**Cell Reports**

RUNX1-ETO Depletion in t(8;21) AML Leads to C/EBPα- and AP-1-Mediated Alterations in Enhancer-Promoter Interaction

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**Highlights**

- Promoter Capture Hi-C links t(8;21) AML-specific cis-elements to correct promoters

- Interacting cis-elements bound by transcription factors form a gene regulatory network

- The product of the t(8;21) translocation, RUNX1-ETO, participates in interactions

- Differential interactions after RUNX1-ETO depletion are driven by C/EBPα and AP-1

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**Authors**

Anetta Ptasinska, Anna Pickin, Salam A. Assi, ..., Peter N. Cockerill, Cameron S. Osborne, Constanze Bonifer

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**Correspondence**

c.bonifer@bham.ac.uk

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**In Brief**

Promoter-Capture Hi-C assays, gene expression, and transcription-factor binding data are used to construct a RUNX1-ETO-dependent dynamic gene regulatory network that maintains acute myeloid leukemia (AML). Ptasinska et al. show that RUNX1-ETO participates in cis-regulatory element interactions and that differential interactions after RUNX1-ETO depletion are driven by C/EBPα and AP-1.

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RUNX1-ETO Depletion in t(8;21) AML Leads to C/EBPα- and AP-1-Mediated Alterations in Enhancer-Promoter Interaction

Anetta Ptasinska,1,5 Anna Pickin,1,5 Salam A. Assi,1,5 Paulynn Suyin Chin,1 Luke Ames,1 Roberto Avellino,3,6 Stefan Gröschel,3,7 Ruud Delwel,3,4 Peter N. Cockerill,1,8 Cameron S. Osborne,2,8 and Constanze Bonifer1,9,*
1Institute of Cancer and Genomic Sciences, University of Birmingham, Birmingham B15 2TT, UK
2Department of Medical & Molecular Genetics, King’s College London, London SE1 9RT, UK
3Department of Hematology, Erasmus University Medical Center, Rotterdam, the Netherlands
4Oncode Institute, Erasmus University Medical Center, Rotterdam, the Netherlands
5These authors contributed equally
6Present address: Department of Immunology, Weizmann Institute of Science, Rehovot 7610001, Israel
7Present address: Molecular Leukemogenesis, Deutsches Krebsforschungszentrum, 69120 Heidelberg, Germany; Department of Internal Medicine V, Heidelberg University Hospital, 69120 Heidelberg, Germany
8Senior author
9Lead Contact
*Correspondence: c.bonifer@bham.ac.uk
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SUMMARY

Acute myeloid leukemia (AML) is associated with mutations in transcriptional and epigenetic regulator genes impairing myeloid differentiation. The t(8;21) (q22;q22) translocation generates the RUNX1-ETO fusion protein, which interferes with the hematopoietic master regulator RUNX1. We previously showed that the maintenance of t(8;21) AML is dependent on RUNX1-ETO expression. Its depletion causes extensive changes in transcription factor binding, as well as gene expression, and initiates myeloid differentiation. However, how these processes are connected within a gene regulatory network is unclear. To address this question, we performed Promoter-Capture Hi-C assays, with or without RUNX1-ETO depletion and assigned interacting cis-regulatory elements to their respective genes. To construct a RUNX1-ETO-dependent gene regulatory network maintaining AML, we integrated cis-regulatory element interactions with gene expression and transcription factor binding data. This analysis shows that RUNX1-ETO participates in cis-regulatory element interactions. However, differential interactions following RUNX1-ETO depletion are driven by alterations in the binding of RUNX1-ETO-regulated transcription factors.

INTRODUCTION

Acute myeloid leukemia (AML) is a hematopoietic malignancy caused by genetic abnormalities in hematopoietic stem cells (HSCs), which restrict their ability to undergo the normal differentiation process (Bonifer and Cockerill, 2015; Kumar, 2011). The transcription factors (TFs) regulating hematopoiesis have to be expressed in a stage- and lineage-restricted fashion since their mutation or de-regulation impairs differentiation and prolongs the proliferative stage, thus increasing the opportunities for cells to further mutate and progress to AML (Bonifer and Cockerill, 2011; Rosenbauer and Tenen, 2007). One of the best-studied subtypes of AML is the t(8:21)(q22;q22) translocation generating the RUNX1-ETO fusion protein (Erickson et al., 1992; Miyoshi et al., 1991). RUNX1-ETO has a modular structure comprising the RUNX1 DNA-binding domain plus four evolutionary conserved functional domains named nervy homology regions 1 to 4 (NHR1 to NHR4) (Kitabayashi et al., 1998), which recruit transcriptional repressors such as the N-CoR/mSin3/HDAC1 complex (Lutterbach et al., 1998). The expression of this abnormal protein results in a block in differentiation and increased cell survival (Dunne et al., 2006; Heidenreich et al., 2003; Martinez et al., 2004; Ptasinska et al., 2012).

The RUNX1-ETO fusion protein is part of a larger TF complex consisting of RUNX1-ETO; CBFβ; the erythroblast transformation-specific (ETS) family of transcription factors (ERG and FLI1); E proteins such as HEB, E2A, and LYL1; and the non-DNA binding factors LDB1 and LMO2 (Martens et al., 2012; Ptasinska et al., 2014; Sun et al., 2013). Each part of the complex is thought to be essential for AML maintenance (Sun et al., 2013). RUNX1-ETO depletion in t(8;21) cells is sufficient to trigger extensive global changes in the transcriptomic and epigenetic profile across hundreds of genes (Ben-Ami et al., 2013; Dunne et al., 2006; Ptasinska et al., 2012; Sun et al., 2013). Depletion upregulates a specific set of RUNX1-regulated genes, such as CEBPA, leading to increased recruitment of RUNX1 and C/EBPa to gene regulatory elements throughout the genome, thereby releasing the block on myeloid differentiation and suppressing self-renewal (Loke et al., 2017; Ptasinska et al., 2014; Sun et al., 2013). We have previously used global TF binding and gene expression information to construct a dynamic gene regulatory network linking genes bound by the RUNX1-ETO
complex to dynamic changes of gene expression (Ptasinska et al., 2014). We used such system-wide information to devise a RNAi dropout screen that identified a number of genes associated with AML maintenance (Martinez-Soria et al., 2019). However, to fully explore the power of genome-wide studies, we need to construct gene regulatory networks that enable us to predict the results of perturbation experiments from such data using modeling approaches. Therefore, a number of issues still need to be resolved. RUNX1-ETO mostly binds to distal cis-regulatory elements, and although we can define genes responding to RUNX1-ETO knockdown, we do not know whether this response is direct or indirect, as we do not know which promoter is linked to the sites of fusion protein binding. In addition, we do not know which other TFs participate in the maintenance of the leukemic state and drive the response to RUNX1-ETO knockdown.

To answer these questions, we identified direct cis-element interactions using the Promoter Capture Hi-C (CHi-C) method (Mifsud et al., 2015) in Kasumi-1 cells, a well-known model of t(8;21) AML, with and without small interfering RNA (siRNA)-mediated RUNX1-ETO depletion. RUNX1-ETO knockdown leads to a rewiring of promoter-enhancer interactions, which is driven by increased C/EBPα and loss of AP-1 binding after knockdown. We integrated these results with chromatin immunoprecipitation (ChIP) and digital footprinting data from cell lines and patients to identify regulatory relationships between binding events and gene expression, which will aid further studies aimed at identifying pathways required for t(8;21) AML leukemic maintenance.

RESULTS AND DISCUSSION

RUNX1-ETO Depletion Does Not Lead to a Global Reorganization of Chromosome Structure but Changes Promoter-Enhancer Interactions within TADs

The tissue specificity of gene expression is controlled by lineage-restricted TFs binding to distal cis-regulatory elements that need to physically interact with their target promoters in order to activate gene expression (de Laat and Duboule, 2013; Plank and Dean, 2014). To examine whether RUNX1-ETO influences genome-wide cis-element interactions, we generated duplicate CHi-C libraries (Mifsud et al., 2015) from Kasumi-1 cells that were either untreated (mismatch control siRNA [siMM]) or following a 4-day siRNA-mediated treatment to knockdown RUNX1-ETO (siRE) (Figure 1A). Data analysis of the sequenced libraries identified 57,775 significant interactions between promoters and distal elements before and 60,681 significant interactions after RUNX1-ETO depletion. CHi-C libraries were highly reproducible with an average of 70% overlap of significant interactions between replicates (Figures S1A–S1D). To align our CHi-C data with the coordinates of cis-regulatory elements, we mapped Deoxyribonuclease I (DNaseI) hypersensitive sites (DHSs) during a knockdown time course (Figure S1E). The presence (siMM) or absence (siRE) of RUNX1-ETO did not influence global chromosomal organization across all chromosomes (Figure 1A), including the organization of this region into topologically associated domains (TADs; large triangles, projected above the DHS pattern) (Gonzalez-Sandoval and Gasser, 2016; Figure 1B). Figure 1C shows a University of California, Santa Cruz (UCSC) genome browser screenshot highlighting active and inactive chromatin compartments plotted alongside RUNX1-ETO ChIP data (Ptasinska et al., 2012) and day-10 DNase I hypersensitive sites sequencing (DNaseI-seq) data (this manuscript). These analyses revealed clusters of interactions within active and inactive regions whose ratio was invariant even after an extended period of RUNX1-ETO depletion (Figure 1D).

To investigate whether specific DHS patterns seen following RUNX1-ETO depletion correlated with a specific stage of myeloid differentiation, we compared DNaseI data from control and RUNX1-ETO-depleted Kasumi-1 cells (days 2, 4, and 10) to published assay for transposase-accessible chromatin using sequencing (ATAC-seq) data defining the open chromatin regions of normal stem and progenitor cells representing different developmental stages (Corces et al., 2016; Figure S1F). DHSs specific for control cells (bottom) aligned more closely with HSCs and early progenitors and showed increased AP-1 motif enrichment, whereas DHSs specific for RUNX1-ETO-depleted cells (top) aligned with those of monocytic cells and were enriched for C/EBP motifs. RUNX1-ETO depletion had a profound effect on gene expression with a large number of genes changing expression by day 10 (Figure S1G). Flow cytometry and principal component analyses of DNaseI-seq data revealed that Kasumi-1 cells gradually lose their stem cell markers (CD34 and CD117) while principal component and correlation clustering analyses of the DNaseI-seq data indicated that at day 10, but not yet at day 4, they had differentiated toward monocytic cells (Figures S1J and S1K). Phenotypic changes were accompanied by changes in protein and mRNA expression for a number of TFs visible already at day 2, in particular C/EBPα (Figures S1L and S1M), which is rapidly upregulated after knockdown. JUN mRNA was strongly downregulated during the first days of knockdown but then was strongly upregulated in concordance with its important role in regulating monocyte and/or macrophage-specific gene expression (Heinz et al., 2010). The expression of JUND protein was upregulated as well, but note that the DNA-binding activity of the AP-1 family of TFs is regulated by signaling-mediated phosphorylation (Beijani et al., 2019).

Around 80% of all DHSs detected in active regions of control cells or RUNX1-ETO-depleted cells participated in promoter-enhancer interactions (Figure 1E, right panels). To identify differential interactions, we used the CHi-C data to assign the respective DHSs to the promoter for RUNX1-ETO-depleted and control cells (Data S1). Figures 2A and 2B show statistically significant control-specific and RUNX1-ETO-specific interactions at 5-kb resolution involving specific DHSs on chromosome 3, which were not seen with shared DHSs (Figure S2A), indicating that it is the differential DHSs that drive these changes. A total of 1104 DHSs were significantly increased and 1209 were significantly decreased after 10 days of RUNX1-ETO knockdown (Figures 2E and S1F). The majority of these DHSs (75% and 76%, respectively) show differential promoter-enhancer interactions already after day 4 of knockdown (Figure 1E), demonstrating that RUNX1-ETO depletion alters the epigenome prior to monocytic differentiation.
RUNX1-ETO-Regulated TFs Drive Differential Cis-Regulatory Element Interactions

We next sought to identify the TFs driving the changes in interactions by performing digital footprinting analysis, using our Wellington algorithm (Piper et al., 2013). This approach reveals TF motifs protected from DNaseI digestion and evaluates genome-wide TF occupancy with high accuracy (Figure 2C). Examples of such footprints for day 10 of knockdown are depicted for ETS and C/EBP motifs at the IL17RA locus in Kasumi-1 cells (Figure S2B). Global binding motif analysis confirmed that AP-1 motifs were preferentially occupied in control (siMM) cells whereas C/EBP motifs were occupied in RUNX1-ETO-depleted (siRE) cells (Figure 2D). Motif occupancy was validated by comparing footprinting data with previously generated ChIP-seq data for C/EBPα, RUNX1-ETO, PU.1, JUND, and RUNX1 (Ptasinska et al., 2014; Martinez-Soria et al., 2019) (Figure S2C).
Two factors capable of mediating long-range interactions are CTCF and LDB1 (Deng et al., 2012; Splinter et al., 2006). To examine their role, we generated new CTCF and LDB1 ChIP data with and without RUNX1-ETO depletion. We correlated changes in gene expression and TF binding at specific DHSs with differential interactions between DHSs and promoters (Figure 2E). These analyses revealed a global increase in C/EBPβ binding after knockdown and a decrease in JUND binding at siMM-specific DHSs (Figure 2E). All other factors showed no or little difference in binding between knockdown and control cells. Changing interactions correlated with differential gene expression (Figure 2E, outermost right panel). Figure 2F shows an example of interactions at the upregulated CCND2 gene, which shows changes in interactions between its promoter and two upstream distal elements (depicted in red). Two observations are noteworthy. First, the CCND2 promoter interacts with a large number of distal DHSs. Second, a large number of RUNX1-ETO binding sites are located within these sites, indicating that RUNX1-ETO is part of an extended and mostly invariant chromatin hub. To validate our Chi-C data, we conducted a circularized chromosome conformation capture (4C) experiment that investigated the SPI1 (PU.1) locus at high resolution, using two different viewpoints (Figure S2D). We detected known interactions between the SPI1 promoter and an upstream enhancer (URE) (Ebralidze et al., 2008), but also with two upstream promoters. These interactions did not change after RUNX1-ETO depletion. The same result was found using Chi-C (Figure S2E).

We next analyzed the behavior of LDB1 in more detail. LDB1 does not bind to DNA directly but via other TFs such as RUNX1 (Wadman et al., 1997). LDB1 binds to both promoter and distal regions (Figure S2E) and RUNX1-ETO depletion led to a loss of 1,506 LDB1 binding sites and the acquisition of 779 new sites (Figure S2F). De novo motif search of siMM- or siRE-specific DHS peaks revealed an enrichment of RUNX1 motifs in both binding site populations, which, however, occurred together with the AP-1 motif in siMM-specific peaks and with C/EBP binding motifs after RUNX1-ETO knockdown (Figure S2G). As expected from it being part of the RUNX1-ETO and RUNX1 complex, LDB1 binding correlated with interactions in control DHSs, which were lost after RUNX1-ETO depletion but also participated in new interactions (Figure S2F, third panel). To test whether LDB1 was required for RUNX1-ETO binding, we depleted it using siRNA knockdown in Kasumi-1 cells with and without RUNX1-ETO knockdown (Figure S3A). LDB1 depletion led to an increase in cell death both by apoptosis and necrosis, but only in RUNX1-ETO-expressing cells, confirming that it is required for the maintenance of the leukemic phenotype (Sun et al., 2013) (Figure S3B). However, LDB1 was not required for RUNX1-ETO binding to chromatin (Figure S3C). LDB1 was also not required for the upregulation or repression of RUNX1-ETO target genes. As expected, RUNX1-ETO knockdown led to increases in expression of the direct RUNX1-ETO target genes C/EBPA, CTSG, and NFE2 and decreases in CD34 and ERG expression. Knockdown of LDB1 alone or together with RUNX1-ETO knockdown had no additive or negative effect on RUNX1-ETO target gene expression changes (Figure S3D). We therefore conclude that other factors besides RUNX1-ETO control LDB1 binding and determine its functional impact.

We next investigated whether the change in interaction was associated with altered TF occupancy. To this end, differential interactions were ranked by fold change in p value (Figure 3A), and associated DHSs were plotted alongside together with C/EBPβ, JUND, LDB1, CTCF, RUNX1-ETO, PU.1, and RUNX1 ChIP-seq data. Beneath, we plotted the average profiles of factor binding for control and RUNX1-ETO-depleted cells (blue, ChIP signals associated with lost interactions; red, gained interactions). Differential interactions were associated with the differential binding of some, but not all, TFs. RUNX1-ETO-bound sites were associated with DHSs involved in both decreased and increased interactions, demonstrating that it is not the sole determinant of the interaction pattern. DHSs associated with gained interactions showed a strong increase in C/EBPβ as well as an increase in RUNX1 binding. Conversely, DHSs associated with decreased interactions after RUNX1-ETO knockdown lost JUND as well as LDB1 binding. An example for a downregulated gene is CCND2 (Figure S2F), whose expression we have previously shown to be dependent on the presence of AP-1 factors (Martinez-Soria et al., 2019). Increased interactions did not involve an increase in LMO2 or PU.1 binding, and loss of interactions did not involve CTCF. The CITED2 gene is an example of a gene with a new interaction driven by C/EBPβ binding (Figure 2G, Figure 2). Differential Promoter-Enhancer Interactions after RUNX1-ETO Depletion Are Driven by Differential TF Binding

(A) Heatmap representing the correlation of normalized interaction ratios across chr3 at 5-kb resolution, showing the correlation of CHiC peaks in regions specific to DHS peaks that are depleted after RUNX1-ETO knockdown. Each pixel represents a 5-kb section of the genome. The left panel shows the interaction heatmap for siMM and the right panel for siRE cells. Positive correlations are shown as red; negative correlation as blue squares. To determine statistically significant interactions, reads from replicates 1 and 2 were merged.

(B) Heatmap representing the correlation of normalized interaction ratios across chr3 at 5-kb resolution and showing the correlation of CHiC peaks in DHS peaks that are newly formed after RUNX1-ETO knockdown. For all other features, see (A).

(C) DNasel cleavage patterns within specific distal footprints predicted by Wellington (Piper et al., 2013). Upper strand cut sites are shown in red and lower strand cut sites in green within a 200-bp window centered on each footprint (gap) for siMM- and siRE-specific footprints.

(D) Analysis of overrepresented binding motifs within each footprint class as defined in (C).

(E) Left panel: time course of DHS development after 2, 4, and 10 days of RUNX1-ETO depletion (see scheme in Figure S1E). Normalized tag counts are ranked alongside day-10 knockdown (KD) and control-specific (bottom) counts; common and siRE-specific DHS are indicated on the left. Alongside the same genomic coordinates, C/EBPβ, JUND, LDB1, CTCF, RUNX1-ETO, LMO2, PU.1, and RUNX1 ChIP-seq reads from Kasumi-1 cells with or without RUNX1-ETO depletion are plotted as indicated (middle panel). The right panel shows the expression levels of the genes linked to the associated DNaseq-sites (right panel).

(F) UCSC browser screenshot depicting interactions between the CCND2 promoter and surrounding DHS (shown as arcs) together with the indicated ChIP-seq data before and after RUNX1-ETO knockdown. Changing interactions are shown in red, and their associated DHS/ChIP peaks are highlighted using a vertical shaded bar.

(G) The same analysis as in (F) for the CITED2 locus.
Figure 3. The Cooperation of Constitutive and Inducible TFs Is Associated with Differential Interactions

(A) Log p values of the differential interactions were plotted ranked from high to low for control and RUNX1-ETO-depleted cells. Red represents an increase in interaction strength and blue represents a decrease. Alongside, the DNaseI-seq fold difference between control and RUNX1-ETO knockdown cells as well as ChIP-seq density profiles for C/EBPα, JUND, LDB1, CTCF, RUNX1-ETO, LM02, and PU.1 are plotted from Kasumi-1 cells, transfected with either siMM or siRE as indicated. The panels below show the average profiles of the binding of the indicated TFs plotted around the peak summit for control and RUNX1-ETO-depleted cells. Red, ChIP signal specific for peaks with increased interactions; blue, ChIP signal specific for peaks with decreased interactions.

(B) Determination of enriched motifs for other TFs in ChIP-seq peaks specific for control and RUNX1-ETO-depleted cells. Motif enrichment was first identified using HOMER and then filtered against digital footprinting data from day 10 of knockout to ensure that these binding motifs were functional. Enrichment scores were subjected to unsupervised clustering for each of the indicated motifs (on the right). The heatmap depicts the degree of motif enrichment with highly enriched motifs shown in red. Peaks were overlaid with the DHS that show new interactions (red brackets at the bottom) or whose interactions are lost (blue brackets). Enrichment scores were calculated by the level of motif enrichment in the unique peaks, as compared to motif enrichment in RUNX1-ETO peaks. Bottom panels: percentage of peaks showing differential interaction with TFs binding to these sites as determined by ChIP-seq (control cells, blue; RUNX1-ETO-depleted cells, red).

(legend continued on next page)
shaded bar). In summary, our study shows that the main drivers of changes in cis-element interactions are the loss of RUNX1-ETO binding together with the loss of LDB1 and AP-1 binding along with the increased binding of C/EBPζ and RUNX1 to new sites.

We next identified additional TFs associated with differential interactions and clustered TF binding motifs enriched in ChIP-seq peaks that either overlapped with new interaction sites or with sites lost after RUNX1-ETO depletion (Figure 3B, left panel and panels below the heatmap). Since the majority of DHS changes participating in differential interactions had already occurred at day 4 of knockdown (Figure 1E), we used our day-10 digital footprinting data to ensure that these motifs were functional and could be occupied. We then calculated the motif enrichment score of such motifs (depicted on the right) (Figure 3B, top-right panel). These analyses showed that the score of enriched motifs for RUNX1 and C/EBP family members increased in differential interactions upregulated after RUNX1-ETO depletion, together with an increase in GFI1, MYB, and MYC/MAX binding site occupancy. In contrast, and in concordance with our ChIP-seq data, AP-1 motif enrichment decreased in interactions that were lost after RUNX1-ETO depletion, together with loss of activating TF (ATF) and nuclear factor κB (NF-κB) motif occupancy. We also detected enrichment of motifs in both gained and lost interactions. This was true for ETS-family factors such as ERG and PU.1, but also for RUNX1, suggesting that factors move to other sites as shown previously (Lichtinger et al., 2012). To confirm this idea, we determined the distribution of distance between RUNX1 binding and other TFs before and after RUNX1-ETO depletion using the ChIP-seq data. This analysis showed a significant co-localization between AP-1 and RUNX1 peaks before, but not after, RUNX1-ETO depletion. In contrast, RUNX1 and C/EBPζ show significant co-localization after RUNX1-ETO depletion (Figure 3C). In spite of the appearance of new RUNX1 binding sites after RUNX1-ETO depletion (Ptasinska et al., 2012, 2014), no significant changes were observed in the distribution of distance between RUNX1 and LDB1 and LMO2 and PU.1 peaks (Figures S3F–S3H), indicating no change in this type of factor collaboration. These analyses suggest that RUNX1 cooperates with different factors regulating different biological processes in control and RUNX1-ETO-depleted cells. To examine TF cooperation after the onset of monocytic differentiation, we performed a bootstrapping analysis (Figure 3D) in RUNX1-ETO-depleted and control cells that identified occupied TF binding motifs co-localizing with high significance within 50 base pairs (bp) as compared to the rest of the active genome (highlighted in red). This analysis again confirmed the strong co-association of occupied C/EBP and RUNX1 motifs in differentiated cells and AP-1, ETS, and RUNX motifs co-occurrence in control cells. Interestingly, the AP-1 or C/EBP motifs were not preferentially footprinted in the DHSs shared between control and knockout cells and did not co-localize with other motifs (Figure S3I), indicating that co-localizing (RUNX1-AP-1) sites are part of the AML-specific cistrome. In summary, these analyses demonstrated that the establishment of specific RUNX1-ETO-dependent cis-element interactions are mediated by the cooperation of a limited set of constitutive and inducible TFs. The depletion of RUNX1-ETO drives the loss and relocation of TFs and thus the establishment of new interactions via new factor collaborations.

The Construction of Transcriptional Networks Grounded in Multi-omics Data

The Kasumi-1 cell line is one of the best-studied human models of t(8;21) AML with numerous multi-omics data available that should be amenable to modeling approaches predicting transcriptional network behavior in response to perturbation. So far we have assigned factor binding site data only to their nearest promoter. However, numerous studies have shown that such assignments were not accurate (Mifsud et al., 2015; Sanyal et al., 2012). In our study, we found that only about 40% of all cis-regulatory elements in control cells interacted with their nearest promoter. Our ChI-C data enabled us to assign DHSs containing active cis-elements and footprinted regions to promoters (Data S2). More than 70% of all DHSs assigned to their rightful promoter in Kasumi-1 cells were also present in t(8;21) but not in FLT3-ITD patients or normal CD34+ hematopoietic stem cell (HPSCs; Figure 3E; Assi et al., 2019). To construct gene regulatory networks and to examine how these networks shift after RUNX1-ETO depletion and differentiation, we used our footprinting data (control and day-10 siRE) to assign occupied motifs to specific TF families capable of binding to this motif (Table S1, indicated as groups in Figure 4). We then plotted the connections between factors and genes that were downregulated (Figure 4B, blue ovals) or upregulated (Figure 4S, red ovals) by at least 2-fold following RUNX1-ETO depletion at day 10, with the former being markers for the leukemic and the latter being markers for differentiated states. We also highlighted which genes were RUNX1-ETO targets (green boundary). This analysis shows a complex web of interactions between effector genes (lined up at the top) and TF encoding genes, many of which are known to respond to RUNX1-ETO depletion, such as C/EBPA or IRF8.

The networks highlight the TFs involved in differentiation, again showing that increased C/EBPζ activity is the main driver of the changes of the t(8;21) transcriptional network after RUNX1-ETO depletion, with C/EBP family members binding to multiple differentiation-specific cis-regulatory elements and driving the upregulation of their respective genes. (Loke et al., 2018; (C) Bar plots illustrating the distribution of distances between the binding sites of the indicated TFs as determined by ChIP-seq. We measured the changing distance between RUNX1 peaks in siMM and siRE cells and C/EBPζ peaks in siMM (top left) and siRE cells (top right), as well as the distance between RUNX1 peaks and JUND control peaks (bottom left) and JUND after R/E KD (bottom right).

(D) Bootstrapping analysis of the significance of co-localizing of footprinted motifs within day-10 DHSs for sites that are either lost (left panel) or gained (right panel) after RUNX1-ETO depletion as compared to the rest of the genome. The heatmap shows the significance of motifs co-localizing within 50 bp as compared to sampling by chance.

(E) Heatmap highlighting the percentage of day-4 Kasumi-1 DHSs with interactions found in different patient groups indicating the similarity between cell-line and primary t(8;21) data. The t(8;21) and FLT3-ITD DHS/ChI-C patient data were downloaded from GEO: GSE108316 (Assi et al., 2019).
An example of a downregulated gene specific to the leukemic state includes *UBASH3B*, which has previously been shown to regulate the proliferation of t(8;21) cells (Goyama et al., 2016). Another such example is *YES1*, which, together with another downregulated gene, *MEIS2*, is involved in maintaining leukemic growth (Vegi et al., 2016). AP-1 members are important for maintaining the leukemic growth phenotype, as shown by expressing a dominant-negative FOS protein in t(8;21) cells. Expression of this peptide downregulates the expression of several cell cycle genes, including *CCND2* (Martinez-Soria et al., 2019), and blocks tumor growth in vivo (Assi et al., 2019).

Such examples of properly annotated RUNX1-ETO-responsive genes with known function show the quality of our analysis with respect to the prediction of important genes required for AML maintenance. Last but not least, our studies serve as paradigm for how high quality multi-omics data can be used to generate in-depth information on the regulatory circuitries of a specific type of AML.

**STAR METHODS**

Detailed methods are provided in the online version of this paper and include the following:

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SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.cell.2019.08.040.

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AUTHOR CONTRIBUTIONS

A. Pickin conducted the Chi-C and 4C experiments; A. Ptasinska designed and performed experiments and wrote the manuscript; P.S.C. performed expression in health and disease. Adv. Exp. Med. Biol. 711, 12–25.
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### STAR METHODS

#### KEY RESOURCES TABLE

| REAGENT or RESOURCE | SOURCE | IDENTIFIER |
|---------------------|--------|------------|
| **Antibodies**      |        |            |
| ETO                 | Diagenode | Cat# C15310197 |
| RUNX1 (C-terminal epitope) | Abcam | Cat# 23980; RRID: AB_2184205 |
| C/EBPα              | Abcam | Cat# 40761; RRID: AB_726792 |
| LDB1                | Abcam | Cat# 96799; RRID: AB_10679400 |
| LMO2                | R&D   | Cat# AF2726; RRID: AB_2249968 |
| CTCF                | Abcam | Cat# 70303; RRID: AB_1209546 |
| JUND                | Santa Cruz | Cat# sc74; RRID: AB_2130177 |
| GAPDH               | Sigma | Cat# F3165; RRID: AB_259529 |
| Anti-Rabbit HRP     | Cell signalling | Cat# 7074; RRID: AB_2099233 |
| Anti-Mouse HRP      | Jackson | Cat# 115-0350-62; RRID: AB_2338504 |
| CD34 Monoclonal Antibody (4H11), PE | eBioscience | Cat# 12-0349-42; RRID: AB_1548680 |
| c-Kit Monoclonal Antibody (104D2), FITC | eBioscience | Cat# 11-1178-42; RRID: AB_2572472 |
| **Oligonucleotides** |        |            |
| Oligonucleotide sequences, see Table S2 | This Paper | NA |
| **Chemicals, Peptides, and Recombinant Proteins** | | |
| TruSeq Stranded mRNA with Ribo-Zero human assay | Illumina | Cat# 20020596 |
| TruSeq RNA Sample Prep kit | Illumina | Cat#RS-122-2001 |
| KAPA hyper Prep Kit | Kapa Biosystems | KK8500 |
| KAPA Library Quantification kit | Kapa Biosystems | Cat#KK4824 |
| MinElute Gel Extraction Kit | QIAGEN | Cat#28604 |
| DNaseI | Worthington, | DPPF grade |
| AMPure XP beads | Beckman Coulter | Cat#A63882 |
| NextSeq500 High output 150 cycles | Illumina | Cat#FC-404-2002 |
| NextSeq500 High output 75 cycles | Illumina | Cat#FC-404-2005 |
| Nucleospin RNA column | Machery Nagel, | 740955.50 |
| OligoDT primer | Promega | C110A |
| Murine Moloney Virus reverse transcriptase | Promega | M170A |
| RNase Inhibitor | Promega | N261A |
| Sybr Green mix | Applied Biosystems | 4309155 |
| Proteinase K | Roche | 03115801001 |
| Di(N-succinimidyl) glutarate (DSG) | Sigma-Aldrich | 80424 |
| MyOne Streptavidin C1 | DynaBeads Invitrogen | 65601 |
| MyOne Streptavidin T1 | DynaBeads Invitrogen | 65001 |
| Formaldehyde | (Pierce, Thermos Scientific, USA) | 28906 |
| (NEB)2 buffer | NEB | 37002 |

**Critical Commercial Assays**

| **Critical Commercial Assays** | | |
| Dead Cell Removal microbeads | Miltenyi Biotec | 130090101 |
| Annexin V-APC/PI staining | Ebioscienes | 88-8007-74 |
| High Sensitivity DNA Chips | Agilent Technologies | 5067-4626 |
| RNA Pico Chips | Agilent Technologies | 5067-1513 |
| High Pure PCR Product Purification Kit | Roche | 11732676001 |
| SureSelect target enrichment | Agilent Technologies | 5190-4393 |
| HindIII | NEB | R0104M |

(Continued on next page)
LEAD CONTACT AND MATERIALS AVAILABILITY

Further information and requests for resources and reagents should be directed to and will be fulfilled by the Lead Contact, Constanze Bonifer (c.bonifer@bham.ac.uk).

This study did not generate new reagents.

EXPERIMENTAL MODEL AND SUBJECT DETAILS

Cell Line Culture
Cells were maintained in a humidified incubator at 37°C with 5% CO2. t(8;21) Kasumi-1 cells were cultured in RPMI with 10% FCS supplemented with 1% glutamine and 1% penicillin/streptomycin.

METHOD DETAILS

siRNA Mediated Depletion of RUNX1-ETO or LDB1
1x10⁷ cells were electroporated using a EPI 3500 (Fischer, Germany) single 350 V pulse for 10ms. After electroporation, the cells remained in their cuvettes for 10 minutes before being directly added to RPMI-1640 with 10% FCS, supplemented with penicillin/streptomycin and glutamine at a concentration of 0.5 x10⁶ cells per ml and returned to an incubator kept at 37°C and 5% CO2. siRNA sequences (SIGMA ALDRICH Germany) specific for the translocation breakpoint of RUNX1-ETO were 5’ CCUCGAAUCGUACGAGAAGU-3’ (sense) and 5’- UCUCAGUACGAUUUCGAGGUU-3’ (antisense). Control siRNA was 5’-CCUCGAAUUCGUUCCAG-3’ (sense) with 5’-UCUCAGAAGAAUCGAGGUU-3’ (antisense). siRNA sequences specific for LDB1 ON-TARGETplus Human LDB1 siRNA SMARTpool (L-016010-00-0005, Dharmacon). siRNA was used at 200 nM.

RNA Extraction
RNA from Kasumi-1 cells was purified using a Nucleospin RNA column (Machery Nagel, France), according to manufacturer’s instructions. The quality of RNA from was assessed using a spectrophotometer, by the ratio of the absorbance at 260 nm and
280 nM wavelengths. RNA has a greater absorbance in the 260 nM wavelength, Eukaryotic Total RNA PICO Bioanalyzer chip (Agilent technologies, USA) allows visualization of the size of the RNA molecules and thus, demonstrates whether the sample is degraded or not.

**RNA Seq Libraries**

RNA-seq libraries were prepared with a Total RNA Ribo-zero library preparation kit (with ribosomal RNA depletion) (Illumina, USA) according to manufacturer’s instructions with the following alterations: 15 cycles of PCR was undertaken to amplify the library and adaptors for multiplexing were used at a 1:4 dilution. Library quality was checked by running the samples on a Bioanalyzer and libraries were quantified using a Kapa library quantification kit (Kapa Biosystems, USA) and run in a pool of eight indexed libraries in two lane of a HiSeq 2500 (Illumina, USA) using rapid run chemistry with 100bp paired end reads.

**cDNA Synthesis**

1 µg RNA was used to make cDNA with 0.5 µg OligoDT primer, Murine Moloney Virus reverse transcriptase and RNase Inhibitor (Promega, USA) according to the manufacturer’s protocol.

**Real-Time Polymerase Chain Reaction**

RT-PCR was performed using Sybr Green mix (Applied Biosystems, UK), at 2x dilution. Primers were used at 100 nM final concentration. cDNA was diluted 1:50 depending on expression levels of targets. A 7900HT system (Applied Biosystems, UK) was used to perform qPCR. Primers used in this project are listed in Table S2.

**Dead Cell Removal and Annexin V/PI Staining for Flow Cytometry**

Dead cell removal was performed using negative selection on a MS column following incubation with Dead Cell Removal microbeads (Mitenyi Biotech, USA) as per manufacturer’s instructions. Dead cell removal was performed on all samples prior to RNA extraction or DHSs mapping. Annexin V-APC/PI staining (Ebiosciences, USA) or was performed according to manufacturer’s instructions.

**DNasel Hypersensitivity Site Mapping**

Prior to DNasel digestion, apoptotic cells were removed using the Dead Cell Removal Kit (Mitenyi Biotech, UK) as per manufacturer’s instructions. 3x 10^7 Kasumi-1 cells were suspended in 1 mL DNase I buffer (0.3M sucrose, 60 mM KCl, 15 mM NaCl, 5 mM MgCl2, 10 mM Tris pH7.4). Digestion on 4.5x10^6 cells was performed with DNase I (Worthington, DPPF grade) at 80 units/ml in DNase I buffer with 0.4% NP-40 and 2 mM CaCl2 at 22°C for 3 minutes. The reaction was stopped with cell lysis buffer (0.3M NaAcetate, 10mM EDTA pH 7.4, 1% SDS) with 1mg/ml Proteinase K and incubated at 45°C overnight. The digested DNase I material was treated with RNase A (Sigma Aldrich, Germany) at a final concentration of 100 µg/ml at 37°C for 1 hr. Genomic DNA was extracted using phenol/chloroform method: an equal volume of phenol was added to the reaction and placed on a rotator wheel for 45 minutes. This was centrifuged for 5 minutes at 16000 x g at room temperature. The top layer was transferred to a new tube and the process was repeated sequentially with phenol/chloroform and chloroform. After purification by chloroform extraction, genomic DNA was precipitated with ethanol. This was pelleted by centrifugation for 5 minutes, at 16000 x g at 4°C. The pellet was resuspended with 70% ethanol and centrifugation for 5 minutes, at 16000 x g at 4°C. The pellet was air-dried and dissolved by Tris-EDTA (40 mM Tris Acetate 1 mM EDTA). DNaseI Hypersensitivity Site Mapping

**DHSs mapping. Annexin V-APC/PI staining (Ebiosciences, USA) or was performed according to manufacturer’s instructions.

**Library Production of DNase I Material for High Throughput Sequencing**

After size selection, a library was prepared using KAPA Hyper Prep Kit sample preparation kit (Kapa Biosystems, USA) as per manufacturer’s protocol. After PCR a final size selection step was performed by running the library on 2% TAE gel, followed by excision of 190-250 bp sized gel fragment. The library was purified from the gel using a MinElute gel extraction kit (QIAGEN, USA) as per manufacturer’s instructions and validated by qPCR. Following this, the size selected sample was validated again by RT-PCR, this time using shorter amplicons to enable detection of the shorter fragments enriched by the size selection process.

**ChIP-qPCR and ChIP-Seq Library Preparation**

**Double Cross-Linking**

A double cross-linking technique was used to optimize the efficiency of transcription factor chromatin immunoprecipitation (ChIP). 2x10^7 cells were washed thrice in PBS. Di(N-succinimidyl) glutarate (DSG) (Sigma-Aldrich, Germany) at 850 µg/ml was added to...
2 × 10^7 cells per ml and were incubated for forty-five minutes. Cells were washed four times and fixed with 1% formaldehyde (Pierce, Thermos Scientific, USA) for ten minutes. Glycine to produce a final concentration of 100 mM was added to stop the reaction. The pellet was washed again with PBS. Buffer A (HEPES pH 7.9 10 mM, EDTA 10 mM, EGTA 0.5 mM, Triton x100 0.25%, complete mini protease inhibitor cocktail (PIC) 1x (Sigma-Aldrich, Germany) was added for 10 mins at 4°C and removed by centrifugation at 500 g for 5 minutes. This was repeated with buffer B (HEPES pH 7.9 10 mM, EDTA 1 mM, EGTA 0.5 mM, Triton x100 0.01%, PIC 1x). The residual nuclei were then spun down at 16000 g at 4°C for 5 minutes and aliquoted at 2 × 10^7 cells for 4 immunoprecipitations.

**Chromatin Immunoprecipitation (ChIP)**

Each aliquot of 2 × 10^7 cells was re-suspended in 600 μL of sonication buffer (Tris-HCL pH 8.25 mM, NaCl 150 mM, EDTA 2 mM, Triton 100X 1%, SDS 0.25%, Protease inhibitor cocktail (PIC) 1x). 300 μL of nuclei in sonication buffer was placed in each polystyrene tube and sonicated at 75% amplitude, 26 cycles: 30 s on and 30 s off per cycle (Q800, Active Motif, USA). Subsequently, 1.2 ml of dilution buffer (Tris-HCL pH 8.25 mM, NaCl 150 mM, EDTA 2 mM, Triton 100X 1%, glycerol 7.5%, PIC 1x) was added to the pooled post sonication material. This was divided equally between four immunoprecipitations (with 5% of input taken for validation). 20 μL protein G beads (Diagenode, Belgium) were washed twice with 500 μL of 50 mM citrate phosphate buffer and once with 100 mM sodium phosphate. 4 μg antibody ETO (Santa Cruz) or 4 μg antibody AML1-ETO (15310197, Diagenode), or RUNX1 (Ab23980, Abcam) or 4 μg antibody C/EBPα (A2814, Santa Cruz) or 2 μg antibody LBD1 (96799, Abcam) or 2 μg antibody LMO2 (AF2726, R&D) or 2 μg antibody CTTF (70303, Abcam) or 2 μg JUND (sc74, Santa Cruz) was added to 10 μL 100 mM sodium phosphate, 0.5% BSA and incubated with protein G beads at 4°C for 1 hour. Chromatin was then added to the protein G beads with antibody and returned to 4°C for 4 hours. Unbound chromatin was separated from the beads by magnet and the attached beads were washed by buffer 1 (Tris HCL 20 mM, NaCl 150 mM, EDTA 2 mM, Triton x100 1%, SDS 0.1%), twice with buffer 2 (Tris HCL 20 mM, NaCl 500 mM, EDTA 2 mM, Triton x100 1%, SDS 0.1%), LiCl buffer (Tris HCL 10 mM, LiCl 250 mM, EDTA 1 mM, NP40 0.5%, sodium deoxycholate 0.5%) and finally twice with wash buffer 4 (Tris HCL pH 8, 10 mM NaCl, 1% EDTA 1mM). The column was eluted twice with 50 μL buffer (NaHCO3 100 mM and SDS 1%) and the eluant containing the chromatin was pooled. Crosslinks were reversed by incubating the samples at 65°C overnight in 500 mM NaCl, 500 μg/mL proteinase K. DNA was purified by Ampure beads (Beckman Coulter, USA), as above, with the DNA eluted with 10 μL water. Validation of the ChIP was performed by qPCR using a standard curve of genomic DNA from untreated Kasumi-1 cells (10ng/μl followed by serial 1:5 dilutions). The input material was diluted 1:5 with water. Primers used in this project are listed in Table S2. Validation was analyzed as a ratio of the qPCR signal from the ChIP material over the input.

**Library Production of ChIP Material for High Throughput Sequencing**

Libraries for high throughput sequencing were prepared using the Tru-seq DNA sample preparation kit (Illumina, USA) or Kapa HyperPrep kit (Kapa Biosystems, USA), as per manufacturer’s protocol. 18 cycles of PCR was performed and 200-350bp fragments were size selected by running the samples in an agarose gel. Libraries were purified from the gel using a MinElute Gel extraction kit (QiAGEN, USA). Libraries were validated by qPCR, with an analysis of the ChIP signal of a positive control region (e.g., PU.1 3H enhancer) over a negative control region (e.g., IVL enhancer) over a negative control region (e.g., IVL). Finally, libraries were quantified by Kapa library quantification kit (Kapa Biosystems, USA) and run in a pool of four indexed libraries in one lane of a HiSeq 2500 (Illumina, USA) or 12 indexed libraries in one lane of a NextSeq 500 (Illumina, USA) using 50 cycle single-end reads.

**Circularized Chromosome Conformation Capture (4C-seq)**

4C analysis was performed exactly as described in Gröschel et al. (2014). 1 × 10^7 Kasumi-1 cells, transfected with mismatch siRNA (siMM) or siRNA specific to siRUNX1-ETO (siRNA), were fixed with 2% formaldehyde and incubated for 10 minutes at room temperature. 1.425 mL of 1M glycine was added to quench the cross-linking reaction. Fixed cells were immediately centrifuged for 8 minutes. Unbound chromatin was separated from the beads by magnet and the attached beads were washed by buffer 1 (Tris HCL 20 mM, NaCl 150 mM, EDTA 2 mM, Triton x100 1%, SDS 0.1%), Licol buffer (Tris HCL 10 mM, LiCl 250 mM, EDTA 1 mM, NP40 0.5%, sodium deoxycholate 0.5%) and finally twice with wash buffer 4 (Tris HCL pH 8, 10 mM NaCl, 1% EDTA 1mM). The column was eluted twice with 50 μL buffer (NaHCO3 100 mM and SDS 1%) and the eluant containing the chromatin was pooled. Crosslinks were reversed by incubating the samples at 65°C overnight in 500 mM NaCl, 500 μg/mL proteinase K. DNA was purified by Ampure beads (Beckman Coulter, USA), as above, with the DNA eluted with 10 μL water. Validation of the ChIP was performed by qPCR using a standard curve of genomic DNA from untreated Kasumi-1 cells (10ng/μl followed by serial 1:5 dilutions). The input material was diluted 1:5 with water. Primers used in this project are listed in Table S2. Validation was analyzed as a ratio of the qPCR signal from the ChIP material over the input.

**Library Production of ChIP Material for High Throughput Sequencing**

Libraries for high throughput sequencing were prepared using the Tru-seq DNA sample preparation kit (Illumina, USA) or Kapa HyperPrep kit (Kapa Biosystems, USA), as per manufacturer’s protocol. 18 cycles of PCR was performed and 200-350bp fragments were size selected by running the samples in an agarose gel. Libraries were purified from the gel using a MinElute Gel extraction kit (QiAGEN, USA). Libraries were validated by qPCR, with an analysis of the ChIP signal of a positive control region (e.g., PU.1 3H enhancer) over a negative control region (e.g., IVL). Finally, libraries were quantified by Kapa library quantification kit (Kapa Biosystems, USA) and run in a pool of four indexed libraries in one lane of a HiSeq 2500 (Illumina, USA) or 12 indexed libraries in one lane of a NextSeq 500 (Illumina, USA) using 50 cycle single-end reads.
The water phase was transferred to a new 50 mL tube to which 7 mL of milli-Q H2O, 7 mL of ethanol was added. Samples were placed at −80 °C overnight. The next day samples were centrifuged at 4 °C for 30 min, 9000 x g. The supernatant was removed and 10 mL of cold 70% ethanol was added. Samples were centrifuged again for 15 min, 9000 x g at 4 °C. The supernatant was removed and the pellet left to dry at room temperature. The pellet was dissolved in 150 μl 10 mM Tris pH 7.5. Each sample was transferred to a 1.7 mL tube, 50 μl 10X restriction buffer and 50 units of the restriction enzyme Csp6I (Fermentas # ER0211) was added and the volume made up to 500 μl with milli-Q H2O. After an overnight incubation, 500 RPM shaking, at 37 °C, a 5 μl aliquot of the sample was taken. This ‘digestion control’ was run on a 0.6% agarose gel. The enzyme was inactivated as previously describe and the samples transferred to a 50 mL tube. 1.4 mL of 10X ligation buffer and 20 μl of ligase (100 U) (Roche Catalog # 10799009001) was added, then the reaction made up to 14ml with milli-Q H2O. After an overnight ligation at 16 °C, 1.4mL 2M NaAC pH 5.6, 14μl glycogen and 35ml of 100% ethanol were added. Samples were stored at −80 °C overnight. The next day samples were centrifuged at 4 °C for 45 minutes, at 3750 RPM. The supernatant was removed and 15 mL of cold 70% ethanol was added. The samples were then centrifuged again for 15 min, at 20 °C and 3750 RPM. Again, the supernatant was removed and the pellet then left to dry at room temperature. Once dry the pellet was dissolved in 150 μl 10 mM Tris pH 7.5 at 37 °C. Samples were then purified using a QIAquick PCR purification kit, according to the manufacturer’s protocol. Samples were eluted in 50 μl 10 mM Tris pH 7.5 and pool samples. DNA concentration of each 4C template was determined via analysis with a NanoDrop 2000 (Thermo Scientific). Restriction fragments greater than 350 bp and within 2kb of the target genomic region were selected as viewpoint fragments, dependent on the ability to design specific primers. A 5’ Illumina adaptor sequence was added so the inverse-PCR products did not need further processing prior to sequencing. Reading primers were designed as close to the primary restriction site as possible, to reduce reads from the known viewpoint sequence. Non-reading primers were designed to regions less than 120kb from the secondary restriction site. 200 ng of 4C template was used per PCR reaction. For each viewpoint and template, 16 PCR reactions were conducted using an Expand Long Template system (ROCHE # 11681834001) (see Table S2 for primer sequences). The pooled PCR products (total volume 800 μl) were then purified using the High Pure PCR Product Purification Kit (Roche cat. no. 11732676001), to remove any adaptor containing primers (< 120 bp). Samples were centrifuged to pellet any beads that escaped the column. The supernatant was then taken, and the concentration and purity of this 4C template was assessed by a NanoDrop 2000 (Thermo Scientific) (260/280 ratio >2 and 260/230 ratio >1.8 was required). The libraries were then visualized on a 1.5% agarose gel. All 4 of the 4C libraries were pooled, and then multiplexed sequencing was performed on the HiSeq 2500 platform. Individual fragment counts were calculated for every 1kb bin. A median was calculated, with a 3kb sliding window, and data from both biological replicates was merged. The R package DESeq2 was used to calculate the log2 fold change (RUNX1/ETO knockdown versus control) at the local genomic coordinates. Viewpoint specific 4C-seq PCR primers used in this project are listed in Table S2.

**Hi-C Library Generation**

Hi-C library generation was carried out as described previously (Mifsud et al., 2015; Lieberman-Aiden et al., 2009), with the following modifications which were detailed with the following modifications. After fixation in 2% formaldehyde for 5 min, 50 million Kasumi-1 cells were homogenized in 10 mL of ice-cold lysis buffer ten times on ice with a tight pestle, incubated on ice for 15 min and then homogenized a further ten times. After overnight digestion with HindIII at 37 °C, DNA ends were labeled with biotin-14–dATP (Life Technologies) in a Klenow end-filling reaction. After phenol-chloroform purification, the DNA concentration was measured using Quant-iT PicoGreen (Life Technologies), and 40 μg of DNA was sheared to an average size of 400 bp, using the manufacturer’s instructions (Covaris). The sheared DNA was end repaired, adenine tailed, and double size selected using AMPure XP beads to isolate DNA ranging from 250 to 550 bp in size. Ligation fragments marked by biotin were immobilized using MyOne Streptavidin C1 DynaBeads (Invitrogen) and ligated to paired-end adaptors (Illumina). The immobilized Hi-C libraries were amplified using PE PCR 1.0 and PE PCR 2.0 primers (Illumina) with 8 PCR amplification cycles.

**Biotinylated RNA Bait Library Design**

Biotinylated 120-mer RNA baits were designed to target both ends of HindIII restriction fragments that overlap Ensembl promoters of protein-coding, noncoding, antisense, snRNA, miRNA and snoRNA transcripts. A target sequence was valid if its GC content ranged between 25 and 65% and the sequence contained no more than two consecutive Ns and was within 330 bp of the HindIII restriction fragment terminus.

**Promoter Capture Hi-C**

Capture HiC of promoters was carried out with SureSelect target enrichment, using the custom-designed biotinylated RNA bait library and custom paired-end blockers according to the manufacturer’s instructions (Agilent Technologies). After library enrichment, a post-capture PCR amplification step was carried out using PE PCR 1.0 and PE PCR 2.0 primers with 4 PCR amplification cycles. CHi-C libraries were sequenced on the Illumina HiSeq 1000 platform.

**Western Blotting**

Protein extracts were prepared using a co-immunoprecipitation kit (Active Motif, USA). Protein extracts were quantified using Bradford protein reagent (Bio-Rad, USA) and 595nM absorbance quantified by spectrophotometry. Absolute concentrations were determined using a standard curve from a known concentration of BSA (Pierce, USA). Protein extracts was run on an acrylamide gel and transferred to nitrocellulose membrane. The antibodies used in this project are listed in Table S2. Enhanced chemiluminescence by SuperSignal PICO (Thermos Scientific, USA) was used to develop the membrane. Chemiluminescence was detected using either developer or Chemidoc XRS system (BioRad, USA).
Antibody Staining for Flow Cytometry

15x10⁴ were centrifuged at 300xg and washed with MACS buffer. The cell pellet was re-suspended in 50 μl MACS buffer and 2 μl of antibody was added and incubated for 15 minutes at 4°C in the dark. After incubation, the cells was washed once with MACS buffer before resuspension in 300 μl MACS buffer and analyzed on Cyan ADP (Beckman Coulter, USA). Data were analyzed on Summit 4.3 (Beckman Coulter, USA). Antibodies used in this project are listed below. CD34 Monoclonal Antibody (4H11), PE, eBioscience Cat #12-0349-42; CD117 (c-Kit) Monoclonal Antibody (104D2), FITC, eBioscience Cat #11-1178-42

QUANTIFICATION AND STATISTICAL ANALYSIS

DNasel Sequencing Data Analysis

DNasel sequences from all experiments were mapped onto the reference human genome (hg38), with Bowtie version 2.3.1 (Langmead and Salzberg, 2012) using default parameters. Low quality reads were trimmed using Trimmomatic-0.36 (Bolger et al., 2014) and quality control (QC) statistics were obtained using FastQC tools. Unique aligned reads were used for downstream analysis. DNasel Hypersensitive Sites (DHSs) were called with MACS2 using callpeak function (nomodel, call-summits and q = 0.005 parameters) (Zhang et al., 2008). Clustering of DNasel-seq samples was carried out using the merged DHSs. The number of reads that mapped to these DHSs was counted in a 400bp window centered on the DHS summit, and subsequently normalized to total sample size using DEseq2 (Love et al., 2014). Pearson correlation coefficients were then calculated for each pair of samples using the log2 of the normalized read counts, and then hierarchically clustered using Euclidean distance and complete linkage clustering of the correlation matrix in R.

ChiP Sequencing Data Analysis

ChiP sequencing reads were aligned to the human genome version hg38 with Bowtie version 2.3.1 (Langmead and Salzberg, 2012). Reads that mapped uniquely to the genome were retained and duplicated reads were removed using the MarkDuplicates function in Picard tools (http://broadinstitute.github.io/picard/). Peaks were identified with MACS version 1.4.2 (Zhang et al., 2008) and DFilter software (Kumar et al., 2013) with recommended parameters (-bs = 100 -ks = 50 –refine). Peaks common to both peak calling methods were considered for further analysis.

Average Tag Density Profile and Heatmap

The tag density and average profiles for Figures S1D and S2E were generated by calculating the tag density normalized as coverage per million within 400bp windows of the DNasel peak summit. The read counts for all union peaks were computed. Coverages were calculated for all union peaks and ranked by log2 fold change. Heatmap images were generated via Java TreeView (http://jtreeview.sourceforge.net/) and average profiles were plotted using R.

RNA-Seq Data Analysis

RNA-seq reads downloaded from GSE54478 were aligned to the human genome hg38 build with STAR (Dobin et al., 2013) using ENCODE recommend parameters. Separate density profiles for the positive and negative strand were generated using bedtools. Cufflinks (Trapnell et al., 2013) was used to calculate the expression values as Fragments Per Kilobase per Million aligned reads (FPKM) from the aligned RNA-seq data and differentially expressed genes were extracted using the limma R package (Ritchie et al., 2015). All genes with p value ≤ 0.01 were considered with at least 2-fold changes between before and after RUNX1-ETO knock down.

Promoter Capture HiC Data Analysis

The Chi-C paired-end sequencing reads were aligned to the human genome hg38 build using HiCUP pipeline (Wingett et al., 2015). The raw sequencing reads were initially separated and mapped against the reference genome. The reads were then filtered for experimental artifacts and duplicate reads, and then re-paired. Statistically significant interactions were called using GOTHIC package (Mifsud et al., 2017) and HOMER software (Heinz et al., 2010). This uses a cumulative binomial test to detect interactions between distal genomic loci that have significantly more reads than expected by chance, by using a background model of random interactions. This analysis assigns each interaction with a p value, which represents its significance. Differential interactions between control and after RUNX1-ETO knock-down were determined with HOMER (Heinz et al., 2010), p value cutoff with at least 0.01 was considered.

4C-Seq Data Analysis

4C-seq data analysis was performed using 4Cseqpipe, as described in van de Werken et al. (2012). Sequence extraction, mapping, normalization, and plotting of cis-contact profiles around PU.1 promoter and enhancer viewpoints were done using packages called by 4Cseqpipe tools. Custom restriction site tracks were built using the -build_re_db option of 4Cseqpipe for the hg19 human genomic version with HindIII as first and second restriction cutters. 4C reads were mapped to the custom hg19 tracks with the in-built 4Cseqpipe mapper. Near-cis domainograms were generated for PU.1 viewpoints using the median stat type and plotting the 20th and 80th quantile of the distribution of normalized contact intensities for 5kb sliding windows.
Motif Identification and Clustering
De novo motif analysis was performed on peaks using HOMER (Heinz et al., 2010). The annotatePeaks function in HOMER was used to find occurrences of motifs in peaks. In this case we used known motif position weight matrices (PWM) from HOMER database.

Motif clustering: Digital footprinting of DNaseI high-depth sequencing data was performed using the Wellington algorithm (Piper et al., 2013) with FDR = 0.01. For the heatmap that shows hierarchical clustering of motif occurrences within specific and common footprints (Figure 3D). The distance between the centers of each motif pairs was calculated and the motif frequency was counted if the first motif was within 50bps distance from the second motif. Z-scores were calculated from the mean and standard deviation of motif frequencies observed in random sets using bootstrapping analysis. For bootstrapping, peak sets with a population equal to that of the footprinted peaks were randomly obtained from the union of DNase-Seq footprints.

DATA AND CODE AVAILABILITY
The CHIP-seq data, DNaseI-seq data, and RNA-seq data generated during this study are available at GEO: GSE121282. The Capture HiC data generated during this study are available at GEO: GSE117108. The published article includes reprogramming ATAC-Seq (Corces et al., 2016) GEO: GSE75384 analyzed during this study. The published article includes Published ChIP-Seq (Ptasinska et al., 2014) GEO: GSE60131 analyzed during this study.
Supplemental Information

RUNX1-ETO Depletion in t(8;21) AML Leads to C/EBPα- and AP-1-Mediated Alterations in Enhancer-Promoter Interaction

Anetta Ptasinska, Anna Pickin, Salam A. Assi, Paulynn Suyin Chin, Luke Ames, Roberto Avellino, Stefan Gröschel, Ruud Delwel, Peter N. Cockerill, Cameron S. Osborne, and Constanze Bonifer
Supplemental Figure 1 (refers to Figure 1)

RUNX1-ETO depletion changes local cis-regulatory element interactions

**A**: The number of high confidence reads associated within open chromatin regions for two independent Capture HiC experiments from control (siMM) and RUNX1-ETO depleted (siRE) cells and.

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**Figure 1 supplementary**

| Dataset     | Total reads | Filtered reads | # interactions | p-value (siRE vs. siMM) |
|-------------|-------------|----------------|----------------|-------------------------|
| siMM rep1   | 85,077,086  | 54,416,195     | 30,862         |                         |
| siMM rep2   | 156,743,091 | 66,187,561     | 49,755         |                         |
| siMM combined | 237,821,176 | 119,593,756    | 70,617         |                         |
| siRE rep1   | 307,887,188 | 21,172,748     | 20,710         |                         |
| siRE rep2   | 65,019,682  | 19,932,170     | 40,844         |                         |
| siRE combined | 372,906,870 | 41,104,918     | 60,551         |                         |

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**Figure 1**

**A**

| siMM rep1 | siMM rep2 | 71% overlap | p-value < 0.01 |
|-----------|-----------|-------------|---------------|
| siRE rep1 | siRE rep2 | 67% overlap | p-value < 0.01 |

**B**

**C**

**D**

**E**

**F**

**G**

**H**

**I**

**J**

**K**

**L**

**M**

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**Supplemental Figure 1** (refers to Figure 1)

**RUNX1-ETO depletion changes local cis-regulatory element interactions**

**A**: The number of high confidence reads associated within open chromatin regions for two independent Capture HiC experiments from control (siMM) and RUNX1-ETO depleted (siRE) cells and.
B: 2-way Venn diagram showing the overlap of interactions between Capture HiC replicates.

C: Smooth scatter plot showing the correlation between capture HiC replicates based on first principle component analysis.

D: Contact matrix across the whole genome. Each pixel represents a 10 Mb section of the genome. Colour intensity represents the interaction frequency. Left hand plots show the interaction matrices generated with data from Kasumi-1 cells transfected with siMM for four days (biological replicate 1 and 2). Right hand plots show the interaction matrices generated with data from Kasumi-1 cells transfected with siRE for four days (biological replicate 1 and 2). Interaction data was generated by Capture HiC.

E: Experimental strategy of RUNX1-ETO knockdown in Kasumi-1 cells. Transfection with either control siRNA or RUNX1-ETO siRNA on days 0, 2, 4, 6 or 8 in Kasumi-1 cells. Cells were collected for RNA, chromatin, DNase I or flow cytometry on designated days.

F: Left panel: Time course of DHS development after 2, 4 and 10 days of RUNX1-ETO depletion (see scheme in Figure S1E). Normalised tag counts (high: light blue, low, dark blue) are ranked alongside those of day 10 knock-down (KD) and control-specific (bottom), common and knock-down specific DHS are indicated on the left. Plotted alongside the same genomic coordinates are the distributions of AP1, C/EBP, ETS, RUNX1, E-box and CTCF motifs enriched in Kasumi-1 cells aligned to the summit of the day 10 DHSs (middle panel). The outermost right panels show ATAC-seq reads from normal hematopietic precursor cells (HSC, MPP, LMPP, CMP, GMP o or monocytes (Mono) from the corresponding interacting region plotted along-side.

G: Heatmap depicting genes differentially expressed during a time-course of 2, 4 and 10 days on RUNX1-ETO depletion ranked alongside up-and down regulated genes at day 10 of depletion.

H: RUNX1-ETO siRNA treatment in Kasumi-1 cells results in reduction in CD34 surface expression. Kasumi-1 cells after 2, 4 and 10 days of either RUNX1-ETO or control siRNA transfection were stained with CD34-PE and CD117 FITC. Representative flow cytometry plot of 3 independent experiments

I: Percentage of CD34+CD117+ cells. Mean of 3 independent experiments and error bars represent S.E.M. * denotes p<0.05 by paired t-test.

J: Principal component analysis with union of DHSs showing that the depletion of RUNX1-ETO leads to changes in the DHS profile of Kasumi-1 cells during 2, 4 and 10 days of RUNX1-ETO depletion.
K: Hierarchical clustering of Jaccard index/coefficient showing the similarity / differences in the footprint patterns.

L: Western blot analyses of protein extracts from: t(8;21) Kasumi-1 cells (transfected with control siRNA or RUNX1-ETO siRNA). Western blots were probed with either an anti-ETO, an anti-RUNX1 (N-terminal epitope antibody) and anti-C/EBPα, anti-LDB1, anti-LMO2, anti-CTCF and anti-JUND antibodies. Anti-GAPDH antibody was used as a loading control. Representative western blot of 3 independent experiments

M: Fold-change of gene expression during the time course of RUNX1-ETO knock-down for selected genes
Supplemental Figure 2 (refers to Figure 2)

**LDB1** participates in differential promoter-enhancer interactions after **RUNX1-ETO** depletion

**A**: DHS shared between siMM and siRE cells do not show changes in interactions. The heatmap represents the correlation of normalized interaction ratios across chr3 at 5 kb.
resolution in DHS peaks shared between control and RUNX1-ETO depleted cells, the left panel shows the interaction heatmap for control and the right panel for knock-down cells. Each pixel represents a 5 kb section of the genome. Positive correlation is shown as red, negative correlation as blue.

B: UCSC genome browser screenshot of ChIP-seq and DHS data aligned with digital footprints at the IL17RA locus within a DHS shared between siMM and siRE samples. It also shows the binding pattern of RUNX1-ETO, JUND, C/EBPα, LDB1 and RUNX1 in Kasumi-1 cells as determined by ChIP. Footprint probabilities as calculated by Wellington (Piper et al., 2013) are indicated as gray columns below the lines. The bottom indicates the location of occupied ETS, and C/EBP motifs

C: Percentage of ChIP-seq high confidence peaks (Ptasinska et al., 2014) which show factor occupancy in digital footprint assays.

D: Validation of Chi-C data. The SPI1 locus does not show any differences in interactions before and after RUNX1-ETO depletion. Validation of Chi-C data and analysis of reproducibility. Local 4C contact profile with a viewpoint from the SPI1 (PU.1) upstream regulatory element (URE) (upper two panels) and its promoter (lower two panels), using chromatin from Kasumi-1 cells transfected with control siRNA (siMM) RUNX1/ETO specific siRNA (siRE). In the top panel (main trend), the contact intensity (black line) is calculated using a running median analysis of normalized read counts with a 3 kb sliding window. The 20th and 80th percentile are visualized as a grey trend graph. In the bottom panel, contact intensities are computed using linearly increasing sliding windows (scaled 2–50 kb) and displayed as a color-coded heat map of positive 4C signal (maximum interaction set to 1). Local colour changes are log-scaled to indicate changes of statistical enrichment of captured sequences, corresponding to the enhancer-promoter interaction. The results presented here are an average of two biological replicates.

E: The SPI1 locus does not show any differences in interactions before and after RUNX1-ETO depletion. UCSC browser screenshot depicting interactions between the SPI1 promoter and surrounding DHS. Interactions are depicted as bars above the distance-dependent threshold level of statistical significance (Chi-C p-Value) together with the indicated ChIP and DHS data before and after RUNX1-ETO knock-down.

F: Graph showing the genomic distribution of LDB1 binding sites before and after RUNX1-ETO knock-down.

G: LDB1 ChIP-seq profiles ranked from top to bottom in order of decreasing relative DNA sequence tag count. Aligned to these coordinates are indicated enriched motifs and ChIP-
seq data. Column 1-2 represent the LDB-1 peaks from siMM or cells depleted of RUNX1-ETO for 2 days. Alongside, columns show enriched motifs for the TFs AP-1, C/EBP, ETS, RUNX1 and E-box in Kasumi-1 cells aligned to the summit of the LDB1 peaks. Then next columns show a binary representation of Capture HiC differential interactions aligned to the union of LDB1 peaks. Alongside, C/EBP, JUND, CTCF, RUNX1-ETO, LMO2, PU.1 and RUNX1 ChIP reads from Kasumi-1 cells with or without RUNX1-ETO depletion are plotted as indicated.

**H:** Results of de novo motif search of LDB1 specific peaks before and after RUNX1-ETO knock-down
Figure S3

A

B

C

D

E

F

G

H

I
Supplemental Figure 3 (refers to Figure 3)

Colocalization analyses highlight different combinatorial TF binding patterns in control and RUNX1-ETO depleted cells

A: Western blot indicating RUNX1-ETO and LDB1 protein expression levels in single- and double knock-down cells as indicated. An antibody against GAPDH was used as control. The bar plot showing quantification of relative LDB1 protein levels in single- and double knock-down as indicated. The graph on the right shows mean of 2 independent experiment, n=2

B: Knock-down of LDB1 leads to cell death. Annexin V and propidium iodide (PI) staining followed by flow cytometry analysis was used to measure cell viability at 10 days after treatment with siRNA. The percentage represents the sum of the proportion of cells positive for Annexin V (top panel) or Annexin V and PI (bottom panel). The graph shows the mean of 3 independent experiment with SD. * denotes p<0.05 by paired t-test

C: ChiP experiment showing that LDB1 depletion does not prevent RUNX1-ETO binding to distinct classes of RUNX1-ETO binding sites as indicated (n=2, with 2 independent experiments plotted individually)

D: LDB1 depletion does not alter the response to RUNX1-ETO knock-down. mRNA levels of the indicated genes 10 days after electroporation with the indicated siRNAs. The graph shows the mean of 3 independent experiment with SD

E: Bar plots show the percentage of Chip-peak overlap of other TFs with with RUNX1 peaks. The left plot shows the percentage of RUNX1 peaks that are shared with ChIP-seq peaks for other factors. The right plot shows percentage of ChIP-seq peaks that shared with RUNX1 peaks.

F, G: Bar plots illustrated the distribution of distances between RUNX1 ChIP-Seq peaks (before (left) and after (right) R/E KD) and LDB1 ChIP-Seq peaks peaks (E), PU.1 ChIP-Seq peaks (F) and LMO2 ChIP-Seq peaks (G).

I: C/EBP and AP-1 motifs do not co-localize in common DHS sites. Bootstrapping analysis of footprinted motifs for DNAseq common DHSs in Kasumi-1 cells. The heatmap shows the significance of co-localizing footprinted motifs clustering together as compared to sampling by chance.
Figure S4

A

Non-TF genes up-regulated by R/E depletion → Link to TF families via footprints → Gene regulatory network

B

Non-TF genes

TF encoding genes

Node and edge attributes

| Node colour | FC(siRE/siMM) |
|-------------|--------------|
| Gene expression fold change (FC) |

| Border colour | RUNX1/ETO target |
|---------------|-----------------|
| Not a R/E target |

| Node shape | DNA binding factor |
|------------|--------------------|
| non DNA binding factor |

| Edge colour | count |
|-------------|-------|
| 1 → 0.5 → 1 → 3 → 4 → 8 → 15 |

count >12
Supplemental Figure 4 (refers to Figure 4)

Connections between factors and genes for genes at least two-fold up-regulated by RUNX1-ETO depletion

(A) Data analysis strategy. (B) Gene regulatory network of all up-regulated (red) non-transcription factor (effector) genes after 10 days of RUNX1-ETO knock-down (upper rows) connected to genes encoding transcription factor families (lower rows) as determined by digital footprinting and CHi-C. Arrows going outwards can come from any TF family within a group, incoming arrows are specific for each gene. Bottom panel: node and edge attributes.
**Table S1.** Curated position weight matrices used for motifs shared between transcription factor families as described in (Assi et al., 2018). Related to Figure 2, 3 and 4.

| motif    | logo         | motif    | logo         | motif    | logo         |
|----------|--------------|----------|--------------|----------|--------------|
| AHR      | TCGTG        | HSF1     | TCTCAAGAAATTC TCA | PRDM1    | AAGAGGTAAAGT |
| AP-1     | TGAATCAGTATG | IKZF     | TTCCCAAGGG     | PU.1     | AGGCAGGATG   |
| AR       | AGAACATATGCTG| IRF      | GAAATGAAACT    | RAR      | AGTCAGGCACA  |
| BCL6     | TTTTCAGGGATAA| IRX      | TACATGCTTA     | RFX      | TCTGCAGGACA  |
| CAMTA    | AGACGCCTGCTA | KLF      | TGCCGCCGCCG    | RUNX     | KTGTGGTTT    |
| C/EBP    | ATTCATCAAC   | LEF1     | ATCTCAAAGG     | RXR      | TGCCAGGCA    |
| CREB/ATF | TACTACGTCA   | MAF      | GCTGATCGCA     | SMAD     | TCTCTTCGG    |
| CTCF     | TGACACGCTAGA | MYC/MAX  | ACACGTGCTGA    | SNAI     | CACCTGGCA    |
| CUT      | CAATGCTAAT   | MEF2     | TATAAAATCAGG   | SOX      | CCTTTGGTG    |
| E2F      | TTTTCAGGAAA  | MEIS     | ATCTCAACTA     | SP1      | GGGGGGGGCCC  |
| EGR      | TGAGTGGGCTTA | MYB      | TGCCAGTTG      | SRF      | CCAATATAGGA  |
| ESRRA    | TCAAGCTGCA   | NF1      | ATCTCTTACA     | ST18     | AAAAAAGTTT   |
| ETS      | ACGGGAAGTT   | NFAT     | AGTGGAATAGG    | STAT3    | TTTCCGGGAA   |
| FOX      | GTTTCATCATA  | NFE2     | TCTGAGTCAG     | STAT5    | TTTCAGGAAA   |
| GATA     | CAGATAGCAT   | NFIL3    | GGGATAATCGG    | STAT6    | TTCCCTAGAA   |
| GFI1     | AAATCAGTGCA  | NF-kB    | GGGATAATCGG    | TAL1     | ACATCTGGA    |
| GLI      | CGGTTGTCGCA  | NFY      | CCAATATAGG     | TCF3     | ACACTAGTC    |
| HES      | GCACGTCGGGA  | NKX      | CACCTGGCCA     | TEAD     | GGGATATG     |
| HHEX     | TATAATATA    | NR       | ATCAAGCGCA     | TFCP2    | AACCCTTGTI   |
| HIC1     | TAATCCACCCCG | NRF1     | CTGCACTCCG     | TFDP1    | AGCCCCGGA    |
| HIF1A    | TACGTGCC     | OCT      | ATCCACAGATG    | TGIF     | TGACAGC      |
| HINFP    | TGCGTGCGC    | PKNOX1   | ATCTCAATCA     | XBP1     | CSGCAGTCA    |
|          |              | POU4F1   | ATATATATTA     |          |              |

**Supplemental Tables**
| Oligonucleotides       | Forward                | Reverse                                      |
|------------------------|------------------------|----------------------------------------------|
| RUNX1-ETO siRNA        | CCUCGAAAUUCGUACUGAG    | UCUCAUGACGAUUUUCGAGGUU                      |
| PU.1 14 3H (CHIP)      | AACAGGAACGCACAGTCGTA   | TGGTGCTTGCTGGTAAT                           |
| LAT2 (CHIP)            | AAACCCAGAACAACCCAGGC   | ATGAGGAAGGATGTGTGTCGGG                      |
| CTSG (CHIP)            | TCAGTTGCTGCTGCTGCTTC   | TTCTCAATCCCTGTCCCTTAC                      |
| NFE2 (CHIP)            | AATACCGGAGGCCCTTTCTTAG | ACCGAAAAGTGGAAAACAAAGG                      |
| TBP (CHIP)             | CTGGCGGAAAGTGACATTAACAA| GCCAGCGGAGGCAAGTTC                          |
| CH18 (CHIP)            | ACTCCCTTTTCATGCTTCTG   | AGGTCCCAGGACATCTCATT                        |
| MEF2 (CHIP)            | TTATGAGCTGAGCGTGCTGT  | ATCTCACAGGGTCTGGGCA                        |
| IVL (CHIP)             | GCCGTGCTTTGGAGTTCTTA   | CCTCTGCTGCTGCCACTT                         |
| IGFBP7 (CHIP)          | GTCAAGCATAAAGGACAAACCG | TGAATGCCACTGGGAG                           |
| GAPDH (cDNA)           | CCTGCGCAAGGTCACTCACT   | AGGGGCTACATCCAGTCTT                        |
| RUNX1/Eto (cDNA)       | TCAAACTACAGTGAGGGTC    | CAGCGTTAGATTGCGCTTCTTACA                   |
| CTSG (cDNA)            | TCCTGGTGGCGAGAAGACTTTA | GGTGTTTTCCGCTGCTGGAA                       |
| C/EBP (cDNA)           | GAGGGACCAGGAGTTATGACA  | AGACGCGCACATTCCACATT                       |
| CD34 (cDNA)            | CACTGGCTATTTTCGTGATGAA | CCACCGTTCTCCGGTGTAATT                      |
| NFE2 (cDNA)            | CCAAGGTGTGTTCCAAGAGGC  | GGAGCCGAGTCCAGAGAGA                       |
| ERG (cDNA)             | ATGGAGGAGAAGACATGCC    | ATAGCCTGGATCTGCTGC                       |
| Actin (short) (DNaseI) | GCAATGATCTGAGGGAGG     | AGCTGTCACATCCAGGGGT                       |
| TBP promoter (short)   | CTGGCGGAAAGTGACATTA    | CCGACCTCAGAACC                              |
| CH18 (short) (DNasel)  | AGGTCCCAGGACATCTCATT  | GTTCAATTTGTGGTTTGATT                      |
| Actin (long) (DNasel)  | GCAATGATCTGAGGGAGG     | GTGTCTTTCCCTGCTGAC                        |
| TBP promoter (long)    | CTGGCGGAAAGTGACATTA    | GCCAGCGAGAAGCGAAGT                        |
| CH18 (long) (DNasel) | ACTCCCTTTTATGTTTCTG | AGGTCCAGGACATATCCATT |
|----------------------|----------------------|----------------------|
| SPI1 promoter forward (4C-seq Primers) | AATGATACGGCGACCACC GAACACTCTTTCCCTACAC GACGCTCTTCCGATCTAGT GAGGACAGTGGCCAGATC | CAAGCAGAAGACGGCATA CGAAGATGCCCTGGGCTCGA |
| SPI1 URE forward (4C-seq Primers) | AATGATACGGCGACCACC GAACACTCTTTCCCTACAC GACGCTCTTCCGATCTTTG CCAGGGAAGCCAGATC | CAAGCAGAAGACGGCATA CGATTCACCAGGCACAGACTT |

**Table S2.** The list of PCR primers used for ChIP, gene expression, validating DNasel digestion before DNasel–Seq, viewpoint specific 4C-seq PCR primers. Related to STAR Methods.