The determinants of African Swine Fever Virus Virulence – the Georgia 2007/1 strain and the host macrophage response

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Short Title:

The ASFV Georgia 2007/1 Strain Transcriptome

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Abstract [217 words]

African swine fever virus (ASFV) has a major global economic impact. With a case fatality in domestic pigs approaching 100%, it currently presents the largest threat to animal farming. Although genomic differences between attenuated and highly virulent ASFV strains have been identified, the molecular determinants for virulence at the level of gene expression have remained opaque. Here we characterise the transcriptome of ASFV genotype II Georgia 2007/1 (GRG) during infection of the physiologically relevant host cells, porcine macrophages. In this study we applied Cap Analysis Gene Expression sequencing (CAGE-seq) to map the 5' ends of viral mRNAs at 5 and 16 hpi. A bioinformatics analysis of the sequence context surrounding the transcription start sites (TSSs) enabled us to characterise the global early and late promoter landscape of GRG. We compared transcriptome maps of the GRG isolate and the lab-attenuated BA71V strain that highlighted GRG virulent-specific transcripts belonging to multigene families including two newly characterised MGF 100 genes I7L and I8L. Structural homology modelling suggest that I7L and I8L encode unorthodox SH2 domain proteins with the potential to interfere with the host's immune response. In parallel, we monitored transcriptome changes in the infected host cells, which showed a pro-inflammatory immune response with the upregulation of NF-kB activated genes, innate immunity, as well as lysosome components including S100 proteins.

Author Summary [196 words]

African swine fever virus (ASFV) causes a haemorrhagic fever in domestic pigs and wild boar with mortality rates approaching 100%, for which there are no approved vaccines or antivirals. The highly-virulent ASFV Georgia 2007/1 strain was the first isolated when ASFV spread from Africa to the Caucasus region in 2007. From here it has spread through Eastern Europe, and more recently across Asia. We have used an RNA-based next generation sequencing technique called CAGE-seq to map the starts of viral genes across the ASFV Georgia 2007/1 strain DNA genome. This has allowed us to investigate how it controls its viral gene expression during different stages of infection in macrophage cells. We have characterised which genes are expressed at different levels during early or late stages of infection, and compared them to the non-virulent ASFV-BA71V strain to identify key genes that enhance virulence. We have discovered new genes, and predicted the likely roles of uncharacterised genes during ASFV infection. In parallel we have investigated how the host cells respond to ASFV infection, which has revealed how the virus early on

41 suppresses components of the host immune response to ultimately win the arms race against its porcine
42 host.

43 Introduction [1,192 words]

44 ASFV originated in Sub-Saharan Africa where it remains endemic. However, following the introduction in
45 2007 of a genotype II isolate to Georgia (1) and subsequent spread in Russia and Europe. The virus was
46 then introduced to China in 2018 (2), from here it spread rapidly across Asia, strongly emphasizing this
47 disease as a severe threat to global food security. ASFV is the only characterised member of the
48 Asfarviridae family (3) in the recently classified Nucleocytoviricota (ICTV Master Species List 2019.v1)
49 phylum (4,5). ASFV has a linear double-stranded DNA (dsDNA) genome of ~170–193 kbp encoding ~150–
50 ~200 open reading frames (ORFs). Little is currently known about either the transcripts expressed from
51 the ASFV genome or the mechanisms of ASFV transcription. Much of what is known about transcription
52 is extrapolated from vaccinia virus (VACV), a distantly-related Nucleocytoviricota member, from the
53 Poxviridae family (6). ASFV encodes a eukaryotic-like 8-subunit RNA polymerase (RNAP), an mRNA capping
54 enzyme and poly-A polymerase, all of which are carried within mature virus particles. These virions are
55 transcription competent upon solubilisation in vitro (7,8) and support mRNA modification by including a
56 5'-methylated cap and a 3' poly-adenylated (polyA) tail of ~33 nucleotide-length (8,9).

57 Viral genes are typically classified according to their temporal expression patterns. ASFV genes have
58 historically been categorised as 'immediate early' when expressed immediately following infection, as
59 'early genes' following viral protein synthesis, as 'intermediate genes' after viral DNA replication, or as
60 'late genes' thereafter. The temporal regulation of transcription is likely enabled by different sets of
61 general transcription initiation factors that recognise distinct early (EPM) or late (LPM) promoter
62 elements, as we previously investigated in the ASFV-BA71V strain (10), and address further in this study.
63 EPM recognition is likely enabled by the ASFV homologue of heterodimeric VACV early transcription factor
64 (VETF), consisting of D1133L (D6) and G1340L (A7) gene products (11,12). Both are late genes, i. e.
65 synthesised late during infection and packaged into virus particles. The ASFV LPM is less well defined than
66 the EPM, but a possible initiation factor involved in its recognition is the viral homolog of eukaryotic-like
67 ASFV-encoded TATA-binding protein (TBP), expressed during early infection. By analogy with the VACV
68 system, additional factors including homologs of A1, A2 and G8 may also contribute to late transcription
69 (6)

70 We have recently carried out a detailed and comprehensive ASFV whole genome expression analysis using
71 complimentary next-generation sequencing (NGS) results and computational approaches to characterise
72 the ASFV transcriptome following BA71V infection of Vero cells at 5 hpi and 16 hpi post-infection (hpi)
73 (10). Most of our knowledge about the molecular biology of ASFV, including gene expression, has been
74 derived from attenuated virus strains, such as BA71V infecting Vero tissue culture cells (9,10). These
75 model systems provide convenient models to study the replication cycle but have deletions of many genes
76 that are not essential for replication, but have important roles in virulence within its natural porcine hosts.
77 (13–15). To date 24 ASFV genotypes have been identified in Africa (15–22), while all strains spreading
78 across Asia and Europe belong to the Type II genotype. Most of these are highly virulent in domestic pigs
79 and wild boar, including the ASFV Georgia 2007/1 (GRG) (23), and the Chinese ASFV Heilongjiang, 2018
80 (Pig/HLJ/18) (24) isolates. Though, a number of less virulent isolates have been identified in wild boar in
81 the Baltic States and domestic pigs in China (25–28). It is crucial to understand the similarities and
82 commonalities between ASFV strains, and to characterise the host response to these in order to
83 understand the molecular determinants for ASFV pathogenicity. Information about the gene content and
84 genome organisation can be gained from comparing virus genome sequences. However, only functional
85 genomics such as transcriptome analyses can provide information about the differences in gene
86 expression programmes and the host responses to infection.

87 On the genome level, most differences between virulent (e. g. GRG) and attenuated (e.g. lab-attenuated
88 BA71V) ASFV strains reside towards the genome termini. Figure 1a shows a whole genome comparison of
89 GRG (left) and BA71V (right) strains with the sequence conservation colour coded in different shades of
90 blue. The regions towards the end of the chromosome are more dynamic compared to the central region
91 of the chromosome that is highly conserved, as genes at the termini are prone to deletion, duplication,
92 insertion and fusion (16,29). Most of the GRG-specific genes are expressed early during infection (early
93 genes are colour coded blue in the outer arch of Figure 1a) and belong to Multi-Gene Families (MGFs,
94 purple in the inner arch). The functions of many MGF members remain poorly understood, though
95 variation among MGFs is linked to virulence (30). MGF 110 is not thought necessary for virulence in pigs
96 due to few members being present in virulent isolate genomes (16), but are highly expressed both on the
97 mRNA (10) and protein level (31), suggesting MGF 110 holds importance during infection. Overall, the
98 functions of MGF 360 and 505 members are better characterised, playing a role in evading the host type
99 I interferon (IFN) response (14,32–36). In summary, comparing the expression of ASFV genes, especially

100 MGFs between the virulent GRG- and the lab adapted BA71V strains, is fundamental in identification of
101 virulence factors and better MGF characterisation.

102 Macrophages are the primary target cells for ASFV, they are important immune effector cells that display
103 remarkable plasticity allowing efficient response to environmental signals (37). They can activate specific
104 functional programs, which can be divided into two main groups: classically activated macrophages (M1)
105 present during acute infections and alternatively activated macrophages (M2) (38). Infection of
106 macrophages with virulent ASFV has been shown to inhibit the expression of IFN, cytokines, chemokines,
107 adhesion molecules and other immunomodulatory genes, thereby interfering with M1 macrophage
108 function (30). Our understanding of why virulent ASFV isolates like GRG can infect macrophages and win
109 the battle with the host immune system, while attenuated strains like BA71V struggle to do so, currently
110 relies on genomic comparison. Little is known about how host macrophages respond to infection apart
111 from a microarray study of primary swine macrophage cells infected with GRG (39), and an RNA-seq study
112 of whole blood isolated from pigs infected either with a low pathogenic ASFV isolate, OURT 88/3, or the
113 highly pathogenic GRG (40).

114 Here we applied CAGE-seq to characterise the transcriptome of the highly virulent GRG isolate (23), in
115 primary porcine macrophages, the biologically relevant target cells for ASFV infection. We have
116 investigated the differential gene expression patterns of viral mRNAs at 5- and 16 hpi and mapped their
117 promoter motifs. Importantly, we have compared the expression levels and temporal regulation of genes
118 conserved in both strains. With a few exceptions, both mRNA expression levels and temporal regulation
119 of the conserved genes are surprisingly similar between BA71V and GRG. This confirms that it is not
120 deregulation of their conserved genes, but the virulent isolate-specific genes, which are the key
121 determinants for ASFV virulence. Most of these genes are MGF members, likely involved in suppression
122 of the host immune-response. The transcriptome analysis of the porcine macrophages upon GRG infection
123 reflects a pro-inflammatory immune response with the upregulation of in particular NF-kB activated
124 genes, but also innate immunity related and lysosome components.

125 Results [4,801 words]

126 Genome-wide Transcription Start Site-Mapping

127 We infected primary porcine alveolar macrophages with ASFV GRG at a high multiplicity of infection (MOI
128 5.0), isolated total RNA at 5 hpi and 16 hpi and sequenced using CAGE-seq (Supplementary Table 1a). The

129 resulting mRNA 5' ends were mapped to the GRG genome (Figure 1b) resulting in the annotation of 229
130 and 786 TSSs at 5 and 16 hpi, respectively (**Error! Reference source not found.**c and d, from
131 Supplementary Table 1b and c, respectively). The majority of TSSs were identified within 500 bp upstream
132 of the start codon of a given ORF, a probable location for a *bona fide* gene TSS. The strongest and closest
133 TSSs upstream of ORFs were annotated as 'primary' TSS (pTSS, listed in Supplementary Table 1d) and in
134 this manner we could account TSS for 177 out of 189 GRG ORFs annotated in the FR682468.1 genome.
135 TSSs signals below the threshold for detection included MGF_110-11L, C62L, and E66L, the remainder
136 being short ORFs designated as 'ASFV_G_ACD', predicted solely from the FR682468 genome sequence
137 (23). The E66L ORF was originally predicted from only the BA71V genome sequence, but likewise
138 undetectable with CAGE-seq (10), making its expression unlikely. Our TSS mapping identified novel ORFs
139 (nORFs) downstream of the TSS, which were included in the curated GRG genome map (Supplementary
140 Table 1d includes pTSSs of annotated ORFs and nORFs in gene feature file or 'GFF' format). In addition to
141 ORF-associated TSSs, some were located within ORFs (intra-ORF or ioTSS), or in between them (inter-ORF
142 TSS), and all detected TSSs are listed in Supplementary Table 1b-c.

143 Expression of GRG genes during Early and Late Infection

144 Having annotated TSSs across the GRG genome, we quantified the viral mRNAs originating from pTSSs
145 from CAGE-seq data, normalising against the total number of reads mapping to the ASFV genome (i. e.
146 RPM or reads per million mapped reads per sample). We compared gene expression between early and
147 late infection, and simplistically defined genes as 'early' or 'late' if they are significantly down- or
148 upregulated (respectively), using DESeq2 (41). In summary, 165 of the 177 detectable genes were
149 differentially expressed (adjusted p-value or padj < 0.05, Supplementary Table 1e). Those showing no
150 significant change were D345L, DP79L, I8L, MGF_100-1R, A859L, QP383R, B475L, E301R, DP63R, C147L,
151 and I177L. 87 of those 165 differentially expressed genes were significantly downregulated, thus
152 representing the 'early genes', while 78 of the 165 genes were upregulated or 'late genes'. The majority
153 of MGFs were early genes, apart from MGF 505-2R, MGF360-2L and MGF 100-1L (Figure 2a). Figure 2b
154 shows the expression patterns of GRG-exclusively expressed genes, which we defined as only having a
155 detectable CAGE-seq TSS in GRG, and not in BA71V (regardless of presence in the BA71V genome). These
156 unsurprisingly, consist of many MGFs (18), all of which were early genes (Figure 2b), barring MGF 100-1L.

157 We extracted the top twenty most highly expressed genes of GRG (as RPM) during 5 hpi (Figure 2c) and
158 16 hpi (Figure 2d) post-infection. Ten genes are shared between both top 20 lists: MGF 110-3L, A151R,

159 MGF 110-7L, MGF 110-5L-6L, I73R, 285L, CP312R, ASFV_G_ACD_00600, MGF 110-4L, and CP204L. It is
160 important to note that the relative expression values (RPM) for genes at 5 hpi are significantly higher than
161 those at 16 hpi. This is consistent with our observations in the BA71V strain (10) and due to the increase
162 in global transcript levels during late infection discussed below. Supplementary Table 1f includes all the
163 GRG annotated ORFs, their TSS locations during early and late infection, their relative distances if these
164 TSS locations differ, and their respective Untranslated Region (UTR) lengths.

165 GRG and BA71V Share Strong Similarity between Conserved Gene Expression

166 Next we carried out a direct comparison of mRNA levels from the 132 conserved genes between the
167 virulent GRG and attenuated BA71V (10) strain making use of our previously published CAGE-seq data.
168 The relative transcript levels (RPM) of the genes conserved between the two strains showed a significant
169 correlation at 5 hpi (Figure 3a) and 16 hpi (Figure 3b), supported by the heatmap in Supplementary Figure
170 1, the RPM for each gene, across both time-points and replicates, showing a strong congruence between
171 the two strains. Of the 132 conserved genes, 125 showed significant differential expression in both strains.
172 119 of these 125 showed the same down- or up-regulated patterns of significant differential expression
173 from 5 hpi to 16 hpi (Figure 3c, early genes in blue, late genes in red). The exceptions are D205R, CP80R,
174 C315R, NP419L, F165R, and DP148R (MGF 360-18R), encoding RNA polymerase subunits RPB5 and RPB10
175 (14), Transcription Factor IIB (TFIIB) (14), DNA ligase (42), a putative signal peptide-containing protein,
176 and a virulence factor (43), respectively. The ASFV-TFIIB homolog (C315R) is classified as an early gene in
177 GRG but not in BA71V, in line with the predominantly early-expressed TBP (B263R), its predicted
178 interaction partner. It is worth noting however, that D205R, CP80R, and C315R are close to the threshold
179 of significance, with transcripts being detected at both 5 hpi and 16 hpi (Supplementary Table 1e).

180 Increased and pervasive transcription during late infection

181 During late infection of BA71V (10), we noted an increase in genome-wide mRNA abundance, as well as
182 an increasing number of TSSs and transcription termination sites, reminiscent of pervasive transcription
183 observed during late Vaccinia virus (44). To quantify and compare the global mRNA increase both in BA71V
184 and GRG, we calculated the ratio of read coverage at 16 hpi versus 5 hpi (log2 transformed ratio of RPM)
185 per nucleotide across the viral genome (Figure 4a, increase shown above- and decrease below the x-axis).
186 This dramatic increase is due to the overall increase of virus mRNAs present, which is visible in both strains
187 (Figure 4b), with a ~2 fold increase in GRG from 5 hpi to 16 hpi, versus ~8 fold in BA71V (Figure 4c).

188 This observation can at least in part be attributed to the larger number of viral genomes during late
189 infection, with increased levels of viral RNAP and associated factors available for transcription, following
190 viral protein synthesis. Viral DNA-binding proteins, such as histone-like A104R (45), may remain associated
191 with the genome originating from the virus particle in early infection. This could suppress spurious
192 transcription initiation, compared to freshly replicated nascent genomes that are highly abundant in late
193 infection. In order to test whether the increased mRNA levels correlated with the increased number of
194 viral genomes in the cell, we determined the viral genome copy number by using quantitative PCR (qPCR
195 against the p72 capsid gene sequence) using purified total DNA from infected cells isolated at 0 hpi, 5 hpi
196 and 16 hpi, and normalized values to the total amount of input DNA. Using this approach, we observed
197 genome copy levels that were consistent from 0 hpi to 5 hpi, followed by a substantial increase at 16 hpi,
198 which was more pronounced in BA71V infection (Figure 4d). This corresponded to a 15-fold increase in
199 GRG genome copy numbers from late, compared to early times post-infection of porcine macrophages,
200 and a 30-fold increase in BA71V during infection of Vero cells (Figure 4e). In summary, the ASFV
201 transcriptome changes both qualitatively and quantitatively as infection progresses, and the increase of
202 virus mRNAs during late infection is accompanied by the dramatic increase in viral genome copies.
203 Interestingly, the increase in viral transcripts and genome copies was less dramatic in the virulent GRG
204 strain.

205 Correcting the bias of temporal expression pattern

206 The standard methods of defining differential gene expression are well established in transcriptomics
207 using programs like DESeq2 (41). This is a very convenient and powerful tool which captures the nuances
208 of differential expression in complex organisms. However, virus transcription is often characterised by
209 more extreme changes, typically ranging from zero to millions of reads. Furthermore, in both BA71V and
210 GRG strains the genome-wide mRNA levels and total ASFV reads increase over the infection time course
211 (Figure 4 and Supplementary Table 1a). As a consequence, such normalisation against the total mapped
212 transcripts per sample (RPM) generates overestimated relative expression values at 5 hpi, and
213 understates those at 16 hpi (10). In order to validate the early-late expression patterns derived from CAGE-
214 seq, we carried out RT-PCR for selected viral genes, as this signal is proportionate to the number of specific
215 mRNAs regardless of the level of other transcripts – with the minor caveat that it can pick up readthrough
216 transcripts from upstream genes. We tested differentially expressed conserved genes including GRG early-
217 (MGF505-7R, MGF505-9R, NP419L), and D345L which showed stable relative expression values (RPM
218 values in Figure 1e). All selected genes showed a consistently stronger RT-PCR signal during late infection

219 in both BA71V and GRG (**Error! Reference source not found.** a-d). The exception is NP419L whose levels
220 were largely unchanged, and this is an example of how a gene whose transcript levels remain constant
221 would be considered downregulated, when almost all other mRNA levels increase (**Error! Reference**
222 **source not found.**b).

223 The standard normalisation of NGS reads against total mapped reads (RPM) is regularly used as it enables
224 a statistical comparison between samples and conditions, subject to experimental variations (46). Keeping
225 this in mind, we used an additional method of analysing the 'raw' read counts to represent global ASFV
226 transcript levels that are not skewed by the normalisation against total mapped reads. Figure 5 shows a
227 side-by-side comparison of RT-PCR results, and the CAGE-seq data normalised (RPM) or expressed as raw
228 counts, beneath each RT-PCR gel. Unlike CAGE-seq, RT-PCR will detect transcripts originating from read-
229 through of transcripts initiated from upstream TSS including intra-ORF TSS (ioTSSs). To detect such
230 'contamination' we used multiple primer combinations in upstream and downstream segments of the
231 gene (Figure 5c, cyan and yellow arrows) to capture and account for possible variations. Overall, our
232 comparative analyses shows that the normalised data (RPM) of early genes such as MGF505-7R and 9R
233 indeed skews and overemphasises their early expression, while the raw counts are in better agreement
234 with the mRNA levels detected by RT-PCR. In contrast, late genes such as NP419L and D345L would be
235 categorised as late using all three quantification methods, in agreement with GRG CAGE-seq but not
236 BA71V from Figure 3c. We validated the expression pattern of the early GRG-specific gene MGF360-12L
237 (Figure 5e). While the RPM values indicated a very strong decrease in mRNA levels from early to late time
238 points, the decrease in raw counts was less pronounced and more congruent with the RT-PCR analysis,
239 showing a specific signal with nearly equal intensity during early and late infection. Lastly, we used qRT-
240 PCR to quantify C315R transcript levels, as this was close to the early vs late threshold, (a log2fold change
241 of 0 in Figure 3c), which showed again that qRT-PCR better agreed with the raw counts.

242 An improved temporal classification of ASFV genes

243 Based on the considerations above, we prepared a revised classification of temporal gene expression of
244 the genes conserved between the two strains based on raw counts. The heatmap in Figure 6a shows the
245 mRNA levels at early and late infection stages of BA71V and GRG strains (all in duplicates) with the genes
246 clustered into five subcategories (1 to 5, Figure 6a) according to their early and late expression pattern,
247 which are shown in Figure 6b. Genes that are expressed at high or intermediate levels during early
248 infection but that also show high or intermediate mRNA levels during late infection are classified as 'early'

249 genes belonging to cluster-1 (8 genes, levels: high to high, H-H), cluster-4 (33 genes, mid to mid, M-M)
250 and cluster-5 (16 genes, low-mid to low-mid, LM-LM). Genes with low or undetectable mRNA levels during
251 early infection, which increase to intermediate or high levels during late infection are classified as 'late'
252 genes and belong to cluster-2 (15 genes, low to high, L-H) and cluster-3 (60 genes, low to mid, L-M),
253 respectively. Overall, the clustered heatmap based on raw counts shows a similar but more emphasised
254 pattern compared to the normalised (RPM) data (compare Figure 6 and Supplementary Figure 1).
255 Calculating the percentage of reads per gene, which can be detected at 16 hpi compared to 5 hpi, reveals
256 only a small number of genes have most (≥70%) of their reads originating during early infection: 30 genes
257 in the GRG strain and 5 genes in the BA71V strain. For over half of the BA71V-GRG conserved genes, 90-
258 100 % of reads can be detected during late infection (Figure 6c). For all GRG genes, this generates a
259 significant difference between the raw counts per gene between time-points (Figure 6d).

260 Below we discuss specific examples of genes subcategorised in specific clusters. I73R is among the top
261 twenty most-expressed genes during both early and late infection according to the normalised RPM values
262 (Figure 2c and d) resides in cluster-1 (H-H) (Figure 6a). While I73R is expressed during early infection, the
263 mRNA levels remain high with >1/3 of all reads detected during late infection in both strains when
264 calculated as raw counts (34 % in GRG and 45 % in BA71V). This new analysis firmly locates I73R into
265 cluster-1 (H-H) and is classified confidently as early gene. Notably, our new approach results in biologically
266 meaningful subcategories of genes that are likely to be coregulated, e. g. the eight key genes that encode
267 the ASFV transcription system including RNAP subunits RPB1 (NP1450L), RPB2 (EP1242L), RPB3 (H359L),
268 RPB5 (D205R), RPB7 (D339L) and RPB10 (CP80R), the transcription initiation factor TBP (B263R) and the
269 capping enzyme (NP868R) belong to cluster-4 (M-M), and transcription factors TFIIS (I243L) and TFIIB
270 (C315R) belong to cluster-5 (LM-LM). The overall mRNA levels of cluster-4 and -5 genes are different, but
271 remain largely unchanged during early and late infection, consistent with the transcription machinery
272 being required throughout infection. In contrast, the mRNAs encoding the transcription initiation factors
273 D6 (D1133L) and A7 (G1340L) are only present at low levels during early- but increase during late infection
274 and thus belong to cluster-3 (L-M), classifying them as late genes. This is meaningful since the
275 heterodimeric D6-A7 factor is packaged into viral particles (7), presumably during the late stage of the
276 infection cycle. The mRNAs of the major capsid protein p72 (B646L) and the histone-like-protein A104R
277 (45,47) follow a similar late pattern but are present at even higher levels during late infection and
278 therefore belong to cluster-2 (L-H).

Architecture of ASFV promoter motifs

In order to characterise early promoter motifs (EPM) in the GRG strain, we extracted sequences 35 bp upstream of all early gene TSSs and carried out multiple sequence alignments. As expected, this region shows a conserved sequence signature in good agreement with our bioinformatics analyses of EPMs in the BA71V strain, including the correct distance between the EPM and the TSS (9-10 nt from the EPM 3' end) and the 'TA' motif characteristic of the early gene Initiator (Inr) element (Figure 7a) (10). A motif search using MEME (48) identified a core (c)EPM motif with the sequence 5'-AAAATTGAAT-3' (Figure 7b), within the longer EPM. The cEPM is highly conserved and is present in almost all promoters controlling genes belonging to cluster-1, -4 and -5 (Supplementary Table 3). A MEME analysis of sequences 35 bp upstream of late genes (Figure 7c), provided a 17-bp AT-rich core late promoter motif (cLPM, Figure 7d), however, this could only be detected in 46 of the late promoters.

In an attempt to improve the promoter motif analyses and deconvolute putative sequence elements further, we probed the promoter sequence context of the five clusters (clusters 1-5 in Figure 7e-i, respectively) of temporally expressed genes with MEME (Supplementary Table 3). The early gene promoters of clusters-1 (H-H), -4 (M-M) and -5 (LM-LM) are each associated with different expression levels, and all of them contain the cEPM located 15-16 nt upstream of the TSS with two exceptions that are characterized by relatively low mRNA levels (Figure 7k). Interestingly, cluster-2 (L-H) promoters are characterized by a conserved motif with significant similarity to eukaryotic TATA-box promoter element that binds the TBP-containing TFIID transcription initiation factor (Figure 7f highlighted with red bracket, detected via Tomtom (49) analysis of the MEME motif output). Cluster-3 (L-M) promoters contain a long motif akin to the cLPM, derived from searching all late gene promoter sequences, and which is similar to the LPM identified in BA71V (Figure 7d and g, green bracket). All motifs described in the cluster analysis above could be detected with statistically significance (p-value < 0.05) via MEME, in every gene in each respective cluster with only two exceptions: MGF 110−3L from cluster-1, and MGF 360-19R from cluster-4, for the latter see details below.

Updating Genome Annotations using Transcriptomics Data

TSS-annotation provides a useful tool for re-annotating predicted ORFs in genomes like ASFV (10) where many of the gene products have not been fully characterized and usually rely on prediction from genome sequence alone. We have provided the updated ORF map of the GRG genome in GFF format (Supplementary Table 1f). This analysis identified an MGF 360-19R ortholog (Figure 8), demonstrating how

309 transcriptomics enhances automated annotation of ASFV genomes by predicting ORFs from TSSs. The
310 MGF 360-19R was included in subsequent DESeq2 analysis showing it was not highly nor significantly
311 differentially expressed (Supplementary Table 1e). Another important feature is the identification of intra-
312 ORF TSSs (ioTSSs) within MGF 360-19R that potentially direct the synthesis of N-terminally truncated
313 protein variants expressed either during early or late infection. The presence of EPM and LPM promoter
314 motifs lends further credence to the ioTSSs (Figure 8). Similar truncation variants were previously reported
315 for I243L and I226R (50) and in BA71V (10). In addition, we detected multiple TSSs within MGF 360-19R
316 encoding very short putative novel ORFs (nORF) 5, 7 or 12 aa residues long; since these ioTSSs were
317 present in both early and late infection they are not all likely to be due to pervasive transcription during
318 late infection.

319 We investigated the occurrence of ioTSS genome wide and uncovered many TSSs with ORFs downstream
320 that were not annotated in the GRG genome (Supplementary Table 2a). These ORFs could be divided into
321 sub-categories: in-frame truncation variants (Supplementary Table 2b, akin to MGF 360-19R in Figure 8),
322 nORFs (Supplementary Table 2c), and simply mis-annotated ORFs. All updated annotations are found in
323 Supplementary Table 1f. Putative truncation variants generated from ioTSSs were predominantly
324 identified during late infection, suggesting these could be a by-product of pervasive transcription.
325 Therefore, those detected early or throughout infection are perhaps more interesting, they span a variety
326 of protein functional groups, and many gene-products are entirely uncharacterised (Figure 9a). The
327 truncation variants additionally showed a size variation of 5'-UTRs between the ioTSSs and downstream
328 start codon (Figure 9b). An example of a mis-annotation would be CP204L (Phosphoprotein p30, Figure
329 9c) gene that is predicted to be 201 residues long. The TSS determined by CAGE-seq and validated by
330 Rapid Amplification of cDNA Ends (5'-RACE) is located downstream of the annotated start codon; based
331 on our results we reannotated the start codon of CP204L which results in a shorter ORF of 193 amino acids
332 (Figure 9c).

333 Our GRG TSS map led to the discovery of many short nORFs, which are often overlooked in automated
334 ORF annotations due to a minimum size, e. g. 60 residues in the original BA71V annotation (14). Some
335 short ORFs have been predicted for the GRG genome including those labeled 'ASFV_G_ACD' in the Georgia
336 2007/1 genome annotation (18). However, their expression was not initially supported by experimental
337 evidence, though we have now demonstrated their expression via CAGE-seq (Figure 2b, Supplementary
338 Table 1e). We have now identified TSSs for most of these short ORFs, indicating at minimum they are

339 transcribed. As described above, we noted that TSSs were found throughout the genome in intergenic
340 regions in addition to those identified upstream of the 190 annotated GRG ORFs (including MGF 360-19R,
341 Supplementary Table 2c). Our systematic, genome-wide approach identified 175 novel putative short
342 ORFs. BLASTP (51) alignments showed that 13 were homologous to ORFs predicted in other strains,
343 including DP146L and pNG4 from BA71V . We validated the TSSs for these candidates using 5'-RACE, which
344 demonstrates the presence of these mRNAs and their associated TSSs at both time-points (Figure 9f and
345 g, respectively), compared to our CAGE-seq data (Figure 9f and g, respectively).

346 Identification of Functional Domains in Uncharacterised Genes

347 Our understanding of the ASFV genome is hampered by the large number of genes with unknown
348 functions. We attempted to remedy this limitation by systematically identifying conserved domains of 47
349 MGF members and 46 uncharacterised ASFV-GRG genes. These candidates included ten genes that are
350 among the highest-expressed genes and ten genes whose protein products are present in viral particles
351 (7). The MGF 100 genes form the smallest multigene family include three short (100–150 aa) paralogs
352 located at both genome ends (right, R and left, L): 1R, 2L (DP141L in BA71V), and 3L (DP146L in BA71V)
353 (29). We predicted the two highly similar GRG ORFs called I7L and I8L (51% sequence identity) to be
354 additional members of the MGF 100 family (Figure 10a). The conservation of I7L and I8L MGF 100
355 members in more virulent and specifically porcine-infecting ASFV strains, combined with their early
356 expression in GRG from our data, and their deletion reducing virulence in swine (52), suggests I7L and I8L
357 play an important role during early infection of porcine macrophages hosts . Through extensive HHpred
358 searches (53), we found that they all include a Src Homology 2 (SH2) domain, with detectable similarity to
359 the N-terminal domain of *C. elegans* Cell death abnormality protein 2, ced-2 (54) (11% seq. id. between
360 I7L and ced-2, E = 0.002 (Figure 10b). SH2 domains, including ced-2, are important protein-protein
361 interaction domains that interact with phospho-tyrosine (pTyr) residues as a part of larger signaling
362 cascades (55). We subsequently generated computational homology models of I7L and I8L, and
363 interestingly both have lost the invariant arginine ßB5 from the canonical pTyr binding pocket, suggesting
364 either a different function or a different mode for recognition of phosphorylated amino acid residues
365 (Figure 10c). In that context it is noteworthy that ASFV genomes encode a putative kinase R298L, which is
366 homologous to vaccinia virus B1R gene (56). Both I7L and I8L show similar overall expression levels to the
367 MGF 100 members. 1L and 1R are already annotated in the GRG genome (Supplementary Figure 1e), I7L
368 and I8L are both early genes, while MGF 100-1L and 1R are late and not significantly changing,
369 respectively.

370 We characterised another gene product, C717R, which is expressed at relatively low levels (< 200 RPM),
371 but upregulated from early to late infection (Supplementary Figure 1e). C717R includes a central domain
372 that is similar to serine/threonine kinases (18% amino acid seq. id. to Vps34, pdb id: 5DFZ over 221 aa, E
373 = 8.4e-15 (Supplementary Figure 3). Besides Asfarviridae, it is conserved also in various Kaumoebavirus
374 and Faustovirus strains. Computational homology modelling shows that, similar to R298L, the canonical
375 ATP-binding loop ('GxGxxG') has been lost, while the catalytic loop ('HRD' motif) is conserved in a slightly
376 modified form (as 'HAD', Supplementary Figure 3). Also, activation segment residues (typically 'DFG') are
377 not conserved in C717R homologs ('DRN' in ASFV).

378 Finally, we investigated the K421R gene product. ASFV transcripts are thought to be polyadenylated by a
379 polyA polymerase (C475L), which is highly conserved with other poxvirus and mimivirus viral polyA
380 polymerases or vPAPs (57). Surprisingly, we discovered that Asfarviridae and related genomes (Abalone
381 asfarvirus, Pacmanvirus, and Faustovirus) encode another vPAP member, represented by K421R in ASFV
382 GRG (12% seq. id. to vPAP, pdb id: 4P37, E = 2.5e-60, (Supplementary Figure 4a). Computational homology
383 modelling of K421R paralogues suggest that they contain the N-terminal dimerisation helix that is
384 characteristic for homodimeric self-processive vPAPs (58) but have lost two out of three acidic active site
385 residues (Supplementary Figure 4b). Consequently, they are predicted to be unable to coordinate metal
386 ions necessary for polyA addition and carry out an unusual unknown function. K421R is a late gene, as the
387 transcript is not detected at 5 hpi and increases to ~550 RPM at 16 hpi, while C475L (polyA polymerase)
388 is also expressed late, but at ~3 times the level of K421R (Supplementary Table 1e). Even more intriguing
389 is the fact that both vPAPs are packaged in viral particles (7), suggesting both may be required for early
390 gene expression.

391 The response of the porcine macrophage transcriptome to ASFV infection

392 In order to evaluate the impact of ASFV on the gene expression of the host cell, we analysed
393 transcriptomic changes of infected porcine macrophages using the CAGE-seq data from 0 (uninfected
394 cells), at 5 and 16 hpi. We annotated 9,384 macrophage-expressed protein-coding genes with CAGE-
395 defined TSSs (Supplementary Table 4). Although primary macrophages are known to vary largely in their
396 transcription profile, the CAGE-seq reads were highly similar between samples (Spearman's correlation
397 coefficients ≥ 0.77).

398 As TSSs are not well annotated for the swine genome, we annotated them *de novo* using our CAGE-seq
399 data with the RECLU pipeline. 37,159 peaks could be identified, out of which around half (18,575) matched

400 unique CAGE-derived peaks annotated in Robert et al. (59) i.e. they were located closer than 100 nt to the
401 previously described peaks. Mapping CAGE-seq peaks to annotated swine protein-coding genes led to
402 identification of TSSs for 9,384 macrophage-expressed protein-coding genes (Supplementary Table 4). The
403 remaining 11,904 swine protein-coding genes did not have assigned TSSs, and therefore their expression
404 levels were not assessed. The majority of genes were assigned with multiple TSSs, and these TSS-assigned
405 genes, were many critical functional macrophage markers, including genes encoding 56 cytokines and
406 chemokines (including CXCL2, PPBP, CXCL8 and CXCL5 as the most highly expressed), ten S100 calcium
407 binding proteins (S100A12, S100A8, and S100A9 in the top expressed genes), as well as interferon and
408 TNF receptors (IFNGR1, IFNGR2, IFNAR1, IFNAR2, IFNLR1, TNFRSF10B, TNFRSF1B, TNFRSF1A, etc.), and
409 typical M1/M2 marker genes such as TNF, ARG1, CCL24, and NOS2 (Supplementary Table 5). The mRNA
410 levels of genes of interest were verified using RT-PCR (Figure 11f).

411 The 9,384 genes with annotated promoters were subjected to differential expression analysis using
412 DESeq2 to compare the three time points (0, 5 and 16) in a pairwise manner. Expression of only 25 host
413 genes was significantly deregulated between 0 and 5 hpi, compared to 652 genes between 5 hpi and 16
414 hpi, and 1325 genes between 0 and 16 hpi (at FDR of 0.05). This implies that the major host transcriptomic
415 response to ASFV does not occur during the early phase of infection. Based on the pairwise comparisons,
416 we could distinguish major response profiles of the host genes. Late response genes, whose expression
417 was significantly deregulated both between 0 and 16 hpi and 5 and 16 hpi, and early response genes,
418 whose expression was significantly deregulated both between 0 and 5 hpi, but not later (Figure 11a). The
419 latter category included only 20 genes, whereas more than 500 genes showed the late differentially
420 regulated response: 344 genes were up-regulated, and 180 genes were down-regulated. Comparison of
421 differences between expression levels at the three time points indicate that macrophage differentially
422 expressed transcription programs start mostly after 5 hpi (Figure 11b and c) i. e. if a gene's expression
423 changes, it has usually happens between 5 hpi and 16 hpi. The upregulated late response genes with
424 highest expression levels included several S100 calcium binding proteins. In contrast, initially high
425 expression of important cytokines (including CCL24, CXCL2, CXCL5 and CXCL8) significantly decreased from
426 5 hpi to 16 hpi (Figure 11d).

427 To investigate the transcriptional response pathways and shed light on possible transcription factors
428 involved in the macrophage response to ASFV infection, we searched for DNA motifs enriched in
429 promoters of the four categories of deregulated genes in Figure 11a. Both late response promoter sets
430 were significantly enriched with motifs, some of which contained sub-motifs known to be recognised by

431 human transcription factors (Supplementary Figure 2). The highest-scored motif found in promoters of
432 upregulated genes contained a sub-motif recognised by a family of human interferon regulatory factors
433 (IRF9, IRF8 and IRF8, Supplementary Figure 2a) that play essential roles in the anti-viral response.
434 Interestingly, both upregulated and downregulated promoters (Supplementary Figure 2b and c,
435 respectively) were enriched with extended RELA/p65 motifs. p65 is a Rel-like domain-containing subunit
436 of the NF-kappa-B complex, regulated by I-kappa-B, whose analog is encoded by ASFV. This pathway being
437 a known target for ASFV in controlling host transcription (60–63).

438 To understand functional changes in the macrophage transcriptome, we also performed gene set
439 enrichment analysis using annotations of human homologs. The top enriched functional annotations in
440 the upregulated late response genes include glycoproteins and disulfide bonds, transmembrane proteins,
441 innate immunity, as well as positive regulation of inflammatory response (Figure 11e). In contrast, sterol
442 metabolism, rRNA processing, cytokines, TNF signalling pathway, inflammatory response as well as innate
443 immunity were the top enriched functional clusters among the downregulated late response genes.
444 Interestingly, the genes associated with innate immunity appear overrepresented in both up- and
445 downregulated gene subsets, yet cytokines are 8-fold enriched only in the downregulated genes.

446 Discussion [2,366 words]

447 In order to shed light on the gene expression determinants for ASF virulence, we focussed our analyses
448 on the similarities and differences in gene expression between a highly virulent Georgia 2007/1 isolate
449 and a nonvirulent, lab-adapted strain (BA71V). Previous annotation identified 125 ASFV ORFs that are
450 conserved between all ASFV strain genomes irrespective of their virulence (15). These represent a 'core'
451 set of genes required for the virus to produce infectious progeny and include gene products like those
452 involved in virus genome replication, virion assembly, RNA transcription and modification, these are
453 located in the central region of the genome (Figure 1a). Besides these essential genes, about one third are
454 non-essential genes for replication, but have roles in evading host defence pathways. Some genes are
455 conserved between isolates, but not necessarily essential core genes, for example apoptosis inhibitors:
456 Bcl-2 family member A179L and IAP family member A224L. Other non-essential genes, especially MGF
457 members, vary in number between isolates. Our transcriptomics analysis captured 119 genes both shared
458 between the BA71V and GRG genomes, and also match expression patterns during early and late
459 infection, according to CAGE-seq (Figure 3, Figure 4a-c). Outliers include DP148R, which is obvious, given
460 its promoter region is deleted in BA71V, and its coding region is interrupted by a frame shift mutation,

461 therefore functional protein expression unlikely. DP148R is a non-essential, early-expressed virulence
462 factor in the Benin 97/1 strain (43) – consistent with our GRG data. Many additional GRG genes, lost from
463 BA71V are MGFs, which are mostly upregulated during early infection and located at the ends of the linear
464 genome (Figure 1a). MGFs have evolved on the virus genome by gene duplication, and do not share
465 significant similarity to other proteins, though some conserved domains, including ankyrin repeats are
466 present in some MGF 360 and 505 family members (16,18).

467 We have predicted the function of two novel MGF 100 members to be SH2 domain-containing protein
468 that have lost the canonical pTyr-binding pocket. Although SH2 domains are primarily specific to
469 eukaryotes, rare cases of horizontally transferred SH2 domains, found in viruses, are implicated in
470 hijacking host cell pTyr signalling (64). A large family of 'super-binding' SH2 domains were discovered in
471 Legionella. Its members, including single SH2 domain-proteins are likely effector proteins during infection
472 (65). Interestingly, loss of MGF 100 members was observed during the process of adapting a virulent
473 Georgia strain to grow in cultured cell lines (66). We also identified a further MGF 100 member in the GRG
474 genome as one of our nORFs, a partial 100-residue copy of DP146L (MGF 100-3L) (Supplementary Table
475 2c). Unlike its annotated MGF 100-1L and MGF 100-1R cousins it was downregulated from 5 hpi to 16 hpi
476 (Supplementary Table 1e). Together with I7L and I8L GRG encodes a total of 5 MGF 100 genes.

477 The Georgia 2007/1 genome was recently re-sequenced which identified a small number of genome
478 changes affecting mapped ORFs and identified new ORFs (17). Adjacent to the covalently cross-linked
479 genome termini, the BA71V genome contains terminal inverted repeats of >2 kbp, in which two short
480 ORFs were identified (DP93R, DP86L). These were not included in previous GRG sequence annotations,
481 however our nORFs included a 55-residue homolog of DP96R, which was a late, but not highly expressed
482 gene. These are yet further examples of how transcriptomics aid in improving ASFV genome annotation.
483 Functional data is available for only a few of proteins coded by ORFs not conserved between BA71V and
484 GRG. This includes the p22 protein (KP177R), which is expressed on the cell membrane during early
485 infection, and also incorporated into the virus particle inner envelope. The function of the KP177R-like
486 GRG gene I10L has not been studied, but may provide an antigenically divergent variant of P22, enabling
487 evasion of the host immune response (18). We found KP177R was highly expressed at 16 hpi, while I10L
488 was also expressed late, but at much lower levels. Their function is unknown, though the presence of an
489 atypical SH2 domain indicates possible roles in signalling pathways (7,18,67).

490 MGF 110 members are among the highest expressed genes during early infection both in GRG (this study),
491 and in BA71V (10), suggesting high importance during infection, at least in porcine macrophages and Vero
492 cells, respectively. However, MGF 110 remains poorly characterised, and 13 orthologues were identified
493 thus far, with numbers present varying between isolates (29). MGF 110 proteins possess cysteine-rich
494 motifs, optimal for an oxidizing environment as found in the ER lumen or outside the cell, and MGF 110-
495 4L (XP124L) contains a KDEL signal for retaining the protein in the endoplasmic reticulum (ER) (68). Since
496 highly virulent isolates have few copies of these genes (for example, only 5 in the Benin 97/1 genome), it
497 was assumed they are not importance for virulence in pigs (16), but their high expression warrant further
498 investigation.

499 There is, good evidence that MGF 360 and 505 carry out important roles in evading the host type I
500 interferon (IFN) response - the main host antiviral defence pathway (32). Evidence for the role of MGF
501 360 and 505 genes in virulence from deletions in tissue-culture adapted and field attenuated isolates as
502 well as targeted gene deletions This correlated with induction of the type I interferon response, which
503 itself is inhibited in macrophages infected with virulent ASFV isolates (33–35). Deletions of these MGF
504 360, and 505 genes also correlated with an increased sensitivity of ASFV replication, to pre-treatment of
505 the macrophage cells with type I IFN (36). Thus, the MGF 360 and 505 genes have roles in inhibiting type
506 I IFN induction and increasing sensitivity to type I IFN. However, it remains unknown if these MGF 360 and
507 MGF 505 genes act synergistically or if some have a more important role than others type I IFN
508 suppression. Our DESeq2 analysis did show that members of both these families showed very similar
509 patterns of early expression (Figure 2 and Figure 3), conserved cEPM-containing promoters, and almost
510 exclusive presence in clusters-1 (H-H), -4 (M-M), and -5 (LM-LM) (Figure 6 and Figure 7), consistent with
511 ASFV prioritising inhibition of the host immune response during early infection.

512 An interesting pattern which emerged during our CAGE-seq analysis was the clear prevalence of ioTSSs
513 within the ORFs, especially in MGFs (Figure 8 and Figure 9). However, it is not clear whether subsequent
514 in-frame truncation variants generate stable proteins, nor what their function could be. Perhaps even
515 more interesting was the discovery of 176 nORFs (including MGF 360-19R), with clear TSSs according to
516 CAGE-seq, highlighting the power of transcriptomics to better annotate sequenced genomes. We were
517 able to detect previously unannotated genes from other strains, and partial duplications of genes already
518 encoded in GRG (Supplementary Table 2).

519 The increase in transcription across the ASFV genome during late infection (10), appears ubiquitous. At
520 least 50 genes have previously been investigated in single gene expression studies using Northern blot or
521 primer extension (for review see references (10,69). Transcripts from over two thirds of these genes were
522 detected during late infection, and a quarter had transcripts detected during both early and late infection.
523 Therefore, clear evidence using several techniques now support this increase in ASFV transcripts at late
524 times post-infection. It is not entirely clear whether it is due to pervasive transcription, high mRNA stability
525 or a combination of factors. However, there is a correlated increase in viral genome copies, potentially
526 available as templates for pervasive transcription. The increase in genome copies is more pronounced in
527 BA71V compared to GRG, which likewise is reflected in the increase in transcripts during late infection
528 (Figure 4).

529 Our transcriptomic analysis of the porcine macrophage host revealed 522 genes whose expression
530 patterns significantly changed between 5 and 16 hrs post-infection (Figure 11a) and only 20 genes were
531 found to change from 0 and 5 hpi. In aggregate, this reflects a relatively slow host response to ASFV
532 infection following expression of early ASFV genes. We observed mild downregulation of some genes e.g.
533 ACTB coding for ß-actin, eIF4A, and eIF4E (Supplementary Table 5), resembling patterns previously shown
534 by RT-qPCR (70). The macrophage transcriptome mainly shuts down immunomodulation between 5 hpi
535 to 16 hpi post-infection; cytokines appeared highly expressed at 5 hpi, but downregulated from 5 hpi to
536 16 hpi. Of the 54 cytokine genes we detected, expression of thirteen was decreased: four interleukin genes
537 (IL1A, IL1B, IL19, IL27), four pro-inflammatory chemokines (CCL24, CXCL2, CXCL5, CXCL8), and tumor
538 necrosis factor (TNF) genes. Since inflammatory responses serve as the first line of host defense against
539 viral infections, viruses have developed ways to neutralise host pro-inflammatory pathways. ASFV
540 encodes a structural analog of IκB, A238L, which was proposed to act as a molecular off-switch for NFκB-
541 targeted pro-inflammatory cytokines (62). In our study, A238L is one of the most expressed ASFV genes
542 at 5 hpi, but significantly downregulated afterwards (Figure 2c**Error! Reference source not found.**).
543 Accordingly, swine homologs of human NFκB target genes were significantly over-represented (3.8 fold)
544 among downregulated macrophage genes (Fisher's exact p-value < 1e-5, based on human NFκB target
545 genes from https://www.bu.edu/nf-kb/gene-resources/target-genes/). Downregulated genes include
546 interleukins 1A, 1B, and 8, and 27 (IL1A, IL1B, CXCL8, IL27), TNF, as well as a target for common
547 nonsteroidal anti-inflammatory drugs, prostaglandin-endoperoxide synthase 2 (PTGS2 or COX-2).
548 Interestingly, promoters of both up- and downregulated genes contained a motif with the sequence
549 preferentially recognised by the human p65-NFκB complex (71) (Supplementary Figure 2). Expression of

550 TNF, a well-known marker gene for acute immune reaction and M1 polarisation, was recorded at a high
551 level at 0 and 5 hpi, but significantly dropped at 16 hpi. It has been already shown that ASFV inhibits
552 transcription of TNF and other proinflammatory cytokines. (62). On the other hand, the downregulation
553 of TNF stands in contrast to previous results from ASFV-E75 strain-infected macrophages in vitro, where
554 TNF expression increased significantly after 6 hpi (72). Therefore, the different time courses of TNF
555 expression induced by the moderately virulent E75 and more virulent Georgia strain may reflect different
556 macrophage activation programs (38).

557 Four S100 family members are among the host genes that are upregulated after 5 hpi (Figure 11b)
558 including S100A8, S100A11, S100A12, and S100A13. S100A8 and S100A12 are among the most highly
559 expressed genes on average throughout infection. S100 proteins are calcium-binding cytosolic proteins
560 that are released and serve as a danger signal, and stimulate inflammation (73). Once released from the
561 cell, S100A12 and S100A8 function as endogenous agonists to bind TLR4 and induce apoptosis and
562 autophagy in various cell types (73). S100A8 and S100A9 were also found in the RNA-seq whole blood
563 study as the top upregulated upon infection of the pigs with Georgia 2007/1, but not of a low pathogenic
564 ASFV isolate OURT 88/3 (40).

565 Two previous studies described global swine transcriptome changes upon ASFV infection using short read
566 sequencing (Illumina): the RNA-seq described above (40), and a microarray study of primary swine
567 macrophage cell cultures infected with the GRG strain, at six post-infection time points (39). Although
568 these varied in designs and selected methods, results of these works both give some indication into the
569 main host immune responses and ways how ASFV could evade them. The latter microarray study indicated
570 similar suppression of inflammatory response after 16 hpi as we observed in this study, with expression
571 of many cytokines down-regulated relatively to non-infected macrophages (39). Neither study obtained
572 the read-depth and nucleotide resolution (obtainable with CAGE-seq), to investigate differential
573 expression of both the virus and host, the former being especially difficult in a compact genome where
574 transcription read-through can undermine results from classical RNA-sequencing techniques (10,74). A
575 recent investigation into ASFV RNA transcripts using long-read based Oxford Nanopore Technologies
576 (ONT) – provides fascinating insight into their length and read-through heterogeneity, but unfortunately
577 lacked the coverage for in-depth host transcript analysis alongside it (75).

578 Here we have demonstrated that CAGE-seq is an exceptionally powerful tool for quantifying relative
579 expression of viral genes across the ASFV genome, as well as making direct comparison between strains

580 for expression of shared genes, and further highlighting the importance of highly-expressed but still
581 functionally uncharacterised viral genes. CAGE-seq conveniently circumvents the issue in compact viral
582 genomes like those of ASFV and VACV, of transcripts reading through into downstream genes which
583 cannot be distinguished from classical short-read RNA-seq (10,40,76). Furthermore, it enables us to
584 effectively annotate genome-wide the 5' ends of capped viral transcripts, and thus TSSs of viral genes, and
585 subsequently their temporal promoters. We have now expanded on promoter motifs we previously
586 described (Figure 7), to identify 5 clusters of genes (Figure 6), with distinct patterns of expression. Three
587 of these clusters (-1: high to high levels, -4: mid to mid, and -5 low-mid to low-mid) have slightly differing
588 promoters, with a highly conserved core EPM. This is akin to the early gene promoter of VACV (74) for
589 VETF recognition and early gene transcription initiation (77,78). We have found late genes can be
590 categorised into two types that either increase from low to extremely high expression levels (e. g. p72-
591 encoding B646L) in cluster-2, or from low to medium expression levels in cluster 3 (e. g VETF-encoding
592 genes). The promoters of these genes show resemblance to the eukaryotic TATA-box (79) or the BA71V
593 LPM (10), respectively. Our analysis additionally shows the potential for a variety of non-pTSSs: alternative
594 ones used for different times in infection, ioTSSs which could generate in-frame truncation variants of
595 ORFs, sense or antisense transcripts relative to annotated ORFs, and finally TSSs generating nORFs, which
596 predominantly have no known homologs.

597 In summary, it is becoming increasingly clear that the transcriptomic landscape of ASFV during infection
598 is far more complex than originally anticipated. Much of this raises further questions about the basal
599 mechanisms underlying ASFV transcription and how it is regulated over the infection time course. Which
600 subsets of initiation factors enable the RNAPs to recognise early and late promoters? Does ASFV include
601 intermediate genes, and what factors enables their expression? What is the molecular basis of the
602 pervasive transcription during late infection? The field of ASFV transcription has been understudied and
603 underappreciated, and considering the severe threat that ASF poses for the global food system and -food
604 security, we now need to step up and focus our attention and resources to study the fundamental biology
605 of ASFV to develop effective antiviral drugs and vaccines.

606 # Methodology [2057 words]

607 ## GRG-Infection of Macrophages and RNA-extraction

608 Primary porcine alveolar macrophage cells collected from two animals following approval by the local
609 Animal Welfare and Ethical Review Board at The Pirbright Institute. Cells were seeded in 6-well plates
610 ($2x10^6$ cells/well) with RPMI medium (with GlutaMAX), supplemented with 10% Pig serum and 100 IU/ml
611 penicillin, 100 µg/ml streptomycin. They were infected as 2 replicate wells for 5 hpi or 16 hpi with a
612 multiplicity of infection (MOI) of 5 of the ASFV Georgia 2007/1 strain, while uninfected cells were seeded
613 in parallel as a control. Total RNA was extracted according to manufacturer's instructions for extraction
614 with Trizol Lysis Reagent (Thermo Fisher Scientific and the subsequent RNAs were resuspended in 50µl
615 RNase-free water and DNase-treated (Turbo DNAfree kit, Invitrogen). RNA quality was assessed via
616 Bioanalyzer (Agilent 2100). 5 µg of each sample was ethanol precipitated before sending to CAGE-seq
617 (Kabushiki Kaisha DNAFORM, Japan). Samples were named as follows: uninfected cells (C1-0 hpi and C2-
618 0h), at 5 hpi post-infection (samples G1-5h and G2-5h), and at 16 hpi post-infection (G3-16h and G4-16h).

619 ## CAGE-sequencing and Mapping to GRG and *Sus scrofa* Genomes

620 Library preparation and CAGE-sequencing of RNA samples was carried out by CAGE-seq (Kabushiki Kaisha
621 DNAFORM, Japan). Library preparation produced single-end indexed cDNA libraries for sequencing: in
622 brief, this included reverse transcription with random primers, oxidation and biotinylation of 5' mRNA
623 cap, followed by RNase ONE treatment removing RNA not protected in a cDNA-RNA hybrid. Two rounds
624 of cap-trapping using Streptavidin beads, washed away uncapped RNA-cDNA hybrids. Next, RNase ONE
625 and RNase H treatment degraded any remaining RNA, and cDNA strands were subsequently released from
626 the Streptavidin beads and quality assessed via Bioanalyzer. Single strand index linker and 3' linker was
627 ligated to released cDNA strands, and primer containing Illumina Sequencer Priming site was used for
628 second strand synthesis. Samples were sequenced using the Illumina NextSeq 500 platform producing 76
629 bp reads. FastQC (80) analysis was carried out on all FASTQ files at Kabushiki Kaisha DNAFORM and CAGE-
630 seq reads showed consistent read quality across their read-length, therefore, were mapped in their
631 entirety to the GRG genome (FR682468.1) in our work using Bowtie2 (81), and *Sus scrofa*
632 (GCF_000003025.6) genome with HISAT2 (81,82) by Kabushiki Kaisha DNAFORM.

633 ## Transcription Start Site-mapping Across Viral GRG Genome

634 CAGE-seq mapped sample BAM files were converted to BigWig (BW) format with BEDtools (83)
635 genomecov, to produce per-strand BW files of 5' read ends. Stranded BW files were input for TSS-
636 prediction in RStudio (84) with Bioconductor (85) package CAGEfightR (86). Genomic feature locations
637 were imported as a TxDb object from FR682468.1 genome gene feature file (GFF3). CAGEfightR was used
638 to quantify the CAGE reads mapping at base pair resolution to the GRG genome - at CAGE TSSs, separately
639 for the 5 hpi and 16 hpi replicates. TSS values were normalized by tags-per-million for each sample,
640 pooled, and only TSSs supported by presence in both replicates were kept. TSSs were assigned to clusters,
641 if within 25 bp of one another, filtering out pooled, RPM-normalized TSS counts below 25 bp for 5 hpi
642 samples, or 50 bp for 16 hpi, and assigned a 'thick' value as the highest TSS peak within that cluster. A
643 higher cut-off for 16 hpi was used to minimise the extra noise of pervasive transcription observed during
644 late infection (10). TSS clusters were assigned to annotated FR682468.1 ORFs using BEDtools intersect, if
645 its highest point ('thick' region) was located within 500 bp upstream of an ORF, 'CDS' if within the ORF,
646 'NA' if no annotated ORF was within these regions. Multiple TSSs located within 500 bp of ORFs were split
647 into subsets: 'Primary' cluster subset contained either the highest scoring CAGEfightR cluster or the
648 highest scoring manually-annotated peak (when manual ORF corrections necessary), and the highest peak
649 coordinate was defined as the primary TSS (pTSS) for an ORF. Further clusters associated with these ORFs
650 were classified as 'non-primary', with their highest peak as a non-primary TSS (npTSS). If the strongest TSS
651 location was intra-ORF, without any TSSs located upstream of the ORF, then the ORF was manually re-
652 defined as starting from the next ATG downstream.

653 ## DESeq2 Differential Expression Analysis of GRG Genes

654 For analysing differential expression with the CAGE-seq dataset, a GFF was created with BEDtools
655 extending from the pTSS coordinate, 25 bp upstream and 75 bp downstream, however, in cases of
656 alternating pTSSs this region was defined as 25 bp upstream of the most upstream pTSS and 75 bp
657 downstream of the most downstream pTSS. HTSeq-count (87) was used to count reads mapping to
658 genomic regions described above for both the RNA- and CAGE-seq sample datasets. The raw read counts
659 were then used to analyse differential expression across these regions between the time-points using
660 DESeq2 (default normalisation described by Love et al. (41)) and those regions showing changes with an
661 adjusted p-value (padj) of <0.05 were considered significant. A caveat of this 'early' or 'late' definition is
662 that it is a binary definition of whether a gene is up- or downregulated between conditions (time-points),

663 relative to the background read depth of reads which map to the genome in question. Further analysis of
664 ASFV genes used their characterised or predicted functions, from the VOCS tool database
665 (https://4virology.net/) (88,89) entries for the GRG genome.

666 Quantification of viral genome copies at different time points of infection

667 Porcine lung macrophages were seeded and infected as described above. *Vero* cells were similarly
668 cultured in 6-well plates in DMEM medium supplemented with 10% Fetal calf serum, 100 IU/ml penicillin
669 and 100 µg/ml streptomycin, when semi-confluent they were infected with MOI 5 of Ba71V. Immediately
670 after infection (after 1h adsorption period, considered '0 hpi), or at 5 hpi, and 16 hpi, the supernatant was
671 removed and nucleic acids were extracted using the Qiamp viral RNA kit (Qiagen) and quantified using a
672 NanoDrop spectrophotometer (ThermoFisher Scientific). For quantification of viral genome copy
673 equivalents, 50 ng of each nucleic acid sample was used in qPCR with primers and probe targeting the
674 viral capsid gene B646L. As previously described (90), standard curve quantification qPCR was carried out
675 on a Mx3005P system (Agilent Technologies) using the primers CTGCTCATGGTATCAATCTTATCGA and
676 GATACCACAAGATC(AG)GCCGT and probe 5'-(6-carboxyfluorescein [FAM])-
677 CCACGGGAGGAATACCAACCCAGTG-3'-(6-carboxytetramethylrhodamine [TAMRA]).

678 Analysis of mRNA levels by RT-PCR and quantitative real time PCR (qPCR)

679 RNA from GRG or Ba71V infected macrophages, or *Vero* cells respectively, or from uninfected cell controls,
680 was collected at the different time points post-infection with Trizol, as described above. RNA was reverse
681 transcribed (800 ng RNA per sample) using SuperScript III First-Strand Synthesis System for RT-PCR and
682 random hexamers (Invitrogen). For PCR, cDNAs were diluted 1:20 with nuclease free water and 1 µl each
683 sample was amplified in a total volume of 20 µl using Platinum™ Green Hot Start PCR Master Mix
684 (Invitrogen) and 200 nM of each primer. Annealing temperatures were tested for each primer pair in
685 gradient PCR to determine the one optimal for amplification. Supplementary Table 7a shows the primers
686 used for each gene target, the amplicon size, PCR reaction conditions, and NCBI accession numbers for
687 sequences used primer design. PCRs were then performed with limited cycles of amplification to have a
688 semi-quantitative comparison of transcript abundance between infection timepoints (by not reaching the
689 maximum product amplification plateau). Amplification products were viewed using 1.5% agarose gel
690 electrophoresis.

691 C315R transcript levels were assessed by qPCR, using housekeeping gene glyceraldehyde-3-phosphate
692 dehydrogenase (GAPDH) expression was used for normalisation. Primer details and the qPCR

693 amplification program are shown in Supplementary Table 7b (GAPDH primers used for *Vero* cells were
694 previously published by Melchjorsen et al., 2009 (91)). Primers were used at 250 nM concentration with
695 Brilliant III Ultra-Fast SYBR® Green QPCR Master Mix (Agilent 600882), 1 µl cDNA in 20 µl (1:20) total
696 reaction volumes, and qPCRs carried out in Mx3005P system (Agilent Technologies). Similar amplification
697 efficiencies (97-102%) for all primers had been observed upon amplification of serially diluted cDNA
698 samples, and the relative expression at each timepoint of infection was calculated using the formula $2^{\Delta Ct}$
699 ($2^{Ct_GAPDH-Ct_C315R}$).

700 ASFV Promoter Motif Analysis

701 DESeq2 results were used to categorise ASFV genes into two simple sub-classes: early; 87 genes
702 downregulated from early to late infection and late; the 78 upregulated from early to late infection. These
703 characterised gene pTSSs were then pooled with the nORF pTSSs, and sequences upstream and
704 downstream of the pTSS were extracted from the GRG genome in FASTA format using BEDtools.
705 Sequences 35 bp upstream of and including the pTSSs were analysed using MEME software (http://meme-
706 suite.org) (92), searching for 5 motifs with a maximum width of 20 nt and 27 nt, respectively (other
707 settings at default). The input for MEME motif searches included sequences upstream of 134 early pTSSs
708 (87 genes and 47 nORFs) for early promoter searching, while 234 late pTSSs (78 genes and 156 nORFs)
709 were used to search for late promoters. For analysis of conserved motifs upstream of the five clusters
710 described in Figure 6a-b, sequences were extracted in the same manner as above, but grouped according
711 to their cluster. MEME motif searches were carried out for sequences in each cluster, searching for 3
712 motifs, 5-36 bp in length, with zero or one occurrence per sequence ('zoops' mode).

713 Identification of TSSs by rapid amplification of cDNA ends - 5'RACE

714 For 5'RACE of GRG genes DP146L, pNG4 and CP204L we designed the gene specific primers (GSP) shown
715 in Supplementary Table 7c, and used the kit: "5´ RACE System for Rapid Amplification of cDNA Ends"
716 (Invitrogen), according to manufacturer instructions. Briefly, 150 ng RNA from either 5 hpi or 16 hpi
717 macrophages (one of the replicate RNA samples used for CAGE-seq) was used for cDNA synthesis with
718 GSP1 primers, followed by degradation of the mRNA template with RNase Mix, and column purification
719 of the cDNA. A homopolymeric tail was added to the cDNA 3'ends with Terminal deoxynucleotidyl
720 transferase, which allowed PCR amplification with an "Abridged Anchor Primer" (AAP) from the 5'RACE
721 kit and a nested GSP2 primer. A second PCR was performed over an aliquot of the previous, with 5'RACE
722 "Abridged Universal amplification Primer" (AUAP), and an additional nested primer GSP3, except for pNG4

723 where GSP2 was re-used due to the small predicted size of the amplicon. Platinum™ Green Hot Start PCR
724 Master Mix (Invitrogen) was used for PCR and products were run in 2% agarose gel electrophoresis (see
725 Supplementary Table 7c for expected sizes). Efficient recovery of cDNA from the purification column
726 requires a product of at least 200 bases and therefore, due to the small predicted size of pNG4 transcripts
727 its GSP1 primer was extended at the 5' end with an irrelevant non-annealing sequence of extra 50 nt in
728 order to create a longer recoverable product.

729 CAGE-seq Analysis for the *Sus scrofa* Genome

730 Analyses of TSS-mapping, gene expression and motif searching with CAGE-seq reads mapped to the *Sus*
731 *scrofa* 11.1 genome were carried out by DNAFORM (Yokohama, Kanagawa, Japan). The 5' ends of CAGE-
732 seq reads were utilised as input for the Reclu pipeline (93) with a cutoff of 0.1 RPM, and irreproducible
733 discovery rate of 0.1. 37,159 total CAGE-seq peaks could be identified, of which around half (16,720)
734 match unique CAGE peaks previously identified by Roberts et al. (59) (i.e. within 100 nt of any of them).
735 TSSs for 9,384 protein-coding genes (out of 21,288) were annotated de novo from the CAGE-defined TSSs
736 (Supplementary Table 4).

737 Protein-coding genes with annotated TSSs (9,384 out of 21,288) were then subjected to differential
738 expression analysis. CAGE-seq reads were summed up over all TSSs assigned to a gene and compared
739 between two time points using edgeR (94) at maximum false discovery rate of 0.05. The full list of host
740 genes with annotated promoters together with their estimated expression levels is provided in
741 Supplementary Table 5. Gene set enrichment analysis was performed with the DAVID 6.8 Bioinformatics
742 Resources (95), using best BLASTP (96) human hits (from the UniProt (97) reference human proteome).
743 The 9,331 genes with human homologs were used as a background, and functional annotations of the
744 four major expression response groups (late/early up-/down-regulated genes) were clustered in DAVID
745 6.8 using medium classification stringency. MEME motif searches were conducted for promoters of four
746 differentially regulated subsets of host genes, as defined in Figure 11a. Promoters sequences were
747 extended 1000 bp upstream and 200 bp downstream of TSSs, searched with MEME (max. 10 motifs, max.
748 100 bp long, on a given strand only, zero or one site per sequence, $E < 0.01$), and then compared against
749 known vertebrate DNA motifs with Tomtom (p-value < 0.01).

750 ## Data Availability

751 Raw sequencing data are available on the Sequence Read Archive (SRA) database under BioProject:
752 PRJNA739166. This also includes CAGE-seq data aligned to the ASFV-GRG (FR682468.1 *Sus scrofa*
753 (GCF_000003025.6) genomes (see methods above) in BAM format. Available for review via the link below:

754 https://dataview.ncbi.nlm.nih.gov/object/PRJNA739166?reviewer=390lg85cohvh81llto5gr1d22n

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1010 the National Center for Biotechnology. Nucleic Acids Res. 2003 Jan 1;31(1):28–33.

1011

1012 Figures

1013 Figure 1. Functional genome annotation of ASFV GRG. (a) Comparison between the genomes of BA71V
1014 and GRG, generated with Circos (http://circos.ca/). Blue lines represent sequence conservation (Blast E-
1015 values per 100 nt). The Inner ring represents genes defined as MGF members (purple), and all others
1016 (grey). The outer ring shows annotated genes which we have defined as early or late according to
1017 downregulation or upregulation between 5 hpi and 16 hpi from DESeq2 analysis. (b) 189 GRG annotated

1018 ORFs are represented as arrows and coloured according to strand. CAGE-seq peaks across the GRG
1019 genome at 5 hpi (c) and 16 hpi (d), normalized coverage reads per million mapped reads (RPM) of 5' ends
1020 of CAGE-seq reads. The coverage was capped at 20000 RPM for visualisation, though multiple peaks
1021 exceeded this. DeepTools (98), was used to convert bam files to bigwig format and imported into Rstudio
1022 for visual representation via packages ggplot, ggbio, rtracklayer, and gggenes was used to generate the
1023 ORF map in (b).

1024

1025 Figure 2. Summary of GRG gene expression (a) Expression profiles for 164 genes for which we annotated
1026 pTSSs from CAGE-seq and which showed significant differential expression. Log2 fold change and
1027 basemean expression values were from DESeq2 analysis of raw counts (see methods). Genes are coloured
1028 according to their log2 fold change in expression as red (positive: upregulated from 5 hpi to 16 hpi) or
1029 blue (negative: downregulated). MGFs are emphasised with a black outline to highlight their
1030 overrepresentation in the group of downregulated genes. (b) Expression profiles for 43 genes (excluding
1031 nORFs) only detected as being expressed in GRG and not BA71V, format as in (a). (c) Expression (RPM) of
1032 20 highest-expressed genes at 5 hpi, error bars represent standard deviation between replicates. (d)
1033 Expression (RPM) of 20 highest-expressed genes at 16 hpi pi, error bars are the standard deviation
1034 between replicates.

1035

1036 Figure 3. Comparison of gene expression profiles for genes shared between GRG and BA71V. Scatter plots
1037 of mean RPM across replicates for shared genes at 5 hpi (a) and 16 hpi (b), coloured according to whether
1038 genes show significant downregulation (blue), or upregulation (red) according to DESeq2 analysis in GRG.
1039 In both (b) and (c) genes with RPM values above 40000 RPM in either strain are labelled. (c) Comparison
1040 of log2 fold change in expression values of genes in GRG and BA71V, in blue are downregulated (early)
1041 genes in both strains, red are upregulated (late) genes in both strains, while the genes which disagree in
1042 their differential expression patterns between strains are in black. R represents the Pearson Correlation
1043 coefficient for each individual plot in (a), (b), and (c).

1044

1045 Figure 4. Increase in virus genome copy number mRNA levels during late infection. (a) The 'log2 change'
1046 represents log2 of the ratio of CAGE-seq reads (normalised per million mapped reads) at 16 hpi vs. 5 hpi

1047 per nucleotide across the genome. Alignment comparisons and calculations were done with deepTools
1048 (98). (b) Replicate means of CAGE-seq reads mapped to either the BA71V (green) or GRG (purple) genomes
1049 throughout infection. (c) Fold change in CAGE-seq reads during infection, calculated via mean value across
1050 2 replicates, but with the assumption number of reads at 0 hpi is 0, therefore dividing by values from 5
1051 hpi. (d) Change in genome copies from DNA qPCR of B646L gene, dividing by value at 0 hpi to represent
1052 '1 genome copy per infected cell'. (e) Fold change in genome copies present at 0 hpi , 5 hpi and 16 hpi
1053 from qPCR in (d). (d) calculated as for (c), but with actual vales for 0 hpi.

1054

1055 Figure 5. RT-PCR results of genes for comparison to CAGE-seq data from (a) MGF505-7R, (b) NP419L, (c)
1056 D345L, (d) MGF360-12L, (e) MGF505-9R, and (f) qRT-PCR results of C315R (ASFV-TFIIB). (NT = no template
1057 control). For each panel at the top is a diagrammatic representation of each gene's TSSs (bent arrow,
1058 including both pTSS and ioTSSs), annotated ORF (red arrow), and arrow pairs in cyan or yellow represent
1059 the primers used for PCR (see methods for primer sequences). Beneath each PCR results are bar charts
1060 representing the CAGE-seq results as either normalised (mean RPM) or raw (mean read counts) data, error
1061 bars show the range of values from each replicate.

1062

1063 Figure 6. Comparison of the raw read counts for genes shared between BA71V and GRG. (a) clustered
1064 heatmap representation of raw counts for genes shared between BA71V and GRG, generated with
1065 pheatmap. (b) broad patterns represented by genes in the 5 clusters indicated in (a). (c) histogram
1066 showing the percentage of the total raw reads per gene which are detected at 16 hpi vs. 5 hpi post-
1067 infection, and comparing the distribution of percentages between GRG and BA71V. (d) Mean read counts
1068 from GRG at 5 hpi vs 16 hpi replicates, showing a significant increase (T-test, p-value: 0.045) from 5 hpi to
1069 16 hpi.

1070

1071 Figure 7. Promoter motifs and initiators detected in early and late ASFV GRG TSSs including alternative
1072 TSSs and those for nORFs. (a) Consensus of 30 bp upstream and 5 bp downstream of all 134 early TSSs
1073 including nORFs, with the conserved EPM (10) and Inr annotated. (b) 30 bp upstream and 5 bp
1074 downstream of all 234 late gene and nORFs TSSs, with the LPM and Inr annotated (c) The conserved EPM
1075 detected via MEME motif search of 35 bp upstream for 133 for 134 early TSSs (E-value: 3.1e-069). The

1076 conserved LPM detected via MEME motif search of 35 bp upstream for 46 for 234 late gene TSSs (E-value:
1077 2.6e-003). The locations of the EPM shown in (b) and LPM shown in (d) are annotated with brackets in (a)
1078 and (b), respectively. Motifs detected via MEME search of 35 bp upstream of genes in clusters from **Error!**
1079 **Reference source not found.**: cluster 1 (7 genes, E-value: 9.1e-012), 2 (15 genes, E-value: 2.6e-048), 3 (60
1080 genes, E-value: 1.0e-167), 4 (32 genes, E-value: 4.7e-105), 5 (16 genes, E-value: 5.7e-036), are shown in
1081 e-i, respectively. For ease of comparison, (e), (g), (i) and (f), (h) are aligned at TSS position. All motifs were
1082 generated using Weblogo 3 (99). (k) shows the distribution of MEME motif-end distances, from last nt (in
1083 coloured bracket), to their respective downstream TSSs.

1084

1085 Figure 8. The TSSs of MGF 360-19R. Panels (a) 5 hpi and (b) 16 hpi show CAGE-seq 5' end data from these
1086 time-points, in red are reads from the plus strand and blue from the minus strand, the RPM scales are on
1087 the right. (c) TSSs are annotated with arrows if they can generate a minimum of 5 residue-ORF
1088 downstream, and grey bars indicate where they are located on the CAGE-seq coverage in (a) and (b). ORFs
1089 identified downstream of TSSs are shown as red arrows (visualized with R package gggenes), including
1090 three short nORFs out of frame with MGF 360-19R. Also shown are three in-frame truncation variants,
1091 from TSSs detected inside the full-length MGF 360-19R 269-residue ORF, downstream of its pTSS at
1092 185213. Blue or yellow boxes upstream of TSSs indicate whether the EPM or LPM (respectively) could be
1093 detected within 35 nt upstream of the TSS using FIMO searching (100).

1094

1095 Figure 9. Summary of intra-ORF TSSs (ioTSSs) and nORFs detected in the GRG genome, further information
1096 in Supplementary Table 2. (a) Summarises the gene types in which ioTSSs were detected, showing an
1097 overrepresentation of MGFs, especially from families 360 and 505, furthermore, the majority of ioTSSs
1098 are detected at 16 hpi. (b) For ioTSSs in-frame with the original, summarised are the subsequent UTR
1099 lengths i.e. distance from TSS to next in frame ATG start codon, which could generate a truncation variant.
1100 (c) Example of a miss-annotation for CP204L, whereby the pTSS is downstream the predicted start codon.
1101 (d) and (e) show the results of 5'RACE for three genes (DP146L, pNG4, and CP204L, see methods for
1102 primers), at 5 hpi and 16 hpi, respectively. Examples of genome regions around DP146L (f) and pNG4 (g),
1103 wherein ioTSSs were detected with capacity for altering ORF length in subsequent transcripts, and
1104 therefore protein output. Primers used for 5'RACE for DP146L and pNG4 are represented as black arrows
1105 in (f) and (g), respectively.

1106

1107 Figure 10. Function prediction of MGF 100 genes. (a) Occurrence of MGF 100 genes in genomes of selected
1108 ASFV strains. Genome of the China/2018 strain missed annotation of MGF 100-3L gene, which is located
1109 at positions 180315–180617 on the minus strand. (b) Structure-guided multiple sequence alignment of
1110 selected MGF 100 members and SH2 domains. Secondary structure for MGF 100 members was predicted
1111 with PSIPRED (springs, A-helices; arrows, B-strands). (c) Structures of SH2 domains (from right to left):
1112 canonical recognising pTyr (PDB ID 1ayb, mouse Ptpn11), atypical recognising pSer (PDB ID 5vkl, yeast
1113 Spt6), and homology model of DP146L from ASFV strain BA71V (based on PDB IDs 4xey and 4fl3). Binding
1114 pockets are shown in the bottom panels.

1115

1116 Figure 11. Changes in the swine macrophage transcriptome upon ASFV GRG infection. (a) Major
1117 expression response profiles of the pig macrophage transcriptome. Late response genes are significantly
1118 deregulated (false discovery rate < 0.05) in one direction both between 0 and 16 hpi as well as between
1119 5 and 16 hpi, but not between 0 and 5 hpi. Early response genes are significantly deregulated in one
1120 direction both between 0 and 5 hpi as well as 0 and 16 hpi, but not between 5 and 16 hpi. (b) Relationship
1121 of log fold changes (logFC) of TSS-derived gene expression levels of the total 9,384 swine genes expressed
1122 in macrophages between 5–16 hpi and 0–16 hpi. Colors correspond to the response groups from the panel
1123 a. (c) Relationship of log fold changes of TSS-derived gene expression levels of the total 9,384 swine genes
1124 expressed in macrophages between 5–16 hpi and 0–5 hpi. (d) MA plot of the TSS-derived gene expression
1125 levels between 5 and 16 hpi based on differential expression analysis with edgeR (94,101). (e)
1126 Representative overrepresented functional annotations of the upregulated (red) and downregulated
1127 (blue) macrophage genes following late transcription response (Benjamini-corrected p-value lower than
1128 0.05). Numbers on the right to the bars indicate total number of genes from a given group annotated with
1129 a given annotation. (f) RT-PCR of four genes of interest indicated in (d). 'C' is the uninfected macrophage
1130 control, NTC is the Non Template Control for each PCR, excluding template DNA. See methods for primers
1131 used.

1132 Supplementary Figures

1133 Supplementary Figure 1. Clustered heatmap of ASFV gene expression for the genes shared between
1134 BA71V and GRG that showed significant differential expression. R package 'pheatmap'-generated

1135 clustered heatmap of per-gene RPM values for genes shared between GRG and BA71V, across time-points
1136 (5 hpi and 16 hpi), strains, with biological replicates as separate columns. Gene names for each row are
1137 listed on the right and both rows and columns were clustered according to Euclidean distance.

1138 Supplementary Figure 2. Comparison of top-scored MEME motifs enriched in promoters of deregulated
1139 host genes to sequences recognised by human transcription factors: a) Motif found in 28 upregulated
1140 gene promoters similar to sequences recognised by human interferon response factors (JASPAR
1141 accessions MA0653.1: IRF9, MA0652.1: IRF8, MA1419.1: IRF4). b) Motif found in 20 upregulated gene
1142 promoters similar to sequences recognised by human p65/RELA protein (JASPAR accessions MA0107.1).
1143 c) Motif found in 16 downregulated gene promoters similar to sequences recognised by human p65/RELA
1144 protein (JASPAR accessions MA0107.1).

1145 Supplementary Figure 3. Structure-guided multiple sequence alignment of selected C717R homologs and
1146 the kinase domain of Vps34 (PDB ID 5dfz). Secondary structure for C717R from African Swine Fever Virus,
1147 GRG (C717R-ASFV) was predicted with PSIPRED (springs, A-helices; arrows, B-strands). Colors of the
1148 secondary structure elements correspond to predicted domains: unknown N-terminal domain (green),
1149 kinase domain (blue), and alpha-helical C-terminal domain (pink). The C717R homologs were aligned with
1150 MAFFT and Vps34 was aligned based on HHpred mapping.

1151 Supplementary Figure 4. Function prediction of K421R. A. Structure-guided multiple sequence alignment
1152 of selected K421R homologs and viral poly(A) polymerases (vPAP). Secondary structure was predicted
1153 with PSIPRED (springs, A-helices; arrows, B-strands). Colors of the secondary structure elements
1154 correspond to predicted domains: dimerization domain (yellow), catalytic domain (red and blue),
1155 duplicated domain (green and blue), and C-terminal domain (purple). The ASFV-K421R sequence
1156 corresponds to K421R from GRG strain. Full set of sequences was aligned using MAFFT, following by
1157 manual corrections using known and predicted secondary structures. Red, black and, yellow triangles
1158 depict acidic residues from the described vPAP active site, the GG motif conserved in NTases, and residues
1159 usually coordinating ATP, respectively. Blue vertical lines denote insertions of non-conserved residues. B.
1160 Homology model of ASFV K421R compared to Vaccinia and *Mimivirus* vPAPs, shown in a cartoon
1161 representation (top panel) together with zoom-in views on the potential active sites (bottom panel). Five
1162 alternative models were generated with Modeller using templates of homodimeric *Megavirus chiliensis*
1163 and *Mimivirus* vPAPs (PDB IDs 4p37 and 4wse) with symmetric restraints, and the best one selected using
1164 the DOPE (Discrete Optimized Protein Energy) method.

1165 Supplementary Tables

1166 Supplementary Table 1. (a) Summary of CAGE-seq reads mapping to the ASFV and *Sus scrofa* genomes
1167 using Bowtie2 and HISAT2, respectively (see methods). Bed file output of clusters detected from separate
1168 CAGEfightR analysis from CAGE-seq data at 5 hpi (b) and 16 hpi (c) post-infection. (d) Table summarizing
1169 pTSS locations in GFF format for either annotated genes or nORFs. TSSs for MGF 100-3L, MGF 110-11L,
1170 MGF 300-2R, E66L, C62L, and KP93L were not detected. (e) Results from DESEq2 analysis of CAGE-seq
1171 peaks at TSSs - both those for primary gene TSSs and those for novel ORFs. DESeq2 output is explained in
1172 Love et al. (41). The DESeq2 default adjusted p-value is a Wald test p-value with Benjamini–Hochberg
1173 correction (102). Per sample coverage is reported in transcripts per million mapped reads (TPM) in the
1174 final four columns. (f) Updated genome coordinates of annotated ORFs in the GRG genome, and for 5 hpi
1175 and 16 hpi each gene's stage-specific pTSS locations, with their nt distances relative to one another. The
1176 Untranslated Region or UTR length for each gene is shown (nt distance from each pTSS to the ORF start
1177 codon), and lastly whether the gene is differently expressed: early, late or not-classified (NC).

1178 Supplementary Table 2. Summary of TSSs detected which potentially generate novel ORFs, unannotated
1179 in the GRG genome by identifying CAGEfightR-annotated TSSs with an unannotated ORF encoded
1180 downstream. (a) All putative unannotated ORF-generating TSSs. (b) The ioTSSs - overlapping in-frame with
1181 annotated ORFs, with potential for generating truncation variants. (c) TSSs with potential for encoding
1182 ORFs downstream (down to 5 residues) which are not among the 189 ORFs annotated in the FR682468.1
1183 genome.

1184 Supplementary Table 3. Results from MEME motif (48) analysis of DNA sequences 35 bp upstream of
1185 conserved genes between ASFV and BA71V split into 5 clusters described in Figure 6.

1186 Supplementary Table 4. List of CAGE-seq peaks (i.e., CAGE-derived transcription start sites, TSSs) found in
1187 *Sus scrofa* ASFV-infected macrophages. TSSs were mapped to the nearest *S. scrofa* 11.1 Ensembl (103)
1188 protein-coding genes using the RECLU pipeline (93). The read coverage was normalised to counts (reads)
1189 per million (CPM).

1190 Supplementary Table 5. TSS-based transcript levels of *S. scrofa* macrophage-expressed genes. The read
1191 coverage was summed over all TSSs assigned to a given gene and normalised to counts (reads) per million
1192 (CPM). Significantly down- or upregulated genes were found with edgeR (94,101) at false discovery rate
1193 of 0.05.

1194 Supplementary Table 6. Functional categories enriched in swine macrophage-expressed genes down- or
1195 upregulated at 16 hpi p.i. found with DAVID 6.8 Bioinformatics Resources (95), using best BLASTP (96,104)
1196 human hits. Supplementary Table 7. (a) ASFV and host genes whose expression level was assessed by RT-
1197 PCR. Primer pair sequences, PCR conditions and Accession Numbers of the sequences used for primer
1198 design are shown. (b) Primer details and qPCR conditions used for quantification of C315R gene
1199 expression. (c) Genes analyzed with 5'RACE and details of the primers used. The predicted locations of
1200 the genes on the GRG complete genome (Accession FR682468) as well as the expected length of upstream
1201 untranslated regions (5'UTR) according to the detected TSSs in CAGE-seq are shown. The final expected
1202 amplicon sizes in the last column are the result of PCR with GSP3 nested primer (GSP2 in pNG4) plus 36
1203 bp added to the final sequence as a result of the 5'RACE polynucleotide tail addition and amplification
1204 with "Abridged Anchor Primer" (AAP). GSP1 primer from pNG4 was extended with 50 non-annealing
1205 nucleotides (small caps italic) to increase the cDNA length.

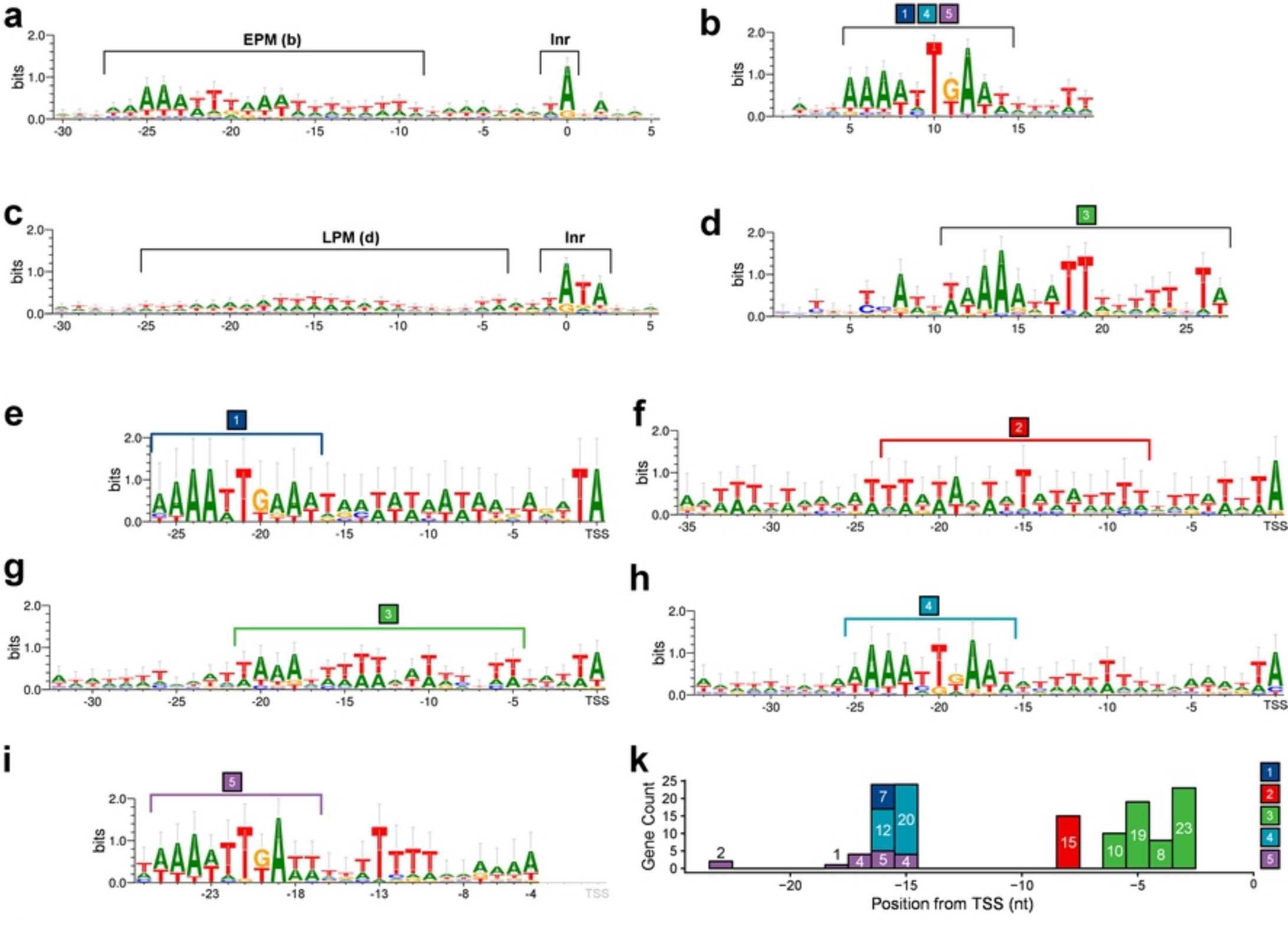

a
EPM (b)
Inr
b
c
LPM (d)
Inr
d
e
f
g
h
i
k
bits
TSS
Gene Count
Position from TSS (nt)

Figure 7

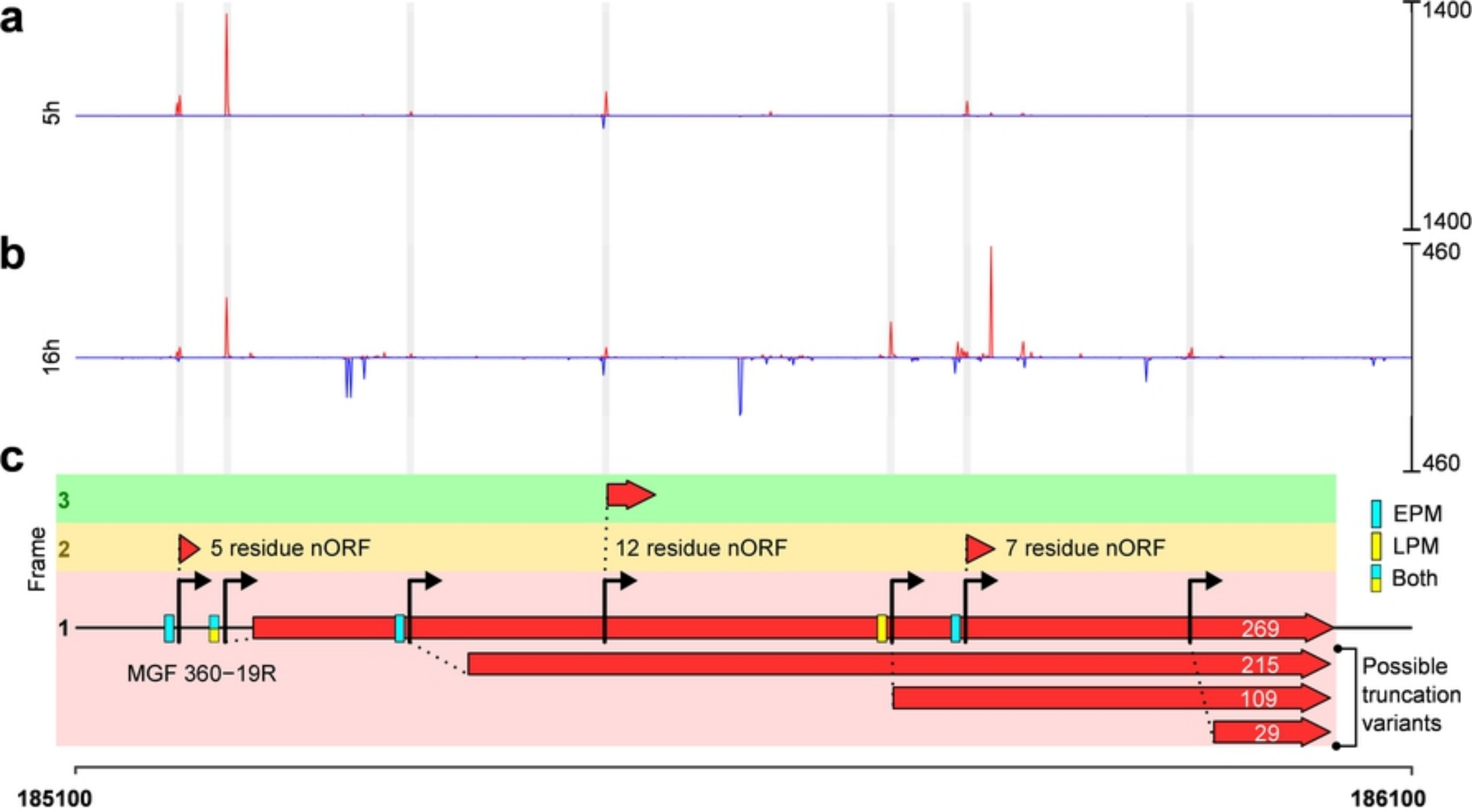

a
5h
1400
1400
b
16h
460
460
c
Frame
3
2
1
5 residue nORF
12 residue nORF
7 residue nORF
EPM
LPM
Both
269
215
109
29
MGF 360−19R
Possible truncation variants
185100
186100

Figure 8

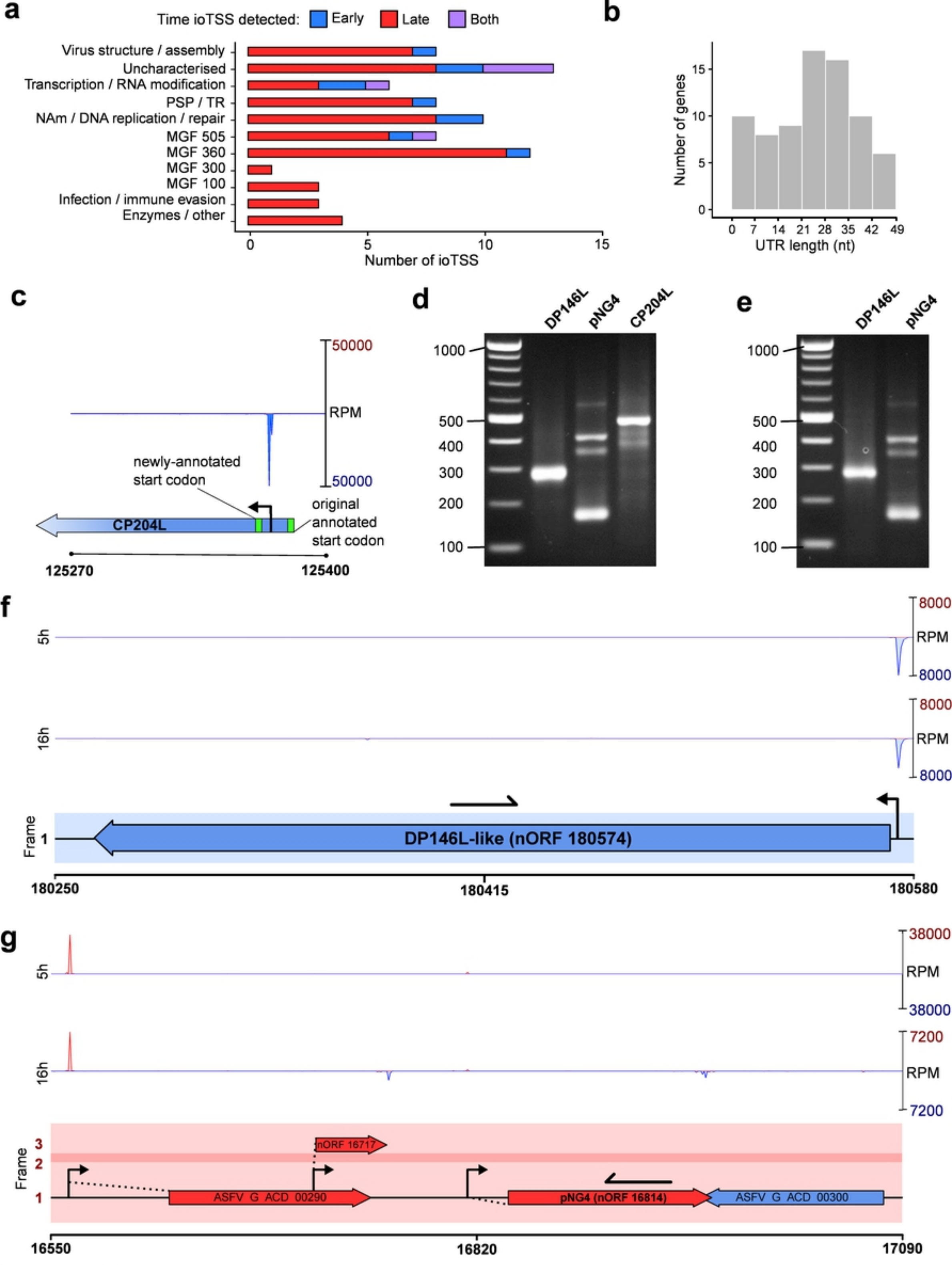

a
Time ioTSS detected:
Early
Late
Both
Virus structure / assembly
Uncharacterised
Transcription / RNA modification
PSP / TR
NAm / DNA replication / repair
MGF 505
MGF 360
MGF 300
MGF 100
Infection / immune evasion
Enzymes / other
0
5
10
15
Number of ioTSS
b
Number of genes
0
5
10
15
0 7 14 21 28 35 42 49
UTR length (nt)
c
50000
RPM
50000
newly-annotated
start codon
original
annotated
start codon
CP204L
125270
125400
d
DP146L
pNG4
CP204L
1000
500
400
300
200
100
e
DP146L
pNG4
1000
500
400
300
200
100
f
5h
16h
8000
RPM
8000
Frame
1
DP146L-like (nORF 180574)
180250
180415
180580
g
5h
16h
38000
RPM
38000
7200
RPM
7200
Frame
3
2
1
nORF 16717
ASFV_G_ACD_00290
pNG4 (nORF 16814)
ASFV_G_ACD_00300
16550
16820
17090

Figure 9

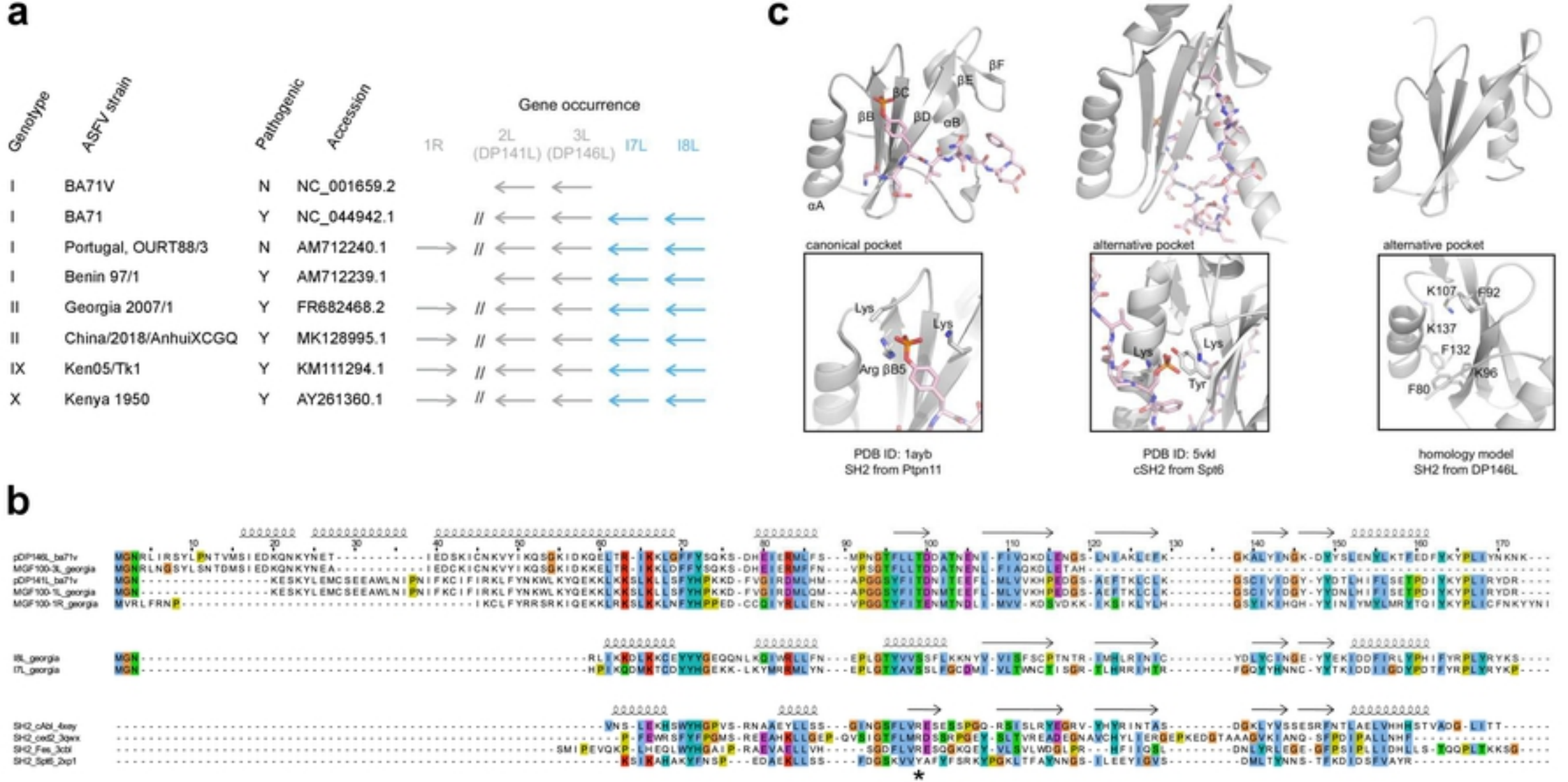

a
Genotype
ASFV strain
Pathogenic
Accession
Gene occurrence
1R
2L (DP141L)
3L (DP146L)
I7L
I8L
I BA71V N NC_001659.2
I BA71 Y NC_044942.1
I Portugal, OURT88/3 N AM712240.1
I Benin 97/1 Y AM712239.1
II Georgia 2007/1 Y FR682468.2
II China/2018/AnhuiXCGQ Y MK128995.1
IX Ken05/Tk1 Y KM111294.1
X Kenya 1950 Y AY261360.1
c
βF
βE
βC
βB
βD
αB
αA
canonical pocket
alternative pocket
alternative pocket
Lys
Lys
Arg βB5
Lys
Lys
Tyr
K107
F92
K137
F132
K96
F80
PDB ID: 1ayb
SH2 from Ptpn11
PDB ID: 5vkl
cSH2 from Spt6
homology model
SH2 from DP146L
b
pDP146L_ba71v
MGF100-3L_georgia
pDP141L_ba71v
MGF100-1L_georgia
MGF100-1R_georgia
I8L_georgia
I7L_georgia
SH2_cAbl_4xey
SH2_ces2_3qwx
SH2_Fes_3cbl
SH2_Spt6_2xp1
*

Figure 10

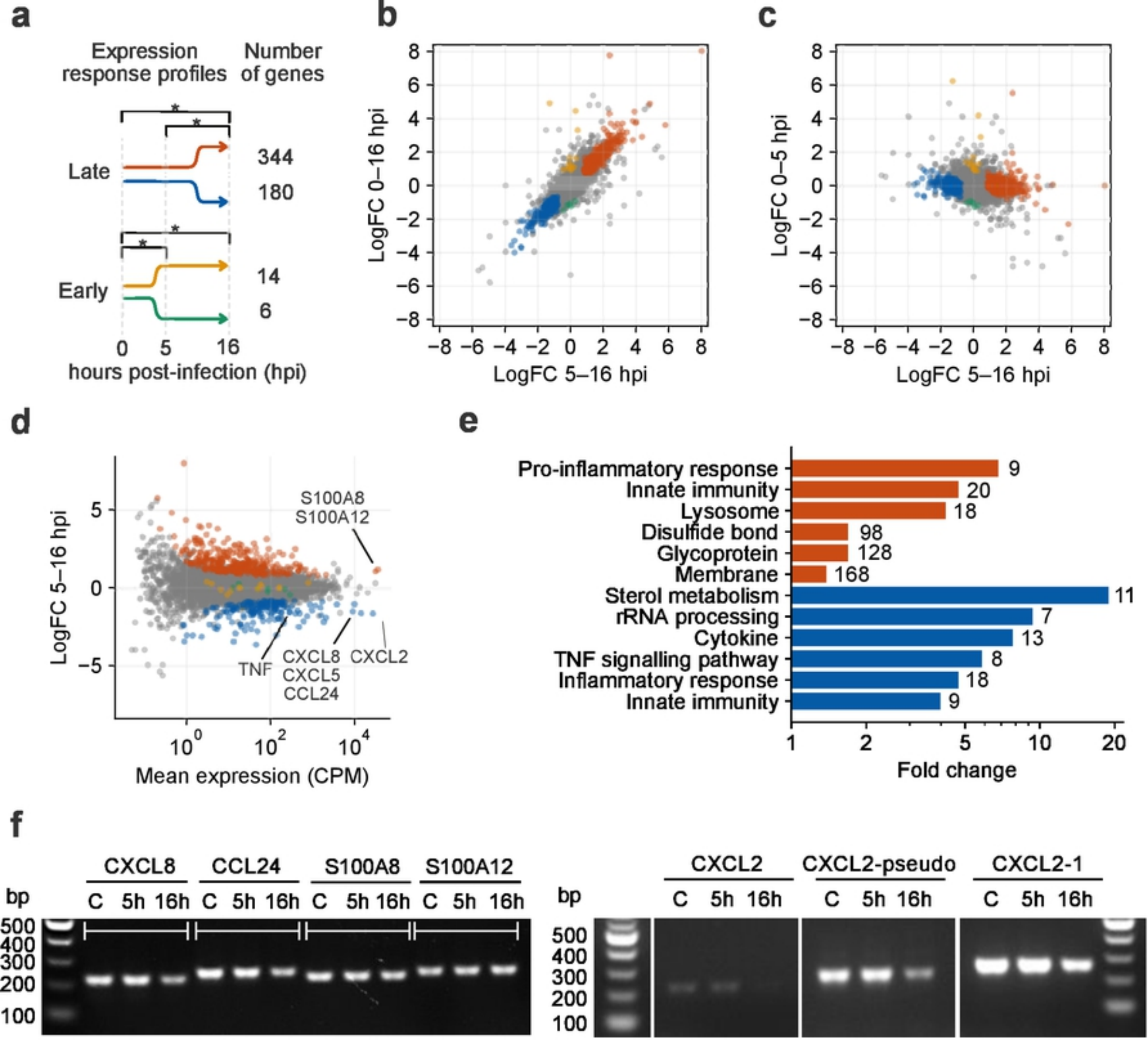

a
Expression response profiles
Number of genes
Late
344
180
Early
14
6
0
5
16
hours post-infection (hpi)
b
LogFC 0–16 hpi
LogFC 5–16 hpi
c
LogFC 0–5 hpi
LogFC 5–16 hpi
d
LogFC 5–16 hpi
Mean expression (CPM)
S100A8
S100A12
TNF
CXCL8
CXCL5
CCL24
CXCL2
e
Pro-inflammatory response 9
Innate immunity 20
Lysosome 18
Disulfide bond 98
Glycoprotein 128
Membrane 168
Sterol metabolism 11
rRNA processing 7
Cytokine 13
TNF signalling pathway 8
Inflammatory response 18
Innate immunity 9
Fold change
f
CXCL8
CCL24
S100A8
S100A12
CXCL2
CXCL2-pseudo
CXCL2-1
C 5h 16h
bp
500
400
300
200
100

Figure 11

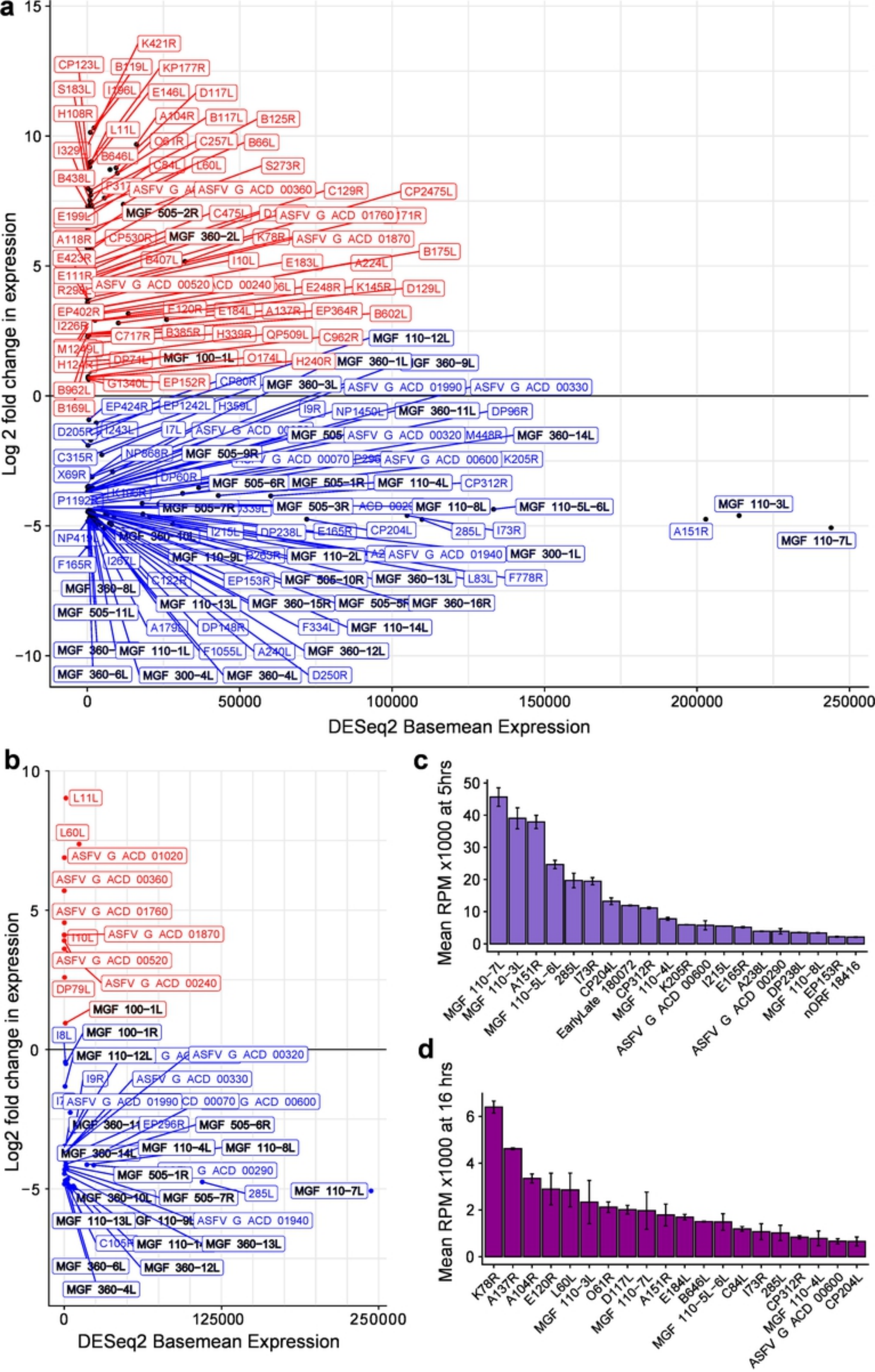

a
Log 2 fold change in expression
DESeq2 Basemean Expression
b
Log2 fold change in expression
DESeq2 Basemean Expression
c
Mean RPM x1000 at 5hrs
d
Mean RPM x1000 at 16 hrs

Figure 2

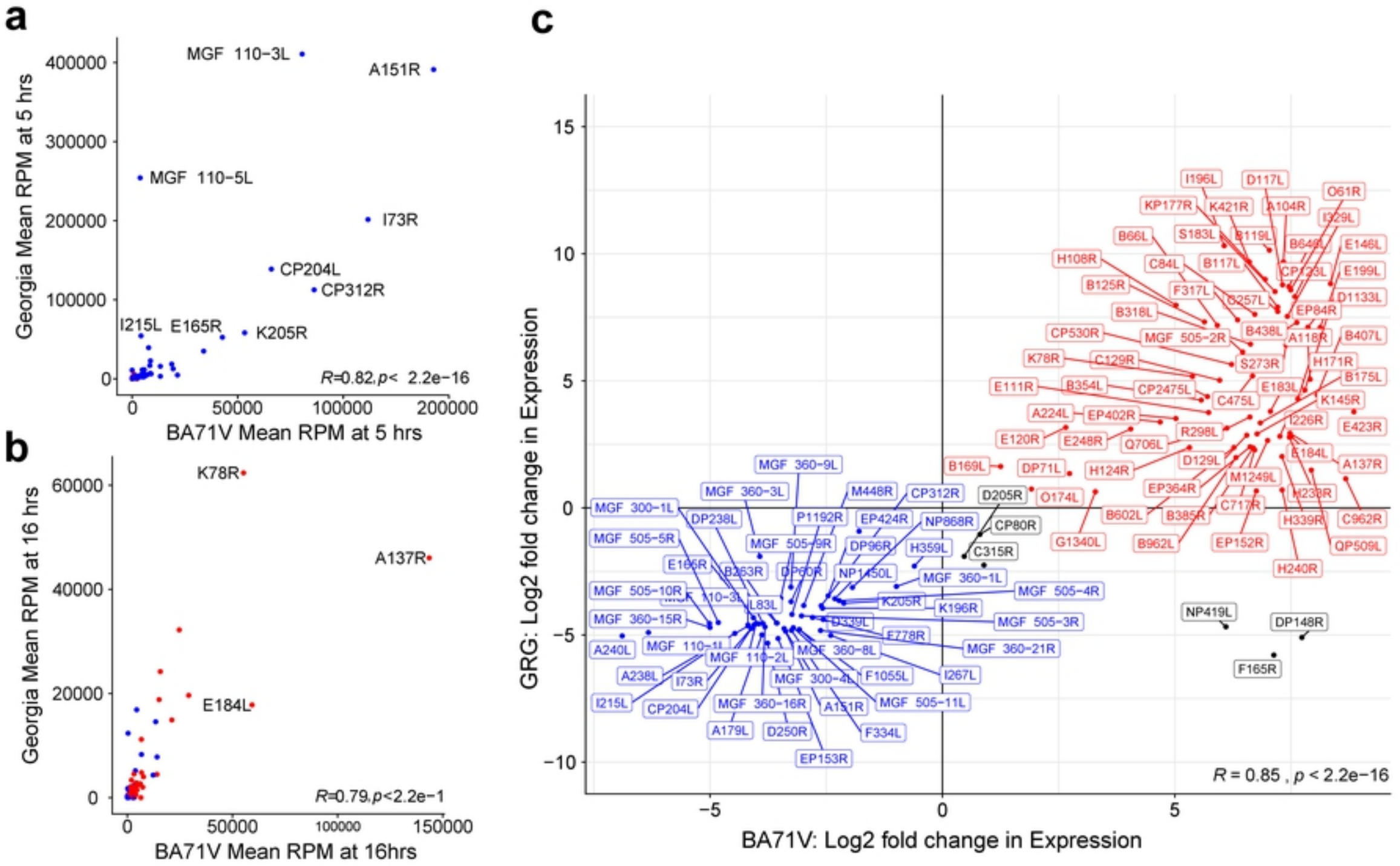

a
Georgia Mean RPM at 5 hrs
BA71V Mean RPM at 5 hrs
MGF 110-3L
A151R
MGF 110-5L
I73R
CP204L
CP312R
I215L
E165R
K205R
R=0.82, p< 2.2e-16
b
Georgia Mean RPM at 16 hrs
BA71V Mean RPM at 16hrs
K78R
A137R
E184L
R=0.79, p<2.2e-1
c
GRG: Log2 fold change in Expression
BA71V: Log2 fold change in Expression
R = 0.85 , p < 2.2e-16

Figure 3

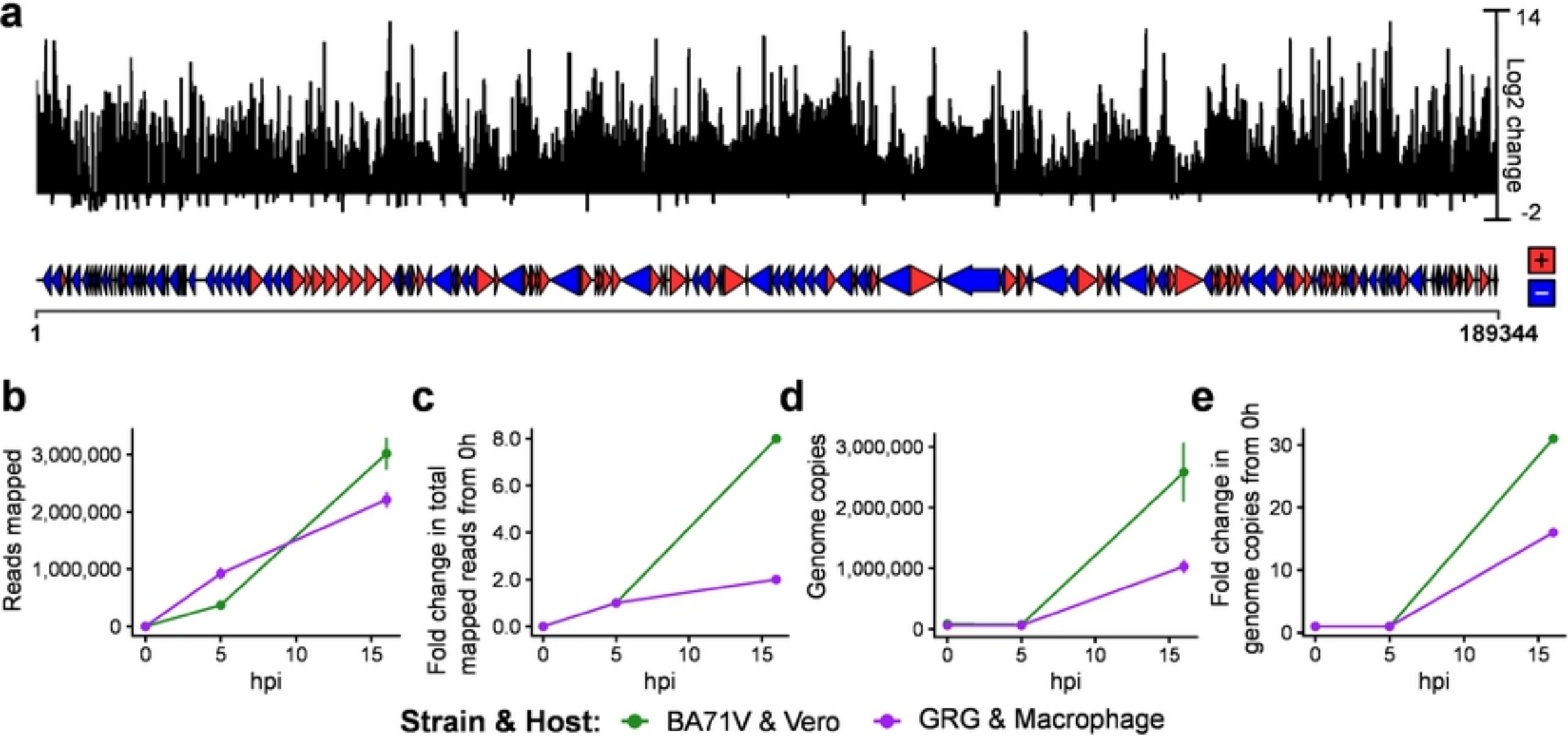

a
14
Log2 change
-2
+
−
1
189344
b
Reads mapped
3,000,000
2,000,000
1,000,000
0
0
5
10
15
hpi
c
Fold change in total mapped reads from 0h
8.0
6.0
4.0
2.0
0.0
0
5
10
15
hpi
d
Genome copies
3,000,000
2,000,000
1,000,000
0
0
5
10
15
hpi
e
Fold change in genome copies from 0h
30
20
10
0
0
5
10
15
hpi
Strain & Host:
BA71V & Vero
GRG & Macrophage

Figure 4

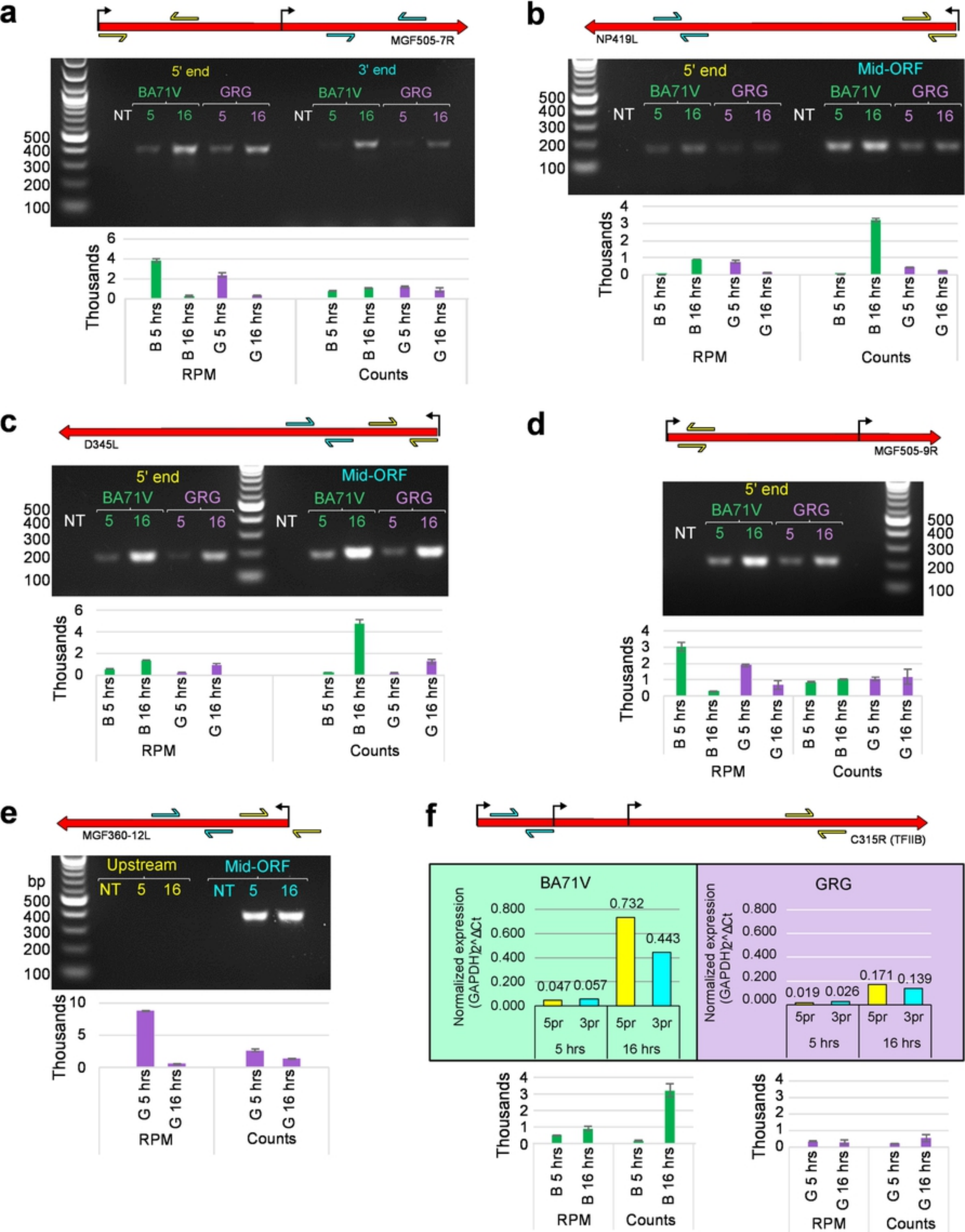

a
MGF505-7R
5' end
3' end
BA71V
GRG
NT
5
16
500
400
300
200
100
Thousands
B 5 hrs
B 16 hrs
G 5 hrs
G 16 hrs
RPM
Counts
b
NP419L
Mid-ORF
c
D345L
d
MGF505-9R
e
MGF360-12L
Upstream
bp
f
C315R (TFIIB)
Normalized expression (GAPDH)2^ΔCt
5pr
3pr
5 hrs
16 hrs
0.047
0.057
0.732
0.443
0.019
0.026
0.171
0.139

Figure 5

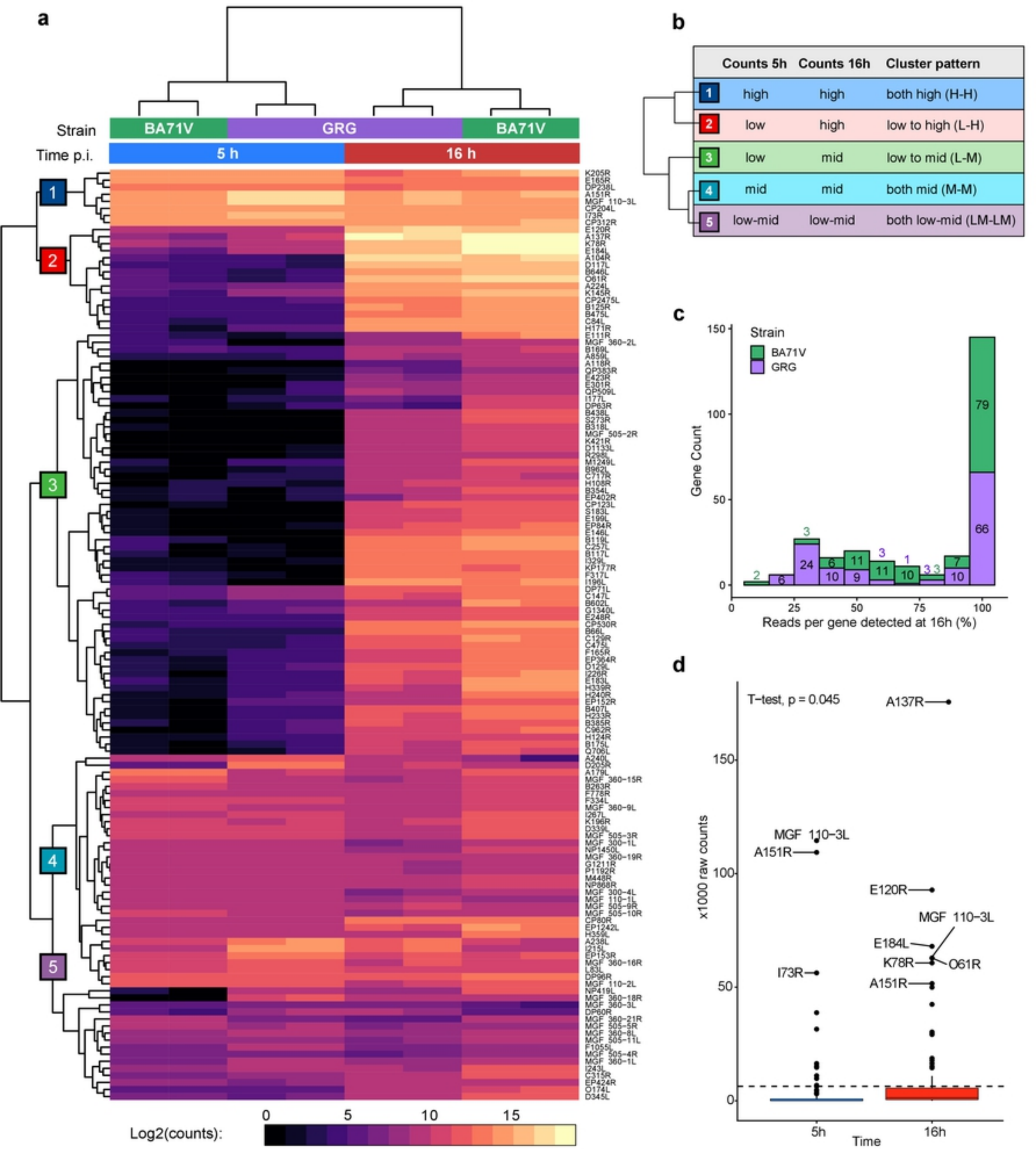
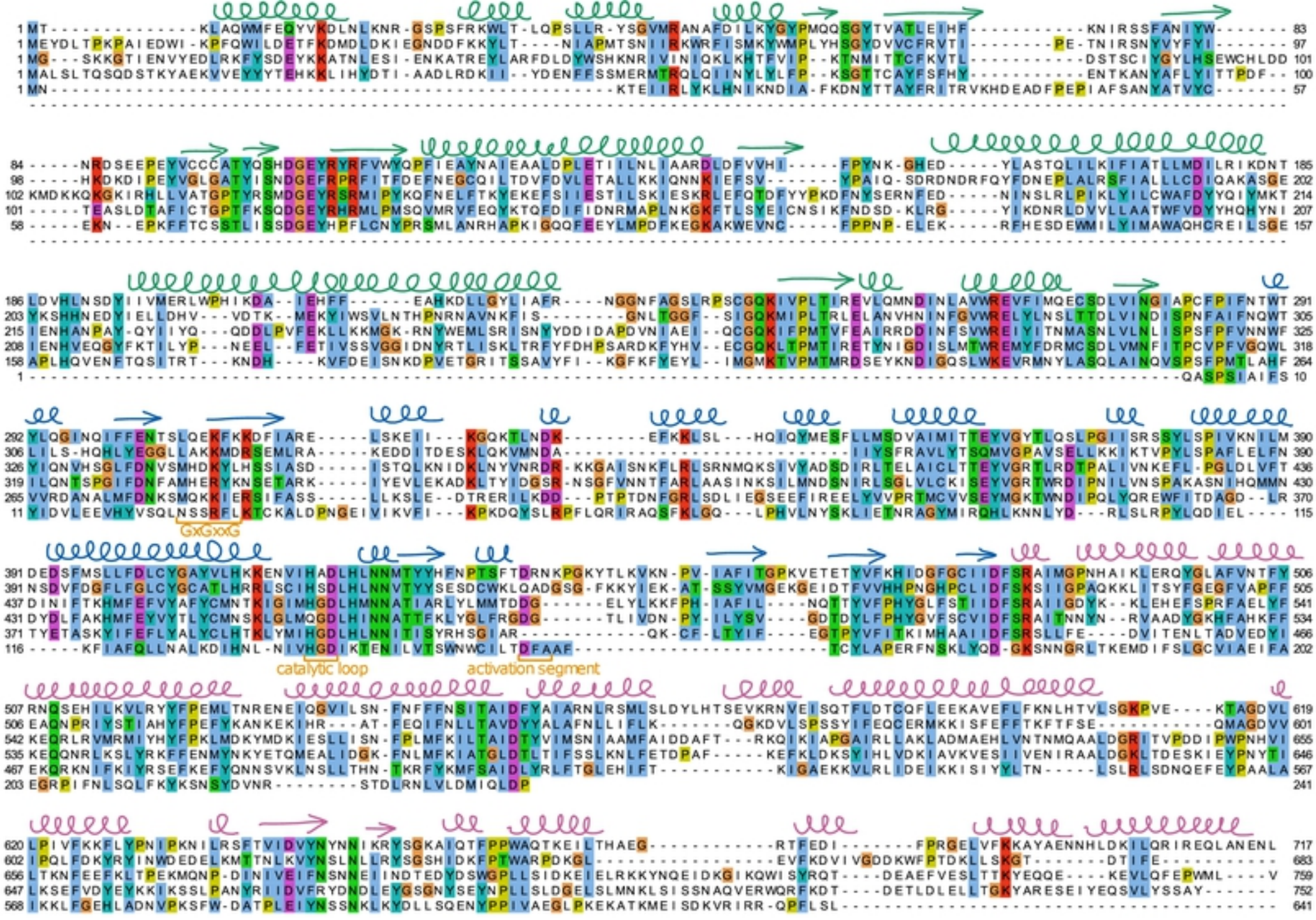
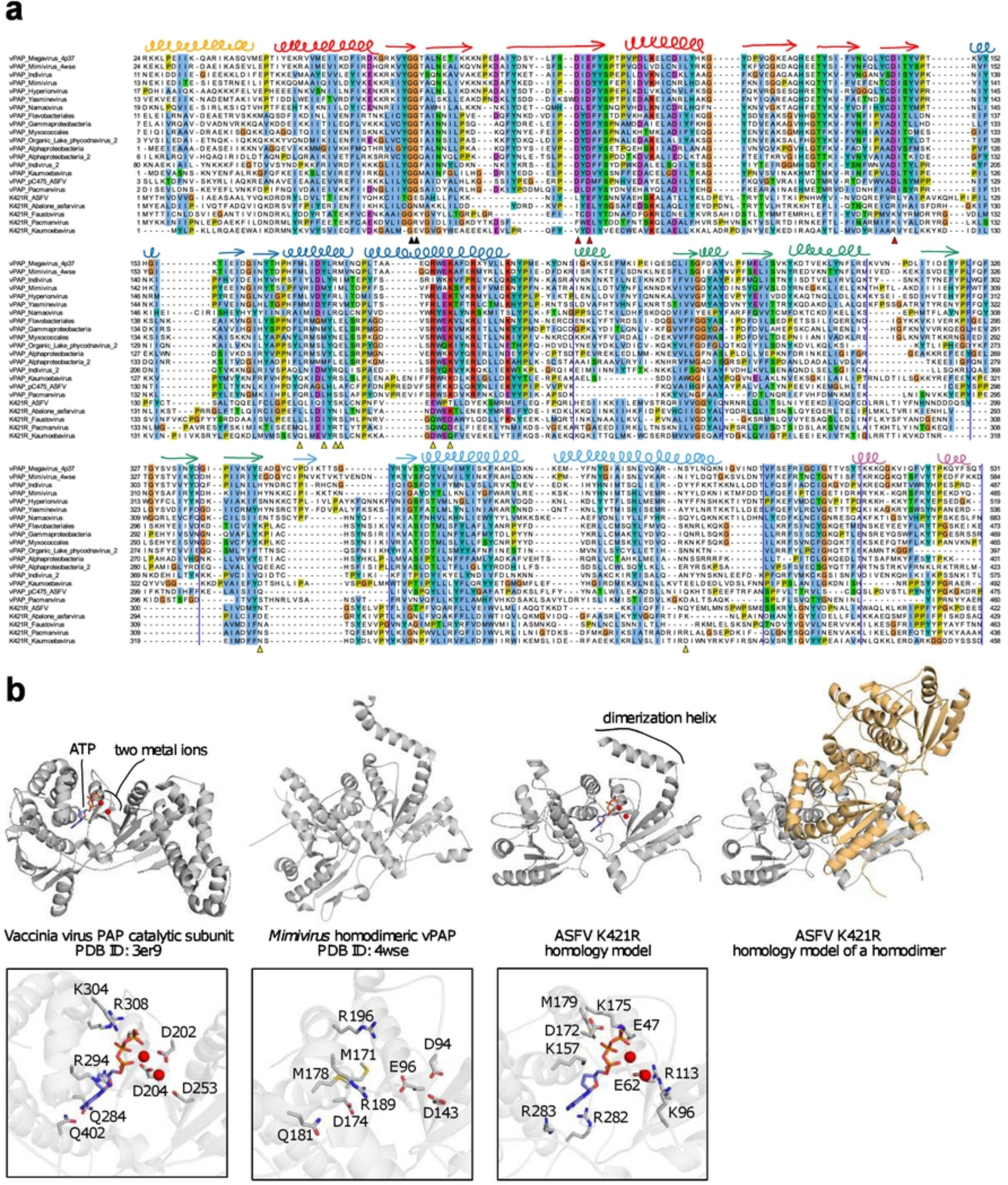

a
Strain
BA71V
GRG
BA71V
Time p.i.
5 h
16 h
1
2
3
4
5
Log2(counts):
0
5
10
15
b
Counts 5h
Counts 16h
Cluster pattern
1 high high both high (H-H)
2 low high low to high (L-H)
3 low mid low to mid (L-M)
4 mid mid both mid (M-M)
5 low-mid low-mid both low-mid (LM-LM)
c
Strain
BA71V
GRG
Gene Count
Reads per gene detected at 16h (%)
d
T-test, p = 0.045
x1000 raw counts
A137R
MGF 110-3L
A151R
E120R
MGF 110-3L
E184L
K78R
O61R
I73R
A151R
5h
16h
Time

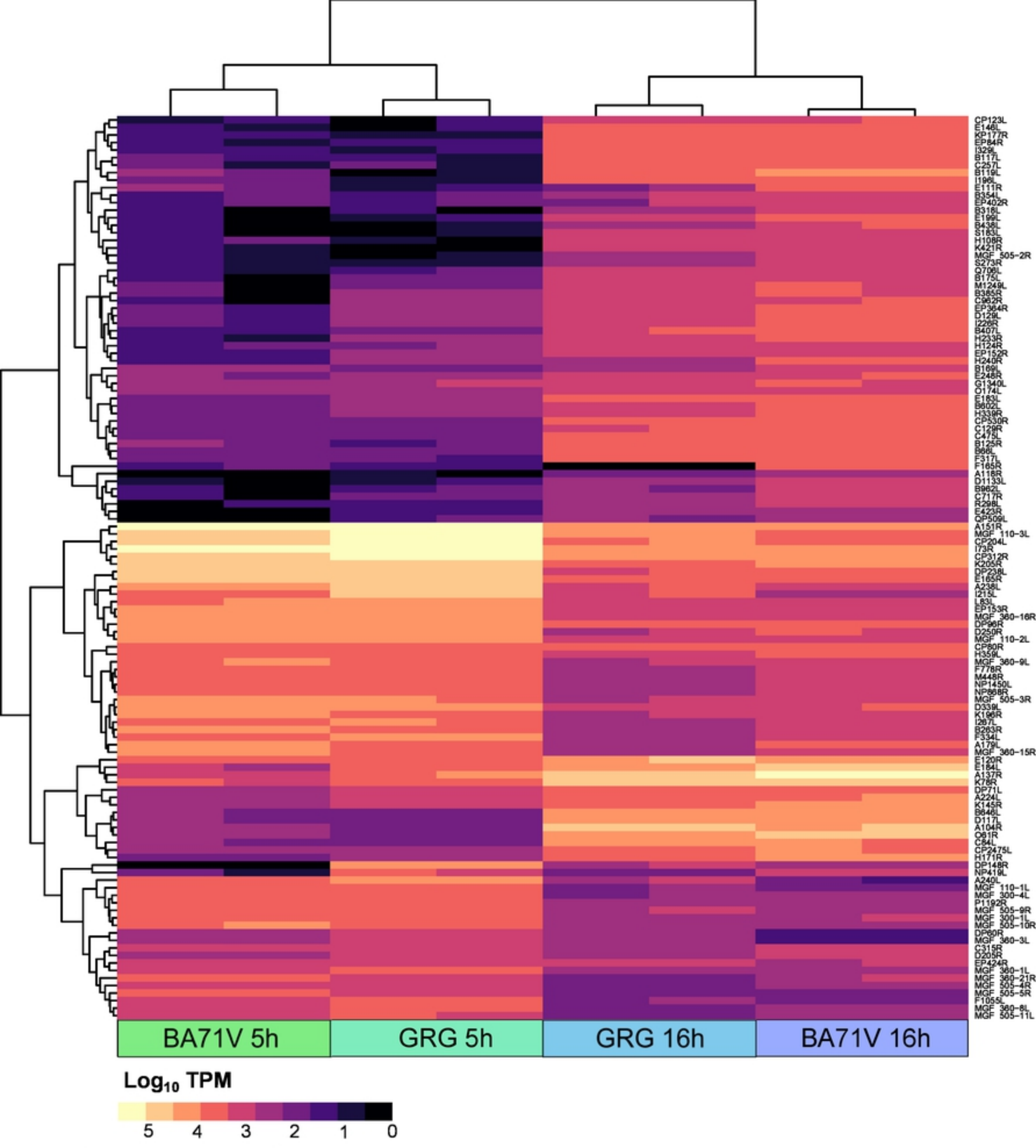
Figure 6



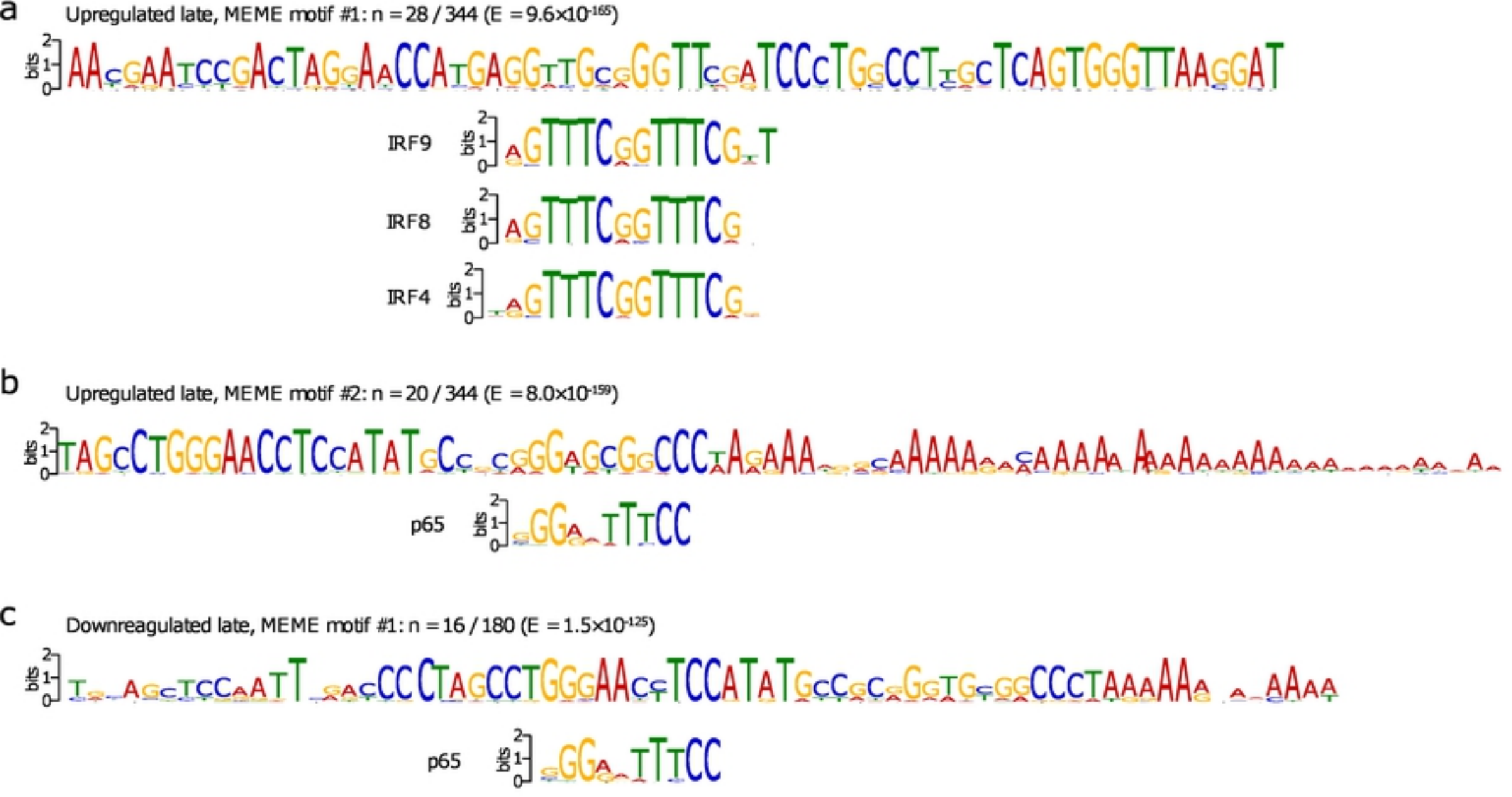
Supplementary Figure 3



Supplementary Figure 4



Supplementary Figure 1



Supplementary Figure 2

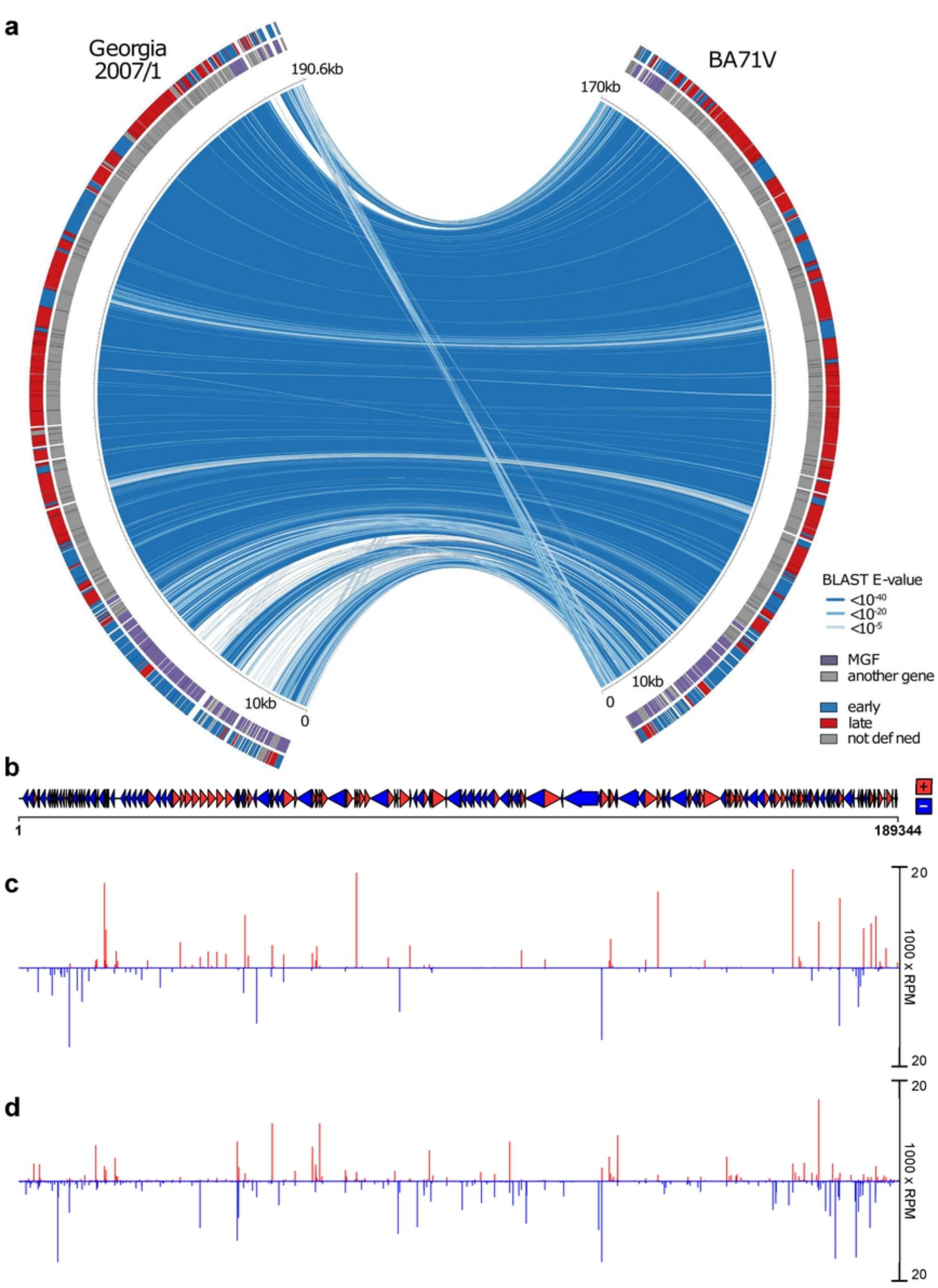

a
Georgia
2007/1
190.6kb
170kb
BA71V
10kb
0
10kb
0
BLAST E-value
<10^-40
<10^-20
<10^-5
MGF
another gene
early
late
not def ned
b
1
189344
c
20
1000 x RPM
20
d
20
1000 x RPM
20

Figure 1