

PKA-dependent regulation of the histone lysine demethylase complex PHF2–ARID5B

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Reversible histone methylation and demethylation are highly regulated processes that are crucial for chromatin reorganization and regulation of gene transcription in response to extracellular conditions. However, the mechanisms that regulate histone-modifying enzymes are largely unknown. Here, we characterized a protein kinase A (PKA)-dependent histone lysine demethylase complex, PHF2–ARID5B. PHF2, a *jmjC* demethylase, is enzymatically inactive by itself, but becomes an active H3K9Me2 demethylase through PKA-mediated phosphorylation. We found that phosphorylated PHF2 then associates with ARID5B, a DNA-binding protein, and induce demethylation of methylated ARID5B. This modification leads to targeting of the PHF2–ARID5B complex to its target promoters, where it removes the repressive H3K9Me2 mark. These findings suggest that the PHF2–ARID5B complex is a signal-sensing modulator of histone methylation and gene transcription, in which phosphorylation of PHF2 enables subsequent formation of a competent and specific histone demethylase complex.

Post-translational modifications of histone amino-terminal tails, including reversible acetylation, methylation, phosphorylation and ubiquitylation, modulate both chromatin structure and gene regulation^{1,2}. Reversible histone methylation defines the state of chromatin; repressive histone methylation marks such as H3K9Me2 inhibit gene transcription from nearby promoters, and removal of these marks by histone lysine demethylases permit transcription. Thus, enzymes such as *jmjC* (Jumonji C)-domain-containing histone lysine demethylases seem to play pivotal roles in epigenetic control^{3–10}. Though histone marks are altered in response to extracellular signals, the underlying mechanism by which this is achieved is largely unknown.

RESULTS

Identification of the PHF2–ARID5B histone H3K9Me2 demethylase complex

During biochemical identification of transcriptional co-regulators for nuclear receptors^{11,12}, we purified a number of direct interactants for nuclear receptors. Among them, a co-activator complex for FXR (farnesoid X receptor) from HepG2 cells was selected for further analysis, because its abundance in the purified fractions was significantly increased when the cells were pretreated with forskolin (FSK), a protein kinase A (PKA) activator (Supplementary Fig. S1a). Matrix-assisted laser desorption/ionization–time of flight mass

spectrometry analysis of the purified complex^{11,12} identified three subunits: plant homeodomain (PHD) finger two (PHF2; ref. 13), AT-rich interactive domain 5B (ARID5B) isoform α and ARID5B isoform β (ref. 14; Fig. 1a and Supplementary Fig. S1b–e). The complex was still detectable after further column purification (Supplementary Fig. S1f). ARID5B contains the ARID/Bright domain, which is seen in subunits of chromatin-remodelling complexes and is considered to be a sequence-specific/nonspecific DNA-attachment domain¹⁴. PHF2 (ref. 13) contains PHD and *jmjC* domains^{4,6}. Unlike several other *jmjC* histone demethylases^{3,5,8,9}, PHF2 lacks the ARID domain. PHF2 and ARID5B genes are expressed in a broad range of tissues, including liver (Supplementary Fig. S2c), and at protein levels as well in various cell lines (Supplementary Fig. S2a,b,d). PHF2 physically interacted with FXR and HNF4 α (hepatocyte nuclear factor 4 α ; Supplementary Fig. S3a,b,d), but not with ER α (oestrogen receptor alpha) or VDR (vitamin D receptor; Supplementary Fig. S3c,d). PHF2 directly interacted with ARID5B *in vitro* (Supplementary Fig. S3e–g).

The PHF2–ARID5B complex was purified from HepG2 cells stably expressing Flag–PHF2. As *jmjC*-domain-containing proteins catalyse lysine demethylation^{3–10}, we investigated the histone lysine demethylation activity of the purified PHF2 complex^{7,10}. The PHF2 complex exhibited lysine demethylase activity *in vitro* as assessed by a formaldehyde release (Fig. 1b). Then we examined

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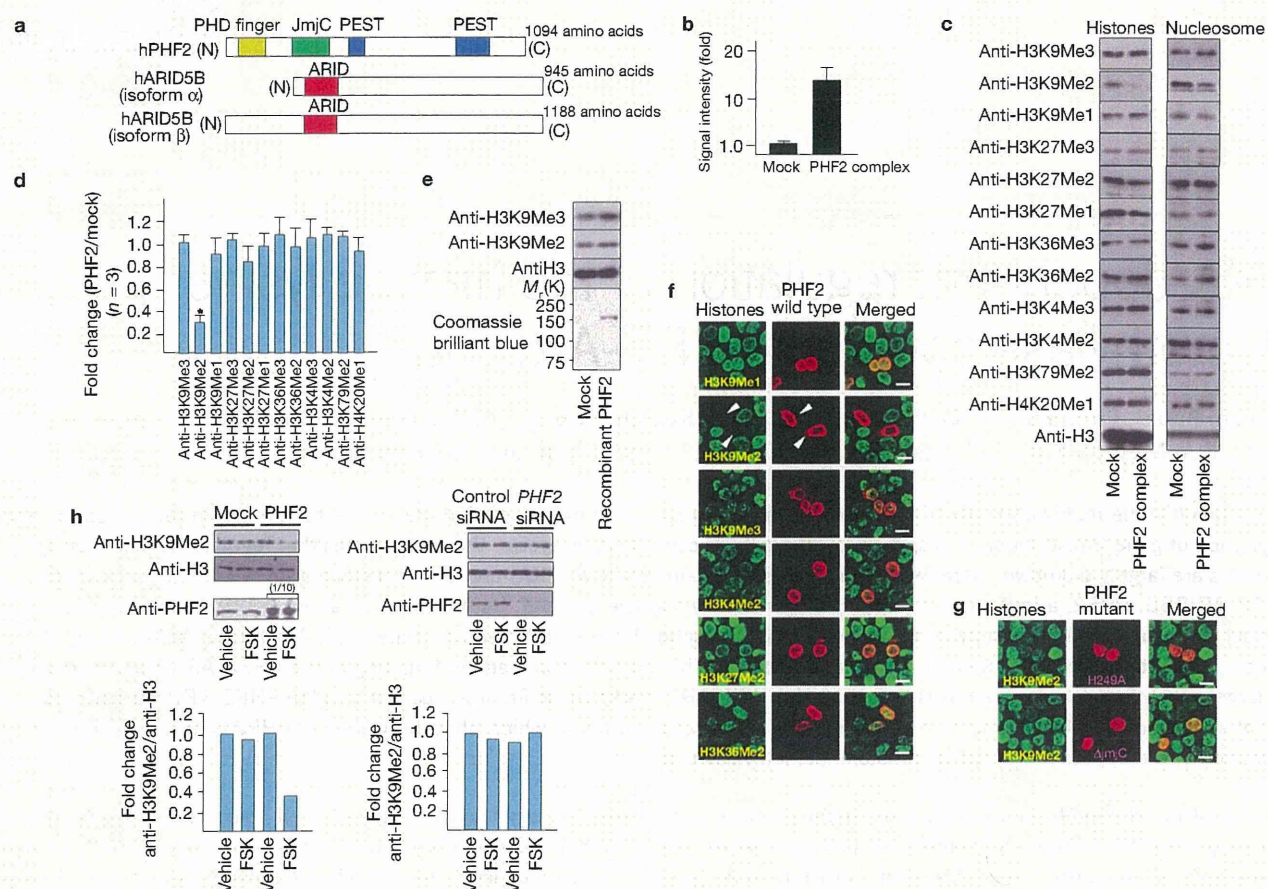


Figure 1 Identification of the PHF2–ARID5B histone H3K9Me2 demethylase complex. **(a)** A schematic representation of domains of PHF2 and ARID5B. **(b–d)** Histone H3K9Me2 demethylase activity of the purified PHF2 complex *in vitro*. **(b)** Native histones were incubated with PHF2 complex, and formaldehyde release was analysed by fluorescence detection. Shown is the average \pm s.d. ($n = 3$) of the relative activity. **(c)** The PHF2 complex was incubated with purified native histones (left) or mononucleosomes (right) for demethylation reaction, and each modification was determined by western blotting as indicated. **(d)** Intensity of histone marks in the demethylation assay of native histones by PHF2 (in **c** and Supplementary Fig. S8a) was quantified, and averages \pm s.d. of three independent experiments are shown. The asterisk shows $P < 0.05$ in Student's *t*-test. **(e)** Recombinant PHF2

the site-specificity of lysine demethylation using native histones or purified mononucleosomes as substrates. *In vitro*, the PHF2 complex demethylated dimethylated Lys 9 on histone H3 (H3K9Me2), but neither mono- nor trimethylated H3K9 (H3K9Me1, Me3) (Fig. 1c,d). Methylated H3K4, K27, K36 and K79 and H4K20 seemed unlikely PHF2 substrates (Fig. 1c,d). Thus it is likely that PHF2 substrate recognition is more specific than the closely related PHF subfamily members such as PHF8 and KDM7/KIAA1718 (refs 15–17). This demethylase activity was not detected in recombinant PHF2 protein (Fig. 1e). PHF2 did not demethylate a methylated peptide (amino acids 1–21 of H3) containing K9Me2 (Supplementary Fig. S4a). Such substrate specificity is known for Lid2 (ref. 18) and yeast Lsd1 (ref. 19), and possibly due to requirement of other regions of H3. Immunostaining analysis of 293F cells confirmed that PHF2 almost entirely demethylated H3K9Me2 in the presence of FSK, but had only marginal effects on H3K27Me2 and the other tested methylated

protein is catalytically inactive. Recombinant PHF2 protein (lower panel) was subjected to *in vitro* demethylation assay (upper panels). **(f)** 293F cells were transfected with Flag–PHF2 expression vectors for 24 h and treated with FSK for 6 h, then cells were fixed and immunostained with the indicated antibodies. Note the decreased level of H3K9Me2 in the anti-Flag-positive cells (arrowheads). Scale bars, 40 μ m. **(g)** 293F cells were transfected with either the Flag–PHF2 ^{Δ jmC} or the HA–PHF2^{H249A} mutant, and immunostaining was carried out as in **f**. Scale bars, 40 μ m. **(h)** H3K9Me2 demethylation activity of PHF2 *in vivo*. 293F cells transfected with the indicated expression vectors or short interfering RNAs (siRNAs), and were treated with FSK for 6 h. The soluble chromatin fraction was subjected to western blotting as indicated. Uncropped images of blots are shown in Supplementary Fig. S9.

histones (Fig. 1f and Supplementary Fig. S4b). The conserved histidine residue within the PHF2 jmjC domain was required for enzymatic activity (Fig. 1g). In 293F cells, overexpression of PHF2 in the presence of FSK decreased H3K9Me2, whereas knockdown of PHF2 did not lead to global increase of this mark (Fig. 1h), raising the possibility that other H3K9 demethylase(s) may compensate for PHF2 in these cells.

PHF2 is phosphorylated by PKA at a specific serine residue

In a co-immunoprecipitation assay, association of PHF2 and ARID5B was inducible on FSK treatment of immortalized hepatocytes²⁰ both in the absence (Fig. 2a) and presence (Supplementary Fig. S4c) of a proteasomal inhibitor, MG132. Consistently, abundance of these proteins was not clearly affected by FSK treatment (Supplementary Fig. S4d). Therefore, we reasoned that phosphorylation of the factor(s) by PKA was a trigger to induce association. Endogenous PHF2, but not ARID5B, was phosphorylated by FSK treatment of the cells (Fig. 2b,c).

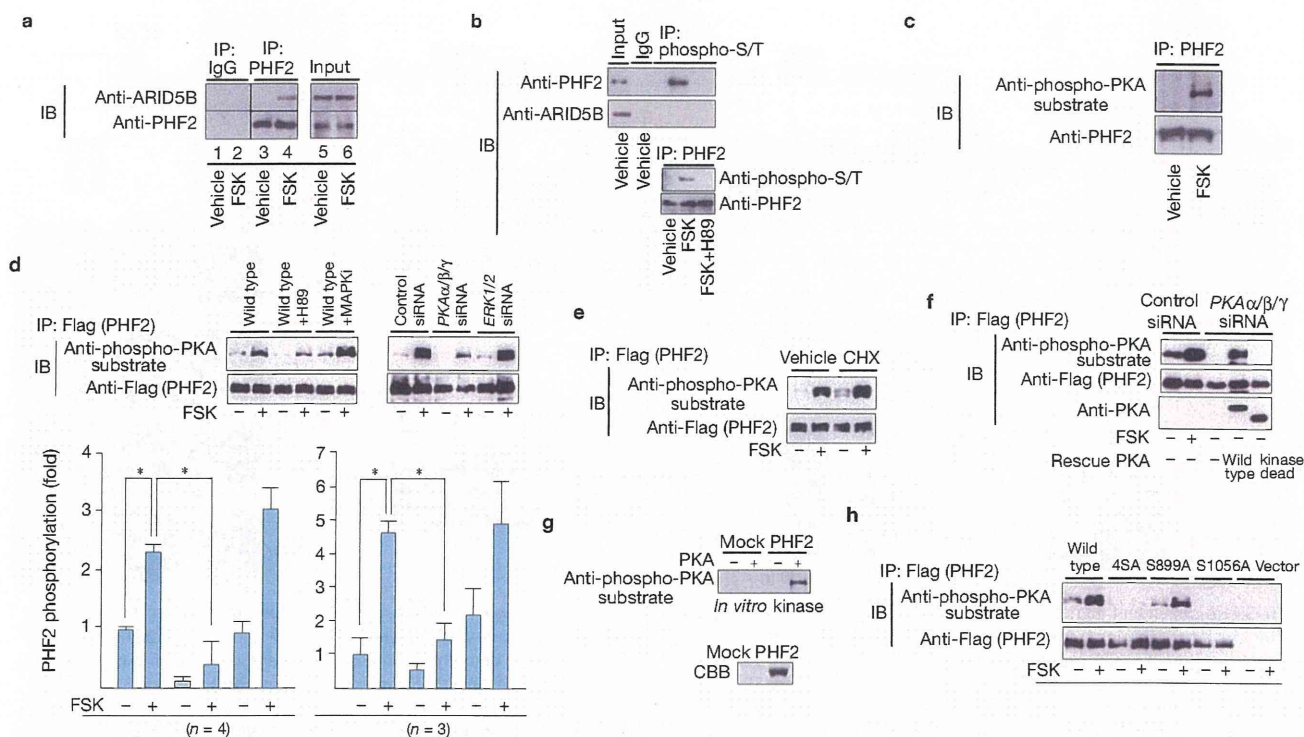


Figure 2 PKA-dependent complex assembly of PHF2-ARID5B. (a) Assembly of the endogenous PHF2-ARID5B complex. Hepatocytes were treated with the indicated compounds for 2 h and were subjected to immunoprecipitation (IP) and immunoblotting (IB) with the indicated antibodies. Specificity of antibodies was confirmed in Supplementary Fig. S2a,b. (b,c) Phosphorylation of endogenous PHF2 by PKA. Hepatocytes (b) or 293F cells (c) were treated with vehicle, FSK, or FSK +H89 as indicated for 2 h, then lysates were immunoprecipitated using either anti-phospho-serine/threonine or anti-PHF2 antibodies. The eluates were subjected to western blotting as indicated. (d-f) 293F

cells transfected with Flag-PHF2 and indicated siRNAs were treated with the indicated inhibitors, and immunoprecipitated with anti-Flag antibodies. Immunoprecipitates were subjected to immunoblotting with an anti-phospho-PKA substrate antibody. (d, lower panel) Averages \pm s.d. The other data sets are shown in Supplementary Fig. S8b,c. The asterisks show $P < 0.05$ in Student's *t*-test. (g) *In vitro* kinase assay with recombinant PHF2 and PKA proteins. (h) PHF2 is phosphorylated by PKA at Ser 757/899/954/1056. In the 4SA mutants, Ser 757/899/954/1056 were replaced with alanines. Uncropped images of blots are shown in Supplementary Fig. S9.

FSK-dependent PHF2 phosphorylation was negated by the PKA inhibitor H89, but not by a MAP kinase inhibitor (MAPKi; Fig. 2d). Cyclohexamide (CHX) did not attenuate PHF2 phosphorylation, indicating that this event does not mediate *de novo* protein synthesis (Fig. 2e). Knockdown of PKA $\alpha/\beta/\gamma$, but not of extracellular signal-regulated kinases ERK1/2, abrogated PHF2 phosphorylation (Fig. 2d,f and Supplementary Fig. S5a). PKA phosphorylated recombinant PHF2 in *in vitro* phosphorylation assays (Fig. 2g). Using recombinant PHF2 deletion mutants, the carboxy-terminal region of PHF2 was mapped to be phosphorylated by PKA (Supplementary Fig. S5b,d), and bears four conserved, PKA consensus serine residues (Supplementary Fig. S5c). Replacement of all of four serine residues by alanines (4SA: Ser 757/Ser 899/Ser 954/Ser 1056) fully abrogated PKA phosphorylation of PHF2 (Fig. 2h). Further mapping revealed that Ser 1056 seemed to be a major phosphorylation site (Fig. 2h).

PKA-dependent demethylase activity of PHF2-ARID5B complex

We then asked if the demethylase activity of PHF2 for H3K9Me2 was also PKA dependent with proteins purified from 293F cells as well as recombinant proteins. Purified PHF2 protein, phosphorylated by PKA *in vitro*, exhibited H3K9Me2 demethylase activity (Fig. 3a-c). Conversely, PHF2 phosphorylated by FSK treatment in cells exhibited

the demethylase activity, but *in vitro* dephosphorylation by BAP (bacterial alkaline phosphatase) negated the demethylase activity (Fig. 3b,c). ARID5B was dispensable for the enzymatic activity of PHF2 *in vitro* (Fig. 3b,c), because ARID5B was absent from the purified PHF2 protein fraction used (Supplementary Fig. S5f). Similarly, recombinant PHF2 was activated by PKA phosphorylation (Fig. 3d-f). PHF2 phosphorylation mutants were not activated by PKA (Fig. 3g). Consistent with the *in vitro* analyses, H3K9Me2 demethylation by overexpression of PHF2-ARID5B in cells was significantly enhanced by FSK treatment, but 4SA was not activated by FSK (Fig. 3h). Subnuclear localization patterns of the PHF2^{4SA} mutant did not look identical to that of wild-type PHF2 (Fig. 3h), raising the possibility that PHF2 phosphorylation is indispensable for chromatin association. Together, these findings suggest that PKA-mediated phosphorylation induces the demethylase activity of PHF2, unlike the other characterized *jmjC* demethylases exhibiting constitutive enzymatic activities both *in vivo* and *in vitro* as recombinant proteins⁴⁻¹⁰.

ARID5B directs PKA-dependent promoter targeting of PHF2

We examined how PKA-mediated activation of the PHF2-ARID5B complex activated transcription at endogenous promoters. In immortalized hepatocytes, glucagon-PKA signalling regulates glucose

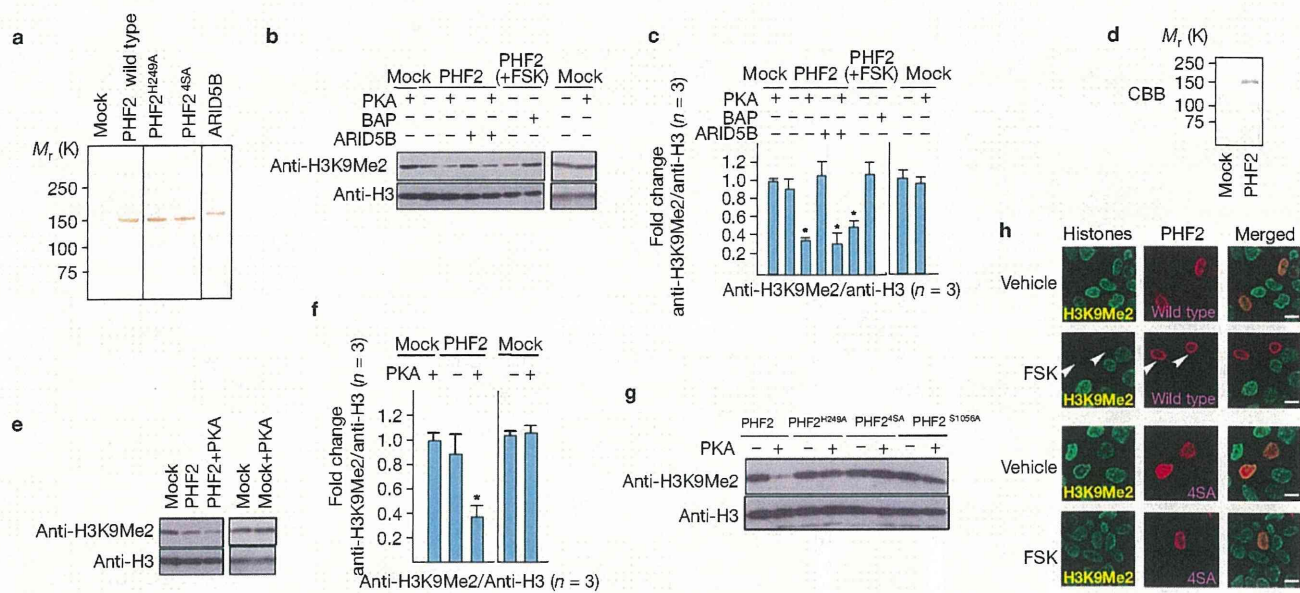


Figure 3 PKA-dependent demethylase activity of the PHF2-ARID5B complex. **(a)** The indicated proteins were purified to near homogeneity from 293F cells. Purification of PHF2 mutants is shown in Supplementary Fig. S5e. Note that purified PHF2 did not include ARID5B (Supplementary Fig. S5f). **(b,c)** *In vitro* histone demethylation assay. Purified PHF2 protein or PHF2 mutants were incubated with either PKA or BAP as indicated, and *in vitro* demethylation assays were carried out with/without purified ARID5B protein. **(c)** The signal intensity of three independent experiments (performed as in **b** and Supplementary Fig. S8d) was quantified. Data are averages \pm s.d.

The asterisks show $P < 0.05$ in Student's *t*-test. **(d-f)** Recombinant PHF2 protein purified to near homogeneity from Sf9 cells was phosphorylated by PKA, and *in vitro* demethylation assay was carried out as in **b,c**. **(f)** Data are averages \pm s.d. ($n = 3$, Supplementary Fig. S8e). The asterisk shows $P < 0.05$ in Student's *t*-test. **(g)** *In vitro* histone demethylation assay as in **b** with the indicated PHF2 mutants. **(h)** H3K9Me2 demethylation activity of PHF2-ARID5B is FSK dependent *in vivo*. 293F cells transfected with wild-type or PHF2^{45A} were treated with FSK for 6 h. Scale bars, 40 μ m. Uncropped images of blots are shown in Supplementary Fig. S9.

homeostasis through induction of gluconeogenic enzymes, such as Pepck and G6Pase (refs 20–23). Chromatin immunoprecipitation (ChIP) analysis revealed glucagon-PKA-induced promoter binding of PHF2-ARID5B at the promoters of *Pepck* and *G6Pase* (Fig. 4a). Sequential ChIP (Re-ChIP) suggested that the endogenous PHF2-ARID5B complex associates with the *Pepck* promoter (Fig. 4b), without protein synthesis (Fig. 4b and Supplementary Fig. S6a). H89 abrogated glucagon-mediated recruitment of these factors (Supplementary Fig. S6b). PHF2 and ARID5B were co-recruited to *Pepck* promoter on similar time-courses (Supplementary Fig. S6c). Demethylation of H3K9Me2 was induced by FSK, coupled with PHF2 recruitment (Fig. 4a and Supplementary Fig. S6c). However, the H3K9Me1 level was not significantly altered by FSK treatment (Fig. 4a), suggesting that newly produced H3K9Me1 was sequentially demethylated by other H3K9 demethylase(s). H3K9Me3 signal was low in both the presence and absence of FSK (Fig. 4a), consistent with the notion that *Pepck* and *G6Pase* gene promoters are converted to euchromatin in hepatocytes.

We further explored the mechanism for PKA-dependent promoter recruitment of PHF2-ARID5B. Although ARID5B was dispensable for PHF2 enzymatic activity *in vitro* (Fig. 3b), ARID5B was required for promoter targeting of PHF2 and H3K9Me2 demethylation *in vivo* (Fig. 4c, lanes 9–12, 4d). Knockdown of PHF2 by RNA interference attenuated FSK-induced recruitment of ARID5B to the promoters (Fig. 4c, lanes 3–4, 4d), indicating the signal-sensing role of PHF2 in directing the complex to target promoters. A specific PHF2 mutant (H249A), lacking a conserved histidine essential for its lysine demethylation activity (Fig. 1g), was unable to anchor PHF2-ARID5B on the target gene promoter (Fig. 4c, lanes 7, 8). We reasoned that

a lysine demethylation event occurred before chromatin association. Therefore, we determined whether ARID5B was a substrate for the PHF2 demethylase. Exogenously expressed ARID5B was lysine-methylated in hepatocytes in the absence of FSK (Fig. 5a, lane 2). PHF2 induced demethylation of ARID5B in the presence of FSK through the jmjC domain (Fig. 5a, lanes 3–4). ARID5B, but not other ARID family proteins, harbours a lysine motif (Lys 336) in the ARID domain that resembles the alignment around histone H3K9 (Supplementary Fig. S6d). When Lys 336 of ARID5B was replaced by alanine (K336A), the methylated form of ARID5B was no longer detected (Fig. 5a, lane 5). An anti-ARID5B-K336Me2 antibody was raised, and the specificity was confirmed by an enzyme-linked immunosorbent assay with methylated ARID5B (Supplementary Fig. S6e) as well as with unmethylated K336A or K336R mutants (Fig. 5b). We found that PHF2 promoted demethylation of ARID5B at Lys 336 (Fig. 5c). Catalytically inactive PHF2^{H249A} increased the ARID5B K336Me2 mark (Fig. 5c), and endogenous ARID5B was demethylated following FSK treatment (Fig. 5d). Moreover, purified PHF2 protein demethylated ARID5B at Lys 336 *in vitro* (Fig. 5e). We then used a DNA pull-down (ABCD) assay to determine if demethylation of Lys 336-methylated ARID5B converted it to an active form on DNA binding. Only when cells were treated with FSK, ARID5B-PHF2 complex was recruited to synthetic oligonucleotides containing the *Pepck* promoter sequences^{24,25} (Fig. 5f). FSK-dependent DNA binding of PHF2-ARID5B was abolished in PHF2^{H249A} and ARID5B^{K336A} mutants (Fig. 5f). Neither PHF2^{H249A} nor ARID5B^{K336A} supported FSK-mediated promoter recruitment and subsequent H3K9Me2 demethylation (Fig. 4c).

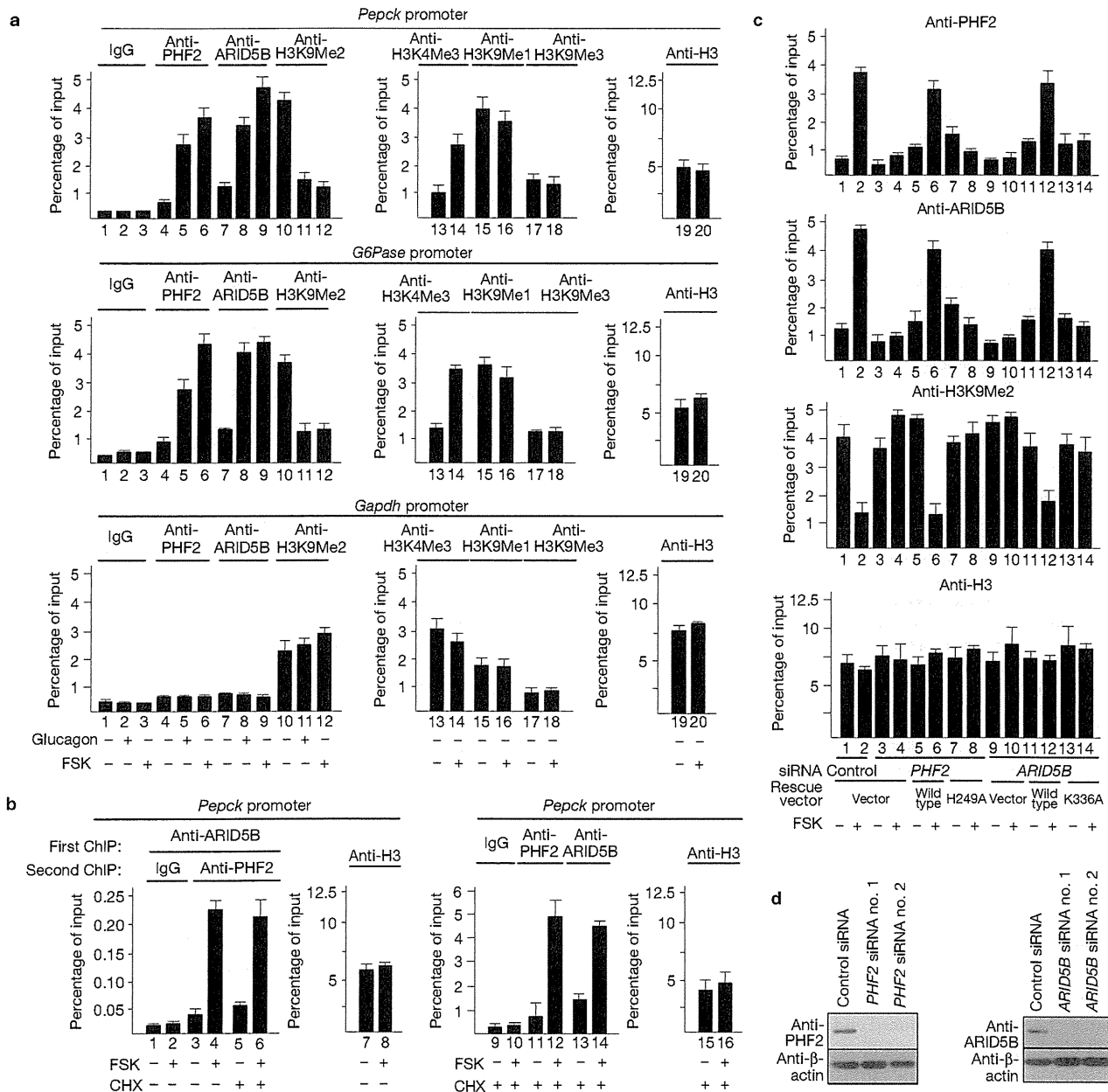


Figure 4 PKA-dependent promoter targeting of PHF2-ARID5B. (a) Endogenous PHF2-ARID5B complex is recruited to the promoter regions of *Pepck* and *G6Pase*, but not to that of *Gapdh*, in a glucagon-PKA-dependent manner. Hepatocytes were treated with the indicated compounds for 4 h, and ChIP assays were carried out using indicated antibodies. Data are average \pm s.d. ($n = 3$). (b) ChIP and Re-ChIP assays. Hepatocytes were treated with the indicated compounds for 4 h, then sequentially immunoprecipitated with the indicated antibodies.

Data are average \pm s.d. ($n = 3$). (c) Promoter targeting and H3K9Me2 demethylase activities of PHF2-ARID5B mutants in ChIP assays. Hepatocytes were transfected with the indicated siRNAs for 24 h, then with the indicated rescue vector for a further 12 h. Then, cells were treated with FSK for 4 h and ChIP assays were carried out. Data are average \pm s.d. ($n = 3$). (d) The knockdown efficiencies of siRNAs in immortalized hepatocytes were determined using samples in c. Uncropped images of blots are shown in Supplementary Fig. S9.

PHF2-ARID5B acts as a co-activator for HNF4 α in liver of fasted mice

The transcriptional effects mediated by PHF2-ARID5B were assessed by monitoring gene expression in hepatocytes. PKA-dependent gene induction of *Pepck* and *G6Pase* was impaired (Fig. 6a) following knockdown of PHF2 or ARID5B in hepatocytes (Fig. 4d). The unphosphorylated PHF2 mutant (PHF2^{4SA}) was unable to

confer the FSK response (Fig. 6a). As HNF4 α is activated by the glucagon-PKA signalling pathway and serves as the primary transcriptional activator on *Pepck* and *G6Pase* promoters^{21,22,26-28}, we further characterized the transcriptional co-activation function of PHF2-ARID5B towards HNF4 α . In a luciferase reporter assay in the presence of FSK (refs 12,29), PHF2 acted as a co-activator for HNF4 α (Fig. 6b) as well as FXR (Supplementary Fig. S7) in 293F

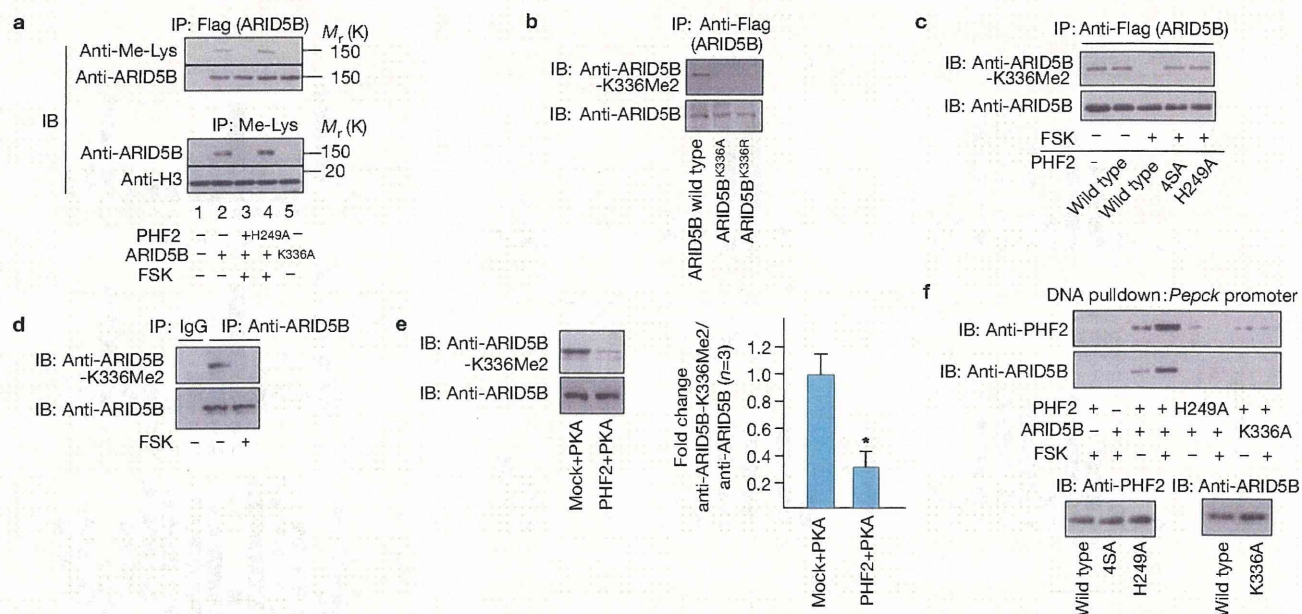


Figure 5 ARID5B directs PKA-dependent promoter targeting of PHF2. **(a)** PHF2 induces demethylation of ARID5B. The methylation state of ARID5B in 293F cells was examined using anti-ARID5B and anti-methyllysine antibodies. Wild-type, but not K336A, ARID5B is a lysine-methylated protein. **(b)** Confirmation of specificity of anti-ARID5B-K336Me2 antibody. 293F cells were transfected with the indicated ARID5B mutants and immunoprecipitated/blotted with the indicated antibodies. **(c)** Demethylation of ARID5B is dependent on the catalytic activity of PHF2 in hepatocytes as revealed by the specified anti-ARID5B-K336Me2 antibody. **(d)** Lys 336 methylation of endogenous ARID5B. 293F cells were treated with FSK for 4 h, then immunoprecipitation was carried out as indicated. **(e)** *In vitro* ARID5B demethylation assay. Flag-ARID5B purified from 293F cells

cells^{24,25}. HNF4 α was enriched with PHF2-ARID5B on the promoter of *Pepck* (Fig. 6c). Knockdown of HNF4 α decreased recruitment of PHF2-ARID5B to the promoters (Fig. 6c) and loss of PKA-dependent gene induction (Fig. 6d). Thus, HNF4 α and FXR have emerged as transcriptional activators co-activated by PHF2-ARID5B in glucagon-PKA-induced gene expression.

Finally, the physiological relevance of the proposed PHF2-ARID5B promoter targeting was examined under fasting conditions where PKA signal was activated by glucagon in intact animals. In fasted mice, co-recruitment of PHF2 with ARID5B was detected in the promoter regions of *Pepck* and *G6Pase* in liver (Fig. 6e) with the expected decrease in H3K9Me2 modification (Fig. 6e).

DISCUSSION

Here, we have identified a PKA-dependent histone demethylase complex that conferred signal-dependent activation of its responsive genes. Assembly of the PHF2-ARID5B complex, its recruitment to target promoters, and its H3H9Me2 demethylase activity were dependent on PKA activity. Thus, the PHF2-ARID5B complex seems to serve as a signal-sensing epigenetic determinant through removal of a repressive histone methylation mark^{1,2,30,31} on the transcriptionally responsive promoters. The molecular basis of signal sensing by the PHF2-ARID5B complex is attributable to PKA-phosphorylation-dependent induction of PHF2 enzymatic activity and complex assembly with the DNA-binding subunit (ARID5B). Unlike PHF2, several other

was incubated with purified PHF2 (Fig. 3a), and the demethylation was detected by western blotting. The signal intensity of three independent experiments (in the upper panel and in Supplementary Fig. S8f) was quantified. Data are averages \pm s.d. ($n = 3$). The asterisk shows $P < 0.05$ in Student's *t*-test. **(f)** DNA pull-down assay. The demethylase activity of PHF2 and the ARID domain of ARID5B are required for promoter DNA binding of PHF2-ARID5B in 293F cells. Cell lysates were mixed with avidin beads which were bound to biotin-conjugated oligonucleotides bearing the indicated promoter sequence. The bound protein was detected by western blotting. There were similar levels of expression of PHF2-ARID5B and their derivatives (lower panels). Uncropped images of blots are shown in Supplementary Fig. S9.

jmjC demethylases possess both jmjC and ARID domains within a single molecule^{3,5,8,9}. Thus, segregation of these two key domains into separate subunits may enable PHF2 enzymatic activity to be linked to PKA signalling through assembly of the PHF2-ARID5B complex and intracomplex communication. Similarly, other jmjC demethylases that are inactive as single subunits may be functionally regulated through post-translational modifications and assembly with their complex partner components. The characterization of a signal-dependent histone demethylase provides further understanding of the regulatory mechanism for dynamic epigenetic modification in physiological contexts such as energy metabolism and homeostasis. \square

METHODS

Methods and any associated references are available in the online version of the paper at <http://www.nature.com/naturecellbiology>

Note: Supplementary Information is available on the Nature Cell Biology website

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AUTHOR CONTRIBUTIONS

A.B., F.O. and S.K. designed the study. A.B., F.O., Y.O., K.Y., M.O. and Y.I. carried out experiments. M.N., C.A.M., K.I., J.K. and M.B. carried out analyses and provided general support. F.O. and S.K. wrote the paper.

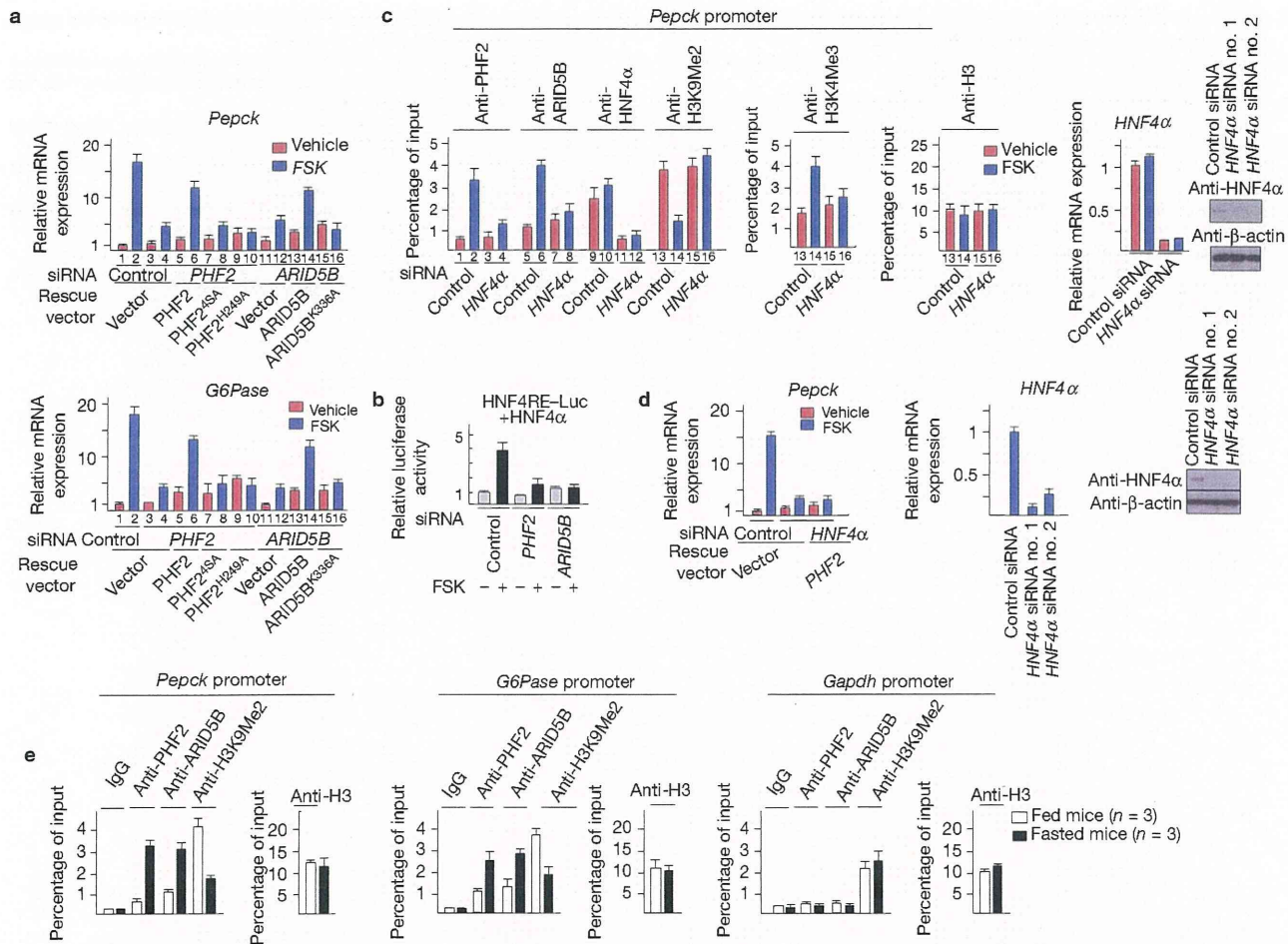


Figure 6 PHF2-ARID5B co-activates HNF4 α in liver of fasted mice. (a) PHF2-ARID5B complex is indispensable for PKA-dependent gene induction of *Pepck* and *G6Pase*. Hepatocytes were transfected with the indicated siRNAs for 24 h, then incubated with the indicated compounds for 24 h, and quantitative PCR with reverse transcription (RT-PCR) was carried out. Data are average \pm s.d. ($n = 3$). (b) PHF2-ARID5B co-activates HNF4 α in the presence of FSK in luciferase assays. 293F cells were transfected with the indicated plasmids in the presence or absence of FSK for 24 h. Data are average \pm s.d. ($n = 3$). (c,d) Immortalized hepatocytes were transfected

with HNF4 α siRNA for 48 h, and ChIP assay (c) and quantitative RT-PCR for gene expression (d) were carried out. Knockdown efficiency was determined in the right panels of (c) and (d). Data are average \pm s.d. ($n = 3$). (e) Livers from either fasted or fed mice ($n = 3$) were subjected to ChIP analyses using either anti-PHF2, anti-ARID5B, anti-H3K9Me2 or control IgG and anti-H3 antibodies. Fasting induces recruitment of PHF2-ARID5B and reduction of the H3K9Me2 mark in *Pepck* and *G6Pase* promoters, but not *Gapdh* promoter. Data shown are average \pm s.d. of three independent experiments. Uncropped images of blots are shown in Supplementary Fig. S9.

COMPETING FINANCIAL INTERESTS

The authors declare no competing financial interests.

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METHODS

Plasmids. Full-length complementary DNAs of human PHF2, ARID5B (full length, β isoform), HNF-4 α and FXR were inserted into pcDNA3 vectors (Invitrogen; ref. 11). Deletion mutants of PHF2 (amino acids 1–229 fused to amino acids 367–1103 for PHF2^{Δ(jmjC)}) and ARID5B (amino acids 1–318 fused to amino acids 423–1188 for ARID5B^{ΔARID}) were amplified by PCR and cloned into pcDNA3 or pGEX4T-1 (Amersham). Point mutants of PHF2 (S1056A point mutation, or S797A, S899A, S954A and S1056A for PHF2^{ΔS8A}) and PHF2 jmjC-domain point mutants (H249A, Y321A and H338A) and ARID5B were generated by site-directed mutagenesis. HNF4RE-tk-luciferase reporter plasmids were generated by insertion of the promoter region of consensus HNF4RE into a pGL3 luciferase plasmid³². FXRE-tk-luciferase reporter plasmids were generated by insertion of the promoter region of human SHP (–572 to –3) containing FXRE into a pGL3 luciferase plasmid. Other plasmids have been described previously^{11,12,32,33}.

Biochemical purification and separation of FXR- or PHF2-associated complexes. The hepatic tumour-derived HepG2 cells were incubated for 4 h with either FSK (1 μ M) and/or H89 (1 μ M), and the nuclear extracts were prepared as previously described. For purification of the FXR-associating complex, the nuclear extracts were bound to glutathione *S*-transferase (GST)–FXR(D/E)–His (amino acids 193–477) columns^{11,12,33}. The bound complexes were eluted with reduced glutathione (15 mM) in elution buffer. Glycerol density gradients were carried out as previously described^{11,12,33}. The complex fraction was further loaded onto a diethylaminoethyl column (Whatman), and eluted with different concentrations of NaCl (150 mM–1 M). The purified proteins were silver-stained, and identified by matrix-assisted laser desorption/ionization–time of flight mass spectrometry (Bruker)^{11,12,33}. For purification of PHF2-associating complex, the nuclear extracts were loaded onto M2 anti-Flag agarose gel (Sigma, A2220, 069K6018). After washing with binding buffer, the bound proteins were eluted by incubation with 1.0 ml of the Flag peptide ([EYKKEEK]₂, 0.2 mg ml^{–1}) (Sigma).

In vitro and in vivo lysine demethylation assay. The *in vitro* histone demethylation assays were carried out as previously described^{7,10}.

For preparation of demethylases from mammalian cells, 293F cells were transfected with Flag–PHF2 plasmid using Lipofectamine 2000 (Invitrogen). After 36 h, the cells were lysed with TNE (20 mM Tris at pH 7.8, 150 mM NaCl, 0.5 mM EDTA, 1% NP40). For phosphorylation of PHF2 *in vivo*, cells were treated with FSK (10^{–6} M) 2 h before harvest, and NaF/Na₂VO₃ added to TNE. Cell lysates were subjected to immunoprecipitation using anti-Flag antibody-conjugated beads (Sigma, A2220, 069K6018). Beads were washed three times with high-salt TNE (20 mM Tris at pH 7.8, 450 mM NaCl, 0.5 mM EDTA, 1% NP40), and then three times with EDTA-free TNE. For phosphorylation of PHF2 *in vitro*, beads were mixed with 20 μ l PKA buffer (0.1 μ g PKA (Upstate), 20 mM Tris at pH 7.5, 10 mM MgCl₂, 100 μ M ATP and incubated for 1 h at 37 °C. Then, beads were washed three times with demethylase stock buffer (20 mM Tris at pH 7.5, 150 mM KCl, 10% glycerol). The prepared PHF2 protein was used immediately for the demethylation reaction. Alternatively, the purified proteins were eluted with Flag elution buffer (200 mg ml^{–1} Flag peptide, 20 mM Tris at pH 7.5, 450 mM KCl, 10% glycerol).

For preparation of recombinant proteins, recombinant Flag–PHF2 was purified using Bac-to-Bac baculovirus expression systems (Invitrogen) according to the manufacturer's instructions. The purified Flag–PHF2 complex was prepared as described in the section on biochemical purification.

For demethylase reaction, 2 μ g of PHF2 protein or 0.2 μ g of PHF2 complex was mixed with substrates (calf thymus histone (10 μ g) (Sigma, H9250), purified mononucleosome (10 μ g), Flag–ARID5B protein purified from 293F cells (2 μ g) or dimethyl H3 (Lys 9) peptide 1–21 (0.2 μ g) (Upstate 12–430)) in the reaction buffer (final volume 20 μ l) (20 mM Tris-HCl at pH 7.5, 150 mM KCl, 50 μ M Fe(NH₄)₂(SO₄)₂·6H₂O, 1 mM α -ketoglutarate, 1 mM ascorbate, 20 μ M ZnCl₂). The mixtures were incubated at 37 °C for 12 h, terminated by boiling for 5 min in SDS sample buffer^{7,10}. The histone modification or methylation of ARID5B was detected by specific antibodies (see the antibody section). The signal intensity of western blots was quantified using Scion Image.

For histone demethylase assay detecting formaldehyde release, purified PHF2 complex (0.2 μ g) was incubated with native histones (10 μ g) for 30 min according to the manufacturer's protocol using DetectXTM (LUMINOS, K010-F1).

For *in vivo* histone demethylation assay, cells were first lysed in TNE, and the pellet fraction was resuspended in TNE and sonicated for 20 s (Tomy SEIKO) to obtain the chromatin fraction^{3,9,16,34}.

Antibodies, immunoprecipitation and western blotting. Anti-PHF2 and anti-ARID5B polyclonal antibodies were raised against PHF2 peptides (5'-ERSVDVTDVTKQKDC-3', 5'-CKPKVVRDEYEVSD-3', 5'-CAYKSDSSDE-GSLH-3') and ARID5B peptides (5'-CDTPQGRNSDHGEDE-3', 5'-CTDQGSNSEK-

VAEEA-3', 5'-CEQTSKYPSTRDMYRE-3'), respectively, by Operon Biotechnology. Anti-ARID5B K336Me2 antibody was raised using the dimethylated peptide (MKER(KMe2)TPIER: ARID5B K336Me2), and purified over a peptide affinity column (MBL). The antibodies that bound to the non-methylated peptide (MKERKTPIER) were removed using an affinity column. The specificity of the antibody toward K336Me2 over K336Me0, Me1 and Me3 peptides was determined in Supplementary Fig. S20 using enzyme-linked immunosorbent assays (MBL).

For immunoprecipitation, cells were treated with FSK (1 μ M) or glucagon (200 nM) for 2 h and cells were lysed in TNE. Cell lysates were incubated with the indicated antibodies listed in Supplementary Table S1. A full list of antibodies and the dilutions used is given in Supplementary Table S1.

Cell culture, transfection and luciferase assays. Mouse immortalized hepatocytes, TLR2 cells, were obtained from RIKEN (cell no. RCB0750; ref. 35). The immortalized hepatocytes were cultured at 33 °C in DMEM containing 2% fetal bovine serum, 1 μ g ml^{–1} transferrin, 1 μ g ml^{–1} insulin and 10 ng ml^{–1} epidermal growth factor, using collagen-coated dishes. Other cell lines are cultured in DMEM supplemented with 10% fetal bovine serum. Cells were treated with glucagon (200 nM), FSK (1 μ M), H89 (1 μ M), CHX (1 μ M), GW4064 (1 μ M), dexametazone (10 nM) or 25-OH cholesterol (10 μ g ml^{–1}) either for 24 h (luciferase assays), for 6 h (*in vivo* demethylation assays) or for 2 h (immunoprecipitation).

For luciferase assays, cells at 40–50% confluence were transfected with the indicated plasmids (0.25 μ g reporter plasmids, 0.1 μ g HNF4 α , 0.1 μ g FXR, 0.05 μ g of PHF2) using Lipofectamine reagent (Gibco BRL). Luciferase activity was determined with the luciferase assay system (Promega) as previously described^{11,12,32,33}.

ChIP experiments. ChIP assays were carried out essentially as previously described^{11,12,33}. Hepatocytes were treated with glucagon (200 nM), FSK (1 μ M) and/or H89 (1 μ M) for 4 h or as indicated. Then, cells were subjected to ChIP experiment as described¹¹. The precipitated DNA fragments were amplified by quantitative PCR (qPCR; TAKARA). For qPCR with reverse transcription, the specific primer sets were designed and provided by TAKARA. The primer sets are shown in Supplementary Table S1.

Fasting responses in mice. All mice were maintained according to the protocol approved by the Animal Care and Use Committee of the University of Tokyo.

For ChIP assays¹¹, eight-week-old C57BL/6 male mice were either deprived of food or fed for 6 h. Livers were isolated, minced and fixed in PBS containing 1% formaldehyde at 4 °C overnight. The cells were washed in PBS twice, then sonicated in PBS containing 0.2 mM EDTA and 1% Triton X-100. The cell lysates were subjected to ChIP assays as previously described¹¹.

RNA isolation and qPCR. Messenger RNA was isolated as previously reported³³. For qPCR with reverse transcription, the specific primer sets were designed and provided by TAKARA. The primer sequences are shown in Supplementary Table S1, and the amount was normalized using glyceraldehyde-3-phosphate dehydrogenase.

RNA interference experiments. The siRNAs as shown in Supplementary Table S1, together with siCONTROL non-targeting siRNA no. 2 (catalogue no. D-001210-02-20), were synthesized by and obtained from Dharmacon/Thermo, and were transfected using Lipofectamine 2000 reagent (Invitrogen) as previously described¹¹. The two siRNAs used for each experiment, and the results of target sequence no. 1 (for PHF2, ARID5B and HNF4 α) are shown.

Immunostaining. Immunostaining was carried out essentially as previously described³⁶. 293F cells were transfected with PHF2 or its derivatives, and 12 h after the transfection the cells were treated with FSK for 6 h, then fixed and subjected to immunostaining³⁶. Antibodies used are described in the antibody section.

In vitro and in vivo kinase assays. Recombinant GST–PHF2 deletion mutants expressed in *Escherichia coli* (1 μ g), or Flag–PHF2 and its derivatives (1 μ g) immunoprecipitated from 293F cells using anti-Flag antibody and eluted by Flag peptide, were incubated with PKA (Upstate; 2 ng) in reaction buffer (20 mM Tris-HCl at pH 7.5, 10 mM MgCl₂, γ -³²P ATP) in the presence or absence of PKA inhibitor (10 μ M H89) for 15 min at 30 °C.

For detection of phosphorylated proteins in cells, hepatocytes were treated with the indicated ligands for 2 h, then subjected to phospho-protein purification using a PhosphoProtein Purification Kit (QIAGEN; ref. 12). Alternatively, cell lysates were immunoprecipitated using anti-PHF2 or anti-Flag as indicated, then western

blotted using anti-phospho-PKA-substrate antibody (Cell Signaling Technology, 100G7E, 9624S). For statistical analysis, the signal intensity of western blots was quantified using Scion Image, and the average \pm s.d. of four independent experiments was shown with Student's *t*-test.

DNA precipitation assays. DNA precipitation assays were carried out essentially as described^{33,37}. Human *Pck1* promoter (−312 ~ 23) was amplified by PCR using biotinylated primers. Then, the biotinylated DNA was annealed and bound to avidin beads (Invitrogen). 293F cells were transfected with Flag-ARID5B, HA-PHF2 and their derivatives, and incubated with/without FSK for 2 h. Cell lysates were incubated with the DNA-bound avidin beads for 30 min in TNE buffer. The samples were subjected to western blotting^{33,37}.

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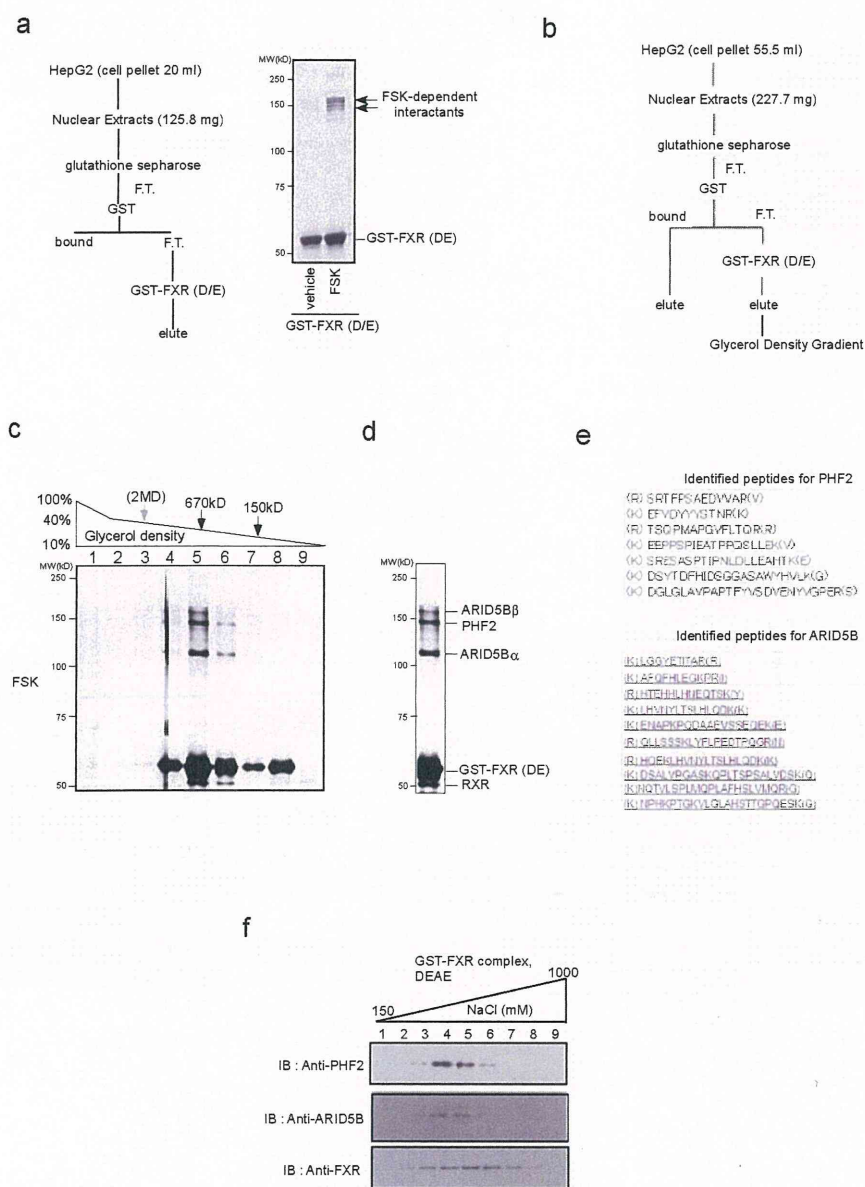


Figure S1 Purification of PHF2/ARID5B complex. **a**, Purification of a signal-dependent GST-FXR-associated proteins from HepG2 cells. Nuclear extracts from FSK-treated HepG2 cells were loaded on GST-FXR-bound glutathione sepharose beads. The bound proteins were analyzed by silver staining. **b**, The scheme for the purification of nuclear receptor-associating complexes. The experimental details were supplied in the supplemental methods. **c**, Purification of a GST-FXR-associated complex from HepG2 cells. Nuclear

extracts from FSK-treated HepG2 cells were loaded on GST-FXR-bound glutathione sepharose beads. The eluted complexes were separated by glycerol density gradients as indicated. **d**, **e**, The isolated complexes were silver stained, and each protein was identified by MALDI-TOF/MS and fingerprinting. **f**, PHF2 and ARID5B form a complex with GST-FXR. The purified GST-FXR-associating complex in (c) was further separated by DEAE column with different NaCl concentrations. The elutants were subjected to Western blotting.

SUPPLEMENTARY INFORMATION

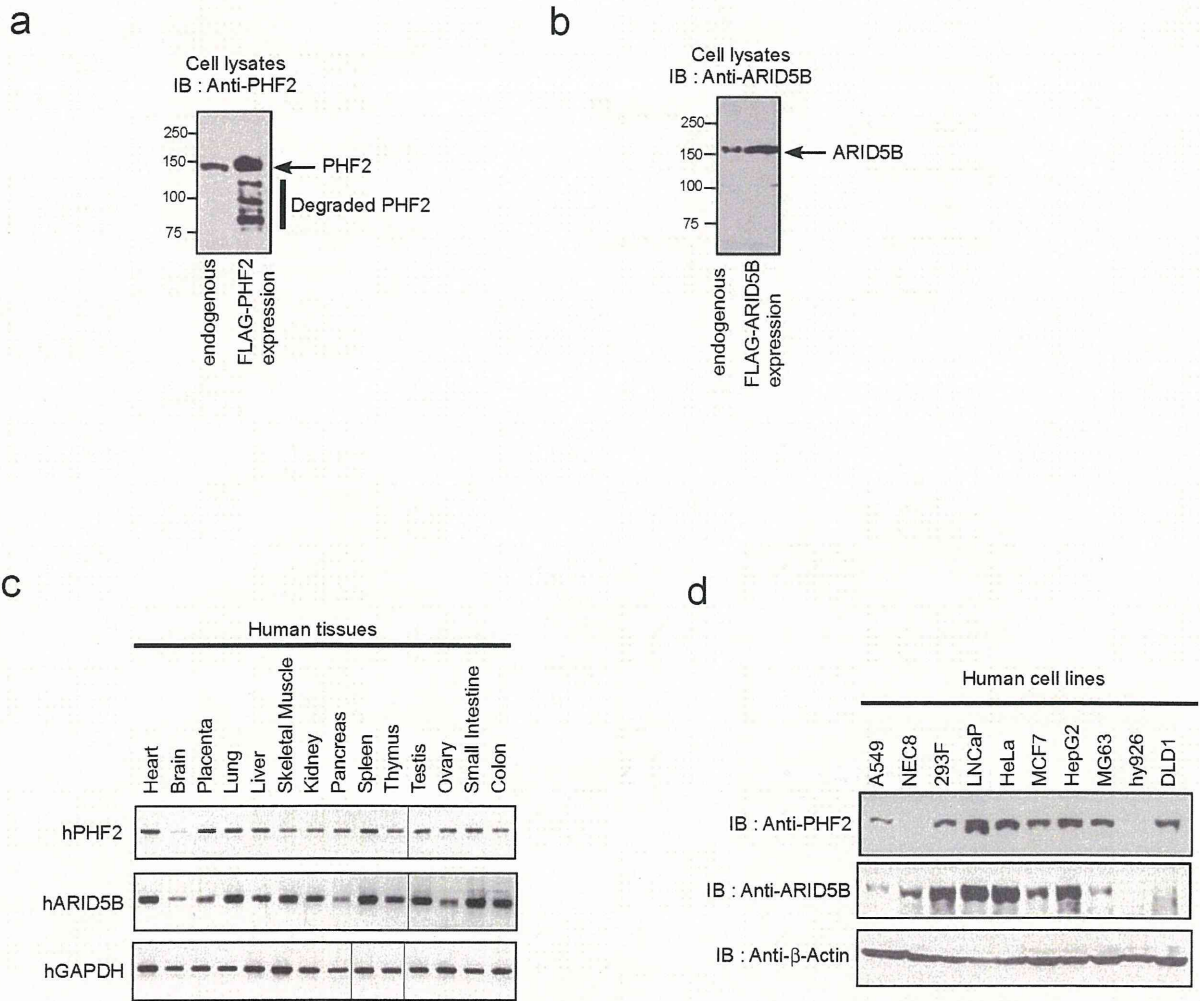


Figure S2 The expression profiles of PHF2 and ARID5B. **a, b**, Specificity confirmation of the newly raised antibodies. Normal 293F cell lysates or lysates transfected with the indicated expression vectors were subjected to Western blotting. This confirmed that these anti-PHF2 (**a**) and anti-ARID5B (**b**) antibodies detect endogenous proteins with high specificity. **c**, The mRNA expression profiles of human PHF2 and ARID5B. The mRNA levels

of PHF2 and ARID5B were determined by semi-quantitative PCR using cDNAs from human tissues (Clontech, human cDNA panel, #636742 and #636743). **d**, Protein expression of PHF2 and ARID5B in various human cell lines. Total cell lysates were prepared from the indicated human cell lines. Equal amounts of proteins were subjected to Western blotting with the indicated antibodies.

SUPPLEMENTARY INFORMATION

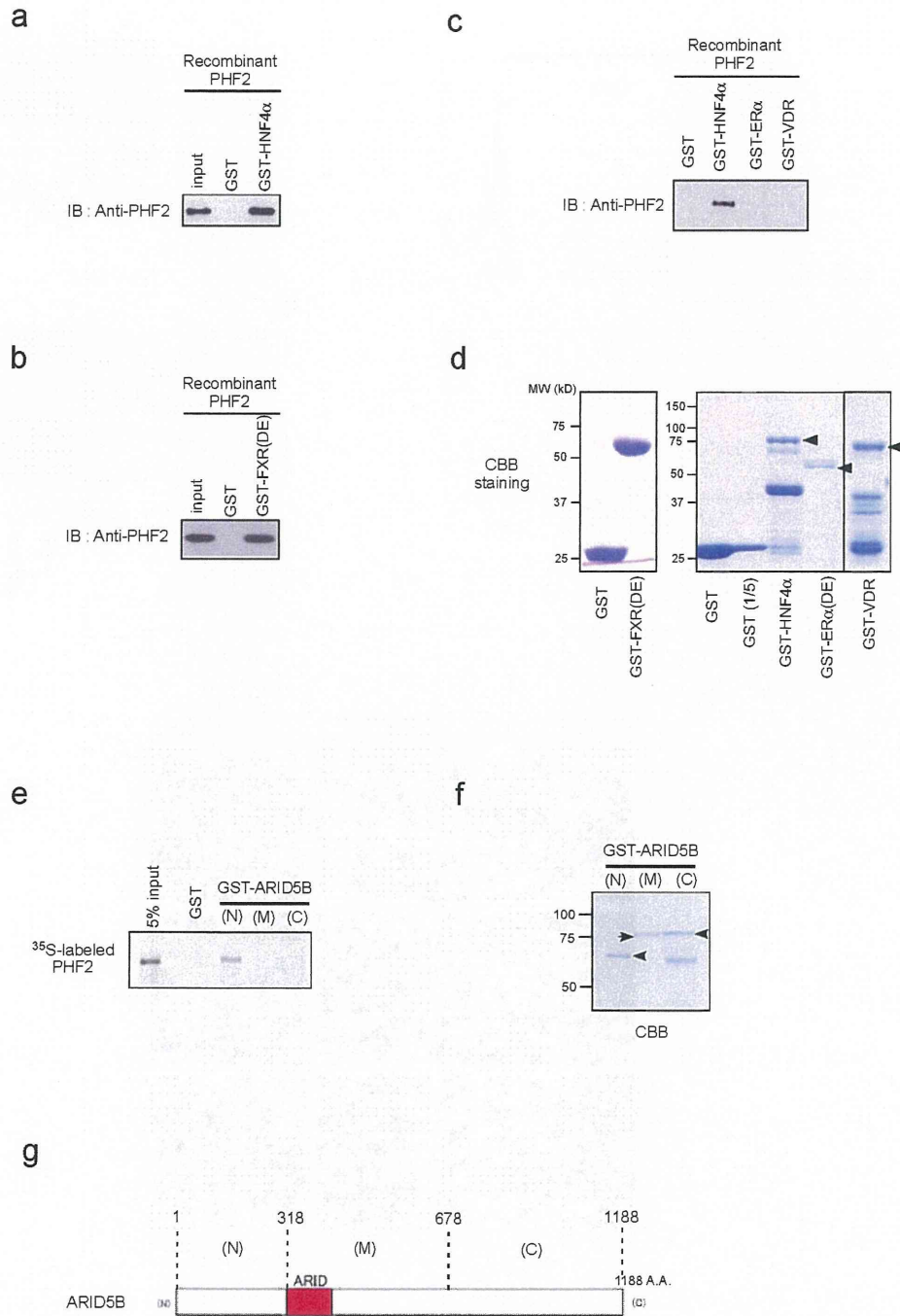


Figure S3 Direct association of PHF2/ARID5B with HNF4 α and FXR. **a-d**, GST pull-down assay with recombinant PHF2 protein and GST-tagged FXR(DE), HNF4 α , ER α (DEF), or VDR. Bound protein was detected with anti-PHF2

antibody. **e-g**, GST pull-down assay with ³⁵S-labeled PHF2 and GST-ARID5B mutants. GST-ARID5B mutants, described in (g), were incubated with *in vitro*-translated PHF2. Bound proteins were detected by autoradiography.

SUPPLEMENTARY INFORMATION

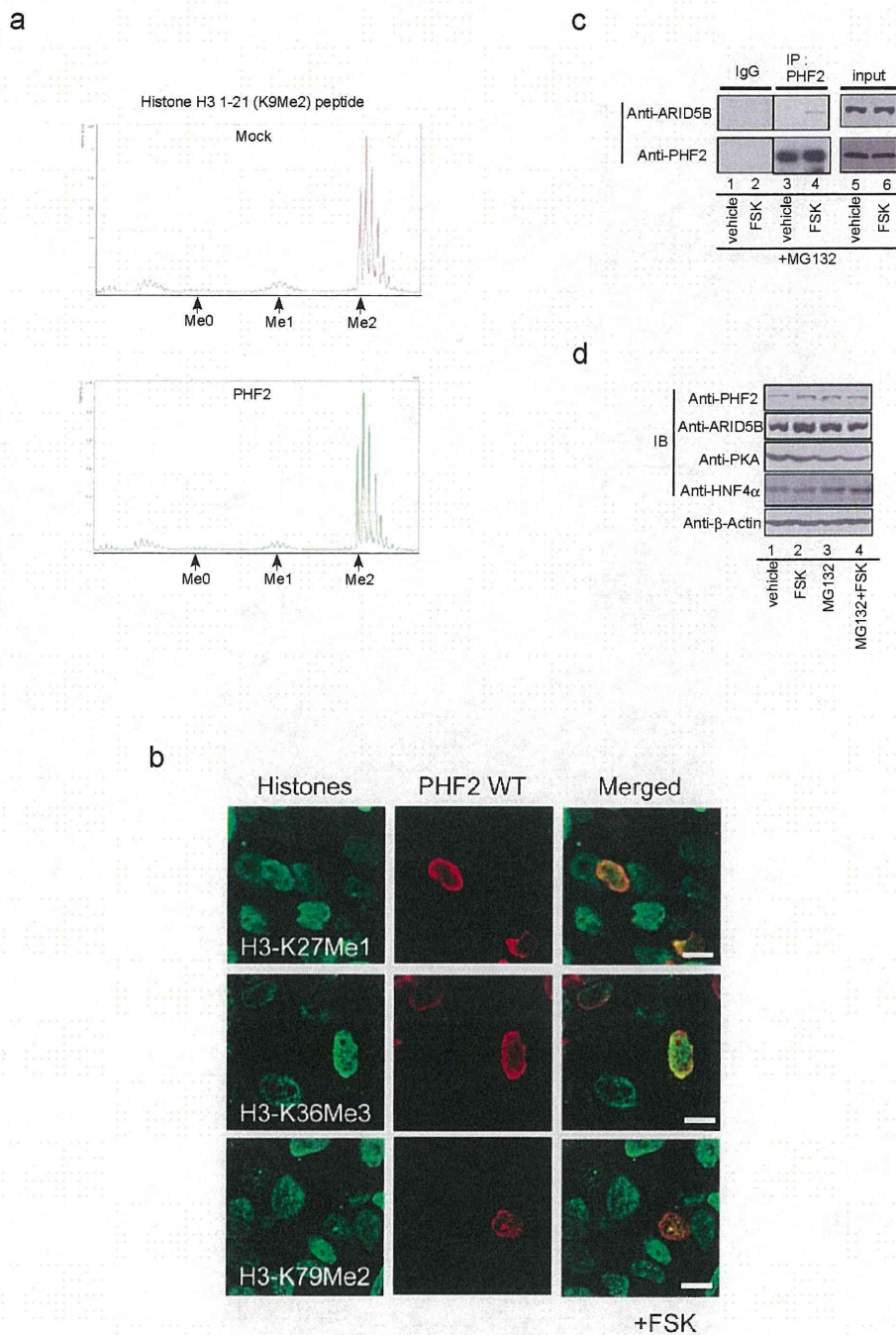


Figure S4 Demethylation activity of PHF2. **a**, Demethylase assay with H3 peptide. Purified PHF2 protein or mock immunoprecipitants incubated with PKA as in Fig. 3b was subjected to the demethylase assay with 0.2 μ g of biotin-conjugated dimethyl histone H3 (Lys9) peptide (residues 1-21) (Upstate, 12-430). Demethylation was determined using MALDI-TOF/MS. Detailed methods were supplied as supplementary methods. **b**,

Immunostaining of 293F cells was performed as described in Fig. 1f. **c**, Hepatocytes were treated with FSK (10^{-6} M) and MG132 (10^{-5} M) for two hrs. Total cell lysates were subjected to immunoprecipitation as indicated. **d**, FSK treatment did not alter protein expression levels of PHF2, ARID5B, or HNF-4 α . Hepatocytes were treated with FSK (10^{-6} M) or MG132 (10^{-5} M) as indicated for 6 hrs. Cell lysates were subjected to Western blotting.

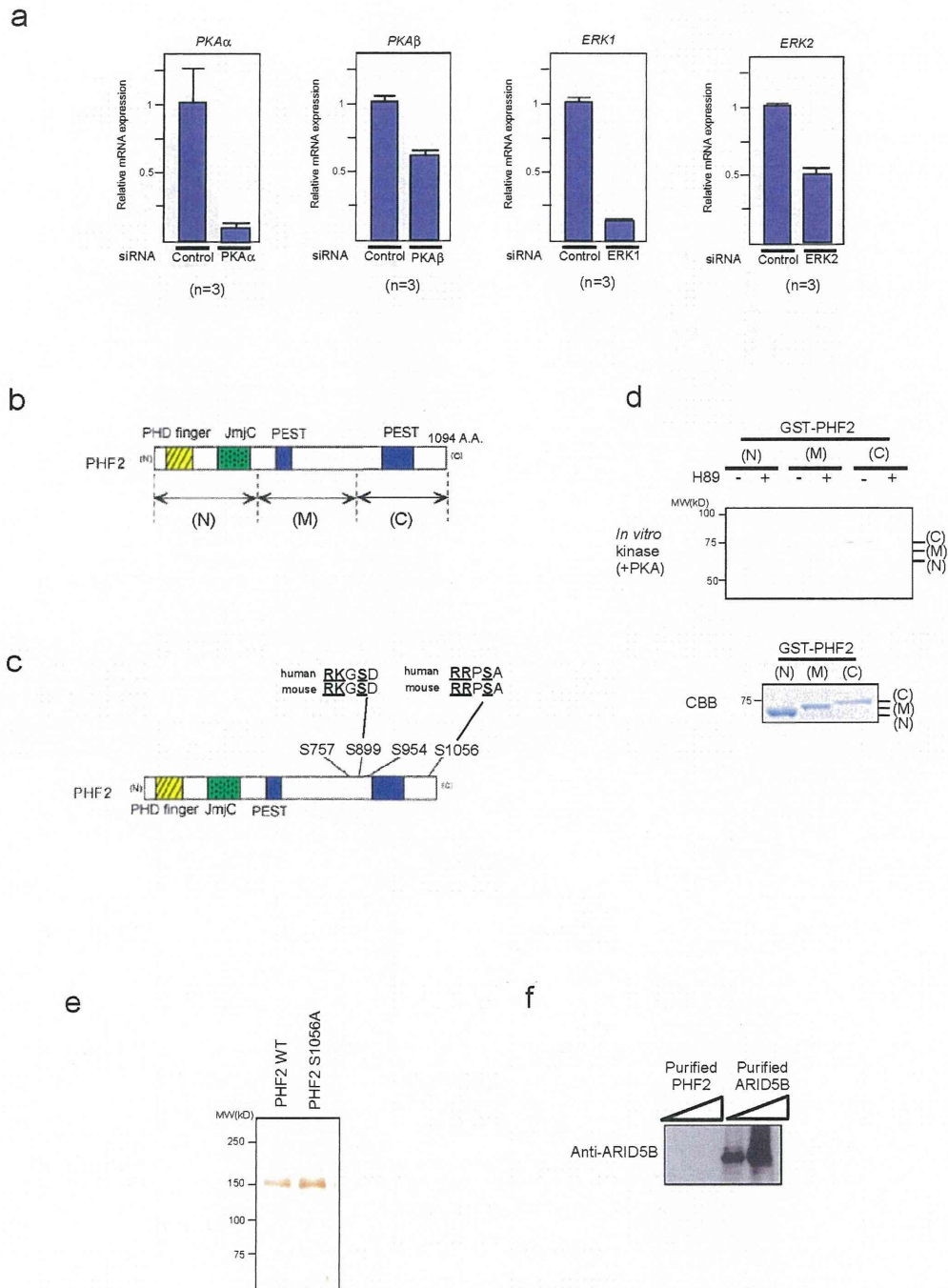


Figure S5 PKA phosphorylates PHF2 *in vitro* and *in vivo*. **a**, As controls for Fig. 2d, expression levels of the indicated genes were quantified by qPCR. Data shows average \pm S.D. (n=3). **b**, The schematic representation of deletion mutants of PHF2 used. **c**, The schematic representation of phosphorylation sites within PHF2 determined in Figure 2. **d**, PHF2 is phosphorylated by PKA at C-terminal region *in*

in vitro. *In vitro* kinase assay as indicated. **e**, 293F cells were transfected with FLAG-PHF2 or its mutant, and PHF2 was purified to of near homogeneity using anti-FLAG affinity column. Purified proteins were subjected to silver staining as indicated. **f**, Purified protein in Fig. 3a were subjected to Western blotting. Note that purified PHF2 did not include ARID5B.

SUPPLEMENTARY INFORMATION

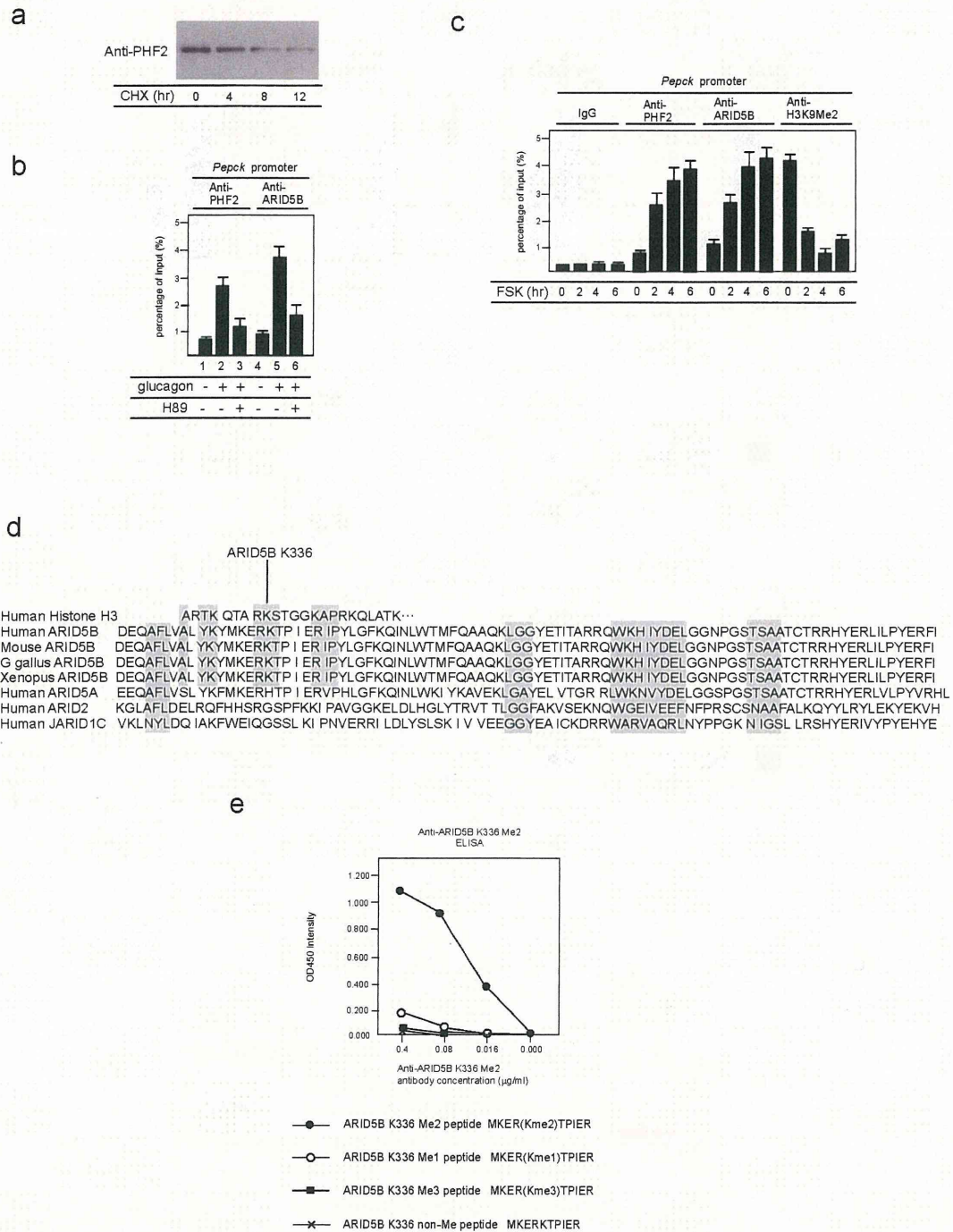


Figure S6 Promoter recruitment of PHF2/ARID5B. **a**, Protein turn-over of PHF2 as revealed by cycloheximide treatment. **b**, Recruitment of PHF2 and ARID5B to the *Pepck* promoter was abolished by a PKA inhibitor, H89. Hepatocytes were treated with glucagon and/or H89 (1 µM) for four hrs, then ChIP assay was performed using the indicated antibodies. **c**, Co-recruitment of PHF2/ARID5B and demethylation of H3K9Me2 in *Pepck* promoter over similar time courses. Hepatocytes were treated with FSK for the indicated time, then a ChIP assay was performed as indicated. **d**, The schematic

representation of amino acid sequences of ARID5B and other ARID family proteins. The sequence of histone H3K9 is also represented. **e**, Specificity of anti-ARID5B K336Me2 antibody. A rabbit polyclonal antibody against di-methylated Lys336 of ARID5B (anti-ARID5B K336Me2) was raised by using the di-methylated peptide [ARID5B K336Me2; MKER(Kme2)TPIER], and purified over a peptide-affinity column. The specificity of antibody toward K336Me2 peptide over non-methylated, mono-methylated, or tri-methylated peptides was determined by ELISA assays.

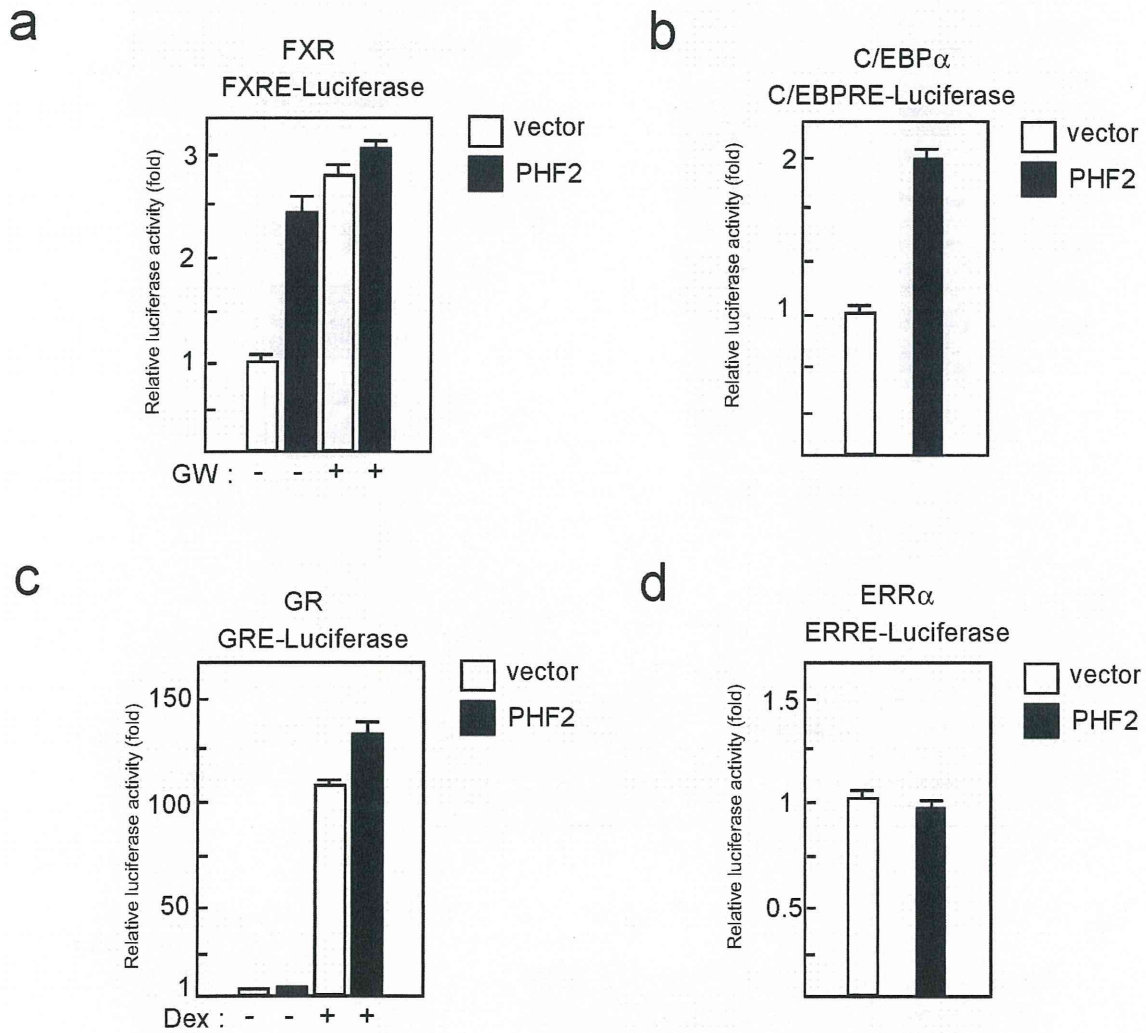


Figure S7 Co-activator activity of PHF2 for known gluconeogenic-related transcription factors. 293F cells were transfected with the indicated expression vectors and reporter plasmids with or without PHF2. Cells were treated with FSK for 24 hrs, then Luciferase assay were performed as indicated.

SUPPLEMENTARY INFORMATION

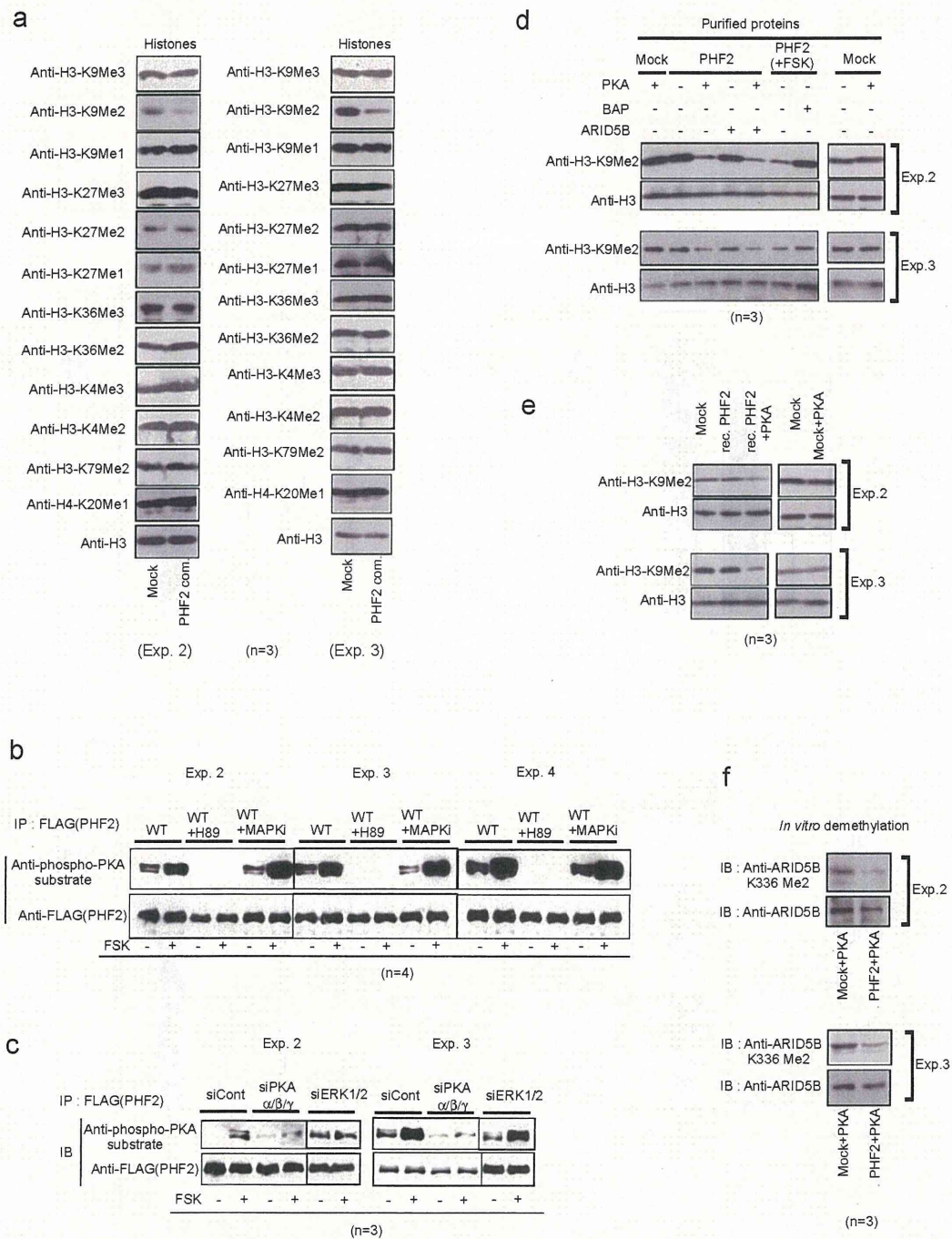


Figure S8 Western blot data for quantification. **a**, For *in vitro* demethylation assay and quantification in Fig. 1c-d, three independent experiments were performed, and histone methylation marks were analyzed by Western blotting as shown in Fig. 1d. The other two sets of data for quantification are shown. **b-c**, Quantification analysis for PKA-mediated phosphorylation of PHF2. Assay was performed as in Fig. 2d, and the other data for quantification in Fig. 2d (left, n=4 and right,

n=3) were shown. **d-e**, Quantification analysis for PKA-dependent PHF2 demethylase activity. Three independent assays were performed as in Fig. 3b-c and 3e-f, and the other two sets of data for quantification (n=3) were shown. **f**, Quantification analysis for demethylation of ARID5B by PHF2 *in vitro*. Three independent assay was performed as in Fig. 5e, and the other two sets of data for quantification in the lower panel of Fig. 5e (n=3) were shown.

SUPPLEMENTARY INFORMATION

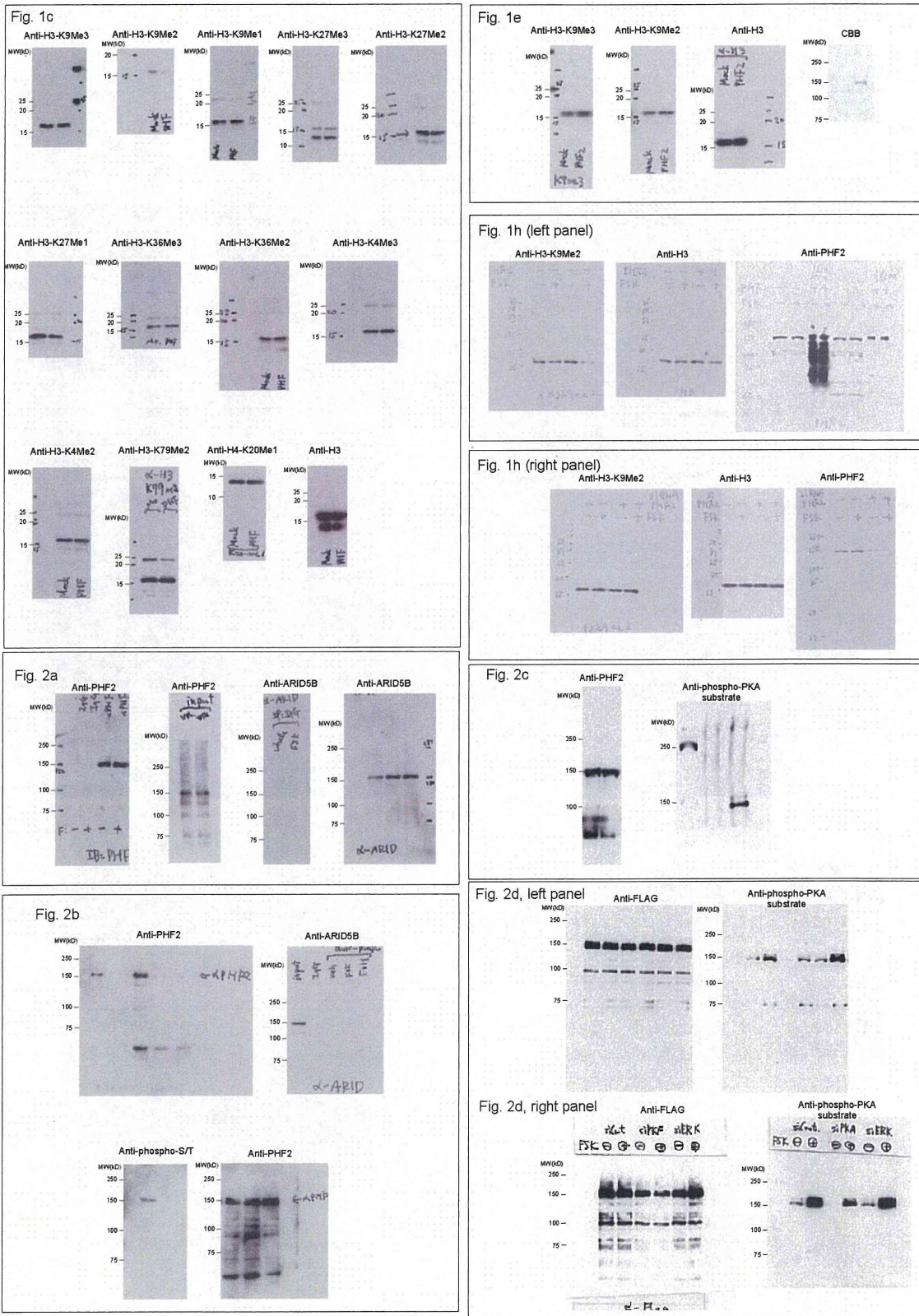


Figure S9 Full scans

SUPPLEMENTARY INFORMATION

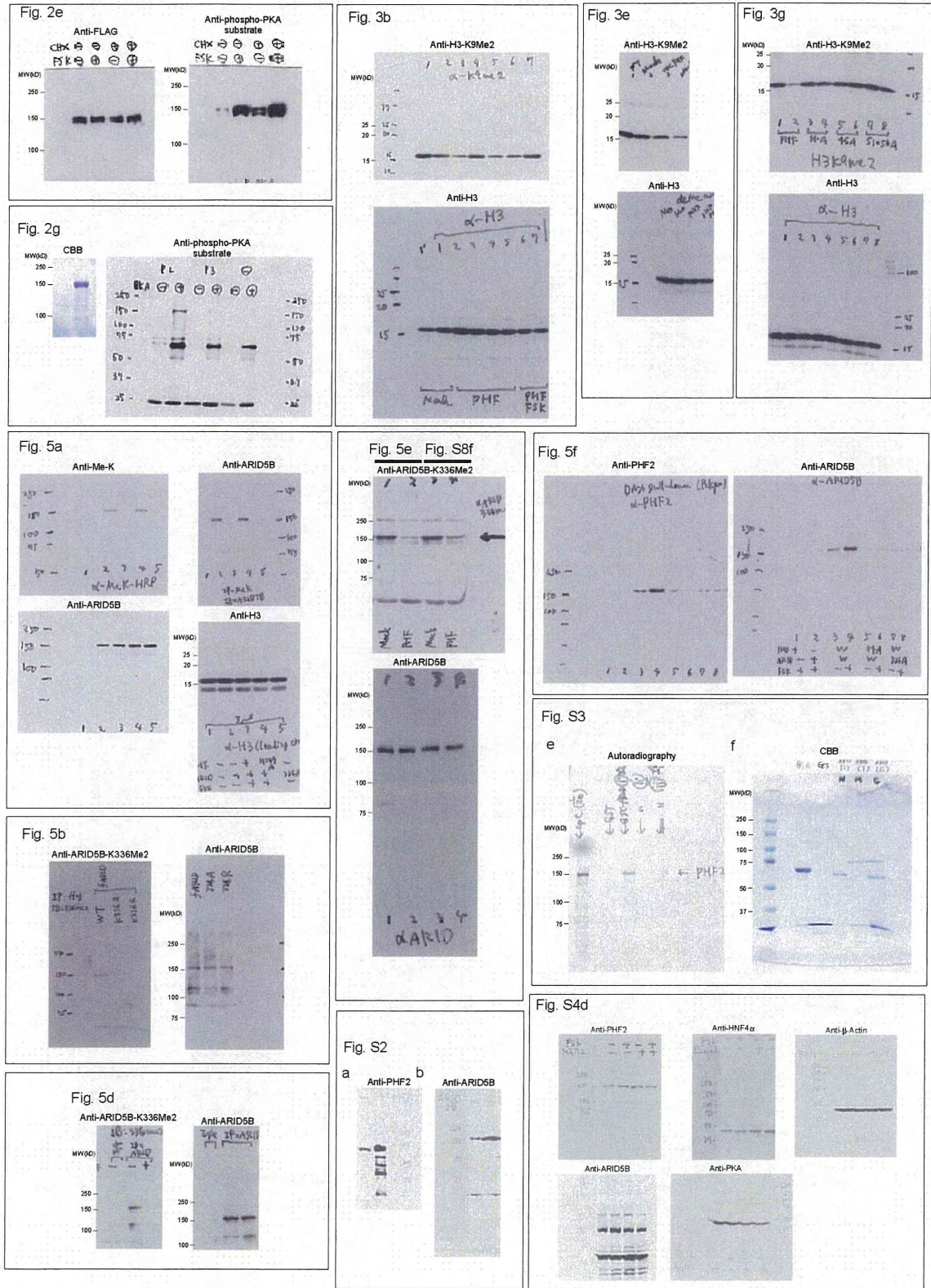


Figure S9 continued