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Large-scale quantitative profiling of the Old English verse tradition

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The corpus of Old English verse is an indispensable source for scholars of the Indo-European tradition, early Germanic culture and English literary history. Although it has been the focus of sustained literary scholarship for over two centuries, Old English poetry has not been subjected to corpus-wide computational profiling, in part because of the sparseness and extreme fragmentation of the surviving material. Here we report a detailed quantitative analysis of the whole corpus that considers a broad range of features reflective of sound, metre and diction. This integrated examination of fine-grained features enabled us to identify salient stylistic patterns, despite the inherent limitations of the corpus. In particular, we provide quantitative evidence consistent with the unitary authorship of *Beowulf* and the Cynewulfian authorship of *Andreas*, shedding light on two longstanding questions in Old English philology. Our results demonstrate the usefulness of high-dimensional stylometric profiling for fragmentary literary traditions and lay the foundation for future studies of the cultural evolution of English literature.

Composed between roughly 600 and 1100, Old English literature represents the earliest phase of literary production in English. Although it is assumed that most works of Old English literature have not survived, the remainder nevertheless encompass not only a broad time period but also multiple streams of influence—Germanic, Christian, and classical Greek and Roman—as well as diverse genres such as heroic poetry, riddles and biblical works[1]. This rich corpus also contains one of the masterpieces of English literature—the epic poem *Beowulf*. Both for its historical importance and its aesthetic merit, Old English literature has attracted the attention of generations of researchers and creative writers, including W. H. Auden, Ezra Pound, Seamus Heaney and J. R. R. Tolkien[2,3].

Within Old English literature, the extant corpus of poetry is relatively small; it comprises around 350 texts, of which over 300 are shorter than 1,000 words in length (Supplementary Fig. 1). The poems are preserved in manuscript copies that provide no direct information about the context in which they originated. Moreover, damage to these manuscripts has frequently resulted in the loss of text, and rendered many poems more or less incomplete. The sparseness and fragmentation of the corpus poses a serious challenge for literary study of the tradition. For instance, it is almost impossible to know how representative, original or popular a particular literary feature might have been when we possess so few comparanda, the authorship or date of extant works is often unknown or uncertain, and the compositional technique of Old English poets is similarly mysterious. Additional difficulties arise due to uncertainties of register, genre and dialect, which complicate efforts to relate literary works to particular chronological or geographical contexts[4]. Lacking the extensive corpora and contextual evidence that are taken for granted in the study of modern literatures, Old English scholars face considerable difficulties when dealing with questions of literary history. Some scholars have even suggested that the surviving materials are insufficient for meaningful conclusions to be drawn on the basis of linguistic analysis[5].

One approach to these problems is to extract more information from the material we already have; rather than examining larger and therefore less frequent components of the literature, such as characters or scenes, we can focus on much smaller units, ranging from individual phrases to word segments and even pauses. A benefit of analysing smaller features is that they are necessarily numerous even within a sparse corpus. By combining attention to multiple features of this kind, it is possible to create a high-dimensional profile of a text, or part of a text, in relation to all others in the corpus. Although manual counting of individual small features may be feasible, the generation of high-dimensional profiles generally requires the application of computational techniques. Such techniques have not been employed extensively in the study of Old English literature compared with modern English or even other pre-modern traditions such as Latin[6–9]. Where computation has been brought to bear on Old English texts, the research has generally been limited to a small set of literary features or a handful of specific works[10–15]. The most significant application of modern stylometric techniques to Old English verse has been the development of 'lexomics' by Drout et al., which involves the use of vocabulary frequency data and hierarchical clustering to discern literary similarities[12,15]. Lexomic methods have been applied to several important problems, including profiling stylistic differences across *Beowulf* and works associated with Cynewulf (the first author to whom multiple English poems can be attributed)[12,15]. Our methodology complements and extends this earlier work in three principal ways: (1) the use of non-lexical features, especially sense-pauses and metre; (2) attention to specialized word usage, in particular rare nominal compounds; and (3) adaptation of clustering techniques to focus on sequences of characters rather than whole words.

Here, we report a large-scale computational analysis of the entire Old English verse corpus. Our central innovation is to extract information on a wide range of fine-grained features—covering aspects of sound, metre and diction—to discern meaningful stylometric patterns within the corpus as they relate to questions of authorship

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and literary resemblance. Additionally, we introduce a variety of computational tools tailored to the specifics of Old English, which in turn may be valuable in the analysis of other literary and linguistic traditions. We use our corpus-wide profiling to address two longstanding questions in the study of Old English literature: whether *Beowulf* is a unified work of a single author or a combination of multiple texts[16,17], and whether the anonymous work *Andreas* was written by the poet Cynewulf[18–20]. We show that several orthogonal stylistic metrics do not differ between possible partitions of *Beowulf*, which is consistent with the hypothesis that portions of the poem were not produced separately, or, if they were, that the styles are remarkably uniform. Although this uniformity cannot adjudicate definitively between single or multiple authorship, it militates against a view of the work either as constructed from chronologically disparate poems or as markedly shaped by scribal intervention. Our results also show strong similarity between *Andreas* and other works signed by Cynewulf. Our approach has implications not only for the practice of literary criticism but also for the study of cultural evolution, by generating data on properties of language that probably evolved from this early tradition through Middle and Modern English[21]. While computational analyses cannot definitively resolve longstanding problems arising from a dearth of empirical evidence and theoretical disagreements about cultural production, nevertheless, they do offer additional, quantifiable data that affect the plausibility of various critical hypotheses.

Functional *n*-grams are short (typically syllable-length) substrings of natural language text (for example, the substring 'ab' in the sentence 'Abel elaborated about his intentions.'), which have proven useful in previous analyses of both English and Latin literary style, and for authorship attribution, as works by the same author tend to have similar phonetic profiles[9,22–25]. In verse corpora, patterns of functional *n*-gram usage can reflect poetic sound play and aural effects. To identify phonetically distinctive poems within the Old English corpus, we computed for each text:

$$\sum_{i=1}^{5} |f_{i,\mathrm{t}} - f_{i,\mathrm{c}}|$$

where $f_{i,\mathrm{t}}$ denotes the frequency of the ith most common n-gram in the text, and $f_{i,\mathrm{c}}$ denotes the corpus-wide frequency of that n-gram. Figure 1 shows a plot of this metric against text length for functional trigrams. Unsurprisingly, numerous short poems appear to have patterns of functional n-gram usage that differ from the bulk corpus. However, of greater interest is that 3 longer texts (each longer than 125 verses) exhibit unusual patterns of functional trigram usage relative to other texts of comparable length. Profiling of functional bigrams and four-grams similarly identified these same three texts—*Widsith*, *Psalm 118* and *Maxims II*—as anomalous (Supplementary Fig. 2). In other words, these three texts exhibit pronounced deviations from phonetic norms that are otherwise relatively homogeneous throughout the corpus of Old English poetry.

These results prompted us to consider why the phonetics of those three texts should appear distinct from the rest of the corpus. In the case of *Widsith*, the anomaly is likely to be attributed to its preponderance of proper names, which are clustered in 3 lengthy catalogues (lines 18–35, 57–87 and 112–124) that might well have circulated orally before the poem's composition[26]. If proper names are the cause, the anomalous phonetics of *Widsith* might be an epiphenomenal reflection of a broader phonetic division between the lexicon and the onomasticon of Old English. *Maxims II* shares with *Widsith* the strong possibility that its author drew on pre-existing material, consisting as it does of gnomic statements that could have circulated in smaller or larger catalogues outside the poem. As such, it is plausible that its anomalous *n*-gram profile reflects phonetic differences between the archaic constituent material of *Maxims II*

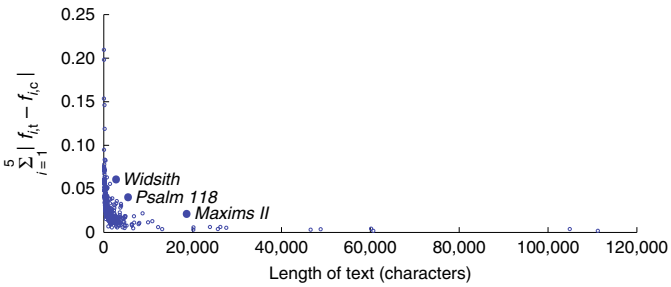

Fig. 1 | Corpus-wide phonetic profiling of literature. Plot of the cumulative difference in functional trigram frequency (for the five most common trigrams) against text length. Each dot denotes one text. Three anomalous texts are highlighted and labelled.

and the later linguistic material of which the bulk of the Old English corpus is comprised. *Psalm 118* is peculiar less for its content than for its aberrant metrics and late prosaic vocabulary. There is frequent lexical and syntactic repetition in *Psalm 118*, whereas *Widsith* and *Maxims II* exhibit a far greater degree of structural repetition. As a close translation of a Latin source that might have originated as an interlinear gloss, *Psalm 118* shares with *Widsith* and *Maxims II* the more essential characteristic that its poet's linguistic freedom was exceptionally constrained by his literary project. Our tests suggest that, under normal conditions, Old English poets generated works that were homogeneous in terms of their phonetic profile. However, this homogeneity was disturbed when a particular literary agenda strongly influenced a poet's diction or source use.

In addition to analysing the phonetics of the Old English corpus in its entirety, we also sought to address longstanding questions regarding particular texts, beginning with *Beowulf*. Scholarship on *Beowulf* has long entertained debate as to whether the poem is a product of unitary or composite authorship. During the nineteenth century, many prominent scholars subscribed to a theory of composite authorship, which held that *Beowulf* consisted of various pagan lays joined together by Christian editors and interpolators[16]. By the middle of the twentieth century, this view possessed few adherents on account of demonstrations by Klaeber[27] and Tolkien[2] that a coherent Christian perspective pervades the entire poem. Literary critics working in the immediate aftermath of these studies thus tended to premise their work on the assumption that *Beowulf* is the masterwork of a single poet[28,29]. However, theories of composite authorship continued to be propounded throughout the twentieth century, with several scholars arguing that *Beowulf* was put together by a scribal editor who combined two distinct texts: one containing the hero's fights with Grendel and his mother, and the other containing the hero's fight with the dragon[30–32]. It has also been argued that scribal interference in the textual transmission of *Beowulf* might have been sufficiently pervasive to render it an essentially composite work[33]. Yet, in the most recent and comprehensive study on the dating and authorship of *Beowulf*, Neidorf[17] adduced a wide range of lexical, metrical, stylistic and palaeographical evidence in support of the contention that the extant manuscript of *Beowulf* faithfully preserves the unitary creation of one poet who composed around the year 700. Here, we offer multiple, orthogonal pieces of quantitative evidence consistent with Neidorf's view.

As noted above, quantitative analysis of stylistic homogeneity in *Beowulf* has tended to focus on word-based features. To investigate the question further, we devised a broad-spectrum feature set that reflects versification, metre and an aspect of diction (nominal compounds) of particular importance in Old English verse. We first considered sense-pauses, which are breaks in speech typically denoted by any punctuation mark other than a comma. Although sense-pause analysis has not been undertaken previously for Old

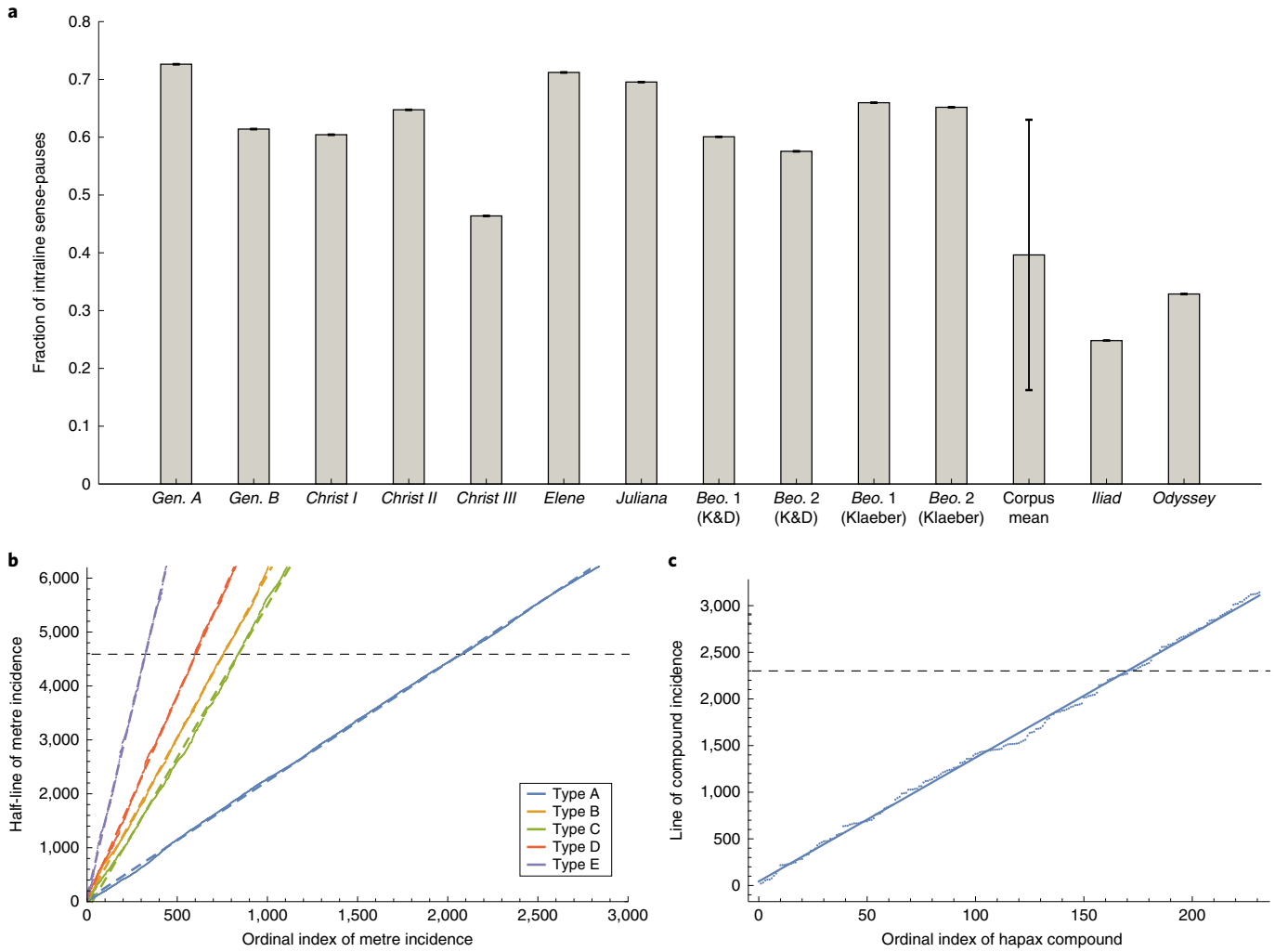

Fig. 2 | Stylistic homogeneity of *Beowulf*. **a**, Ratio of intraline to total sense-pauses for the partition of *Beowulf*, the mean of all texts in the Old English verse corpus, some salient individual texts, and Homer's *Iliad* and *Odyssey*. The error bar for the corpus mean denotes one s.d. of the ratios for all of the texts. *Beo., Beowulf; Gen., Genesis;* K&D, Krapp and Dobbie. **b**, Rate of use of different metres (types A, B, C, D and E) in *Beowulf*. The coloured diagonal lines are linear fits. The dotted horizontal line indicates line 2,300 of the text. **c**, Rate of use of hapax compounds in *Beowulf*. The blue line is a linear fit. The dotted horizontal line indicates line 2,300 of the text.

English literature, it has been applied to questions of stylistic evolution in other traditions. For instance, Fitch[34] demonstrated that the ratio of intraline to total sense-pauses is a reliable marker of relative chronology for the tragedies of Sophocles, Seneca and Shakespeare, perhaps because frequent inclusion of sense-pauses not coincident with line breaks reflects a more confident and mature poetic style.

Theories of composite authorship differ as to the exact division between the component poems, but most suggestions (for example, refs. [16,17]) cluster around line 2,300, which is not long after the scribal hand changes in the manuscript (in the middle of line 1,939)[32]. As such, we computed the ratio of intraline to total sense-pauses for lines 1–2,300 and 2,301–end of Krapp and Dobbie's edition of *Beowulf*, along with the corpus-wide average. We calculated that the ratios for lines 1–2,300 and 2,301–end are within 4% of each other (Fig. 2a). As is typical for pre-modern texts, there is no punctuation in the extant Old English manuscripts. However, the editorial judgements about where punctuation is required are guided by various metrical and syntactic regularities, such as those codified in Kuhn's laws, which reliably indicate where clauses begin and end in Old English poetry[35,36]. To account for the remaining freedom in editorial practice regarding punctuation, we analysed another text of *Beowulf* (edited by Klaeber and revised by Bjork, Fulk and Niles). We found that although the absolute value of the ratios varies between the two editions, the relative difference between lines 1–2,300 and 2,301–end is small in both cases. This comparison suggests that while editorial policies may differ, their consistent application ultimately does not obscure the stylistic regularities in a given poem. The consistency in the handling of intraline sense-pauses across both sections of *Beowulf*, in both editions, therefore provides support for the stylistic unity of the poem.

We sought to corroborate the results of the sense-pause analysis of *Beowulf* through comparison with other Old English poems and with ancient Greek epic. *Genesis*—one of the longest extant Old English poems—is known to be the work of multiple authors; it consists of a later poem, called *Genesis B*, which is approximately 600 lines long and is embedded within the remaining 2,300 or so lines of the older main poem, *Genesis A*. Differences between the two poems have previously been identified using other conventional and quantitative techniques[12]. In our research, we found a marked difference in the intraline-to-total sense-pause ratio between *Genesis A* and *B* (Fig. 2a), suggesting that sense-pause analysis can distinguish between passages of Old English verse about

similar subject matter but composed by different poets. Likewise, the ratio differs between all three *Christ* poems (*Christ I–III*), which are widely held to have been composed by multiple authors. In contrast, we find that the ratio is consistent between *Elene* and *Juliana*, both of which are signed Cynewulfian poems. In aggregate, sense-pause differences are significantly higher in the *Genesis* and *Christ* group than in the *Cynewulf* and *Beowulf* group (two-tailed *t*-test, $t(5) = 2.94$; $P = 0.0322$; Cohen's $d = 2.25$; 95% confidence interval (CI) = 0.013 to 0.194).

Like *Beowulf*, the Greek epics *Iliad* and *Odyssey* have also generated much debate about their authorship and composition. Conventionally attributed to a single author—Homer—both works nevertheless clearly originate in a long oral tradition and show signs of considerable evolution in the course of their transmission history, including the possible influence of written versions[37,38]. Since the two Homeric epics have numerous features in common, we hypothesized that they might also have a similar pattern of sense-pauses. However, as shown in Fig. 2a, the *Odyssey* has a higher proportion of intraline sense-pauses relative to the *Iliad*. This difference suggests a slight change of compositional practice between the two Greek poems, whether due to a single poet's stylistic evolution or natural variation across the oral tradition. Had the two parts of *Beowulf* shown a similar or greater disparity in the sense-pause data when compared with the *Iliad* and the *Odyssey*, this might have supported the view that two different poems had been conjoined. However, as it stands, the comparative uniformity of the data suggests that the compositional practice of both parts was the same, at least with respect to sense-pauses.

We then examined the metre of *Beowulf*. We used a scansion devised by Sievers[39], which categorizes half-lines into five major sound patterns denoted as types A, B, C, D and E. We investigated both the total frequency of the five verse-types and their sequence within *Beowulf*. Strikingly, we found that the usage rate of each type of metre remains linear across the entirety of *Beowulf* (Pearson's $r(2{,}860) = 0.998$; $P < 0.001$ for type A; $r(1{,}008) = 0.997$; $P < 0.001$ for type B; $r(1{,}241) = 0.998$; $P < 0.001$ for type C; $r(826) = 0.997$; $P < 0.001$ for type D; $r(445) = 0.995$; $P < 0.001$ for type E), with no discernible shift near line 2,300 and no differences in the frequencies of any particular metrical type (Fig. 2b). To quantify this effect, we computed the difference in slope between the two sections of 1,000 randomly chosen partitions of *Beowulf*; for 4 of the 5 metre types, the mean difference across the partitions is greater than the difference between lines 1–2,300 and 2,301–end (mean = 0.148; s.d. = 0.063 versus 0.0498 for type A; mean = 0.715; s.d. = 0.884 versus 0.331 for type B; mean = 0.717; s.d. = 0.389 versus 0.492 for type C; mean = 0.524; s.d. = 0.697 versus 0.750 for type D; mean = 1.56; s.d. = 1.75 versus 0.575 for type E).

Finally, we considered the distribution of nominal compounds in *Beowulf* and across the Old English verse corpus. Nominal compounds, which are words formed by combining two nouns, are a particularly important aspect of Old English poetry[40]. Examples in Old English include *hron-rad* (whale-road), referring to the sea, and *ban-hus* (bone-house) for the human body. It is generally believed that the number and inventiveness of compounds in a poem is an important marker of literary creativity in the Old English tradition[1,40]. To generate a list of compound words, we identified all entries in the Bosworth–Toller dictionary that are connected with a hyphen and that consist of two separate headwords (hyphens do not appear in native Old English texts)[41]. Supplementary Fig. 3 shows the distribution of compound words by frequency of occurrence. For our initial analysis, we considered inter-authorial differences in the usage of hapax legomena compound words (that is, compounds that appear only once in the entire poetic corpus). The rate of usage of hapax compounds can be very different between authors, as illustrated in Supplementary Fig. 4 for two of the longest extant poems (*Genesis* and *Exodus*). As discussed above, *Genesis* is known to be a composite work. We partitioned *Genesis A* into two random sections that are of comparable length to *Genesis B* and analysed the rate of hapax usage. Linear fits to the data for both sections of *Genesis A* have very similar slopes and differ from the fit to the *Genesis B* data (Supplementary Fig. 4a). In contrast, *Exodus*—the unitary authorship of which has never been in dispute—shows clear homogeneity when analysed in the same way (Supplementary Fig. 4b).

Taken together, these results demonstrate that nominal compounds are an effective metric for Old English stylistic and attribution studies. We therefore constructed a profile of hapax compounds across the whole of *Beowulf* (Fig. 2c). This profile revealed that the rate of compound usage is linear throughout the poem (Pearson's $r(229) = 0.992$; $P < 0.001$), with no change in slope observed around line 2,300. The difference in slope between lines 1–2,300 and 2,301–end is 1.50 (mean = 1.42; s.d. = 1.02 for 1,000 random partitions). The small nonlinearity evident around line 1,500 corresponds to Beowulf's fight with Grendel's mother, which is known to be particularly rich in compound words and other distinctive linguistic features. Accordingly, our analysis of nominal compounds provides further evidence (orthogonal to the sense-pause and metrical data) for the stylistic homogeneity of *Beowulf*.

Our other major results concern a collection of poems written by an author called Cynewulf, or by a broader 'Cynewulfian school'. Four Old English poems—*Elene*, *Juliana*, *Christ II* and *Fates of the Apostles*—conclude with epilogues that ascribe their composition to an otherwise unknown individual named Cynewulf. Many scholars, perceiving stylistic or thematic affinities between these signed works and other anonymous poems, have sought to expand Cynewulf's corpus to include such works as *Andreas*, *Guthlac A/B*, *Christ I/III*, *Judith*, *The Phoenix* and *The Dream of the Rood*, among other poems[42–44]. While once considered products of Cynewulf's own hand, these poems are now more commonly regarded as products of a Cynewulfian school of poetry, if they are believed to possess any meaningful connections to his work at all[45]. The majority of scholars in the past half-century consider Cynewulf to be the author of only the four signed poems, although some have maintained that either *Guthlac B*, *Andreas* or both should be included in his corpus as well, in part based on computational stylometric analysis[12,46]. In addition, whether Cynewulf should even be regarded as the author of the four poems bearing his signature has been questioned, since it is theoretically possible that Cynewulf added his epilogues to poems that other authors originally composed[20,47]. Our tests assuage such doubts by identifying a strong degree of stylistic homogeneity among three of the four signed works of Cynewulf. This homogeneity supports the longstanding assumption that one author composed at least three, and possibly all four, of the poems in question. We also find compelling evidence for an association between *Andreas* and Cynewulf's poetry, which might indicate—in contrast with current opinion—that Cynewulf composed this poem as well.

We first compared the usage of hapax compounds across ten Old English poems, including three control texts not by Cynewulf (*Beowulf*, *Exodus* and *Christ and Satan*), the four signed Cynewulf poems and three poems often associated with Cynewulf (*Andreas*, *Guthlac B* and *The Phoenix*) (Supplementary Fig. 4c). The three control poems, which are thought to be by different authors writing during different periods in Anglo-Saxon history, unsurprisingly show distinct patterns of compound usage. However, the signed Cynewulf poems appear similar both to each other (although *Christ II* shows less affiliation with the other works) and to *Andreas*.

This result prompted us to examine the similarity of *Andreas* to the signed poems of Cynewulf on the basis of a broader range of nominal compounds beyond hapax legomena. In Old English, multiple compounds could denote a single object or concept. There are at least 17 completely distinct compound words in the poetic corpus that denote 'the sea', for example, and 11 compounds meaning 'warrior'[48,49]. Therefore, an author's particular choice of compound

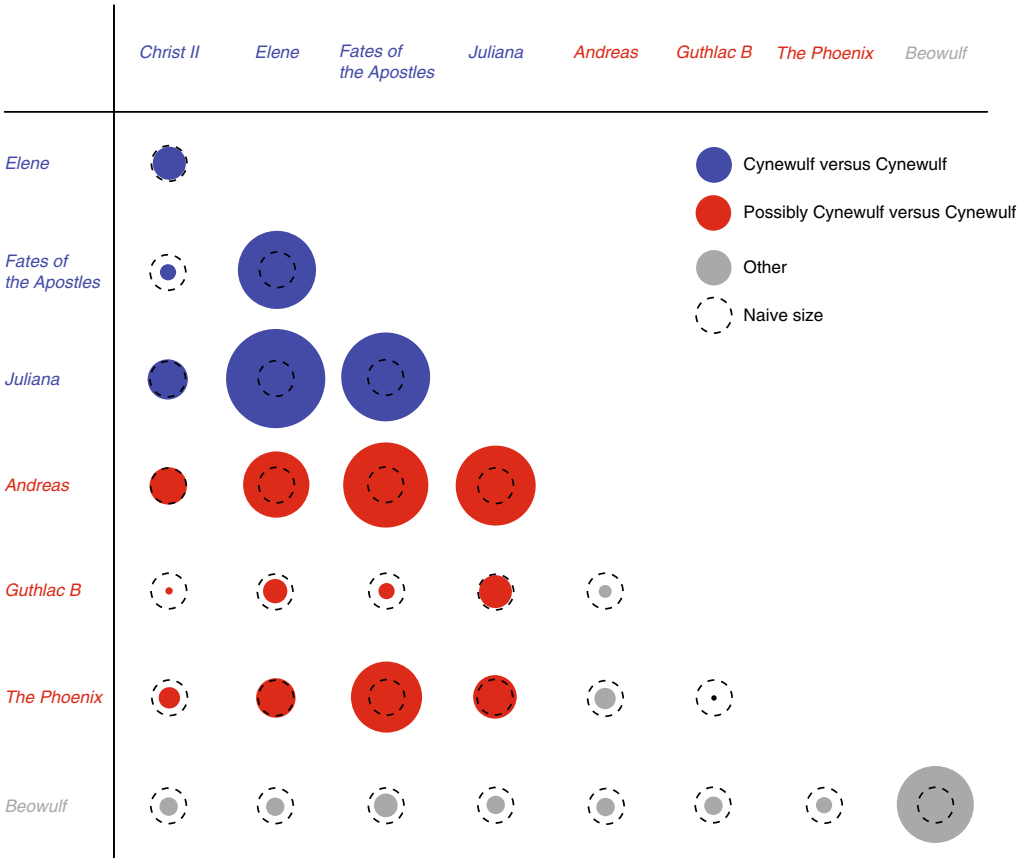

Fig. 3 | Use of nominal compounds is similar between Cynewulf and *Andreas*. Distribution of non-unique compounds in six poems either signed by Cynewulf (blue) or of possible Cynewulfian authorship (red) and in *Beowulf* (grey). The size of each filled circle indicates the number of compounds shared by the corresponding pair of texts. The dotted open circles indicate the expected size if all compounds were distributed at random. The circle in the bottom right is for comparison of *Beowulf* 1–2,300 and *Beowulf* 2,301–end.

might reflect a variety of factors: nuance in meaning, literary influence or other linguistic considerations. Accordingly, the usage of compounds forms an important part of the stylistic profile of an Old English author. We performed a large-scale analysis of non-hapax compounds (excluding only *wuldorcyning*, *heofoncyning* and *heofonrice* ('wonder-king', 'heaven-king' and 'heaven-kingdom', respectively), which occur with extremely high frequency throughout much of the Old English religious poetry) in the verse corpus (Fig. 3). Each solid circle in Fig. 3 denotes the degree of correlation between the two indicated texts, compared with a random distribution of compound words based on their overall frequency and the lengths of the individual poems (dotted circles). By this measure, most of the signed works of Cynewulf are strongly correlated. However, *Christ II* is close to naively correlated, perhaps due to an absence of the compounds that are typically used in the hagiographical poems (*Elene* and *Juliana*) to express the divine relationship between the saint and God (for example, *mundbyrd* ('suffrage/aid')). By the same measure, *Andreas* is strongly correlated with the signed poems of Cynewulf, in agreement with our analysis of hapax compounds (Supplementary Fig. 4). Supporting these observations, at least one of the Cynewulf/Cynewulf (blue circles), Cynewulf/*Andreas* (top line of red circles) and Cynewulf/other (remaining red circles) comparison groups is significantly different from the others (one-way analysis of variance, $F(2,18) = 5.73$; $P = 0.0119$). There is no significant pairwise difference between Cynewulf/Cynewulf and Cynewulf/*Andreas* ($Q(18) = 0.653$; $P = 0.890$; Cohen's $d = -0.244$; 95% CI = −0.952 to 1.37), but there is a significant difference between Cynewulf/Cynewulf and Cynewulf/other ($Q(18) = 3.75$; $P = 0.0410$; Cohen's $d = 1.32$; 95% CI = −1.86 to −0.0354) and between Cynewulf/*Andreas* and Cynewulf/other ($Q(18) = 3.98$; $P = 0.0294$; Cohen's $d = 2.04$; 95% CI = −2.21 to −0.108; all values are from post-hoc Tukey–Kramer tests). Additionally, we observe that *Beowulf* is self-correlated when partitioned into lines 1–2,300 and 2,301–end, which provides further support for unitary composition.

Finally, we used hierarchical agglomerative clustering to investigate the possible association of *Andreas* with the signed poems of Cynewulf on the basis of functional *n*-gram frequencies, which are often used for authorship attribution studies involving literary texts written in Modern English[22,24]. As described in detail in the Methods, we computed the frequencies of the 25 most common trigrams (based on the corpus-wide frequency) in the 50 longest poems, with *Beowulf* partitioned into 2 parts as usual. We used hierarchical agglomerative clustering with this feature set to construct the dendrogram shown in Fig. 4. In line with our other studies, *Beowulf* lines 1–2,300 and 2,301–end cluster together. Furthermore, we find that *Andreas* clusters next to *Elene* and in close proximity to *Juliana*, *Fates of the Apostles* and *Christ I/II/III*. Also in this cluster is *Guthlac A* and *B*, the latter of which Drout et al. associated with the works of Cynewulf based on a clustering analysis with word-level features and a small subset of the Old English verse corpus[12]. To investigate the robustness of these observations, we repeated the clustering with bigrams and four-grams and found that key aspects of the dendrogram structure, including the side-by-side positioning of the two parts of *Beowulf*, and the positioning of *Andreas* next to *Elene* and in close proximity to at least two other signed

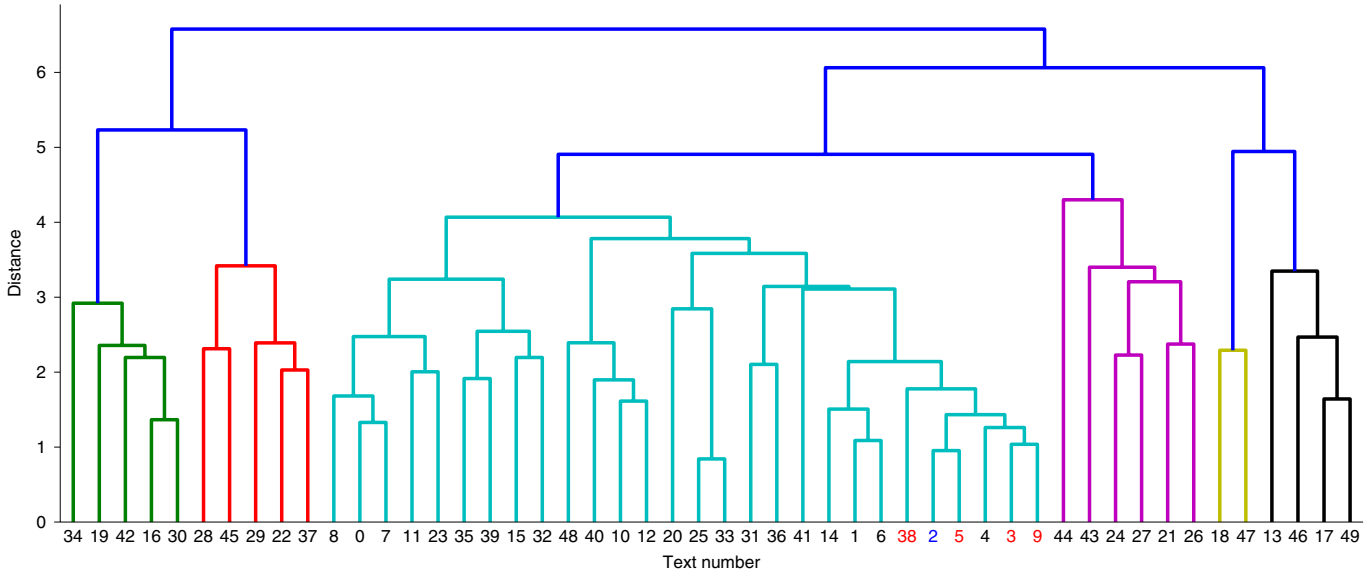

Fig. 4 | *Andreas* clusters with the signed Cynewulfian poems. Dendrogram generated from hierarchical agglomerative clustering of the 50 longest poems, with high-frequency functional trigrams as features. The text numbers are given in Supplementary Table 1; for reference, *Andreas* is text 2 (blue) and the Cynewulfian poems are all red (*Christ*, 3; *Elene*, 5; *Juliana*, 9; and *Fates of the Apostles*, 38). *Beowulf* 1–2,300 is 1, and *Beowulf* 2,301–end is 6.

Cynewulfian poems, were preserved in both cases (Supplementary Fig. 5). Our results, obtained using unsupervised learning and a type of feature (high-frequency functional *n*-grams) well-established in the attribution literature, thus corroborate the stylistic association between Cynewulf and *Andreas* that we identified through analysis of nominal compounds.

The tests we have conducted indicate some ways in which quantitative profiling of the Old English verse tradition can help to answer or raise questions of considerable interest to researchers. With regard to *Beowulf*, our tests tilt the scales of probability between hypotheses that are currently in competition. In contrast, with Cynewulf, our tests encourage scholars to reconsider a possibility that has not been seriously entertained in the past half-century. Our evidence for the stylistic homogeneity of *Beowulf* does not prove that the poem is the work of one individual, but it substantially enhances the probability of unitary authorship, while presenting serious obstacles to those who would advocate for composite authorship or scribal recomposition. Our evidence for the extraordinary affinities between the language of *Andreas* and the language of the signed works of Cynewulf similarly does not prove that *Andreas* was composed by Cynewulf, but it demands that this possibility be explored further in future studies. Orchard, noticing many formulaic expressions shared between *Andreas* and the works of Cynewulf, interpreted the overlap as an indication that the *Andreas* poet read the works of Cynewulf and borrowed extensively from them[19]. Given the lack of decisive evidence, we must acknowledge the possibility, both for *Beowulf* and *Andreas*, that some combination of generic constraints and highly skilled imitation might account for the patterns observed. In each case, however, the most economical explanation of the data is similar: unitary composition of *Beowulf* and Cynewulfian authorship of *Andreas*. Furthermore, in view of the fact that *Andreas* immediately precedes *Fates of the Apostles* in the Vercelli Book (the manuscript in which these two poems are preserved), we might tentatively regard Cynewulf's signature at the end of the latter as a claim to authorship of the former as well.

Our results show the utility of taking a wide range of quantitative approaches to the study of a literary corpus, from simple frequency counts to machine learning. However, crucial to the success of any large-scale profiling is the selection of features used to characterize the corpus[50]. In this case, the variety of features complements and enhances the more established focus on word usage and distribution, incorporating in addition phonetic, formulaic, rhythmic and metrical elements. In doing so, we exploit features that are known to play an important role in the specific tradition (for example, nominal compounds), as well as validate the extension of features that have proven useful for studying traditions in other languages (for example, functional *n*-grams and sense-pauses) to Old English[9,23,34]. In our analysis of Cynewulf, we show that a corpus-specific feature (nominal compounds) can be combined with a general-purpose stylometric technique (unsupervised learning with character *n*-grams) to provide broad-based support for the Cynewulfian authorship of *Andreas*. Moreover, the quantitative tests designed to analyse nominal compounds might be profitably applied in the future to other languages and traditions where aspects of word formation allow for the free combination of simpler lexical items into larger, often unique units, such as agglutinative and polysynthetic languages[51]. In summary, our diverse combination of methods and features constitutes an effective response to the challenges posed by sparse corpora. In particular, the computational analysis of many microscopic features yields results that either cannot be obtained using conventional critical methods or can only be obtained with great difficulty.

Our approach provides a model applicable to other literary traditions. Although potentially useful for the analysis of any corpus of literature, the techniques described here offer a particular advantage for the study of corpora posing similar challenges as Old English poetry, such as other medieval traditions including Old Norse, Old Irish and Old French[52–54]. These languages exhibit many characteristics shared with Old English and are hence especially amenable to the same methods. However, all pre-modern literary traditions suffer to a greater or lesser extent from the problem of text loss, and hence sparse corpora—a situation compounded by the frequent lack of contextual information about the date or authorship of works. Our study suggests some general ways of overcoming or circumventing these challenges, and of finding data that can shed light on both work-specific and corpus-wide questions. Generating quantitative profiles for multiple literary traditions would also represent an initial step towards a quantitative analysis of literature

across cultures. Furthermore, in focusing on a pre-modern tradition—especially one that has seen relatively little computational research—our work broadens the digital humanities' predominant concern with modern literature, and lays the foundation for future diachronic profiling of the English literary tradition with substantial time depth[55].

Methods

Corpora and text processing. The texts of the Old English verse corpus were obtained from the University of Calgary's Online Corpus of Old English Poetry (OCOEP) in UTF-8 encoding (http://www.oepoetry.ca/), which preserves native Old English characters and contains character markings separating half-lines and full-lines, as well as different poems. Except in the following two cases, we used the complete, unaltered OCOEP for corpus-wide analyses: (1) before computing the corpus mean for sense-pauses (Fig. 2a), we aggregated related short texts (for example, the poems of the *Paris Psalter* and the *Meters of Boethius* into single files; and (2) we restricted the hierarchical clustering analysis to the 50 longest texts in the unaltered corpus, with the two partitions of *Beowulf* counted separately (Fig. 4 and Supplementary Fig. 5). Greek texts of the *Iliad* and *Odyssey* were obtained from the Tesserae Project, whose corpus is derived from the Perseus Digital Library (http://www.perseus.tufts.edu/hopper/).

Natural language processing. All natural language processing tasks were performed using Python 3.6.4.

Calculation of sense-pause frequency. Following the definition of Fitch for Greek, Latin and modern English poetry[34], we determined sense-pause frequencies by tabulation of punctuation marks other than commas (., ?, !, ;, :, (,), -, ‘, ’, “ and ”). Any punctuation mark not coincident with a line break was considered to be an intraline sense-pause.

Metrical analysis. To supplement the OCOEP text file of the corpus for metrical analysis, we sought scansions of the longest poems, which were provided by G. Russom[56]. We then identified for *Beowulf* the total frequency of each of the five verse-types, as well as the half-lines on which they occurred.

Identification of nominal compounds. We compiled a list of compound words from the set of hyphenated noun–noun headwords in the online Bosworth–Toller dictionary[41], excluding only one compound (*middangeard*, which means 'middle-land' or 'Earth' and inspired Tolkien's 'Middle Earth'). This compound is used with unusually high frequency (135 instances) and appears to have been used in a manner distinct from other poetic compounds throughout most of the Old English literary period. For each compound in the list, we identified the set of all poems in which that compound occurs, which was used to generate Fig. 2c and Supplementary Fig. 4. We also computed a measure of correlation between poems, defined relative to a random distribution of compound words according to a compound's frequency and the length of the poem. This random distribution of compound words was calculated 10,000 times per compound word to generate a well-defined distribution over the corpus for that word. For Fig. 3, we summed all of the compound words that appear in multiple poems, which quantifies the extent to which each pair of poems has shared compounds. The radius of each circle in Fig. 3 is the ratio of this number to the number predicted by the random distribution.

Hierarchical agglomerative clustering. To generate feature sets for clustering analysis, we determined the 25 most common functional bigrams, trigrams and four-grams in the Old English verse corpus and computed their frequency in the 50 longest poems (with *Beowulf* partitioned into lines 1–2,300 and 2,301–end). We used the scipy implementation of hierarchical agglomerative clustering with the Euclidean distance metric and Ward's linkage criterion to cluster those 50 texts. Dendrograms for the bigram and four-gram clustering are shown in Supplementary Fig. 5, and a dendrogram for the trigram clustering is shown in Fig. 4.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

All datasets are freely and publicly available at https://github.com/qcrit.

Code availability

All custom code is freely and publicly available at https://github.com/qcrit.

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Author contributions

L.N., M.S.K., P.C. and J.P.D. designed the study. M.S.K., M.Y. and J.P.D. performed the study. All authors analysed the results. L.N., M.S.K., P.C. and J.P.D. wrote the manuscript, which was read and approved by all authors.

Competing interests

The authors declare no competing interests.

Additional information

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Study description	The study was mixed-methods, involving quantitative text analysis followed by qualitative literary critical and philological interpretation.
Research sample	The research sample was texts contained in the University of Calgary's Online Corpus of Old English Poetry, which is freely and publicly available at http://www.oepoetry.ca/.
Sampling strategy	No sampling was done; all results are based on exact calculations using some or all of the Online Corpus of Old English Poetry.
Data collection	N/A
Timing	N/A
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Beowulf single-authorship claim is unsupported

Petr Plecháč[1,6] ✉, Andrew Cooper[2,6] ✉, Benjamin Nagy[3,6] ✉ and Artjoms Šeļa[4,5,6] ✉

ARISING FROM L. Neidorf et al. *Nature Human Behaviour* https://doi.org/10.1038/s41562-019-0570-1 (2019)

Neidorf et al.'s quantitative stylometric profile of Old English verse[1] used several methods. Their study supports the unitary authorship of *Beowulf* and Cynewulfian authorship of *Andreas*, on the basis of the ostensible homogeneity of a variety of features. The authors provided full access to their code and data, which demonstrates a praiseworthy commitment to open and replicable science. However, we argue that the methods presented are unsuitable for their purposes. Our replication study uses their unmodified data and text preprocessing steps, identifies errors in their analyses, questions the reliability of their results and shows marked stylistic heterogeneity in *Beowulf*.

The authors' first argument is based on sense-pauses, identified by the presence of certain punctuation marks, all of which are editorial emendations. The suitability of this method for determining authorship has not been established for Old English. The unreliability of this method is demonstrated when the authors find "a marked difference in the intraline-to-total sense-pause ratio between *Genesis A* and *B*" and claim that it "can distinguish between passages of Old English verse about similar subject matter but composed by different poets" (p. 562). In fact, owing to a coding error, both samples are from *Genesis A* and the radically metrically different *Genesis B* is not included in the analysis. The "marked difference" is thus found between two pieces of a single text, the unitary authorship of which has never been questioned.

This metric seems to be unstable even within a single text. When texts are partitioned into 100-line samples, ratios vary (Supplementary Fig. 1). No significant difference is found between samples from *Christ I* and *Christ II* ($t(6)=0.94$; $P=0.3838$), nor between *Christ I* and *Christ III* ($t(9)=1.03$; $P=0.3319$). The significant difference between samples from *Genesis A* and *B* ($t(27)=2.07$; $P=0.0483$) may be explained by their different line lengths (*A*, 9.72 syllables per line; *B*, 12.07 syllables per line), due to *B*'s Saxon origin.

The analysis of *Beowulf*'s metre is inconclusive for at least two reasons. First, the authors analyse only half-line patterns. This choice conforms with nineteenth and twentieth century attempts to categorize metrical features (for example, refs. [2,3] and summarized by ref. [4]). For a modern study, it is an arbitrary choice. The largest unit of Old English verse is the line and some recent studies have refocused on it (for example, refs. [5,6] and summarized by ref. [7]). In any case, the two halves of the line are not statistically independent: the metre of the full line contains rich stylistic information, which is lost in the half-line analysis. By combining Sievers' five types for half-lines into 25 types for full lines, it is clear that figure 2b from the original article conceals pronounced variation in the metrical patterns of *Beowulf*, as shown in Fig. 1 (half-line variation is shown in Extended Data Fig. 1).

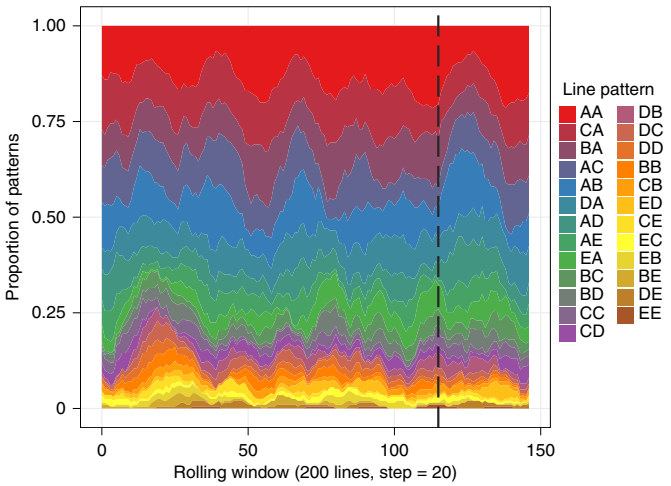

Fig. 1 | Full-line pattern variation. Relative proportions of each pattern, taken over a 200-line rolling window throughout the text. The horizontal line shows the start of the disputed section.

Second, the authors' slope-based methods using Pearson's *r* are not powerful enough to reliably compare pattern distributions (discussed further below). We used the authors' data to perform standard chi-square tests on the half-line metrical patterns as well as the full-line patterns. In addition, we empirically verified the full-line results using simulation. There is no significant difference in the pattern frequencies when measured at half-lines—although it was not shown that half-line frequencies are able to differentiate authors at all. However, a chi-square (goodness-of-fit) test indicates ($P=0.0112$) that the full-line patterns before and after line 2,300 are significantly different. We reiterate that we are not attempting to prove multiple authorship, simply to show that the claim of single authorship is not supported.

The analysis of hapax compounds is methodologically similar to the authors' analysis of metre. Pearson's *r* is measured for a running count of hapax legomenon compounds compared to the line index. Divergences in slope are considered to be an indicator of shift of authorship. In general, this test suffers from an unproven assumption—that the consistency of the slope for count data is an indicator of shared authorship. The fragility of this method is demonstrated in the data used in the original study. When, for example, *Elene* is divided into halves, the difference between the slopes (Extended Data Fig. 2a) is comparable to that reported between *Genesis A* and

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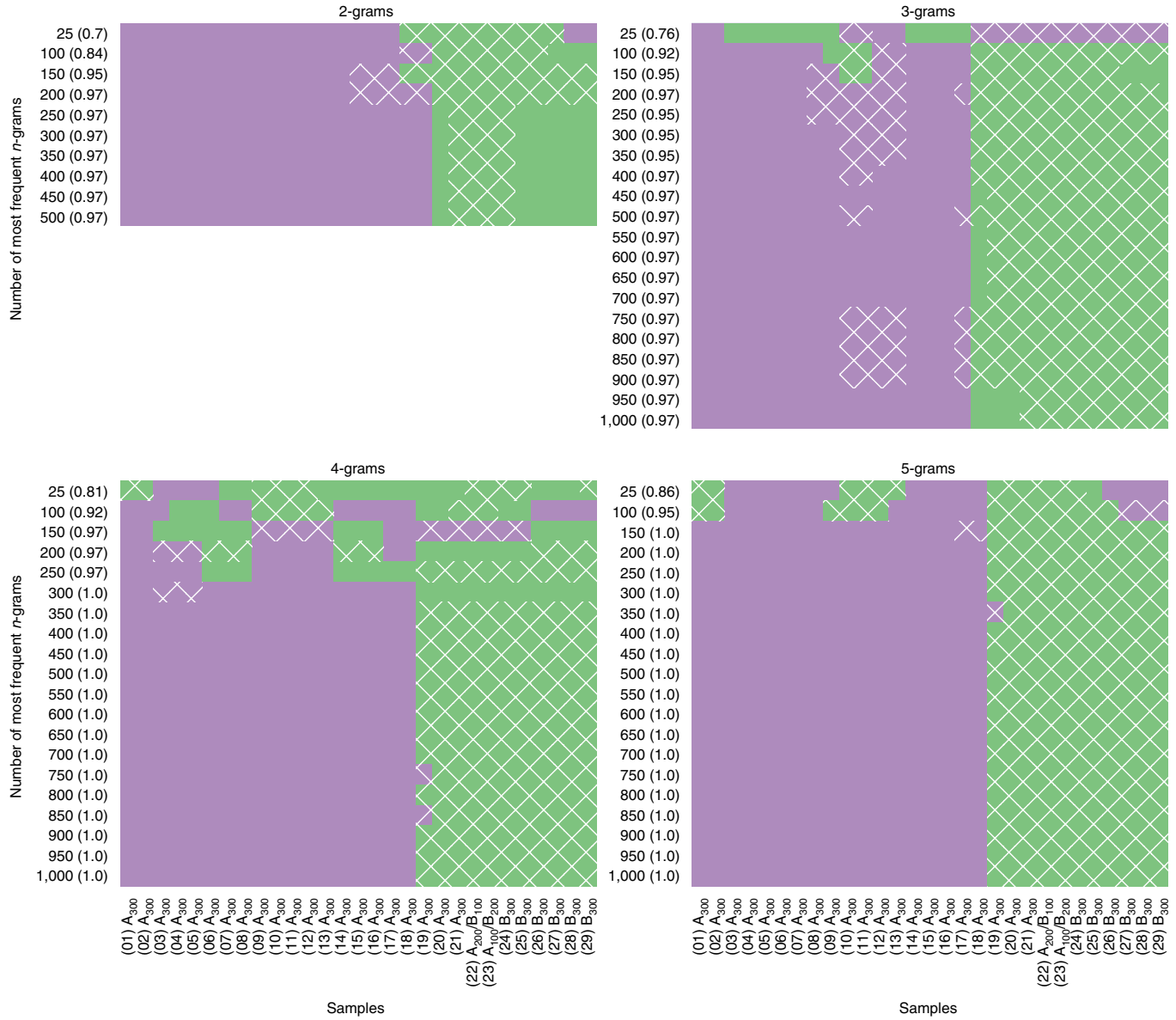

Fig. 2 | Hierarchical agglomerative clustering of overlapping samples of 300 lines from Beowulf based on 25 and 100, 150, 200, … , 1,000 most frequent character 2-, 3-, 4- and 5-grams. Colour indicates to which of the top two clusters the sample belongs. Hatching indicates top two clusters when texts are normalized for spelling variations with þ/ð and eo/io. The number in parentheses (following the label at *y* axes) indicates the accuracy of nearest-neighbour classification with non-overlapping samples.

B (supplementary figure 4a of the original article). We then merged three texts for which no common authorship has been adduced: *Elene*, *Genesis B* and *Phoenix*. The slopes match neatly, with a correlation coefficient comparable to that claimed by the authors for *Beowulf*. The same can be seen when merging *Genesis A* and *Andreas* (Extended Data Fig. 2b). This tendency to show both false positives and false negatives calls into question the ability of this slope-based method to determine authorship and, hence, the reliability of the results reported for *Beowulf*.

Next, the authors compare the number of compounds shared by any pair of poems to a model in which all compounds are randomly distributed. They find a strong correlation between known Cynewulf poems as well as between *Beowulf* lines 1 to 2,300 and *Beowulf* lines 2,301 to end. We were unable to replicate this result. On the basis of our re-analysis of the code and data as provided by the authors, the two parts of *Beowulf* are much less correlated than indicated by their figure. Additionally, by considering additional texts, we show that this method is sensitive to common topics and thus it is expected that the two halves of *Beowulf* be correlated (Extended Data Fig. 3). As such, this cannot be accepted as "further support for unitary composition" of *Beowulf*.

The authors then claim that their cluster analysis based on the 25 most frequent character 2-, 3- and 4-grams (p. 564) presents further evidence for unitary authorship. Choosing just 25 *n*-grams seems to be an arbitrary choice of parameter. We therefore examined the robustness of this analysis using the six longest texts in the corpus (*Beowulf*, *Genesis A*+*B*, *Andreas*, *Christ I*+*II*+*III*, *Guthlac A*+*B* and *Elene*) divided into 300-line samples and performed nearest-neighbour classifications. We duplicated the authors' analysis of the 25 most frequent character 2-, 3- and 4-grams, complementing it with further analyses (adding 5-grams, considering a larger range of *n*-grams). With the original settings (25 *n*-grams), just 70–86% of samples were correctly classified (depending on *n*-gram size). By considering additional *n*-grams, the accuracy

increases to 92–100%. This suggests that the original parameter is too low to manage the variance in the underlying data.

To better examine the internal lexical and grammatical homogeneity of *Beowulf*, we split the text into overlapping samples, still using a window of 300 lines but reducing the step to 100 (so sample 1 contains lines 1–300, sample 2 lines 101–400 and so on). Figure 2 shows that the top two clusters consistently split the text into two continuous parts, breaking around the point where the scribal hand changes in the manuscript (around line 1,939, not at line 2,300). This clustering is resistant both to changes in the number of *n*-grams analysed and the *n*-gram length. The results remain stable when Old English orthographic variation is normalized (for example, þ/ð).

The hypotheses presented in ref. [1] may be plausible but we argue that the paper fails to prove them. The original article does too many things at once: selecting features and parameters without clear justification, applying unproven methods and drawing hasty conclusions as a result. Stylometric studies can be a powerful and exciting adjunct to literary research but they are complicated and difficult for non-specialists to interpret. It is therefore vitally important that practitioners do everything possible to validate their methods, ensure that they are robust and be open about their limitations.

Reporting Summary

Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The data necessary to reproduce the analyses are provided at https://github.com/versotym/beowulf.

Code availability

The complete set of analysis code is available at https://github.com/versotym/beowulf, allowing all the analyses to be fully examined.

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Author contributions

P.P., A.C., B.N. and A.Š. designed the study. P.P. and B.N. wrote the code. All authors analysed the results and wrote the manuscript.

Competing interests

The authors declare no competing interests.

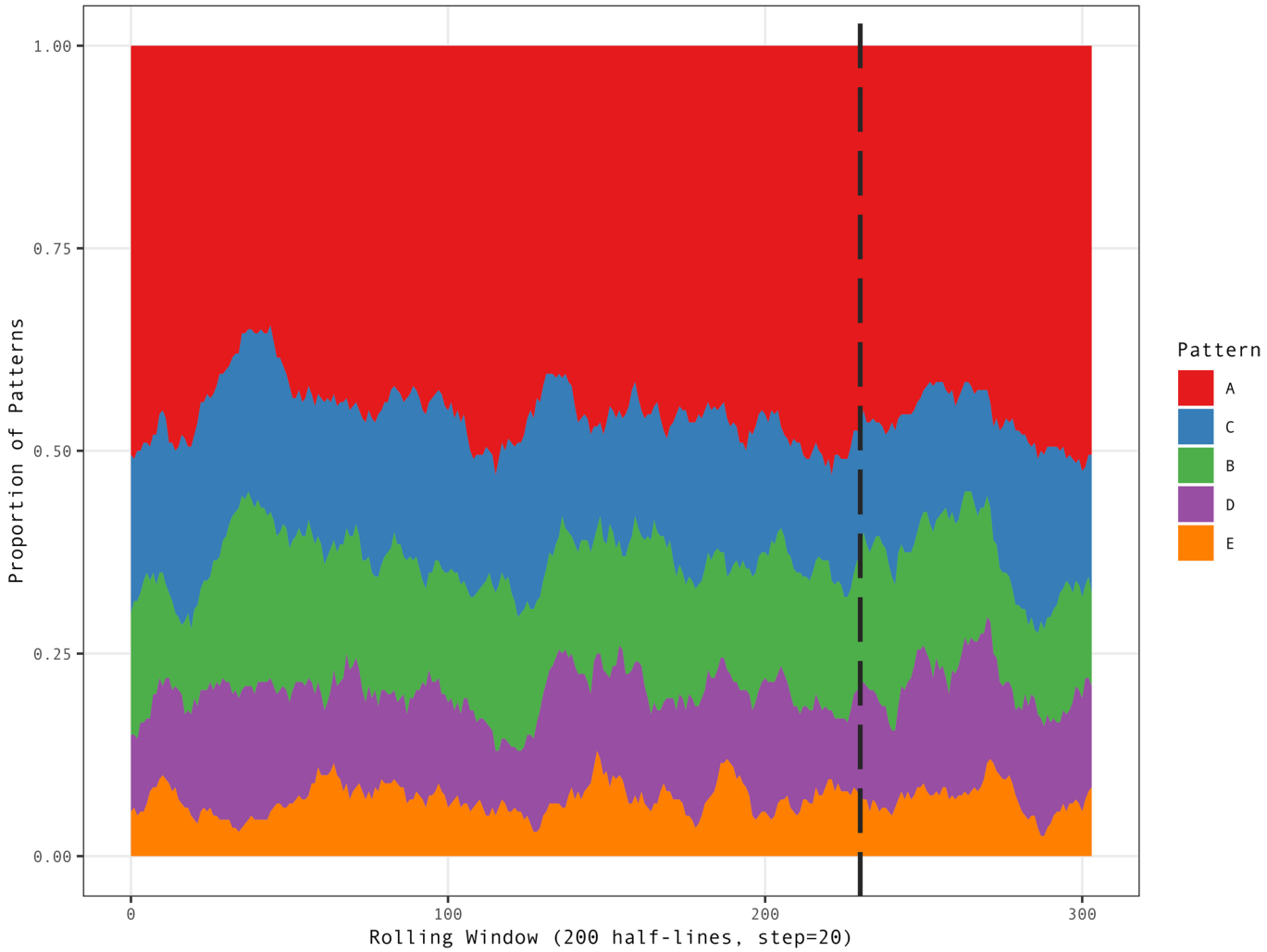
Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41562-021-01222-5.

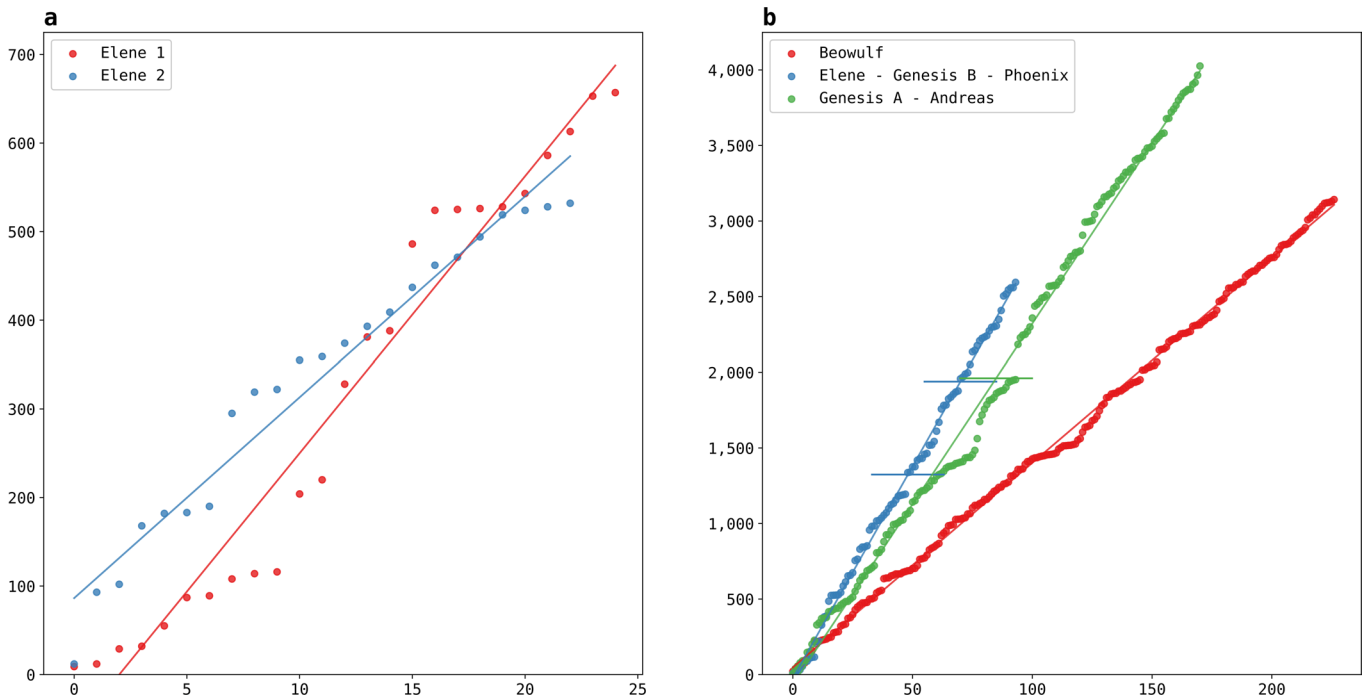
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41562-021-01222-5.

Correspondence and requests for materials should be addressed to Petr Plecháč, Andrew Cooper, Benjamin Nagy or Artjoms Šeļa.

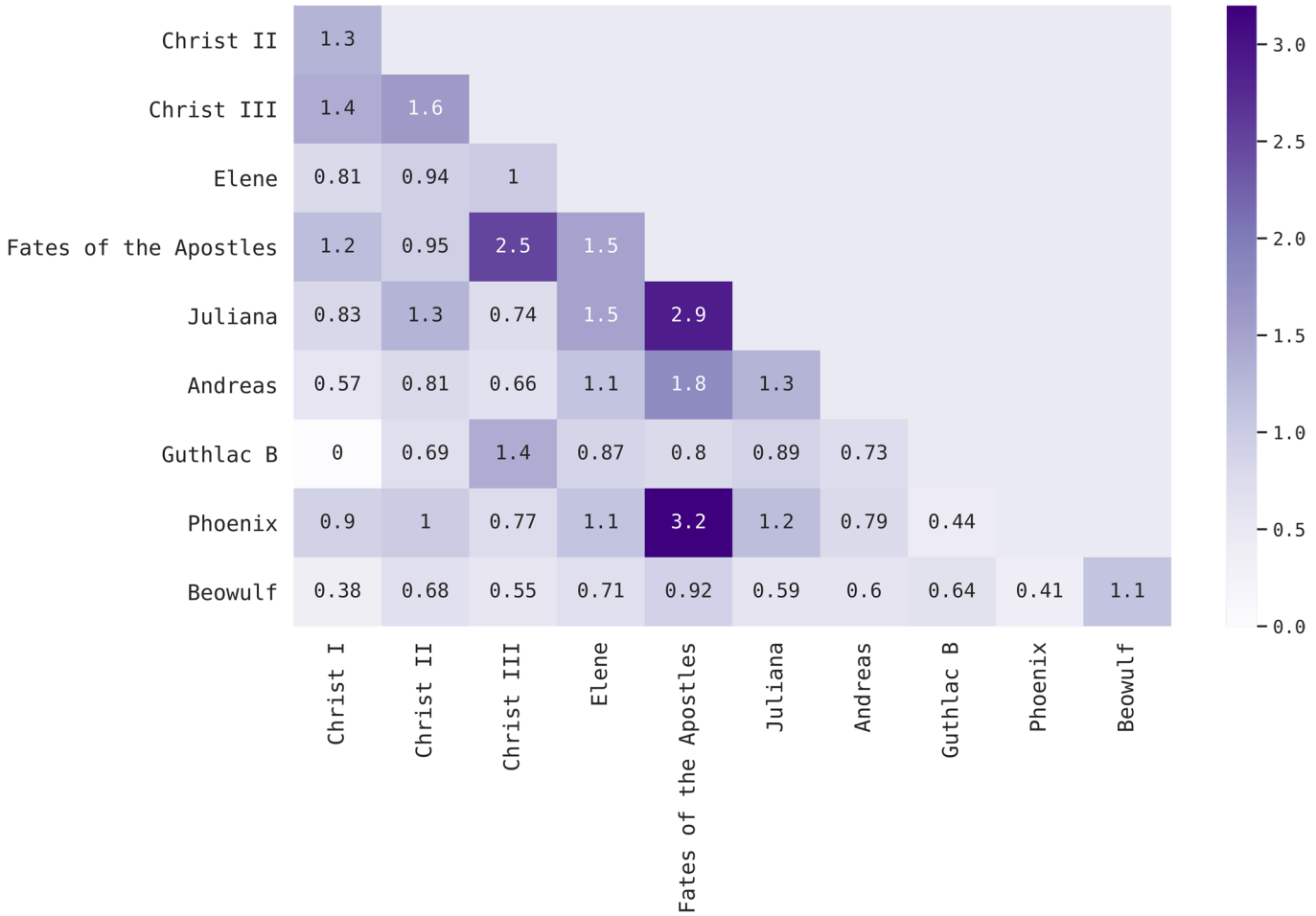
Peer review information *Nature Human Behaviour* thanks Michael Drout and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.



Extended Data Fig. 1 | Half-line pattern variation. Relative proportions of each pattern, taken over a 200-line rolling window throughout the text. The horizontal line shows the start of the disputed section.



Extended Data Fig. 2 | Usage of hapax compounds. a. Difference between slopes for two samples of *Elene* is comparable to the difference reported between *Genesis A* and *B* in supplementary figure 4 of the original article (sample 1: slope = 31.25; $r = 0.9792$; sample 2: slope = 22.67; $r = 0.9798$). **b**. When *Elene*, *Genesis B* and *Phoenix* are merged together, the quality of linear fit is comparable to that of *Beowulf* (slope = 28.05; $r = 0.9983$). Merging together *Genesis A* and *Andreas* produces a good quality fit as well (slope = 23.88; $r = 0.9972$).



Extended Data Fig. 3 | Shared compounds. Replication of original figure 3 with *Christ I* and *Christ III* added to the chart. Despite the fact that *Christ I, II, III* are claimed to be written by different authors, their mutual correlations do not significantly differ from those of poems signed by Cynewulf ($t(7) = 0.19$; $p = 0.8567$). This suggests that the method is sensitive to a common topic and as such cannot be accepted as "further support for unitary composition" of *Beowulf*.

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Behavioural & social sciences study design

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Study description	Quantitative study. Replication of "Large-scale quantitative profiling of the Old English verse tradition"
Research sample	Only data provided by original authors were used
Sampling strategy	Both discrete samples and rolling window were used. The sample size comply with the conclusions of cross-language studies in stylometry.
Data collection	N/A
Timing	N/A
Data exclusions	N/A
Non-participation	N/A
Randomization	N/A

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https://doi.org/10.1038/s41562-021-01223-4

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Reply to: Beowulf single-authorship claim is unsupported

Madison S. Krieger[1]✉, **Pramit Chaudhuri**[2] and **Joseph P. Dexter**[3]✉

REPLYING TO P. Plecháč et al. *Nature Human Behaviour* https://doi.org/10.1038/s41562-021-01222-5 (2021)

Plecháč et al.[1] question the validity and reproducibility of key claims in our computational study of Old English poetry[2]. Although our paper considers many aspects of the verse tradition, almost all of their objections centre on our discussion of stylistic homogeneity in *Beowulf*. Here we argue that Plecháč et al.'s critique depends on selective interpretation of statistical evidence and, even more crucially, idiosyncrasies in the handling of Old English philology. Furthermore, we find that their analysis provides independent confirmation of several of our primary results.

Due to an oversight, data based on an incorrect partition of *Genesis* was included in figure 2 in our original paper and in our supporting code repository. We apologize for any confusion caused but emphasize that all of our conclusions, including the "marked difference in the intraline-to-total sense-pause ratio between *Genesis A* and *B*", remain valid (Extended Data Fig. 1); moreover, the difference between *Genesis A* and *B* is corroborated by Plecháč et al.'s own statistical analysis. (For a full discussion of the methods for sense–pause analysis, see the Supplementary Information.)

Plecháč et al. present a further analysis in which they partition each text into samples of 100 lines and evaluate the statistical significance of the various comparisons of interest on the basis of the partitioned data. Despite considering all possible pairwise comparisons in their accompanying code notebook (https://github.com/versotym/beowulf/blob/master/sense_pauses.ipynb), they discuss only three examples: they report a significant difference between *Genesis A* and *B* (two-tailed *t*-test, $t(27) = 2.07$, $P = 0.0483$) and non-significant differences between *Christ I* and *Christ II* (two-tailed *t*-test, $t(6) = 0.939$, $P = 0.384$) and between *Christ I* and *Christ III* (two-tailed *t*-test, $t(9) = 1.03$, $P = 0.332$). They also find, however, that there is a significant difference between *Christ II* and

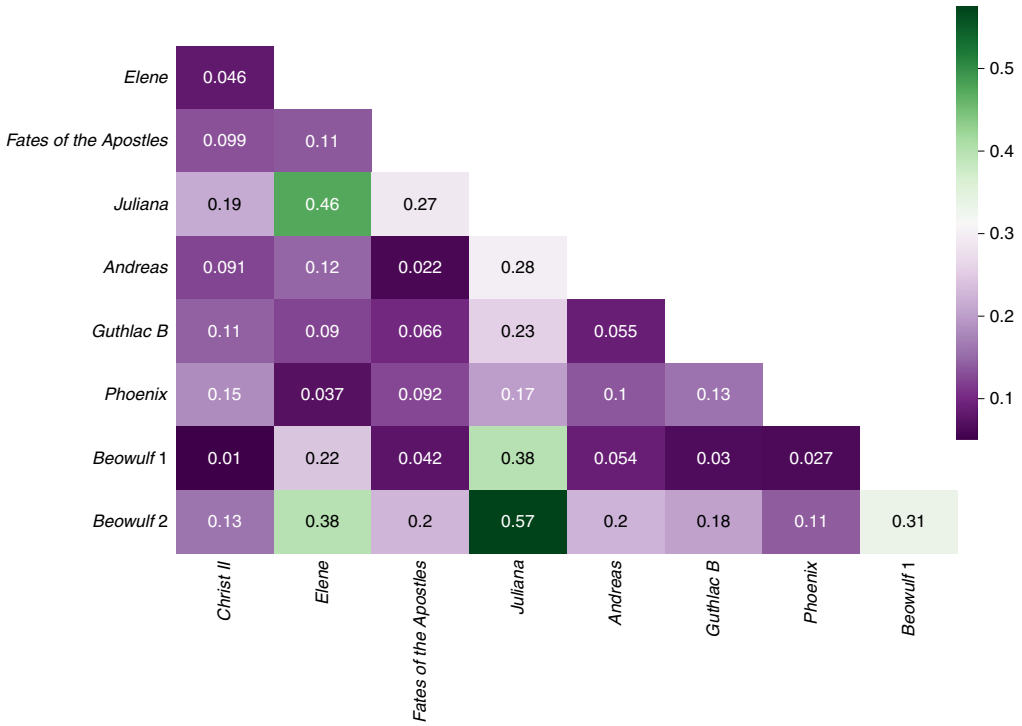

Fig. 1 | Heat map of the fraction difference between the prior distributions from our original study and the re-analysis of Plecháč et al. Their incorrect identification of compounds leads to large errors in the expected shared compounds, especially in *Juliana*, *Elene* and *Beowulf*.

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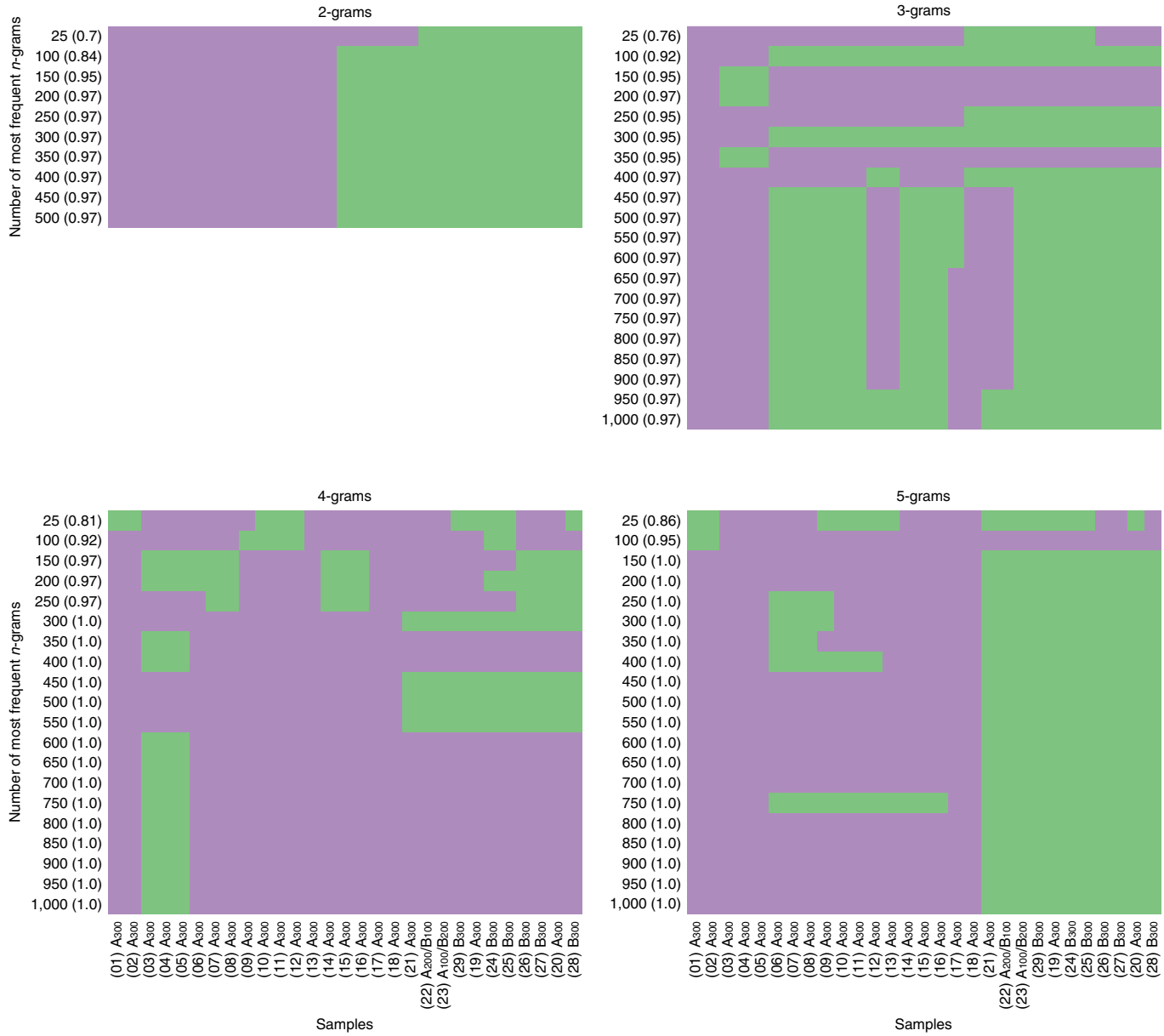

Fig. 2 | Replication of figure 2 of Plecháč et al. following fuller normalization of orthographic differences in *Beowulf*. The design of the figure mirrors that of the original. Purple and green denote membership in the top two clusters. The number in parentheses in each row is the accuracy of nearest-neighbour classification using that number of *n*-grams for non-overlapping chunks of the six longest texts in the corpus (not normalized for spelling).

Christ III (two-tailed *t*-test, $t(9)=2.51$, $P=0.0333$) and that the difference between *Elene* and *Juliana*, two poems of common authorship, is non-significant (two-tailed *t*-test, $t(18)=0.256$, $P=0.801$), as is the difference between lines 1–2300 and 2301–end of both the Krapp and Dobbie (two-tailed *t*-test, $t(28)=0.369$, $P=0.715$) and the Klaeber (two-tailed *t*-test, $t(29)=0.632$, $P=0.532$) editions of *Beowulf*. Most importantly, the authors do not consider the influence of sample size in their interpretation of the results. The *Christ* poems are all relatively short, such that each binary comparison involves no more than 11 100-line bins in total, compared to 20 for *Elene* and *Juliana*, 29 for *Genesis*, and 30 or 31 for *Beowulf*. Their null result for *Christ I* alone therefore provides limited evidence against the informativeness of the method for longer texts.

In their discussion of metre, Plecháč et al. assert, "For a modern study, [the half-line] is an arbitrary choice." However, this choice is consistent with what Germanic poets thought the basic metrical unit to be. In the *Háttatal*, a thirteenth-century study of Old Icelandic poetry, the poet Snorri Sturluson writes:

> There are twelve staves in the stanza, and three are put in each quarter-stanza [*fjórthung* = full-line]. In each quarter-stanza there are two [*vísuorth* = half-line]. Each *vísuorth* contains six syllables. In the second *vísuorth* there is put first in the *vísuorth* the stave which we call the chief stave [*höfustaf*]. This stave determines the alliteration. (Translation adapted from Sturluson and Faulkes[3], p. 166)

The choice of Plecháč et al. to set aside both the vast majority of the scholarship on metre and the primary evidence available also affects their statistical claims. The trend towards significance observed with the full-line data is probably due to the increase in the number of categories considered (25 instead of 5), which substantially increases the statistical degrees of freedom.

Plecháč et al. argue for the fragility of analysing authorship on the basis of a single measurement of Pearson correlation between the rate of hapax usage on two sides of a putative authorship break. This is not the approach we used in our study. Instead, we used a permutation test to situate the correlation of interest among the correlations measured from 1,000 different putative two-author breaks in *Beowulf*. As we reported, the proposed two-author partition of *Beowulf* is not statistically significant when compared to these random partitions. We have included histograms of slope differences from these permutation tests, which corroborate the original result that *Beowulf* is markedly more homogeneous even in comparison to the single-author works discussed by Plecháč et al. (Extended Data Fig. 2).

Despite their claim to have used our "unmodified data", Plecháč et al. wrote new code, available in their accompanying notebook (https://github.com/versotym/beowulf/blob/master/shared_compounds.ipynb), to extract nominal compounds. Due to their handling of Old English grammar, this re-analysis of shared compounds introduces several errors, which belong to four classes:

1. Compounds containing other compounds are double-counted (for example, *wanhoga*/*anhoga* and *secgplega*/*ecgplega*).
2. Common orthographic variants, including *þ*/*ð*, *y*/*i* and *eo*/*io*, are ignored.
3. Although the feature under consideration is restricted to nouns, multiple adjectives appear.
4. Failure to account for inflectional endings results in the omission of certain compounds.

Outside these four main classes, many other compounds were omitted (see the Supplementary Information for a list and directions to check the errors against primary texts). As a result, the numbers of both expected and observed shared compounds are distorted. In the case of *Beowulf*, for instance, their priors differ from ours by more than 30% (Fig. 1).

Finally, Plecháč et al. use hierarchical clustering to investigate the distribution of character-level *n*-gram frequencies across *Beowulf*. They observe that *Beowulf* partitions into two distinct clusters, with the division corresponding to the scribal hand change at line 1,939, and interpret this geometry as contrary to the evidence for stylistic uniformity that we published (see figure 2 in Plecháč et al.). It is well-known that the orthographic practices of the two *Beowulf* scribes differ in a consistent manner; as such, dendrograms based on raw *n*-gram frequencies almost always divide the text according to the scribal change[4,5]. To account for the influence of orthography, Plecháč et al. normalize two of the most common variants (*þ*/*ð* and *eo*/*io*) to be consistent across the poem. As shown in figure 2 in Plecháč et al., this preprocessing has a substantial impact on the results obtained with trigrams, such that the clustering no longer splits the text into two continuous segments.

The variants *þ*/*ð* and *eo*/*io*, however, are only two of many orthographic differences between the scribes. To investigate the influence of these other variants on Plecháč et al.'s results, we replicate their analysis using a version of Klaeber's *Beowulf* in which almost all scribal spelling differences have been normalized (Extended Data Fig. 3). With this more extensively normalized text, we find that *Beowulf* fails to cluster into continuous segments for a wide range of *n*-gram features (Fig. 2).

In addition, we note that Plecháč et al.'s replication corroborates the main result of the original clustering analysis—namely, the possible Cynewulfian authorship of *Andreas*[2], as described in detail in the Supplementary Information.

For pre-modern traditions, the absence of large text corpora, secure historical information and a full range of corresponding analytical techniques necessarily affects the range and strength of interpretive claims. It is nevertheless possible to design appropriate quantitative analyses yielding valuable new information. To that end, our work emphasizes the importance of careful attention to philological detail and to the choice of specific statistical methods.

Reporting Summary

Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The normalized version of Klaeber's *Beowulf* is available from the authors on request. All other datasets are freely and publicly available at https://github.com/qcrit.

Code availability

All custom code is freely and publicly available at https://github.com/qcrit.

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Author contributions

M.S.K., P.C. and J.P.D. designed the study, performed the study, analysed the results and wrote the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41562-021-01223-4.

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41562-021-01223-4.

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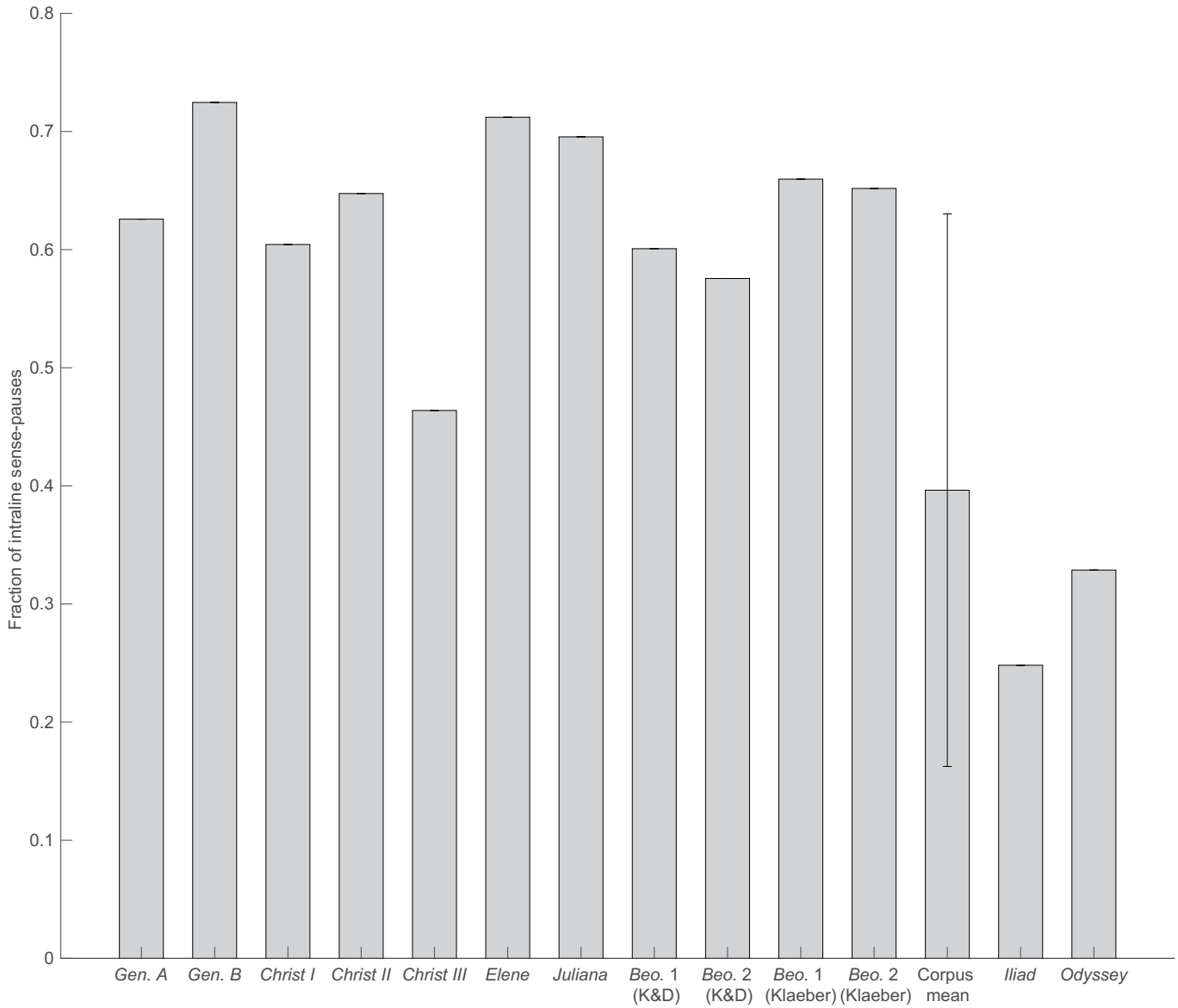
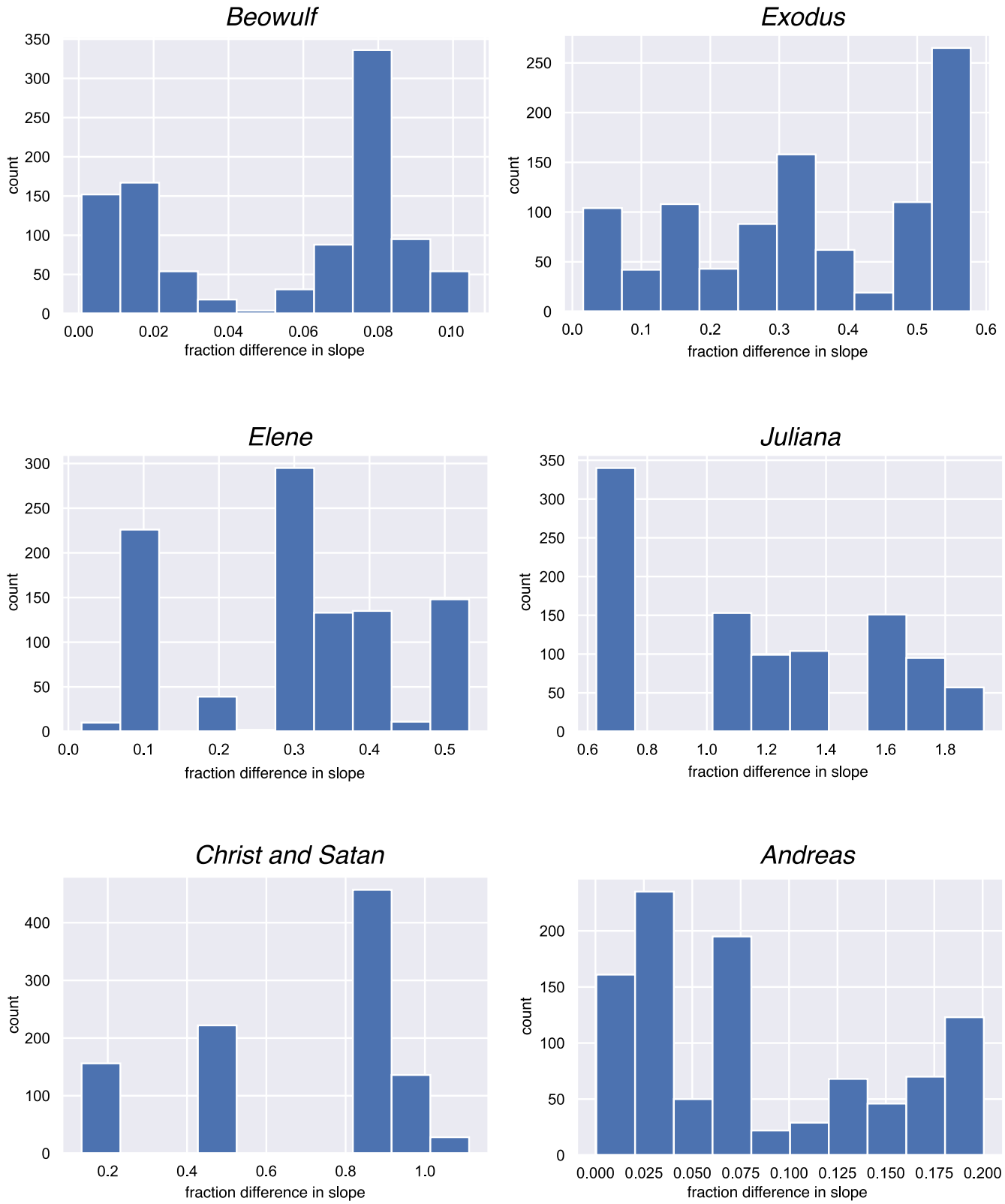


Extended Data Fig. 1 | Ratio of intraline to total sense-pauses for the partition of *Beowulf*, the mean of all texts in the Old English verse corpus, some salient individual texts, and Homer's *Iliad* and *Odyssey*. The error bar for the corpus mean denotes one s.d. of the ratios for all of the texts. This figure is a replication of figure 2a in our original paper with the correct texts for *Genesis A* and *Genesis B*. *Beo., Beowulf; Gen., Genesis*; K&D, Krapp and Dobbie.



Extended Data Fig. 2 | Histograms of fraction difference in slope for hapax compounds for 1,000 binary partitions of *Beowulf* and five other texts (*Exodus, Elene, Juliana, Christ and Satan*, and *Andreas*). Note that the horizontal scale differs between histograms. *Beowulf* appears markedly more homogeneous than the comparison texts.

Line number(s)	Original spelling	Amended version
5	meodosetla	medusetla
7	frofre	frofor
12,19	eafera	eafora
15	aldorlease	ealdorlease
16,31	lange	longe
25	man	mon
26	gescæphwile	gesceaphwile
28	hyne	hine
41	mænigo	menigeo
43	Nalæs	Nealles
46	ænne	an
52	heofenum	heofonum
56	aldor	ealdor
58	guðreouw	guðreow
60	weoroda	weroda
64	gyfen	gifen
65	winemagas	winemægas
67	magodriht	magodryht
68	healreced	heallreced
69	medoærn	meduærn
73	feorum	feorhum
75	manigre	monigre
77	ealgearo	eallgearu
78	healærna	heallærna
86	ellengæst	ellengast
90	swutol	sweotol
93	wang	wong
99	drihtguman	dryhtguman

Extended Data Fig. 3 | Sample data for the orthographic normalization of *Beowulf*. A large number of alterations is needed to normalize spelling between the two scribal hands. The table shows the changes required for the first 100 lines of the poem; a complete list of changes is available from the authors on request.

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☒	☐	A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
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Behavioural & social sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	The study was mixed-methods, involving quantitative text analysis followed by qualitative literary critical and philological interpretation.
Research sample	The research sample was texts contained in the University of Calgary's Online Corpus of Old English Poetry, which is freely and publicly available at http://www.oepoetry.ca/.
Sampling strategy	No sampling was done; all results are based on exact calculations using some or all of the Online Corpus of Old English Poetry.
Data collection	N/A
Timing	N/A
Data exclusions	N/A
Non-participation	N/A
Randomization	N/A

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Human research participants
☒	☐ Clinical data
☒	☐ Dual use research of concern

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging