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Heterogeneously entrapped, vapor-rich melt inclusions record pre-eruptive magmatic volatile contents

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22   **ABSTRACT**

23   Silicate melt inclusions (MI) commonly provide the best record of pre-eruptive H_2O and CO_2

24   contents of subvolcanic melts, but the concentrations of CO_2 and H_2O in the melt (glass) phase

25   within MI can be modified by partitioning into a vapor bubble after trapping. Melt inclusions

26   may also enclose vapor bubbles together with the melt (i.e., heterogeneous entrapment), affecting

27   the bulk volatile composition of the MI, and its post-entrapment evolution. Here, we use

28   numerical modeling to examine the systematics of post-entrapment volatile evolution within MI

29   containing various proportions of trapped vapor from zero to 95 volume percent. Modeling

30   indicates that inclusions that trap only a vapor-saturated melt exhibit significant decrease in CO_2

31   and moderate increase in H_2O concentrations in the melt upon nucleation and growth of a vapor

32   bubble. In contrast, inclusions that trap melt plus vapor exhibit subdued CO_2 depletion at

33   equivalent conditions. In the extreme case of inclusions that trap mostly the vapor phase (i.e.,

34   CO_2-H_2O fluid inclusions containing trapped melt), degassing of CO_2 from the melt is negligible.

35   In the latter scenario, the large fraction of vapor enclosed in the MI during trapping essentially

36   serves as a buffer, preventing post-entrapment modification of volatile concentrations in the

37   melt. Hence, the glass phase within such heterogeneously entrapped, vapor-rich MI records the

38   volatile concentrations of the melt at the time of trapping. These numerical modeling results

39   suggest that heterogeneously entrapped MI containing large vapor bubbles represent amenable

40   samples for constraining pre-eruptive volatile concentrations of subvolcanic melts.

41   *Keywords:* silicate melt; melt inclusions; fluid inclusions; vapor bubbles; H_2O; CO_2; degassing

42

1. INTRODUCTION

Silicate melt inclusions (MI) are aliquots of melt trapped within crystals during crystal growth or fracture healing (Lowenstern 1995; Lowenstern 2003; Bodnar and Student 2006; Cannatelli et al. 2016), although Lowenstern (1995) noted that trapping secondary MI in volcanic phenocrysts may be unlikely owing to the viscosity of silicate melts. As such, MI represent samples of the melt during various stages of fractionation in an evolving magmatic system, providing a record of igneous processes which may be otherwise inaccessible. The evolution of dissolved volatiles (e.g., CO_2, H_2O, Cl, S, etc.) in the melt is one such process. Crystal-hosted melt inclusions in volcanic rocks can be analyzed to constrain the concentrations of volatile components dissolved in the melt prior to volcanic eruption and/or degassing. If the melt reached saturation with a magmatic fluid or vapor phase prior to eruption, then measured volatile concentrations can be interpreted according to solubility models (e.g., Holloway and Blank 1994; Newman and Lowenstern 2002; Papale et al. 2006; Shishkina et al., 2014) to constrain depths of magma emplacement as well as progressive degassing of an initially CO_2-enriched melt during ascent (Lowenstern 1994; Métrich and Wallace 2008).

Apparently coeval melt inclusions commonly record wide ranges of CO_2 concentrations in the glass phase (Esposito et al. 2014). Variation in volatile concentrations of MI glasses can be induced independently of magma degassing, as a result of several potential post-entrapment processes. Firstly, volatile concentrations in the melt in an inclusion can be modified by diffusive re-equilibration with the exterior carrier melt (Qin et al. 1992; Danyushevsky et al. 2000; Portnyagin et al. 2008; Mironov and Portnyagin 2011; Gaetani et al. 2012; Bucholz et al. 2013; Mironov et al. 2015; Hartley et al. 2015). This process can occur on timescales of days to hours in some cases. Secondly, volatile components within MI can be partitioned between the melt and

66   a vapor phase (bubble) subsequent to trapping (Anderson and Brown 1993; Steele-MacInnis et

67   al. 2011; Hartley et al. 2014; Moore et al. 2015; Wallace et al. 2015; Tuohy et al. 2016; Aster et

68   al. 2016). A vapor phase within an initially homogeneous melt inclusion may nucleate and grow

69   after trapping as a result of differential thermal contraction of melt versus the host crystal

70   (Lowenstern 2003; Moore et al. 2015), by post-entrapment crystallization (PEC; Steele-MacInnis

71   et al. 2011) of the host mineral on the inclusion walls, or a combination of these processes. In all

72   three scenarios, nucleation and growth of the vapor bubble results in strong depletion of CO_2

73   from the melt phase with concomitant minor variation in the H_2O concentration. The divergent

74   trends in CO_2 versus H_2O concentration in the melt are a consequence of the extremely different

75   CO_2/H_2O ratios in the melt versus the exsolving fluid phase: In general, the CO_2/H_2O ratio in the

76   exsolving vapor is significantly greater than that in the coexisting melt (i.e., CO_2-rich vapor

77   exsolved from a melt which is generally more enriched in H_2O), and as such the exsolution of the

78   vapor phase drives the CO_2/H_2O ratio of the melt to lower values. Thus, several studies have

79   used Raman spectroscopy to determine the amount of CO_2 exsolved into the bubble to constrain

80   the bulk CO_2 content of the inclusion (e.g., Esposito et al. 2011; Moore et al. 2015; Hartley et al.

81   2014; Tuohy et al. 2016). The H_2O in the vapor bubble has not generally been detected during

82   Raman spectroscopic analysis of MI vapor bubbles, but has recently been detected as a rim of

83   H_2O-rich liquid at the glass/bubble interface in re-heated MI (Esposito et al. 2016). Like the case

84   for CO_2, Esposito et al. (2016) suggested that depending on the initial conditions, most of the

85   H_2O and of the S of the originally trapped melt may be stored in the bubble.

86   Heterogeneous entrapment represents an alternative origin for the vapor bubbles in some

87   MI. In this scenario, the host phenocryst encloses a multi-phase assemblage of vapor-saturated

88   melt plus vapor. Evidence for heterogeneous entrapment of melt plus magmatic fluid has been

89   reported in several studies. For example, Harris et al. (2003), Zajacz et al. (2008) and Stefanova

90   et al. (2014) described MI from high-temperature porphyry veins, containing globules of high-

91   density, high-salinity brine. In these studies, the brine globules are interpreted as trapped

92   hydrothermal fluid, which presumably exsolved from the silicate melt prior to trapping of the

93   melt inclusions. Bodnar and Student (2006) noted that in the case of heterogeneous entrapment,

94   the volume fraction of vapor would likely be variable for groups of coevally entrapped MI (or

95   melt inclusion assemblages; MIA). Moore et al. (2015) developed a numerical model to estimate

96   the maximum volume fraction of vapor expected as a result of differential thermal contraction

97   for MI hosted in various minerals, and concluded that in general, vapor bubbles of up to a few

98   percent of the MI volume are consistent with bubble nucleation and growth by this mechanism.

99   As such, vapor bubbles exceeding a few volume percent of the MI may represent trapped vapor

100   (Fig. 1). Aster et al. (2016) similarly used a numerical model to estimate the maximum volume

101   fraction of vapor expected purely from cooling, PEC and quenching of initially homogeneous

102   trapped melt, and used this information to infer which MI appeared to have trapped some portion

103   of vapor. Hartley et al. (2014) and Moore et al. (2015) reported melt inclusions containing

104   exceptionally large vapor bubbles up to several tens of volume percent, suggesting that these MI

105   trapped melt plus vapor. In the most extreme example reported by Hartley et al. (2014) and

106   Moore et al. (2015), the MI vapor bubble represented >90 vol.% of the inclusion; as such, the

107   most vapor-rich MI approach the limiting case of magmatic CO_2-H_2O fluid inclusions containing

108   a small proportion of trapped melt, similar to clinopyroxene-hosted fluid inclusions reported for

109   example by Belkin et al. (1985) and Belkin and De Vivo (1993); and olivine-hosted fluid

110   inclusions by Mironov and Portnyagin (2011), Zanon and Frezzotti (2013), and Zanon and

111   Pimentel (2015). Note, however, that H^+ diffusion out of the MI may also promote formation of

112 anomalously large vapor bubbles (Bucholz et al., 2013; Aster et al. 2016), which is not

113 considered in the present study. In addition, decrepitation and/or leakage of MI may also

114 contribute to forming anomalously large bubbles, as discussed below.

115   The occurrence of MI containing a heterogeneously trapped vapor phase raises questions

116 as to the systematics of melt-vapor partitioning within inclusions that trapped both melt and

117 vapor. Conceptually, coeval melt inclusions and fluid inclusions are expected to follow different

118 temperature-pressure trajectories subsequent to trapping (Fig. 2). The pressure-temperature

119 trajectory followed by a vapor-saturated silicate melt inclusion is a function of compressibility

120 and expansivity of melt and vapor, the vapor solubility relations, and the evolution of PEC

121 (Student and Bodnar 1996; Steele-MacInnis et al. 2011; Schiavi et al. 2016). In contrast, the

122 temperature-pressure trajectory for CO_2-H_2O fluid inclusions is constrained by the isochore

123 (pressure-temperature locus of constant density) of the CO_2-H_2O fluid phase (Sterner and

124 Bodnar, 1991; Diamond, 2003) according to the composition and bulk density of the fluid. For

125 example, Mironov and Portnyagin (2011) estimated the trapping temperature and pressure

126 conditions of coeval melt and fluid inclusions hosted in olivine by intersecting the temperature

127 estimated from MI with the isochores of the coeval CO_2-H_2O fluid inclusions. As such, the

128 temperature-pressure trajectory followed by heterogeneously entrapped, vapor-rich MI is

129 expected to vary between these two endmembers according to the proportion of trapped vapor

130 (Fig. 2). Moreover, the temperature-pressure trajectory of the MI is expected to tend towards the

131 coeval fluid-inclusion isochore at high proportions of trapped vapor. Steele-MacInnis et al.

132 (2011) reported that evolution of CO_2 and H_2O concentrations in the melt (glass) within MI is

133 correlated to the pressure-temperature trajectory followed by the MI after trapping. Hence, we

134 expect that the volatile systematics of heterogeneously entrapped MI will also vary according to

135   the proportion of trapped vapor. Stated differently, the partitioning of volatile components

136   between melt and vapor is sensitive to the relative proportions of phases trapped. Thus,

137   interpreting volatile contents of MI glass, bubble, and bulk inclusion can be complicated by

138   heterogeneous entrapment.

139   In this study, we build upon the earlier thermodynamic modeling of Steele-MacInnis et

140   al. (2011) to characterize volatile evolution of MI melt (glass) and vapor during post-entrapment

141   crystallization of heterogeneously entrapped MI. Steele-MacInnis et al. (2011) focused on MI

142   that trapped only vapor-saturated melt (without trapped vapor), and reported contrasting behavior

143   of CO_2-rich versus H_2O-rich melts and intermediate CO_2-H_2O-saturated melts. Here, we extend

144   these results to heterogeneously entrapped inclusions, including end-member scenarios of

145   homogeneously entrapped melt or vapor, and several intermediate scenarios with various relative

146   proportions of trapped melt and vapor. In the present contribution, we do not include the effects

147   of diffusive re-equilibration, nor the effects of bubble expansion during syn-eruptive cooling and

148   quenching, although we recognize that these effects may be significant for many natural MI and

149   that future studies incorporating them will be necessary. As such, the present contribution

150   represents one endmember of the various complexities that can manifest in MI volatile

151   systematics. The results of this analysis indicate that for inclusions that trap a large proportion of

152   vapor, the H_2O and CO_2 concentrations in the melt (glass) phase within the inclusion are

153   relatively insensitive to post-entrapment crystallization. These results thus suggest that

154   heterogeneously entrapped MI may represent amenable samples for characterizing pre-eruptive

155   dissolved volatile contents of melts.

156

157   **2. METHODS**

158   The methods used here were mostly described in detail by Steele-MacInnis et al. (2011),

159   so here we provide only an abridged overview (see Steele-MacInnis et al., 2011 for additional

160   details). We modeled the effects of volatile exsolution during post-entrapment crystallization of

161   an albitic ($NaAlSi_3O_8$) melt trapped in albite using constant volume (isochoric), constant

162   composition (closed) boundary conditions. The albitic model was used primarily because this

163   system represents a relatively simple endmember, and because the parameterization is very well

164   constrained. In addition, we extended this model to basaltic melts trapped in olivine, because the

165   latter system is one of the most widely studied in terms of natural MI and information relative to

166   bubble and MI are available from the literature (e.g., Hartley et al. 2014; Moore et al., 2015). The

167   methods used in this modeling are described below.

168   For the albitic melt, solubilities of H_2O and CO_2 in the melt were calculated according to

169   the models described by Holloway and Blank (1994). Volumetric properties of albitic melt and

170   albite were calculated using the model of Burnham and Davis (1971; 1974). To initiate the

171   model, the composition of vapor-saturated melt in equilibrium with albite was calculated, which

172   defined the composition of the initial melt aliquot. The volume of the melt inclusion (constant in

173   all subsequent steps) was calculated according to the specific volume of melt and the mass of the

174   aliquot. In each subsequent step, a portion of melt (arbitrarily set to 1% of the albitic component

175   of the initial melt) was crystallized. Consequently, the remaining melt was enriched in CO_2 and

176   H_2O via subtraction of $NaAlSi_3O_8$ into newly-formed albite (i.e., PEC). However, because the

177   melt was initially vapor-saturated, enrichment in CO_2 and H_2O drives the melt towards

178   supersaturation, and some portion of CO_2 and H_2O must be released into a free vapor phase, or

179   bubble. In a closed system, at any given temperature and pressure the CO_2/H_2O ratio of the

180   exsolved vapor phase is constrained by the CO_2/H_2O ratio in the coexisting melt, and an iterative

181   procedure is employed to solve for melt-vapor equilibrium. The density and volume of the

182   exsolved vapor phase was calculated using the Redlich-Kwong equation of state (Redlich and

183   Kwong, 1949) with the parameters of Holloway (1977). To achieve constant volume conditions,

184   a nested iterative procedure was also employed to adjust internal pressure (with temperature

185   constrained by the vapor-saturated liquidus surface). Note that in the latter isochoric constraint,

186   the volume of the inclusion was defined by the sum of volumes of melt plus vapor plus albite

187   formed during PEC (i.e., albite crystallized on the walls of the inclusion). The two constraints

188   (mass balance and isochoricity) were solved simultaneously for each increment of PEC, to obtain

189   a trajectory of evolving pressure-temperature-composition (melt+vapor) conditions. The

190   calculations did not treat external pressure as a variable, nor did they account for compressibility

191   of the host mineral.

192   In addition to the simulations using an albitic melt composition trapped in albite, we

193   conducted several simulations using a basaltic melt composition trapped in olivine. The

194   solubility model for volatile species in the basaltic melt (based on an average tholeiitic basalt

195   composition) was from Holloway and Blank (1984). The volumetric properties of the basaltic

196   melt, as well as the volume of fusion of olivine, were modeled based on the data of Lange and

197   Carmichael (1990). Effect of H_2O on the olivine crystallization temperature was modeled based

198   on the data of Almeev et al. (2007). Our model is thus somewhat simplified and does not invoke

199   compositional changes or effects in the basaltic melt (nor host olivine) but nevertheless serves to

200   compare and contrast the mafic system with the earlier albitic model.

201   Note that the recent study by Tuohy et al. (2016) reported new numerical modeling

202   showing a greater volume fraction of vapor at equivalent degree of PEC than reported by Steele-

203   MacInnis et al. (2011). The model described by Tuohy et al. (2016) used similar methods to

204   those used by Steele-MacInnis et al. (2011), but including MI of basaltic composition entrapped

205   in olivine (rather than albitic composition entrapped in albite). The larger volume fractions of

206   vapor predicted for olivine-hosted MI by Tuohy et al. (2016) is consistent with the numerical

207   model of Moore et al. (2015), which also showed that the relative volume contraction during

208   cooling of olivine-hosted MI is significantly greater than that of MI hosted in alkali feldspar (see

209   Fig. 8a versus 8e of Moore et al. 2015). Thus, Moore et al. (2015) stated that among MI trapped

210   in olivine, pyroxenes, feldspars and quartz, the MI trapped in alkali feldspars are expected to

211   exhibit the smallest vapor bubbles, in terms of relative volume fractions. These same effects are

212   reproduced by the model described here, when using the parameters appropriate for a basaltic

213   melt and olivine host. We should note that Steele-MacInnis et al. (2011) stated that the effect of

214   PEC in olivine-hosted MI would be less than that in albite-hosted MI according to a lesser

215   volume of fusion of olivine compared to albite; however, this statement was incorrect because of

216   failure to account for the different stoichiometries of one formula unit of albite versus olivine

217   reported by Lange and Carmichael (1990). When compared at an equivalent 8-oxygen basis

218   (NaAlSi$_3$O$_8$ versus (Fe,Mg)$_4$Si$_2$O$_8$), olivine exhibits a greater ΔV_{fusion} than albite, which leads to a

219   greater volume fraction of vapor produced in olivine-hosted MI at equivalent degrees of PEC

220   (Moore et al. 2015; Tuohy et al. 2016).

221   The key addition to the methods described above, for the case of heterogeneously

222   entrapped inclusions, was to set the initial conditions within the MI such that the inclusion

223   initially contained vapor-saturated melt plus a finite volume of trapped vapor. Thus, at the initial

224   pressure-temperature conditions, the composition of vapor in equilibrium with melt was

225   calculated using the model of Holloway and Blank (1994), and an initial mass of H$_2$O and CO$_2$ in

226   the vapor phase was defined according to the calculated CO$_2$/H$_2$O ratio. The volume of the

227 resulting trapped vapor phase was calculated using the Redlich-Kwong equation of state. The

228 combined volume of initial melt plus vapor was then used as the reference volume for constant-

229 volume calculations in all subsequent steps.

230   We conducted simulations for an albitic melt composition hosted in albite using a

231 trapping temperature and pressure of 930 °C and 200 MPa (equivalent to the model shown in

232 Fig. 10 of Steele-MacInnis et al. 2011), for 12 starting volume fractions of vapor: 0, 5, 10, 15,

233 20, 40, 60, 80, 85, 90 and 95 vol.% vapor. We conducted additional simulations for a basaltic

234 melt composition hosted in olivine using a trapping temperature and pressure of 1200 °C and 120

235 MPa, for six starting volume fractions of vapor: 0, 5, 10, 15, 20 and 40 vol.% vapor. In each

236 simulation, we traced the evolution of H_2O and CO_2 concentrations in the melt, as well as

237 temperature and internal pressure, during PEC up to 10% (by mass) of the silicate (albitic or

238 basaltic) component of the melt. We modeled up to 10% PEC because greater degrees of PEC

239 than this are rarely reported in literature (Steele-MacInnis et al. 2011).

240

3. RESULTS

242 Results of our simulations are shown in Figs. 3 and 4. For the homogeneously entrapped vapor-

243 saturated melt (0 vol.% vapor), the results for the albitic melt are equivalent to those reported by

244 Steele-MacInnis et al. (2011). The basaltic melt hosted in olivine shows a similar trajectory,

245 although the decrease in internal pressure as well as CO_2 concentration in the glass is somewhat

246 greater for basaltic MI compared to albitic MI, at equivalent degrees of PEC (Figs. 3B and 4B).

247 Figure 3 also shows heterogeneously entrapped MI with 5-20 vol.% trapped vapor, and Fig. 4

248 shows heterogeneously entrapped MI with 5-40 vol.% trapped vapor. Figures 3 and 4 do not

249 show the heterogeneously entrapped MI with higher volume fractions of trapped vapor (up to

250   95% vol.%) because the data points and trend lines at these high volume fractions of trapped

251   vapor all overlap.

252   Figure 3 shows that as the volume fraction of trapped vapor increases, an equivalent

253   degree of PEC is achieved at lower degree of cooling. Stated differently, if a group of MI are all

254   trapped at the same temperature but initially contain various proportions of trapped vapor, those

255   containing more trapped vapor are predicted to undergo more post-entrapment crystallization

256   during the same interval of cooling. We should note that this latter prediction depends upon the

257   assumption of thermodynamic equilibrium, and does not account for potentially differing cooling

258   rates, nor differing glass-transition behavior discussed below. Figure 3 also shows that with

259   increasing volume fraction of trapped vapor, the decrease in internal pressure within an MI

260   concomitant with decreasing temperature/increasing PEC is reduced. Thus, at 10% PEC (by

261   mass), the albitic inclusion that trapped no vapor has undergone an internal pressure decrease of

262   ~50 MPa, whereas the albitic inclusion that trapped 10 vol.% vapor has undergone only ~5 MPa

263   of pressure decrease. For the albitic inclusion that trapped 20 vol.% vapor, the pressure decrease

264   at 10% PEC is only ~1 MPa, and the pressure-temperature trajectory is essentially equivalent to

265   that of the CO_2-H_2O fluid isochore corresponding to the composition and density of the trapped

266   vapor. Analogous trends are evident in the models for basaltic MI hosted in olivine (Fig. 3B).

267   As PEC, cooling and decompression progress, the silicate melt within the MI gradually

268   exsolves H_2O and CO_2 into the vapor bubble (Steele-MacInnis et al. 2011). However, the

269   concentrations of these volatiles in the remaining melt (glass) phase diverge owing to the order-

270   of-magnitude difference in their solubilities in the melt, versus their relative concentrations in the

271   conjugate vapor phase (Steele-MacInnis et al. 2011). Hence, for the albitic MI that trapped no

272   vapor, after 10% PEC the CO_2 concentration in the melt decreases from 520 to 230 ppm,

273   whereas the H_2O concentration in the melt increases from 3.8 to 4.2 wt.% (Fig. 4). With

274   increasing volume fraction of trapped vapor, these effects are more subdued (Fig. 4). For

275   example, for the albitic MI that traps 10 vol.% of vapor, at 10% PEC the CO_2 concentration in

276   the melt has decreased from 520 to 450 ppm, and the H_2O concentration in the melt has

277   increased from 3.8 to 4.0 wt.%. At $\geq$60% trapped vapor, both the CO_2 concentration and the H_2O

278   concentration in the melt remain essentially constant (~520 ppm and ~3.8 wt.%, respectively) up

279   to 10% PEC. Again, analogous trends are evident for the basaltic MI trapped in olivine (Fig. 4B).

280

4. DISCUSSION

282   As expected, as the volume fraction of trapped vapor in the melt inclusion increases, the

283   pressure-temperature trajectory followed by the MI during PEC and cooling approaches that of a

284   coeval CO_2-H_2O fluid-inclusion isochore (Fig. 3). Indeed, at volume fractions of trapped vapor

285   greater than ~20 vol.% for the albitic melt, and ~40 vol.% for the basaltic melt, the pressure-

286   temperature trajectory of the MI is indistinguishable from a coeval fluid-inclusion isochore.

287   Consequently, the internal pressure decreases more gradually in inclusions containing more

288   trapped vapor, and thus degassing of CO_2 and H_2O into the vapor bubble is more subdued.

289   Hence, the volatile concentrations in the melt show less change from the initial composition at

290   equivalent degrees of PEC, in inclusions containing more trapped vapor. In the extreme case of

291   >60 vol.% trapped vapor, the concentrations of CO_2 and H_2O in the melt (and thus, in the glass

292   in quenched MI) are predicted to be equal within the uncertainty of standard analytical

293   techniques to those in the originally trapped melt.

294   As the volume fraction of trapped vapor increases, we also see a decrease in the degree of

295   cooling required to achieve an equivalent degree of PEC (Fig. 3). This phenomenon is a result of

296   mass-balance constraints on the vapor-saturated solidus temperature of the MI. According to

297   Burnham and Davis (1974), the solidus temperature of a vapor-saturated albitic melt is a function

298   of the ratio of H_2O to CO_2 in the vapor phase. In a melt inclusion which traps only vapor-

299   saturated melt (with no trapped vapor), the composition of the vapor phase becomes increasingly

300   enriched in H_2O during cooling and PEC (i.e., the composition of each aliquot of exsolved vapor

301   is more H_2O-rich at each increment of PEC). Because this inclusion traps only a vapor-saturated

302   melt, and because the H_2O concentration in such a melt is commonly an order of magnitude

303   greater than the CO_2 concentration, the inclusion is able to achieve a very H_2O-rich vapor bubble

304   at the later stages of degassing of H_2O. As such, as cooling and PEC occur, the vapor-saturated

305   solidus temperature is increasingly depressed, allowing PEC to proceed towards the H_2O-

306   saturated solidus (Burnham and Davis 1974). In contrast, melt inclusions that trap a vapor bubble

307   have their volatile budgets buffered by the composition of the trapped vapor, which is commonly

308   significantly more CO_2-rich than the corresponding melt phase. Inclusions that trap a large

309   proportion of vapor thus have higher vapor-saturated solidus temperatures, and may undergo an

310   equivalent degree of PEC in a smaller temperature interval. In the extreme case of an inclusion

311   that traps ≥60 vol.% vapor, the vapor-saturated solidus temperature is approximately equal to the

312   trapping temperature, and the melt may undergo some amount of PEC nearly isothermally.

313   Notably, this process may induce variation in the measured major-element composition of the

314   glass phase within MI containing different proportions of trapped vapor.

315   An additional consequence of the different predicted solidus temperatures of MI

316   containing different proportions of trapped vapor is potentially differing glass-transition

317   behavior. As noted above, our numerical model assumes thermodynamic equilibrium, and thus

318   the glass transition is not included explicitly in our results. Nevertheless, we can make some

319   qualitative predictions based on our results and experimental data on glass transition

320   temperatures. According to Giordano et al. (2008), the glass transition temperature of silicate

321   liquids is depressed by increasing concentrations of H_2O. In our results, MI that contain no

322   trapped vapor experience increasing concentration of H_2O in the melt during cooling and PEC.

323   Consequently, these trends suggest that the glass transition temperature of such MI may be

324   progressively depressed during cooling and PEC, inhibiting vitrification. In contrast, MI that

325   contain trapped vapor undergo less H_2O enrichment in the melt. In particular, for MI in which

326   the proportion of trapped vapor exceeds 40 vol.%, the H_2O concentration in the melt remains

327   nearly constant during PEC for both albitic and basaltic MI (Fig. 4). Thus, the glass transition

328   temperature of such MI will not be depressed during cooling and PEC, suggesting that MI that

329   trap vapor may be more readily quenched to glass. Note that at present this possibility is

330   speculative, and further work is required to assess the glass-forming tendency of MI with

331   different contents of trapped vapor.

332   The key consequence of trapping some portion of vapor within MI is the potential for

333   preservation of the original volatile concentrations of the melt, or glass, irrespective of cooling

334   and PEC. Preservation of the volatile concentrations in the glass is achieved via reducing the

335   depressurization at equivalent degrees of cooling, and in effect buffering the H_2O and CO_2

336   concentrations in the melt by fixing the corresponding vapor composition. Moreover, the vapor

337   phase within such heterogeneously trapped MI is also buffered in terms of composition and

338   density, as the MI evolves along the vapor isochore, and thus the properties of the trapped

339   magmatic fluid phase are also preserved in such MI.

340   The simulations described here involving an albitic melt hosted in albite all used

341   equivalent initial conditions to those of Steele-MacInnis et al. (2011) of 930 °C, 200 MPa, and

342   initial volatile concentrations of 3.8 wt.% H_2O and 520 ppm CO_2. The basaltic melt simulations

343   used initial conditions of 1200 °C, 120 MPa, and initial volatile concentrations of 0.95 wt.% H_2O

344   and 535 ppm CO_2. One interesting question to consider is how the predicted trends in PEC and

345   volatile evolution within the MI may vary with different initial conditions. Steele-MacInnis et al.

346   (2011) reported that CO_2-absent MI containing only dissolved H_2O undergo immediate and

347   sustained pressure increase with decreasing temperature and PEC, tracking the H_2O-saturated

348   albitic solidus. Conversely, H_2O-absent, CO_2-bearing MI undergo pressure decrease during

349   cooling and PEC, tracking the CO_2-saturated albitic solidus. Inclusions that trap a melt

350   containing dissolved H_2O plus CO_2 follow trends that are initially more similar to the CO_2-

351   endmember, and evolve towards more H_2O-dominated trends as PEC and cooling progress

352   (Steele-MacInnis et al. 2011). We expect that the results of simulations included here, for MI that

353   trap vapor along with the melt, can be extended to other initial conditions, with the only major

354   difference being the initial trajectory of MI which trap little or no vapor. Regardless of the initial

355   conditions and initial H_2O-CO_2 concentrations of the trapped melt±vapor, inclusions trapping a

356   high proportion of vapor are expected to conform to a *P-T* trajectory resembling the isochore of

357   the vapor phase. However, it must be stressed that additional processes such as diffusive

358   reequilibration or decrepitation, which are not modeled here, may cause deviation from this

359   model *P-T* trajectory. Some of these factors are discussed briefly below.

360   Examples of photomicrographs showing MI with anomalously large (>10 vol.%) bubbles

361   are fairly common in the literature, but it should be stressed that based on photomicrographs

362   alone it is commonly impossible to differentiate large bubbles generated by heterogeneous

363   entrapment versus other processes, such as diffusive reequilibration (Gaetani et al. 2012;

364   Bucholz et al. 2013) or stretching, leakage and/or decrepitation (Maclennan, 2017). In addition,

365 based on photomicrographs alone it is impossible to determine the volume of glass polished

366 away during sample preparation, as well as if any additional bubble(s) was polished away to

367 exposed the MI at the sample surface. Moreover, photomicrographs are sometimes unrevealing

368 in terms of whether MI exposed by polishing were originally fully enclosed, or rather connected

369 to the exterior ("hourglass inclusions") – in the latter scenario, bubble formation can accompany

370 evacuation of some of the melt to the exterior during decompression (Anderson 1991). Thus, we

371 advocate an approach using coeval assemblages of melt inclusions (Fig. 1A), and using

372 additional petrologic indicators to test for timing and post-entrapment modifications of MI (e.g.,

373 Hartley et al. 2015). In the following section, we evaluate evidence for heterogeneous

374 entrapment in the two datasets of Hartley et al. (2014) and Moore et al. (2015).

375   Few analytical data are available in literature on the H_2O and CO_2 concentrations of the

376 glass phase within inclusions containing significant trapped vapor. This probably reflects to

377 some extent that such inclusions are deliberately not targeted for microanalysis because of their

378 anomalously large bubbles. Moreover, analysis of glass in such inclusions may be difficult

379 because of the small analytical volume, for instance in melt-bearing "fluid inclusions" with only

380 a thin film of silicate glass. Our comparison with existing analytical data is therefore limited to

381 vapor bubble CO_2 densities from Hartley et al. (2014) and Moore et al. (2015). Both these

382 studies characterized the CO_2 density within MI vapor bubbles using Raman spectroscopy. The

383 MI described in these two studies are shown in Fig. 5, in terms of inclusion volume versus

384 bubble volume (based on the diagrams of Moore et al. 2015 and Aster et al. 2016). Key

385 observations from Fig. 5 are that both datasets include several inclusions with anomalously large

386 vapor bubbles (>10 vol.%), and that there is no obvious relationship between MI size and bubble

387   size (see also Fig. 1A). This latter point is consistent with heterogeneous entrapment of vapor in

388   some of the MI, if it is assumed that MI were formed at the same time.

389   Figure 6A shows the results of the present modeling of an albitic MI, plotted in terms of

390   the density of the vapor bubble versus the vapor volume fraction, for trapped vapor fractions

391   ranging from zero to 95 vol.%. At low volume fractions of trapped vapor, the density of the

392   vapor bubble decreases abruptly with relatively low degrees of PEC. In contrast, at higher

393   volume fractions of trapped vapor, PEC up to 10% has essentially no effect on the density of the

394   vapor phase. The grey-shaded field on Fig. 6A thus delimits a distribution of bubble density

395   versus volume fraction, corresponding to MI that trap various proportions of vapor and undergo

396   various degrees of PEC up to 10%, with the assumption that all MI were trapped at the same

397   pressure-temperature conditions and with the same H_2O and CO_2 concentrations in the trapped

398   melt.

399   Figures 6B shows the data of Hartley et al. (2014), on MI bubbles hosted in olivine from

400   the AD 1783-1784 Laki eruption, southeast Iceland. Figure 6C shows the data of Moore et al.

401   (2015) on MI bubbles hosted in olivine from the 1959 Kilauea Iki and 1960 Kapoho eruptions,

402   Hawaii. Both of these datasets show a similar distribution: Most of the data are clustered towards

403   relatively low volume fractions of vapor up to ~5-10 vol.%, and within this range the vapor

404   densities show a wide range of variability. However, a small number of MI show much higher

405   volume fraction of vapor up to ~100 vol.%, and these MI also show variable, but generally

406   higher densities. For example, the majority of the MI measured by Hartley et al. (2014) contain

407   <10 vol.% vapor and have vapor densities range from <50 to ~250 kg/m^3. In contrast, among the

408   MI with >10 vol.% vapor, densities range from ~100 to ~300 kg/m^3. Notice also that the lowest

409   vapor density occurs at low volume fraction of vapor, whereas the highest vapor density occurs

410   at the highest volume fraction of vapor. The data of Moore et al. (2015) similarly show a greater

411   variation in vapor density at low volume fractions of vapor, compared to generally more

412   consistent vapor densities at volume fractions >10 vol.%. Moreover, the densities of vapor

413   bubbles that comprise >10 vol.% in the data of Moore et al. (2015) cluster around ~130 kg/m^3,

414   which is around the maximum of the low-volume fraction cluster of data. The grey-shaded

415   regions in Figs. 6B and 6C were constructed using the same numerical methods described above,

416   assuming a basaltic melt composition hosted in olivine. Initial conditions for the modeling in Fig.

417   6B were 1210 °C and 85 MPa, whereas the initial conditions for the modeling in Fig. 6C were

418   1210 °C and 45 MPa. In both cases, the initial (trapping) pressures are less than those

419   constrained by H_2O-CO_2 solubility calculations (Hartley et al. 2014; Moore et al. 2015) in order

420   to match the relatively low density of the vapor bubbles. Stated differently, these initial pressures

421   were selected according to the pressure on the relevant CO_2-H_2O isochore at the presumed

422   trapping temperature of 1210°C. The discrepancy in modeled initial pressure versus inferred

423   trapping pressure for the studied MI likely reflects expansion (and concomitant decrease in

424   density) of the vapor bubble during quenching of the glass (Esposito et al., 2011), or vapor loss

425   by decrepitation (Maclennan, 2017). Nevertheless, in both cases the predicted trends for MI that

426   trapped some fraction of vapor and subsequently underwent various degrees of PEC are broadly

427   consistent with the analytical data. Certainly, these results do not provide definitive evidence of a

428   role of heterogeneous trapping and PEC in the distribution of data from Laki, Kilauea Iki and

429   Kapoho, but the results are at least consonant with this general model. However, we stress once

430   again that this interpretation relies on the assumption that the MI shown in Figs. 6B or 6C were

431   trapped coevally, whereas we lack petrographic information to test this assumption.

432   The recent study of Aster et al. (2016) provides another dataset on MI vapor bubble

433   densities and volume fractions from four cinder cones: two in the Cascade Arc and two in the

434   Trans-Mexico volcanic belt. Aster et al. (2016) only report vapor bubbles occupying up to 15

435   vol.% of the MI. The densities of vapor bubbles measured by Aster et al. (2016) do not show any

436   systematic relationship with bubble volume fraction. They inferred heterogeneous entrapment of

437   some of the vapor bubbles by calculating the maximum expected volume fraction of vapor

438   produced by cooling, PEC and quenching of the MI, and determined that most of the bubbles

439   could have formed by these processes alone (i.e., without heterogeneous trapping of vapor).

440   These results by Aster et al. (2016) indicate that the predictions made in the present study do not

441   always apply to olivine-hosted MI, such as in the case when only bubbles up to ~15 vol.% are

442   observed. Nevertheless, the comparison with the datasets of Hartley et al. (2014) and Moore et

443   al. (2015) indicate that bubbles with larger volume fractions (up to ~100 vol.%) occur in olivine-

444   hosted MI from volcanic systems, and MI hosting such bubbles may be amenable for analysis of

445   pre-eruptive volatile concentrations.

446   The comparison of our model predictions with these literature data from Hartley et al.

447   (2014) and Moore et al. (2015) are not unequivocal, partly because of sparseness and scatter in

448   the data, and likely also because various factors affect the vapor densities of olivine-hosted MI.

449   For example, MI may have been trapped at various depths, and certainly re-equilibration of

450   volatile constituents is likely to play a role. Hartley et al. (2015) used the H_2O/Ce ratios of some

451   of the same MI discussed here, to evaluate the degree of H_2O loss or gain by diffusion. This type

452   of analysis could in principle be used to help constrain the degree of re-equilibration of MI

453   containing anomalously large bubbles, but such inclusions were not analyzed by Hartley et al.

454   (2015). An additional complication is that MI that trap relatively small volume fractions of vapor

455   may not exhibit anomalously large vapor bubbles (Aster et al. 2016). In some cases, trapping of

456   vapor may be only distinguishable by calculating the volume fraction of vapor formed via pre-

457   eruptive cooling coupled with the effects of cooling and quenching to the glass transition

458   temperature (Aster et al. 2016). Nevertheless, the data shown in Figs. 5 and 6 are broadly

459   consistent with the prediction that MI which trapped significant proportions of vapor can

460   maintain a relatively high vapor density at room temperature, compared to inclusions that

461   trapped little to no vapor. A corollary of this prediction is that the glass phase in such inclusions

462   is expected to retain concentrations of H_2O and CO_2 that reflect the composition of the melt at

463   the time of trapping. As such, these data and model predictions suggest that microanalysis of the

464   glass phase within MI containing trapped vapor may be an amenable method to directly sample

465   the H_2O and CO_2 concentrations of the trapped melt, independently of PEC. Moreover, analysis

466   of the CO_2 and H_2O concentrations in the corresponding (heterogeneously entrapped) vapor

467   bubble using the methods developed by Esposito et al. (2016) may be an amenable and

468   complementary method to determine the composition of the coeval, equilibrium magmatic vapor

469   phase.

470   In interpreting the patterns in vapor density versus volume fraction in Fig. 6, we must

471   emphasize that the available data do not permit us to evaluate whether the MI record coeval

472   entrapment. As such, it is not currently possible to verify whether the MI in Fig. 6 record similar

473   physical and chemical conditions of trapping. The best method to constrain the relative timing of

474   MI trapping would be to study MI in the context of coeval assemblages (Esposito et al. 2014). In

475   the case of melt inclusions from a single eruptive event in which suitable assemblages are absent,

476   an alternative method would be to categorize MI based on the forsterite content of the

477   immediately adjacent host olivine, or the major element composition of the MI, or some

478 combination of these parameters. Such procedures may allow us to better define the trends of

479 melt-volatile composition with trapped vapor fraction. Similarly, direct analysis of the CO_2 and

480 H_2O concentrations in the glass phase of MI containing anomalously large bubbles would be

481 extremely beneficial to assess the model predictions described here. Unfortunately, the available

482 data do not allow us to assess these various potential indicators for coeval trapping (as well as for

483 potential diffusive reequilibration, etc.) – we hope that future studies will provide additional

484 constraints to evaluate these various factors.

485   Another potential issue that may influence trends such as those shown in Fig. 5B and 5C

486 is the precipitation of carbonate at the glass/bubble interface (e.g., Kamenetsky et al. 2001;

487 Moore et al. 2015; Esposito et al. 2016), which will lower the CO_2 density measured in the

488 bubble. It is important to note that Kamenetsky et al. (2001) showed a positive correlation

489 between the relative volume fraction of the vapor bubble and the amount of precipitates at the

490 glass/bubble interface.

491   A final caveat that must be addressed is the possibility of forming large vapor bubbles

492 within MI by processes other than heterogeneous entrapment, namely bubble growth as a result

493 of H^+ diffusion or following stretching, leakage and/or decrepitation. Hydrogen diffusion will

494 result in an increased density (decreased molar volume) of the melt phase, which can result in

495 formation of a bubble by contraction of the melt. Similarly, stretching, leakage and/or

496 decrepitation may effectively reduce the *bulk* density (increase the bulk molar volume) of the

497 inclusion, thereby favoring the subsequent production of large bubbles. Regarding H^+ diffusion,

498 we calculated the volume fraction of vapor that would be expected in a basaltic melt inclusion

499 with a starting H_2O concentration of 5 wt.%, assuming different proportions of H_2O loss,

500 according to the effect of H_2O on the density of the silicate glass (Lange and Carmichael 1987;

501   1990; Ochs and Lange 1999; Iacovino 2014). Our calculation was based on a basaltic melt

502   trapped at 100 MPa and 1100 °C. In this example, if the H_2O concentration is reduced to 4 wt.%

503   by diffusive reequilibration, then the expected volume fraction of vapor would be ~2 vol.%. In

504   the extreme case where all H_2O was lost (resulting in an anhydrous glass) then the maximum

505   volume fraction of the shrinkage bubble would be ~9 vol.%. As such, bubbles exceeding 2-9

506   vol.% vapor (e.g., Figs. 5 and 6) suggest additional factors besides diffusive reequilibration. We

507   note that H_2O/Ce data (e.g., Hartley et al. 2015) and hydrogen isotopic analyses of MI glasses

508   may add constraints to evaluate the extent of diffusive reequilibration in future studies.

509   Stretching, leakage and decrepitation (SLD) may all be induced by internal overpressure within

510   the inclusion during exhumation and cooling (Maclennan, 2017), analogous to the same

511   phenomena in aqueous fluid inclusions (Bodnar et al. 1989). In some cases in which SLD occurs

512   as a result of brittle deformation (cracking) of the mineral host, it may be possible to identify

513   signs of fluid loss from melt inclusions based on the presence of annealed cracks or decrepitation

514   halos (e.g., Fig. 3b in Cannatelli et al., 2015). Although we did not consider or account for

515   stretching, leakage or decrepitation in this study, we do not mean to suggest that *all* large bubbles

516   in inclusions are generated by heterogeneous trapping, and indeed we expect that some MI

517   containing large bubbles may reflect SLD. In particular, MI trapped at high pressures (which

518   thus exsolve a high-density CO_2-H_2O fluid phase during PEC and cooling) may be particularly

519   susceptible to SLD because of the potential for internal overpressure of the high-density, CO_2-

520   rich fluid (Maclennan, 2017). Again, this suggestion is based on the experience of high-density,

521   CO_2-bearing fluid inclusions, which are susceptible to high internal pressures and, thus,

522   decrepitation (Diamond, 2001). Importantly, the trends expected from such processes would

523   differ from those predicted in the case of heterogeneous entrapment. Specifically, the density of

524   the vapor bubble would be expected to decrease in response to SLD, owing to the overall

525   increase in the bulk molar volume. Thus, large bubbles produced by SLD processes would be

526   expected to exhibit relatively low density compared to bubbles of modest volume fraction within

527   unmodified inclusions. Thus, Figs. 5 and 6 provide some basis for comparing heterogeneous

528   entrapment versus SLD. Heterogeneous entrapment is expected to yield larger bubbles

529   containing vapor of relatively high density compared to the smaller vapor bubbles in the same

530   sample. In contrast, SLD are expected to yield larger vapor bubbles of relatively low density

531   compared to the smaller bubbles in the same sample. Figure 6 shows that in the samples from

532   Laki, Kilauea Iki and Kapoho, the majority of the anomalously large bubbles exhibit relatively

533   high densities suggesting heterogeneous entrapment. Nevertheless, some of the larger vapor

534   bubbles (e.g., the bubble at ~56 vol.% in the Kapoho samples; Fig. 6C) show relatively low

535   densities and may reflect SLD. Figure 5 also allows some qualitative estimation of the expected

536   effects of diffusive reequilibration as well as SLD processes, because both would be expected to

537   yield systematic relationships between MI and bubble size: In the case of diffusive H^+ loss,

538   smaller inclusions would be more severely affected (Qin et al. 1992; Bucholz et al. 2013),

539   whereas larger inclusions are more susceptible to SLD processes (Bodnar et al. 1989). The

540   results shown in Figure 5 indicate no particular relationship between inclusion size and bubble

541   volume, which is at least broadly consistent with heterogeneous trapping, although this inference

542   relies on the assumption that the MI were trapped at the same time (see also Fig. 1A).

543   Nevertheless, ultimately a combined model accounting for heterogeneous entrapment, PEC *and*

544   the effects of SLD will be required to assess these mutually interacting processes.

545

5. CONCLUSIONS

547   The predictions described above are testable, and future studies aimed at microanalysis of

548 the glass phase within vapor-rich MI should be conducted to determine the variability of melt

549 volatile contents. Based on the numerical modeling described herein, we suggest that MI

550 containing high volume fractions of vapor (>10 vol.%) probably originate by trapping of

551 magmatic vapor along with the silicate melt, and that the compositions of both the melt and

552 vapor phases in such inclusions are preserved in their original (trapping) states as a result of this

553 process. As such, MI containing trapped vapor probably should not be ignored or deliberately

554 omitted from microanalysis, but rather should be targeted in order to estimate the original melt-

555 volatile composition. We hope that this insight will provide an additional tool in the arsenal

556 applied to melt inclusion volatiles in volcanic systems.

557

564

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Figure Captions:

Fig 1 Assemblages of heterogeneously trapped inclusions of melt plus magmatic vapor exhibit a wide range in the relative volume of vapor bubbles including anomalously high (>5 vol.%) volume fractions of vapor. The transmitted light photomicrographs show: (A) An assemblage and (B) a group of olivine-hosted of silicate melt inclusions from the 1959 eruption of Kilauea Iki, Hawaii (Moore et al., 2015); (C) olivine-hosted MI from the 1783-84 Laki eruption, Iceland (Hartley et al., 2014); (D) an assemblage and (E) a group of plagioclase-hosted MI from the 1783-84 Laki eruption, Iceland. Arrows in panels A, B, C and E indicate inclusions with different volume fractions of vapor (labelled). Notice the variable proportions of vapor, including anomalously large bubbles, in the assemblage shown in (A) suggesting heterogeneous entrapment. The color differences between MI in (C) probably reflect variations in light scattering between inclusions of different size

Fig. 2 Heterogeneously trapped inclusions of melt plus magmatic vapor follow pressure-temperature trajectories intermediate between those of coeval vapor-saturated melt inclusions and magmatic CO_2-H_2O fluid inclusions. The pressure-temperature phase diagram shows the vapor-saturated solidus-liquidus of albitic melt contoured by activity of H_2O (Burnham and Davis 1974) and the liquid-vapor solvus and isochores of a CO_2-H_2O fluid of 40 mol.% CO_2 (Connolly and Bodnar 1983). This fluid composition corresponds to the vapor in equilibrium with albitic melt at the trapping condition of 930 °C and 200 MPa, indicated by the star. Path "a" represents the isochore of a CO_2-H_2O fluid inclusion trapped at this condition, whereas path "b" represents the pressure-temperature trajectory followed by a melt inclusion which trapped only vapor-saturated melt during cooling and PEC. Heterogeneously trapped melt+vapor inclusions are expected to follow a pressure-temperature trajectory intermediate between these two endmembers, exemplified by path "c." Shaded box expanded in Fig. 3A

Fig. 3 Melt inclusions that trap vapor undergo subdued decompression during cooling and PEC. Model results for (A) an albitic melt trapped in albite at 930 °C and 200 MPa, and (B) a basaltic melt trapped in olivine at 1200 °C and 120 MPa. The results of our numerical model show that with increasing volume fraction of trapped vapor, the pressure-temperature pathway followed by the MI approaches that of the coeval CO_2-H_2O fluid inclusion (indicated by 100 vol.% vapor, and corresponding to the fluid-inclusion isochore). At ≥20 vol.% trapped vapor, the pressure-temperature path for the albitic MI is virtually indistinguishable from the fluid-inclusion isochore. Symbols on each curve represent 1% increments of PEC

Fig. 4 CO_2-H_2O systematics of vapor-saturated MI during PEC vary with the proportion of trapped vapor. Model results for (A) an albitic melt trapped in albite at 930 °C and 200 MPa, and (B) a basaltic melt trapped in olivine at 1200 °C and 120 MPa. The inclusions that trapped only vapor-saturated melt (0% trapped vapor) undergo the most significant decrease in CO_2 content in the melt, whereas MI that trapped more vapor experience less CO_2 loss from the melt, for both albitic and basaltic MI. Symbols on each curve represent 1% increments of PEC

Fig. 4 Volumes of vapor bubbles versus volumes of melt inclusions from (a) the AD 1783-84 Laki eruption, Iceland (Hartley et al. 2014), and (b) the 1959 Kilauea Iki and 1960 Kapoho eruptions, Hawaii (Moore et al. 2015).

Fig. 6 Densities of MI vapor bubbles vary systematically with the proportion of trapped vapor. (a) Results of our numerical model. (B) MI from the AD 1783-84 Laki eruption, Iceland (Hartley et al. 2014). (C) MI from the 1959 Kilauea Iki and 1960 Kapoho eruptions, Hawaii (Moore et al. 2015). The dashed vertical line in (B) and (C) corresponds to 5 vol.% vapor, representing the cutoff applied by both Hartley et al. (2014) and Moore et al. (2015) to differentiate MI vapor bubbles likely generated by differential thermal contraction and/or PEC (<5 vol.%) versus bubbles potentially indicating heterogeneous trapping (>5 vol.%). The light shaded regions in (B) and (C) were calculated as described in the text

Figure 1

100 µm

30 vol.%

100 vol.%
vapor

10 vol.%

A

30 vol.%
vapor

100 µm

2 vol.%

2 vol.%

B

50 µm

D

15 vol.%

2 vol.%

2 vol.%

200 µm

C

100 µm

10 vol.%

2 vol.%

E

Figure 3　　　　　　　　　　　　　　　　　Click here to download Figure Steele-MacInnis_Fig3_rev.pdf ⬇

A Albitic MI hosted in albite

B Basaltic MI hosted in olivine

Figure 4

Figure 4

Figure 5

Figure 6   Click here to download Figure Steele-MacInnis_Fig6_rev.pdf ⬇