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Deep roots for mid-ocean ridge volcanoes revealed by plagioclase-hosted melt inclusions

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The global mid-ocean ridge system is the most significant magmatic system on our planet and is the site of 75% of Earth volcanism¹. The vertical extent of mid-ocean ridge magmatic systems has been considered to be restricted: even at the ultraslow-spreading Gakkel Ridge, where the lithosphere is thickest, crystallisation depths of magmas feeding eruptions are thought to be <9 km². These depths have been determined using the volatile contents of melt inclusions, small volumes of melt that become trapped within crystallising minerals. In studies of basaltic magmatic systems, olivine is the mineral of choice for this approach^{2–6}. However, pressures derived from olivine-hosted melt inclusions are at odds with pressures derived from basalt major element barometers⁷ and geophysical measurements of the lithospheric thickness⁸. Here, we present a comparative study of olivine- and plagioclase-hosted melt inclusions from the ultraslow-spreading Gakkel mid-ocean ridge (Arctic Ocean). We show that the volatile contents of (complexly zoned) plagioclase-hosted melt inclusions correspond to significantly higher crystallisation pressures (mean 270 MPa) than (simply zoned) olivine-hosted melt inclusions (mean 145 MPa). The higher pressures are more consistent with both the thickness of the Gakkel Ridge lithosphere and pressures reconstructed from glass compositions. Contrary to

previous studies using olivine-hosted melt inclusions, our results demonstrate that mid-ocean ridge volcanoes may have magmatic roots deep in the lithospheric mantle, at least at ultraslow spreading rates.

Direct constraints on the depth of crystallisation beneath mid-ocean ridge volcanoes, the most productive magmatic system on Earth, come from melt inclusions^{2–7}. Crystallisation pressures determined from melt inclusion volatile contents typically correspond to the depth of seismically imaged melt lenses⁵ and reveal that much of the crystallisation is restricted to crustal depths^{4–6} (nominally 6 km), with limited crystallisation up to 9.9 km⁶. These pressure suggest that mid-ocean ridge volcanoes have shallow magmatic roots that are largely restricted to the lower oceanic crust, with limited sourcing of eruptions from the lithospheric mantle^{5,6,9–11}. However, lithospheric thickness⁸ and crystallisation pressures determined from basalt major element barometers⁷ are greater than that suggested by olivine-hosted melt inclusions, particularly at ultraslow-spreading ridges. A case in point is the Gakkel Ridge, where melt inclusion vapour saturation pressures (40–309 MPa or 0–9 km below seafloor^{2,3}) are substantially less than the proposed lithospheric thickness (≤ 30 km⁸) and petrological estimates of crystallisation pressures from basalt major elements (≤ 600 MPa or ~ 20 km)⁷. These contradictory records raise the question as to whether, using current constraints, we can confidently constrain the true vertical extent of mid-ocean ridge magmatic systems.

Melt inclusions are key tools to address this issue. Whilst major element systematics of basalts may also be used to constrain crystallisation pressures, the values essentially integrate what is essentially a polybaric crystallisation path. Furthermore, these pressures are based on the assumption that no melt-crystal reactions occur in the magmatic plumbing system – a process for which there is abundant evidence¹². Basalt compositions, therefore, are unlikely to record unique depths. In contrast, melt inclusions have the potential to record an accurate, fine-scale, polybaric pressure record if they are trapped within host minerals at

different depths during melt transport through the magmatic plumbing system. Olivine-hosted melt inclusions are often preferred because: (1) olivine is a primitive, early-formed mineral¹³, and hence should, in principle, track the earliest stages of magmatic differentiation; and (2) olivine is viewed as a tighter “vessel” compared to plagioclase, which possesses cleavage planes along which volatiles may escape^{14,15}. However, the low vapour saturation pressures recorded by olivine-hosted melt inclusions, not only from mid-ocean ridges, but also from a range of low-H₂O basaltic settings including ocean islands, continental rifts and arcs, poses a significant question as to their ability to capture the full depth range of the magmatic plumbing systems from which they are sourced¹⁶.

Here, we suggest that plagioclase may preserve a more complete record of crystallisation pressures than olivine. For example, plagioclase crystals typically show more complex compositional zoning and variable crystal habits than olivine. Whilst slower major element diffusion in plagioclase¹⁷ compared to that in olivine¹⁸ may account for the zoning, the sheer variety of zoning patterns raises the possibility that plagioclase may preserve a more extensive part of the crystallisation history than olivine. Furthermore, plagioclase is frequently more abundant in volcanic rocks (including mid-ocean ridge basalts) compared to olivine^{19,20}. Hence, if plagioclase-hosted melt inclusions prove to provide a reliable record of pressures, this would improve reconstructions of magmatic plumbing systems.

We have combined detailed textural analysis of host olivine and plagioclase crystals with measurements of the volatile (H₂O and CO₂) contents of 30 olivine-hosted and 75 plagioclase-hosted melt inclusions from the Gakkel Ridge to compare their respective records of crystallisation. The 15 samples studied were retrieved from nine locations that cover the full extent of the Gakkel Ridge (Extended Data Fig. 1). These data are supplemented by trace element data on 93 melt inclusions, and by existing data from olivine-hosted melt inclusions from this region^{2,3}.

The contrasting textural complexity of olivine and plagioclase is illustrated in figures 1 and Extended Data Fig. 2. Whilst both phases exhibit a range of crystal habits (Fig.1), plagioclase shows more evidence of resorption (Fig.1a compared to d,f,h,i) and more complex zoning, although both phases may also lack zoning (Fig. 1b,c and h). Zoning patterns in plagioclase include, but are not restricted to, reverse zoning (Fig. 1e,g), concentric zoning punctuated by undulose resorption interfaces (Fig. 1f) and complex combinations of patchy and concentric zoning (Fig. 1i). Complex zoning patterns (Fig. 1d,e,f,i), and large amoeboid melt inclusions interpreted as the product of resorption (Fig. 1h,i), indicate that plagioclase crystals have experienced protracted growth ($\pm$ resorption) histories within open magmatic systems.

Olivine-hosted melt inclusions are found in host crystals with both skeletal (37%; Fig.1 b) and non-skeletal morphologies (63%; Fig. 1c). In euhedral and subhedral olivine, inclusions are randomly distributed (Fig. 1c) whilst those in skeletal olivine are found in hour-glass arrangements or located close to the host margins (Fig. 1b). The inclusions in olivine are not associated with observable zonation, although whilst not mapped, trace elements (i.e., P) may preserve zoning²¹. Melt inclusions in plagioclase may be randomly distributed throughout the host crystal (Fig. 1h,i), restricted to cores (Fig. 1g), or associated with resorption interfaces (Fig. 1f); only 4% are directly associated with resorption interfaces.

The Gakkel Ridge volatile data are presented in Figure 2, along with other olivine-hosted melt inclusion data for which saturation pressures have been calculated. H₂O concentrations of both olivine- and plagioclase-hosted melt inclusions are similar and range from 0.12-0.56 wt.% H₂O. However, plagioclase-hosted melt inclusions record a larger range of CO₂ (282-2857 ppm) than olivine-hosted melt inclusions (94-1984 ppm). Furthermore, plagioclase-hosted melt inclusions have significantly higher median CO₂ contents (1668 ppm) compared to olivine-hosted melt inclusions (637 ppm). There is no correlation between melt inclusion size or location and CO₂ content (Extended Data Fig. 3 and Supplementary Fig. 2b

respectively). Two lines of evidence indicate that the Gakkel melt inclusions, including the CO₂-rich plagioclase-hosted inclusions, are CO₂ saturated (see Supplementary discussion). First, inclusions define a positive Mg#-CO₂ correlation (Supplementary Fig. 2) indicative of concomitant crystallisation and degassing. Second, whilst the maximum CO₂/Ba ratio of 145 is consistent with the proposed CO₂/Ba ratio of the mantle (~140; ref. 22), the remaining inclusions have lower ratios consistent with variable degrees of degassing (Supplementary Fig. 1).

The CO₂ record of Gakkel plagioclase-hosted melt inclusions is unlike that of olivine from either the Gakkel Ridge or from mid-ocean ridges elsewhere, being offset to higher values (Fig. 2). The volatile contents of Gakkel Ridge melt inclusions correspond to entrapment pressures of ≤ 506 MPa (equivalent to 16.4 km below the seafloor) and ≤ 340 MPa (10.6 km) for plagioclase- and olivine- hosted melt inclusions respectively. In olivine, entrapment pressures correlate with host crystal morphology (Fig. 3), such that inclusions hosted within skeletal crystals (Fig. 1a) have lower CO₂ contents (<1000 ppm), and correspondingly lower pressures (<~145 MPa , or <3.6 km below the seafloor) than non-skeletal olivines, which preserve a range in entrapment pressures of 49-340 MPa (0.2-10.6 km below the seafloor).

For direct comparison, we examine data from three locations along the Gakkel Ridge where both olivine- and plagioclase-hosted melt inclusions have been analysed (31°E Basement Ridge, 18°50' E Basement Ridge and 3°E Seamounts, Extended Data Fig. 1; Fig. 4a-c). The data show a systematic offset in pressures, such that mean pressures are 215, 242 and 54 MPa higher in plagioclase-hosted melt inclusions than those recorded by olivine-hosted melt inclusions at the same location. This translates into mean depths of crystallisation that are 7, 9 and 2 km higher in plagioclase-hosted melt inclusions compared to olivine-hosted melt inclusions, with only limited overlap between the two records. Critically, the difference between the melt inclusion pressures in the two phases is present in the dataset as a whole

(Fig. 2 and Fig. 4e), in particular locations (Fig. 4a-c), and within individual samples (Fig. 4d and Extended Data Fig. 4); from this we conclude that the volatile contents are not reflecting specific ascent and quenching conditions. Instead we suggest they reflect a fundamental difference in the pressure record of olivine- and plagioclase-hosted melt inclusions, with olivine being biased towards low pressures. There are three potential explanations for this difference. First, the entrapment pressures may be geologically significant and record crystallisation conditions within the magmatic system. Alternatively, the olivine data may be compromised by either decrepitation^{16,23} or volatile loss into bubbles^{24,25}.

First, we examine the possibility of secondary volatile loss. If olivine and plagioclase are, respectively, tight and leaky vessels, one might expect olivine-hosted inclusions to record higher CO₂ contents, and in turn greater entrapment pressures, than plagioclase. However, Figures 2 and 4 demonstrate the opposite. Loss of CO₂ by decrepitation, or breaking of inclusions, is the more common explanation, and has been used to explain why 95% of olivine-hosted melt inclusions from a range of low-H₂O basaltic settings record similar, low entrapment pressures (≤ 200 MPa)¹⁶. Whilst this might explain the shallow pressures recorded by olivine-hosted melt inclusions, we see no physical evidence of decrepitation (e.g., melt filled fractures²⁶ and melt inclusion halos around larger melt inclusions²⁷). Finally, CO₂ may be sequestered into bubbles^{24,25} formed as result of post-entrapment crystallisation²⁸ or thermal contraction of the melt inclusion²³. Either case would make the pressure estimates minima, as demonstrated in Figure 4b, which shows that the only analysed bubble-bearing plagioclase-hosted melt inclusion yields significantly lower pressures (88 MPa) than the remainder of inclusions in that host plagioclase (339-391 MPa). Similarly, the only analysed bubble-bearing olivine-hosted melt inclusion records slightly lower pressure (~52 MPa) than an inclusion in the same host with no visible bubble (~57 MPa; Fig. 1b). These observations, along with the absence of observed bubbles in most measured melt inclusions, suggests that bubble formation does not control the melt

inclusion pressure record. We conclude, therefore, that the lack of physical evidence of either decrepitation or bubbles, in combination with the preservation of high crystallisation pressures in plagioclase-hosted melt inclusions despite the assumed “leaky” nature of plagioclase, is inconsistent with a secondary cause for the difference in pressure between olivine- and plagioclase-hosted melt inclusions.

Observations of the host crystals suggest that the data are recording geologic processes. Firstly, complex zoning patterns and abundant evidence of resorption in plagioclase attests to protracted growth histories within an open magmatic system. Whilst similar textures in the olivine hosts may have been erased by fast major element diffusion¹⁸, the observation remains that there is a correlation between textural complexity and crystallisation pressures. In fact 58% of olivine crystals hosting melt inclusions with <1000 ppm CO₂ have skeletal morphologies and record shallower mean crystallisation pressures (72 MPa) compared to host crystals with non-skeletal morphologies (178 MPa). This suggests that skeletal olivines formed in the shallow portion of the plumbing system, consistent with their inferred origin via rapid, late-stage growth. Interestingly, the olivine crystal with the highest melt inclusion crystallisation pressure (340 MPa; 10.6 km) forms part of a poly-mineralic glomerocryst (i.e., a crystal aggregate comprising more than one crystal phase) that also contains complexly zoned plagioclase crystals (Extended Data Fig. 5).

The volatile data can be reconciled in a model where olivine and plagioclase experience different crystallisation histories, with plagioclase capturing multi-stage processes in a deep-seated crystal mush, and olivine forming predominantly during late stage crystallisation in shallower portions of the plumbing system. Whilst phase relationships show that olivine is the first phase to crystallise from mid-ocean ridge basalts, and therefore should record crystallisation at elevated pressures, the high density of olivine (3.2 gcm⁻³) compared to that of plagioclase (~2.7 gcm⁻³) and basaltic melt (~2.6 gcm⁻³) may prevent its eruption from

deeper within the plumbing system. This would account for the sparsity of olivine-hosted melt inclusions that record pressures as high as those recorded by plagioclase-hosted melt inclusions. The poly-mineralic glomerocryst of high-pressure olivine intergrown with complexly zoned, resorbed plagioclase (Extended Data Fig. 5) provides a direct snapshot of this olivine-plagioclase mush. Moreover, plagioclase crystallisation at depths as shallow as olivine is absent in the melt inclusion dataset at two of the three locations (Fig. 4a,b). We suggest that this may reflect an absence of analysable melt inclusions in plagioclase that crystallised shallowly. Indeed, whilst skeletal plagioclase in samples from both locations may represent shallow level crystallisation analogous to that recorded by skeletal olivine, these crystals do not contain analysable melt inclusions, as inclusions are either absent, too small or microcrystalline. Thus, textural observations of olivine and plagioclase host crystals suggest that the disparity between recorded crystallisation pressures is primary.

Our data provide important insights into the physical nature of magmatic systems at mid-ocean ridges and reveal, contrary to current constraints, that magmatic roots are vertically extensive, at least at ultraslow-spreading ridges. More specifically, the Gakkel Ridge magmatic system extends from the seafloor to at least 16.4 km. Moreover, the depth distribution revealed by plagioclase-hosted inclusions (Fig. 4) places most crystallisation in the lithospheric mantle. Finally, we have demonstrated that plagioclase-hosted melt inclusions preserve reliable vapour saturation pressures, and that plagioclase provides a comprehensive record of the deeper levels of crystallisation in magmatic systems. In contrast, olivine captures predominantly shallower levels. Hence, combined studies of olivine- and plagioclase-hosted melt inclusions will enable significantly improved reconstructions of the true extent of magma plumbing systems.

Methods

Melt inclusions volatile analysis. Melt inclusion CO_2 , H_2O , K_2O and B contents were measured using the Cameca IMS4f ion microprobe at the Edinburgh Ion Microprobe Facility.

A ~ 5 nA $^{16}\text{O}^-$ primary beam with a 14.5 kV impact energy beam was used. Melt inclusions were analysed for CO_2 first in a separate measurement before H_2O and other elements, with CO_2 measured at high mass resolution ($M/\Delta M = 1200$) sufficient to avoid interference between $^{24}\text{Mg}^{2+}$ and $^{12}\text{C}^+$. Energy filtering of the secondary ions was applied, using offsets of 75 eV and 50 eV for H_2O and CO_2 , respectively, using a 50 eV energy window. Image fields of 25 μm and 50 μm and field apertures with effective diameters of 8 μm and 16 μm were used during H_2O and CO_2 analysis, respectively. Prior to each measurement the beam was aligned relative to the centre of the field aperture. H_2O and CO_2 target locations were rastered for 2 and 4 minutes prior to each analysis using analysis beam conditions to remove surface contamination; during this time peak mass positions were centred. Each analysis ran for 4 minutes following rastering. For H_2O and CO_2 measurements, counts were normalised to ^{30}Si and corrected for known SiO_2 content of the samples, except $^1\text{H}/^{30}\text{Si}$ as this has been shown to have a matrix effect proportional to the material's SiO_2 content. The analyses were calibrated against a set of basaltic glass standards of known CO_2 (0-2183 ppm) and H_2O (0.00-3.07 wt.%) contents²⁹. Instrumental blank measurements for H_2O and CO_2 were made on plagioclase in each mount and subtracted from the raw count rates: targets in 12 mounts were analysed. Uncertainty and accuracy of SIMS analysis can be found in Supplementary Table 1 and Extended Data Fig. 6 respectively. Raw volatile element data are present in Supplementary Table 2.

Melt inclusion and host crystal major element analysis. Following ion microprobe analysis, melt inclusions and their host crystals were analysed using Cardiff's Zeiss Sigma HD field emission gun SEM, which is equipped with two 150mm² Oxford Instruments X-MaxN silicon drift EDS detectors. A 1 nA beam current, 20.0 kV accelerating voltage, fixed working distance of 8.9 mm and 60 nm aperture were used. EDS spectra were acquired over 20s live time using both detectors with an output count rate of ~ 136 kcps. A defocused beam rastering over 5-10 μm^2 areas was used to minimise Na loss in both plagioclase and melt inclusions. Oxford Instruments Aztec Software was used to process and quantify raw

data using the internal XPP matrix correction. A total of 31 olivine-hosted and 75 plagioclase-hosted melt inclusions and their hosts were analysed. Host An and Fo content and glass major element compositions are reported in Supplementary Table 2. All analysed melt inclusions were $\geq 20\mu\text{m}$ in diameter and glassy. A comprehensive suite of standards were used to calibrate EDS analysis of all mineral phases and glass. Supplementary Tables 3 and 4 report the precision and accuracy of glass and mineral secondary standard measurements. Back-scattered electron images of each inclusion and host crystal were acquired to assess whether inclusions showed signs of crystallisation and if hosts showed evidence of compositional zoning.

Melt inclusion corrections. The major and volatile element compositions of both olivine- and plagioclase-hosted melt inclusions were corrected for the effects of post-entrapment crystallisation (PEC). Raw and corrected melt inclusion compositions (major and volatile elements) are reported in Supplementary Table 2. Olivine compositions were corrected by iteratively adding equilibrium olivine back into the melt until the melt and host olivine were in equilibrium with one another³⁰. This assumed an equilibrium Fe-Mg distribution coefficient (K_D) of 0.3 and $\text{Fe}^{3+}/\Sigma\text{Fe}$ of 0.1³¹. Olivine PEC corrections range from 2-22% (median 13.0%) (Supplementary Table 2). To date there is no widely accepted method of correcting PEC in plagioclase-hosted melt inclusions. Previously, PEC corrections have been undertaken by adding plagioclase (equilibrium plagioclase or host plagioclase) to the melt inclusion until its $\text{MgO-Al}_2\text{O}_3$ ¹⁵ or $\text{TiO}_2\text{-Al}_2\text{O}_3$ ³² systematics are consistent with regressions through Icelandic glass arrays. However, these corrections are unconstrained in that the melt inclusion compositions can move in both MgO or TiO_2 and Al_2O_3 space toward these regressions. Here we employed an empirical correction which assumes that during plagioclase crystallisation, Al_2O_3 is the most modified melt component, whilst $\text{Mg\#}$ remains unchanged because both Mg and Fe are incompatible in plagioclase. Plagioclase was therefore added to the melt inclusion composition until the melt inclusions met the Al_2O_3 content (at a given

Mg#) of the combined Gakkel glass^{33,34} (see Extended Data Fig. 7 caption) and olivine-hosted melt inclusions^{2,3} datasets. In practice we created a pseudo-liquid line of decent (see Extended Data Fig. 7 caption for details) and then iteratively added host plagioclase compositions to the melt inclusions until this liquid line of decent was intersected. Plagioclase-hosted melt inclusion PEC corrections ranged from 0-41.5% (median 14.8%) (Supplementary Table 2). This approach has two benefits over previous approaches: (1) Mg# does not change during the correction and therefore the melt inclusion composition only changes vertically in Al_2O_3 space; and (2) the addition of the line drawn through the olivine-hosted melt inclusion data to create the pseudo-liquid line of decent prevents corrections that would result in melt inclusion compositions with unrealistically high Al_2O_3 contents compared to the Gakkel glass and olivine-hosted melt inclusion arrays. To test the effect of the choice of pseudo-liquid line of decent, a second pseudo-liquid line of decent passing through the olivine-hosted melt inclusion data was used for a second correction; new PEC corrections range from 0-37.5% (median 11.5%). It can be seen from Extended Data Fig.9d that pressures calculated from this second PEC correction show negligible change from those calculated following the first PEC correction. There is no correlation between the percentage correction and calculated depth of crystallisation (Extended Data Fig. 8).

Saturation pressure calculation and depth conversion. Following correction for post-entrapment crystallisation (PEC) of major and volatile elements, vapour saturation pressures were calculated using MagmaSat³⁵. Melt inclusions with visible bubbles were avoided, however, because polished blocks were used during ion microprobe analysis, the presence or absence of vapour bubbles deeper inside the inclusions could not be determined. Because these vapour bubbles may sequester CO_2 ^{24,25}, pressures determined from melt inclusions here are minima. Pressures were converted to crystallisation depths accounting for the pressure of the overlying water and crust, assuming a crustal density of 2.9 g/cm^3 .

Saturation (i.e., entrapment) pressures recorded by olivine-hosted melt inclusions from mid-ocean ridge have to date been determined almost exclusively using VolatileCalc³⁶. This is a mixed H₂O-CO₂ solubility model based on parameterisations of Dixon³⁷. This model uses melt temperature and, SiO₂, CO₂ and H₂O content of the melt to calculate the saturation pressure. However, this model only allows SiO₂ contents between 40-49 wt.% SiO₂ and thus does not account for compositional variability present at a given SiO₂ content. MagmaSat³³, a thermodynamic mixed CO₂-H₂O model, is calibrated for H₂O and CO₂ solubility and mixed fluid saturation in silicate melts. A benefit of this model is that it accounts for the effects of melt composition on H₂O-CO₂ solubility. When pressures are calculated with VolatileCalc using the SiO₂ specific to that inclusion, pressures are lower than with the default 49 wt.% because CO₂ solubility increases with reduced SiO₂³⁸ (Extended Data Fig. 9).

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Author contributions

E.N.B. and C.J.L. conceived of the study. E.N.B. collected all data, except melt inclusion trace element data collected by F.E.J.. E.N.B. wrote the manuscript under supervision of C.J.L. K.V.C. and M-A.A. contributed to critical discussions and commented on the manuscript.

Competing interests. The authors declare no competing interests.

Materials & Correspondence. Correspondence to E.N.B.

Data availability. All data supporting the findings of this study are available within the paper and supplementary information.

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Figure 1
complexity of olivine and plagioclase and melt inclusion distribution and associations. Backscattered electron images of olivine (a-c) and plagioclase (d-i). Scale bars are 100 μm (b,c,f,g) and 250 μm (a,d,e,h,i). Small numbers show the locations of analysed melt inclusions; numbers correspond to highlighted analyses in Supplementary Table 2.

Textural

Figure 2 **Volatile contents of Gakkel Ridge olivine- and plagioclase-hosted melt inclusions.** CO₂ versus H₂O for Gakkel Ridge plagioclase- (circles) and olivine- (diamonds) hosted melt inclusions. Black outlined points are from this study; those from 85°Seamount are from ref. 2, points with no outlines are from ref. 3. Grey fields include the following data: Lucky Strike volcano on the Mid-Atlantic Ridge (MAR)⁶; Galapagos Spreading Centre (GSC)⁴; Juan de Fuca Ridge (JDF) and East Pacific Rise (EPR)⁵. Comparative datasets have all used volatiles to investigate crystallisation pressures and are from on-axis locations.

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Figure 3: **Crystallisation depth and pressures recorded in olivine.** Histogram showing the difference in the distribution of crystallisation depths recorded in skeletal (green) and non-skeletal (blue) olivine. The one bubble-bearing melt inclusion analysed plots at 0 km. Pressures correspond to the pressure below the seafloor.

499 Figure 4: **Comparison of crystallisation depths recorded in melt inclusions.** Histograms
500 showing the distribution of crystallisation depths recorded in olivine- and plagioclase-hosted
501 melt inclusions at three locations along the Gakkel Ridge (31°E Basement Ridge, **a**; 18°50'
502 Basement Ridge, **b**; and 3°E Seamounts, **c**). **d** Comparison of pressures recorded by
503 olivine- and plagioclase-hosted melt inclusions in a single sample (HLY0102-D48-SG) from
504 31°E Basement Ridge; olivine data here are from ref. 3. All data are compared in **d**.
505 Pressures correspond to the pressure below the seafloor.