.19	99.39	98.41
Mg#	0.61	0.61	0.61	0.64	0.65	0.66	0.61	0.62	0.64	0.63	0.63	0.62	0.63	0.63	0.65
Trace elements (ppm)															
Rb	2.18		2.37				2.14								
Ba	23.68		23.3				23.95								
Th	0.27		0.24				0.26								
U	0.1		0.09				0.08								
Nb	4.2		3.3				3.7								
Ta	0.23		0.18				0.21								
La	4.85		4.74				4.64								
Ce	12.97		12.83				13.54								
Pb	0.78		0.81				0.89								
Pr	1.8		1.97				1.91								
Sr	201		199				199								
Nd	10.74		9.93				10.02								
Sm	3.34		3.56				2.82								
Zr	104.44		101.48				104.3								
Hf	2.32		2.35				2.25								
Eu	1.22		1.31				1.22								
Gd	3.51		3.66				3.87								

Table 2. Cont.

Sample		30I-TVG2-1													
Rystal	C1-1	C1-2		C1-3			C1-4		C1-6	C1-7				C1-8	
MI Inclusions	1-1MI1	1-2MI1	1-2MI2	1-3MI1_1	1-3MI1_2	1-3MI2	1-4MI1	1-4MI2	1-6MI1	1-7MI1	1-7MI2	1-7MI3	1-7MI4	1-7MI5	1-8MI1
Size (μm)	200	80	250	50	80	50	250	75	35	40	40	60	60	40	70
Tb	0.64		0.65				0.59								
Dy	4.09		4.32				4.33								
Ho	0.95		0.83				0.98								
Y	22.76		23.03				22.94								
Er	2.18		2.59				2.31								
Tm	0.31		0.3				0.36								
Yb	2.42		2.28				2.68								
Lu	0.39		0.37				0.36								
Eu/Eu*	1.09		0.88				1.13								
(La/Sm) _N	0.94		0.86				1.06								
(Sm/Yb) _N	1.53		1.74				1.17								
Sample		30I-TVG2-2													
Crystal	C2-1		C2-2	C2-4	C2-6		C2-7		C2-8						
MI Inclusions	2-1MI1	2-1MI2	2-2MI1	2-4MI	2-6MI1	2-6MI2	2-7MI1	2-7MI2	2-8MI1	2-8MI2	2-8MI3	2-8MI4			
Size (μm)	20	80	100	250	300	200	80	60	30	80	50	50			
Major elements (wt %)															
SiO ₂	51.86	51.58	51.87	52.54	52.49	52.7	52.47	51.85	51.73	52.06	52.64	51.66			
TiO ₂	1.39	1.48	1.21	1.07	1.09	1.26	1.35	1.35	1.32	1.21	1.08	1.36			
Al ₂ O ₃	14.84	15.21	15.39	15.73	16.11	15.84	15.28	15.64	15.75	15.65	15.84	15.62			
Cr ₂ O ₃	0.02	0.07	0.1	0.03	0.1	0.03	0.05	0.14	0.04	0.05	0.02	0.09			
FeO	7.39	7.76	7.39	7.31	6.94	6.97	7.46	7.22	7.05	7.43	7.23	7.36			
MnO	0.15	0.18	0.19	0.09	0.14	0.02	0.14	0.11	0.18	0.09	0.12	0.16			
MgO	7.97	7.58	7.43	7.06	7.37	7.52	7.42	7.25	7.77	7.49	7.53	7.44			
CaO	9.9	10.22	10.03	9.78	10.22	10.17	10.13	10.28	9.89	10.2	10.01	10.49			
Na ₂ O	4.11	3.76	3.76	4	4	4.06	3.87	4.11	4.01	3.99	4.14	3.69			
K ₂ O	0.33	0.23	0.25	0.32	0.31	0.32	0.27	0.25	0.31	0.29	0.32	0.26			
P ₂ O ₅	0.15	0.21	0.15	0.15	0.15	0.1	0.16	0.18	0.13	0.18	0.14	0.22			
Total	98.1	98.28	97.76	98.06	98.92	99	98.6	98.38	98.17	98.62	99.08	98.35			
Mg#	0.66	0.64	0.64	0.63	0.65	0.66	0.64	0.64	0.66	0.64	0.65	0.64			

Table 2. Cont.

Sample		30I-TVG2-2										
Crystal	C2-1		C2-2	C2-4	C2-6		C2-7		C2-8			
MI Inclusions	2-1MI1	2-1MI2	2-2MI1	2-4MI	2-6MI1	2-6MI2	2-7MI1	2-7MI2	2-8MI1	2-8MI2	2-8MI3	2-8MI4
Size (µm)	20	80	100	250	300	200	80	60	30	80	50	50
Trace elements (ppm)												
Rb		2.07	2.05									
Ba		22.57	22.13									
Th		0.33	0.29									
U		0.1	0.06									
Nb		4.1	3.8									
Ta		0.31	0.17									
La		5.93	5.32									
Ce		15.85	14.16									
Pb		0.58	0.74									
Pr		2.21	2.11									
Sr		208	207									
Nd		12.5	10.81									
Sm		3.03	2.84									
Zr		128.4	109.04									
Hf		2.84	2.61									
Eu		1.27	1.17									
Gd		3.9	3.43									
Tb		0.67	0.69									
Dy		4.6	4.18									
Ho		1.03	0.89									
Y		26.97	24.09									
Er		3.06	2.64									
Tm		0.48	0.36									
Yb		3.14	2.83									
Lu		0.41	0.34									
Eu/Eu*		1.13	1.15									
(La/Sm) _N		1.26	1.21									
(Sm/Yb) _N		1.07	1.12									

MI: melt inclusions. Mg# = Mg/(Mg + Fe), Mg and Fe represent molar proportions.

Figure 4. (a) Chondrite normalized rare earth element (REE) and (b) primitive mantle normalized trace element patterns for Mount Jourdanne basalts and plagioclase-hosted melt inclusions. Literature data for the basalts from the volcanic and ultramafic seafloor, SWIR (61–67° E) are plotted for comparison [30]. Primitive mantle, average N-MORB and E-MORB data from Sun and McDonough [46]. Chondrite normalized values from McDonough and Sun [47].

6. Discussion

6.1. Post-Entrapment Crystallization (PEC) and Diffusive Equilibration

Plagioclase-hosted melt inclusions are commonly affected by post-entrapment processes, including crystallization and diffusive re-equilibration, which can greatly modify the original chemistry of the inclusions [4,48–50]. Petrographic investigation has revealed that plagioclase-hosted inclusions in Mount Jourdanne PUBs did experience substantial PEC prior to quenching. For example, a low-An plagioclase halo was often observed around the large melt inclusions, indicating overgrowth of the plagioclase (Figure 2h). It has been demonstrated that PEC may result in compositional depletion for elements that are compatible with the host crystal (e.g., Al_2O_3 for plagioclase). In order to evaluate the effect of PEC, plagioclase-hosted melt inclusions were compared with Mount Jourdanne basalts and

the modeled LLDs (Figure 5). The LLDs were determined by reverse crystallization calculation using the Petrolog 3 software [51]. During calculations, olivine, plagioclase and/or clinopyroxene were added to the known compositions of the PUB host glass until the final liquids are in equilibrium with mantle olivine (Fo_{90}). The equilibrium models for olivine-melt, clinopyroxene-melt and plagioclase-melt are from Danyushevsky [52] and the oxygen buffer was set as QFM. The LLD calculation shows that crystallization of plagioclase was initiated at $MgO \approx 8.5$ wt % and the Mount Jourdanne basalts define an olivine + plagioclase cotectic at $MgO < 8$ wt % (Figure 5). Due to the effect of PEC, the plagioclase-hosted melt inclusions plot away from the LLDs and show depletion in CaO and Al_2O_3 , and enrichment in MgO content (Figure 5). The influence of PEC is variable among different melt inclusions and is more significant in melt inclusions with small size. The composition of plagioclase-hosted melt inclusion at the moment of entrapment was estimated (i.e., PEC correction) by incrementally adding equilibrium plagioclase back into the melt inclusions until it reached the olivine + plagioclase cotectic. The parameters used during PEC correction were the same as those of the LLD calculation above. The recalculated melt inclusions are given in Table S5. They plot consistently along the LLD of Mount Jourdanne basalts on the MgO versus Al_2O_3 diagram (Figure 5a). However, for other elements (e.g., SiO_2 and CaO), the melt inclusions after PEC correction still plot outside the LLD.

On the other hand, melt inclusions could also be affected by the diffusion of the elemental species from the host lavas through the host plagioclase [53]. The effect of elemental diffusion on a population of melt inclusions decreases the variation in the elemental concentrations and the standard deviation of their distribution coefficients, especially for compatible and rapidly diffusing elements [48]. In the case of plagioclase, where Sr, Eu and LREE are more compatible than heavy rare earth elements (HREE), the diffusive re-equilibration would lead to a group of melt inclusions to exhibit a wide range of HREE but a narrow range of Sr, Eu and LREE. In this study, the melt inclusions did not show much smaller variations of Sr, Eu and LREE than HREE (Figure 4), which rules out the influence of post-entrapment diffusion. However, it should be noted that some plagioclase crystals in the studied samples exhibited compositional zoning. This kind of plagioclase is not rare in Mount Jourdanne PUBs and they usually display resorption texture (Figure 2e,f). It probably indicates that they were not in equilibrium with host lavas during magma cooling or chemically fluxing at a shallow magma reservoir [53]. However, the investigated melt inclusions are mainly hosted in the plagioclase core and away from the compositional boundary (e.g., Figure S1), implying an insignificant effect of diffusion re-equilibration.

6.2. Insights into the Mantle Source Lithologies of Mount Jourdanne Basalts and the 61–67° E Basaltic Lavas

In the easternmost part of SWIR (61–67° E), most of the basalts are characterized by typical E-MORB compositions (Figure 4). N-MORBs were only sporadically found in this region, (e.g., dredge ed20, ed22 and ed26 [30]), which displayed low $(La/Sm)_N$ (<0.8) and Zr/Y ratios (<2.9), but high Zr/Nb (50–80) and Y/Nb (17.5–30.5) ratios (Figure 6a–c). We infer that garnet is a residual phase during mantle melting for generation of those N-MORBs. Supporting evidence is their high $(Lu/Tb)_{PM}$ (>1) (Figure 6d), as garnet is much more effective in fractionating Lu/Tb than clinopyroxene [54]. At the Mount Jourdanne massif, the melt inclusions and the PUB host glass display similar primitive mantle-normalized trace element patterns (Figure 4). It suggests that the magmatic process during the period of PUB formation does not significantly modify their geochemical signature. They show a close similarity in trace element compositions to the 61–67° E E-MORB (Figures 4 and 6), probably indicating that they share a common mantle source.

Figure 5. (a) Al_2O_3 , (b) TiO_2 and (c) Na_2O versus MgO variation diagrams of melt inclusion compositions before and after post-entrapment crystallization correction—Mount Jourdanne basalts, PUB bulk rocks and host glasses. Also shown are the 61–67° E basalts [30] and liquid line of descent (calculated with Petrolog 3 software [51]).

Figure 6. Binary plots in (a) chondrite-normalized $(\text{La}/\text{Sm})_N$ versus Zr/Nb , (b) Nb/Y versus Zr/Y , (c) Y/Nb versus Zr/Nb and (d) primitive mantle normalized $(\text{Lu}/\text{Tb})_{PM}$ versus Th_{PM} diagrams for Mount Jourdanne basalts and PUBs, plagioclase-hosted melt inclusions and regional basalts from SWIR (61–67° E). Data for the 61–67° E basalts are from Paquet et al. [30]. The value for chondrite is from Sun and McDonough [46] and for primitive mantle (PM) is from McDonough and Sun [47]. In panels (b) and (c), the pink color indicates enriched samples with the ratios Nb/Y and Zr/Y > PM and Y/Nb and Zr/Nb < PM. The light blue color indicates depleted samples with Nb/Y and Zr/Y < PM and Y/Nb and Zr/Nb > PM. Boundary line between plume and non-plume sources in (b) and (c) are from Fitton et al. [55]. Composition of depleted MORB mantle (DMM) is from Condie [56].

Although peridotite is widely believed to be the dominant lithology in the MORB mantle source, several lines of evidence indicate that pyroxenite may exist in the MORB mantle [57–59]. For this reason, many chemical markers of pyroxenite (e.g., MgO – CaO trend, Fe/Mn ratio, and FC3MS parameter) have been proposed based on major element compositions of basaltic lavas [60]. Recently, a more powerful parameter called FCKANTMS was obtained to constrain the mantle source lithology [61]. On the other hand, ratios of moderately incompatible trace elements and major elements, such as Zn/Fe and Zn/Mn [62,63], can be good indicators of the lithology and residual mineral assemblages of the magma sources. In order to evaluate the mantle source beneath Mount Jourdanne massif and the other 61–67° E axial region, we discuss the melt inclusions and the 61–67° E basalts in context with the pyroxenite source indicators listed above.

Based on the melting behavior of fertile peridotite, Herzberg and Asimow [64] suggested that the CaO – MgO relation can be used to identify the source lithology of basalts. Magmas derived from pyroxenite sources generally show lower CaO at a given MgO compared to magmas from peridotite sources [64]. In the CaO – MgO diagram, the plagioclase-hosted melt inclusions, Mount Jourdanne basalts and other 61–67° E axial lavas all plot below the MgO – CaO dividing line, seemingly implying a pyroxenite-dominated mantle source (Figure 7a). However, low- CaO tholeiitic melts can also be produced from harzburgite sources and would be plotted in the pyroxenite source field in the CaO – MgO

diagram [60]. On the other hand, partial melting of lherzolite at a low pressure may also produce low-CaO melts, which further increase the ambiguity of interpretation on mantle source lithology based on the CaO–MgO relationship. In the FC3MS space, most of the basalts from Mount Jourdanne and 61–67° E region have FC3MS values of <0.65 (Figure 7b), consistent with a peridotite dominated mantle source. Nevertheless, some low-to-moderate degree partial melts of typical pyroxenite and hornblendite also have FC3MS lower than 0.65, and these low FC3MS melts of mafic lithology may be erroneously regarded as derived from peridotite. Thus, caution should be taken in identifying the source lithology of basalts with low FC3MS values as well.

Figure 7. (a) CaO versus MgO, (b) FC3MS versus $\text{Na}_2\text{O} + \text{K}_2\text{O}$ and FCKANTMS versus, (c) Mg#, (d) $\ln(\text{SiO}_2/(\text{CaO} + \text{Na}_2\text{O} + \text{TiO}_2))$ and (e) $\ln(\text{CaO}/\text{TiO}_2)$ for Mount Jourdanne basalts and PUBs, plagioclase-hosted melt inclusions and regional basalts from SWIR (61–67° E). FC3MS = $\text{FeO}/\text{CaO} - 3 \times \text{MgO}/\text{SiO}_2$, all in wt % [65]. FCKANTMS = $\ln(\text{FeO}/\text{CaO}) - 0.08 \times \ln(\text{K}_2\text{O}/\text{Al}_2\text{O}_3) - 0.052 \times \ln(\text{TiO}_2/\text{Na}_2\text{O}) - 0.036 \times \ln(\text{Na}_2\text{O}/\text{K}_2\text{O}) \times \ln(\text{Na}_2\text{O}/\text{TiO}_2) - 0.062 \times (\ln(\text{MgO}/\text{SiO}_2))^3 - 0.641 \times (\ln(\text{MgO}/\text{SiO}_2))^2 - 1.871 \times \ln(\text{MgO}/\text{SiO}_2) - 1.473$, all in wt % [61]. The solid line in (a) is an experimental divide between peridotite and pyroxenite partial melts [64]. The red dashed line in (b) is upper limit

for peridotite melts [65]. The dashed lines in (c)–(e) are boundaries for melts derived from different lithologies [61]. The dashed line in (d) marked with $Mg\# = 0.7$ indicates the upper boundary of normal peridotite and harzburgite melts when their $Mg\# = 0.7$. Note that the Mount Jourdanne basalts and plagioclase-hosted melt inclusions are in the field of mafic and transitional lithology and some 61–67° E basalts show high FCKANTMS values indicating a mafic lithology.

The uncertainties in CaO–MgO and FC3MS, however, can be resolved by the newly proposed FCKANTMS parameter, especially when combined with $\ln (SiO_2/(CaO + Na_2O + TiO_2))$ and $\ln (CaO/TiO_2)$ [61]. In general, the 61–67° E lavas (including the Mount Jourdanne basalts) show a wide range of FCKANTMS (0–0.6) (Figure 7c–e). In the FCKANTMS versus $Mg\#$ diagram (Figure 7c), the Mount Jourdanne basalts, two types of volcanic seafloor basalts and the ultramafic seafloor basalts are broadly consistent with fractionation and accumulation trends of olivine. Most of the Mount Jourdanne basalts and plagioclase-hosted melt inclusions fall in the range of mafic and transitional lithology field, with only a small portion in the peridotite field. Some 61–67° E basalts have FCKANTMS values higher than those of melts derived from normal peridotites and transitional lithology (Figure 7c–e). Note that melts derived from harzburgite source may also have high FCKANTMS values, but with a higher $(SiO_2/(CaO + Na_2O + TiO_2))$ values (>1.5) than the samples we investigated (Figure 7d). Therefore, the primary magmas of these high FCKANTMS samples should be derived from a mafic lithology source, likely pyroxenite. Finally, we observe that large variations exist in $\ln (CaO/TiO_2)$ values for Mount Jourdanne basalts and the 61–67° E lavas (Figure 7e). It implies significant compositional heterogeneity in their primary magma, because an olivine fractionation or accumulation cannot fractionate $\ln (CaO/TiO_2)$ values. Note that if their FCKANTMS values are higher than the upper boundary for normal peridotites partial melts, then, the heterogeneous mantle beneath the 61–67° E region should consist of a transitional or mafic lithology. The transitional lithology could be either an olivine pyroxenite or a refertilized peridotite. This inference is consistent with the observation that more abundant clinopyroxene-rich (up to 9%) lithologies were exhumed on the seafloor in the SWIR 61–67° E region [66]. In addition, the pertinence of pyroxenite–peridotite bimodal melting is evidenced by clinopyroxene compositions in peridotites from the SWIR 61–67° E axial region [67,68]. Brunelli et al. [69] suggest that these trace element compositions can be modeled with open-system melting of the peridotites accompanied by influx of garnet field-generated enriched melts. Certainly, pyroxenite can be a good candidate for the source of these enriched melt.

Le Roux et al. [62,63] found that Zn/Fe , Fe/Mn and Zn/Mn do not fractionate between olivine, orthopyroxene and partial melts, but are strongly fractionated when garnet or clinopyroxene are the dominant phases involved during melting or crystallization. Moreover, Le Roux et al. [63] and Davis et al. [70] determined mineral/melt partition coefficients of first row transition elements in experiments and calculated model partial melt compositions of peridotite. Their results show that partial melts of eclogite or garnet pyroxenite have higher Zn/Fe , Zn/Mn and Fe/Mn ratios than partial melts of peridotite. As shown in Figure 8, Fe/Mn , Zn/Mn and $Zn/Fe \times 10^4$ of plagioclase-hosted melt inclusions and Mount Jourdanne basalts are 59 ± 16 , 0.06 ± 0.02 and 11 ± 3.6 , respectively, similar to those of volcanic seafloor basalts in the SWIR 61–67° E region (58 ± 18 , 0.06 ± 0.02 and 10.9 ± 1.6). Notably, some samples show significant higher Fe/Mn , Zn/Mn and $Zn/Fe \times 10^4$ than the range for MORB and peridotite (Figure 8). This evidence implies that non-peridotite components contribute to the mantle source of the SWIR 61–67° E basalts. Taken together, we hold the view that the easternmost part of SWIR consists of a hybrid mantle lithology.

Figure 8. (a) Fe/Mn, (b) Zn/Mn and (c) $\text{Zn/Fe} \times 10^4$ versus MgO for Mount Jourdanne basalts and PUBs, plagioclase-hosted melt inclusions and regional basalts from SWIR (61–67° E). Field for peridotite is from Le Roux et al. [62] and MORBs (unfilled grey cycles) are from PETDB database (<http://petdb.ldeo.columbia.edu/petdb>). Note that some samples have higher Fe/Mn, Zn/Mn and Zn/Fe than the range of MORBs and peridotites, indicating a pyroxenitic component in the mantle source.

Nearly all of the 61–67° E basalts show negative Pb anomalies and positive Sr anomalies, whereas only the plagioclase-hosted melt inclusions and a small portion of Mount Jourdanne basalts show slightly positive Eu anomalies (Figure 4a). Generally, positive Sr and Eu anomalies are rare in MORB samples, which have been interpreted by partial melting of plagioclase-bearing mantle sources [71]. This hypothesis, however, is not favored as it is against the presence of garnet during mantle melting.

It is possible that the positive Sr and Eu anomalies represent a recycled component in the mantle source [57]. Note that the positive Sr anomalies are common in the 61–67° E N-MORB and E-MORB, whereas the Eu anomalies are absent and sometimes even negative in these samples (Figure 4). We infer that the positive Sr and Eu anomalies are inherited characteristics of the primary magma. However, these characteristics were often obscured during magmatic differentiation, because plagioclase crystallization always produces negative Sr and Eu anomalies in magma. As a consequence, the Mount Jourdanne basalts likely represent a mixture of enriched melts derived from an enriched component (e.g., pyroxenite) and depleted melts derived from the mantle peridotite. Again, this interpretation is consistent with the bimodal melting model suggested by Paquet et al. [30], that the primary melt was derived from a hybrid mantle source consisting of a peridotite and a pyroxenitic lithology.

6.3. Melt/Mantle Reactions: Insight from Mount Jourdanne PUBs and Spatially Related Plagioclase-Bearing (Ultra)Mafic Rocks

It was inferred that the primary melts of the SWIR 61–67° E basalts have been variably modified by melt/mantle reactions [30]. The composition of residual peridotites sampled in the region attests to a metasomatic history of the subaxial lithosphere [66–68]. The question remaining is whether the melts trapped by plagioclase in Mount Jourdanne PUBs and their host magma also preserve the record of the melt/mantle reaction process.

In general, fractional crystallization and melt/mantle reactions are two opposite processes. The Petrolog calculation always predicts fractional crystallization of olivine followed by plagioclase (decreasing MgO in melt; e.g., LLD in Figure 5), whereas the melt/mantle reaction may lead to olivine dissolution (increasing MgO in melt). As noted by Paquet et al. [30], the early portion of LLDs and melt/mantle reaction trends are comparable at intermediate MgO contents (7.5–8.5 wt %). Therefore, the LLDs and melt/mantle reaction trends show strong similarity over a wide range of melt/rock ratios for the major elements (SiO₂, CaO and Na₂O, etc.). We compare the Mount Jourdanne basalts, PUB host glasses and plagioclase-hosted melt inclusions with the LLDs and the melt/mantle reaction trends in Figure 9. Both the LLDs and melt/mantle reaction trends are modified from Paquet et al. [30]. The LLDs are calculated with Petrolog 3 with an ultramafic seafloor sample SMS16-3-5 as the starting melt compositions, whereas the melt/mantle reaction trends are calculated with a mass balance model [30]. Obviously, the LLDs do not fit the Mount Jourdanne basalts because the PUB and host melt compositions cannot be reproduced by fractional crystallization with the chosen starting composition. It shows that most of the ultramafic seafloor basalts can be fitted by the melt/mantle reaction model at high melt/mantle ratios (Figure 9). Some Mount Jourdanne basalts and plagioclase-hosted melt inclusions plot close to the melt/mantle reaction trend at ratios <30, indicative of relatively low degrees of melt/mantle reaction. Specifically, some plagioclase-hosted melt inclusions are characterized by high SiO₂, and low MgO, CaO and TiO₂ contents (Figure 9a,c,e). We infer that these melt inclusions preserve the low-Mg and high-Si nature in primary magmas, which survives from the melt/mantle reaction. When compared to the volcanic seafloor basalts, the melt inclusions are distinctive for their positive Eu anomalies (Figure 4), excluding abundant plagioclase fractionation before entrapment as melt inclusions. In this case, the plagioclase-hosted melt inclusions are more likely to witness and preserve the record of melt/mantle reaction process. Moreover, the plagioclase-hosted melt inclusions show REE patterns and concentrations resembling those of the ultramafic seafloor basalts (Figure 4a). The latter was interpreted as parent melts variably modified by melt/mantle reactions [30]. Above all, we conclude that the plagioclase-hosted melt inclusions not only inherit the “low-Mg and high-Si” characteristics of the primary magma, but also as with the Mount Jourdanne basalts, preserve the record of melt/mantle reaction in the axial lithosphere.

The plagioclase macrocrysts in Mount Jourdanne PUBs display variable An contents (60.6%–69.5%). The low-An values are comparable to those measured in the large plagioclase grains (An contents: 55%–67%) in troctolites and gabbros exposed on the ultramafic seafloor, but the PUB plagioclases have higher K₂O contents at similar An values (Figure 10). In contrast, the plagioclase grains in plagioclase-bearing ultramafic rocks (e.g., websterite and lherzolite) have very small sizes and much higher An values (74%–91.6%). High-An plagioclases have been observed in several suites of plagioclase-bearing abyssal peridotites, which were explained as the result of a reaction between the percolating melt and the peridotites [72,73]. The reaction was inferred to occur in the walls of narrow dikes that formed conduits for primitive MORB melts to migrate into shallow levels [30]. Clearly, the melts in which the low-An plagioclases were derived were not in equilibrium with the residual mantle. Therefore, the troctolites and gabbros probably represent the aggregated melt extracted along those conduits from the deep melting mantle.

Figure 10. Plots of K₂O content as a function of anorthite content (An) for plagioclase in Mount Jourdanne PUBs. The plagioclase in the plagioclase-bearing ultramafic to gabbroic suites (data from Paquet et al. [30]) are also plotted for comparison. The grey field corresponds to the compositional range of plagioclase in sample SMS6-5-7 (see Paquet et al. [30] for details). In this sample, the plagioclase abundances vary significantly over scales of a few centimeters, with modal mineralogy varying from websterite to gabbro-norite.

Finally, we found that the trace element compositions equilibrated with these plagioclase cores from troctolites and gabbros are inconsistent with our data, especially for HREE (Figure 11). As inferred by Paquet et al. [30], this inconsistency probably reflects that the available plagioclase/liquid partition coefficients are not appropriate for HREE. On the other hand, the plagioclase-hosted melt inclusions show similar compositions with calculated melts in equilibrium with the clinopyroxene (Figure 11) [30]. Based on this latter evidence, we suggest that plagioclase macrocrysts in Mount Jourdanne PUBs may share the same origin as those in gabbros and/or troctolites. It is the most likely that these plagioclase macrocrysts were derived from disrupted gabbro bodies, and were entrained as fragments by the ascending basaltic magmas to form the PUBs. The origin of Mount Jourdanne PUBs will be discussed further below.

Figure 11. Chondrite-normalized REE concentrations for Mount Jourdanne basalts, PUBs and plagioclase-hosted melt inclusions. The volcanic seafloor basalts and ultramafic seafloor basalts are shown for comparison (as in Figure 4a). Also plotted are melts calculated to be in equilibrium with the plagioclases and clinopyroxene (polygon with purple dashed line and yellow solid line, respectively) in regional plagioclase-rich rock types (i.e., troctolites and gabbros), modified from Paquet et al. [30]. Chondrite normalized values from McDonough and Sun [47].

6.4. The Petrogenetic Model for the Mount Jourdanne PUBs at ~64° E

The recent activity of the 61–67° E volcanic domains is mainly characterized by the production of aphyric basalts [29,30]. Although PUBs are found in SWIR [20], they have not been documented in this region. The occurrence of PUBs at Mount Jourdanne may provide new insights into the shallow magmatic process during a specific period of this volcanic massif. Several models have been invoked to explain PUBs genesis at mid-ocean ridges. Below, we evaluate the various models for the origin of PUBs from Mount Jourdanne.

Although magmas with similar MgO contents to our melt inclusions could preferentially crystallize plagioclase relative to the other mineral phases from the high-Al melts, the data is consistent with cotectic fractional crystallization of olivine and plagioclase based on Petrolog modeling (e.g., 2 kbar in Figure 9). However, these mineral phases do not exist in cotectic proportions in Mount Jourdanne PUBs. It was also noted that the Petrolog modeling cannot reproduce the low CaO and high SiO₂ contents of the melt inclusions (Figure 9). Thus, crystallization from high-Al magma as the origin of Mount Jourdanne PUBs is ruled out.

Plagioclase macrocrysts and glomerocrysts in our PUB samples may be derived from mechanical disaggregation of gabbroic cumulates. Plagioclase with a cumulative origin, also, has been suggested for the PUB formation in different contexts [16,18,20,21,27,74,75]. It was proposed that PUB forms by plagioclase accumulation via flotation during a shallow magma chamber and is transported in a high-density melt [16,18]. However, this mechanism works only when plagioclases have positive buoyancy. Here, we calculated the liquid density of host glass using the MELTS algorithm (Table 3). The MELTS calculation also gives the density of the solid phases (i.e., plagioclase and clinopyroxene) at liquidus temperature. Notably, the calculated An contents of liquidus plagioclase are similar to those of plagioclase macrocrysts in our PUB samples. It shows that the density of plagioclase crystals (2.654 g cm⁻³) is slightly higher than that of the liquid (<2.652 g cm⁻³) at pressure less than 2 kbar, but less than clinopyroxene for all pressures. Thus, the plagioclase crystals would sink in the liquid

rather than float. However, liquid density may increase with pressure. For the estimated density of plagioclase (2.654 g cm^{-3}), pressures over 2 kbar ($\sim 6 \text{ km}$) are required for these plagioclases to be neutrally buoyant within the liquid. As the seismic and gravity-derived crustal thickness is $\sim 6 \text{ km}$ beneath the center of segment #11, SWIR [36,76], the plagioclase cannot be buoyant even if the magma reservoir exists in the lower crust.

Table 3. Liquid and mineral phase densities calculated with the MELTS ¹.

Pressure	T	Proportion of Phases (wt %)					D (Liq) ³	D (Plg) ³	D (Cpx) ³
		Liq	Plg	Cpx	Sp	An ²			
1kbar	1212 ⁴	99.94	0.06	-	-	70	2.636	2.654	-
	1192	84.40	10.79	4.09	-	65	2.646	2.645	3.215
2kbar	1217 ⁴	98.93	1.03	-	-	68	2.652	2.654	-
	1207	87.23	7.35	5.36	0.07	65	2.655	2.648	3.218
4kbar	1245	98.61	-	1.39	-	-	2.674	-	3.219
	1235 ⁴	91.75	1.23	5.64	-	65	2.671	2.654	3.226
6kbar	1280	99.94	-	0.06	-	-	2.697	-	3.219
	1250 ⁴	83.36	1.65	14.99	-	62	2.688	2.654	3.242
8kbar	1302	94.48	-	5.52	-	-	2.719	-	3.228
	1262 ⁴	75.87	2.08	22.06	-	59	2.704	2.655	3.260

¹ The starting composition corresponds to the average compositions of PUB host glass (see supporting information Table S3). Buffer of Oxygen fugacity: QFM (quartz-fayalite-magnetite). ² Anorthite content (%) of the feldspar formed at liquidus temperature of plagioclase. Note that the anorthite contents are similar to the plagioclase ($\text{An}_{60.6-69.5}$) in the Mount Jourdanne PUB samples. ³ Density of the liquid and solid phases calculated with MELTS software (g cm^{-3}). Note that the density of liquidus plagioclase at $<2 \text{ kbar}$ is larger than the density of the liquid. ⁴ Liquidus temperature of plagioclase. Abbreviations: Liq, liquid; Plg, plagioclase; Cpx, clinopyroxene; Ol, olivine; Sp, spinel.

As mentioned above, we suggest that the Mount Jourdanne PUBs are formed by disruption of plagioclase-bearing cumulates during magma ascent. Although such cumulates are rarely exposed on the volcanic seafloor, they are widely found on the ultramafic seafloor [30]. Sinton and Detrick [9] proposed that a gabbroic mush zone with sill-like bodies underlies the rift valley at slow spreading ridges. We inferred that such a disruption process probably occurs beneath the Mount Jourdanne volcano when a batch of magma passes through the crustal mush zone (Figure 12a). The small density contrast between plagioclase and the melt in the lower crust may facilitate the incorporation of these plagioclase crystals.

In order to generate plagioclase enriched basalts, the segregation rate should be fast enough to efficiently segregate the plagioclase from the other phases (Figure 12b). The rates of setting for the minerals can be approximately estimated with Stokes' law, which is dependent on density contrast between melt and the crystals, crystal size and viscosity of the melt. Density was shown in Table 3, with density contrast varying from 0.002 g cm^{-3} to 0.018 g cm^{-3} at pressure less than 2 kbar. The maximum size of plagioclase in Mount Jourdanne PUBs ($\sim 3 \text{ cm}$) was used in order to calculate the minimum necessary ascending velocity for PUB eruption. The melt viscosity was obtained using MELTS at $\sim 1200^\circ \text{C}$. For the magma to counteract the sinking force and transport the plagioclase macrocrysts to the surface, magma ascent velocities of 5 m d^{-1} are necessary. This velocity is not as fast as expected for typical MORB samples (e.g., 1 km d^{-1} , [20]). Note that this value is a minimum estimation for the magma ascent, but more rapid ascent velocities are possible. However, we inferred that a slightly longer residence time during magma ascent may facilitate the remobilization of the crustal mush or plagioclase-rich cumulates, which would further lead to the chemical zoning of plagioclase macrocrysts in Mount Jourdanne PUBs. On the other hand, it should be noted that if the plagioclase-rich melts enter a shallow magma chamber ($<6 \text{ km}$), the upward velocity would go to zero (Figure 9c). Hence, the plagioclases would start to sink because of the negative buoyancy, which would make it impossible for PUBs to erupt. Above all, we propose that the Mount Jourdanne PUBs was formed when a new

batch of magma passed through the crustal mush zone, triggering the remobilization of troctolitic or gabbroic cumulate and simultaneously entraining abundant plagioclase crystals. In contrast, the formation of the Mount Jourdanne volcanic massif was likely during a period with enhanced magma supply, where conduit systems and possible axial magma chamber had already developed.

Figure 12. Cartoon showing the magma plumbing system beneath Mount Jourdanne massif with a model for the petrogenesis of the PUBs. (a) Sketch showing the melt extraction, melt/rock reaction and migration through the gabbroic mush zone at the crustal level. During melt extraction, the melts derived from the hybrid mantle sources pool at the base of axial lithosphere. The dashed arrows show the low degrees of partial melts migrating along the base of lithosphere in a high porosity channel. When the melt is percolating through the lithosphere, the melt/mantle reaction occurs mainly in the walls of melt conduits. Subsequent fractional crystallization of melts may occur in the shallow melt lens. Meanwhile, the veins and dikes may also form at shallow levels in the brittle lithosphere. (b) Upward migration of a new batch of magma disturb the gabbroic mush, resulting the rapid segregation of minerals by density contrast. The plagioclase incorporation in the lower crust is aided by the small difference of density contrast between magma and plagioclase. The ascent rate of magma is high enough to overcome the settling velocity of plagioclase, but not fast enough to carry denser clinopyroxene and olivine. (c) When a plagioclase-bearing melt enters a shallow magma reservoir, the upward velocity decreases to zero, resulting in the sinking of plagioclase and hence the PUBs will never be erupted at the seafloor. White rectangles, plagioclase; blue rectangles, clinopyroxene; green hexagons, olivine.

7. Conclusions

Plagioclase ultraphyric basalts from the Mount Jourdanne massif, Southwest Indian Ridge (~64° E) contain up to 40% of plagioclase macrocrysts. Textural observations and the compositions of plagioclase-hosted melt inclusions show variable degrees of post-entrapment crystallization with a minor influence from diffusion re-equilibration. The melt inclusions have low MgO and high SiO₂ contents, exhibiting typical E-MORB type REE patterns with positive Eu and Sr anomalies. Those features indicate the presence of a pyroxenitic lithology in the mantle source. In addition, the FCKANTMS parameter also suggests a hybrid mantle lithology in the SWIR 61–67° E region. The presence of plagioclase-rich aggregates in the PUBs, combined with the chemical similarity between the plagioclase-hosted melt inclusions and melts equilibrated with clinopyroxene cores from regional troctolites and gabbros suggest that these plagioclase macrocrysts arose from the segregation of a gabbroic mush. We propose that the segregation process took place in the lower crust, where the plagioclase macrocrysts were entrained by the ascending magma to form the Mount Jourdanne PUBs. The ascend velocity required for PUB formation, however, is not as high as the eruption rate for typical

MORB samples, implying a period with reduced magma supply. In contrast, the Mount Jourdanne aphyric lavas were likely formed during a period with enhanced magmatism, leading to the fast volcanic construction of the Mount Jourdanne massif.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2075-163X/9/8/493/s1>, Figure S1: Backscatter electron images and chemical transects for two selected plagioclase macrocrysts, Table S1: Analytical results of XRF standards, Table S2: Analytical results of ICP-MS standards, Table S3: plagioclase compositions, Table S4: PUB host glass compositions, Table S5: compositions of plagioclase-hosted melt inclusions after PEC correction.

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