THE UNIVERSITY of EDINBURGH

Edinburgh Research Explorer

A global analysis of low-complexity regions in the Trypanosoma brucei proteome reveals enrichment in the C-terminus of nucleic acid binding proteins providing potential targets of phosphorylation

OPEN ACCESS

Check for updates

RESEARCH ARTICLE

REVISED

A global analysis of low-complexity regions in the *Trypanosoma brucei* proteome reveals enrichment in the C-terminus of nucleic acid binding proteins providing potential targets of phosphorylation [version 2; peer review: 2 approved]

Mathieu Cayla (iD), Keith R. Matthews (iD), Alasdair C. Ivens (iD)

Centre for Immunity, Infection and Evolution, Institute for Immunology and Infection Research, School of Biological Sciences, University of Edinburgh, Edinburgh, Scotland, EH9 3JT, UK

Abstract

Background: Low-complexity regions (LCRs) on proteins have attracted increasing attention recently due to their role in the assembly of membraneless organelles or granules by liquid-liquid phase separation. Several examples of such granules have been shown to sequester RNA and proteins in an inactive state, providing an important mechanism for dynamic post-transcriptional gene regulation. In trypanosome parasites, post-transcriptional control overwhelmingly dominates gene regulation due to the organisation of their genome into polycistronic transcription units. The purpose of the current study was to generate a substantially more comprehensive genome-wide survey of LCRs on trypanosome proteins than currently available .

Methods: Using the Shannon's entropy method, provided in the R package 'entropy', we identified LCRs in the proteome of *Trypanosoma brucei*. Our analysis predicts LCRs and their positional enrichment in distinct protein cohorts and superimposes on this a range of post-translational modifications derived from available experimental datasets.

Results: We have identified 8162 LCRs present on 4914 proteins, representing 42% of the proteome, placing *Trypanosoma brucei* among the eukaryotes with the highest percentage of LCRs. Our results highlight the enrichment of LCRs in the C-terminal region of predicted nucleic acid binding proteins, these acting as favoured sites for potential phosphorylation. Phosphorylation represents 51% of the post-translational modifications present on LCRs compared to 16% on the rest of the proteome.

Conclusions: The post-translational modifications of LCRs, and in

Open Peer Review

Reviewer Status ✔ ✔

	Invited Reviewers	
	1	**2**
version 2 (revision) 18 Nov 2020	✔ report	
	↑	
version 1 21 Sep 2020	? report	✔ report

1. **Susanne Kramer**, Universität Würzburg, Würzburg, Germany

2. **Sebastian Hutchinson** (iD), Institut Pasteur, Paris, France

Any reports and responses or comments on the article can be found at the end of the article.

particular phosphorylation events, could contribute to post-transcriptional gene expression control and the dynamics of protein targeting to membraneless organelles in kinetoplastid parasites.

Keywords
Low-complexity regions (LCRs), proteome, phosphorylation, liquid-liquid phase separation, nucleic acid binding proteins, granules

Corresponding authors: Mathieu Cayla (mathieu.cayla@ed.ac.uk), Alasdair C. Ivens (Al.Ivens@ed.ac.uk)

How to cite this article: Cayla M, Matthews KR and Ivens AC. **A global analysis of low-complexity regions in the *Trypanosoma brucei* proteome reveals enrichment in the C-terminus of nucleic acid binding proteins providing potential targets of phosphorylation [version 2; peer review: 2 approved]** Wellcome Open Research 2020, **5**:219 https://doi.org/10.12688/wellcomeopenres.16286.2

First published: 21 Sep 2020, **5**:219 https://doi.org/10.12688/wellcomeopenres.16286.1

REVISED Amendments from Version 1

This new version of the text responds to the comments of the reviewers. It includes a discussion comparing results obtained with the entropy methodology to the previous method using the SEG algorithm (results included in supplement file 2). We have also included a new dataset of mRNA binding proteins[33] and analysed the presence of LCRs and PTMs. The results obtained confirm our observations (results included in supplement file 6). In addition, we confirmed the enrichment of phosphorylation events in LCRs, compared to other defined domains, even after normalisation by the frequency of representation of the amino acid on which it has been detected (results included in the new Figure 12). Finally, we updated the code and modified the Figure 6 and Figure 8 to respond to the reviewers' request.

Any further responses from the reviewers can be found at the end of the article

Introduction

Prion-like-domains are responsible for the self-aggregation of proteins into amyloid-fibres causing, for example, neurodegenerative diseases. These domains present lower amino-acid complexity than the surrounding background and are frequently enriched in polar amino acids such as asparagine and glutamine[1]. Contrasting with these fibres, low-complexity regions (LCRs) can also contribute to biological function, an example being in ribonucleotide binding proteins that assemble dynamic polymers in a hydrogel state, via liquid-liquid phase separation[2]. The ability of LCRs to influence the liquid-liquid phase separation of proteins, resulting in the formation of membraneless organelles or granules in different cellular compartments, creates a specialised local environment such as the nucleolus or for example P-bodies and stress granules. The latter are responsible for a local sequestration of RNA and proteins in an inactive state[3]. As a consequence, the analysis of LCRs has developed over the last two decades from a pathogenic curiosity to a new exciting field of research focused on regulatory gene expression operating at the post-transcriptional level.

One group of organisms that show a marked reliance on post-transcriptional regulation of gene expression is kinetoplastid parasites. These include the important tropical pathogens *Trypanosoma cruzi*, *Leishmania* spp and the experimentally tractable African trypanosome, *Trypanosoma brucei*. These organisms transcribe RNAs as part of polycistronic transcription units that are subsequently processed to mRNA. As a result, transcriptional regulation is not a significant contributor to differential gene expression. Rather, genes are regulated through mRNA stability and translation. Several protein factors have been identified that contribute to the stability of mRNAs and their relative translational competencies. When characterised cytologically, it has been observed that some mRNA regulators concentrate into discrete foci under conditions of cellular stress, or during life cycle development. The foci resemble nuclear periphery granules, pole granules, P-bodies and stress granules. Similar to other eukaryotes, these structures are compositionally enriched in nucleotide binding proteins and translation initiation factors[4].

By inference from what is known for other model eukaryotes, it is plausible that the aggregation into membraneless structures could be influenced by the presence and/or distribution of LCRs in the protein sequences themselves[5]. At present, information on predicted LCRs in the *T. brucei* proteome can be obtained from the TriTrypDB genome website as an implementation of the SEG algorithm, which does not account for amino acid usage across the proteome[6]. These available data were derived using a limited range of parameters, yielding a potentially sub-optimal output in terms of broader applicability or utility[7]. The goal of the current study was to generate a substantially more comprehensive LCR dataset for the encoded *T. brucei* proteome that would enable us to explore their potential association with distinct protein families or as targets of post-translational modifications. Our analysis provides an enhanced description of LCRs across the trypanosome proteome and highlights their enrichment in the C-terminal region of predicted nucleic acid binding proteins. Moreover, analysis of experimentally determined post-translational modifications on proteins suggests that the LCRs of RNA-binding proteins might be a preferential site of phosphorylation that could contribute to post-transcriptional gene expression control in kinetoplastid parasites.

Methods

LCR identification – entropy method

Protein sequences for *Trypanosoma brucei brucei* TREU927/4 were obtained from the TriTrypDB website in fasta format (release 46) (https://tritrypdb.org/common/downloads/Current_Release/TbruceiTREU927/).

All processing of the sequences was performed in the R/Bioconductor environment using BioStrings[8], entropy[9], dplyr[10], and bedr[11] packages.

Briefly, each protein sequence was processed as a series of overlapping windows, with each subsequent window starting one amino acid further towards the carboxy terminal. For each of the full-sized windows, amino acid entropy was calculated using the entropy.plugin() function[9]. The empirical cumulative distribution function (ecdf) distribution was calculated for all entropy values for the window size, and a threshold value at 0.5% determined. All amino acid sequence windows with entropy values below this threshold were deemed to be part of an LCR. Overlapping LCR regions within the same protein sequence were subsequently merged using the bedr R cran package[11].

This process was repeated for a series of amino acid window sizes (10, 20, 30, 40, 50, 60, 75, 100, 150). Once all 0.5% threshold LCR regions had been identified for each of the nine different window sizes, these were in turn merged, using the bedr package, for further analysis.

The R scripts used to perform the analyses are provided (LCR_TREU927_RSCRIPTS.tar.gz, see *Data availability*)[12].

InterPro domain mapping

InterPro domain mapping information was obtained from TriTrypDB (release 46) in tab-delimited text format. Regions of InterPro domain overlapping with the LCR regions were determined using bedtools intersect (v2.23.0).

Sequence property analysis

Properties of amino acid sequences, including the acid, aliphatic, aromatic, basic, bulkiness, net-charge, hydropathy, length and polarity indices were obtained with the alakazam R package[13].

PTM mapping

Post-translational modification (PTM) mapping information was obtained from available online datasets: phosphorylation during the *T. brucei* (procyclic form) cell cycle[14], post-translational modification of *T. brucei* and *T. b. evansi* bloodstream forms[15], differential phosphorylation analysis between bloodstream and procyclic stage of *T. brucei*[16], phosphorylation in the TbDYRK knock-out strain of *T. brucei*[17], phosphorylation events during heat shock[18], comparative analysis of lysine acetylation in trypanosomes[19], arginine methylation in slender forms of *T. brucei*[20], arginine methylation in mitochondria of *T. brucei*[21].

Gene Ontology analysis

The molecular function Gene Ontology analysis was performed on the TriTrypDB website from computed and curated association with a p-value cutoff of 0.01.

Statistical analysis

Statistical analysis comparing proportions were performed using a z-test for the PTMs analysis and for the comparison of categorical variables, i.e. the location of LCRs, using a Chi-squared test in R.

Results

The *T. brucei* proteome is biased toward some amino acids

The widely used algorithm to identify LCRs, SEG, is based on an analogue measure of the Shannon's entropy, assuming a uniform probability of representation of each amino-acid[6]. This also implies that LCRs have to be intrinsically distinct from their surroundings to be detected. Therefore, we initially analysed the *Trypanosoma brucei* proteome to determine if there was evidence for a bias in the representation of particular amino acids. The proteome was processed as a series of amino acid window sizes (10, 20, 30, 40, 50, 60, 75, 100 and 150) and examples of the density of unique amino acids per window represented in Figure 1A. Interestingly, we observed a clear bias towards particular amino acids. Indeed, the mean number of unique amino acids was only 11.51 ± 1.65 with a window of 20 amino acids, 17.34 ± 1.64 unique amino acids were present per window of 60 amino acids, and only for the windows 75 and 100 did we observe the 20 amino acids represented within one window, with a mean of unique amino acids per window of 18.09 ± 1.52 and 18.8 ± 1.34, respectively.
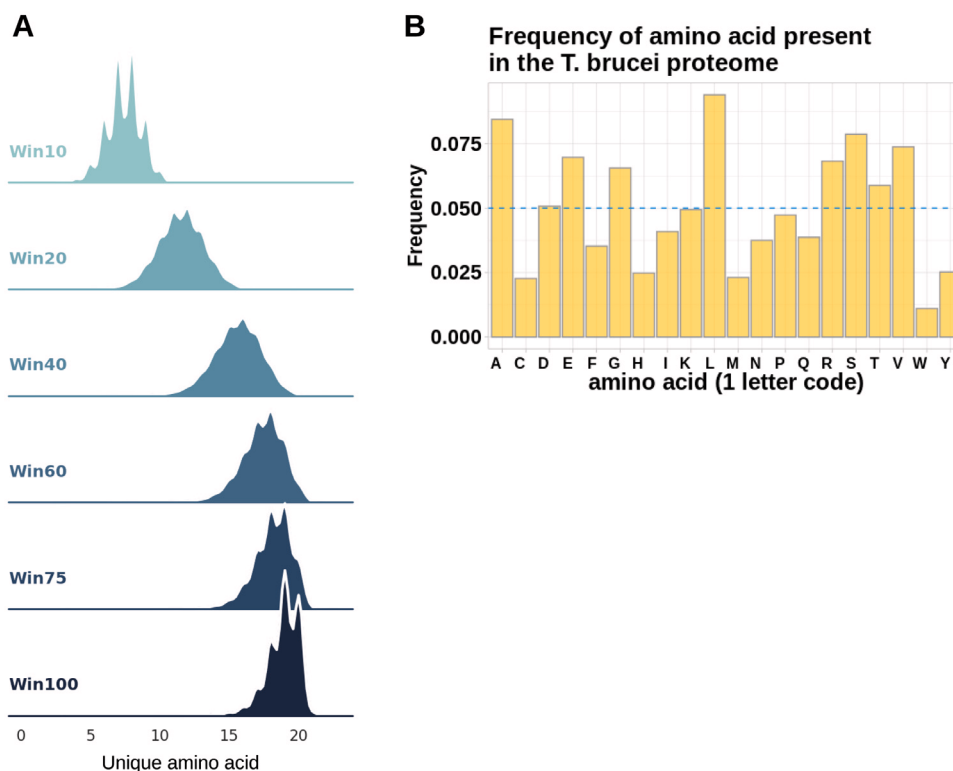
Figure 1. Amino-acid diversity in the *Trypanosoma brucei* proteome. A) The *T. brucei* proteome has been processed as a series of different window sizes, ranging from 10 to 150 amino acids, and the distribution of unique amino acids per window visualized; six of the nine window sizes assessed are illustrated. **B**) Frequency of each amino acid in the *T. brucei* proteome. Amino acids are indicated with the one letter code and the 1/20th value represented by the blue dashed line.

In regards of this apparent bias, we then calculated the relative abundance of the 20 different amino acids and compared them to the expected frequency if all amino acids were equally present (0.05, dashed blue line, Figure 1B). Eight amino acids were over-represented in the proteome of *T. brucei*, including for example alanine, leucine, serine and threonine, whereas five amino acids were present at half the expected frequency: cysteine, histidine, methionine, tryptophan and tyrosine. The other eight amino acids presented an abundance ranging from the expected value (aspartic acid, lysine and proline) to 0.025 (Figure 1B). These results are similar to those obtained in the study of codon bias usage in a set of highly expressed genes[22] and led us to re-visit the LCR prediction for the proteome of *T. brucei,* with a method that takes into account the compositional bias of amino acids in the proteome.

LCR calling using the Shannon's entropy method

To examine the LCRs in the proteome of *T. brucei*, we used the Shannon's entropy calculation[23], a well-accepted methodology to measure complexity in biological sequences. We processed the proteome as a series of amino-acid window sizes ranging from 10 to 150 amino acids, with each subsequent window being one amino acid further towards the carboxy terminal. As indicated by Battistuzzi *et al.*[7], for the SEG algorithm, the initial parameters chosen for the threshold of selection of the LCRs determine the final identification. The ecdf was calculated for all entropy values for the window size, and different thresholds, from 0.5 to 5 %, were plotted on each of the cumulative curves (Figures S1 and S2, *Extended data*[24]). As described in Coletta *et al.*[25], we visually inspected the thresholds to subjectively select the portion under the curve where the flat tail is located. Two stringent entropy thresholds were first selected, i.e. 0.5% and 1%, below which a region was deemed to be a putative LCR. As described in the 'Methods', overlapping LCRs within the same protein sequence were subsequently merged among each window size and between the different windows as well. The final LCRs obtained were then compared for the two thresholds. We were able to identify 12933 or 8162 unique LCRs on 6579 or 4914 unique proteins (59% or 43.8% of the proteome) using the 1% or 0.5% thresholds, respectively. The distribution of unique amino acids per LCR (Figure 2A) indicates that for both thresholds, LCRs are mainly composed of four to five different amino acids. There is a second peak at seven amino acids with the 1% threshold (grey arrowhead on Figure 2A).

LCRs identified with the 1% threshold ranged in size from nine to 3315 amino acids, whereas with the 0.5% threshold, LCR regions ranged from nine to 1384 amino acids. Of the 6579 or 4914 proteins containing predicted LCRs, relatively few, 424 or 219, were longer than 100 amino acids, using the 1% or 0.5% thresholds, respectively. When the 0.5% threshold was applied, (Figure 2B; Figure 3) there was a global reduction of the size of the LCRs, with a relative enrichment of LCRs with a size ranging from nine to 18 amino acids.

Next, we compared the number of LCRs per protein using the two thresholds. Figure 2C indicates a minor reduction in the number of LCRs per protein with the 0.5% threshold compared to 1%, likely due to the fewer number of LCRs identified with this more stringent threshold (Figure 3). Finally, we explored the size of the overlapping regions of the LCRs with domains identified in the InterPro database. Overlaps ranged from one to 816 or 204 amino acids, respectively, using the 1% or 0.5% thresholds. Both thresholds presented the same pattern with two peaks, one between ~9 to 12 amino acids overlap and one between ~16 to 19 amino acids overlap (Figure 2D; Figure 3). We note that there is, however, an over-representation of the first peak with the 0.5% threshold suggesting a reduction of the overlap with this setting.

In conclusion, the more stringent threshold (0.5%) selects for shorter LCRs that are of relatively lower complexity and reduces the size and frequency of overlap with previously identified domains, without significantly affecting the number of LCRs per protein. Therefore, we applied the most stringent 0.5% threshold for the remainder of our analysis.

Previous information available on LCRs on the TriTrypDB website were generated using the SEG algorithm. We therefore identified LCRs using this algorithm to compare the results obtained with the entropy methodology using the 0.5% threshold. We chose three different window sizes of 12, 25 and 45 amino acids, with a complexity threshold of 2-2.2, 3-3.3, 3.4-3.75 as initial parameters, as described in Wotton *et al*. 1994[6]. The results indicate that the SEG algorithm is highly dependent on the initial window size parameters, as previously observed[7], with the complexity in amino acids and the length of the LCRs varying greatly for each window size (supplement figure S3, *Extended data*[24]; supplement file 2, *Underlying data*[26]). A similar distribution of the number of LCR per protein is observed with the different windows and with the entropy methodology. We also note the presence of extremely long LCRs obtained with the SEG methodology. 1433 proteins present LCRs identified with both methodologies with any initial parameters, 2486 proteins are identified with the entropy and at least one parameter of the SEG methods, and 435 proteins are unique to the entropy methodology (supplement figure S3, *Extended data*[24]; supplement file 2, *Underlying data*[26]). In conclusion, this analysis indicates that the entropy methodology allows the identification of more diverse LCRs, is not biased by the initial parameters chosen and limits the identification of very long, potentially artefactual, LCRs.

To represent each predicted protein in the proteome, a series of plots was generated for all proteins encoded in the trypanosome genome, excluding variant surface glycoproteins (VSGs; supplement file 1, *Extended data*[24]), where we indicate the combined final LCR, obtained by the entropy method with the 0.5% threshold, in red, as well as the InterPro domains in blue and the overlapping regions in yellow. Examples of Alba proteins, polyadenylate-binding proteins, translation initiation factors and RNA-binding proteins are presented in Figure 4. In addition, we show the position of the distinct post-translational modifications (PTMs) identified in different published datasets[14–17,19,20]. The corresponding dataset of the
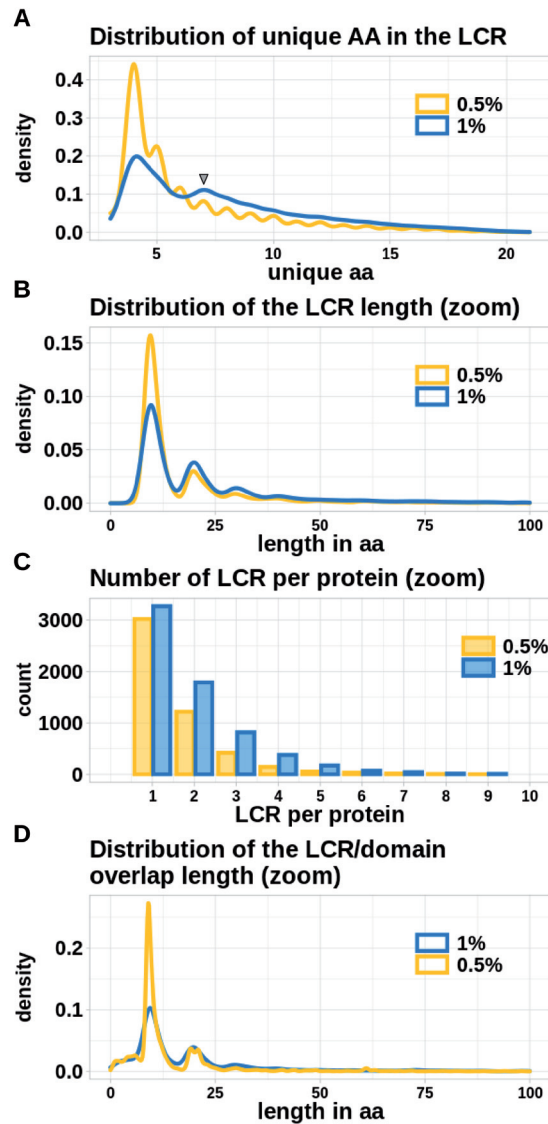
Figure 2. Comparison of the two different empirical cumulative distribution function (ecdf) thresholds, 1% and 0.5%.
A) Distribution of unique amino acids per low-complexity region (LCR) after merging. The arrowhead indicates the second peak of seven unique amino acids per LCR present with the 1% threshold. **B**) Distribution of the length of the LCRs, zoomed to include only those in the range from 0 to 100 amino acids. **C**) Distribution of the numbers of LCRs per protein, zoomed to include only those in the range from 0 to 10 LCRs per protein. **D**) Analysis of the LCRs identified by the entropy method overlapping with domains identified in the InterPro database. Size distribution of the overlapping regions, zoomed to include those in the range from 0 to 100 amino acids.

Threshold	Number of LCR	Number of proteins with LCR	Size of LCR (range in aa)	Number of proteins with LCR >100aa	Overlap size range LCR vs InterPro domain (in aa)
1%	12933	6579	9-3315	424	1-816
0.5%	8162	4914	9-1384	219	1-204

Figure 3. Values for different low-complexity region (LCR) parameters obtained from the 1% and 0.5% analysis threshold.
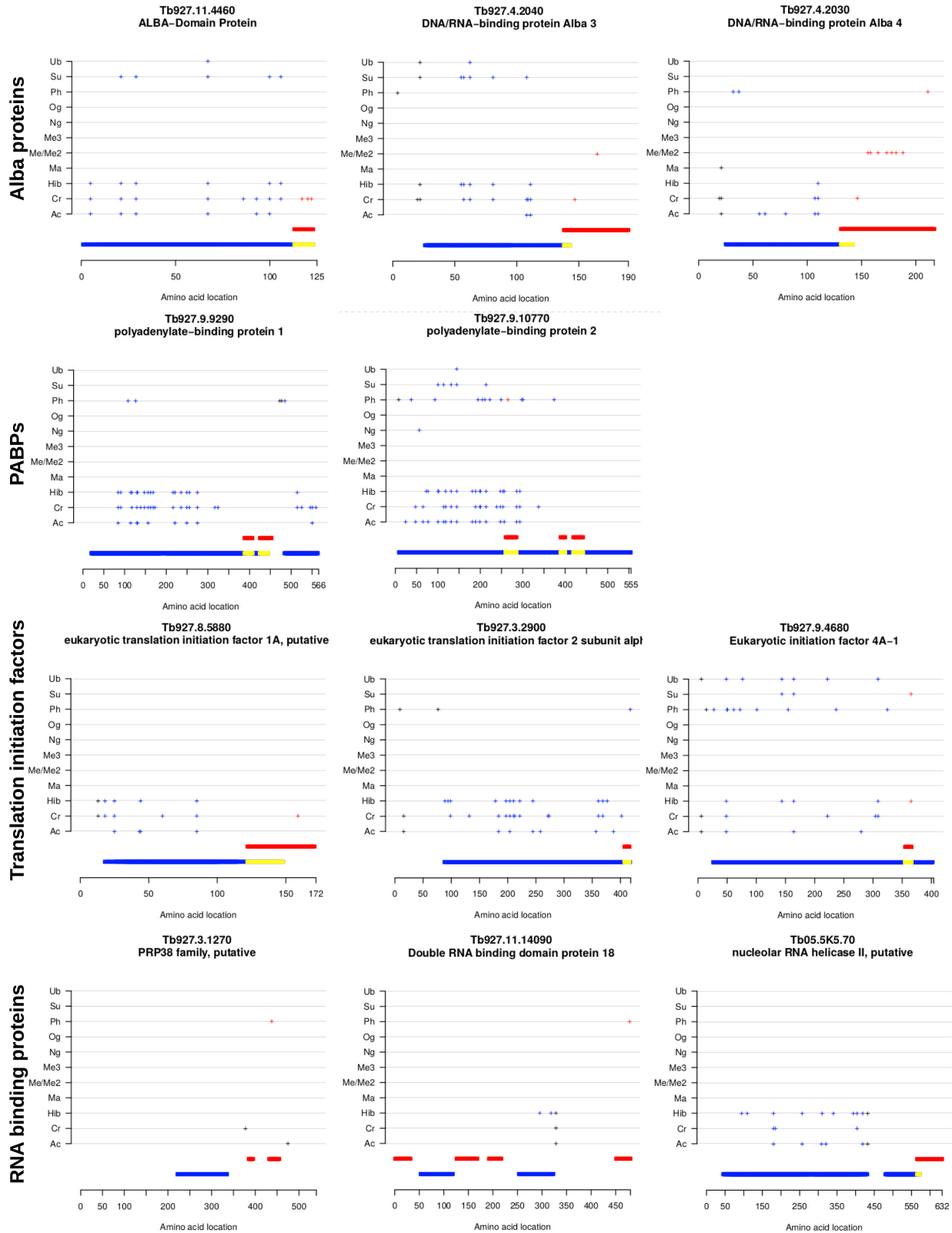
Figure 4. Examples of supplementary file 1 (see *Extended data*) protein pages. Each plot represents a protein (ID and product). The X-axis indicates the protein size in amino acids and on the plot are represented the final combined low-complexity regions (LCRs; in red), the identified InterPro domains (in blue) and the overlap regions between LCR and InterPro domain indicated in yellow. Post-translational modifications (PTMs) identified in experimental analysis by different studies are indicated above by "+" symbol. Each modification is coloured in blue when present in an InterPro domain, in red when present in an LCR or in black when present in neither.

Trypanosoma brucei proteome with the start and end position of InterPro domains and identified LCRs can be found in supplement file 2 (see *Underlying data*)[26].

Nucleotide binding proteins are enriched for the presence of LCRs in their C-terminal region

Previous studies of LCRs have suggested that the position of LCRs in a protein can influence its function. Coletta *et al.* demonstrated that LCRs in the proteome of *Saccharomyces cerevisiae* were preferentially located toward sequence extremities and that proteins with LCRs at these positions have more binding partners than proteins with LCRs in a more central position[24]. To analyse the distribution of LCRs in the *Trypanosoma brucei* proteome, we computed the frequency of an LCR for each relative position for all proteins. We excluded VSGs from further analysis which could introduce bias for the characterisation of LCRs for the rest of the proteome. Across the proteome, LCRs were enriched in the amino-terminal 10% and in the last 25% forming the C-terminal regions (Highlighted in Figure 5A by the grey areas).

Reflecting the positional distribution of LCRs, we artificially split the dataset into three categories for proteins containing at least one LCR within the first 25% of the relative protein size (N-terminal), between 25–75% (central) and starting between 75% and ending above 80% of the relative protein size (C-terminal) (depicted in the Venn diagram in Figure 5B). The input data comprised proteins having one or more LCR in their N-terminal region (1397 proteins), central region (2490 proteins) or C-terminal region (1315 proteins). Many proteins had an LCR in more than one region, as indicated by the numbers shown in the Venn overlap regions. Conversely, 720 proteins had a predicted single LCR in their N-terminal domain, 1559 a single centrally-located LCR, and 638 proteins a single C-terminal LCR. Molecular function Gene Ontology analysis indicates that proteins with one or more LCRs are generally enriched for a molecular binding function. Functional enrichment was most notable when the LCR was N-terminal or C-terminal (Figure 6; supplement file 3, *Underlying data*[26], with a p-value < 0.01). Indeed, when located on the N-terminal domain, LCRs were enriched for proteins with predicted cyclase (GO:0009975, 3.8-fold change (FC) with respect to all proteins), hydrolase (GO:0016817 and GO:0016818, 1.3 FC), lyase (GO:0016829, 2.38 FC) and phosphotransferase activities (arginine kinase GO:0004054, 7.03 FC). In contrast, when proteins possessed C-terminal LCRs, they were mainly enriched for nucleotide binding (RNA GO:0003729 (1.96 FC), DNA GO:0031490 (5.78 FC), purines GO:0032555 (1.2 FC), adenyl GO:0032559 (1.27 FC)). We also note some enrichment for cytoskeleton binding (2.01, 1.77 and 1.9 FC, GO:0008092, GO:0008017 and GO:0015631), peptidase (2.82 and 2.27 FC, GO:0004197 and GO:0008234) and hydrolase activities (GO:0016817, 1.39 FC) in the C-terminal LCR subset. Examples of known RNA interactors are highlighted in Figure 4. Alba proteins, PAPBs and translation initiation factors have been identified in P-bodies and stress granules in *T. brucei*[4]. In conclusion, these results implicate a potential role of LCRs in the function or interactions of nucleotide binding proteins in

Trypanosoma brucei when positioned in the C-terminal region. Indeed, the enrichment was such that the identification of LCRs in the C-terminal region of proteins with no functional annotation may suggest a possible involvement in nucleotide binding.

LCRs are highly diverse and present a general increase of polar amino acids

The composition of LCRs can be highly divergent and has been shown to play a major role in, for example, protein liquid-liquid phase separation and the formation of membraneless organelles[5]. Therefore, understanding the molecular composition and physico-chemical properties of LCRs in *T. brucei* could help us to understand the evolution and function of such regions in this organism.

To start, the relative abundances of the different amino acids were calculated for the identified LCRs and compared to that obtained from domains identified in the InterPro database (TriTrypDB, release 46). The compositional bias of the InterPro domain sequences is highly similar to the total proteome shown in Figure 1 with an enrichment of alanine, glycine, leucine and valine and a poor representation of cysteine, methionine, histidine and tryptophan (Figure 7A). In contrast, the compositional analysis of LCRs revealed an increase of alanine, glutamine and serine, and a decrease of leucine, proline and valine, relative to the composition observed in the InterPro domains. Contrary to what has been shown in *Plasmodium falciparum* or in yeast prion-like domains, the level of asparagine was relatively low and similar to that observed in the InterPro domain sequence set[1,7].

Several parameters of LCRs have previously been described to influence liquid-liquid phase separation, including LCRs with a polar backbone, punctuated by aromatic and charged amino acids (reviewed in 27,28). Nine different properties were used to compare InterPro domains and LCRs using the alakazam R package, i.e. the acid, aliphatic, aromatic, basic, bulkiness, net-charge, hydropathy, length and polarity indices[13]. Comparisons of the domains/LCRs position, whether in the C-terminal region or elsewhere, were then performed for all these properties (Figure 7B; supplement file 4, *Underlying data*[26]). The first conclusion from this analysis was that the nature of LCRs is highly diverse compared to defined InterPro domains, and that LCRs are shorter overall. The net charge stays similar between InterPro domains and LCRs (pH7.4), and acid and base indices are only mildly lower in the LCR regions. Interestingly, LCRs are more polar than defined InterPro domains and this is accompanied by a reduction of hydrophobicity (Figure 7B). There is a reduction of the aliphatic and aromatic indices, also represented by a reduction of bulkiness, indicating an under representation of such amino acids in the highly polar LCRs of the *T. brucei* proteome.

Due to the diversity of LCRs, we manually subdivided them into three categories, according to their polarity index: below eight (named "low" for the rest of the study), between eight and nine (values where most of the InterPro domains are

A

B
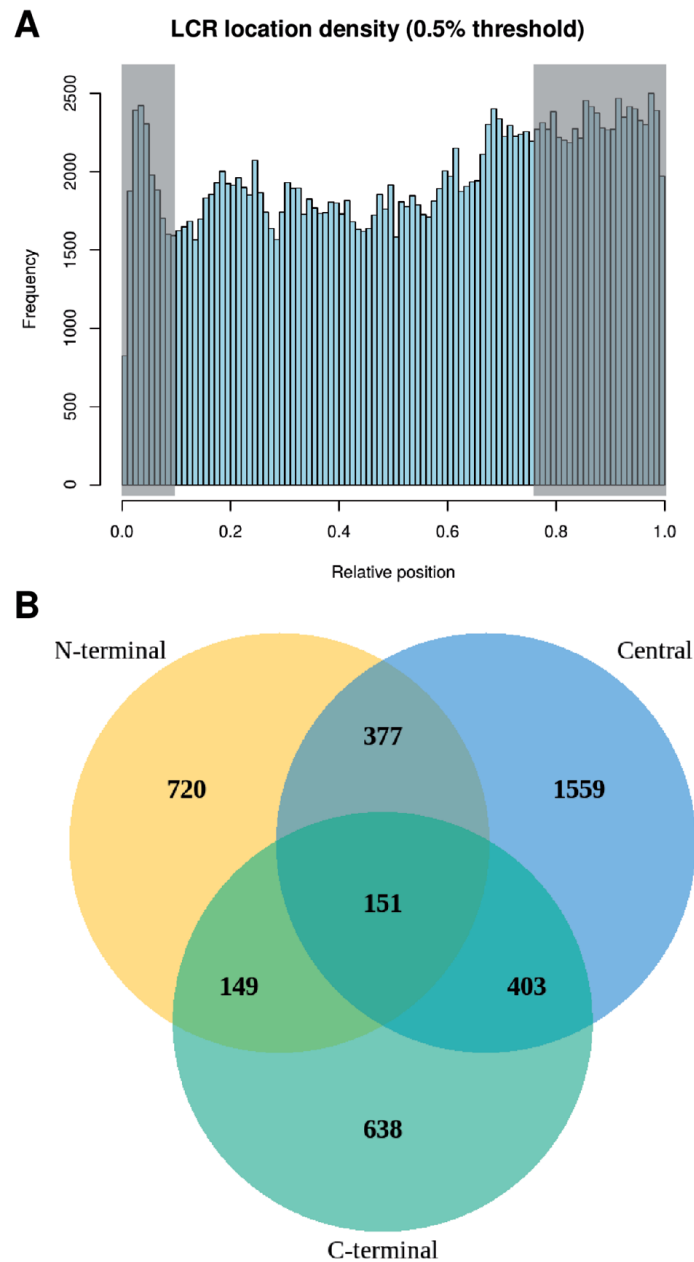
Figure 5. Relative location of low-complexity regions (LCRs) on proteins. A) Each position on the proteins, relative to the size of the protein (normalised for each protein to 1, the first 10%, i.e. from 0 to 0.1, and last 25%, i.e. from 0.75 to 1, are highlighted by grey areas), have been analysed for the presence of an LCR. The density of the presence of an LCR has been plotted relative to the size of the proteins for the entire proteome with a threshold of 0.5%. **B**) The Venn diagram represents the number of proteins with at least one LCR (threshold 0.5%): starting and ending in the first 25% of their relative size (yellow: N-terminal); starting and ending between 25%-75% of their relative size (blue: Central); starting after 75% and ending after 80% of their relative size (green: C-terminal). Overlap regions indicate proteins possessing LCRs in two or more of the regions.

included, named "intermediate") and above nine (named "high" for the rest of the study). 2226 proteins have LCRs with high polarity characteristics (Figure 8; supplement file 5, *Underlying data*[26]); GO enrichment analysis identified nucleotide binding (RNA, DNA, purine, adenyl, GO:0003723, GO:0003676, GO:0003729, GO:0031490, GO:0032555,

GO:0030554) and translation initiation factors (GO:0031369), similar to that observed when considering LCRs located on the C-terminal part of proteins. GO analysis of the 1373 proteins with low polar LCRs showed enrichment for enzymatic activities such as transferase, ATPase, cyclase, lyase and protein transporters, as already noted for N-terminal region LCRs
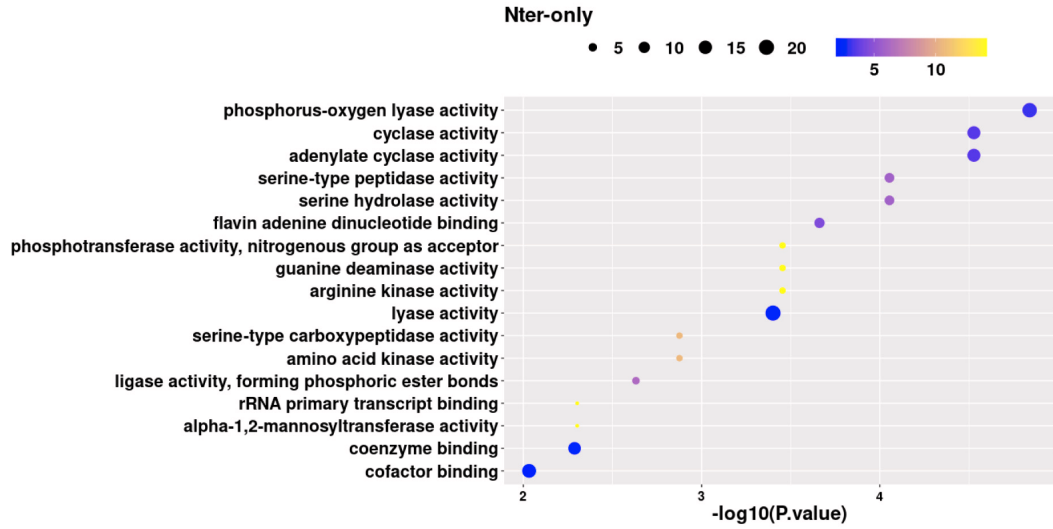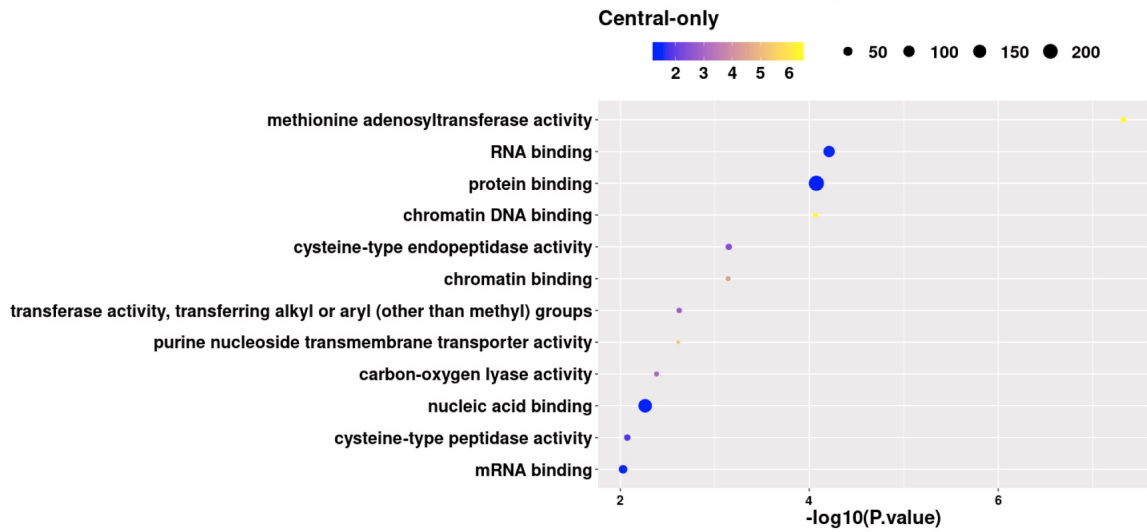
Figure 6. Graphical representation of the -log10 of the p-value obtained with the molecular function Gene Ontology (GO) term analysis for proteins that possess low-complexity regions (LCRs) either only located in their N-terminal (**A**), Central (**B**) or C-terminal (**C**) part. Gradient indicate the log2 fold-change and the size of the dots represent the numbers of proteins.
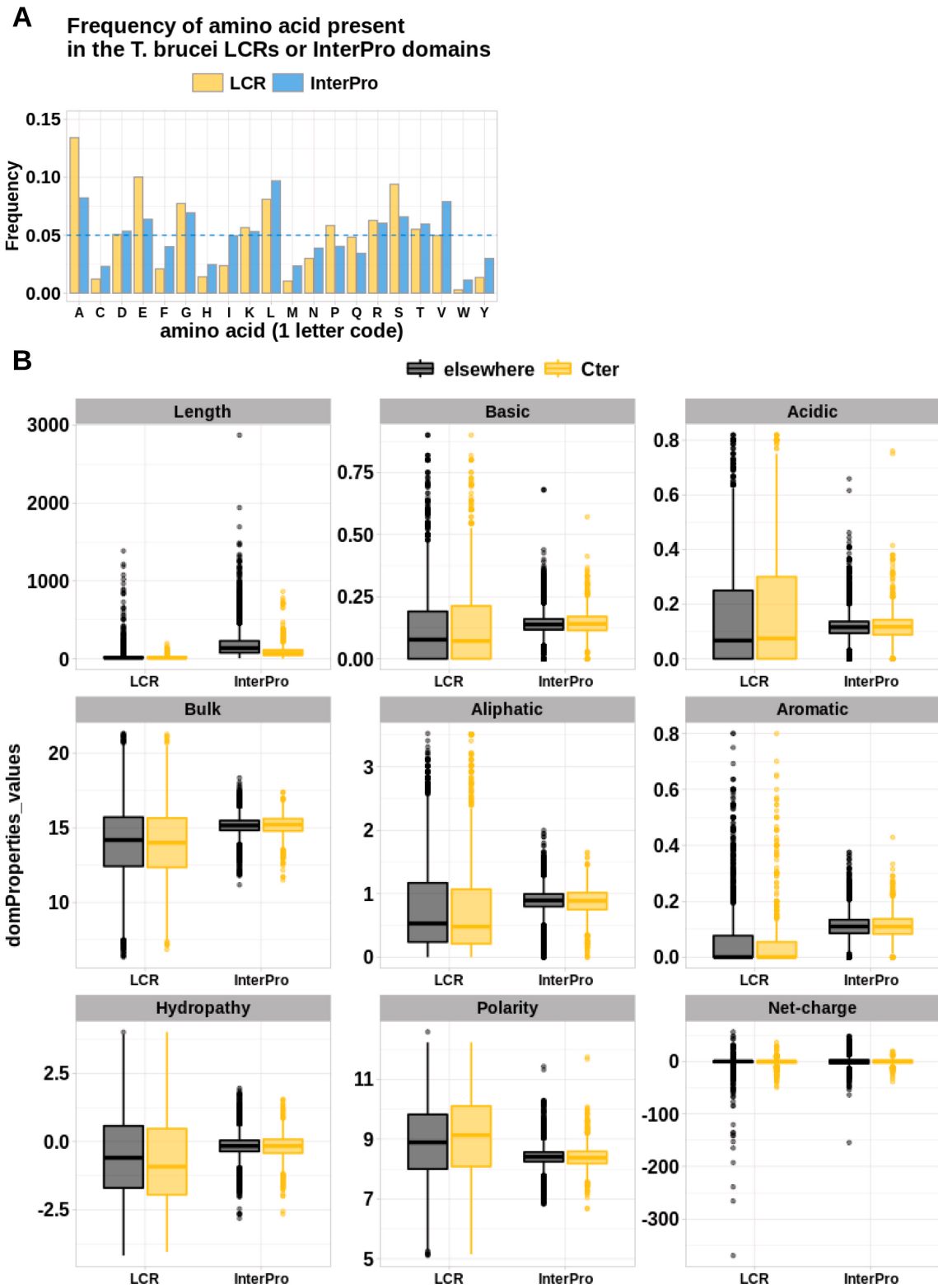
Figure 7. Amino acid composition and properties of low-complexity regions (LCRs). A) Frequency of each amino acid in LCRs (yellow) and InterPro domains (blue). Amino acids are indicated with the one letter code and the 1/20th value represented by the blue dashed line to indicate over- or under-representation as an average. **B**) The amino-acid sequence properties (Alkazam R package[12]) of LCRs and InterPro domains were analysed according to their localisation in the C-terminal region (yellow) or elsewhere (grey) on the proteins. Nine properties were analysed: acid, aliphatic, aromatic, base, bulkiness, net-charge, hydropathy, length and polarity indices.

(GO:0016758, GO:0043492, GO:0009975, GO:0016829 and GO:0022804; Figure 8; supplement file 5, *Underlying data*[26]). Consequently, we compared the list of proteins with extreme LCR polarity to those obtained from the location of LCR at the extremities of the proteins. The majority of proteins with

highly polar LCRs had LCRs in their C-terminal region, whereas most proteins with low polar LCRs had LCRs located in their N-terminal extension (Figure 9; supplement file 5, *Underlying data*[26]; X-squared = 32.602, df = 1, p-value = 1.131e-8). It can be noted that 1472 genes harbour a signal
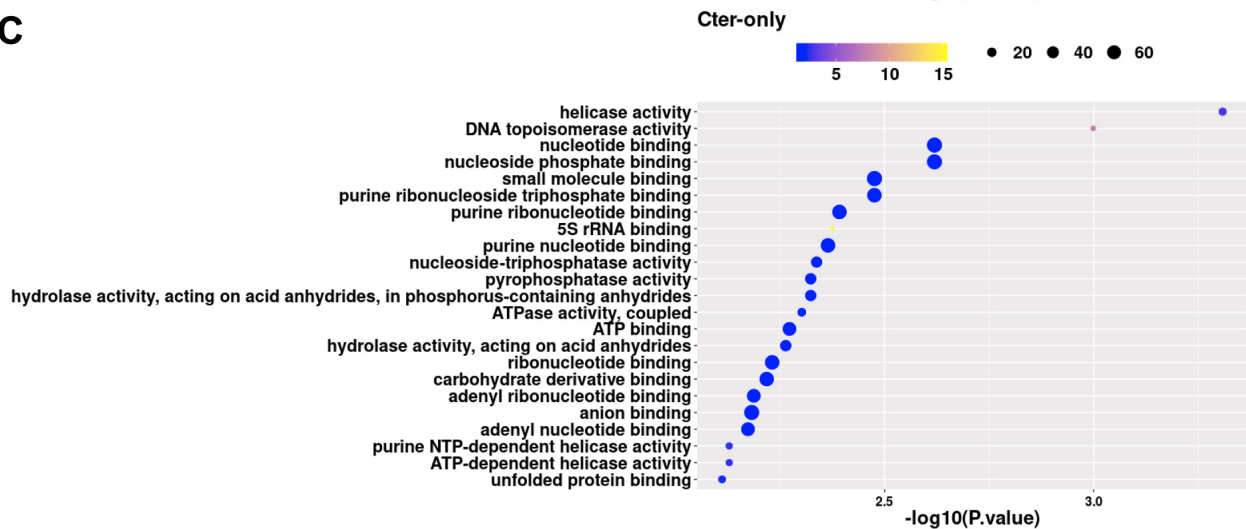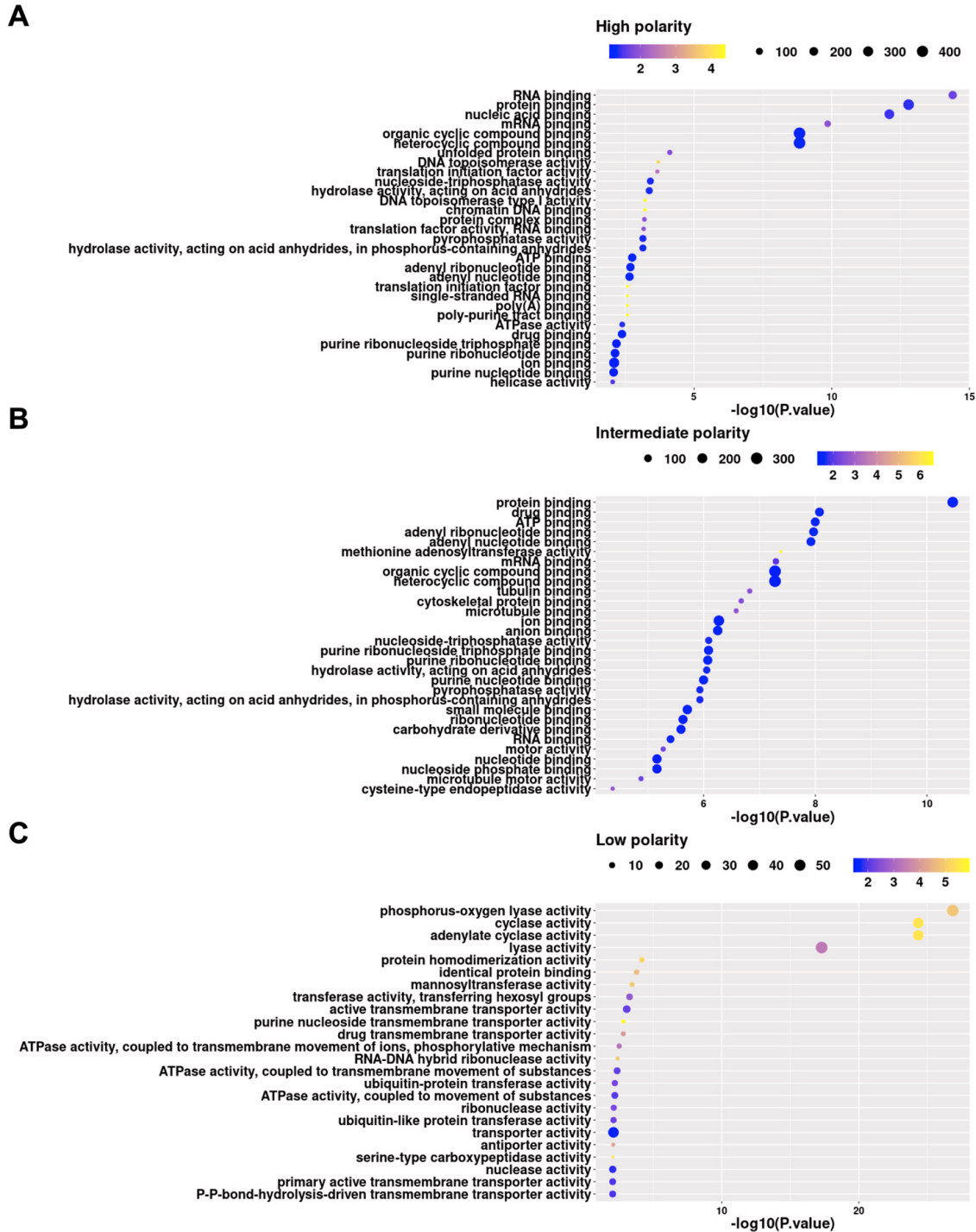

Figure 8. Graphical representation of the -log10 of the p-value obtained with the molecular function Gene Ontology (GO) term analysis for proteins that possess low-complexity regions (LCRs) of either High (**A**), Intermediate (**B**) or Low (**C**) polarity indices. Gradient indicate the log2 fold-change and the size of the dots represent the numbers of proteins.
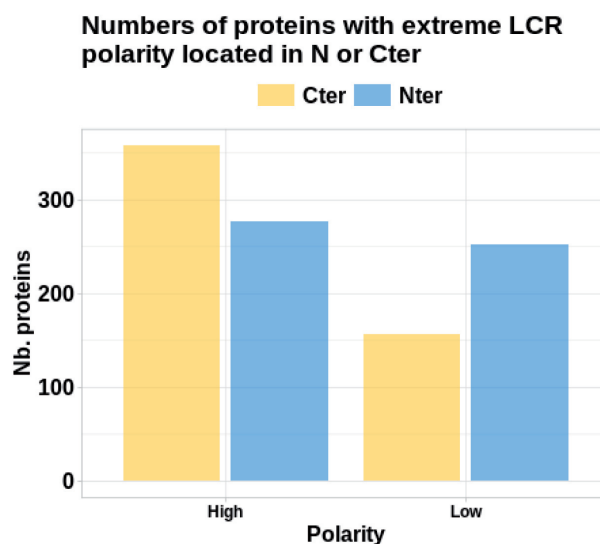
Numbers of proteins with extreme LCR polarity located in N or Cter

Figure 9. Numbers of proteins with High or Low polarity low-complexity regions (LCRs), located either in the N-terminal or C-terminal.

peptide and one or more LCRs. The overlap between LCRs and signal peptides are presented in supplement file 7 (see *Underlying data*)[26].

Overall, these results suggest that highly polar LCRs are located preferentially on the C terminal region of proteins involved in DNA/RNA binding and the regulation of gene expression, whereas low polar LCRs are located mainly on proteins implicated in diverse enzymatic activities. As previously recognised in other organisms, *T. brucei* LCRs are characterised by a reduction of aromatic, aliphatic and basic amino acids, known to enhance liquid-liquid phase separation[27,28].

LCRs are overrepresented by phosphorylation events in *T. brucei*

The dynamism of membraneless granule formation, via liquid-liquid phase separation, has been shown to be regulated by post-translational modifications (PTMs)[29,30]. Consequently, we looked for the presence of PTMs in the LCRs of the *T. brucei* proteome. First, we analysed the extensive dataset of PTMs of *T. brucei* bloodstream forms obtained by Zhang *et al.*[15]. We plotted the percentage of each modification relative to the total number of PTMs either independently of their localisation, present in LCRs or present in LCRs located in the C-terminal regions (Figure 10A; supplement file 6, *Underlying data*[26]). Among the 10 PTMs analysed in this study, acetylations were decreased in LCRs compared to the whole proteome, as were ubiquitinations and, to a lesser extent, N-glycosylation. In contrast, phosphorylation events were relatively enriched in the bloodstream stage in LCRs independently of the LCR's localisation within a protein (FC = 1.47, p-value < 0.001).

To have a broader picture of the different possible post-translational modifications, we then merged the dataset of Zhang *et al.*[15] with the phosphorylation datasets obtained by Urbaniak *et al.*[31], Benz *et al.*[14], Cayla *et al.*[17], Ooi *et al.*[32], the mono/di-methylation datasets obtained by Fisk *et al.*[21] and Lott *et al.*[20] and also the lysine acetylation dataset obtained by Moretti *et al.*[19]. It should be noted that we chose to disregard the life cycle stage, stress conditions or the genetically modified strain in which the PTMs were determined. We plotted the percentage of each modification relative to the total number of PTMs in the InterPro domains and LCRs, InterPro domains only or LCRs only, by either looking for the presence of these PTMs in domains/LCRs located in the C-terminal region or elsewhere (Figure 10B). The raw count numbers of PTMs present on LCRs and InterPro domains are provided in Figure 11 and supplement file 6 (see *Underlying data*[26]). The combined dataset indicated that LCRs may be relatively depleted of acetylations (FC = 2.31, p-value < 0.001), crotonylations (FC = 1.62, p-value < 0.001) and 2-hydroxybutyrylations (FC = 1.88, p-value < 0.001), with no significant difference between LCRs located in the C-terminal or elsewhere. The same observation was also noted for sumoylations (FC = 3.48, p-value < 0.001) and ubiquitinations (FC = 2.91, p-value < 0.001), whereas an enrichment was observed in methylations (FC = 3.66, p-value < 0.001) in the LCRs. Interestingly, phosphorylations were found to represent ~51% of the modifications observed in LCRs but only ~16% of the modifications observed in the InterPro domains (FC = 3.22, p-value < 0.001, Figure 10B). As this strong enrichment for phosphorylation was less evident in the Zhang dataset, we controlled for bias in the additional datasets by analysing phosphorylations within LCRs. The results presented in Figure 10C indicate a similar distribution of phosphorylation events between all the datasets. Likewise, the distribution of phosphorylation on the different residues is similar between the different datasets (Figure 11C). We conclude that the relative increase of phosphorylation events in the LCRs is not due to a bias of the datasets analysed but is of likely biological relevance.
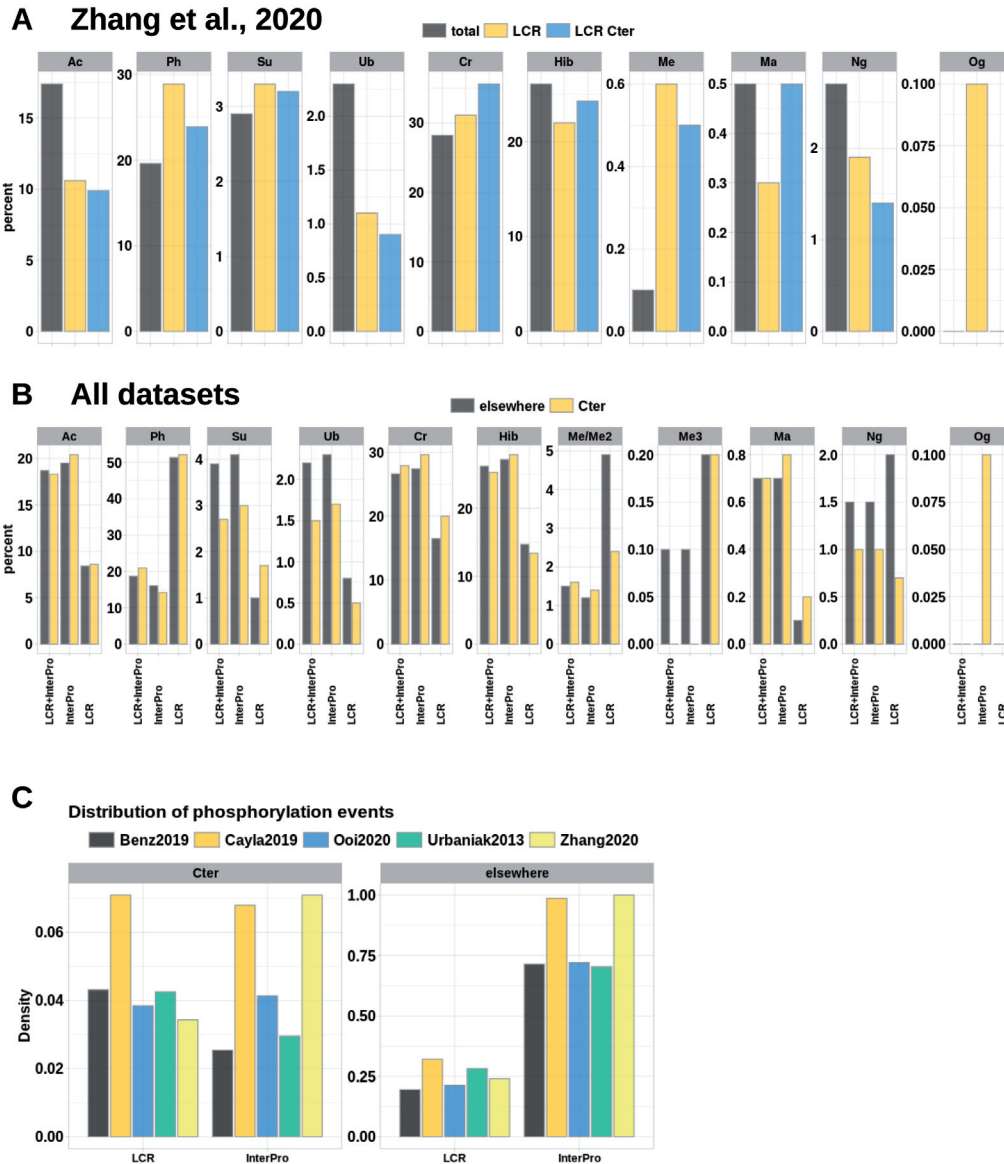
Figure 10. Mapping of post-translational modifications. A) The relative representation (percent) of post-translational modifications, identified in *T. brucei* bloodstream parasites by Zhang *et al.*[15], were analysed in the total proteome (grey), in the low-complexity regions (LCRs; yellow) or in the LCRs located in the C-terminal region of their corresponding protein (blue). **B**) The Zhang *et al.* dataset[15] was merged with those obtained by: Urbaniak *et al.*, 2013, Benz *et al.*, 2019, Cayla *et al.*, 2019, Ooi *et al.*, 2020 for the analysis of phosphorylation, Fisk *et al.*, 2013 and Lott *et al.*, 2013 for the mono/di-methylation and Moretti *et al.*, 2018 for the lysine acetylation[14–17,19–21,32]; to obtain the positions of all documented modifications. The relative representation (percent) of post-translational modifications was analysed in the InterPro domains + LCRs, InterPro domains only or LCRs only, according to the position within the domain/LCR on which they are located, i.e. C-terminal (yellow) or elsewhere (grey). The distributions of phospho-residues were compared between the different datasets for their position within domains/LCRs, according to the position of the domain/LCR on which they are located: C-terminal or elsewhere. **C**) Density distribution of the phosphorylation event from the different datasets.

To investigate if the enrichment of phosphorylation events in LCRs was due to the relative increase of phosphorylable residues in these regions, we normalised the percentage of presence of each PTM by the frequency of the amino acid they have been identified on, either for the LCRs or the domains identified in the InterPro database (Figure 12). The results

confirmed our previous observations, with a very strong increase of phosphorylation on LCRs, mainly on serine residues, compared to the InterPro domains.

We finally analysed the dataset published by Lueong *et al.* 2016[33], revealing a set of 155 mRNA-binding proteins, and
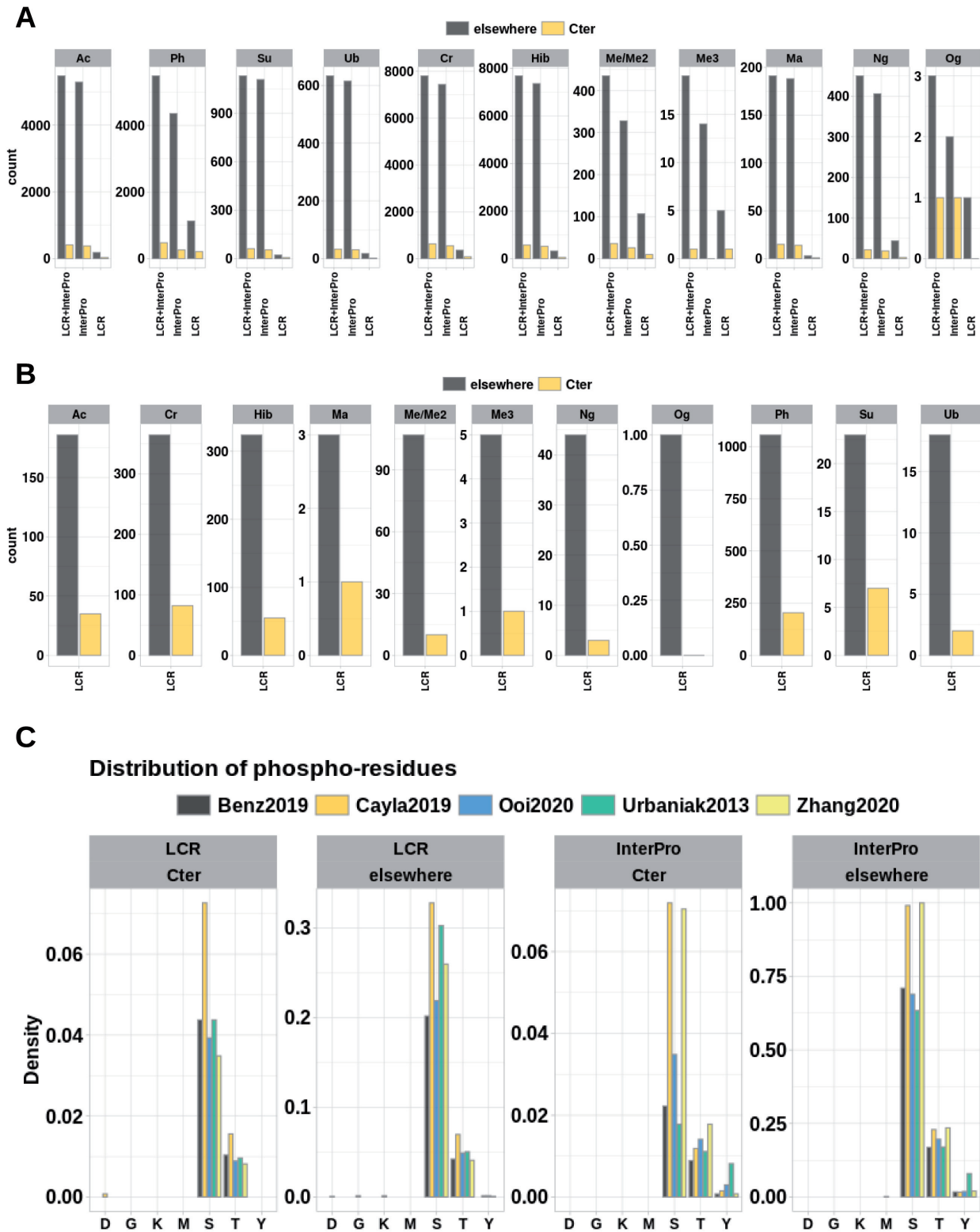
Figure 11. Mapping of post-translational modifications. Raw numbers of PTMs present on 'LCR and InterPro', 'InterPro only' or 'LCR only' (**A**). The same dataset is plotted on **B**, but only the 'LCR' is presented. **C**) Density distribution of the phosphorylation on the residues indicated in X-axis, from the different datasets. PTM, post-translational modification; LCR, low-complexity region.
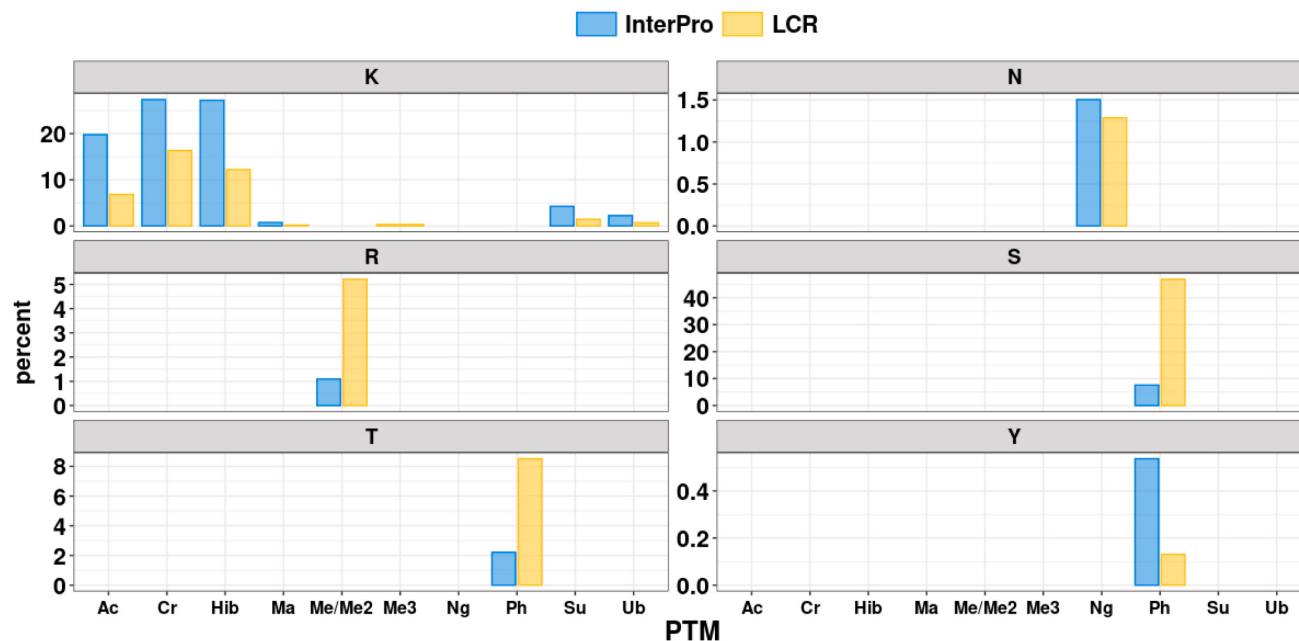
Figure 12. Mapping of post-translational modifications on the corresponding residue. The relative representation (percent) of post-translational modifications was analysed in the InterPro domains (blue) or LCRs (yellow), after normalisation by the frequency of each amino acid in the corresponding regions/domains.

extracted their LCRs and PTMs. Among these mRNA-binders, 99 proteins harboured one or more LCRs, with 42 having a LCR located in their C-terminal region. 82 of 155 were phosphorylated and 35 were phosphorylated on LCRs, including Alba 4, pumilio/PUF 6 and 9, UBP2 and the zinc finger proteins ZC3H1-like and ZC3H40, for example (supplement file 6, *Underlying data*[26]). This analysis confirmed and highlighted our observations that nucleotide binding proteins were enriched for the presence of LCRs, particularly in their C-terminal regions, and potentially regulated by phosphorylation.

Discussion

In this study, we provide a comprehensive analysis of LCRs predicted within the *T. brucei* proteome. A number of the physicochemical properties of LCRs in trypanosomes and the positional biases of LCRs for certain protein classes are likely to be relevant for their biological interactions. Our analysis has revealed the presence of LCRs on 42% of proteins, excluding the VSG repertoire. This indicates that *T. brucei* harbours among the highest level of LCRs in eukaryotes (where 10–20% of proteins have LCRs), similar to other protozoan eukaryotes, *P. falciparum* and *Dictyostelium discoideum* (which each have at least 50%)[6,34].

In yeast, the positions of LCRs in proteins can be a marker for proteins exhibiting enhanced protein interactions when they are located on the extremities of the proteins[25]. In *T. brucei*, enrichment is similarly observed for a subset of molecular

functions, such as enzymatic transferases or nucleotide binding, in the N-terminal and C-terminal regions, respectively. By analogy, the human DYRK3 kinase associates with stress granules via an N-terminal LCR that regulates the granule's dynamics[35]; ribonucleotide binding proteins have also been shown to be rich in C-terminal LCRs. Indeed, P-bodies and stress granules, which are membraneless organelles, contain RNA binding proteins enriched for LCRs and depleted for regions with high levels of hydrophobicity (bulky, aromatic and hydrophobic residues)[36].

The composition of LCRs and their physico-chemical properties are starting to be understood. For example, yeast proteins containing prion-like domains exhibit a prevalence of polar amino acids and in particular, asparagine, within their LCRs. The same observation has been made in the LCRs of *P. faciparum,* while other species of Plasmodium do not exhibit such properties[7]. From our analysis, it would appear that in *T. brucei,* LCRs have evolved differently to *P. falciparum*. Indeed, asparagine is an underrepresented amino acid in the proteome and is not enriched in LCRs. However, there is a notable over-representation of two other polar amino acids in the LCRs of *T. brucei*: serine and glutamine. This particular characteristic could suggest that granular structures in *T. brucei* could be 'harder' than in other species, as these two residues have been shown to promote hardening through formation of labile-cross-beta-sheets, while glycine enhances fluidity (reviewed in 28). The same observation was made for the enrichment of serine in human LCRs[27].

Several parameters, intrinsic to the sequence of LCRs, influence phase separation. *T. brucei* LCRs are enriched in polar residues but aromatic residues are under-represented. This confirms previous observations in which LCRs with a polar backbone, punctuated by aromatic and charged amino acids, enhanced protein condensation (reviewed in 27,28). Our results also suggest that the molecular functions of proteins could influence the nature of the different LCRs in *T. brucei*, or conversely, proteins with enzymatic functions have low polar index LCRs, while proteins involved in nucleotide binding and gene expression regulation have LCRs with a high polar index.

Recent studies have demonstrated that phase separation mediated via LCRs was also a mechanism regulated by post-translational modifications. For example, O-linked-N-acetylglucosamine-glycosylation enhances stress granule formation by favouring aggregation of untranslated messenger ribonucleoproteins (reviewed in 29). It has also been shown that threonine and arginine govern saturation/concentration of phase separation via threonine-threonine interaction, electrostatic interaction (negatively charged amino acids) and threonine-arginine interactions[28]. These two residues are subject to modification by phosphorylation and methylation, respectively. Arginine methylation of the repetitive RGG or RG motifs present on ribonucleotide binding proteins, reduces liquid-liquid phase separation by interfering with arginine-aromatic interactions (reviewed in 29,30). Interestingly, in the datasets we analysed, methylations were infrequent, despite their relative enrichment in LCRs. However, there was a marked enrichment of phosphorylation sites in the LCRs of *T. brucei* compared to the rest of the proteome. Phosphorylation modifies the aromatic-cationic interactions or aromatic-aromatic interactions of proteins, which can influence phase separation of ribonucleotide-binding proteins either positively or negatively (reviewed in 29). In the literature, there are now numerous examples of the phosphorylation of residues present on LCRs or adjacent to LCRs that influence phase separation (reviewed in 30). Firstly, phosphorylation on multiple S/T sites on the neurodegeneration-linked protein FUS interferes with phase separation and reduces the binding of the FUS/LCR. This was also shown to have consequences for tethered proteins, which do not possess LCRs, which were less associated with the hydrogel structures when FUS was phosphorylated. A second example is the MARK2 kinase which phosphorylates Tau protein on serine residues in the microtubule associated domain. Tau is an RNA-binding protein that condenses *in vitro* and promotes microtubule polymerisation. The phosphorylation provides additional negative charges which promotes electrostatic interactions and drives phase separation of Tau. Thirdly, in yeast, Ime2 kinase phosphorylates the amyloid-like translational repressor Rim4 on residues located in LCR, causing the de-condensation of Rim4 and its rapid degradation (reviewed in 30).

There are numerous examples of the dynamic formation of stress granules in these and related parasites during nutritional stress[4,37–40]. Recent evidence for altered phosphorylation of RNA regulators has also been observed under conditions of heat shock[32]. In that study, the authors revealed that nearly 200 sites exhibit changes in phosphorylation on RBPs, protein kinases, translational components, and P- body / stress granule proteins after one hour of heat shock[32]. Our analysis highlights that 50 of these phosphorylation changes, on 21 proteins, are present on LCRs including on kinases, nucleoporins, ligases and translation initiation factors (eIF4G4, eIF4E3; supplement file 6, *Underlying data*[26]). In addition, using a published dataset of confidently identified mRNA-binding proteins[33], we revealed that 99 proteins out of 155 present LCRs, with 35 proteins phosphorylated on these LCRs, including for example the Alba 4 protein (supplement file 6, *Underlying data*[26]), previously identified as a component of stress granules in *T.brucei*[40]. These results reveal potential components implicated in stress granules regulation by phosphorylation. However, it is well known that starvation stress granules and heat shock stress granules[4,37–40] are compositionally distinct, and we hypothesise that protein targeting to membraneless granules could be regulated by different signalling pathways in response to different physiological stresses.

In conclusion, we propose that the different properties of LCRs (polarity and distribution within resident proteins) and their potential regulation by phosphorylation in *T. brucei* could help to regulate the formation of membraneless granules or the hydrogel microenvironment. Added to this, the local depletion of ATP by active protein kinases targeted to the granular structures or liquid droplets may influence the dynamics of phase separation, as suggested by the study of *Xenopus laevis* oocytes, in which the nucleolus becomes more viscous when ATP is depleted[41]. In combination, the phosphorylation of LCRs on target proteins and the ATP balance within the microenvironment of the granule could drive the dynamic assembly and disaggregation of gene regulators, controlling the parasite's adaption to environmental change.

Data availability
Underlying data
Zenodo: Cayla *et al.*, 2020 Wellcome Open Research – Underlying data. https://doi.org/10.5281/zenodo.4135199[26].

This project contains the following underlying data:

- **supplement_file_2.xlsx** (Position of every InterPro domain and LCR identified. All genes are provided with indication on chromosome localisation, presence of transmembrane domains, signal peptides and the localisation of the encoded proteins, either predicted using DeepLoc[42] or observed (Tryptag[43]). LCR identified with the SEG algorithm, using the window size of 12, 25, 45 amino acids, are indicated in the third sheet).

- **supplement_file_3.xlsx** (List of genes and Molecular Function gene ontology (GO) enrichment analysis of proteins with predicted LCRs in the N-terminal, central part or C-terminal or the different possible combinations.)

- **supplement_file_4.xlsx** (Property analysis of sequences of every InterPro and LCRs identified.)

- **supplement_file_5.xlsx** (List of genes and Molecular GO enrichment analysis of proteins presenting a Low (<8) or High (>9) polarity index level.)

- **supplement_file_6.xlsx** (List and position of PTMs present on InterPro domains and LCRs. The different datasets from which the PTMs have been extracted can be found in the Zhang2020, Benz2019, Cayla2019, Urbaniak2013, Ooi2020, Fisk2012, Lott2012 and Moretti2017[14,15,17,19–21,31,32] columns. The sequence properties of the domains/LCRs on which these PTMs are located are also indicated. The list of modifications identified in Ooi *et al.* 2020[32] present on LCRs are indicated in the second sheet. Third sheet indicate the list of proteins identified in Lueong *et al*. 2020[33], presenting LCRs and the fourth sheet indicate the PTMs identified in the proteins identified in Lueong *et al*. 2020[33].)

- **supplement_file_7.xlsx** (List and positions of LCRs, signal peptides and their overlapping regions.)

Extended data
Zenodo: Cayla *et al.*, 2020 Wellcome Open Research – Extended data. https://doi.org/10.5281/zenodo.4135190[24].

This project contains the following extended data:
- **Supplement Figure S1** (Cumulative distribution functions of the entropy values. Representation of the empirical cumulative distribution functions (ecdf) of the entropy values of the *T. brucei* proteome, calculated with the Shannon's formula as implemented in the entropy.plugin() function, for the different window sizes. The vertical lines represent the different possible thresholds: 0.5, 1, 1.5, 2, 3.5, 4, 4.5, 5% under which LCR have been called.)

- **Supplement Figure S2** (Statistics on the LCRs obtained from different thresholds.Statistical values obtained from the cumulative ecdf distributions for each window size (Windows). Values = numbers of LCRs identified, Mean and SD = mean and standard-deviation obtained from the cumulative ecdf, the remainder of the numbers are the different possible thresholds: 0.5, 1, 1.5, 2, 3.5, 4, 4.5, 5% under which LCR have been called, with their value indicated for each window size.)

- **Supplement** Figure S3 (Comparison of the LCRs obtained the SEG algorithm with three different initial window parameters, 12, 25 or 45 amino acids. A) Distribution of unique amino acids per low complexity region (LCR) after merging. B) Distribution of the length of the LCRs, zoomed to include only those in the range from 0 to 100 amino acids. C) Distribution of the numbers of LCRs per protein, zoomed to include only those in the range from 0 to 10 LCRs per protein. D) Values for different LCR parameters obtained from the 12, 25 and 45 amino acids analysis windows. E) The Venn diagram represents the number of proteins with at least one LCR identified with the SEG algorithm with the windows parameters of 12 amino acids (blue), 25 amino acids (green) or 45 amino acids (red) and the ones identified with the entropy methodology threshold 0.5% (yellow). Overlap regions indicate proteins possessing LCRs with different methodology.)

- **supplement_file_1.pdf** (Visualisation of LCRs, InterPro domain (InterPro) and PTMs for every protein (excluding VSGs) of the *T. brucei* proteome. Each plot represents a protein (ID and product). The X-axis indicates the protein size in amino acids and on the plot are represented the final combined LCRs (in red), the identified InterPro domains in blue and the overlap regions between LCR and InterPro domain indicated in yellow. Post-translational modifications (PTMs) identified in experimental analysis by different studies are in dictated above by "+" symbol. Each modification is coloured in blue when present in an InterPro domain, in red when present in an LCR or in black if present in neither.)

Zenodo: Cayla *et al.*, 2020, Wellcome Open Research - Code availability. https://doi.org/10.5281/zenodo.4135175[12].

This project contains the following extended data:
- **LCR_TREU927_RSCRIPTS_v2.tar.gz** (Compressed file containing the necessary code to generate LCRs of the proteome of *Trypanosoma brucei*.)

References

1. Alberti S, Halfmann R, King O, *et al.*: **A Systematic Survey Identifies Prions and Illuminates Sequence Features of Prionogenic Proteins.** *Cell.* 2009; **137**(1): 146–158.
   PubMed Abstract | **Publisher Full Text** | **Free Full Text**
2. Kato M, Han TW, Xie S, *et al.*: **Cell-free formation of RNA granules: Low complexity sequence domains form dynamic fibers within hydrogels.** *Cell.* 2012; **149**(4): 753–767.
   PubMed Abstract | **Publisher Full Text** | **Free Full Text**
3. Kedersha N, Anderson P: **Stress granules: Sites of mRNA triage that regulate mRNA stability and translatability.** In *Biochem Soc Trans.* Portland Press,

2002; **30**(Pt 6): 963–969.
   PubMed Abstract | **Publisher Full Text**
4. Kramer S: **RNA in development: how ribonucleoprotein granules regulate the life cycles of pathogenic protozoa.** *Wiley Interdiscip Rev RNA.* 2014; **5**(2): 263–284.
   PubMed Abstract | **Publisher Full Text**
5. Alberti S, Gladfelter A, Mittag T: **Considerations and Challenges in Studying Liquid-Liquid Phase Separation and Biomolecular Condensates.** *Cell.* 2019; **176**(3): 419–434.
   PubMed Abstract | **Publisher Full Text** | **Free Full Text**

6.   Wootton JC: **Non-globular domains in protein sequences: Automated segmentation using complexity measures.** *Comput Chem.* 1994; **18**(3): 269–285.
      PubMed Abstract | **Publisher Full Text**

7.   Battistuzzi FU, Schneider KA, Spencer MK, *et al.*: **Profiles of low complexity regions in Apicomplexa.** *BMC Evol Biol.* 2016; **16**: 47.
      PubMed Abstract | **Publisher Full Text** | **Free Full Text**

8.   Pagès H, Aboyoun P, Gentleman R, *et al.*: **Biostrings: Efficient manipulation of biological strings.** R package version 2.46.0. 2017.
      Reference Source

9.   Hausser J, Strimmer K: **entropy: Estimation of Entropy, Mutual Information and Related Quantities.** *Cran R.* 2014.
      Reference Source

10.   Wickham H, François R, Henry L, *et al.*: **A Grammar of Data Manipulation Version.** *R J.* 2020; 1–50.

11.   Haider S, Waggott D, Boutros PC: **bedr: Genomic Region Processing using Tools Such as 'BEDTools', 'BEDOPS' and 'Tabix'.** 2019.
      Reference Source

12.   Cayla M, Matthews KR, Ivens AC: **Cayla *et al.*, 2020, Wellcome Open Research - Code availability.** Wellcome Open Research. *Zenodo*. 2020.
      http://www.doi.org/10.5281/zenodo.4135175

13.   Gupta NT, Heiden JAV, Uduman M, *et al.*: **Change-O: A toolkit for analyzing large-scale B cell immunoglobulin repertoire sequencing data.** *Bioinformatics.* 2015; **31**(20): 3356–3358.
      PubMed Abstract | **Publisher Full Text** | **Free Full Text**

14.   Benz C, Urbaniak MD: **Organising the cell cycle in the absence of transcriptional control: Dynamic phosphorylation co-ordinates the *Trypanosoma brucei* cell cycle posttranscriptionally.** *PLoS Pathog.* 2019; **15**(12): e1008129.
      PubMed Abstract | **Publisher Full Text** | **Free Full Text**

15.   Zhang N, Jiang N, Zhang K, *et al.*: **Landscapes of Protein Posttranslational Modifications of African *Trypanosoma* Parasites.** *iScience.* 2020; **23**(5): 101074.
      PubMed Abstract | **Publisher Full Text** | **Free Full Text**

16.   Urbaniak MD, Guther MLS, Ferguson MAJ: **Comparative SILAC proteomic analysis of *trypanosoma brucei* bloodstream and procyclic lifecycle stages.** *PLoS One.* 2012; **7**(5): e36619.
      PubMed Abstract | **Publisher Full Text** | **Free Full Text**

17.   Cayla M, McDonald L, MacGregor P, *et al.*: **An atypical DYRK kinase connects quorum-sensing with posttranscriptional gene regulation in *Trypanosoma brucei*.** *eLife.* 2020; **9**: e51620.
      PubMed Abstract | **Publisher Full Text** | **Free Full Text**

18.   Ooi CP, Rotureau B, Gribaldo S, *et al.*: **The flagellar arginine kinase in *trypanosoma brucei* is important for infection in tsetse flies.** *PLoS One.* 2015; **10**(7): e0133676.
      PubMed Abstract | **Publisher Full Text** | **Free Full Text**

19.   Moretti NS, Cestari I, Anupama A, *et al.*: **Comparative Proteomic Analysis of Lysine Acetylation in *Trypanosomes*.** *J Proteome Res.* 2018; **17**(1): 374–385.
      PubMed Abstract | **Publisher Full Text**

20.   Lott K, Li J, Fisk JC, *et al.*: **Global proteomic analysis in trypanosomes reveals unique proteins and conserved cellular processes impacted by arginine methylation.** *J Proteomics.* 2013; **91**: 210–225.
      PubMed Abstract | **Publisher Full Text** | **Free Full Text**

21.   Fisk JC, Li J, Wang H, *et al.*: **Proteomic analysis reveals diverse classes of arginine methylproteins in mitochondria of trypanosomes.** *Mol Cell Proteomics.* 2013; **12**(2): 302–311.
      PubMed Abstract | **Publisher Full Text** | **Free Full Text**

22.   Horn D: **Codon usage suggests that translational selection has a major impact on protein expression in trypanosomatids.** *BMC Genomics.* 2008; **9**: 2.
      PubMed Abstract | **Publisher Full Text** | **Free Full Text**

23.   Shannon CE: **A mathematical theory of communication.** *Bell Syst Tech J.* 1948; 623–656.
      Reference Source

24.   Cayla M, Matthews KR, Ivens AC, *et al.*: **Cayla *et al.*, 2020, Wellcome Open Research - Extented data.** *Wellcome Open Research*. 2020.
      http://www.doi.org/10.5281/zenodo.4135190

25.   Coletta A, Pinney JW, Solís DYW, *et al.*: **Low-complexity regions within protein sequences have position-dependent roles.** *BMC Syst Biol.* 2010; **4**: 43.
      PubMed Abstract | **Publisher Full Text** | **Free Full Text**

26.   Cayla M, Matthews KR, Ivens AC: **Cayla *et al.*, 2020, Wellcome Open Research - Underlying data [Data set].** Wellcome Open Research. *Zenodo*. 2020.
      http://www.doi.org/10.5281/zenodo.4135199

27.   Martin EW, Mittag T: **Relationship of Sequence and Phase Separation in Protein Low-Complexity Regions.** *Biochemistry.* 2018; **57**(17): 2478–2487.
      PubMed Abstract | **Publisher Full Text** | **Free Full Text**

28.   Wang J, Choi JM, Holehouse AS, *et al.*: **A Molecular Grammar Governing the Driving Forces for Phase Separation of Prion-like RNA Binding Proteins.** *Cell.* 2018; **174**(3): 688–699.e16.
      PubMed Abstract | **Publisher Full Text** | **Free Full Text**

29.   Grimaldi G, Catara G, Palazzo L, *et al.*: **PARPs and PAR as novel pharmacological targets for the treatment of stress granule-associated disorders.** *Biochem Pharmacol.* 2019; **167**: 64–75.
      PubMed Abstract | **Publisher Full Text**

30.   Hofweber M, Dormann D: **Friend or foe—Post-translational modifications as regulators of phase separation and RNP granule dynamics.** *J Biol Chem.* 2019; **294**(18): 7137–7150.
      PubMed Abstract | **Publisher Full Text** | **Free Full Text**

31.   Urbaniak MD, Martin DMA, Ferguson MAJ: **Global quantitative SILAC phosphoproteomics reveals differential phosphorylation is widespread between the procyclic and bloodstream form lifecycle stages of *Trypanosoma brucei.*** *J Proteome Res.* 2013; **12**(5): 2233–2244.
      PubMed Abstract | **Publisher Full Text** | **Free Full Text**

32.   Ooi CP, Benz C, Urbaniak MD: **Phosphoproteomic analysis of mammalian infective *Trypanosoma brucei* subjected to heat shock suggests atypical mechanisms for thermotolerance.** *J Proteomics.* 2020; **219**: 103735.
      PubMed Abstract | **Publisher Full Text**

33.   Lueong S, Merce C, Fischer B, *et al.*: **Gene expression regulatory networks in Trypanosoma brucei: Insights into the role of the mRNA-binding proteome.** *Mol Microbiol.* 2016; **100**(3): 457–471.
      PubMed Abstract | **Publisher Full Text**

34.   Malinovska L, Palm S, Gibson K, *et al.*: ***Dictyostelium discoideum* has a highly Q/N-rich proteome and shows an unusual resilience to protein aggregation.** *Proc Natl Acad Sci U S A.* 2015; **112**: E2620–E2629.
      PubMed Abstract | **Publisher Full Text** | **Free Full Text**

35.   Wippich F, Bodenmiller B, Trajkovska MG, *et al.*: **Dual specificity kinase DYRK3 couples stress granule condensation/ dissolution to mTORC1 signaling.** *Cell.* 2013; **152**(4): 791–805.
      PubMed Abstract | **Publisher Full Text**

36.   Kershaw CJ, Nelson MG, Lui J, *et al.*: **Integrated multi-omics reveals common properties underlying stress granule and P-body formation.** *bioRxiv.* 2020; 2020.05.18.102517.
      Publisher Full Text

37.   Cassola A, De Gaudenzi JG, Frasch AC: **Recruitment of mRNAs to cytoplasmic ribonucleoprotein granules in trypanosomes.** *Mol Microbiol.* 2007; **65**(3): 655–670.
      PubMed Abstract | **Publisher Full Text**

38.   Cassola A: **RNA Granules Living a Post-Transcriptional Life: the Trypanosome's Case.** *Curr Chem Biol.* 2011; **5**(2): 108–117.
      PubMed Abstract | **Publisher Full Text** | **Free Full Text**

39.   Fritz M, Vanselow J, Sauer N, *et al.*: **Novel insights into RNP granules by employing the trypanosome's microtubule skeleton as a molecular sieve.** *Nucleic Acids Res.* 2015; **43**(16): 8013–8032.
      PubMed Abstract | **Publisher Full Text** | **Free Full Text**

40.   Subota I, Rotureau B, Blisnick T, *et al.*: **ALBA proteins are stage regulated during trypanosome development in the tsetse fly and participate in differentiation.** *Mol Biol Cell.* 2011; **22**(22): 4205–4219.
      PubMed Abstract | **Publisher Full Text** | **Free Full Text**

41.   Brangwynne CP, Mitchison TJ, Hyman AA: **Active liquid-like behavior of nucleoli determines their size and shape in *Xenopus laevis* oocytes.** *Proc Natl Acad Sci U S A.* 2011; **108**(11): 4334–4339.
      PubMed Abstract | **Publisher Full Text** | **Free Full Text**

42.   Almagro Armenteros JJ, Sønderby CK, Sønderby SK, *et al.*: **DeepLoc: prediction of protein subcellular localization using deep learning.** *Bioinformatics.* 2017; **33**(21): 3387–3395.
      PubMed Abstract | **Publisher Full Text**

43.   Dean S, Sunter JD, Wheeler RJ: **TrypTag.org: A Trypanosome Genome-wide Protein Localisation Resource.** *Trends Parasitol.* 2017; **33**(2): 80–82.
      PubMed Abstract | **Publisher Full Text** | **Free Full Text**

Open Peer Review

Current Peer Review Status: ✓ ✓

Version 2

Reviewer Report 19 November 2020

https://doi.org/10.21956/wellcomeopenres.18062.r41489

✓ **Susanne Kramer**

Zell- und Entwicklungsbiologie, Universität Würzburg, Würzburg, Germany

I'm happy with the changes. All my concerns were addressed.

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: RNA biology of kinetoplastida, RNA granules, phase separation

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Version 1

Reviewer Report 12 October 2020

https://doi.org/10.21956/wellcomeopenres.17894.r40535

✓ **Sebastian Hutchinson** [ID]

Trypanosome Cell Biology Unit and INSERM U1201, Institut Pasteur, Paris, France

This manuscript describes the identification of protein low complexity regions by Shannon's entropy method in *Trypanosoma brucei,* and the bioinformatic characterisation of those regions. The authors find low complexity regions in approximately half of the proteome. Instances of polar LCRs are overrepresented in N and C termini of proteins, and in nucleic acid binding proteins.

Finally, by comparing LCRs to know post translational modifications the authors find that LCRs are frequently associated with phosphorylation events. This is a useful analysis which I believe will offer new lines of inquiry for the *T. brucei* community.

Minor points:

As the authors state that in the abstract that the purpose of the study was to "generate a substantially more comprehensive genome-wide survey of LCRs", I feel it would be useful to discuss their data in comparison with what is available on TriTrypDB.

Referencing: specific instances below (I think the appropriate references are in the text, just missing from these statements):
- ○ Introduction "By inference from what is known for other model eukaryotes, it is plausible that the aggregation into membraneless structures could be influenced by the presence and/or distribution of LCRs in the protein sequences themselves."

- ○ Results "The composition of LCRs can be highly divergent and has been shown to play a major role in, for example, protein liquid-liquid phase separation and the formation of membraneless organelles."

Please specify TriTrypDB versions. I noticed that the R script gave an error as the "current version" used in the script is not the "current" one.

In running the authors R script, I noticed several Variant surface glycoproteins in the datasets. VSG encoding genes seem to have a variety of annotations on TriTryp. "variant surface protein, putative" and "Variant Surface Glycoprotein, putative" (upper case sensitivity in grep seems to be the reason).

Supplement file 1 is reported in the text associated to
http://www.doi.org/10.5281/zenodo.4015044 but is
at http://www.doi.org/10.5281/zenodo.4015084[1].

References
1. Mathieu C, Matthews KR, Ivens AC: Cayla et al., 2020, Wellcome Open Research - Underlying data. 2020. Publisher Full Text | Reference Source

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and is the work technically sound?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?

Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Trypanosoma brucei molecular biology and bioinformatic analysis

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Author Response 27 Oct 2020
Mathieu Cayla, University of Edinburgh, Edinburgh, UK

Reviewer Report 12 Oct 2020
Sebastian Hutchinson Trypanosome Cell Biology Unit and INSERM U1201, Institut Pasteur, Paris, France

This manuscript describes the identification of protein low complexity regions by Shannon's entropy method in Trypanosoma brucei, and the bioinformatic characterisation of those regions. The authors find low complexity regions in approximately half of the proteome. Instances of polar LCRs are overrepresented in N and C termini of proteins, and in nucleic acid binding proteins. Finally, by comparing LCRs to know post translational modifications the authors find that LCRs are frequently associated with phosphorylation events. This is a useful analysis which I believe will offer new lines of inquiry for the T. brucei community.
Minor points:
As the authors state that in the abstract that the purpose of the study was to "generate a substantially more comprehensive genome-wide survey of LCRs", I feel it would be useful to discuss their data in comparison with what is available on TriTrypDB.
  ○ We thank the reviewer for this comment. A discussion comparing the results obtained with SEG algorithm and the entropy methodology has now been added in the paper P8L17-33 and supplement figure S3 and the data were included in supplement file 2.

Referencing: specific instances below (I think the appropriate references are in the text, just missing from these statements):
  1. Introduction "By inference from what is known for other model eukaryotes, it is plausible that the aggregation into membraneless structures could be influenced by the presence and/or distribution of LCRs in the protein sequences themselves."
  2. Results "The composition of LCRs can be highly divergent and has been shown to play a major role in, for example, protein liquid-liquid phase separation and the formation of membraneless organelles."

  ○ Done P6L13 and P11L4.
Please specify TriTrypDB versions. I noticed that the R script gave an error as the "current version" used in the script is not the "current" one.

- As specified in the material and method section – 'InterPro domain mapping', the version used at the time of the analysis was the release 46. We have now also added that specification in the LCR identification section P4L30.
- Concerning the code giving an error as "the current version", althoughthat the reviewer is strictly correct, a comment in the script specifies that the link would need to be changed according to the organism and the date of analysis:

Download the proteome and interpro datasets
NOTE:: wget file link names will depend on the organism and date of download
In running the authors R script, I noticed several Variant surface glycoproteins in the datasets. VSG encoding genes seem to have a variety of annotations on TriTryp. "variant surface protein, putative" and "Variant Surface Glycoprotein, putative" (upper case sensitivity in grep seems to be the reason).

- We thank the reviewer for spotting that error. A new version of the script has been uploaded in the code availability section. However, the 59 variant surface genes that were left, were filtered out for downstream analysis and therefore do not affect the results obtained.

Supplement file 1 is reported in the text associated to http://www.doi.org/10.5281/zenodo.4015044 but is at http://www.doi.org/10.5281/zenodo.4015084.

- We thank the reviewer for highlighting that mistake, generated during the editorial processing.

Competing Interests: No competing interests were disclosed.

Reviewer Report 06 October 2020

https://doi.org/10.21956/wellcomeopenres.17894.r40536

?

Susanne Kramer

Zell- und Entwicklungsbiologie, Universität Würzburg, Würzburg, Germany

In this study, the authors have used the Shannon's entropy method to define low complexity regions in the proteome of Trypanosoma brucei. They find LCRs in 42% of all proteins, and have done extensive bioinformatic studies to find common features among the proteins with LCRs in their N or C termini or central region. They used a range of published data on PTMs to investigate negative and positive enrichments among their LCRs. This study is well done and useful, given the current progress in understanding liquid liquid phase separation as a novel contributor to cellular organisation. I only have a few comments.

The abstract is very general and would benefit from some numbers (how many proteins with LCRs, how enriched are the phosphorylations).

The authors show the distribution of amino acid frequency for trypanosomes. How does this compare with other protozoa and opisthokonts; in other words, how unique is this pattern to trypanosomes?

A discussion on how these new LCR data compare with the currently available LCR annotations with the SEG algorithm is missing. The new LCR data should be integrated into TriTrypDB.

Go term analysis: I felt these automatic predictions should be presented in a little less raw version. Some can be pooled (in particular features with very few proteins are highly error prone in this kind of analysis) and others can be omitted (Go-features like 'binding' or 'molecular function' are not very meaningful). I m also not sure whether the p-value is the best way to sort the data, at least the fold enrichment (which is more intuitive) should be shown in addition. RNA binding proteins: As this is a major (and highly interesting) point of this paper, it would be very interesting to explore at least one experimental dataset too, for example the oligo dT binders[1].

Posttranslational modifications: For all of these positive and negative enrichments, were the differences in amino acid frequencies between LCR and whole proteome considered? In other words, can part of the enrichment in phosphorylation in the LCRs be explained by the fact, that these simply contain a higher proportion of serine residues? (and respectively for all the other PTMs).

References
1. Lueong S, Merce C, Fischer B, Hoheisel JD, et al.: Gene expression regulatory networks in Trypanosoma brucei: insights into the role of the mRNA-binding proteome.*Mol Microbiol*. **100** (3): 457-71 PubMed Abstract | Publisher Full Text

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and is the work technically sound?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: RNA biology of kinetoplastida, RNA granules, phase separation

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 27 Oct 2020
Mathieu Cayla, University of Edinburgh, Edinburgh, UK

Reviewer Report 06 Oct 2020
Susanne Kramer Zell- und Entwicklungsbiologie, Universität Würzburg, Würzburg, Germany

In this study, the authors have used the Shannon's entropy method to define low complexity regions in the proteome of Trypanosoma brucei. They find LCRs in 42% of all proteins, and have done extensive bioinformatic studies to find common features among the proteins with LCRs in their N or C termini or central region. They used a range of published data on PTMs to investigate negative and positive enrichments among their LCRs. This study is well done and useful, given the current progress in understanding liquid liquid phase separation as a novel contributor to cellular organisation. I only have a few comments.

The abstract is very general and would benefit from some numbers (how many proteins with LCRs, how enriched are the phosphorylations).
   ○ The abstract has now been updated to include numbers, as suggested P3.

The authors show the distribution of amino acid frequency for trypanosomes. How does this compare with other protozoa and opisthokonts; in other words, how unique is this pattern to trypanosomes?
   ○ As indicated in the text, LCRs of *Trypanosoma brucei* are not enriched in asparagine. This observation differs from what has been seen in *Plasmodium falciparum* and yeast prion-like domains. However, this enrichment in asparagine has not been observed in other Plasmodium species.
The under representation of this polar amino acid could be compensated, in the LCRs of *T. brucei*, by the over-representation of serine and glutamine residues. The over-representation of serines in LCRs was already described in Humans (Martin and Mittag, Biochemistry, 2018). The serine enrichment, as well as the presence of glutamine is thought to influence the fluidity of the aggregates by promoting hardening through the formation of labile-cross-beta-sheets.
These comparisons with other organisms, highlighting the unique features of LCRs of *T. brucei*, are present in the discussion.
A discussion on how these new LCR data compare with the currently available LCR annotations with the SEG algorithm is missing. The new LCR data should be integrated into TriTrypDB.
   ○ We thank the reviewer for this comment. A discussion comparing the current SEG

data to the entropy analysis has now been included in the Results section P8L17-33 and supplement figure S3 and the data were included in supplement file 2.
- ○ We also agree with the reviewer that these data should be included in the TriTrypDB and have initiated dialogue with the database curators to do so.

Go term analysis: I felt these automatic predictions should be presented in a little less raw version. Some can be pooled (in particular features with very few proteins are highly error prone in this kind of analysis) and others can be omitted (Go-features like 'binding' or 'molecular function' are not very meaningful). I m also not sure whether the p-value is the best way to sort the data, at least the fold enrichment (which is more intuitive) should be shown in addition. RNA binding proteins: As this is a major (and highly interesting) point of this paper, it would be very interesting to explore at least one experimental dataset too, for example the oligo dT binders.
- ○ Regarding the Go term analysis, we have now updated the Figures 6 and 8 to include the representation of the fold changes (gradient) and the number of proteins used for each molecular function (size of the dots), as suggested by the reviewer. The generic terms "binding" and "molecular function" have also been filtered out. However, we believe that ordering the data by p-value is the most appropriate way since this reflects the significance of the value unlike fold change, Therefore, we did not modify this representation.
- ○ We thank the reviewer for the suggestion of using the mRNA-binding proteins dataset published by Lueong et al. In this dataset, 155 proteins have been confidently identified as mRNA binding proteins. 99 proteins possess a LCR with 42 of them having a LCR in their C-terminal region. 82 of these proteins are phosphorylated with 35 on an LCR. This analysis confirms our observation that RNA binding proteins are rich in LCR. This discussion point has been added in the text P15L5-12 and P16L41-45 and results have been included in supplement file 6.

Posttranslational modifications: For all of these positive and negative enrichments, were the differences in amino acid frequencies between LCR and whole proteome considered? In other words, can part of the enrichment in phosphorylation in the LCRs be explained by the fact, that these simply contain a higher proportion of serine residues? (and respectively for all the other PTMs).
- ○ The reviewer raised a very interesting question. To look if the relative abundance of phosphorylable residues in LCRs (mainly serine) compared to the rest of the proteome could explain the enrichment of phosphorylation in these regions, we normalised the percentage of each post-translational modifications by the relative frequency of the residue on which they have been identified. The results can now be found in Figure 12 and P14L33-P15L4. Briefly, no change is observed after normalisation by the frequency of the corresponding residue, confirming our observations that phosphorylation events are enriched in LCRs.

Competing Interests: No competing interests were disclosed.