Invited review article

Rates and processes of crystallization in on-axis and off-axis MOR basaltic melts

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abstract

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Crystal residence times
Geospeedometry

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A B S T R A C T

Residence times of olivine and plagioclase phenocrysts and xenocrysts in mid-ocean ridge (MOR) basaltic
melts have been studied since the mid 1980s using geospeedometric techniques (i.e. using diffusion of
major and trace elements) in order to constrain the processes of melt ascent and differentiation in this impor-
tant magmatic setting. Residence times range from a few hours to several years, but potential links between
these timescales and specific tectonomagmatic variables such as spreading rate and relative locations of
eruption site and ridge axis have remained elusive. Here we demonstrate how incomplete chemical diffusion
of Sr within plagioclase crystals from MOR basalts erupted in on- and off-axis settings on a number of ridges
with variable spreading rates provide geospeedometric constraints. We combine electron probe microanalyt-
cal crystal maps with detailed laser ablation profiles of almost 70 plagioclase crystals from the fast spreading
East Pacific Rise (EPR) at 9–10°N, the intermediate spreading Gorda and Juan de Fuca (JdF) ridges, and the
ultraslow spreading Gakkel ridge to calculate crystal residence times. These range from a few days to several
months. The scarcity of residence times exceeding years corroborates previous data indicating that most of
the growth of plagioclase phenocrysts occurs within the conduit at the onset of and during eruption on the
sea floor, and extends this result to the fast-spreading EPR. Further, statistical analysis is employed to show
for the first time that residence times are systematically longer at slower spreading rates, in off-axis samples,
and samples sourced from laterally distal axial melt lenses. Plagioclase textures and residence time variations
appear to be linked to differences in the dynamics of late-stage, pre-eruptive magma storage and ascent in
the different tectonomagmatic settings investigated. In the future, geospeedometric work on MOR samples
will be required to assess if the effect of spreading rate on crystallization timescales are globally applicable,
and to investigate potential variations in magma plumbing systems within individual ridge segments.

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1. Introduction

The global MOR system produces the greatest proportion of mafic magmas on Earth, yet we still know little about the mechanisms and timescales of eruptive processes in this environment. It is therefore important to establish potential differences in petrogenetic processes and magma ascent rates in different tectonomagmatic settings of ridges with variable spreading rates. Thickness, runout, and morphology of submarine lava flows are governed by melt viscosity and flow emplacement conditions such as extrusion and cooling rates (Fink and Griffiths, 1992; Gregg and Fink, 1995) and local topography (Escartin et al., 2007; Gregg and Smith, 2003). Flow morphologies range from pillowed mounds at slow effusion rates through lobate flows to various kinds of sheet flows at higher effusion rates (Rubin et al., 2012, and references therein). Eruption dynamics and magma ascent rates have also been recently constrained from observations of syn-emplacement degassing of dissolved CO₂ (Soule et al., 2012). However, potential links between flow emplacement and magma ascent rates, and the variables that determine melt transfer timescales, have to date remained elusive, and the present review outlines a promising approach to elucidate this aspect of MOR magmatism.

Rates of magma genesis and melt transfer may be constrained by studies of short-lived U-series disequilibria, and yield timescales of ~10³ years based on ²²⁶Ra–²³⁰Th disequilibria (Rubin and Macdougall, 1988; Sims et al., 2002), and more recently of as little as a few decades based on ²¹⁰Pb–²²⁶Ra disequilibria (Rubin et al., 2005). These represent upper limits for the ages of phenocrysts growing from MOR basaltic melts. Since the mid 1980s, crystal residence times in MOR basalts have been inferred through modeling the diffusion of ions in olivine crystals. Examples include Ni diffusion in olivine (Humler and Whitechurch, 1988; Nabelek and Langmuir, 1986), and Fe-Mg interdiffusion between olivine and melt (Pan and Batiza, 2002) or between olivine host crystals and their melt inclusions (Danyushevsky et al., 2002). Fig. 1 provides an example of simple Fe-Mg interdiffusion between an olivine from the East Pacific Rise (EPR) and its host glass as modeled by Pan and Batiza (2002). The initial composition of the grain is given by the constant core composition of about Fo₈⁹. The decrease in forsterite content towards the rim is interpreted to be due to Fe-Mg interdiffusion between the crystal and the less magnesian melt, which for this particular crystal yields a residence time of 140 days based on the liquidus temperature of the host glass (for details, see Pan and Batiza, 2002). More recently, plagioclase residence times have been studied using Mg diffusion (Costa et al., 2010) and Sr diffusion (Zellmer et al., 2011a,b). Table 1 provides a summary of previous studies on the timescales of crystalization in MOR basaltic melts, which typically range from a few hours to a few years (Costa et al., 2010; Danyushevsky et al., 2002; Humler and Whitechurch, 1988; Nabelek and Langmuir, 1986; Pan and Batiza, 2002; Zellmer et al., 2011b).

MORB basalt (MORB) samples are commonly sparsely phric, particularly at fast spreading ridges, where > 70% of samples carry less than 5% crystals (Coogan, 2007). However, when crystals are abundant, their zoning profiles are often more complex than shown in Fig. 1. Therefore, previous studies of olivine and plagioclase residence times have generally focused on the few MORB samples suitable for such diffusion studies. Together with a general absence of constraints on precise eruption locations and geologic settings, this has significantly hampered attempts to relate phenocryst residence times to variations in geodynamic parameters between different ridges or ridge segments.

At constant crustal thickness, MOR spreading rates can be regarded as a proxy for average melt supply (Perfit and Chadwick, 1998; Small, 1998). Although this relationship breaks down over short time scales or near hot spots (Rubin and Sinton, 2007; Rubin et al., 2009), spreading rate nevertheless provides a first order context for the interpretation of timescales of generation, differentiation, and ascent of MOR magmas. The present study compares plagioclase crystal residence times from ultra-slow, intermediate, and fast spreading ridges, from on-axis and off-axis settings, and from seamounts and different lava flow morphologies, thereby providing a first glance into differences in crystal residence times within different MOR eruptive and tectonomagmatic settings. Here we use these constraints to investigate potential differences in the dynamics of magma storage and ascent between the respective magmatic plumbing systems.

![Fig. 1](https://example.com/figure1.png)  
(a) A backscattered electron microprobe image showing a typical olivine zoning texture from the EPR basalts studied by Pan and Batiza (2002). Darker shading of olivine corresponds to higher forsterite (Fo) contents. ol, olivine; pl, plagioclase. The solid bar provides a 100 µm scale. (b) Core to rim compositional profile of the olivine grain shown in (a). Error bars are smaller than symbol size. The solid curve is a calculated spherical diffusion profile. Adapted from Pan and Batiza (2002).
Previous geospeedometry results on crystal residence times in MOR basaltic melts.

<table>
<thead>
<tr>
<th>Location</th>
<th>Mineral, diffusing element(s)</th>
<th>No. of samples studied</th>
<th>Total No. of crystals</th>
<th>Range of residence times in melt</th>
<th>Reference</th>
<th>Comment/interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>East Pacific Rise, Siqueiros transform fault</td>
<td>Olivine, Mg-Fe</td>
<td>1</td>
<td>1</td>
<td>~23 days</td>
<td>Danyshevsky et al. (2002)</td>
<td>Total residence time of single grain, modelled in two distinct cooling episodes of ~22.5 days and ~3 h before eruption.</td>
</tr>
<tr>
<td>East Pacific Rise, 9°30’N and 10°30’N</td>
<td>Olivine, Mg-Fe</td>
<td>4</td>
<td>199</td>
<td>&lt;1 day to 9.3 years</td>
<td>Pan and Batiza (2002)</td>
<td>Crystal growth in open system axial magma chamber, with magma residence times of the order of months.</td>
</tr>
<tr>
<td>Central Indian Ridge, near Rodríguez triple junction</td>
<td>Olivine, Ni</td>
<td>1</td>
<td>1</td>
<td>1 to 102 h</td>
<td>Humler and Whitechurch (1988)</td>
<td>Crystals grow in a hybrid magma reservoir, with residence times representing the time between mixing of rising magma batches into the evolved upper reservoir and eruption.</td>
</tr>
<tr>
<td>Mid-Atlantic Ridge, FAMOUS area</td>
<td>Olivine xenocrysts, Ni</td>
<td>1</td>
<td>5</td>
<td>15 days to 4.4 years</td>
<td>Nabelek and Langmuir (1986)</td>
<td>Xenocrysts are thought to be derived from earlier solidified low-Ni basalts. Residence times represent the time between uptake of xenocryst into high-Ni host melt and its eruption.</td>
</tr>
<tr>
<td>Mid-Atlantic Ridge, Serocki Volcano (ODP Hole 648B)</td>
<td>Plagioclase xenocrysts, Mg</td>
<td>3</td>
<td>16</td>
<td>~1 to 10 years</td>
<td>Costa et al. (2010)</td>
<td>Crystals are interpreted to represent xenocrysts from a mush zone, and residence times are maximum times between xenocryst entrainment and eruption on the sea floor.</td>
</tr>
<tr>
<td>Costa Rica Rift (ODP Hole 896A)</td>
<td>Plagioclase xenocrysts, Mg</td>
<td>3</td>
<td>13</td>
<td>Several days to &lt;10 years</td>
<td>Costa et al. (2010)</td>
<td>Crystals are interpreted to represent xenocrysts from a mush zone, and residence times are maximum times between xenocryst entrainment and eruption on the sea floor.</td>
</tr>
<tr>
<td>North Gorda Ridge</td>
<td>Plagioclase, Sr</td>
<td>1</td>
<td>7</td>
<td>A few weeks to months*</td>
<td>Zellmer et al. (2011a,b)</td>
<td>Crystals growth during dike injection of initially aphyric compositionally heterogeneous basaltic melts.</td>
</tr>
<tr>
<td>Juan de Fuca Ridge, Coaxial Segment</td>
<td>Plagioclase, Sr</td>
<td>2</td>
<td>13</td>
<td>~1 week to several months*</td>
<td>Zellmer et al. (2011a,b)</td>
<td>Crystal growth during dike injection of initially aphyric compositionally heterogeneous basaltic melts.</td>
</tr>
<tr>
<td>Gakkel Ridge, Western Volcanic Zone</td>
<td>Plagioclase, Sr</td>
<td>1</td>
<td>3</td>
<td>Several months*</td>
<td>Zellmer et al. (2011a,b)</td>
<td>Crystal growth during dike injection of initially aphyric compositionally heterogeneous basaltic melts. Megacrysts form by synneusis of crystals during diking.</td>
</tr>
</tbody>
</table>

* Zellmer et al. (2011a,b) calculated equilibration times of 0.2 to 14 years and argued for actual crystal residence times of at least one order of magnitude shorter.

2. Background of studied MOR samples

In this study, we have chosen well-characterized samples in terms of eruption location, and eruption date (if available), covering a range of spreading rates, and including Axial Seamount eruptions to investigate the potential influence of hot spots. One condition was the presence of plagioclase crystals large enough for geospeedometry (ca. 100 μm across, or larger). Samples studied come from the East Pacific Rise (EPR) at 9–10°N, the Juan de Fuca (JdF) Ridge, the Gorda ridge and the Gakkel ridge, with spreading rates ranging from >10 cm yr⁻¹ to <1.5 cm yr⁻¹. EPR on-axis eruptions are represented by the 1994 Gravity Cruise sample 2772-3 of unknown eruption age (cf. Sims et al., 2003), and the Knorr dredge sample D48-1x of the 2005-6 flow, which is of the same composition as the other dredge 48 samples (cf. Goss et al., 2010). EPR off-axis eruptions are represented by the 2004 Alvin Dive samples 3970-11 and 3974-10 of unknown eruption age (cf. Hinds, 2005; Schouten et al., 2004). The former is taken from a pillow mound believed to represent a true off-axis eruption, while the latter was recovered from a flow front about 1.2 km from the axis and may represent a channelized flow originating from the axial summit trough (Soule et al., 2005). JdF Southern Cleft on-axis eruptions of unknown eruption age are represented by the 2000 Tiburon Dive samples T178-G4, T183-G16 and T183-G17 (cf. Stakes et al., 2006). Of these, T178-G4, although recovered from the axial valley, appeared to have erupted along the bounding fault about 1 km away from the axial summit trough. We also studied a young Southern Cleft off-axis seamount sample, T461-G20, collected during the 2002 Tiburon Dive (cf. Stakes et al., 2006). Further, JdF Axial Seamount eruptions are represented by the 1988 NOAA Vents Dive central caldera flow sample 2087-3 and the 2000 Ropos Dive central 1998 flow sample R501-12 (cf. Embley et al., 1995). Finally, we include into our analysis of crystal residence times on-axis samples from recent MORB eruptions that were studied previously (Zellmer et al., 2011a,b). These include basalts 2792-4R and 2794-2R from the JdF Coaxial segment, erupted during 1982-91 and in 1993, respectively; and basalts W9604-C3 (cf. Rubin et al., 1998) and D27-16 (cf. Michael et al., 2003) from the northern Gorda Ridge and the Gakkel Ridge, respectively. The 1993 Coaxial flow, like most other eruptions from the intermediate spreading JdF flow, was studied previously (Zellmer et al., 2011a,b). These include basalts 2792-4R and 2794-2R from the JdF Coaxial segment, erupted during 1982-91 and in 1993, respectively; and basalts W9604-C3 (cf. Rubin et al., 1998) and D27-16 (cf. Michael et al., 2003) from the northern Gorda Ridge and the Gakkel Ridge, respectively. The 1993 Coaxial flow, like most other eruptions from the intermediate spreading JdF and Gorda ridges, was associated with lateral dike injection (Embley et al., 2000; Smith, 1999). However, the distance over which the dike propagated from the seismically imaged location of the northern end of the Coaxial magma lens (Menke et al., 2002) to the eruption site was unusually large (60 km along-axis, compared to typically 5–30 km at ridge segments away from Axial seamount, cf. Dziak et al., 2007). A summary of all sampling locations and sample details, including their flow morphologies, is given in Table 2. The samples we studied range from pillow lavas and lobate flows to sheet flows, arguably covering the full range of MORB effusion rates (Gregg and Fink, 1995). Our complete dataset comprises 69 plagioclase crystals from 10 newly and 4 previously studied (Zellmer et al., 2011a) MOR samples.
Table 2
Sample details.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Location</th>
<th>Details</th>
<th>Relative age</th>
<th>SiO₂</th>
<th>MgO</th>
<th>Mg#</th>
<th>Number of crystals</th>
<th>Figure</th>
<th>Min. T [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2772-3</td>
<td>EPR 9–10 N on-axis</td>
<td>Lobate flow, axial summit trough</td>
<td>1</td>
<td>49.57</td>
<td>7.57</td>
<td>0.56</td>
<td>3</td>
<td>S1</td>
<td>1135</td>
</tr>
<tr>
<td>D48-1x</td>
<td>EPR 9–10 N on-axis</td>
<td>Lobate flow, 2005–2006 eruption</td>
<td>0</td>
<td>50.66</td>
<td>8.16</td>
<td>0.61</td>
<td>4</td>
<td>S2</td>
<td>1155</td>
</tr>
<tr>
<td>3970-11</td>
<td>EPR 9–10 N off-axis</td>
<td>Pillow, off-axis pillow mound</td>
<td>2</td>
<td>50.72</td>
<td>7.77</td>
<td>0.58</td>
<td>7</td>
<td>S3</td>
<td>1140</td>
</tr>
<tr>
<td>3974-10</td>
<td>EPR 9–10 N off-axis</td>
<td>Pillow, pillow front of flow channel off-axis</td>
<td>2</td>
<td>50.11</td>
<td>8.33</td>
<td>0.61</td>
<td>4</td>
<td>S4</td>
<td>1155</td>
</tr>
<tr>
<td>T178-G4</td>
<td>JdF Cleft on-axis</td>
<td>Pillow, axial pillow mound</td>
<td>1</td>
<td>53.72</td>
<td>4.89</td>
<td>0.43</td>
<td>4</td>
<td>S5</td>
<td>1150</td>
</tr>
<tr>
<td>T183-G16</td>
<td>JdF Cleft on-axis</td>
<td>Pillow, elongate pillow flow</td>
<td>1</td>
<td>50.45</td>
<td>7.99</td>
<td>0.56</td>
<td>4</td>
<td>S6</td>
<td>1120</td>
</tr>
<tr>
<td>T183-G17</td>
<td>JdF Cleft on-axis</td>
<td>Sheet flow in axial valley</td>
<td>1</td>
<td>50.67</td>
<td>7.25</td>
<td>0.53</td>
<td>4</td>
<td>S7</td>
<td>1120</td>
</tr>
<tr>
<td>T461-G20</td>
<td>JdF Cleft off-axis</td>
<td>Pillow, part of off-axis volcanic construct</td>
<td>1</td>
<td>48.50</td>
<td>9.77</td>
<td>0.68</td>
<td>4</td>
<td>S8</td>
<td>1170</td>
</tr>
<tr>
<td>2087-3</td>
<td>JdF Axial Smt.</td>
<td>Pillow, part of elongate flow in central caldera</td>
<td>1</td>
<td>49.04</td>
<td>8.42</td>
<td>0.61</td>
<td>7</td>
<td>S9</td>
<td>1160</td>
</tr>
<tr>
<td>R501-12</td>
<td>JdF Axial Smt.</td>
<td>Sheet flow, hackley flow section of 1998 flow</td>
<td>1</td>
<td>49.54</td>
<td>7.40</td>
<td>0.56</td>
<td>5</td>
<td>S10</td>
<td>1150</td>
</tr>
<tr>
<td>2792-4R</td>
<td>JdF Coaxial</td>
<td>Sheet flow, folded section of 1982–91 flow site</td>
<td>0</td>
<td>49.30</td>
<td>7.20</td>
<td>0.51</td>
<td>6</td>
<td>Published</td>
<td>1080</td>
</tr>
<tr>
<td>2794-2R</td>
<td>JdF Coaxial</td>
<td>Pillow, small flow at distal end of 1993 flow site</td>
<td>0</td>
<td>50.60</td>
<td>6.90</td>
<td>0.50</td>
<td>7</td>
<td>Published</td>
<td>1100</td>
</tr>
<tr>
<td>W9604-C3</td>
<td>North Gorda</td>
<td>Pillow, 1996 flow, RV Wecoma camera sled</td>
<td>0</td>
<td>51.22</td>
<td>8.65</td>
<td>0.65</td>
<td>7</td>
<td>Published</td>
<td>1130</td>
</tr>
<tr>
<td>D27-16</td>
<td>Western Gakkel</td>
<td>Tubular pillow, 2001 USCGC Healy dredge</td>
<td>7</td>
<td>48.33</td>
<td>8.84</td>
<td>0.67</td>
<td>3</td>
<td>Published</td>
<td>1145</td>
</tr>
</tbody>
</table>

* Relative ages: 0 = historic flow, 1 = very young likely in past 100 years, 2 = unknown, but < 80 ka.
* Sims et al. (2003).
* Goss et al. (2010).
* Stakes et al. (2006).
* Chadwick et al. (2005).
* Rubin et al. (1998).
* Michael et al. (2003), composition from Zellmer et al. (2011a).
* Zellmer et al. (2011a).
* Based on lowest anorthite content of all crystals in each rock sample and assuming 0.5 wt.% H₂O in the primitive magma.

that are representative for a range of MOR tectonomagmatic settings and spreading rates.

3. Analytical techniques

Electron microprobe and laser ablation inductively-coupled plasma mass spectrometry (LA-ICPMS) facilities were identical to those employed by Zellmer et al. (2011a) in order to facilitate direct comparison of the new data with the results of previous work on MORB crystal residence times. All details of these instruments and the analytical methods employed have been described previously (Zellmer et al., 2011a). Therefore, we only give a very brief summary here.

MORB plagioclase crystals were characterized in terms of their major element compositional variations by chemical mapping using a 193 nm Eximer laser with 16 μm beam diameter. Zoning wave-lengths of the crystals studied were typically larger, so that mixing of different growth zones and associated compositional mixing effects were not an issue. Further, mixing below the sample surface due to progressive ablation into the sample did not occur, as we monitored signal intensity during ablation. The method of major oxide analysis by LA-ICPMS through the use of a FE-EPMA-characterized working standard has been described in detail by Zellmer et al. (2012). The main advantage of this approach is that it circumvents the problem of cross-correlation of major and trace element data obtained through different analytical methods. In this regard, it should be noted that the geospeedometric method used in this study relies on a high relative precision of any two measurements within an individual crystal, and will remain valid even if accuracy is low (e.g., due to analytical bias). In the present study, we were able to precisely characterize intracrystalline chemical variations in terms of Xₘ in and Sr concentration to within ± 0.6% and ± 18% (1σ), respectively, as yielded by repeat LA-ICPMS analysis of a plagioclase working standard chosen from the MORB samples investigated.

To insure consistency with previous work (Zellmer et al., 2011a), we have not considered trace element substitution into the crystal structure in calculations of plagioclase stoichiometry, so that SiO₂, Al₂O₃, CaO and Na₂O sum to 100% in Table S1, with totals being slightly higher. However, this has no significant effect on the calculated anorthite contents of our samples.

4. Plagioclase petrography and mineral chemistry

Plagioclase crystals from MOR lavas display a wide variety of textures and morphologies (Fig. 2). In our set of samples, the simplest crystal morphologies are found in on- and off-axis samples from the fast spreading EPR and in on-axis samples from the intermediate spreading JdF ridge. They are lath-like (Fig. 2a) or tabular (Fig. 2b).
and display such small concentric chemical zonation that it is only discernable by chemical mapping (cf. supplementary figures with chemical profiles for ranges in anorthite content across each crystal). This zoning may be normal, with crystals becoming less calcic towards their rim, but is often complex, displaying repeated overgrowth of more and less calcic zones on euhedral crystal faces without evidence of resorption (cf. Fig. 2b). Occasionally, sector zoning is observed (Fig. 2c). However, more complicated zoning with chemically heterogeneous, irregular growth zones, likely associated with resorption events, is seen in some crystals (Fig. 2d). In samples with higher total crystallinity, clusters of crystals are present (e.g. Fig. 2c, e). The off-axis sample from the intermediate spreading JDF ridge we studied displays strong, irregular resorption textures on preexisting clusters of complexly zoned large plagioclase crystals (Fig. 2f). We have also studied two samples from the JDF Axial seamount. One shows complexly zoned plagioclase crystals, including some large laths that begin to form crystal clusters (Fig. 2g). The other carries abundant plagioclase megacrysts. Their textures indicate synneusis of smaller crystals to build clusters (glomerophenocrysts), which form the cores of megacrysts that continue to incorporate small crystals during their growth (Fig. 2h). Large, blocky megacrysts formed by synneusis of smaller crystals have also been described from the Galápagos ridge sample studied previously (Zellmer et al., 2011a, cf. Fig. 21).

Compositional, plagioclase from the ridges we studied spans the range from An80 to An91. Some crystals display small (typically <50 µm, but occasionally up to a few hundred microns across) but distinct nuclei of very calcic plagioclase (An84-91), which are most clearly evident in Fig. 2b, e, and g. These small calcic cores may have crystallized from primitive high Ca/Na melts that constituted a volumetrically minor fraction of the bulk melt supplied to the newly forming MOR crust (cf. Ridley et al., 2006). They can thus be considered xenocrystic, serving as nuclei for overgrowth within the axial magma chamber (AMC) or in the conduit during magma ascent to the sea floor. The small size of most of these calcic cores is in line with results from previous work that indicate that incorporation of large crystals from the gabbroic rocks in oceanic layer 3 is rare; that most erupted MOR magmas begin their ascent through the upper oceanic crust as essentially aphyric melts; and that the majority of plagioclase crystals have grown during melt extraction in the conduit, from a compositionally heterogeneous melt derived from pooled, compositionally distinct melt lenses (cf. Zellmer et al., 2011a).

5. Sr geospeedometry in plagioclase — a methodological review

To determine plagioclase crystal residence times, we use the geospeedometric approach of intracrystalline diffusional equilibration of Sr at magmatic temperatures. In the following, we reiterate and supplement the details of this geospeedometric method, which has been developed and employed in several previous studies (Zellmer et al., 1999, 2003, 2011a,b) and was last reviewed by Zellmer et al. (2011a): Calculating crystal residence times at magmatic temperatures involves (1) determination of the chemical equilibrium concentration of Sr within the plagioclase crystal under consideration, (2) choosing an appropriate initial Sr concentration profile, and (3) applying known Sr diffusion rates within the crystal to derive a residence time.

5.1. Determination of Sr chemical equilibrium

In chemical equilibrium, the relative Sr concentration of any two parts i and j of a plagioclase crystal will be determined by a solid–solid partition coefficient $D_{ij}^\theta$, which is a function of the difference in their anorthite contents, $X_{An}$, and of temperature, $T$:

$$D_{ij}^\theta = \exp \left(\frac{\Delta G_{ij}^\theta}{RT}\right),$$

where $R$ is the universal gas constant (8.31451 J mol$^{-1}$ K$^{-1}$) and $\Delta G_{ij}^\theta$ is a constant, the value of which has empirically been determined as $-26,700 \pm 1900$ J mol$^{-1}$ (Blundy and Wood, 1991) or $-30,400 \pm 1100$ J mol$^{-1}$ (Bindeman et al., 1998). Following previous work, we use the $w_S$ value of Blundy and Wood (1991). Further, we estimate the minimum temperature of crystal growth for each rock sample based on MELTS modeling of bulk rock composition combined with the lowest anorthite content of the crystals studied in the sample (cf. Zellmer et al., 2011a). Minimum temperature estimates range from 1080 to 1170 °C and are provided in Table 2. It should be noted that at such temperatures, uncertainties in $w_S$ and $T$ translate into a negligible (of the order of a few percent at most) variation in relative partitioning of Sr for growth zones with an anorthite difference of $\Delta X_{An} = 0.1$.

Absolute bulk crystal equilibrium profiles can be calculated by adopting a boundary condition such as preservation of total Sr content within the crystal (e.g., Zellmer et al., 1999, 2003, 2011a), or chemical equilibrium of the crystal with an infinite melt reservoir of the composition of the glass (e.g., Costa et al., 2003, 2010). However, regardless of which boundary condition is used, the assessment of Sr chemical equilibrium or deviation thereof involves comparing Sr concentration ratios of different parts of a plagioclase crystal (rather than their absolute Sr concentrations) to the expected chemical equilibrium ratios derived for these parts. Chemical equilibrium between two parts i and j of a crystal is attained when

$${\frac{C_{i}}{C_{\text{obs}}}} = {\frac{C_{\text{equil}}}{C_{\text{equil}}}} = D_{ij}^\theta,$$

where $C$ denotes trace element (in this case, Sr) concentration, implying that in equilibrium,

$${\frac{C_{i}}{C_{\text{obs}}}} = {\frac{C_{\text{equil}}}{C_{\text{equil}}}}.$$

If parts i and j are adjacent points within a traverse, local equilibration may be assessed as follows: We define $\rho$ as the ratio between observed and equilibrium concentration at each point within the traverse, based on any chosen boundary condition:

$$\rho = \frac{C_{\text{obs}}}{C_{\text{equil}}}.$$

Local equilibration is attained when the $\rho$-profile has no slope, i.e. when $d\rho/dx = 0$, x being distance along the traverse. It should be noted that distinct crystal growth zone boundaries are not required to assess local chemical equilibrium between adjacent parts of a crystal. This is a major advantage over conventional geospeedometric approaches, which use diffusion across sharp compositional contrasts to estimate crystal residence times.

In practice, the assessment of local disequilibria requires knowledge of the uncertainties in both anorthite contents and trace element concentrations under consideration. It can be demonstrated (Zellmer et al., 2003) that concentrations $C_{i}$ and $C_{j}$ can be considered in equilibrium at the 95% confidence limit if

$$\left|\frac{C_{j}}{C_{i}} - D_{ij}^\theta\right| \leq 2\sqrt{\left(\frac{\sigma(C_{i})}{C_{i}}\right)^2 + \left(\sigma(D_{ij}^\theta)\right)^2},$$

where $\sigma$ denotes standard deviation, and

$$\sigma_{D_{ij}^\theta} = \frac{w_S}{RT} D_{ij}^\theta \left(\frac{\sigma(X_{An})}{X_{An}}\right)^2 + \left(\sigma(D_{ij}^\theta)\right)^2.$$

Crystals that do not display any local Sr disequilibria are in bulk Sr equilibrium, which may be due to (i) original crystal growth in
equilibrium or (ii) diffusion of initial disequilibria over time. However, it should be noted that crystal growth in equilibrium would require a constant Sr content in the melt during crystal growth, so that the Sr concentration in the crystal would be governed by its anorthite content only. This is unlikely, as crystal growth itself is changing the Sr content of the melt locally (as long as $D_{\text{Sr}}^{\text{plag-melt}} \neq 1$). We note that crystals in bulk Sr equilibrium are fairly uncommon, which confirms disequilibrium growth. In the few cases of bulk Sr equilibrium, it is likely that crystal residence time was sufficiently long for equilibration, but crystal growth in equilibrium cannot be strictly precluded. Such crystals therefore do not lend themselves to geospeedometric dating.

5.2. Choosing an appropriate initial Sr concentration profile

The choice of an initial Sr concentration profile is the least constrained task in determining plagioclase crystal residence times. In conventional geospeedometry, sharp compositional contrasts, e.g. in major element chemistry, are assumed to have initially also been displayed by the diffusing species, providing a strong boundary condition (e.g. Costa et al., 2003). In the absence of sharp compositional contrasts, however, other constraints need to be applied. For example, extreme initial concentration contrasts across adjacent crystal growth zones can be employed to derive residence time maxima (e.g., Zellmer et al., 1999, 2011a). Alternatively, initial concentration profiles may be modeled if reasonable assumptions can be made about the petrogenetic processes operating during crystal growth. For example, Zellmer et al. (2003) demonstrated that in plagioclase from the Soufriere Hills andesites, Montserrat, initial Sr concentrations were relatively invariant across phenocrysts due to the counterbalancing effect of Sr depletion in the melt during crystallization with $D_{\text{Sr}}^{\text{plag-melt}} \approx 1$ and increasing partitioning of Sr into progressively less calcic plagioclase that is formed during progressive crystallization from the evolving melt.

In the present contribution, we have studied the trace element profiles of a relatively large number of crystals. This facilitates an estimation of initial disequilibria, because there is independent evidence that some MORB crystals record residence times of a few hours only (cf. Table 1; Humler and Whitechurch, 1988; Pan and Batiza, 2002). Thus, the initial profile may be tagged to the largest disequilibria observed in the large set of MORBs studied, as these disequilibria reflect crystals that resided in the plumbing system for very short time periods (cf. Section 6, below). All calculated crystal residence times are therefore relative to the short residence times of the crystals with the greatest disequilibria.

5.3. Deriving crystal residence times through known Sr diffusion rates

Anorthite profiles are preserved over the time scales considered here, because coupled diffusion of Na, Ca, Al and Si is very slow (Morse, 1984) compared to diffusion of Sr (Cherniak and Watson, 1994; Giletti and Casserly, 1994). The diffusion coefficient of Sr in plagioclase, $D_{\text{Sr}}$ (where the use of $D$ is to avoid confusion with the partition coefficient, $D$), is a function of temperature and anorthite content:

$$D_{\text{Sr}} = 10^{-4.1X_{\text{An}}} \times 10^{-0.08} \exp(-3.32 \times 10^4 / T).$$

where the analytical uncertainty of $D_{\text{Sr}}$ is approximately a factor of 2 at the $\pm 2\sigma$ level (Giletti and Casserly, 1994). The effect of temperature on diffusivity is large by comparison, with a temperature change of 150 °C resulting in a diffusivity change of about 1 order of magnitude. The diffusivity of Sr increases with decreasing anorthite content during melt evolution, but this is balanced by the concomitant decrease in diffusivity with decreasing temperatures, so that the Sr diffusion coefficient remains roughly constant and is of the order of $10^{-17}$ m$^2$/s$^{-1}$ (Zellmer et al., 2011a). This is illustrated in Fig. 3.

Crystals that show Sr concentration profiles in chemical disequilibrium have cooled to temperatures below which Sr diffusion is insignificant, before being able to fully equilibrate. In nature, bulk crystal Sr disequilibria are frequently preserved (e.g., Costa et al., 2010; Zellmer et al., 1999, 2003, 2011a,b), indicating that crystal residence times at magmatic temperatures are generally much shorter than required for bulk crystal equilibration. However, one of the strengths of the methodology applied here is that it allows the assessment of local chemical disequilibria between closely spaced parts of a plagioclase crystal, irrespective of distinct growth zone boundaries. Thus, while the entire crystal may not have attained complete chemical equilibration through Sr diffusion, some parts of the crystal may already have equilibrated locally. Yet, if significant chemical disequilibria are retained at a local level, short crystal residence times are implied. Therefore, fine scale analysis potentially allows crystal residence time constraints to be extended to very short timescales.

In theory, the location of local disequilibrium within a crystal is relevant for the interpretation of residence times. Disequilibria within the rim of a crystal put constraints on the time of rim overgrowth, while disequilibria close to the core of a crystal may allow the determination of the total residence time of the crystal from shortly after its nucleation to its final eruption (cf. Zellmer and Clavero, 2006). In praxis, it is difficult to achieve this resolution, as initial local disequilibria are likely variable, depending on open system processes during crystallization. In most MORB plagioclase crystals, the magnitude of local disequilibria do not display a broad decrease towards the core of a crystal (Zellmer et al., 2011a). In the present study, whenever possible, we have selected local disequilibrium close to the crystal cores to approximate total crystal residence time since their nucleation or overgrowth on xenocrystic cores.

6. Determination of plagioclase residence times in the MORB samples of this study

Fig. 4a is an example of an EPR on-axis MORB plagioclase crystal (2772-3-P1) with a partially resorbed, likely xenocrystic (cf. Ridley et al., 2006) calcic core ($A_{\text{An}}=85-89$) mantled by an oscillatory zoned, euhedral and less calcic overgrowth ($A_{\text{An}}=70-78$). Its $X_{\text{An}}$ profile is provided in Fig. 4b. Its Sr concentration profile as determined by LA-ICPMS is given in Fig. 4c, together with its calculated equilibrium profile as determined from the observed anorthite content variations. While the observed Sr concentration profile broadly follows the equilibrium profile, there are
significant differences in detail, resulting in about 20 µm wide bands of local disequilibria that are most prominent at about 210 µm, 300 µm and 360 µm (Fig. 4d). Local disequilibria represent differences in the relative slopes between observed and equilibrated Sr profiles between two closely spaced parts of a crystal, and their chemical equilibration is a function of both their magnitude and the widths over which they occur, here referred to as “bandwidth” (cf. Zellmer et al., 1999, 2003, 2011a). 52 of the 69 crystals studied (cf. supplemental Table S1, Figs. S1a - S10a, and Zellmer et al., 2011a,b) preserve local disequilibria inward of their outermost overgrowth rims (cf. supplemental Figs. S1b - S10b). Were possible, we have selected one significant disequilibrium zone close to the core (marked in grey in supplemental Figs. S1b, S10b), in order to estimate the timescale between nucleation (or shortly thereafter) and eruption. Absolute values of these local disequilibria, and their bandwidths, are plotted in Fig. 5. Local disequilibria of up to about $1.5 \times 10^{-2}$ µm$^{-1}$ and bandwidths of about 10 to 55 µm are observed.

The main challenge in diffusion modelling is the reliable estimation of the initial distribution of Sr within each studied crystal. Previous work has addressed this issue by assuming initial concentration profiles in extreme chemical disequilibrium, such that the crystal residence times derived were considered to be overestimates (Zellmer et al., 1999, 2011a). Superimposed on the data in Fig. 5 are timelines for the chemical equilibration of Sr. In Fig. 5a, those timelines are based on the initial disequilibrium profile of Zellmer et al. (2011a), in that study, the initial profile was recognized as an extreme overestimate that could be used to obtain maximum equilibration times. Actual crystal residence times were thought to be at least one order of magnitude shorter. In the present study, the large number of crystals available facilitates a more reasonable estimation of initial disequilibria. Based on independent evidence that some MORB crystals record residence times of a few hours only (cf. Table 1; Humler and Whitechurch, 1988; Pan and Batiza, 2002), the initial profile may be tagged to the largest disequilibrium observed in the large set of MORB crystals studied here. This has been done in Fig. 5b. Evidently, most plagioclase crystals record residence times of the order of several days to months, with on-axis samples from ridges with intermediate spreading rates spanning the entire range of recorded timescales.

7. Analysis of age clustering
7.1. Functional form of sample residence time distributions and clustering

In the following, we refer to the range and distribution of plagioclase crystal residence times determined by diffusion modeling as “residence time distributions”. With exception of a single outlier (crystal W-9604-C3-2, yielding a residence time of 1.5 years), residence time distributions of individual samples are close to lognormal. This is evident when residence times are transformed by taking the natural log...
logarithm, and then checking for normality using a Kolmogorov–Smirnov test (excluding datapoints that are within error of zero age, cf. Fig. 6). Thus, the transformed residence time distributions are indistinguishable from normal distributions and are suitable for t-testing. Employing a simple Student’s t-test, we find that (a) the residence time distributions of on-axis samples 2772-3 and D48-1x from the fast spreading EPR are statistically indistinguishable, (b) the residence time distributions of samples R501-12 and 2087-3 from Axial seamount are also indistinguishable, and (c) the residence time distributions of most on-axis samples from intermediate spreading ridges are indistinguishable from each other, with exception of sample JdF 2794-2R, which yields significantly older residence times than most other on-axis samples from intermediate spreading ridges (see Table 3). We note that the latter sample comes from the 1993 eruption, which drained magma from the north end of the Coaxial melt lens (Menke et al., 2002) into a dike that propagated laterally along-axis over a distance of about 60 km, much further than in most other observed eruptions from the JdF and Gorda ridges (typically 5–30 km, Dziak et al., 2007).

Based on the preceding analysis, we combine the plagioclase residence times of samples from the same tectonomagmatic setting (with exception of sample JdF 2794-2R) into age clusters for further examination of potential variations in residence times between different tectonomagmatic settings.

7.2. Qualitative analysis of age clusters

Despite the significant scatter of the data displayed in Fig. 5, the large number of crystals studied allows us to identify clustering of ages, which serves to elucidate some first order differences between MORB samples erupted in different tectonomagmatic settings (Fig. 7). It is evident that EPR on-axis samples record the shortest residence times (less than 3 weeks median age), while off-axis samples appear to be somewhat older (about 2 months median age). Residence times of about 2 months are also yielded by about two thirds of on-axis samples from the intermediate spreading JdF and Gorda ridges. Remarkably, plagioclase crystals from Axial Seamount basalts record a comparable median age and thus differ little from those of most other JdF on-axis samples, despite a higher melt supply at Axial and evident differences in crystal morphologies (cf. Fig. 2). In contrast, the 1993 JdF Coaxial flow yields longer residence times with a median age of about 5 months. The off-axis sample from the Cleft segment (T461-G20) records the longest residence times at this ridge, with a median age of about 7 months. Only two crystals were studied from the ultra-slow spreading Gakkel ridge, and they yield a median residence time of about 1 year (Fig. 7).

7.3. Functional form of age clusters and significance of residence time differences

Application of another t-test may clarify if the differences in the obtained age clusters are statistically significant. Again, we find that each data cluster is roughly lognormally distributed using a Kolmogorov–Smirnov test (cf. Fig. 8). Even without taking uncertainties of individual ages into account, the transformed residence time data (by taking the natural logarithm) are consistent with normal distributions. Normal quantile plots show that all individual age uncertainties overlap with the straight line of the theoretical normal distributions (Fig. 8), and that all transformed data distributions are thus suitable to be subjected to t-testing.

The variances of the residence time distributions clearly differ between different tectonomagmatic settings, with the greatest variance displayed by on-axis samples from ridges with intermediate spreading rates, spanning the full age range of all crystals studied here. Intermediate spreading ridges are thought to have tectonomagmatic characteristics that can vary in time and space between those exhibited by fast and slow spreading ridges (Perfit and Chadwick, 1998; Small, 1998), and this may be the reason for their large crystal residence time variance.

Another possibility is that the differences in residence time variances result from the variable number of crystals studied from each tectonomagmatic setting, with variances increasing as more crystals are investigated. Further studies, particularly of crystals from slow spreading ridges, will be required to address this issue. In any case, an unequal variance t-test (Ruxton, 2006) will inform whether the observed age clusters from different tectonomagmatic environments are

![Fig. 6. Examples of Kolmogorov–Smirnov cumulative distribution curves that show that crystals from individual samples yield close to lognormally distributed residence time distributions, and are thus suitable for t-testing. Plotted are the cumulative logarithms of crystal residence times for (a) EPR sample 3970-11, (b) Gorda sample W9604-C3, (c) Axial Seamount sample 2087-3, and (d) JdF sample 2794-2R, with logarithmic averages of 0.60, 0.60, 0.82 and 1.72, respectively. Data distributions are indistinguishable from normal distributions around these averages (solid lines), with exception of a single outlier of sample W9604-C3 that is clearly evident in (b).](image-url)
Table 3
T-values (top right) and degrees of freedom (bottom left) of Student’s t-test, intermediate spreading rates.

<table>
<thead>
<tr>
<th>Sample</th>
<th>3970-11</th>
<th>T183-G16</th>
<th>T183-G17</th>
<th>JdF 2792-4R</th>
<th>T178-G4</th>
<th>W-9604-C3</th>
<th>JdF 2794-2R</th>
</tr>
</thead>
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<tr>
<td></td>
<td>0.66</td>
<td>1.17</td>
<td>0.22</td>
<td>1.90</td>
<td>3.45</td>
<td>1.07</td>
<td>1.75</td>
</tr>
<tr>
<td>3970-11</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T183-G16</td>
<td>0.86</td>
<td></td>
<td>0.26</td>
<td>0.93</td>
<td>2.84</td>
<td></td>
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</tr>
<tr>
<td>T183-G17</td>
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<td>1.47</td>
<td>0.83</td>
<td>1.90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>JdF 2792-4R</td>
<td></td>
<td>3.47</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>T178-G4</td>
<td></td>
<td></td>
<td>0.99</td>
<td>0.57</td>
<td>0.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W-9604-C3</td>
<td>8</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>1.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>JdF 2794-2R</td>
<td>9</td>
<td>6</td>
<td>7</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td></td>
</tr>
</tbody>
</table>

Underline = significant at 95% probability (p = 0.05).
Italic = significant at 90% probability (p = 0.1).

statistically distinguishable. Table 4 lists t-values and degrees of freedom for unequal variance t-tests undertaken for individual pairs of data clusters. Underlined t-values indicate that the distributions are distinguishable at the 95% confidence limit (p = 0.05). The statistical analysis confirms the results of our qualitative analysis above: EPR on-axis crystal residence times are significantly shorter than EPR off-axis, intermediate spreading rate on-axis, and Axial Seamount residence times, which in turn are significantly shorter than the 1993 Coaxial flow and intermediate spreading rate off-axis crystal residence times. Crystals from the ultra-slow spreading rate Gakkel Ridge have the longest median residence times, but these are not statistically distinguishable from the crystal residence times of intermediate off-axis lavas (cf. Table 4 and Fig. 8f).

In summary, the data presented here provide evidence that MOR crystal residence times are linked to (a) spreading rates, with slower spreading ridges generally yielding longer median crystal residence times than faster spreading ridges in magmas erupted on-axis; and (b) local variations in the magma plumbing systems, with samples sourced from the centre of an axial magma chamber (AMC) yielding shorter residence times than samples sourced from its edge or from deeper, isolated melt lenses, which commonly erupt off-axis (Fig. 9). In Table 5, median plagioclase residence times are summarized for each tectonomagmatic environment and are compared to previously published estimates (cf. Zellmer et al., 2011b). The residence times derived here are shorter, because they consider lower, more realistic initial disequilibria (cf. Fig. 5) than the previous work, in which it was acknowledged that the obtained times represented maxima that overestimated actual residence times.

8. Discussion

The majority of plagioclase crystals in on-axis samples from fast spreading ridges and from intermediate spreading ridges yield residence times of the order of several to months, similar to the overall duration of many MOR eruption episodes (Rubin et al., 2012, and references therein). Further, such short residence times of crystals reaching hundreds of micrometers in size indicate growth rates of the order of 10⁻⁶ cm s⁻¹, consistent with rapid cooling rates of up to 1 °C h⁻¹, such as those calculated to occur in dikes (Cashman, 1993). Zellmer et al. (2011a) therefore concluded that plagioclase phenocrysts grow mostly during dike injection leading up to eruption on the seafloor, and that incorporation of older, xenocrystic material from the gabbroic mush zone into MOR magmas, although occasionally observed (Costa et al., 2010; Ridley et al., 2006), may be relatively uncommon. While initial dike propagation is rapid, with propagation rates ranging from 0.01 to 10 m s⁻¹ (e.g., Dziak et al., 2007; Rubin, 1995), time-averaged melt ascent rates through the established conduits are likely significantly lower, considering total emplaced magma volumes of as little as 10⁻⁴ km³ at fast spreading rates (cf. Perfit and Chadwick, 1998), emplaced over periods of weeks to months (e.g., Rubin et al., 1994, 2012). Thus, it should be noted that “crystal growth during dike injection” is to be understood sensu latu, in that growth occurs during magma transport in a thermally insulated environment, encompassing melt ascent through the gabbroic mush section from deeper lying lower crustal melt lenses, ascent through a readily established conduit, and magma transport within an active flow field during inflation of flow lobes. The observed differences in plagioclase residence times between ridges of variable spreading rates may in part be due to differences in AMC depth below the sea floor, and differences in magma transport pathways such as vertical versus lateral dike injections. Seismic imaging suggests that AMC depth varies approximately by a factor of 3 (Purdy et al., 1992), from about 1.2 km beneath the EPR, to 2.1–2.7 km beneath the JdF, and to >3 km beneath slow spreading ridges (cf. Rubin et al., 2009).

Only very few data exist at present on plagioclase residence times at slow spreading ridges (cf. Table 1). Data from the Mid-Atlantic ridge suggest xenocryst residence times of 1–10 years, interpreted to represent the timing between xenocryst entrainment from the crystal mush and eruption on the sea floor (Costa et al., 2010). There are at present no residence time data on plagioclase phenocrysts from MOR samples erupted at slow spreading rates. Likewise, no data exist for superfast spreading rates (such as the southern EPR). Further work will be required to elucidate the crystallization processes operating at these ridges, which in terms of geospeedometric constraints are undersampled (cf. Fig. 9).

A common origin of MORB plagioclase phenocrysts at fast to intermediate (and ultraslow) spreading rates by growth during magma ascent through the conduit may at first be counterintuitive given the
highly variable crystal morphologies displayed in Fig. 2. Sector-zoned laths are indicative of rapid cooling rates of >1 °C per hour (Smith and Lofgren, 1982) and thus consistent with growth during dike injection. Concentrically zoned laths and euhedral tabular forms (Fig. 2a–c) are also easily reconcilable with growth during magma ascent, with variations in crystal chemistry due to melt heterogeneities within the conduit (Zellmer et al., 2011a). The apparent lack of significant plagioclase crystal growth in the AMC has been attributed to very short residence times of originally aphyric magmas that are aggregated from small, sill-shaped melt lenses at the onset of eruption (Zellmer et al., 2011a). In this context, plagioclase megacrysts (e.g. Fig. 2h, i) are thought to be formed by synneusis within the ascending magma (Zellmer et al., 2011a), a process clearly evident in Fig. 2h. More complex patterns, which are observed in a few samples and involve one or several resorption events, appear to be an exception, but they are more difficult to explain as part of an individual melt ascent episode. Instead, in these cases plagioclase crystals likely began to grow in a crustal magma reservoir (e.g. the AMC) prior to eruption. In the following, we discuss the crystal residence time and zoning results of samples studied here in some more detail.

8.1. On-axis MOR samples from the fast spreading East Pacific Rise

For on-axis EPR samples, short plagioclase residence times of a few weeks contrast with typically longer, previously reported average olivine residence times of about 2 to 3 months, which have been modeled to represent growth within the AMC during temporary magma storage (Pan and Batiza, 2002, cf. Table 1). If mafic melts (> 8 wt.% MgO) enter the AMC, they will have olivine on the liquidus, and olivine growth therefore begins during early stages of cooling within the AMC. Onset of plagioclase crystallization is in part a function of magmatic water content, which for on-axis samples of the EPR at 9-
10°N is up to about 0.2 wt.% (Le Roux et al., 2006). MELTS and Petrolog crystallography models suggest that such melts will have to cool by 10–40 °C below their liquidus before plagioclase begins to form. With median ages for olivine and plagioclase crystals of 64 and 17 days, respectively (Pan and Batiza, 2002, and this study), the AMC would thus have to experience a rapid cooling rate of the order of 0.5 °C per day for plagioclase phenocryst growth to occur prior to melt extraction from the AMC. Such a scenario appears unlikely given (a) the scarcity of olivine phenocrysts in our sample, and (b) the small change in lava composition and thus inferred temperature between the 1991 and 2005 eruptions, which suggests recharging of the melt lens over decadal time scales (Goss et al., 2010). We conclude that few if any plagioclase crystals grow prior to melt extraction through a conduit at the onset of eruption. This analysis corroborates previous data that indicated plagioclase phenocryst formation during dike emplacement (Zellmer et al., 2011), extends this result to the fast spreading EPR, and is consistent with the simple concentric or sector zoning patterns displayed by all EPR plagioclase crystals. An exception is the presence of some (generally quite small) highly calcic crystal cores that can be attributed to be xenocrystic and have likely been remobilized from the gabbroic mush zone in oceanic layer 3 (e.g. Fig. 2b).

8.2. On-axis MOR samples from ridges with intermediate spreading rates

With the exception of the 1993 Coaxial flow, plagioclase crystals from on-axis segments of the JdF and Gorda ridges yield a median age of 53 days. Again, most crystals are euhedral and show relatively simple zoning textures, consistent with growth in the conduit. Longer residence times than obtained from the fast spreading EPR may thus be largely attributable to longer magma ascent times as a consequence of being sourced from deeper melt lenses at intermediate spreading ridges (2.1–2.7 km beneath the JdF compared to about 1.2 km beneath the EPR) and long lateral dike distances from the melt lens to the eruption site, which are common at intermediate spreading rate ridges (Dziak et al., 2007). However, sample T178-G4, a basaltic andesite from the southern Cleft segment, shows some complex plagioclase growth zones that indicate intermittent crystal resorption. This sample is evolved enough (4.9 wt.% MgO) to have had a prolonged AMC history, with some plagioclase crystallization starting within the AMC shortly (days to weeks) prior to eruption. Erupted from the edge of the axial valley along the fault-bounded walls rather than the axial summit trough, this basaltic andesite may have been sourced from the edge of the cooling axial melt lens. Its eruption may have been triggered by influx of new melt into the reservoir, leading to magma mixing and partial resorption and overgrowth of a preexisting crystal load (cf. Wanless et al., 2010).

Interestingly, samples from Axial Seamount, a ridge-centered seamount that lies in the middle of the Axial segment of the JdF ridge, yield similar residence times to most other normal sections of the JdF ridge. This is true even for sample RS01-12, which carries complexly zoned megacrysts of plagioclase that show clear evidence of having formed by synneusis of smaller crystals that served as building blocks. Comparing EPMA maps and disequilibrium profiles of individual megacrysts in detail (Fig. S10), it is apparent that few local disequilibria separate large sections (some several hundred microns across) that are in chemical equilibrium. Some of those disequilibria mark the boundaries between the building blocks of smaller crystals and their megacrystic overgrowth (e.g., at ~350 μm and ~800 μm in crystal RS01-12-P2P). Using seismic evidence, West et al. (2001) has argued for the presence of a large (250 km3), long-lived mush zone beneath Axial volcano, with up to about 25% porosity at about 2.5 km below the sea floor, consistent with increased melt supply to this ridge segment. The combined evidence of complex plagioclase morphology formed by synneusis of smaller, smaller crystals, and short megacryst residence times, indicates that plagioclase crystallization occurred during rapid melt ascent through this subvolcanic mush zone, with incorporation of small crystals from the mush resulting in the formation of megacrysts. Our geospeedometric data therefore show that while the building blocks of the plagioclase megacrysts may be somewhat older, the formation of megacrysts occurred very recently. This suggests that the rates of melt accumulation into an ephemeral eruptible melt lens, followed by melt transfer to the surface, are independent of the melt supply rate from the mantle.

Plagioclase crystals of the 1993 flow from the JdF Coaxial segment, just northeast of Axial Seamount, yield residence times of several months, about 3 times longer than most on-axis samples from

Table 5
Calculated timescales for plagioclase equilibration and residence in MOR basaltic melts.

<table>
<thead>
<tr>
<th>Setting</th>
<th>Zellmer et al. (2011) equilibration time overestimate (months)</th>
<th>Residence time using best initial from this study (months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast on-axis</td>
<td>–</td>
<td>0.6</td>
</tr>
<tr>
<td>Fast off-axis</td>
<td>–</td>
<td>1.9</td>
</tr>
<tr>
<td>Intermediate on-axis</td>
<td>0.3</td>
<td>1.7</td>
</tr>
<tr>
<td>Axial seamount</td>
<td>10</td>
<td>2.2</td>
</tr>
<tr>
<td>Intermediate lateral on-axis</td>
<td>13</td>
<td>5.3</td>
</tr>
<tr>
<td>Intermediate off-axis</td>
<td>15</td>
<td>7.3</td>
</tr>
<tr>
<td>Ultralow</td>
<td>88</td>
<td>11</td>
</tr>
</tbody>
</table>

Fig. 9. Plagioclase crystal residence time averages and standard deviations as a function of spreading rate. Intermediate spreading rates slightly offset from each other for clarity. Note the systematic shift to longer residence times for off-axis lavas and fast lateral dike propagation. Transitions between ultralow, slow, intermediate, fast and superfast are approximate (e.g., Dick et al., 2003). There is at present no data available at slow and superfast spreading rates, which should be targeted by future studies. See text for discussion.
intermediate spreading centers. However, crystals show relatively simple zoning patterns similar to other samples erupted at intermediate spreading rates. The 1993 flow is more evolved (in terms of SiO$_2$, cf. Table 2) than the 1982–91 flow erupted adjacent to it, and has been associated with a laterally propagating dyke, which travelled over an unusually long distance (ca. 60 km), compared to typical lateral propagation distances at intermediate spreading ridges of 5–30 km (cf. Dzika et al., 2007). Growth zones of plagioclase crystals from the 1993 eruption in local equilibrium are not uncommon (cf. Fig. S3 of Zellmer et al., 2011a), and local disequilibria are typically less pronounced than in crystals from other JdF eruption products (Fig. 5). The simplest interpretation of these data in the context of the 1993 diking event would be plagioclase growth during prolonged along-axis magma transfer from the northern end of the Coaxial melt lens to the distal eruption site 60 km to the north, although we cannot preclude that some crystal growth began in a somewhat more differentiated edge region of the AMC.

8.3. Off-axis MOR samples

The off-axis samples studied here yield consistently longer average plagioclase residence times than samples recovered on-axis, by several weeks for the fast spreading EPR, and by several months for the intermediate spreading JdF ridge (Fig. 7). For the EPR, where plagioclase crystals are euhedral and show simple textures in both on- and off-axis samples, longer off-axis residence times are consistent with slower vertical transport of magma away from the axis as inferred from geochemical magma-vapour equilibrium considerations (le Roux et al., 2006). In contrast, the prominent and multiple resorption textures characterizing the plagioclase crystals of the JdF off-axis sample we studied (cf. Fig. 2f) are indicative of an extended growth history in an open system characterized by highly variable temperatures, e.g. due to repeated recharge heating. The key to understanding longer residence times of off-axis magmas lies in the identification of the source of these melts. At intermediate spreading rates, the occasional formation of relatively young pillow mounds and small mafic seamounts several kilometers away from the ridge has been attributed to the eruption of isolated, deep off-axis melt lenses such as those seismically imaged at a depth of 5 to 6 km several kilometers from the axis of the Cleft segment on the JdF Ridge (Canales et al., 2009). If mafic off-axis basalts, such as the Cleft seamount sample studied here, are indeed sourced from such lower crustal melt lenses, their longer plagioclase residence times are likely linked to significant crystal growth and residence within slowly cooling, thermally insulated, open-system off-axis reservoirs, rather than being solely attributable to slower melt ascent rates through a thicker crustal section away from the actively spreading part of the ridge.

8.4. MOR samples from ultraslow-spreading ridges

We have too few data to provide reliable insights into magma storage and ascent processes at slower spreading ridges, but our two data from sample D27-16 from the ultraslow-spreading Gakkel ridge both yield a residence time of about 1 year, following the overall trend to longer plagioclase residence times as spreading rate decreases. The large crystals of this sample have been interpreted to have formed by synnesis of plagioclase phenocrysts that grew within the conduit during melt ascent (Zellmer et al., 2011a). While it cannot be precluded that some of these crystals may have started to grow within a deep, short-lived, mafic AMC, their residence times clearly indicate that they are phenocrysts that formed several months prior to eruption, rather than xenocrysts sourced from decade to century old mafic zones. However, as is the case for slow spreading ridges, further work will be required on samples erupted at ultraslow spreading rates in order to elucidate the range of crystal growth processes operating in this setting.

8.5. Outstanding issues and future work

Fig. 9 serves well in showing the suggested dependence of plagioclase crystal residence time on spreading rate, while pointing out the importance of other parameters such as the effects of melt ascent through on- versus off-axis conduits, and great lateral melt injection distances that may prolong crystal residence times during melt transfer from the gabbroic zone to the site of eruption. However, the figure also clearly shows that a significant range of spreading rates in the slow and superfast regime have not yet been investigated, and that our knowledge of the processes controlling plagioclase growth and residence during magma transfer from source to surface is still quite preliminary. Future work will have to target on- and off-axis samples from slow and superfast spreading ridges to improve our understanding of magma ascent and crystallization processes at the global MOR system. One key issue will be sampling statistics: the present review has clearly shown the limitations of dealing with small sample sets. Future progress will likely depend on the availability of geospeedometric data from larger number of crystals and a greater set of MOR lavas. Finally, a larger number of samples will need to be studied to address potential relationships between flow morphologies (pillow, lobate, or sheet flows), which have been linked to effusion rates, and plagioclase crystal residence times, which typically reflect magma transfer times from source to surface, as we have argued here. A priori, rapid effusion rates would imply short transfer times, implying that sheet flows may yield the shortest residence times and pillow lavas the longest. However, our analysis has shown that this relationship is not as clear cut as one might think: although the Gakkel ridge sample and the off-axis flows studied in this paper are all pillow lavas, consistent with long magma transfer times, the EPR-on axis samples with the shortest residence times are lobate flows, not sheet flows, and the intermediate spreading JdF Cleft segment produces both pillow and sheet flows hosting crystals with essentially indistinguishable residence times. Clearly, local effusion rates are a function not only of magma ascent rate, but may be affected by other parameters, e.g. differences between conduit width at the site of eruption and at depth. Further work on morphologically well-characterized lavas will be required to further elucidate this issue.

9. Conclusions

• MOR basalts are typically aphyric to sparsely phryic, with about 60% of all samples having less than 5% crystals. This suggests that many MORB magmas traverse the lower crust as virtually crystal-free melts.

• Residence times of olivine and plagioclase phenocrysts and xenocrysts in their host basaltic melt have been reported in the literature and range from a few hours to several years. For the relatively large set of samples we studied, xenocrystic calcic plagioclase cores are small (typically <50 μm in size) or absent, suggesting that most MORB plagioclase crystals are phenocryst.

• Short plagioclase residence with a median age of less than 2 weeks in EPR samples erupted on-axis corroborates previous work, which suggested that plagioclase residence times decrease with increasing spreading rates. This is consistent with the bulk of plagioclase crystallization occurring during melt ascent from an AMC, the depth of which decreases with increasing spreading rates. In contrast, olivine phenocrysts may begin to grow (and fractionate) earlier, during pre-eruptive magma storage.

• Plagioclase crystals in the off-axis lavas we studied yield longer residence times than those in on-axis lavas from the same ridge segment. This is consistent with longer melt ascent timescales, but may also be due to some crystal growth occurring in deep, thermally buffered lower crustal melt lenses tapped by off-axis eruptions. Further work will be required to assess if these systematics are general features, or specific to the samples we investigated. Judging from similar plagioclase residence times in the two studied JdF Axial Seamount
lavas compared to most other on-axis lavas erupted at intermediate spreading centers, crustal magma ascent rates may be independent of the melt supply rate from the mantle. Again, additional samples need to be investigated to assess the reliability of this result, as it is unclear whether the samples investigated represent the full range of extant melt supply or storage conditions at this ridge segment.

- The range of plagioclase crystal residence times obtained from individual MORB samples highlights the need to study a relatively large number of crystals to obtain statistically reliable results on magma transfer timescales. In the future, even larger sets of samples from individual eruption sites will need to be studied to develop more robust conclusions.

- At present, our understanding of crystal growth and residence in MOR lavas is still quite limited, and further work will be required to extend our knowledge to the slow and superfast spreading regimes. Nevertheless, this contribution shows the great potential of geospeedometric dating in constraining some of the processes operating at the onset of MOR eruptive activity.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.lithos.2012.07.019.

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