An ER-resident calcium binding protein modulates egress of malaria parasites from erythrocytes

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Abstract

Calcium signaling pathways coordinate the lifecycle progression of apicomplexan parasites, specifically playing a key role in egress from host cells. The main Ca^{2+}-signaling hub in these divergent eukaryotic parasites is presumed to be the endoplasmic reticulum (ER); however, no proteins involved in Ca^{2+}-signaling have been identified in the ER of these deadly human parasites. In this study, we explored the role of the Endoplasmic Reticulum-resident Calcium-binding protein (ERC) in the lifecycle of two apicomplexan parasites, *Toxoplasma gondii* and *Plasmodium falciparum*. We find that the *Toxoplasma* ortholog (TgERC) plays a role in the storage of Ca^{2+} in the ER but is dispensable for the asexual lytic cycle. On the other hand, the *Plasmodium* ortholog (PfERC) is essential for asexual growth but not required for Ca^{2+} storage, organelle biogenesis, or protein trafficking. Instead, knockdown of PfERC inhibits parasite egress and invasion. Our results show that PfERC is critical for the rupture of the parasitophorous vacuole membrane, which is the first step in the egress of malaria parasites from erythrocytes. Surprisingly, PfERC knockdown does not affect the Ca^{2+}-dependent autoprocessing of the key egress protease, SUB1, but knockdown inhibits the second proteolytic maturation of SUB1 that occurs during its secretion from exoneme vesicles. We have therefore identified the first ER-resident protein in *Plasmodium* that modulates egress of malaria parasites.

52 **Introduction**

53 Members of the phylum *Apicomplexa* are responsible for severe human diseases
54 such as malaria, toxoplasmosis, and cryptosporidiosis. Together, this group of obligate
55 intracellular parasites causes several hundred million infections every year and remains
56 one of the major drivers of infant mortality (1-4). In fact, malaria results in nearly half a
57 million deaths each year and most of the mortality is attributed to one species,
58 *Plasmodium falciparum*. All the clinical symptoms of malaria are directly correlated to the
59 invasion and lysis of the host red blood cells by these parasites. Malaria remains a vast
60 health and economic burden in susceptible parts of the world and, despite continuous
61 attempts for eradication and control, there is no effective vaccine and resistance has
62 emerged to all existing drugs (5-8). This highlights the importance of understanding the
63 factors that control the intracellular growth and development of the parasite, which will
64 lead to the identification of key targets for antimalarial drug development.

65 Egress and invasion of apicomplexan parasites are ordered and essential
66 processes which are regulated by signaling pathways dependent upon the second
67 messengers, cGMP and Ca^{2+} (9-13). Upon invading the host cell, the parasites create
68 and reside within a host-derived vacuole called the parasitophorous vacuole (PV). Within
69 this vacuole, the parasites grow and divide into daughter cells, called merozoites in
70 *Plasmodium*, which must egress from the host cell to complete the life cycle. This event
71 is triggered by the activation of a cGMP dependent protein kinase (PKG) and the inhibition
72 of PKG activity blocks egress (10, 14, 15). Ca^{2+}-signaling also induces egress although it
73 is uncertain whether this pathway works downstream (11) or synergistically with cGMP
74 signaling (10, 16, 17). For example, studies have shown that blocking the release of Ca^{2+}
75 from intracellular stores using cell permeable Ca^{2+} chelators blocks egress in malaria
76 parasites (17-19). It has been suggested that this release of Ca^{2+} into the cytoplasm
77 comes from the parasite ER; however, the parasite genome lacks identifiable orthologs
78 of ligand-gated Ca^{2+} channels such as the inositol 1,4,5,-triphosphate or ryanodine
79 receptors (20). Increase in cytoplasmic Ca^{2+} is thought to activate calcium dependent
80 protein kinases (CDPKs) resulting in release of egress-related vesicles (16, 21).

81 In malaria parasites, these egress-related vesicles contain specific proteases that
82 are proteolytically processed and activated, perhaps upon release into the PV (22-24).

83 For example, one such pivotal enzyme is the serine protease, Subtilisin 1 (SUB1), which
84 undergoes two cleavage events. First, the zymogen undergoes Ca^{2+} dependent
85 autoprocessing in the ER (25, 26) and then, it is cleaved again by the recently identified
86 aspartic protease, Plasmepsin X (PMX), probably during its secretion into the PV (23, 24).
87 The proteolytic cleavage and activation of SUB1 is understood to be the point of no-return
88 as the release of SUB1 into the PV results in the rapid (~10 minutes) breakdown of the
89 parasitophorous vacuole membrane (PVM) (22, 27). Then, substrates of SUB1 such as
90 merozoite surface protein 1 (MSP1) and serine-repeat antigen 6 (SERA6) help
91 breakdown the RBC cytoskeleton and the RBC membrane (RBCM) (28, 29). Once egress
92 is completed, the merozoites subsequently invade fresh RBCs to start the cycle again.
93 Like egress, invasion requires specific secretory events such as fusion of micronemes to
94 the merozoite membrane and secretion of rhoptry contents into the host cell, which
95 provides the ligand-receptor pair essential for driving the parasite into the host cell (30,
96 31).

97 The parasite endoplasmic reticulum (ER) is thought to play a key role in egress
98 and invasion of daughter merozoites. The putative functions of the parasite ER during
99 these lifecycle stages, include biogenesis of the specific egress and invasion related
100 organelles, transporting proteins to these organelles, and propagating Ca^{2+} signals
101 essential for egress and invasion (32, 33). However, none of the proteins responsible for
102 these ER-related functions during egress and invasion of apicomplexan parasites have
103 been identified. We hypothesized that an ER-resident calcium binding protein (ERC) that
104 is conserved in both *P. falciparum* (PfERC: PF3D7_1108600) and *T. gondii* (TgERC:
105 TGME49_229480) plays a role in the Ca^{2+} signaling function of the parasite ER. In malaria
106 parasites, this protein has been shown to bind calcium (34). However, the biological
107 function of ERC is unknown in either apicomplexan parasite.

108 To address this, we used a ribozyme-based conditional knockdown system to
109 study the role of PfERC in the asexual lifecycle *P. falciparum*, and we used a knock-out
110 approach to study the role of TgERC in the biology of *T. gondii*. We characterized the role
111 of both Ca^{2+} binding proteins, PfERC and TgERC, and propose a model for their potential
112 roles in Ca^{2+} signaling and in the life cycle of both parasites. This is the first ER resident

113 protein identified in *P. falciparum* that is critical for the egress of malaria parasites from
114 human red blood cells.
115
116 **Results**
117 PfERC and TgERC are EF-hand containing proteins localized in the ER
118 PfERC (PF3D7_1108600) and TgERC (TgME49_229480) are proteins related to
119 the CREC (Calumenin, Reticulocalbin 1, ERC-55, Cab-45) family of proteins, which are
120 characterized by the presence of multiple EF-hands and localize in various parts of the
121 secretory pathway (35) (Figure 1A and Supplementary Figure 1). Like CREC members in
122 other organisms, both PfERC and TgERC contain a signal peptide, multiple EF-hands,
123 and an ER-retention signal (Figure 1A). However, TgERC differs from its *Plasmodium*
124 homolog in that it only contains 5 EF-hands while PfERC contains and extended C-
125 terminus that may contain a 6th, though degenerate, EF-hand (residues 314-325)
126 (Supplementary Figure 1) (34). Since both proteins have an ER-retention signal they are
127 predicted to reside within the lumen of the ER.
128
129 Generating conditional mutants of PfERC
130 In order to determine the biological role of PfERC, we used CRISPR/Cas9 gene
131 editing to generate mutant parasite lines where the endogenous locus of PfERC was
132 tagged with the conditional knockdown system employing the inducible ribozyme *glmS* or
133 the inactive version of the ribozyme, *M9* (termed PfERC-*glmS* and PfERC-*M9*
134 respectively) (Figure 1B and 1C) (36). Western blot and PCR analysis of PfERC-*glmS*
135 and PfERC-*M9* parasite clones from two independent transfections demonstrate the
136 correct insertion of the HA tag and the *glmS/M9* ribozymes at the PfERC locus (Figure
137 1D and 1E). Co-localization of PfERC with an ER marker also confirmed its sub-cellular
138 localization to this organelle (Figure 1F).
139
140 PfERC is essential for asexual growth and for schizont to ring transition
141 To determine if PfERC was essential for intraerythrocytic survival, we grew
142 asynchronous PfERC-*glmS* and PfERC-*M9* parasites in the presence of glucosamine
143 (GlcN), which activates the *glmS* ribozyme leading to mRNA cleavage (Figure 1B).

144 Western blot analysis shows that this leads to a reproducible reduction of PfERC
145 expression in PfERC-*glmS* parasites while there is no reduction of protein levels in
146 PfERC-*M9* parasites grown under identical conditions (Figure 2A-B). Importantly, this
147 reduction in PfERC levels inhibited the asexual expansion of PfERC-*glmS* parasites,
148 while there was no effect on the growth of PfERC-*M9* parasites (Figure 2C). The response
149 of PfERC-*glmS* parasites was dose-dependent upon GlcN (Supplementary figure 2A)

150 Since our data show that PfERC was essential for growth within the host RBC, we
151 used synchronous parasites to determine which asexual stage was affected by
152 knockdown. We added GlcN to synchronized schizonts and took blood smears at regular
153 intervals during the intraerythrocytic life cycle to detect morphological development of the
154 asexual stages (Figure 2D). Our data show that all intracellular stages developed
155 normally in both PfERC-*glmS* and PfERC-*M9* parasites grown with GlcN (Figure 2D and
156 Supplementary Figure 2B). However, 55hrs after addition of GlcN, the PfERC-*glmS*
157 parasites remained either as morphologically normal schizonts or were observed as
158 daughter merozoites in the extracellular space as well as some that were attached to
159 RBCs (Figure 2D). On the other hand, PfERC-*M9* parasites were able to egress and re-
160 invade fresh RBCs and developed into ring stage parasites (Figure 2D and
161 Supplementary figure 2B).

162 These data suggest that the knockdown of PfERC resulted in a defect in the
163 conversion from schizonts to rings. Therefore, we induced knockdown and observed the
164 conversion of schizonts into rings via flow cytometry at 44, 48, and 56 h post-addition of
165 GlcN. The data show that over the course of 12 hours, PfERC-*M9* parasites transitioned
166 from schizonts to rings as determined by the ring:schizont ratio while PfERC-*glmS*
167 parasites were unable to convert from schizonts into rings resulting in a drastically
168 reduced ratio (Figure 2E). These data show that there was a delay in the disappearance
169 of the morphologically normal PfERC-*glmS* schizonts over the final few hours of the
170 asexual life cycle compared to PfERC-*M9* schizonts, suggesting that knockdown of
171 PfERC led to a defect in egress (Figure 2F and 2G). Consequently, the delayed egress
172 may lead to reduced numbers of ring stage parasites in PfERC-*glmS* parasites unlike
173 PfERC-*M9* parasites (Figure 2F and 2H).

174

175 PfERC is required for PVM breakdown

176 Egress of daughter merozoites from the infected RBC is an ordered and rapid
177 process where the PVM breakdown precedes the disruption of RBCM (Figure 3A).
178 Therefore, we analyzed how egress of PfERC-*glmS* parasites was failing during
179 knockdown. We took synchronized PfERC-*glmS* and PfERC-*M9* schizonts and initiated
180 knockdown with addition of GlcN. These schizonts were allowed to reinvade fresh RBCs
181 and proceed through the asexual stages for 48 hours until they developed into schizonts
182 again. Then, these second cycle schizonts were incubated with inhibitors that block key
183 steps during egress of *P. falciparum* (Figure 3A). To ensure synchronized egress, we
184 used reversible inhibitors of PKG, Compound 1 (C1) or Compound 2 (C2), because
185 inhibition of PKG allows merozoites to develop normally but prevents them from initiating
186 egress (Figure 3A) (10, 15). We used flow cytometry to observe PfERC-*glmS* and PfERC-
187 *M9* schizonts after washing off C1 and saw that there was a delay in the egress of PfERC-
188 *glmS* schizonts while the majority (>60%) of the PfERC-*M9* schizonts were able to
189 complete egress within two hours after washout of C1 (Figure 3B). Removal of C1 initiates
190 the breakdown of the PVM followed by RBCM rupture (Figure 3A), suggesting that
191 PfERC-*glmS* parasites fail to breach one of these membranes down despite removal of
192 the PKG inhibitor.

193 Therefore, we tested whether PfERC knockdown prevented rupture of PVM or if
194 PfERC functioned during RBCM breakdown (Figure 3A). PfERC-*glmS* and PfERC-*M9*
195 schizonts (where knockdown had been initiated in the previous cycle) were incubated
196 with C2 (10, 15) and observed by scanning electron microscopy (SEM) (Figure 3A and
197 3C). We observed that parasites treated with C2 were morphologically identical and had
198 developed into mature schizonts within the PVM inside the RBC (Figure 3C). Then, we
199 washed C2 from the parasites and observed these schizonts after 30 mins by SEM
200 (Figure 3C). During this time period, PfERC-*M9* schizonts were able to initiate egress
201 after removal of C2 and we observed free merozoites attached to the RBC as well as
202 clusters of merozoites that had broken out of the PVM but were contained by a collapsed
203 RBCM wrapped around them (Figure 3C). In contrast, the PfERC-*glmS* schizonts were
204 still stuck within the RBC and looked identical to the C2 arrested schizonts, suggesting
205 that they had not initiated egress even though PKG was no longer inhibited (Figure 3C).

206 These data suggest that knockdown of PfERC blocks egress at an early step, perhaps
207 blocking the rupture of the PVM (Figure 3C).
208 We directly observed if breakdown of the PVM was impacted by knockdown of
209 PfERC using transmission electron microscopy (TEM) (Figure 3D). Knockdown was
210 induced by adding GlcN to PfERC-*glmS* and PfERC-*M9* schizonts and these parasites
211 were allowed to go through one asexual cycle and develop into schizonts again 48hrs
212 later. These schizonts were prevented from completing egress using the irreversible
213 cysteine protease inhibitor, E64 (Figure 3A). This inhibitor blocks the breakdown of the
214 RBCM but allows both the breakdown of PVM and poration of the RBCM, which results
215 in the loss of the electron dense contents of the infected RBC (Figure 3A) (15, 29, 37).
216 Our results show that the PfERC-*M9* schizonts were able to break down the PVM as well
217 as proceed with the poration of the RBCM after an 8-hour incubation with E64, while the
218 PfERC-*glmS* mutants were unable to proceed through the first step of egress and failed
219 to rupture the PVM (Figure 3D). Overall, these data demonstrate that PfERC function is
220 critical for the breakdown of the PVM (Figure 3C and 3D).
221
222 <u>Generating knockouts of TgERC</u>
223 We hypothesized that the ortholog of PfERC in the related apicomplexan parasite,
224 *T. gondii,* may play a similar in the egress of this parasite from its host cell. Therefore, we
225 studied the biological role of TgERC by disrupting the transcription of the *tgerc* gene using
226 CRISPR/Cas9 gene editing to insert the selection marker gene, dihydrofolate reductase
227 (DHFR), in the *tgerc* locus (38, 39) (Figure 4A). Insertion of this gene into the *tgerc* locus
228 interfered with the synthesis of the correct transcript and allowed the selection of clonal
229 populations with pyrimethamine. The mutant *Δtgerc* was isolated by limiting dilution, and
230 a PCR product of 6.1 kb obtained from the mutant parasites DNA indicated the insertion
231 of the marker in the predicted locus (Figure 4B). This fragment was only amplified from
232 DNA of mutants while a fragment of 2.9kb was amplified from parental cells, which
233 correspond to the intact locus of *tgerc* (Figure 4B).
234 In order to verify the localization of TgERC, we cloned and expressed TgERC in
235 *E. coli* and the purified recombinant protein to immunize mice for the generation of specific
236 antibodies. Western blot analysis using this antibody showed the presence of a ~38kDa

237 band corresponding to TgERC in the parental (RH) parasites but absent in the Δ*tgerc*
238 mutants (Figure 4C). Furthermore, IFAs using this antibody showed that TgERC localized
239 predominantly to the endoplasmic reticulum in both extracellular and intracellular
240 tachyzoites (Figure 4D).
241
242 TgERC is required for Ca^{2+} storage but PfERC is not
243 To determine whether TgERC was essential for the lytic cycle of the parasites, we
244 performed plaque assays comparing growth of RH wild type with *Δtgerc* (Figure 4E). Our
245 data show that the mutant parasites were able to form plaques about the same size as
246 the controls (Figure 4F). These data suggest that unlike PfERC, TgERC was not required
247 for egress from the host cell nor was it essential for the lytic cycle of *T. gondii*.
248 We next tested the if TgERC had any role in the storage of Ca^{2+} by testing for
249 increases in cytoplasmic Ca^{2+} in response to thapsigargin. This inhibits the SERCA-
250 Ca^{2+} ATPase, exposing leakage of Ca^{2+} from the ER into the cytoplasm as detected by
251 fluorescence changes in parasites loaded with the Ca^{2+} indicator Fura-2AM (Figure 4G-
252 J) (40, 41). We observed that the cytoplasmic Ca^{2+} increase in the *Δtgerc* mutants after
253 adding thapsigargin was not significantly different than the response obtained under
254 identical conditions when using wild type parasites (Figure 4G). However, when we
255 performed the same experiment in the presence of extracellular Ca^{2+} (Figure 4I), the
256 response to thapsigargin in *Δtgerc* tachyzoites was significantly reduced. The reduced
257 response in the *Δtgerc* parasites indicates that the ER of these parasites is unable to
258 store Ca^{2+} as efficiently as the wild type. This indicates that TgERC is part of the ER
259 machinery involved in storing Ca^{2+}. However, it is evident that other mechanisms are in
260 play since the parasites are still able to grow normally (Figure 4E-F).
261 Since knockout of TgERC resulted in defects in Ca^{2+} storage in the ER of *T. gondii*
262 (Figure 4I and 4J), we hypothesized that PfERC is required for egress because it plays a
263 similar role in *P. falciparum* and does not have redundant mechanisms like *T. gondii* that
264 compensate for the lack of TgERC. To test this hypothesis, synchronized PfERC-*glmS*
265 and PfERC-*M9* schizonts were incubated with GlcN and allowed to proceed through one
266 asexual cycle until they formed schizonts again. The second cycle schizonts were isolated
267 using saponin lysis and loaded with Fluo-4AM to measure cytosolic Ca^{2+} (Supplementary

268 Figure 3A). To assess if the storage of Ca^{2+} in the ER of the parasite was affected by
269 knockdown of PfERC, we added the SERCA-Ca^{2+} ATPase inhibitor Cyclopiazoic acid
270 (CPA) to these saponin-isolated parasites (Supplementary Figure 3A and 3B) (42).
271 Inhibiting the SERCA-Ca^{2+} ATPase allows Ca^{2+} stored in the ER to leak into the
272 cytoplasm, which results in a detectable change in the fluorescence of Fluo-4AM
273 (Supplementary Figure 3B). Our measurements show that there was no difference in the
274 amount of Ca^{2+} that leaked from the parasite ER, upon SERCA-Ca^{2+} ATPase inhibition,
275 between PfERC-*glmS* and PfERC-*M9* schizonts (Supplementary Figure 3B).
276 To test if there was a defect in Ca^{2+} storage in neutral stores, we used the
277 ionophore, Ionomycin, which releases Ca^{2+} from all neutral stores in the cell and
278 measured the release of Ca^{2+} into the cytoplasm of PfERC-*glmS* and PfERC-*M9*
279 schizonts. The parasites were isolated as described above and the changes in
280 cytoplasmic Ca^{2+} were measured using Fluo-4AM (Supplementary Figure 3A and 3C).
281 Again, we did not observe any difference in the amount of Ca^{2+} released into the
282 cytoplasm of PfERC-*glmS* and PfERC-*M9* schizonts treated with ionomycin
283 (Supplementary Figure 3C). These data suggest that the availability of free Ca^{2+} in the
284 ER of *P. falciparum* is not affected by knockdown of PfERC. Furthermore, these data
285 suggest that the observed egress defect upon PfERC knockdown was not a result of
286 disequilibrium of Ca^{2+} in the parasite ER.
287
288 <u>Efficient SUB1 activation requires PfERC</u>
289 Electron microscopy data show that knockdown of PfERC prevents the breakdown
290 of the PVM (Figure 3). A key event required for PVM breakdown is the proteolytic
291 processing of SUB1, which starts a cascade that ends in the release of merozoites from
292 the infected RBC (22, 29). Therefore, we tested if knockdown of PfERC affects processing
293 of PfSUB1. This protease is processed twice, once in the ER, where it undergoes a Ca^{2+}-
294 dependent autocatalytic processing from its zymogen form (83-kDa) into a 54-kDa semi-
295 proenzyme form (p54) (25, 26, 43). From the ER, SUB1 is transported to the egress-
296 related secretory vesicles, the exonemes, which are secreted into the PV to initiate
297 breakdown of the PV membrane. It is proposed that during secretion of SUB1, it is
298 processed by PMX from its semi-proenzyme form (p54) to its mature form (p47) (23, 24).

299 The secretion of mature p47 form of SUB1 initiates the breakdown of the PVM (22, 43).
300 We hypothesized that PfERC is required for the first Ca^{2+}-dependent autoprocessing of
301 SUB1, in the ER, from the 82-kDa zymogen into the p54 semi-proenzyme.
302 To test this hypothesis, PfERC-*glmS* and PfERC-*M9* schizonts were incubated with
303 GlcN and allowed to progress through one asexual growth cycle (48 hours) to develop
304 into schizonts again. Lysates from these synchronized schizonts were separated on a
305 Western blot and probed with antibodies against SUB1 (Figure 5A and Supplementary
306 Figure 4A). No change was observed in the Ca^{2+}-dependent autoprocessing of the
307 zymogen-form of SUB1 into the semi-proenzyme (p54) form (Figure 5A and
308 Supplementary Figure 4A). Surprisingly, we observed a reproducible and significant
309 decrease in the processing of SUB1 from p54 to the p47 form in PfERC-*glmS* parasites
310 (Figure 5A and 5B). Compared to PfERC-*M9* parasites, there was a >50% decrease in
311 the amount of processed SUB1 (p47) in PfERC-*glmS* parasites (Figure 5B). These data
312 suggest that PfERC is required for the secretion-dependent processing of SUB1 in
313 exoneme vesicles.
314 Since we observed the presence of some mature SUB1 in PfERC-*glmS* parasites
315 (Figure 5A), we tested if the activity of SUB1 was affected upon knockdown of PfERC by
316 assaying for the processing of a known substrate of SUB1, the merozoite surface protein
317 1 (MSP1). MSP1 is required for the initial attachment of merozoites onto RBCs and it has
318 been shown that correct processing of MSP1, by SUB1, is also required for efficient
319 egress as it plays a role in breakdown of the RBC cytoskeleton after release from the
320 PVM (28, 44-46). Lysates from synchronized second-cycle PfERC-*glmS* and PfERC-*M9*
321 schizonts, treated as above, were separated on a Western blot and probed using anti-
322 MSP1 antibodies (Figure 5C and Supplementary Figure 4B). Our data show that the there
323 was a ~60% reduction in MSP1 processing in our PfERC-*glmS* parasites as compared to
324 PfERC-*M9* parasites after knockdown (Figure 5C). In fact, we observed that PfERC-*glmS*
325 schizonts had 3 times more unprocessed MSP1 in contrast to PfERC-*M9* schizonts
326 (Figure 5D). These data reveal that knockdown of PfERC leads to defects in SUB1
327 processing and activity, and consequently, MSP1 processing (Figure 5).
328
329 <u>Knockdown of PfERC does not affect protein trafficking or organelle biogenesis</u>

330 MSP1 is a GPI-anchored merozoite membrane protein that is presumably
331 processed by SUB1 once the protease is secreted into the PV (28, 29). Therefore, we
332 wanted to verify that knockdown of PfERC led to a specific defect in the egress cascade
333 and is not due to a block in protein trafficking via the ER or defects in the biogenesis of
334 egress and invasion related organelles. To address this, we used super resolution
335 structured illumination microscopy (SR-SIM) to observe if there was a difference in the
336 surface expression of MSP1 between PfERC-*glmS* and PfERC-*M9* schizonts upon
337 knockdown of PfERC (Figure 5E). As before, knockdown was initiated in synchronized
338 PfERC-*glmS* and PfERC-*M9* schizonts and after 48 hours, these schizonts were stained
339 with anti-MSP1 antibodies. Our data shows that there was no difference in the trafficking
340 of MSP1 to the surface of developing PfERC-*glmS* or PfERC-*M9* merozoites after
341 knockdown (Figure 5E). In addition, we also tested whether the localization of other
342 egress-and invasion-related proteins that traffic through the ER where affected after
343 knockdown by staining similarly treated schizonts for the micronemal protein AMA1 and
344 the rhoptry-bulb protein RAP1. Our data show that, again, there was no difference in the
345 localization of these proteins in schizonts between PfERC-*glmS* and PfERC-*M9* parasites
346 suggesting that the knockdown of PfERC does not cause a generalized defect in the
347 secretory pathway (Figure 5F&G).
348 As the ER generates the lipid membranes required for generating organelles
349 essential for egress and invasion, we wanted to see if their biogenesis was inhibited upon
350 knockdown. If true, this could explain the processing defects that we observe for SUB1
351 and MSP1. We observed E64-treated schizonts (Figure 3A) by transmission electron
352 microscopy and these data show that both micronemes and rhoptries remain
353 morphologically intact in both PfERC-*glmS* and PfERC-*M9* parasites after knockdown
354 was induced (Figure 5H). Successful knockdown was confirmed by the lack of PVM
355 membrane fragments in PfERC-*glmS* parasites, which are present in the PfERC-*M9*
356 parasites, suggesting that PVM rupture occurred normally in the presence of PfERC but
357 not when the protein is knocked down (Figure 5H). These data suggest that the
358 knockdown of PfERC does not lead to defects in organelle biogenesis (Figure 3D and
359 Figure 5H).
360

361 PfERC is required for invasion of merozoites

362 The synchronized growth assays suggest that knockdown of PfERC inhibits the
363 invasion of merozoites into RBCs (Figure 2D, H and Figure 5C, D). To assess if invasion
364 was reduced upon knockdown, PfERC-*glmS* and PfERC-*M9* schizonts in the second
365 cycle after 48 hours in GlcN, were incubated with the PKG inhibitor, C1, for four hours
366 (Figure 3A). The inhibitor was then washed off and the formation of ring stages was
367 observed over two hours by flow cytometry (Figure 6A). We observed that there was a
368 delay in the formation of ring stages as well as a drastic decrease in the numbers of ring
369 stage parasites formed in PfERC-*glmS* parasites compared to the PfERC-*M9* control
370 (Figure 6A). This could be due to loss of egress or could be a combination of effects on
371 egress and invasion due to PfERC knockdown.

372 To decouple the egress and invasion phenotypes, we directly measured the
373 efficiency of merozoite invasion (Figure 6B). This was accomplished by incubating second
374 cycle PfERC-*glmS* and PfERC-*M9* schizonts with E-64 and then mechanically releasing
375 the merozoites (Figure 6B) (47). Incubation with E-64 for 8 hours allows for the completion
376 of schizogony and formation of invasion-competent merozoites. These purified
377 merozoites were then allowed to invade fresh RBCs and the invasion rate was quantified
378 using flow cytometry as described previously (Figure 6C) (47). These data show that there
379 was a drastic reduction in the invasion efficiency of PfERC-*glmS* merozoites as compared
380 to the control PfERC-*M9* merozoites, thus demonstrating that knockdown of PfERC led
381 to a defect in invasion as well (Figure 6C).

382

383 PfERC knockdown affects proteolytic processing of AMA1

384 The reduced invasion of PfERC-*glmS* merozoites could be explained by the
385 reduction in processing of MSP1, which is known to be required for the initial attachment
386 of merozoites to the RBC (44, 45, 48). Invasion of RBCs by *P. falciparum* merozoites
387 requires secretion of contents from another apical organelle, the rhoptries, into the RBC
388 (49-51). Proteins in the rhoptries, like the rhotry-bulb protein, RAP1, require proteolytic
389 processing for their activity (23, 24). Once in the rhoptry, RAP1 is processed by the
390 aspartic protease, Plasmepsin IX (PMIX), from a pro-form (p83) to a mature form (p67)
391 (23, 24, 52, 53). Therefore, we tested if RAP1 processing was affected by knockdown of

392 PfERC using Western blot analysis (Figure 6F and Supplementary Figure 4C). Our data
393 show that the proteolytic processing of RAP1 was not affected by the knockdown of
394 PfERC (Figure 6G), showing that knockdown does not lead to a generalized defect in the
395 processing of all proteins that traverse through the secretory pathway.

396 Another key and essential step in invasion of merozoites is the formation of a tight
397 junction between the parasite and the RBC and AMA1 is critical for the formation of this
398 tight junction (30, 31). AMA1 is trafficked from micronemes to the merozoite surface and
399 there it is processed from its pro-form (p83) to its mature form (p66) by an unknown
400 protease (54-56). The proteolytic processing of AMA1 is critical for its function during
401 invasion (57). Therefore, we tested if the processing of the AMA1 was affected upon
402 knockdown of PfERC. As before, after initiating knockdown in synchronized schizonts,
403 we separated lysates from second cycle PfERC-*glmS* and PfERC-*M9* schizonts on a
404 Western blot and probed it with anti-AMA1 antibodies (Figure 6D and Supplementary
405 Figure 4D). We observed a significant reduction in the proteolytic processing of AMA1
406 upon knockdown (Figure 6D). Indeed, there was a >40% decrease in the processing of
407 AMA1 in PfERC-*glmS* mutants compared to the PfERC-*M9* control (Figure 6E). These
408 data suggest that PfERC is required for the correct processing of AMA1 and therefore,
409 essential for invasion of merozoites into the host RBC.

410

411 **Discussion**

412 In this study, we addressed the biological role of a conserved Ca^{2+}-binding protein
413 that resides in the lumen of the ER of apicomplexan parasites. We have shown that the
414 *Toxoplasma* homolog, TgERC, is dispensable for *in vitro* growth, and the *Plasmodium*
415 homolog, PfERC, is essential for asexual replication (Figures 2 and 3). Our data show
416 that knockdown of PfERC did not affect the ring and trophozoite development but had a
417 clear effect on the subsequent schizont-to-ring transition (Figures 2D-H, 3B, 6A, and
418 Supplementary Figure 2). Specifically, these data show that PfERC is required for both
419 egress from infected RBCs (Figures 2D, 2G, and 3) and invasion into host erythrocytes
420 (Figures 2D, 2H and 6A-C). This is consistent with data that suggest PfERC may be
421 transcriptionally controlled by the invasion-specific transcription factor PfAP2-I (58). Our
422 data show that knockdown of PfERC leads to defects in the processing of proteins critical

423 for invasion of merozoites into the host RBC, namely, MSP1 and AMA1 (Figures 5C-D
424 and 6 D-E). However, the observed invasion defect is likely a secondary effect because
425 several proteins critical for invasion are processed during egress (28, 29). Given the
426 limitations of the conditional knockdown system, we cannot tease out a specific role for
427 PfERC in invasion. As invasion occurs rapidly (<2mins), a potential specific invasion-
428 related function of PfERC could be tested using a small molecule that specifically targets
429 PfERC (59). Overall, these data show that PfERC is essential for egress of merozoites
430 from the infected RBC and for invasion of merozoites into the host erythrocyte.

431 It has been observed previously that the mechanisms at play during egress of
432 daughter parasites from the host cells differs between *Toxoplasma* and *Plasmodium.* This
433 is highlighted by studies showing that orthologs of apicomplexan proteins can serve
434 different functions in their respective organisms. For example, TgCDPK3 is required for
435 egress of *T. gondii* tachyzoites while its *Plasmodium* ortholog, PfCDPK1, is essential for
436 both egress and invasion (60). Similarly, another calcium dependent protein kinase,
437 TgCDPK1, plays a vital role in egress and invasion of *Toxoplasma* tachyzoites but the
438 *Plasmodium* ortholog, PfCDPK4, was shown to be required for the development of sexual
439 stages (60). Additionally, TgSUB1 localizes to micronemes and is used for processing of
440 micronemal proteins that are required for invasion of *T. gondii* into host cells (61).
441 However, PfSUB1 is critical for egress of *Plasmodium* merozoites, localizes to exonemes,
442 and upon secretion into the PV, processes both micronemal and non-micronemal proteins
443 (22, 62). These differences could be related to their development within different host
444 cells. *Plasmodium* prefers the erythrocyte for its asexual expansion and *Toxoplasma* is
445 able to make its home within any nucleated cell. Another factor is the difference in the
446 primary structure of TgERC and PfERC, which possesses an additional putative EF-hand
447 domain compared to its homolog in *T. gondii.* Therefore, it is not surprising that the
448 biological role of TgERC may be different from the function of PfERC. This was evident
449 in the data that suggest that TgERC plays a role in ER Ca^{2+} storage but PfERC may not
450 (Figures 4I, 4J and Supplementary Figure 3). It is interesting to note that there are no
451 orthologues of many Ca^{2+} entry channels such as store-operated channels (ORAI), or
452 their partners such as the ER sensor protein stromal interaction molecule (STIM) in the
453 genome of apicomplexan parasites. Future work on identifying the interacting partners of

454 TgERC may provide some clues as to the identity of putative ER Ca^{2+} sensors that could
455 regulate the function Ca^{2+} entry channels in these divergent parasites.
456 During the formation of daughter merozoites in schizonts, several key egress and
457 invasion related organelles essential for propagation of the infection are generated. The
458 ER is thought to play a key role in the biogenesis of these organelles and the ER is
459 responsible for transporting the essential proteins to these organelles (32, 33). As an ER-
460 resident protein, knockdown of PfERC could affect several ER functions such as protein
461 trafficking, organellar biogenesis, and Ca^{2+} signaling. Therefore, we tested if PfERC
462 functions in the trafficking of proteins required for schizont to ring transition such as MSP1,
463 AMA1, and RAP1. A defect in the secretory pathway would explain the observed
464 deficiencies in the proteolytic processing of SUB1, MSP1 and AMA1, as transport out of
465 the ER is required for their maturation (10, 26, 52, 63). However, super-resolution and
466 electron microscopy experiments showed that trafficking of proteins to the merozoite
467 surface, micronemes, and rhoptries or their biogenesis are not affected (Figures 3D and
468 5E-5H). Likewise, Western blot analysis showed that the proteolytic processing of a
469 rhoptry protein, RAP1, which is processed after transport to the organelle, is not affected
470 by knockdown of PfERC (Figures 5G, and 6F-G) (23, 24). These data show that
471 knockdown of PfERC does not result in a generalized defect in protein trafficking via the
472 ER or in organelle biogenesis.
473 Immunofluorescence microscopy, electron microscopy, and Ca^{2+} measurements
474 ruled out a role for PfERC in Ca^{2+} storage, protein trafficking, or organelle biogenesis
475 (Figures 3D, 5E-G, 6F, 6G and Supplementary Figure 3). Another interesting possibility
476 is that PfERC may play a role the signal-dependent release of Ca^{2+} from the ER. PfERC
477 is a member of the CREC family of proteins and other members of this family are known
478 to play key roles in the function of ligand-gated Ca^{2+} channels. For example, calumenin
479 and reticulocalbin 1 have been shown to interact with the Ryanodine and IP_3 receptors,
480 respectively, and regulate their function (64, 65). It has also been suggested that some
481 CREC members serve as Ca^{2+} sensors in the ER as they exhibit calcium-dependent
482 structural changes (66, 67). This is difficult to test in *Plasmodium* since there are no clear
483 homologs for a ligand-dependent Ca^{2+} channel in its genome (20). At present, Ca^{2+}
484 measurements in *P. falciparum* require lysis of the RBCM that results in loss of the RBC

485 contents and this complicates any conclusions reached from egress-related experiments
486 since it is unknown if components in the RBC are essential for the signaling pathway
487 required for egress. However, this may be addressed by using less invasive approaches
488 that do not require lysis of the RBCM such as genetically-encoded Ca^{2+} indicators (GECI)
489 to measure changes in ER Ca^{2+} during egress or by studying the egress-related roles of
490 proteins that interact with PfERC.

491 Consistent with a role for PfERC in signal-dependent release of Ca^{2+} from the ER,
492 we observed that knockdown resulted in a clear defect in egress (Figures 2G, 3, and 5A-
493 D). Egress is a rapid process and the genetic mechanisms in the ER of apicomplexan
494 parasites that control the signal-dependent release of Ca^{2+} from the ER are unknown.
495 Our data supports a model where PfERC functions in the signaling pathway that releases
496 Ca^{2+} from the ER required for the egress of merozoites from the infected RBC. This model
497 would also predict that PfERC plays a role in the release of Ca^{2+} from the ER, such that
498 in the absence of PfERC, the ER is unable to release Ca^{2+} upon the requisite signal. Such
499 a putative role for PfERC is supported by data which show that knockdown of PfERC
500 inhibits egress by preventing the breakdown of the PVM (Figure 3C-D).

501 A key enzyme that is required for initiating egress is the protease SUB1. Another
502 hypothesis we tested was if PfERC was required for the Ca^{2+} dependent activity of SUB1.
503 This serine proteases plays a critical role in disruption of both the PVM and RBCM. It is
504 produced as an 82-kDa zymogen in the ER, where it rapidly self-processes into a 54-kDa
505 semi-proenzyme that remains associated with the cleaved prodomain, thus inhibiting its
506 activity (43). The autocatalytic activity of SUB1 is Ca^{2+} dependent and therefore, it was
507 possible that PfERC was required for this autoprocessing event by providing the required
508 Ca^{2+} to SUB1. This would explain the phenotypes observed during knockdown of PfERC
509 as they are similar to that seen when SUB1 is conditionally knocked out (29). However,
510 our data show only the second processing step of SUB1 that produces the mature, active
511 form of the protease (p54 to p47), is affected (Figure 5A-B and Supplementary Figure
512 4A). There is no effect on the Ca^{2+} dependent autoprocessing of SUB1 (p83 to p54) that
513 occurs in the ER (Figure 5A-B and Supplementary Figure 4A). The processing of SUB1
514 from p54 to p47 occurs once it is trafficked out of the ER and putatively during secretion
515 of exoneme vesicles (25). This processing defect reduces the activity of SUB1 as it is

516 defective in processing its substrate, MSP1 (Figure 5A-D). This processing event
517 happens after the secretion of SUB1 into the PV as MSP1 is a GPI-anchored protein on
518 the membrane of merozoites (28). These data suggest that PfERC is required for
519 secretion of exonemes, which is consistent with a role for PfERC in signal-dependent
520 release of Ca^{2+} from the ER.

521 A principal finding of these studies is the identification of the first protein in the ER
522 of *P. falciparum* with a specific role in egress of malaria parasites from RBCs and
523 potentially in the invasion of parasites into the RBC (Figures 2, 3, 5 and 6). These studies
524 lay the foundation for understanding the vital and key role that ER-resident proteins play
525 in the egress of human malaria parasites from their infected RBC and their re-entry into
526 the host cell. Some studies have suggested that a key class of antimalarials containing
527 endoperoxides, which includes the frontline antimalarial artemisinin, may target PfERC
528 (59) and one of the transcriptomic responses of artemisinin-resistant parasites is the
529 overexpression of PfERC (68). These data suggest that targeting PfERC, and thus
530 egress, is a viable strategy for antimalarial drug development.

531

532 **Material and Methods**

533 **Cell culture and transfections.** *Plasmodium* parasites were cultured in RPMI 1640
534 medium supplemented with Albumax I (Gibco) and transfected as described earlier (69-
535 72). *T. gondii* tachyzoites were maintained in vitro by serial passage in Dulbecco's
536 modified minimal essential media (DMEM) with 1% FBS, 2.5 µg/ml amphotericin B, and
537 100 µg/ml streptomycin. Host cells were human telomerase reverse transcriptase
538 immortalized foreskin fibroblasts (hTERT) (73).

539 To generate PfERC-*glmS* and PfERC-*M9* parasites, a mix of two plasmids (50µg
540 of each) was transfected in duplicate into 3D7 parasites. The plasmid mix contained
541 pUF1-Cas9-guide (74) which contains the DHOD resistance gene, and pPfERC-HA-
542 SDEL-*glmS* or pPfERC-HA-SDEL-*M9*, which are marker-free. Drug pressure was applied
543 48hrs after transfection, using 1µM (DSM1) (75), selecting only for Cas9 expression.
544 DSM1 was then removed from the culturing medium once the parasites were detected in
545 the culture, around 3 weeks post-transfection.

546 The *Δtgerc* knock-out line was generated by inserting the dihydrofolate reductase
547 (DHFR) gene into the first ~300 nucleotides of the *tgerc* gene to disrupt the coding
548 sequence. The CRISPR/Cas9 gene knockout method previously reported was used (39).
549 A fragment corresponding to the single guide RNA (sgRNA) using primers 1+2 was
550 cloned into pSAG1:CAS9::U6:sgUPRT (Addgene #54467) using the Q5 site-directed
551 mutagenesis kit (NEB). The resulting pSAG1:CAS9::U6:sgTgERC was co-transfected
552 with the DHFR cassette (in proportion 3:1) using primers 3+4 to tachyzoites of the RH
553 strain. After pyrimethamine selection (1 μM), parasites were sub-cloned by limiting dilution
554 and screened for positive clones by PCR using primers 5+6 shown in Table S1.
555
556 **Construction of PfERC plasmids.** Genomic DNA was isolated from *P. falciparum*
557 cultures using the QIAamp DNA blood kit (Qiagen). Constructs utilized in this study were
558 confirmed by sequencing. PCR products were inserted into the respective plasmids using
559 the In-Fusion cloning system (Clontech), the sequence- and ligation-independent cloning
560 (SLIC) method (71, 72), T4-ligation (New England BioLabs), or site-directed mutagenesis
561 using QuickChange (Agilent). To generate the pHA-SDEL-*glmS*/*M9* plasmid, primers 7+8
562 were used to add an SDEL sequence at the end of the HA tag in pHA-*glmS* and pHA-*M9*
563 plasmids (71, 72).
564 For the generation of the PfERC-*glmS*/*M9* conditional mutants, pHA-SDEL-
565 *glmS*/*M9* plasmid was used as a donor DNA template consisting of two homology regions
566 flanking the HA-SDEL tag and the *glmS* or *M9* sequence. To allow efficient genomic
567 integration of the pHA-SDEL-*glmS* and pHA-SDEL-*M9* donor plasmids, 800-bp
568 sequences were used for each homology region. The C-terminus of the *pferc* coding
569 region was PCR amplified from genomic DNA using primers 9+10 (containing the shield
570 mutation) and was inserted into pHA-SDEL-*glmS* and pHA-SDEL-*M9* using restriction
571 sites SacII and AfeI. The 3'UTR of *pferc* was PCR amplified from genomic DNA using
572 primers 11+12 and was inserted into pHA-SDEL-*glmS* and pHA-SDEL-*M9* (already
573 containing the C-terminus region) using restriction sites HindIII and NheI. For expression
574 of PfERC guide RNA, oligos 13+14 were inserted into pUF1-Cas9-guide as previously
575 described (74, 76). Briefly, pUF1-Cas9-guide was digested with BtgZI and annealed

576 oligos were inserted using the SLIC method. Primers 9+12 and primers 9+15 (which
577 recognizes the *glmS*/*M9* sequence) were used for clone verification.
578
579 ***Plasmodium* growth assays**. Asynchronous growth assays were done as described
580 previously (71, 72). Briefly, 5mM glucosamine (GlcN) (Sigma) was added to the growth
581 medium and parasitemia was monitored every 24hrs via flow cytometry using a CyAn
582 ADP (Beckman Coulter) or CytoFLEX (Beckman Coulter) instrument and analyzed by
583 FlowJo software (Treestar, Inc.). As required, parasites were subcultured to avoid high
584 parasite density, and relative parasitemia at each time point was back-calculated based
585 on actual parasitemia multiplied by the relevant dilution factors. One hundred percent
586 parasitemia was determined as the highest relative parasitemia and was used to
587 normalize parasite growth. Data were fit to exponential growth equations using Prism
588 (GraphPad Software, Inc.).
589 To determine the ring:schizont ratio of PfERC-*glmS* and PfERC-*M9* parasites,
590 7.5mM GlcN was added to percoll isolated schizont-stage parasites and parasites were
591 allowed to egress and reinvade fresh RBCs. Two hours later, 5% sorbitol +7.5mM GlcN
592 was added to the invaded culture to lyse any remaining schizonts and isolate two-hour
593 rings. The ring-stage parasites were grown again in media supplemented with GlcN. Then
594 samples were taken at 44hrs, 48hrs, and 56hrs, and read by flow cytometry to determine
595 the population of rings and schizonts present at those times using FlowJo software
596 (Treestar, Inc.). To determine the development of each life cycle stage during the asexual
597 lifecycle of PfERC-*glmS* and PfERC-*M9* parasites, 7.5mM was added to percoll isolated
598 schizont-stage parasites and parasites were allowed to egress and reinvade fresh RBCs.
599 Time points were then taken by blood smears and the percentage of the specific lifecycle
600 stage was calculated as: $\% \; of \; stage = \frac{number \; of \; specific \; stage}{total \; number \; of \; parasites}$. Time 0hr is when GlcN was
601 added. To determine the % amount of egressing or invading parasites, we took the %
602 values of schizonts or rings at 44hrs and subtracted that number from % values of
603 schizonts or rings at 12hrs later.
604 For growth assays using Compound 1, synchronized schizonts were grown with
605 7.5mM GlcN for about 48hrs. Then, schizonts were percoll isolated and incubated with
606 Compound 1 for 4hrs and then removed by gently washing parasites twice with 1mL of

607 warm, complete RPMI. Parasites were resuspended with fresh media and RBCs and
608 samples were taken and read by flow cytometry. DNA content was determined using
609 Hoechst staining (ThermoFisher).
610
611 **Plaque assays.** Plaque assays were done as previously described (77). Two hundred
612 freshly egressed tachyzoites were used to infect a confluent monolayer of hTERT
613 fibroblasts followed by 7 days of growth. Monolayers were fixed and stained with 5x
614 crystal violet. Plaque sizes were analyzed with FIJI by measuring the area of fifteen
615 plaques per biological replicate. At least 3 biological experiments were done for wild type
616 control RH and TgERC knockout.
617
618 **Generation of TgERC antibody.** The *tgerc* gene (TgGT1_229480) was identified from
619 ToxoDB. Total RNA of the wild type strain (RH) was extracted from freshly lysed parasites
620 using Trizol® reagent (Sigma) following the manufacturer's instructions. The RNA sample
621 was further treated with DNAse I for 10 min at 37 °C (New England Biolabs) to remove
622 contaminating DNA. Four micrograms of purified mRNA were used to synthesize cDNA
623 using the superscript III first-strand synthesis system according to the manufacturer's
624 protocol (ThermoFisher Scientific-Life Technologies). *T. gondii* cDNA was used as a
625 template for amplifying the *tgerc* gene (~ 1 Kb) with the primers 16+17 (Table S1). The
626 PCR product was gel purified and cloned using the pET32 Ek/LIC vector system
627 (Novagen). The construct was sequenced and transformed into *E. coli* BL21(DE3)-
628 CodonPlus. Expression of the TgERC protein was induced for 3 h at 37°C with 0.4 mM
629 isopropyl-β-D-thiogalactopyranoside (IPTG). Cells were pelleted and resuspended in
630 equilibration/binding buffer (50 mM Na_3PO4, 300 mM NaCl, 10 mM Imidazole, and 1:500
631 protease inhibitor cocktail P-8849). Cells were then sonicated on ice for 80 seconds total
632 with amplitude set to 30% (Branson Digital Sonifier Model 250) and centrifuged at 12,000
633 rpm at 4°C for 20 min. The supernatant was filtered through a 0.45 µm cellulose acetate
634 filter (VWR) and the protein was purified using HisPur Ni-NTA chromatography following
635 instructions from the manufacturer. Unbound proteins were washed off with a total volume
636 of 12 ml of wash buffer (50 mM Na_3PO_4, 300 mM NaCl and 20 mM Imidazole) and the

637 TgERC recombinant protein was eluted with 5 ml of elution buffer (50 mM Na_3PO_4 ,300
638 mM NaCl and 250 mM Imidizole). Elution fractions were verified by SDS-PAGE.
639 Antibodies against the TgERC recombinant protein were generated in mice. Six
640 CD-1 mice (Charles River, Inc.) were intraperitoneally injected with 100 µg of purified
641 TgERC recombinant protein mixed 1:1 with complete Freund adjuvant. Mice were
642 boosted twice with 50 µg of antigen and the final serum was collected by cardiac puncture
643 after CO_2 euthanasia (IACUC protocol A2018 02-021-Y1-A0)
644
645 **Western blotting.** Western blotting for *Plasmodium* parasites was performed as
646 described previously (71, 72). Briefly, parasites were permeabilized selectively by
647 treatment with ice-cold 0.04% saponin in PBS for 10 min and pellets were collected for
648 detection of proteins with the parasite. For detection of MSP1, schizonts were isolated on
649 a Percoll gradient (Genesee Scientific) and whole-cell lysates were generated by
650 sonication. The antibodies used in this study were rat anti-HA (3F10; Roche, 1:3,000),
651 rabbit anti-HA (715500; Invitrogen, 1:100), rabbit anti-PfEF1α (from D. Goldberg,
652 1:2,000), mouse anti-plasmepsin V (from D. Goldberg, 1:400), rabbit anti-SUB1 (from Z.
653 Dou and M. Blackman, 1:10,000), rat anti-AMA1 (28G2; Alan Thomas via BEI Resources,
654 NIAID, NIH 1:500), mouse anti-MSP1 (12.4; European Malaria Reagent Repository,
655 1:500) and mouse anti-RAP1 (2.29; European Malaria Reagent Repository, 1:500). The
656 secondary antibodies that were used are IRDye 680CW goat anti-rabbit IgG and IRDye
657 800CW goat anti-mouse IgG (LICOR Biosciences) (1:20,000). The Western blot images
658 were processed using the Odyssey Clx LICOR infrared imaging system software (LICOR
659 Biosciences). Calculation of knockdown and processing ratios was determined by both
660 the Odyssey infrared imaging system software and ImageJ 1.8 (NIH).
661 For *T. gondii*, lysates were prepared by resuspending a pellet of 1 x 10^8 tachyzoites
662 in 50 µl of Cell Lytic^M lysis buffer containing 12.5 U benzonase and 1X protease cocktail
663 inhibitor (P8340 Sigma). The reaction was stopped with one volume of 2% SDS and 1
664 mM EDTA. Total lysates were boiled in Laemmli sample buffer (BioRad) (78).
665 Immunoblots were done following established protocols using polyclonal mouse anti-
666 TgERC serum (1:1,000). The Odyssey Clx LICOR system was used for detection, and
667 the secondary antibody was goat anti-mouse IRDye 800WC (1:10,000).

668

669 **Immunofluorescence microscopy.** For IFAs, cells were fixed as described previously
670 (71, 72). The antibodies used for IFA were: rat anti-HA antibody (clone 3F10; Roche,
671 1:100), rat anti-PfGRP78 (MRA-1247; BEI Resources, NIAID, NIH 1:100), mouse anti-
672 MSP1 (12.4; European Malaria Reagent Repository, 1:500), rat anti-AMA1 (28G2; Alan
673 Thomas via BEI Resources, NIAID, NIH 1:500), and mouse anti-RAP1 (2.29; European
674 Malaria Reagent Repository, 1:500). Secondary antibodies used were anti-rat antibody
675 conjugated to Alexa Fluor 488 or 546 and anti-rabbit antibody conjugated to Alexa Fluor
676 488, (Life Technologies, 1:100). Cells were mounted on ProLong diamond with 4',6'-
677 diamidino-2-phenylindole (DAPI) (Invitrogen) and imaged using a Delta-Vision II
678 microscope system with an Olympus IX-71 inverted microscope using a 100x objective
679 or an Elyra S1 SR-SIM microscope (Zeiss, Jena, Germany). Image processing, analysis,
680 and display were performed using SoftWorx or Axiovision and Adobe Photoshop.
681 Adjustments to brightness and contrast were made for display purposes.
682 For *T. gondii* IFAs, extracellular parasites were collected and purified as previously
683 described (77). Parasites were washed once with buffer A with glucose (BAG, 116 mM
684 NaCl, 5.4 mM KCl, 0.8 mM $MgSO_4$, 5.5 mM glucose and 50 mM HEPES, pH 7.4) and an
685 aliquot with 2 x 10^4 parasites was overlaid on a coverslip previously treated with poly-L-
686 Lysine. Intracellular tachyzoites were grown on hTERT cells on coverslips previously
687 infected with freshly lysed parasites. Both extracellular and intracellular parasites
688 preparations were fixed with 2.5% paraformaldehyde for 20 min at room temperature
689 (RT), permeabilized with 0.25% Triton X-100 and blocked with 3% bovine serum albumin
690 (BSA). For co-localization studies parasites were exposed to primary antibodies mouse
691 anti-TgERC 1:1000 and rabbit anti-GFP 1:800 after transfection with the P30-GFP-HDEL
692 plasmid (79). The secondary antibodies were Alexa-Fluor488 goat-anti mouse and Alexa-
693 Flour594 goat-anti rabbit at 1:1,000. Slides were examined using an Olympus IX-71
694 inverted fluorescence microscope with a photometric CoolSNAP HQ charge-coupled
695 device (CCD) camera driven by DeltaVision software (Applied Precision).
696

697 **Invasion Rate Quantification.** To calculate the invasion rate, parasites were treated as
698 described previously (47). Briefly, 7.5mM GlcN was added to percoll isolated schizont-

699 stage parasites and parasites were allowed to egress and reinvade fresh RBCs. 48hrs
700 later, schizonts were percoll purified and incubated with 20μM E-64 (Sigma) at 37°C in
701 an incubator for 7-8hrs. Once incubation was done, merozoites were isolated by gently
702 resuspending and passing the schizonts through a 1.2μm Acrodisic Syringe Filter (PALL).
703 Merozoites were spun at 2000xg for 5min, and then resuspended in 100μL of complete
704 RMPI medium and added to a 1mL culture of uninfected RBCs at 2% hematocrit. Cultures
705 were grown in a FluoroDish cell culture dish (World Precision Instruments) and gassed in
706 a chamber for 20-24hrs. Invasion rate was then measured by the following equation: $IR =$
707 $iRBC \cdot \left[\frac{RBC/\mu L}{Mz/\mu L}\right]$ where "*iRBC*" is the parasitemia 20-24hrs later, "*RBC/μL*" are the free
708 RBCs used before addition of merozoites and "*Mz/μL*" are the merozoites found in the
709 100μL suspension used before adding to fresh RBCs. Values for these variables were
710 acquired by flow cytometry (CytoFLEX Beckman Coulter) with cells stained with acridine
711 orange. The data were normalized using the IR values for PfERC-*M9* merozoites as
712 100%.
713
714 **Transmission Electron Microscopy.** 7.5mM GlcN was added to percoll isolated
715 schizont-stage parasites and parasites were allowed to egress and reinvade fresh RBCs.
716 48hrs later, parasites were percoll-isolated and then incubated with 20μM E-64 for 8hrs.
717 After incubation, parasites were washed with 1X PBS and gently resuspended in 2.5%
718 glutaraldehyde in 0.1M sodium cacodylate-HCl (Sigma) buffer pH 7.2 for 1hr at room
719 temperature. Parasites were then rinsed in 0.1M Cacodylate-HCl buffer before agar-
720 enrobing the cells in 3% Noble agar. Parasites were post fixed in 1% osmium
721 tetroxide/0.1M Cacodylate-HCl buffer for 1 hour and rinsed in buffer and deionized water.
722 Dehydration of the parasite samples was done with an ethanol series and then exposed
723 to Propylene oxide before infiltration with Epon-Araldite. The blocks of parasites were
724 trimmed, and sections were obtained using a Reichert Ultracut S ultramicrotome (Leica,
725 Inc., Deerfield, IL). 60-70nm sections were placed on 200-mesh copper grids and post-
726 stained with ethanolic uranyl acetate and Reynolds Lead Citrate. Grids were viewed with
727 a JEOL JEM-1011 Transmission Electron Microscope (JEOL USA, Inc., Peabody, MA)
728 using an accelerating voltage of 80 KeV. Images were acquired using an AMT XR80M

729 Wide-Angle Multi-Discipline Mid-Mount CCD Camera (Advanced Microscopy
730 Techniques, Woburn, MA).
731
732 **Scanning Electron Microscopy.** 7.5mM GlcN was added to percoll isolated schizont-
733 stage parasites and parasites were allowed to egress and reinvade fresh RBCs. 48hrs
734 later, parasites were percoll-isolated and then incubated with 2μM Compound 2 for 4
735 hours without shaking at 37°C in an incubator. After incubation, parasites were washed
736 twice with warm, complete RPMI + 7.5mM GlcN. Samples were taken immediately after
737 washing off Compound 2 and then 30min after and fixed as with TEM samples. Parasites
738 were rinsed with 0.1M Cacodylate-HCl buffer before placing on glass coverslips prepared
739 with 0.1% Poly-L-lysine. Parasites were allowed to settle onto the glass coverslips in a
740 moist chamber overnight and then post fixed in 1% osmium tetroxide/0.1M Cacodylate-
741 HCl buffer for 30 minutes. Cells on coverslips were rinsed three times in deionized water
742 and then dehydrated with an ethanol series. The glass coverslips were critical point dried
743 in an Autosamdri-814 Critical Point Dryer (Tousimis Research Corporation, Rockville,
744 MD), mounted onto aluminum pin stubs with colloidal paint, and sputter coated with gold-
745 palladium with a Leica EM ACE600 Coater (Leica Microsystems Inc., Buffalo Grove, IL).
746 Stubs were examined with the FE-SEM FEI Teneo (FEI, Inc., Hillsboro, OR) using the
747 secondary electron detector to obtain digital images.
748
749 **Calcium Measurements.** To measure Ca^{2+} in PfERC mutants, knockdown was induced
750 on synchronized schizonts. After 48hrs, schizonts were percoll purified and permeabilized
751 selectively by treatment with ice-cold 0.04% saponin in PBS for 10 min. Isolated parasites
752 were then washed 2X with BAG Buffer (116mM NaCl, 5.4mM KCl, 0.8mM $MgSO_4 \cdot 7H_2O$,
753 50mM HEPES, 5.5mM Glucose) + 7.5mM GlcN and incubated with 10μM Fluo-4AM
754 (ThermoFisher) for 45min while rocking at 37°C. After incubation, cells were washed 2X
755 with BAG buffer + 7.5mM GlcN and immediately taken for fluorimetric measurements.
756 Fluorescence measurements were carried out in a cuvette (Sarstedt) containing parasites
757 suspended in 2.5 ml of BAG buffer and 100uM EGTA (Sigma). The cuvette was placed
758 in a Hitachi F-4500 fluorescence spectrophotometer and Fluo-4AM excitation was done
759 at 505 nm with emission read at 530 nm (80). Drugs and reagents were added via a

760 Hamilton syringe. Final concentration of CPA (Sigma) was 3 μM, and Ionomycin (Sigma)
761 at 2μM.
762 Loading of *Toxoplasma gondii* tachyzoites with Fura-2AM (ThermoFisher) was
763 done as previously described (40). Briefly, freshly collected parasites were washed twice
764 with BAG by centrifugation (706 g for 10 min) and resuspended at a final density of 1 x
765 10^9 parasites/ml in loading buffer (BAG plus 1.5% sucrose, and 5μM Fura-2AM). The
766 suspension was incubated for 26 min at 26 °C with mild agitation. Subsequently, parasites
767 were washed twice with BAG to remove extracellular dye, re-suspended to a final density
768 of 1 x 10^9/ml in BAG and kept on ice. For fluorescence measurements, 2 x 10^7
769 parasites/ml were placed in a cuvette with 2.5 ml of BAG buffer. Fluorescence
770 measurements were done in a Hitachi F-7000 fluorescence spectrophotometer using the
771 Fura-2AM conditions for excitation (340 and 380 nm) and emission (510 nm). The Fura-
772 2AM fluorescence response to Ca^{2+} was calibrated from the ratio of 340/380 nm
773 fluorescence values after subtraction of the background fluorescence of the cells at 340
774 and 380 nm as described previously (81). The Ca^{2+} release rate is the change in Ca^{2+}
775 concentration during the initial 20 s after compound addition (41).
776
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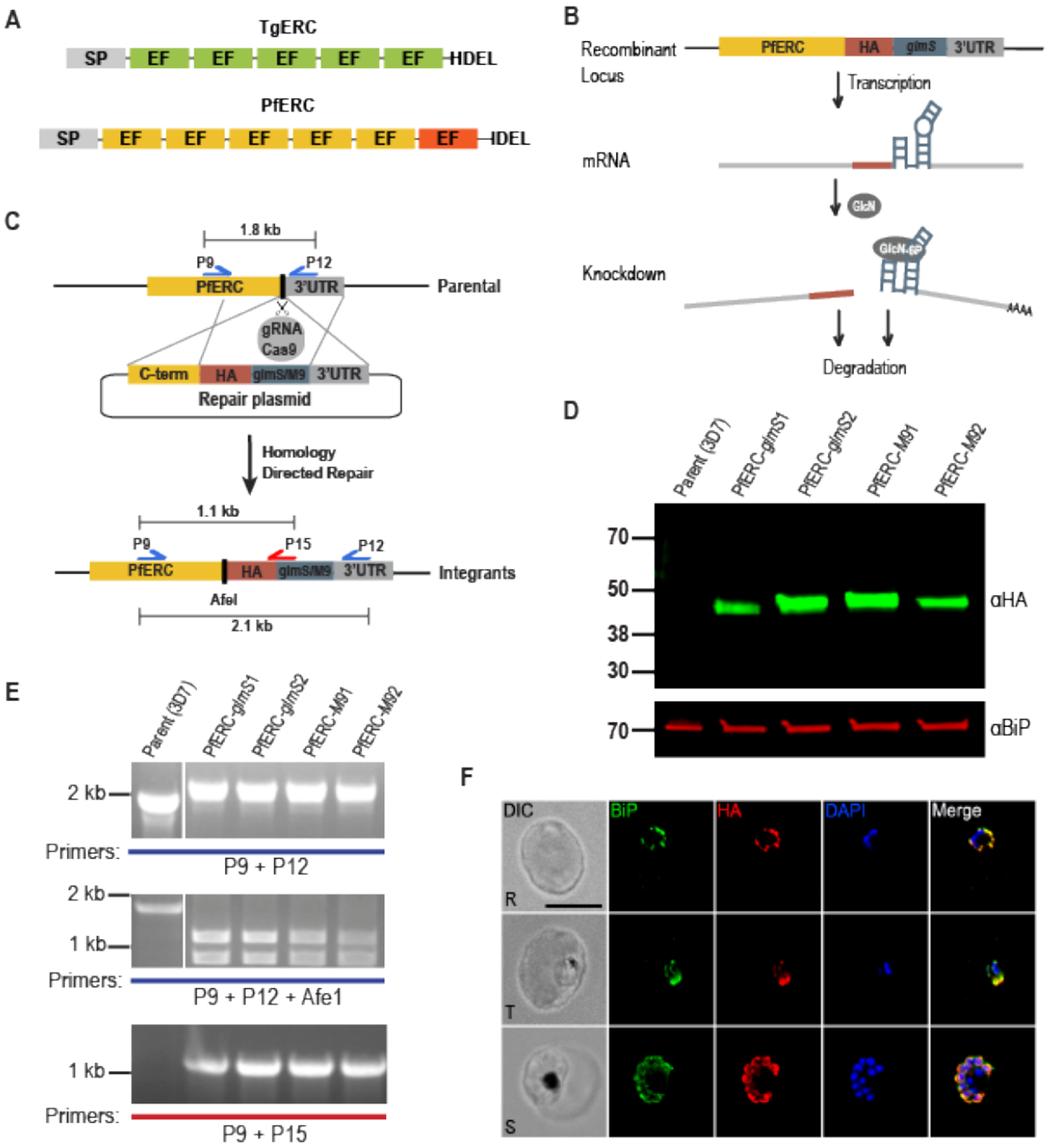

Figure 1: Generating PfERC-*glmS*/*M9* mutant parasites. (A) Schematic representation of the domain structure of PfERC and TgERC. Both proteins contain a signal peptide, 5 (TgERC) or 6 (PfERC) EF hands, and an ER-retention signal. (B) Mechanism of the conditional expression of PfERC using the *glmS* ribozyme system. This is an inactive ribozyme that is transcribed, but not translated, with the mRNA of a protein of interest. Addition of glucosamine (GlcN) leads to its phosphorylation within the

1032 cell to glucosamine-6-phosphate (GlcN-6P). GlcN-6P binds to the transcribed PfERC-
1033 *glmS* mRNA and the *glmS* ribozyme is activated and cleaves itself from the mRNA. This
1034 leads to disassociation of the mRNA from its poly-A tail and leads to the degradation of
1035 target specific mRNA. The resulting decline in mRNA levels leads to reduced protein
1036 levels and, thus, loss of gene expression. As a control, we generated parasite lines
1037 containing a mutated version of the *glmS* ribozyme, called *M9*, which cannot cleave
1038 itself upon binding of GlcN. (C) Using the CRISPR/Cas9 system, we induced a double-
1039 stranded break in the PfERC locus that was repaired by a donor plasmid containing
1040 homology templates to the PfERC locus and appended a C-terminal 3XHA tag and a
1041 stop codon followed by the *glmS* or *M9* sequence to the targeted gene. The location of
1042 diagnostic primers used to demonstrate the repair of the locus via double cross-over
1043 homologous integration are also shown (P5, P8 and P11). (D) Western blot of lysates
1044 isolated from two independent clones and the parental line (3D7) probed with anti-HA
1045 antibodies show that the PfERC gene was tagged with HA in the mutants but not the
1046 parental line. PfBiP was the loading control. (E) PCR analysis of the generated mutants
1047 using specific primers (P5+P8; Table S1) in the C-terminus and 3'UTR of PfERC shows
1048 integration of the HA tag and *glms*/*M9* ribozymes into the PfERC locus. Modification of
1049 PfERC gene introduces an AfeI restriction enzyme site in this locus that is absent in the
1050 parental line. Digesting the PCR products (using AfeI) resulting from amplification using
1051 primers P5+P8 shows that AfeI is able to digest the PCR products from our mutants but
1052 not the parental line. PCR analysis using another primer pair (P5+P11) that sits on the
1053 *glmS*/*M9* sequence shows that amplification only occurs in the mutants but not in the
1054 parental line. (F) Representative IFA of PfERC-*M9* parasites showing that tagged
1055 PfERC localizes to the ER as shown with co-localization with the ER chaperone BiP in
1056 all asexual stages of the parasite. From left to right, the images are phase-contrast
1057 micrographs of parasites, parasites stained with anti-BiP antibody (green), parasites
1058 stained with anti-HA antibody (red), parasite nucleus stained with DAPI (blue), and
1059 fluorescence merge images of the parasites. Abbreviations: R, rings; T, trophozoites; S,
1060 schizonts. Scale bar, 5μm.

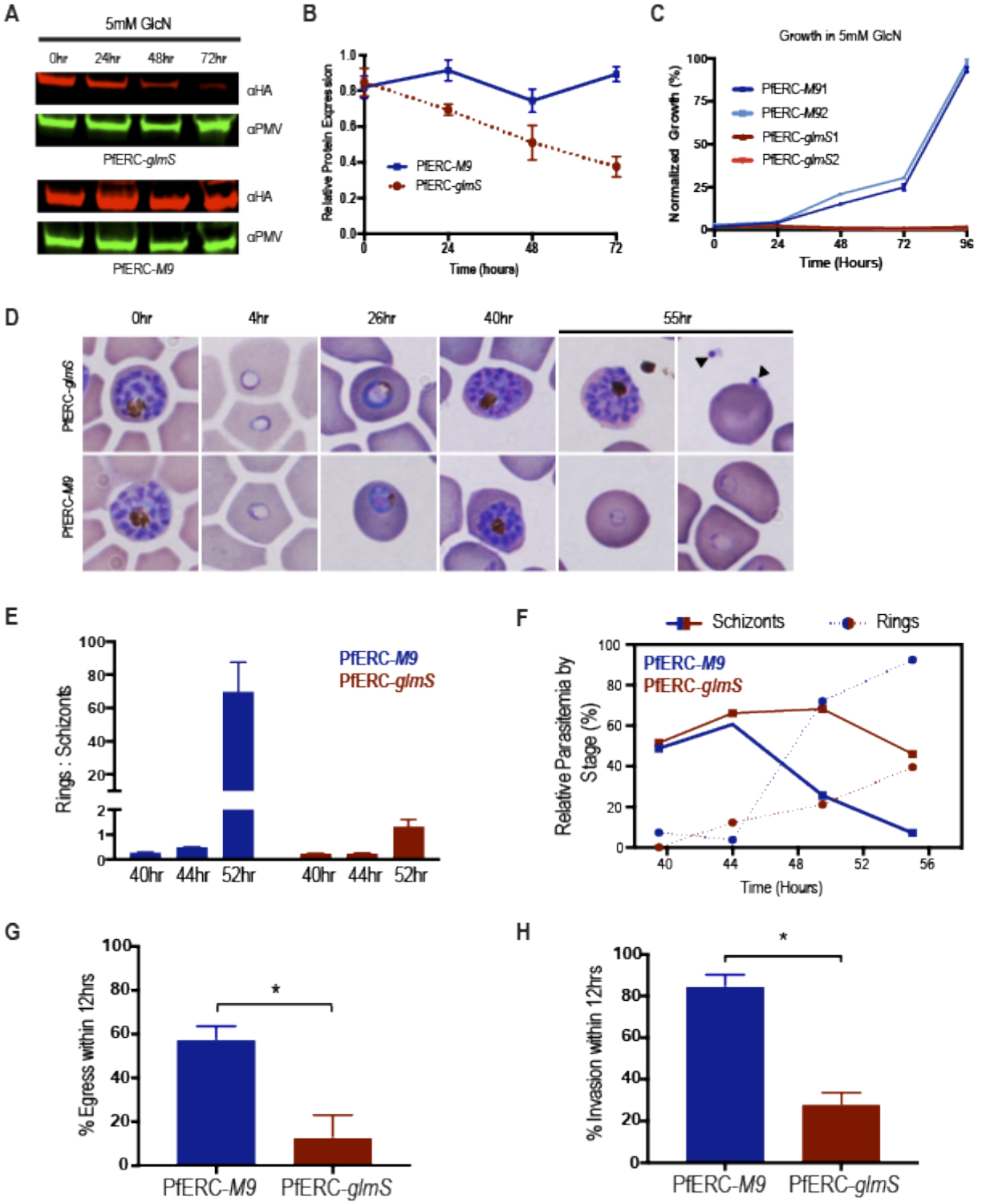

Figure 2: PfERC mutants fail to transition from schizonts to rings. (A) Western blot of parasite lysates isolated from PfERC-*glmS* and PfERC-*M9* parasites grown in the presence of 7.5 mM GlcN and probed with antibodies against HA (red) and against the ER-resident protease Plasmepsin V (PMV; green). One representative experiment out of

1065 four is shown. (B) Quantification of the overall reduction in PfERC in PfERC-*glmS* and
1066 PfERC-*M9* parasites over time after addition of GlcN, as shown in (A). Data were
1067 normalized to the loading control (PMV) and are represented as mean ± SEM (n=4
1068 biological replicates). (C) Growth curve of asynchronous PfERC-*glmS* and PfERC-*M9*
1069 clones grown in the presence of GlcN shows that PfERC is essential for asexual
1070 reproduction. Data are normalized to parasites grown without GlcN and are represented
1071 as the mean ± SEM (n=3 biological replicates). (D) Representative blood smears of
1072 synchronous PfERC-*glmS* and PfERC-*M9* parasites grown in the presence of GlcN (n=2
1073 biological replicates). (E) Ring:schizont ratio of synchronous PfERC-*glmS* and PfERC-*M9*
1074 parasites taken at 40-52hrs post-addition of GlcN. Data are represented as the mean ±
1075 SEM (n=3 biological replicates). (F) The parasites shown in blood smears (D) were
1076 counted. The amount of each lifecycle stage (ring, trophozoite, schizont) was determined
1077 as a percentage of the total number of parasites for each time point. (G) The egress of
1078 PfERC-*glmS* or PfERC-*M9* parasites was quantified by determining the amount of
1079 schizonts in blood smears as in (D) present at 44hrs and at 56hrs. Egress was quantified
1080 using the following equation: (# of schizonts at 56h / # schizonts at 44h) x100. Data are
1081 represented as mean ± SEM (n=2 biological replicates; *P<0.05, unpaired *t*-test). (H)
1082 Invasion of PfERC-*glmS* or PfERC-*M9* parasites was quantified by determining the
1083 amount of ring stages in blood smears as in (D) present at 44hrs and at 56hrs. This was
1084 quantified using the following equation: (# of rings at 44h / # rings at 56h) x100. Data are
1085 represented as mean ± SEM (n=2 biological replicates; *P<0.05, unpaired *t*-test).

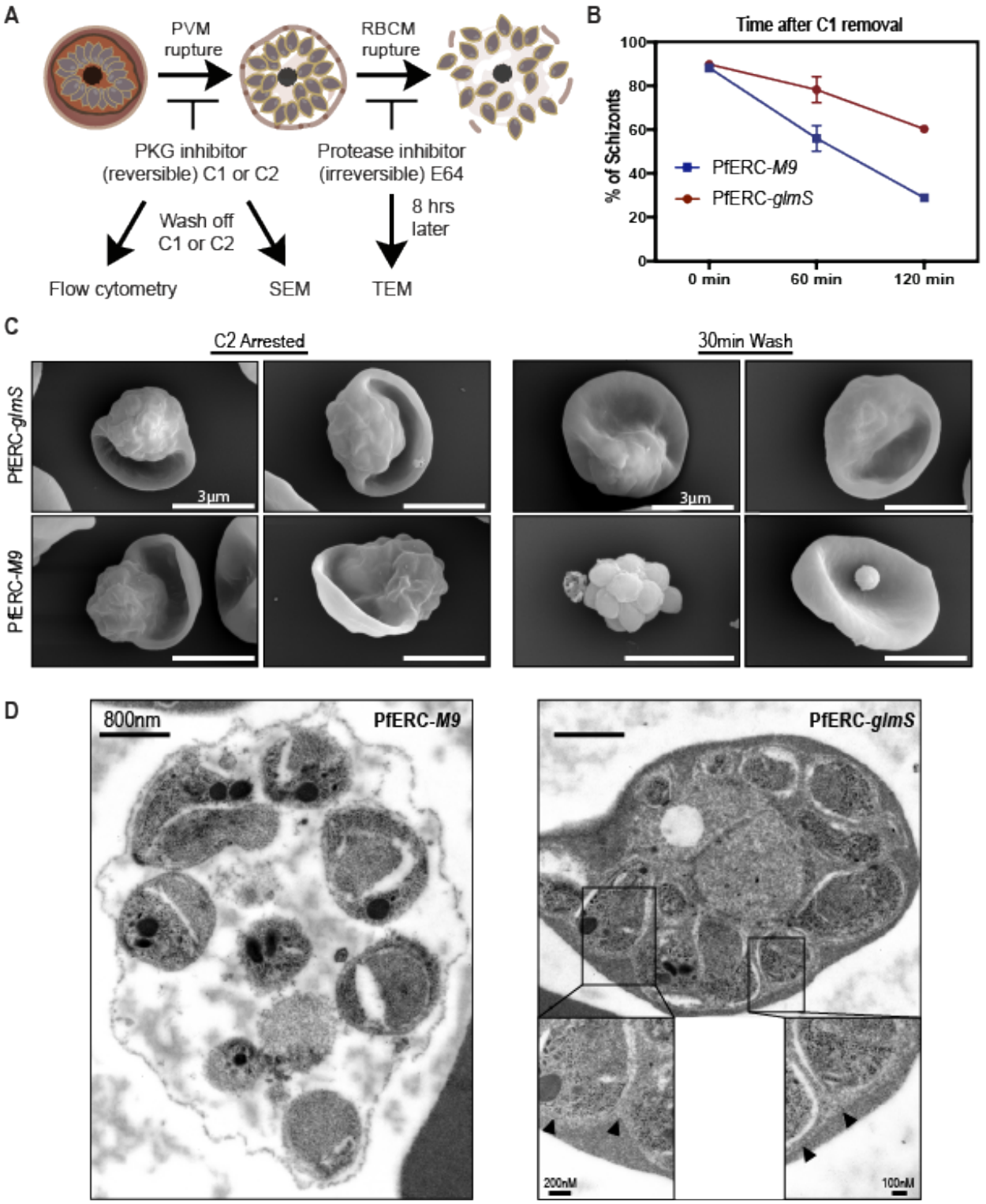

Figure 3: PfERC knockdown prevents PVM breakdown. (A) Schematic showing the experimental layout to study the effect of PfERC knockdown using compounds that inhibit egress in parasites. Abbreviations: C1/2- PKG inhibitors, compound 1 or compound 2;

1089 SEM- Scanning Electron Microscopy; TEM- Transmission Electron Microscopy. (B) As
1090 shown in (A), synchronized PfERC-*glmS* and PfERC-*M9* schizonts were observed by flow
1091 cytometry after removal of C1 (time 0hr). Schizonts were quantified as a percentage of
1092 the total amount of parasites as determined by flow cytometry. Data are represented as
1093 the mean ± SEM (n=3 biological replicates). (C) Representative SEM images of C2
1094 arrested PfERC-*glmS* (n=2 biological replicates) and PfERC-*M9* (n=2 biological
1095 replicates) mutants fixed immediately after washing off C2 and after 30mins, as shown in
1096 (A). Scale bar, 800nm. (D) Representative TEM images of PfERC-*glmS* (n=2 biological
1097 replicates) and PfERC-*M9* (n=2 biological replicates) schizonts incubated with E-64, as
1098 shown in (A). PVM is marked by black arrowheads.

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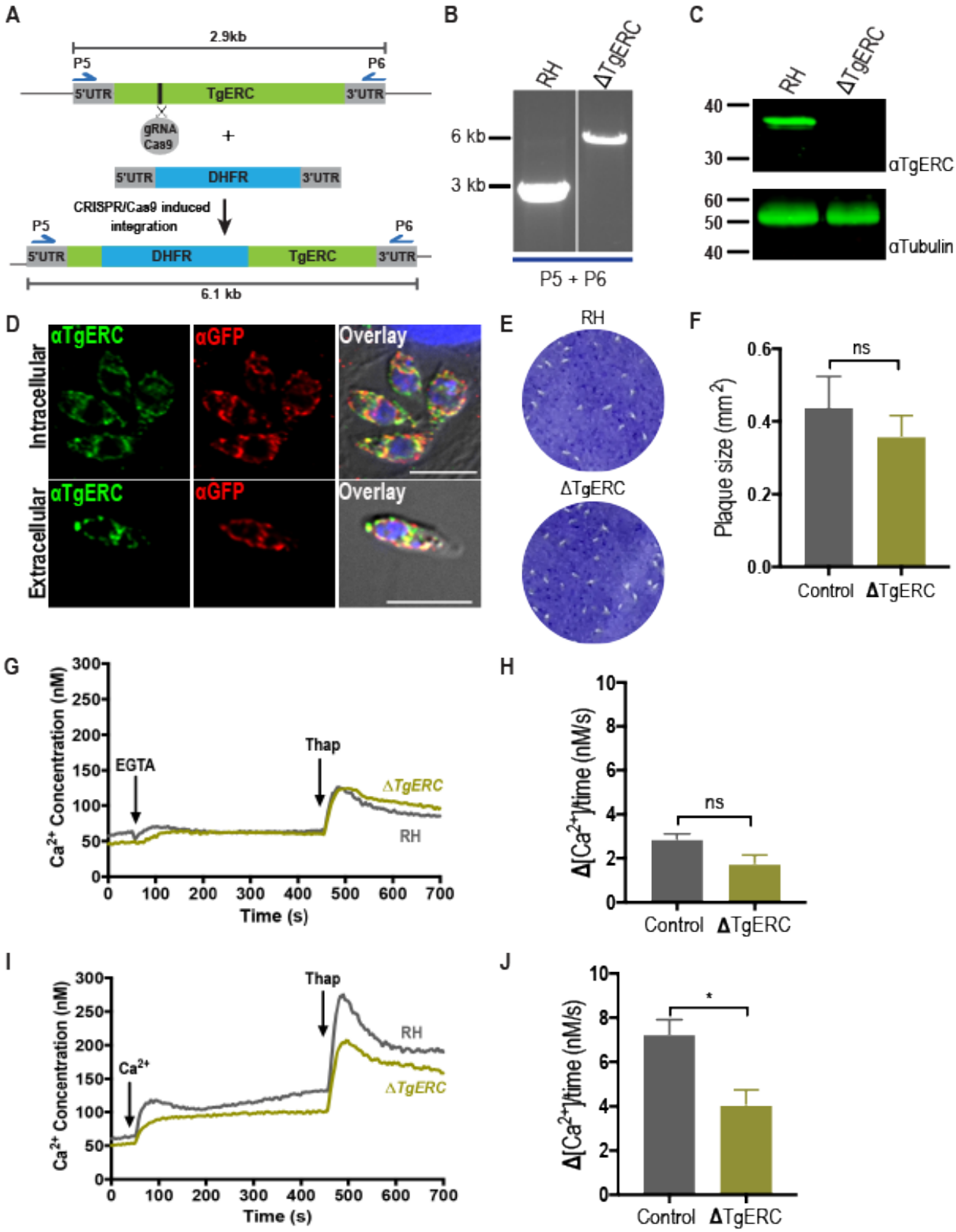

Figure 4: Generation and characterization of TgERC mutants. (A) Using CRISPR/Cas9, we generated *Δtgerc* mutants by introducing a DHFR cassette that

1103 disrupted the open-reading frame of TgERC. (B) PCR analysis using primers that sit on
1104 the homology regions used for insertion showing amplification of the WT band (~3Kb) and
1105 insertion of the DHRF cassette as demonstrated by a higher product (~6Kb) in the
1106 mutants. (C) Western blot using generated antibodies against TgERC showing the
1107 presence of TgERC in the RH (WT) parasites but not in the *Δtgerc* mutants. αTubulin was
1108 used as the loading control. (D) IFAs of either extracellular or intracellular *Δtgerc* mutants
1109 transiently transfected with the P30-GFP-HDEL plasmid (79) which contains an ER-
1110 localized GFP. Left panel shows parasites probed with anti-TgERC antibodies, middle
1111 panel shows presence of transfected GFP, and right panel shows overlay of staining with
1112 DIC. Scale bar, 5μm. (E) Representative image of one plaque assay out of three biological
1113 replicates. (F) Quantification of plaque sizes between RH and *Δtgerc* parasites (n=3
1114 biological replicates; n.s=non-significant, unpaired *t*-test). (G) Representative Ca^{2+}
1115 tracings of RH and *Δtgerc* parasites treated with the extracellular Ca^{2+} chelator EGTA and
1116 the SERCA pump inhibitor thapsigargin. (H) Quantification of the rate of Ca^{2+} release of
1117 RH and *Δtgerc* parasites from (G) (n=3 biological replicates; n.s=non-significant, unpaired
1118 *t*-test). (I) Representative Ca^{2+} tracings of RH and *Δtgerc* parasites treated with the
1119 extracellular Ca^{2+} and thapsigargin. (J) Quantification of the rate of Ca^{2+} release of RH
1120 and *Δtgerc* from (I) (n= 3 biological replicates, *$P<0.05$, unpaired *t*-test).

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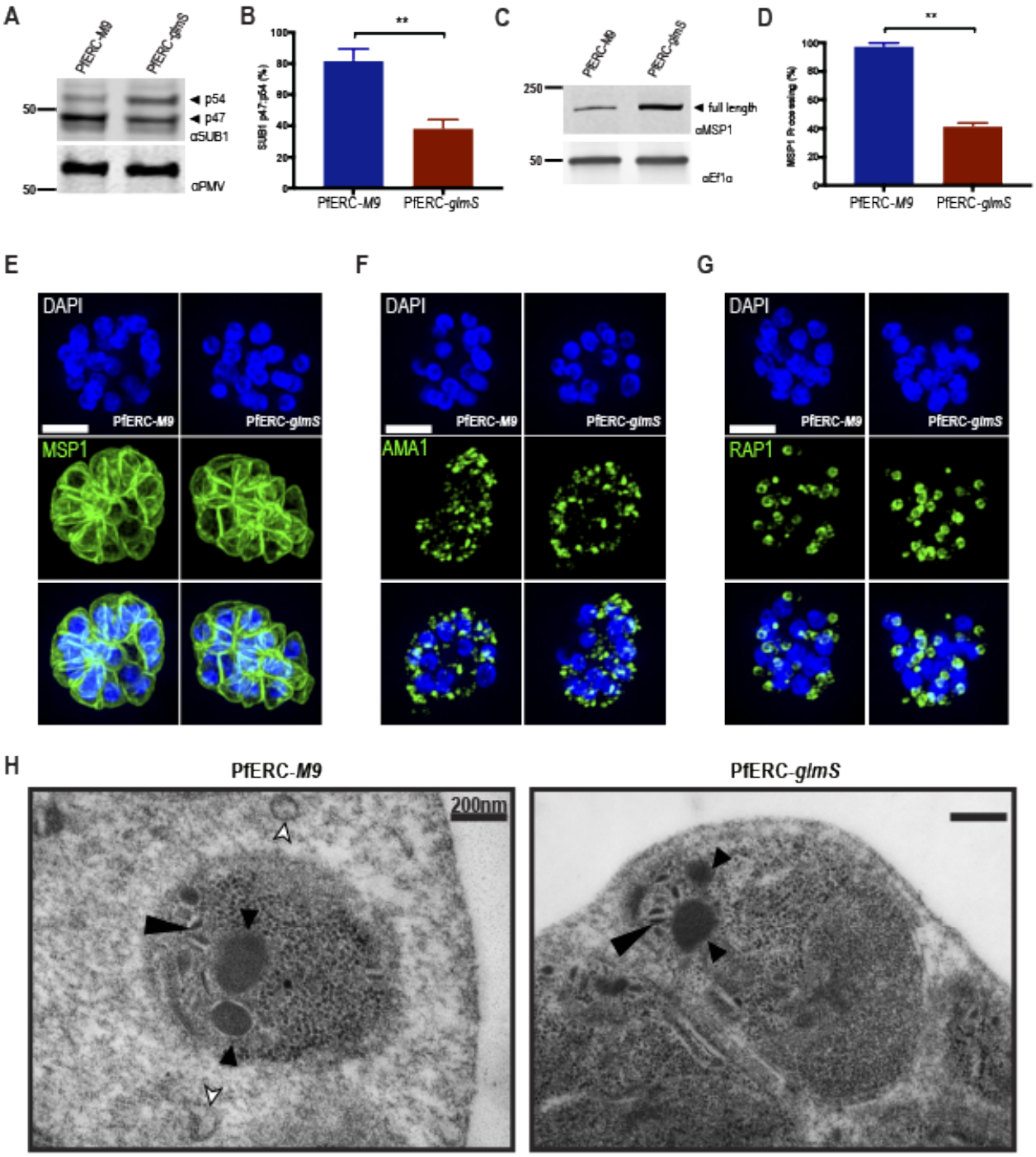

Figure 5: PfERC knockdown inhibits SUB1 and MSP1 processing. (A) Western blot of parasite lysates isolated from PfERC-*glmS* and PfERC-*M9* schizonts grown in the presence of GlcN for 48 hours and probed with anti-SUB1 antibodies (top panel) and against the ER-resident protease PMV (loading control, bottom panel). One representative experiment out of four is shown. The protein marker sizes that co-migrated

1127 with the probed protein are shown on the left. (B) Quantification of the overall reduction
1128 in processing of SUB1 in PfERC-*glmS* and PfERC-*M9* parasites over time after addition
1129 of GlcN, as shown in (A). Data were normalized to the total SUB1 (processed +
1130 unprocessed) and are represented as mean ± SEM (n=4 biological replicates; $^{**}P<0.005$
1131 unpaired *t*-test). (C) Western blot of parasite lysates isolated from PfERC-*glmS* and
1132 PfERC-*M9* schizonts grown in the presence of GlcN for 48 hours and probed with anti-
1133 MSP1 antibodies (top panel) and against the anti-EF1α (loading control, bottom panel).
1134 One representative experiment out of two is shown. The protein marker sizes that co-
1135 migrated with the probed protein are shown on the left. (D) Quantification of the overall
1136 reduction in processing of MSP1 in PfERC-*glmS* and PfERC-*M9* parasites over time after
1137 addition of GlcN. Quantification of the overall reduction in MSP1 in PfERC-*glmS* and
1138 PfERC-*M9* parasites over time after addition of GlcN, as shown in (B). Data were
1139 normalized to the loading control (EF1α) and are represented as mean ± SEM (n=2
1140 biological replicates; $^{**}P<0.005$ unpaired *t*-test). (E-G) Representative Super-Resolution
1141 SIM images of PfERC-*glmS* and PfERC-*M9* schizonts stained with antibodies against
1142 MSP1, AMA1, and RAP1. From top to bottom, the images are parasites stained with anti-
1143 MSP1 (E), anti-AMA1 (F), anti-RAP1 (G) antibodies (green), parasite nucleus stained with
1144 DAPI (blue), and fluorescence merge images of the schizonts incubated with GlcN for
1145 48hrs (n=2 biological replicates). Scale bar 2μm. (H) Representative TEM images of
1146 PfERC-*glmS* and PfERC-*M9* schizonts grown for 48hrs with GlcN and incubated with E-
1147 64 for 8 hours, as shown in Figure 3A (n=2 biological replicates). Small arrowheads point
1148 to rhoptries, large arrowheads to micronemes, and white arrowheads to PVM fragments
1149 (15). Scale bar, 200nm.

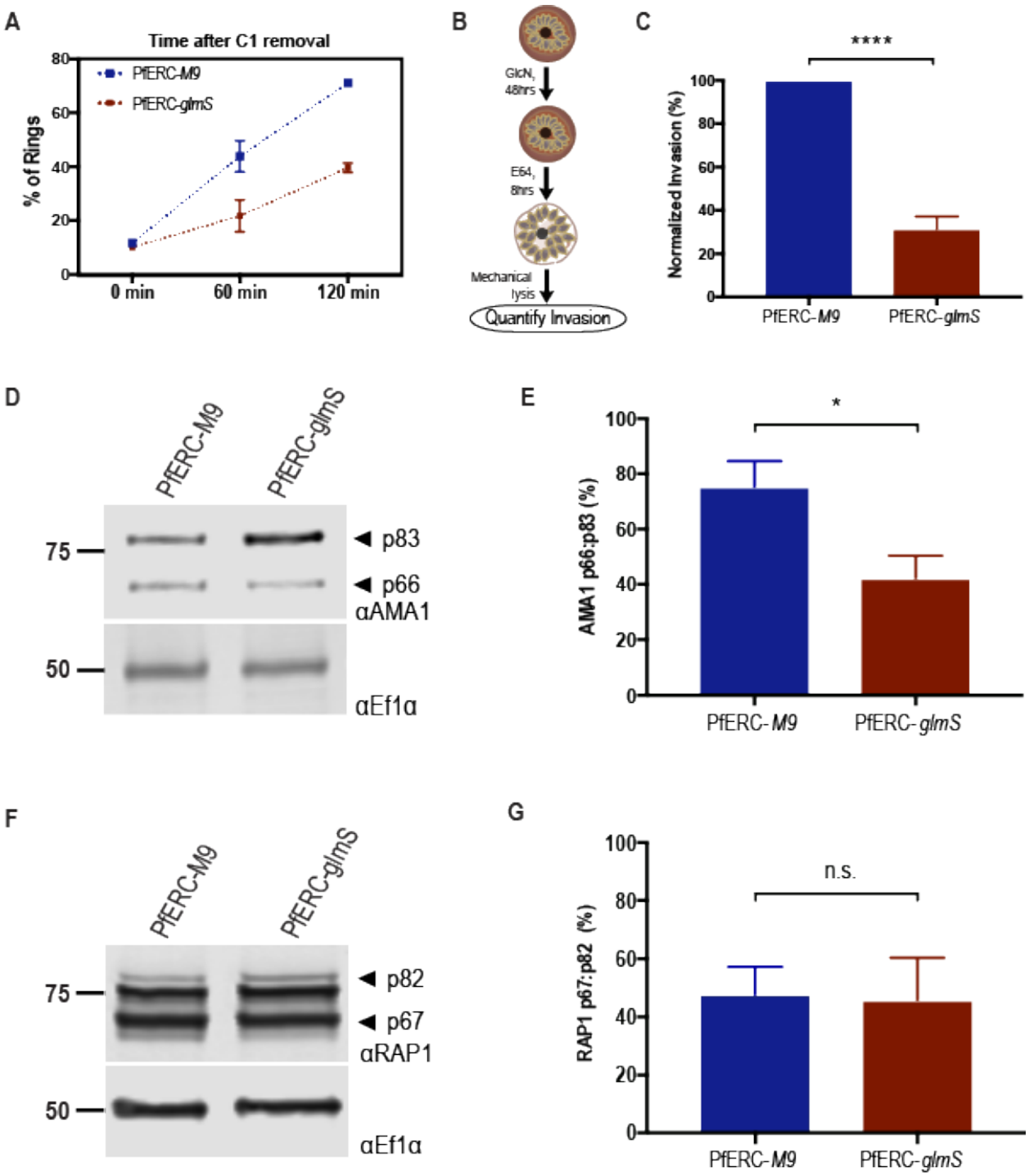

Figure 6: PfERC knockdown prevents invasion of RBCs. (A) As shown in Figure 4A, synchronized PfERC-*glmS* and PfERC-*M9* parasites were observed by flow cytometry after removal of C1 (time 0hr). Rings were quantified as a percentage of the total amount of parasites as determined by flow cytometry. Data are represented as the mean ± SEM (n=3 biological replicates). (B) Schematic showing the experimental layout to study the

1155 effect of PfERC knockdown on invasion of merozoites into host RBCs. Merozoites were
1156 purified using mechanical lysis after 8hr incubation with E64. (C) Invasion rates of
1157 mechanically purified merozoites from PfERC-*glmS* and PfERC-*M9* parasites, as shown
1158 in (B), were quantified using flow cytometry (47). All replicates were normalized to PfERC-
1159 *M9* merozoites. Data are represented as mean ± SEM (n=7 biological replicates;
1160 ****P<0.0001, unpaired *t*-test). (D) Western blot of parasite lysates isolated from PfERC-
1161 *glmS* and PfERC-*M9* schizonts grown in the presence of GlcN for 48 hours and probed
1162 with anti-AMA1 antibodies (top panel) and anti- EF1αantibodies (loading control, bottom
1163 panel). One representative experiment out of eight is shown. The protein marker sizes
1164 that co-migrated with the probed protein are shown on the left. (E) Quantification of the
1165 overall reduction in processing of AMA1 in PfERC-*glmS* and PfERC-*M9* parasites over
1166 time after addition of GlcN, as shown in (D). Data were normalized to the total AMA1
1167 (processed + unprocessed) and are represented as mean ± SEM (n=8 biological
1168 replicates; *P<0.05 unpaired *t*-test). (F) Western blot of parasite lysates isolated from
1169 PfERC-*glmS* and PfERC-*M9* schizonts grown in the presence of GlcN for 48 hours and
1170 probed with anti-RAP1 antibodies (top panel) and anti- EF1α antibodies (loading control,
1171 bottom panel). One representative experiment out of five is shown. The protein marker
1172 sizes that co-migrated with the probed protein are shown on the left. (G) Quantification of
1173 the overall reduction in processing of RAP1 in PfERC-*glmS* and PfERC-*M9* parasites over
1174 time after addition of GlcN, as shown in (F). Data were normalized to the total RAP1
1175 (processed + unprocessed) and are represented as mean ± SEM (n=5 biological
1176 replicates; n.s=non-significant, unpaired *t*-test).

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Cab45        1 -----------MVWPWVAMASRWGPLIGLAPCCLWLLGAVLLMDASARPANHSSTREPVA
ERC-55       1 ----------------MRLGPRTAALGLLL-LCAA---------------------AAGA
Calumenin    1 --------------------MDLRQFLMCLSLCTAFA------------------LSKPT
RCN1         1 ----------------MARGGRGRRIGLALGLLLALV------------LAPRVLRAKPT
TgERC        1 MAAFADRPTCRVSLGAVFLARELHRLRKSLPLCVFSL-----------------------
PfERC        1 -------------------MMKINLYKLLCFICVIFL-----------------------

Cab45       50 NREENEILPPDHLNGVKLEMDGHLNRGEHQEVFLG--KDLGGFDEDAEPRRSRRKLMVIF
ERC-55      23 GKAEELHYP---LGERRS--------DYDREALLGVQEDVDEYVK-LGHEEQQKRLQAII
Calumenin   23 EKKDRVHHEPQ-LSDKVHNDAQ--SFDYDHDAFLG-AEEAKTFDQ-LTPEESKERLGKIV
RCN1        33 VRKERVVRPDSELGERPPEDNQ--SFQYDHEAFLG-KEDSKTFDQ-LTPDESKERLGKIV
TgERC       38 ---FLFSFAFSALSGAPSQFAE------AAMPKLS-GEKLAELMQ-MDVKDIKERMLALF
PfERC       19 ------LHKNVVRSGDNMKYND--MKGLDDLSKLN-DDQVKDILG-LKIDGAKERIEKLF

Cab45      108 SKVDVNTDRKISAKEMQRWIMEKTAEHFQEAMEESKTHFRAVDPDGDGHVSWDEYKVKFL
ERC-55      71 KKIDLDSDGFLTESELSSWIQMSFKHYA---MQEAKQQFVEYDKNSDDTVTWDEYNIQM-
Calumenin   78 SKIDGDKDGFVTVDELKDWIKFAQKRWI---YEDVERQWKGHDLNEDGLVSWEEYKNAT-
RCN1        89 DRIDNDGDGFVTTEELKTWIKRVQKRYI---FLNVAKVWKDYDRDKDDKISWEEYKQAT-
TgERC       87 DLIDTNQDNTIDTEEAKEWSAKLKNAMH---QHQVRMEFQAIDKDNDGKVSLSELEAT--
PfERC       69 HLIDKNNDKEITEEELNTWSSFLKNEIF---LKQVQAEMGQIDSDKDGFISLNELNDA--

Cab45      168 ASKGHSEKEVADAIRLNEELKVDEETQEVLENLK---DRWYQADSPPADLLLTEEEFLSF
ERC-55     127 ---------YDRVIDFDENTALDDAFEESFRKLHLKDKKRFEKANQDSGPGLSLEEFIAF
Calumenin  134 ---------YGYVLDDP-----DPDDGFNYKQMMVRDERRFKMADKDGDLIATKEEFTAF
RCN1       145 ---------YGYYLGNPAEFH-DSSDHHTFKKMLPRDERRFKAADLNGDLTATREEFTAF
TgERC      142 ---------YVDSL--------DQKQLEQHKKEV---EQRFKTVDKDNDGLLDLSEIRIL
PfERC      124 ---------FAQNL--------DAKEVEKHSEGL---LKRFQIVDKDKDGKLSINEVGLL

Cab45      225 LHPEHSRGMLRFMVKEIVRDLDQDGDKQLSVPEFISLPVGTVENQQGGDIDDNWVKDRKK
ERC-55     178 EHPEEVDYMTEFVIQEALEEHDKNGDGFVSLEEFL----GDYRWDPTANEDPEWILVEKD
Calumenin  180 LHPEEYDYMKDIVVQETMEDIDKNADGFIDLEEYI----GDMYSHDGNTDEPEWVKTERE
RCN1       195 LHPEEFEHMKEIVVLETLEDIDKNGDGFVDQDEYI----ADMFSHEENGPEPDWVLSERE
TgERC      182 MDPGKDEGLMKIEIEEILNAQDKNGDRKITVTEFI--------ETEGTGSLNDVEKTELE
PfERC      164 IDPMKDEELKELEINEILEHHDVNKDGKISLDEFK-----QTRSDESSGVKKD-DEMALD

Cab45      285 EFEELIDSNHDGIVTAEELESYMDPMNEYNALNEAKQMIAVADEN-QNH-HLEPEEVLKY
ERC-55     234 RFVNDYDKDNDGRLDPQELLPWVVPNNQGIAQEEALHLIDEMDLN-GDK-KLSEEEILEN
Calumenin  236 QFVEFRDKNRDGKMDKEETKDWILPSDYDHAEAEARHLVYESDQN-KDG-KLTKEEIVDK
RCN1       251 QFNEFRDLNKDGKLDKDEIRHWILPQDYDHAQAEARHLVYESDKN-KDE-KLTKEEILEN
TgERC      234 KEFKSYDLNADGAIDVEELQQIL----KDPHSHEIRMLLEEFTKDLKDG-KVGREQWEKE
PfERC      218 DF-NFFDANKDGFIDKEEIIKVY----FDPAHESGAINVNEIKENIFEGKKITYLLWNEK

Cab45      343 SEFFTGSKLVDYARSV-------------------------------------H-----
ERC-55     292 PDLFLTSEATDYGRQLH--------------------------------DDYFYH-----
Calumenin  294 YDLFVGSQATDFGEALV-------------------------------------RH-----
RCN1       309 WNMFVGSQATNYGEDLT-------------------------------------KNH-----
TgERC      289 FESFAVSMLTDNGEVLRFPEDY-----SGIEFP------FKTAVPQVDLDDEDKH-----
PfERC      273 ALKIAVTSLTDYGDVIRYPEDFKLDIGKNVILPTARSRAFEDDDMDADNTEDDKDEADDA

Cab45      360 --------EEF
ERC-55     315 --------DEL
Calumenin  313 --------DEF
RCN1       329 --------DEL
TgERC      333 --------DEL
PfERC      333 SQQKSPAIDEL
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1178 **Supplementary Figure 1:** Sequence alignment of TgERC and PfERC to other members
1179 of the CREC family of proteins using MUSCLE alignment, viewed using JalView Software
1180 (http://www.jalview.org/) and BOXSHADE (82). Alignment was done using the human
1181 homologs: Cab-45, ERC-55 (RCN2), Calumenin, and Reticulocalbin1 (RCN1). Identical
1182 residues are shaded in black, similar residues are shaded in gray, and EF-hands are
1183 highlighted in red.

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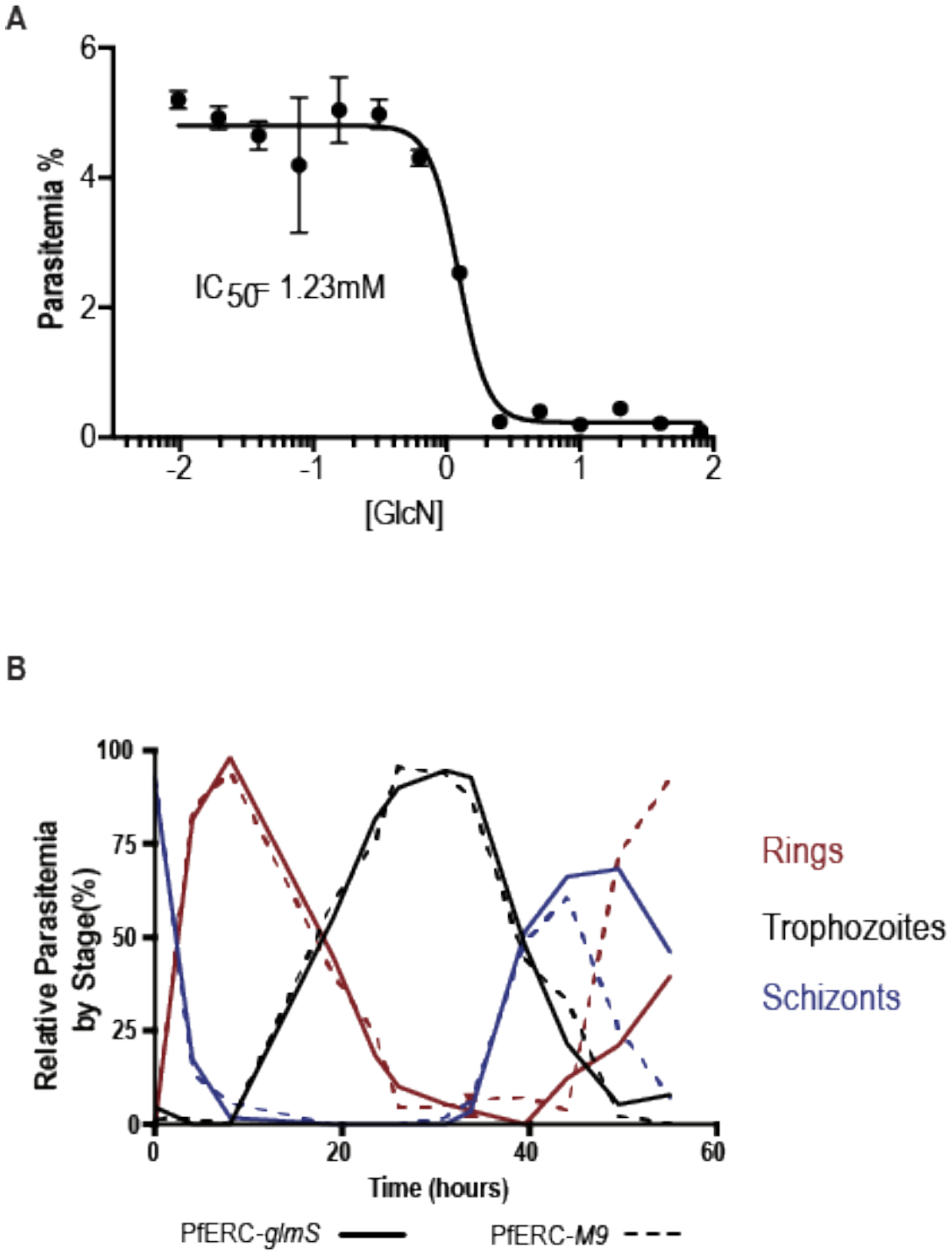

1201 **Supplementary Figure 2:** Effect of PfERC knockdown on parasite growth. (A)
1202 Representative graph (one out of three) showing dose-dependent response of PfERC-
1203 *glmS*2 to GlcN. Asynchronous PfERC-*glmS* parasites were incubated in different
1204 concentrations of GlcN and growth after three days was assessed by flow cytometry. Data

1205 are represented as mean ± SEM of n=3 biological replicates. (B) Representative life cycle
1206 graph showing all stages from Figures 3D and 3F (n=2 biological replicates).

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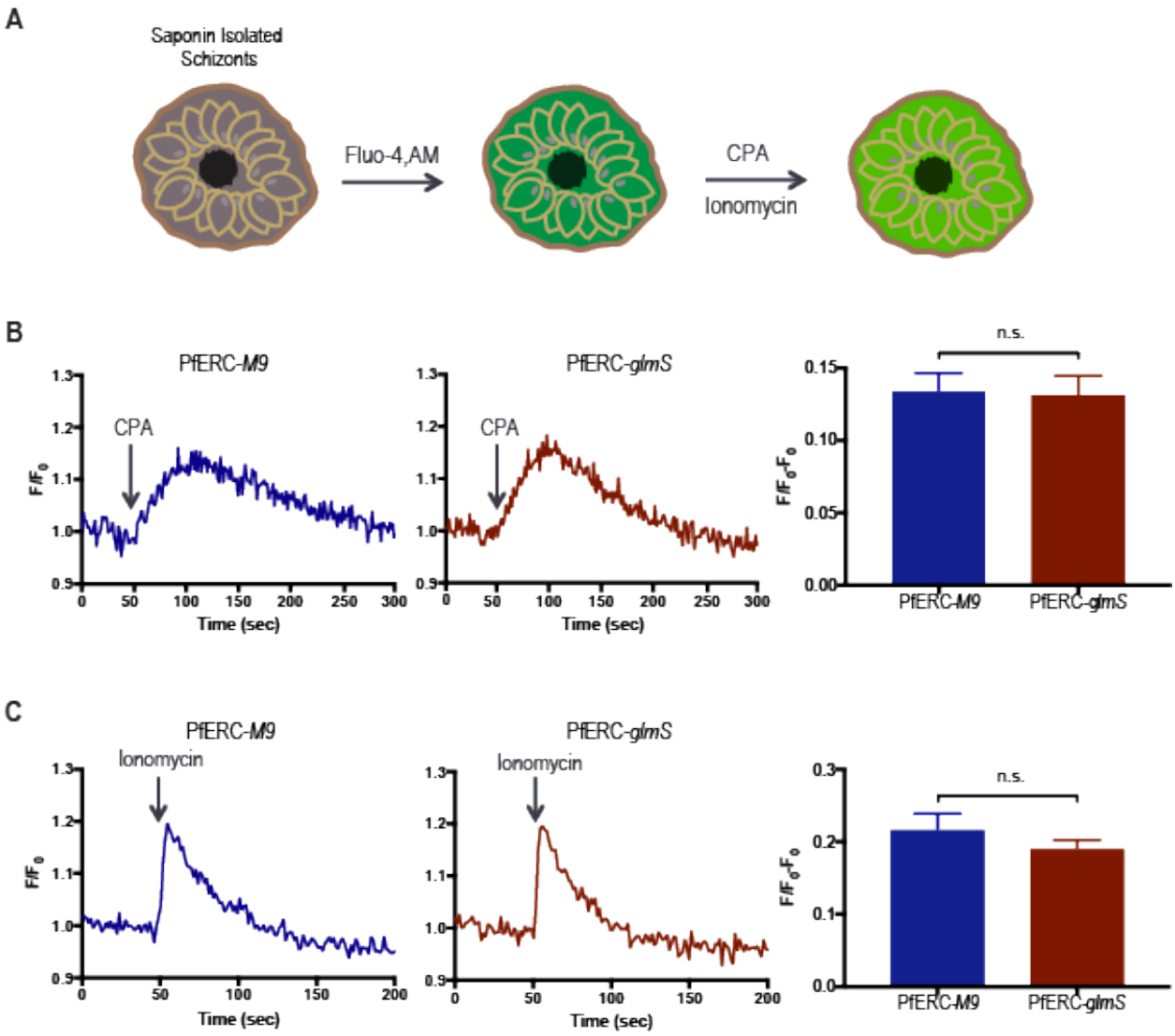

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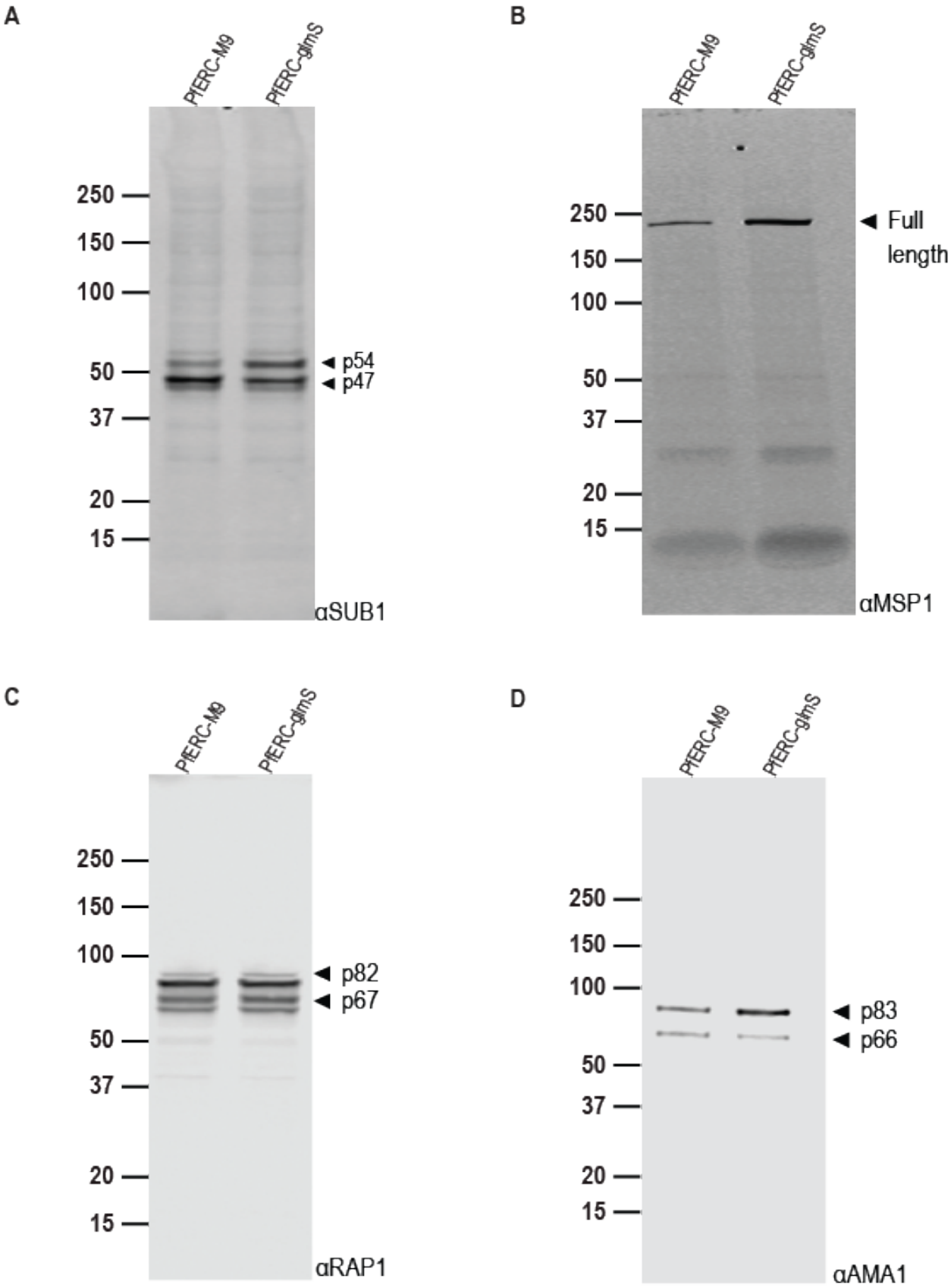
1215 **Supplementary Figure 3:** Effect of PfERC knockdown on $Ca2^{2+}$ in the ER. (A)
1216 Experimental schematic showing how Ca^{2+} measurements were done in PfERC-*glmS*
1217 and PfERC-*M9* mutants. Synchronized PfERC-*glmS* and PfERC-*M9* schizonts were
1218 incubated with GlcN for 48 hours and isolated using saponin lysis, which lyses the RBC
1219 membrane but leaves the PV intact. Abbreviations: CPA- cyclopiazoic acid (B)
1220 Representative fluorescence tracings after CPA addition to PfERC-*glmS* and PfERC-*M9*
1221 schizonts, isolated as in (A). Quantification was done by calculating the difference in
1222 fluorescence between the basal to the highest peak of fluorescence. Data are
1223 represented as the combined mean ± SEM (PfERC-*glmS;* n=15 biological replicates;
1224 PfERC-*M9;* n=9 biological replicates; n.s- non-significant, unpaired *t*-test). (C)

1225 Representative fluorescence tracings after Ionomycin addition to PfERC-*glmS* and
1226 PfERC-*M9* schizonts, isolated as in (A). Quantification was done by calculating the
1227 difference in fluorescence between the basal to the highest peak of fluorescence. Data
1228 are represented as the combined mean ± SEM (PfERC-*glmS;* n=9 biological replicates;
1229 PfERC-*M9;* n=5 biological replicates; n.s- non-significant, unpaired *t*-test).


A
PfERC-M9
PfERC-glmS
250
150
100
50
37
20
15
p54
p47
αSUB1
B
PfERC-M9
PfERC-glmS
250
150
100
50
37
20
15
Full length
αMSP1
C
PfERC-M9
PfERC-glmS
250
150
100
50
37
20
15
p82
p67
αRAP1
D
PfERC-M9
PfERC-glmS
250
150
100
50
37
20
15
p83
p66
αAMA1

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1231 **Supplementary Figure 4:** Representative whole-blot images of Western blots of lysates
1232 from PfERC-*glmS* and PfERC-*M9* schizonts incubated with GlcN for 48 hours, probed
1233 with anti-SUB1, anti-MSP1, anti-AMA1, and anti-RAP1 antibodies from Figures 5 and 6.
1234 The protein marker sizes that co-migrated with the probed protein are shown on the left.

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1254 **Table S1:** Primers used in this study.

Primer	Primer Sequence
1	GCGGCGATGCCCAAGTTGTCGTTTTAGAGCTAGAAATAGC
2	AACTTGACATCCCCATTTAC
3	CGACTGTTCCCCCCAATCAATTCTACTTTCGTCGCTTATCTCGAGAAAACAAAGCTTCGCCAGGCTGTAAATCC
4	CTCCTGTCCGCAGAAGCTCTGTACGTGTTCTCAACAACTAGCTCTTCATGTTCATCCTGCAAGTGCATAGAAGGAAAGTTG
5	TCCGACTCTCCAACGTGGTTGC
6	GCTGCTACACAGCACTCCCTG
7	CTGCAGGTCTGGACATTTAAAGTTCATCACTAGCGTAATCTGGAACATCG
8	CGATGTTCCAGATTACGCTAGTGATGAACTTTAAATGTCCAGACCTGCAG
9	AATTCGCCCTTTCCGCGGAGAATAGAAAAATTATTTCATTTGATAGATAAAAACAATGAT
10	TGGGTAACTAGTAGCGCTTAATTCATCAATTGCTGGGGATTTTTGTTGCGATGCATCGTC
11	ATGATCTTGCCGGCAAGCTTTTTATATAAACATATTTTTTTTTTTTTTAACATAAAGGG
12	CCTTGAGCTCGCTAGCGACAAATTGGATAGATAATAGGGGGTACAAATATACATAC
13	AAGTATATAATATTCAATTGCTGGGGATTTTTGTGTTTTAGAGCTAGAA
14	TTCTAGCTCTAAAACACAAAAATCCCCAGCAATTGAATATTATATACTTA
15	GCAAGATCATGTGATTTCTCTTTGTTCAAGGAGTCACCCCC
16	GACGACGACAAGATAATGGCGGCCTTCGCAGACAG
17	GAGGAGAAGCCCGGTCAGTTCATCGTGTTTGTCTTCGTCGTCG

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