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Elongated sandstone concretions record river system evolution across the Cretaceous–Paleogene boundary, Montana, USA

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ABSTRACT

The Cretaceous–Paleogene (K–Pg) extinction caused significant environmental upheaval, including the disappearance of non-avian dinosaurs and widespread disruption of ecosystems. The Hell Creek and Fort Union formations in the upper Great Plains of North America preserve a record of environmental change across the K–Pg boundary (KPB). Sedimentological studies suggest that the Hell Creek Formation represents a well-drained floodplain, with increased standing water leading to the formation of ponds and peat bogs close to the KPB. This shift has been attributed to the disruption of river systems by short-term extinction-driven flooding in the Western Interior. To test this, we analyze ~2900 paleocurrent measurements from elongate concretions mapped over ~5000 km² in the Hell Creek area of eastern Montana, USA. These measurements, combined with previously published chronostratigraphic constraints, allow us to trace river system evolution over time. Paleocurrents shift from a uniform NW–SE direction to a chaotic and later bimodal pattern ~400 k.y. after the KPB, but no major shifts occur at the KPB itself. Additionally, we develop a method to identify meandering rivers based on paleocurrent distributions and use it to assess river planform changes. Environmental crises have been suggested to cause transitions from meandering to braided rivers, but we find no evidence of such a change. This suggests that the K–Pg extinction did not significantly disrupt regional drainage or river systems in the Hell Creek area. The results demonstrate the potential of remote sensing for reconstructing paleoriver dynamics and suggest that some river systems may be stable across mass extinction events.

INTRODUCTION

The Cretaceous–Paleogene (K–Pg) mass extinction (ca. 66 Ma) caused the disappearance of non-avian dinosaurs and many lineages of plants and insects. It is considerably less well-studied on land than in the oceans due to the scarcity of continuous, fossiliferous sedimentary records in terrestrial settings. The Hell Creek and Fort Union formations, exposed in the upper Great Plains of North America, span the extinction interval and have been crucial for reconstructing terrestrial environmental changes across the extinction boundary. They preserve abundant flora, fauna, and trace fossils as well as geochemical markers. Moreover, the Hell Creek and Fort Union formations have comparatively high stratigraphic resolution for terrestrial records (Wilf et al., 2003; Tobin et al., 2014; Fastovsky and Bercovici, 2016; Fendley et al., 2019; Sprain et al., 2015), making them especially valuable for studying environmental changes near the boundary.

The mostly Late Cretaceous Hell Creek Formation was deposited on a fluvial plain, with rivers draining sources from the Laramide Orogen to the west into the Western Interior Seaway to the east. Sedimentological studies suggest that the Hell Creek deposits represent a well-drained floodplain with occasional marine or tidal influence (Belt et al., 1985; Fastovsky and Dott, 1986; Fastovsky, 1987; Retallack, 1994; Murphy et al., 1995, 2002; Johnson et al., 2002). At the Cretaceous–Paleogene boundary (KPB), the amount of standing water increased drastically, leading to the formation of ponds and peat bogs. The transition to a poorly-drained depositional environment is evidenced by the widespread occurrence of coals, lignites, siltstones, and shales in the Tullock Member of the conformably overlying Fort Union Formation (e.g., Bendixen, 2021). The lowermost Fort Union coal (IrZ coal) contains a volcanic ash layer and a thin clay bed preserving the iridium anomaly, spherules, and shocked quartz from the bolide impact that defines the KPB (Alvarez, 1983). The con-

tact between the Hell Creek and Fort Union formations is almost isochronous across a large area, implying that the transition from a well-drained floodplain to a wet, marshy landscape was geologically rapid (Johnson et al., 2002).

Because the shift in depositional environment occurred close to the KPB, it has been suggested that the mass extinction triggered widespread, short-term flooding in the Western Interior (e.g., Sheehan et al., 2004; Fastovsky et al., 2008), possibly by means of a tsunami (Kruge et al., 1994; Smit et al., 1996; Schulte et al., 2010; Range et al., 2022). One hypothesis is that the bolide impact ignited forest fires that burned across North America (Wolbach et al., 1985, 1988, 1990; Melosh et al., 1990; Kruge et al., 1994; Sheehan et al., 2004; Robertson et al., 2004, 2013; Santa Catharina et al., 2022). Additionally, soot and other impact debris in the atmosphere could have caused an “impact winter” that devastated vegetation worldwide (Bardeen et al., 2017; Tabor et al., 2020).

Without plants reinforcing slopes and river channels, runoff and erosion would have increased, clogging rivers with sediment and causing floods. These effects might be observable in the geological record. In the Piceance Creek basin of western Colorado (USA), the Paleocene–Eocene thermal maximum (PETM) coincided with a shift to multistoried sandstone beds with upper-flow-regime sedimentary structures, which record increasing sediment supply and discharge. The deposits also contain abundant crevasse splays, suggesting that flooding was common during and after the PETM (Foreman et al., 2012). These changes may be partially due to the sudden loss of vegetation at the PETM. A similar effect has been documented at the Permian–Triassic boundary in South Africa, where a sudden increase in braided river deposits was attributed to the loss of vegetation that had previously stabilized riverbanks and favored meandering rivers (Ward et al., 2000). If the K–Pg extinction was equally severe in North America, the ensuing loss of vegetation could have triggered flooding and

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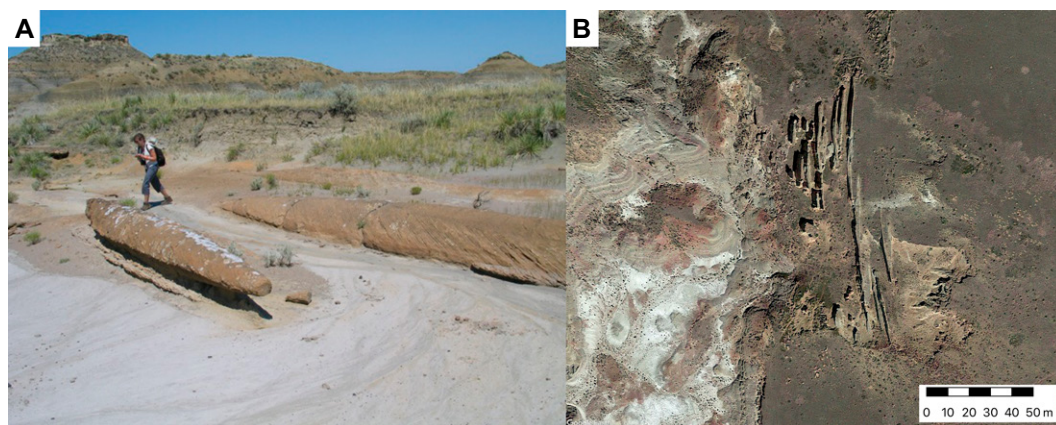


Figure 1. (A) Elongated, calcite-cemented sandstone concretions in the Hell Creek area in Montana, USA. The average dip direction of internal trough cross-bedding parallels the elongation direction of the concretions. (B) Satellite view of a cluster of parallel concretions, located at 106.409°W, 47.712°N. Image from Google Earth.

river planform changes in the Hell Creek area. Alternatively, the environmental shift may have been driven by regional tectonics (Catuneanu et al., 2000), fluctuations in the relative sea level of the Western Interior Seaway (Johnson et al., 2002), or both.

Detailed records of fluvial changes and their timing relative to the KPB can be used to test proposed causes of environmental change. Stratigraphic studies (e.g., Fowler, 2020; Bendixen, 2021) have provided insights into shifts in depositional settings, with some studies supplying paleocurrent data from specific sites (e.g., Bendixen, 2021). However, paleocurrent and river planform changes across the KPB have not been analyzed at large spatial scales.

Here, we present a dataset of 2941 paleocurrent measurements recorded by elongate concretions. Because the long axes of elongate concretions align with paleocurrents recorded in trough cross-bedding, the concretions' elongation directions can be used as paleocurrent proxies. The concretions were mapped on satellite imagery across an ~5000 km² area south of the Fort Peck reservoir in eastern Montana, USA. We analyze this dataset to trace river system changes across the KPB. Moreover, we develop a method to identify meandering rivers from paleocurrent distributions and use it to determine whether river planform styles changed at the KPB. The results shed light on how depositional environments and river drainage evolved in the Hell Creek area during the Late Cretaceous and early Paleocene.

GEOLOGICAL BACKGROUND

The fluvial sediments of the Hell Creek and Fort Union formations in eastern Montana, North Dakota (USA), and South Dakota (USA) preserve large elongate concretions, which are thought to have formed within buried river channels. Some are prolate ellipsoids or spheroids with tapered ends, while others are tabular in

shape. They are 2–100 m in length and 0.5–3 m in width, large enough to be easily identifiable on satellite imagery (Fig. 1). Multiple studies of locations within the USA have documented similar features in eastern Montana (Brown, 1907; Archibald, 1982; Murphy, 1986; Rigby and Rigby, 1990; Weaver et al., 2022), North Dakota and South Dakota (Todd, 1903; Stevenson, 1954; Frye, 1967; Royse, 1970; Groenwold, 1971; Cherven, 1973; Jacob, 1973; Parsons, 1980; Biek, 1994), and Nebraska (Darton, 1903; Schultz, 1941).

The elongate concretions typically occur in parallel sets, many of which can be traced laterally for several kilometers and vary systematically in orientation. They typically protrude from the surrounding sandstone matrix, which is poorly consolidated, less well-sorted, and finer-grained in comparison. Brown (1907) and Jacob (1973) observed that the concretions are cemented by calcite, which Archibald (1982) interpreted as a post-depositional feature.

Trough cross-bedding is characteristic of the elongate concretions. The cross-bedding extends continuously from the concretions into the less well-cemented matrix, indicating a shared depositional history. Concretions protrude from the sandstone matrix due to their higher degree of cementation, which renders them more resistant to weathering and erosion. The average dip direction of trough cross-bedding within the elongate concretions aligns with their long axes, as has been previously observed in North Dakota and South Dakota (Stevenson, 1954; Frye, 1967; Groenwold, 1971; Jacob, 1973; Parsons, 1980). Parsons (1980) measured paleocurrent directions in channel deposits surrounding elongate concretions in the Paleogene Bullion Creek and Slope formations (North Dakota). He confirmed a strong correlation between the measured paleocurrent directions and the long axes of the concretions.

Building on Frye (1967) and Groenwold (1971), Parsons (1980) proposed a model for

the formation of elongate concretions. He suggested that buried paleochannels have higher porosity and permeability than the surrounding sediments due to their coarser grain size, a result of deposition in running water. Groundwater preferentially flows along these porous channels, following the original river's course. Calcite precipitating from the groundwater also preferentially follows the paleochannel. This process ultimately leads to the formation of elongate concretions that trace paleochannels, with their elongation direction corresponding to the paleocurrent direction. Thus, the concretions are not strictly primary depositional features, but they reveal such features conspicuously.

Based on this model, Groenwold (1971) and Jacob (1973) suggested that elongate concretions could be used to infer paleocurrent directions and map paleochannels. Previous studies on fluvial dynamics in the Hell Creek area have relied on field campaigns to collect paleocurrent data (Groenwold, 1971; Jacob, 1973; Parsons, 1980). However, because the concretions are visible on satellite images, they can be mapped and their elongation directions measured using remote sensing. Paleocurrent data from concretions can capture both regionally uniform fluvial changes, likely driven by large-scale factors like tectonics, eustatic fluctuations, or mass extinctions; and localized changes, which likely have smaller, locally variable drivers.

METHODS

Remote Sensing of Concretions

Concretions in the Hell Creek region of northeastern Montana (UTM Zone 13) were mapped using Google Earth. A total of 2941 concretion clusters were identified across an area of ~5000 km². For each cluster, we recorded the mean Universal Transverse Mercator (UTM) coordinates, elevations, and orientations. Clusters comprised 2–20 concretions and were aligned

within 10° . Each cluster was defined so that the elevations of all included concretions were consistent within 3 m. Data were collected at image magnifications corresponding to eye altitudes of 2–3 km. Each cluster was represented by a single data point, with the measured coordinates recording the approximate center of the cluster. Because cross-bedding dip directions could only be measured in the field for a small fraction of elongate concretions, the orientations measured on satellite imagery are generally bipolar; i.e., each measurement represents two potential paleoflow directions, which are opposite to each other.

Within the study area, a subtle regional dip to the southeast exposes older strata in the north and younger strata in the southeast. Tobin et al. (2014) calculated this dip to be 0.2° with a strike trending 49° and presented an equation for a plane defining the contact between the Hell Creek and Fort Union formations. This plane approximates the KPB in the Hell Creek region. We adjusted our measurements for this regional dip by calculating the stratigraphic height of each data point relative to the KPB. Several horizons within concretion-bearing stratigraphic sections have been $^{40}\text{Ar}/^{39}\text{Ar}$ -dated (Sprain et al., 2015, 2018), so ages can be assigned to concretions based on their stratigraphic positions.

Data Reduction

To understand how river patterns in the Hell Creek area changed over time, we group the data into temporal and spatial bins. We define seven time bins based on their stratigraphic position relative to the KPB: -100 m to -36 m, -36 m to 0 m, 0 – 25 m, 25 – 50 m, 50 – 75 m, 75 – 100 m, and 100 – 125 m. The stratigraphic positions are converted to ages using published $^{40}\text{Ar}/^{39}\text{Ar}$ ages of sanidine in interbedded tephra (Sprain et al., 2015, 2018). These ages include systematic uncertainties that can be neglected when comparing them to other $^{40}\text{Ar}/^{39}\text{Ar}$ ages, e.g., in calculating intervals between ages or sediment accumulation rates.

The assigned ages are subject to uncertainties on the $^{40}\text{Ar}/^{39}\text{Ar}$ ages, the regional dip correction, and the elevations measured on satellite imagery. The $^{40}\text{Ar}/^{39}\text{Ar}$ ages have typical uncertainties of ~ 0.05 m.y. The elevation uncertainty was assessed by comparing satellite-derived elevation measurements at eight road intersections with surveyed elevations shown on topographic maps. The results agreed within 1 m, implying that satellite-derived elevations are generally accurate within that range. For the regional dip correction, Tobin et al. (2014) reported that elevations calculated from their best-fit plane differed from elevations measured in the field by

a root mean square error of 3.8 m, with a maximum error of 8 m. Thus, ages assigned to the stratigraphic bins may have uncertainties anywhere between 0.05 m.y. (assuming the regional dip correction and satellite-derived elevations are accurate) and 0.25 m.y. (assuming 0.05 m.y. uncertainty on $^{40}\text{Ar}/^{39}\text{Ar}$ ages and maximum uncertainties of 1 m and 8 m on the satellite-derived elevations and regional dip correction, respectively). Considering the associated uncertainties, we suggest that the ages assigned to the temporal bins are not more accurate than ± 0.15 m.y.

For spatial analysis, we divide the study area into 5×5 km boxes. Analyzing fluvial changes within individual 5×5 km boxes is challenging because few boxes contain data for all time bins. We therefore use clustering algorithms to identify regions with similar temporal patterns. Clustering algorithms typically perform best on low-dimensional data, but our dataset is inherently high-dimensional. The study area is divided into $197 \times 5 \times 5$ km spatial boxes, each containing up to seven time bins and 18 paleocurrent values representing 10° bins across a 180° range. Because the elongation direction of concretions in satellite images cannot determine flow polarity (e.g., NW-SE is indistinguishable from SE-NW), we record all paleocurrents as angles between 0° and 180° . Although flow polarity could be uniquely inferred by directly measuring cross-bedding dip directions, obtaining such measurements for all mapped concretions would be intractable considering the large study area and would require access permission for many private properties. Instead, we use symmetrical 180° paleocurrent distributions and mirror them along the N-S axis to create complete paleocurrent rose diagrams. This results in a dataset with 21,276 dimensions.

We use the Uniform Manifold Approximation and Projection (UMAP) algorithm to reduce this high-dimensional dataset (McInnes et al., 2018). UMAP projects the data into a 2-D space while preserving its topological structure. We then apply Density-Based Spatial Clustering of Applications with Noise (DBSCAN) algorithms to identify clusters. DBSCAN detects cluster centers in high-density regions of the data and expands outward, with an adjustable parameter ϵ controlling the search radius. DBSCAN was chosen because it handles noise and outliers well and does not require a predefined number of clusters.

Distinguishing Meandering and Braided Rivers

The regular patterns of meandering rivers suggest that their flow direction distributions should

also display a degree of regularity. In many cases, sampling flow directions from either side of a meander bend produces a bimodal distribution (Figure S1 in the Supplemental Material¹). Conversely, braided rivers do not follow regular patterns and are unlikely to produce bimodal flow direction distributions. The distinction between bimodal and non-bimodal distributions may offer a means of distinguishing meandering and braided rivers in the geological past, provided that paleocurrent data are available. We test whether flow direction distributions can be used to distinguish braided from meandering rivers, beginning with theoretical models of meandering rivers and subsequently applying our analysis to real rivers.

A theoretical meandering river can be represented by a sine-generated curve, formulated by Langbein and Leopold (1970) to describe the path that minimizes the total work required to cause an overall change in direction (Figure S2). Angle distributions in real streams agree well with the predictions of sine-generated curves (Thakur and Scheidegger, 1968). We therefore use sine-generated curves to model meandering rivers.

A sine-generated meandering river should produce a symmetric distribution of flow directions, which may be bimodal. To test this hypothesis, we model sine-generated rivers with a range of sinuosities and spatial scales (1–10 meanders) and randomly sample points to produce synthetic flow direction distributions. We conduct the same analysis on skewed sine-generated rivers, which include a distortion parameter that skews meander bends up- or downstream (Guo et al., 2019), and on 20 real meandering rivers observed on satellite imagery. We also analyze 20 braided rivers, which are used as statistical controls to assess the significance of bimodality tests for the meandering rivers. A detailed description of the method is provided in the Supplemental Material.

We find that bimodality detection depends on sinuosity. For meandering rivers with low sinuosity, bimodal distributions are easily detectable. At intermediate sinuosity, bimodality is difficult to detect due to the broadening of river bends, which causes the underlying flow direction distributions to become chaotic or quadrimodal. At high sinuosity, bimodal flow distributions are again detectable. Bimodality detection also

¹Supplemental Material. Description of custom algorithms to model sine-generated meandering rivers, approximate flow direction distributions of mapped rivers, and evaluate bimodality of flow distributions. Please visit <https://doi.org/10.1130/GSAB.S.30421945> to access the supplemental material; contact editing@geosociety.org with any questions.

depends on sample density and the spatial scale of the analysis, represented here by the number of meanders. In general, increasing either sample density or meander number improves detection. Analyzing at least five meanders increases the probability of success.

Fourteen of 20 real meandering rivers produce statistically significant ($p < 0.05$) bimodality results at sample densities ≤ 10 samples/meander, and 12 show statistically significant results at densities < 5 samples/meander. Thus, bimodality detection is feasible in real meandering rivers using only sparse, point-like flow direction data. However, bimodality detection is only successful for real meandering rivers whose overall (thalweg) direction and sinuosity do not vary strongly in the studied section. If the overall direction or sinuosity vary significantly, the underlying flow direction distributions become non-bimodal, making detection unlikely even at high sample densities. We find that real meandering rivers generally lack the regularity required for bimodality detection on scales > 5 meanders. At larger scales, topographic or other environmental changes frequently alter a river's flow direction or sinuosity, resulting in non-bimodal distributions. To maximize the likelihood of detecting bimodality in real rivers, we therefore recommended analyzing spatial scales corresponding to ~ 5 meanders. This scale balances the need for sufficient data with the occurrence of regular meanders.

In the Hell Creek area, clusters of concretions that apparently trace curves, possibly meander bends, can be fitted to circles with radii of ~ 500 m (e.g., Figure S123). Measured radii in the study area range from 110 m to 970 m, with an average of 502 ± 238 m (one standard deviation [1σ], $N = 27$). The large radius of curvature indicates that the elongate concretions represent big rivers. Leopold and Wolman (1960) reported that a river's curvature radius R and width w are empirically related by

$$w = \frac{R}{2.3}. \quad (1)$$

Equation 1 implies an average width of $218 \text{ m} \pm 104 \text{ m}$ (1σ) for Late Cretaceous and early Paleocene rivers in the Hell Creek area. On average, pre-KPB rivers are slightly wider than post-KPB rivers ($315 \pm 105 \text{ m}$ [1σ], $N = 5$, and $196 \pm 87 \text{ m}$ [1σ], $N = 22$, respectively), but the difference is not statistically significant.

We use the information about river size to select a suitable spatial scale for analyzing the elongate concretion data. A curvature radius of 500 m implies a minimum meander wavelength of 1 km. To maximize the likelihood of detect-

ing bimodality, we divide the study area into 5×5 km boxes so that each box can be expected to contain approximately five meanders.

Finally, we implement a statistical test for bimodality. To be identified as bimodal, a distribution must (1) have two main modes of similar height, and (2) the two main modes must be significantly higher than any other modes in the distribution. The thresholds for these criteria are calibrated to produce agreement with a reference set of visually classified distributions. More information is available in the Supplemental Material.

RESULTS

Mapped Concretions

The mapped elongate concretions are shown in Figure 2.

Paleocurrent Changes Across the Cretaceous-Paleogene Boundary

Figure 3 shows the time series of paleocurrent directions across the study area. Before the KPB, paleocurrents show a near-uniform distribution dominated by a NW-SE axis, which likely reflects southeastward drainage from the Laramide Orogen into the Western Interior Seaway. Beginning at ~ 0.3 m.y. before the KPB, the distribution becomes less uniform, with emerging modes oriented SSE-NNW and SW-NE. This pattern persists until ~ 0.4 m.y. post-KPB. After that, the paleocurrent distribution changes drastically, with a broad SW-NE mode emerging as dominant. By ~ 0.8 m.y. post-KPB, the distribution resolves into a bimodal pattern with distinct SW-NE and NW-SE modes. A roughly SW-NE component dominates from ~ 1.1 m.y. to 1.4 m.y. post-KPB. After that, the NW-SE mode returns as the dominant flow direction, but the distribution is not unimodal and many elongated concretions continue to record SW-NE paleocurrents. Importantly, there is no sign of a catastrophic change in river patterns at or directly after the KPB. This conclusion holds even when the concretion data are grouped using smaller stratigraphic bins (Figure S124).

Local Changes

The DBSCAN clustering results are shown in Figure 4. The paleocurrent distributions for each cluster are shown in Figure 5. Some clusters display drastically different paleocurrent patterns over the studied interval. Prior to ~ 0.3 m.y. pre-KPB, all clusters containing data (1, 4, and 5) have dominant NW-SE or WNW-ESE flow

directions. From ~ 0.3 m.y. pre-KPB until the KPB, flow patterns become more diverse. The northernmost region (cluster 5) retains the dominant WNW-ESE flow direction, but also shows minor modes oriented NNW-SSE and W-E. In addition to their previous NW-SE modes, cluster 1 develops a NNW-SSE mode and cluster 4 develops two new modes oriented roughly SW-NE. This implies that river patterns became more chaotic in the end-Cretaceous.

From the KPB to ~ 0.4 m.y. post-KPB, clusters 1 and 5 exhibit a dominant NW-SE flow direction. The paleocurrents of cluster 2 show a pronounced N-S orientation, while cluster 4 shows a chaotic, non-uniform distribution.

From ~ 0.4 m.y. to 0.8 m.y. post-KPB, cluster 1 shows a broad SW-NE mode accompanied by a NW-SE mode. The distribution of cluster 2 is non-uniform, with most orientations trending roughly NW-SE. In clusters 3 and 5, the main modes are approximately S by W to N by E and SSW-NNE, respectively. However, the results of cluster 3 may be unreliable due to a small number of samples. Cluster 4 has a bimodal flow distribution with modes oriented WNW-ESE and SW-NE.

From ~ 0.8 m.y. to 1.1 m.y. post-KPB, cluster 1 becomes multimodal, while the distribution of cluster 2 is bimodal with modes oriented WNW-ESE and SW-NE. Clusters 3 and 4 show similar patterns to the previous time interval.

From ~ 1.1 m.y. to 1.4 m.y. post-KPB, cluster 1 has a bimodal distribution with modes oriented NW-SE and SW-NE. In cluster 2, the distribution is non-uniform, but most paleocurrents are oriented approximately SW-NE. Cluster 3 shows a multimodal distribution with most paleocurrents oriented NW-SE and SW-NE. The results of cluster 4 may be unreliable due to insufficient samples.

Finally, after ~ 1.4 m.y. post-KPB, cluster 1 has a non-uniform paleocurrent distribution with a dominant SW-NE orientation. Few samples are available from cluster 2. Cluster 3 is bimodal, with modes oriented approximately WNW-ESE and W by S to E by N. Notably, the geometry of spatial boxes assigned to this cluster suggests they may trace the course of a single river (Fig. 3), whose bimodal paleocurrent distribution may indicate a meandering river.

The paleocurrent distributions of individual 5×5 km spatial boxes were calculated for each time interval and evaluated for bimodality. On average, $\sim 23\%$ of paleocurrent distributions were identified as bimodal. These values were largely similar in successive time intervals, with the exception of a drop from 27% to 17% across the KPB (see Fig. S125). However, this drop was not observed when limiting the evaluation to 5×5 km boxes containing at least 10 data

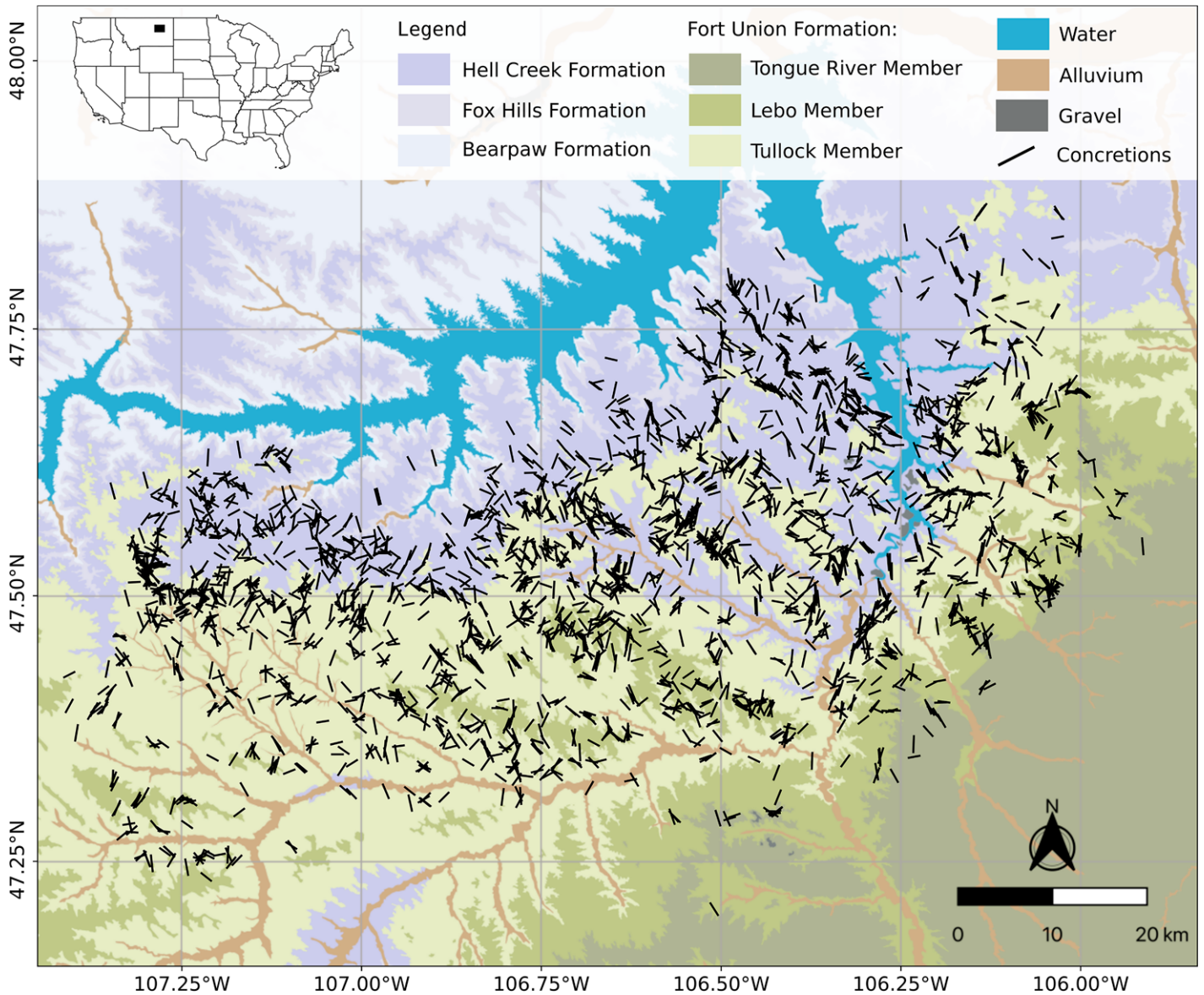


Figure 2. Mapped elongate concretions in the Hell Creek area in Montana, USA. Inset map shows the location of the study area. Coordinates according to World Geodetic System 84 (WGS 84). Geological map from McCafferty et al. (2023).

points, which corresponds to an approximate sample density of two samples/meander for an assumed meander wavelength of 1 km (Figure

S126). Because sample densities ≥ 2 samples/meander are recommended for bimodality testing, the drop in bimodality across the KPB is

not considered significant. Thus, no detectable shift from meandering to braided rivers occurred at the KPB.

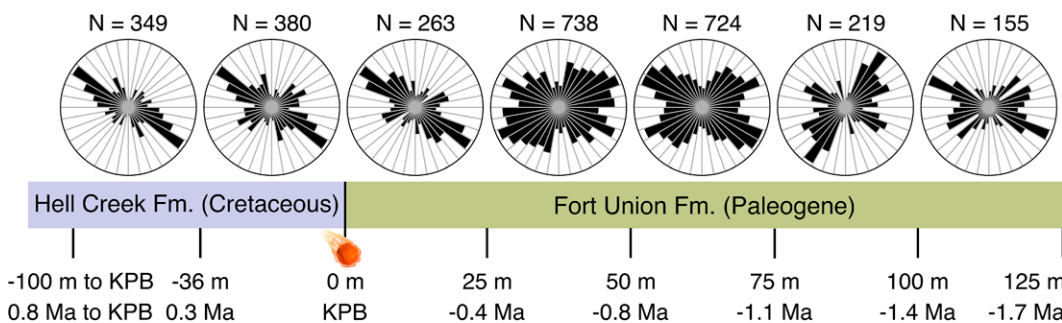


Figure 3. Paleocurrent distributions in the end-Cretaceous and early Paleogene, inferred from elongate concretions in the Hell Creek area in Montana, USA. Ages are based on published $^{40}\text{Ar}/^{39}\text{Ar}$ data (Sprain et al., 2015, 2018) and given relative to the Cretaceous-Paleogene boundary (KP). Fm.—Formation.

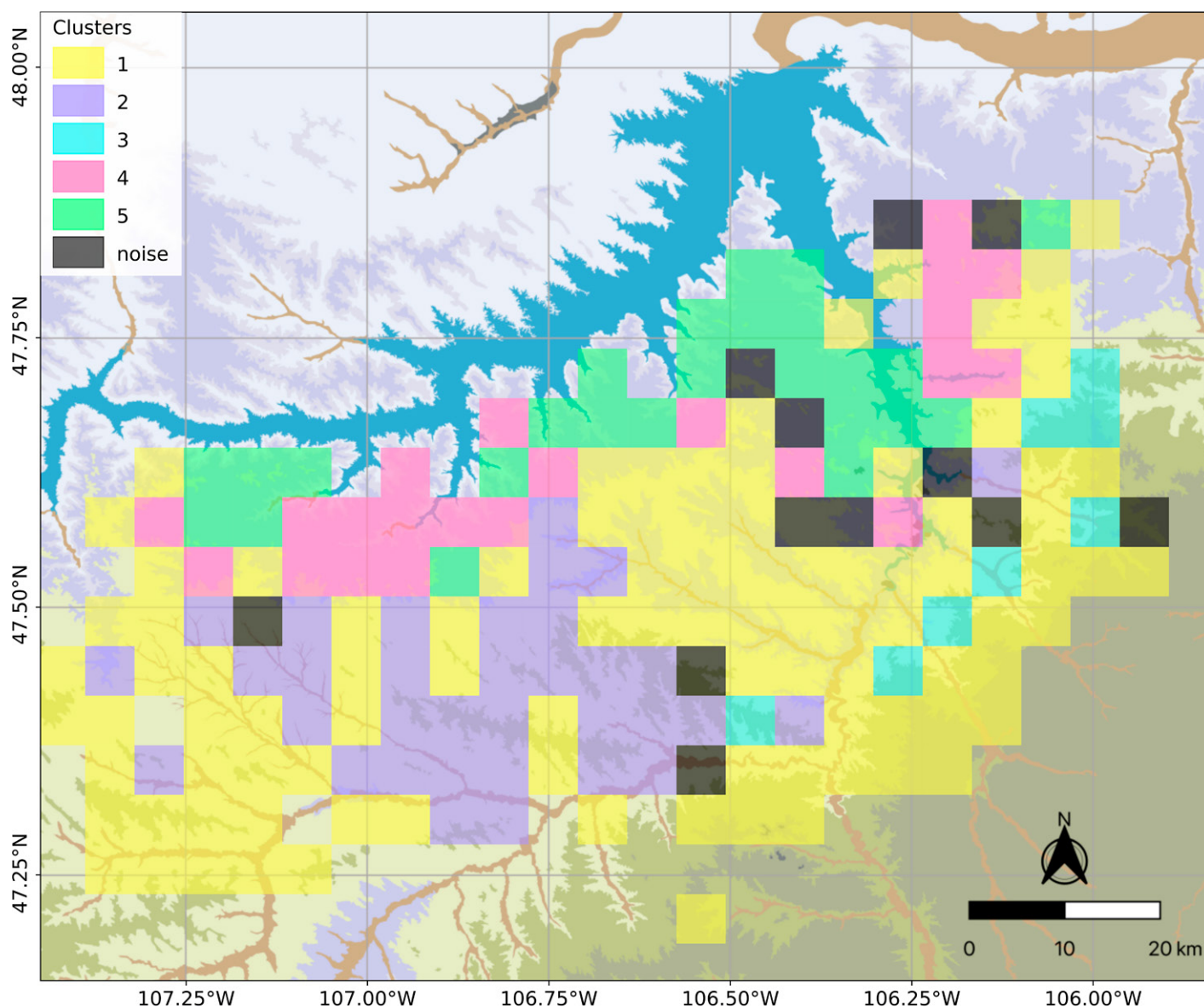


Figure 4. Clustered 5×5 km boxes in the Hell Creek area in Montana, USA. Clustering was performed on the elongate concretion data using the Uniform Manifold Approximation and Projection (UMAP) and Density-Based Spatial Clustering of Applications with Noise (DBSCAN) algorithms to identify regions in which paleocurrent patterns changed similarly over time. Clusters are grouped by color, with black boxes identified as noise that is not assigned to any cluster. Coordinates according to World Geodetic System 84 (WGS 84). Geological map from McCafferty et al. (2023).

DISCUSSION

Paleocurrent Analysis

Our paleocurrent analysis is valuable for identifying meandering rivers, a task often difficult in the field due to the similar appearance of meandering and braided river deposits. For instance, amalgamated sheet sandstones are often interpreted as braided river deposits where other indicators are lacking (Moody-Stuart, 1966; Van de Graaff, 1972; Campbell, 1976; Chan

and Pfaff, 1991), but may also be deposited by high-sinuosity channel belts (Miall, 1980; Hartley et al., 2015, 2018). This applies especially to unvegetated settings, where meandering rivers are less likely to develop high sinuosity (Hasson et al., 2024). Similarly, lateral accretion features, commonly associated with meandering rivers (Moody-Stuart, 1966; Miall, 1980), also occur in braided systems (Bluck, 1979; Allen, 1983; Bridge, 1985; Bristow, 1987; Miall, 1994). This highlights the difficulty of distinguishing between braided and meandering rivers based

solely on sedimentary features and emphasizes the potential of using statistical methods to analyze paleocurrent data.

Previous studies have suggested using sinuosity and paleocurrent direction variance to distinguish meandering rivers (Ferguson, 1977; Bridge, 1985; Semeraro, 2019). Our method offers another way to identify meandering rivers. It may be better at identifying meandering rivers with low sinuosity, which would not be recognized by analyzing dispersion of paleocurrent values. A limitation of this method is that

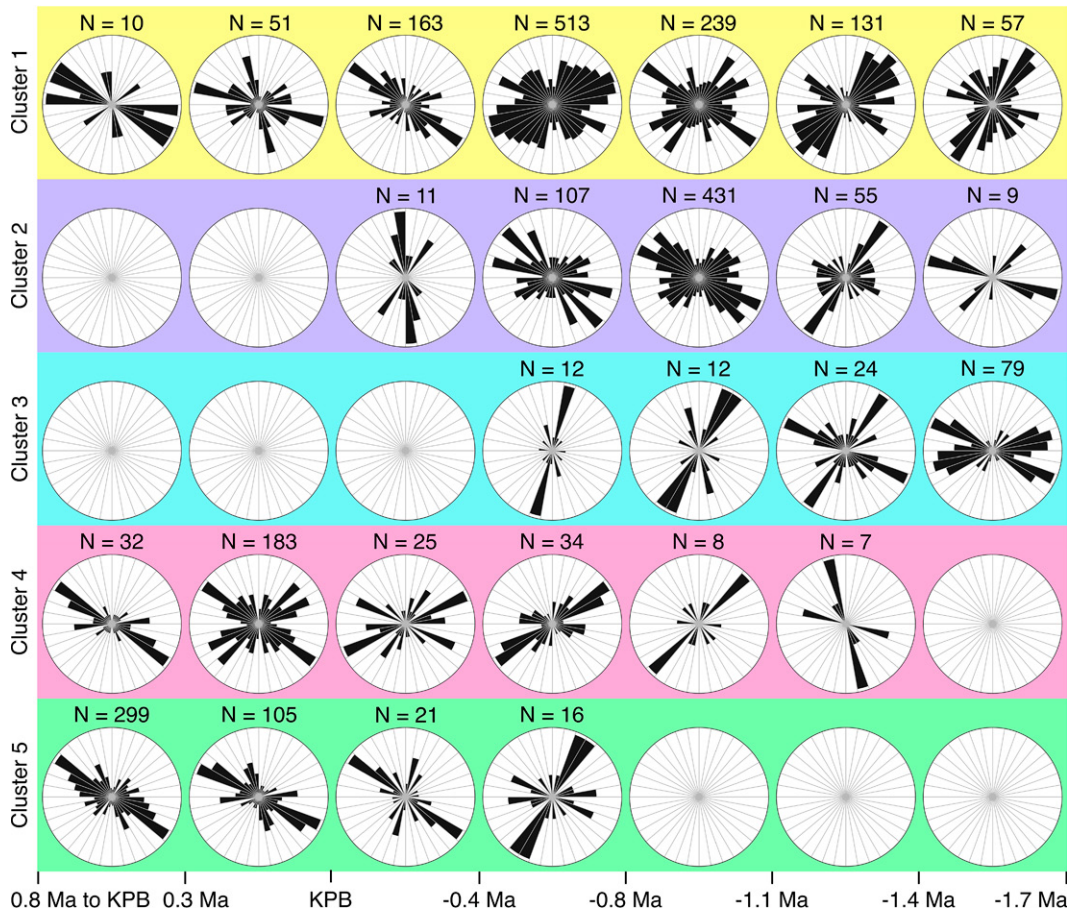


Figure 5. Paleocurrent distributions for each Density-Based Spatial Clustering of Applications with Noise (DBSCAN) cluster and time interval. Not all clusters contain data in each time interval due to the varying exposure of geological units across the study area in the Hell Creek area in Montana, USA. Ages are based on published $^{40}\text{Ar}/^{39}\text{Ar}$ data (Sprain et al., 2015, 2018) and given relative to the Cretaceous-Paleogene boundary (KPb).

it can confirm the presence of bimodality, but cannot confirm its absence—a river cannot be definitively classified as braided if bimodality is not detected. However, our approach has successfully identified bimodality in certain cases, demonstrating that it is potentially useful for distinguishing river types when sedimentary data are inconclusive.

Studying transitions between braided and meandering rivers can provide insights into paleoenvironmental change. These transitions are relevant both to short-term environmental disturbances and long-term evolutionary trends in river systems. It is thought that sheet-braided rivers dominated the continents before the rise of land plants (Schumm, 1968; Went and McMahon, 2018). The development of roots and trees is believed to have stabilized riverbanks (Smith, 1976), promoting meandering and anastomosing river systems (Davies and Gibling, 2010, 2011). Conversely, the removal of vegetation could lead to less cohesive riverbanks (Prosser and Slade, 1994), promoting formation of braided rivers (Schumm, 1985; Murray and Paola, 1994, 1997; Ielpi et al., 2022). By providing another way to distinguish braided and meandering river deposits, the method presented here could

inform whether the rise of land plants triggered a widespread change in river planform styles. On short time scales, the possibility of catastrophic environmental change at extinction boundaries could be assessed by comparing paleocurrent distributions before and after an extinction.

In addition, this study demonstrates that remote sensing can complement traditional field studies by enabling researchers to identify and analyze geological features at broad spatial scales, generating large datasets that can reveal regional patterns. In arid regions with sparse vegetation, such as the Hell Creek area, exposed river systems and paleocurrent markers are particularly well-suited for satellite-based mapping. Notably, collecting paleocurrent data across an area of this size—nearly 5000 km², much of it inaccessible by road, characterized by steep terrain, or situated on private land—would be practically impossible using only ground-based fieldwork.

Our workflow provides a framework for applying remote sensing to exposed paleoriver systems, expanding the scope of paleofluvial and paleoenvironmental research. Where abundant data are available, this workflow can identify regions where paleocurrents display

similar changes over time. These regions may correspond to individual catchments influenced by shared environmental or geological factors. Areas where elongated concretions are present and where this method could be applied include upper Devonian sediments in New York, USA (Colton, 1967); Early Triassic sandstones in the South African Karoo Sequence (Johnson, 1989); Late Triassic–Early Jurassic sediments in England (Raiswell and White, 1978); Upper Cretaceous deposits in Antarctica (Pirrie, 1987); Miocene sediments in Spain (Pomar et al., 2004) and Nebraska (Schultz, 1941); and Pleistocene deposits in Italy (McBride et al., 1994), Norway (Theakstone, 1981), and New Mexico, USA (Mozley and Davis, 1996). The Karoo sandstones may be especially well-suited to this approach because their concretion elongation directions match independent paleocurrent indicators (Johnson, 1989). Using concretions as paleoflow proxies could help assess the proposed transition from meandering to braided rivers following the end-Permian mass extinction (Ward et al., 2000). Although elongate concretions have not been reported directly below the Permian–Triassic boundary in South Africa, they have been observed in the underlying Ecca

Group (ca. 303–290 Ma; Nonhlanhla, 2014; Baiyegunhi and Liu, 2021) and may also occur in younger strata.

Fluvial Changes Across the Cretaceous–Paleogene Boundary

Our analysis provides a detailed view of river dynamics in the Hell Creek area across the KPB. Bendixen (2021) found no change in paleocurrents across the KPB, noting a consistent east-southeastward trend in the Hell Creek and Fort Union formations near Glendive, Montana, ~200 km southeast of Fort Peck Reservoir. In contrast, our study identifies both spatial and temporal shifts in paleocurrent direction. This underscores the benefit of using large datasets from remote sensing to capture paleofluvial changes in detail.

In the Late Cretaceous Hell Creek Formation, elongate concretions record a dominant NW–SE paleocurrent direction, which is consistent with southeastward drainage from the Laramide Orogen into the Western Interior Seaway. In the lower Fort Union Formation, paleocurrent directions develop a prominent SW–NE mode in addition to the earlier NW–SE direction. Interestingly, the transition from a uniform NW–SE paleocurrent distribution to a bimodal distribution only initiates ~400 k.y. after the KPB, apparently indicating that the Cretaceous–Paleogene mass extinction did not significantly affect river systems on a large scale.

We also observe small-scale variations in river patterns, with changes occurring both spatially and temporally. For instance, when the paleocurrent data are clustered statistically, the change from a uniform NW–SE distribution to a chaotic or bimodal distribution does not occur simultaneously across all clusters. Some clusters begin to deviate from a uniform NW–SE flow ~300 k.y. before the KPB, although the widespread shift to a SW–NE flow direction only occurs ~400 k.y. after the boundary.

We do not observe a sudden change in flow direction at the KPB or a transition from meandering to braided flow styles, as reported by Ward et al. (2000) at the Permian–Triassic boundary in South Africa. Thus, our data record no evidence that the K–Pg extinction caused catastrophic flooding that significantly affected river systems in the Hell Creek area.

This is supported by previous studies on K–Pg environments in the Western Interior. Although the transition from a well-drained to poorly drained setting at the KPB indicates an overall hydrological shift, river channel deposits are generally similar across the boundary. Murphy et al. (1995), working in North Dakota, noted that it is difficult to distinguish Hell Creek and

Fort Union river sandstones because both consist of fine- to medium-grained sand and are otherwise similar in appearance. Bendixen (2021) also reported consistent grain sizes in channel sandstones from eastern Montana, with fine- to medium-grained sand dominating both the upper Hell Creek and lower Fort Union formations. The thickness of channel bodies is also consistent across the KPB. Channel sandstones from both the Hell Creek and Fort Union formations often form stacked deposits up to 30 m thick (Bendixen, 2021) and show fining-upward sequences within a single channel. Finally, Fastovsky (1987) assigned both Hell Creek and lower Fort Union deposits to a suspended and dissolved-load regime based on grain size distributions. These similarities suggest that river discharge and sediment supply did not change significantly at the KPB. In particular, an increase in clastic sedimentation, which would be expected if the K–Pg extinction caused denudation and accelerated erosion of the landscape, is not recorded in river deposits at the KPB. Thus, observed trends in river dynamics must be driven by other environmental or geophysical factors.

Because the sediments are lithologically similar throughout the studied section, we rule out varying substrate erodibility as an influence on river dynamics. Crystalline basement rocks, which are less susceptible to erosion than sediments and could confine channels, are not exposed anywhere in the study area. Varying formation or preservation of elongate concretions is also unlikely to produce the observed changes because concretions occur across the KPB with similar lithological compositions and cementation (Frye, 1967).

The overall transition from a uniform to bimodal paleocurrent distribution may result from the same process that led to wetter, flood-prone environments after the KPB. One hypothesis suggests that Laramide tectonics altered the shoreline and increased accommodation space in the foreland basin (Bendixen, 2021). Laramide uplift and the associated foredeep migrated north in the latest Cretaceous and early Paleogene (Cataneanu et al., 2000; Copeland et al., 2017). If tectonics drove fluvial variations at that time, paleocurrents should change gradually, with rivers being diverted northward as the foredeep moved. While the paleocurrent data presented here record an increasing SW–NE component from 0.4 m.y. post-KPB, they also record abrupt, short-term fluctuations (Figure S123), which are unlikely to result from tectonic processes. We conclude that Hell Creek paleocurrent data do not support tectonic loading to the west as the only driver of fluvial change.

Sequence stratigraphic analyses support this interpretation. Fowler (2020) and Bendixen

(2021) identified 3–4 depositional cycles from low- to high-accommodation settings in Late Cretaceous units. Fowler (2020) estimated the cycles lasted 0.25–0.5 m.y. based on radioisotopic ages (Sprain et al., 2015, 2018). This is too short for typical tectonic uplift and subsidence cycles, implying that other processes influenced river dynamics on geologically short time scales.

The change to a poorly drained floodplain has also been linked to rising sea level in the Western Interior Seaway, which led to transgression of the Cannonball Sea (Fastovsky and McSweeney, 1987; Johnson et al., 2002). The Cannonball transgression likely caused flooding, favored development of wetlands, and influenced river systems near the shore. Several transgressive-regressive sequences are recorded in the latest Cretaceous and early Paleocene, including the Fox Hills Formation and the Breien and Cantapeta members (Hoganson and Murphy, 2002; Murphy et al., 2002; Johnson et al., 2002). Such recurring, short-lived base level fluctuations could have rapidly altered river patterns and depositional styles.

Alternatively, climate change may have influenced river systems in the Late Cretaceous and early Paleocene. Temperature fluctuations in the Hell Creek area (Tobin et al., 2014; O'Connor et al., 2024) were likely accompanied by changes in precipitation. Numerical models indicate that the rise of mountain ranges during the Sevier and Laramide orogenies, combined with the presence of an inland sea to the east and a warm global climate, may have driven a summer monsoon on the eastern margin of the Sevier highlands (Weaver et al., 2024; Fricke et al., 2010; Sewall and Fricke, 2013). Oxygen isotope data from Montana and Alberta, Canada, support a monsoonal influence on Late Cretaceous precipitation, with foreland rivers fed by both high-elevation monsoon rains and local lowland rainfall (Fricke et al., 2008, 2010). As the Western Interior Seaway transgressed and regressed in the Late Cretaceous, the moisture source supporting monsoon rainfall also varied, which may have altered river discharge, direction, and planform style.

West et al. (2021) invoked a monsoon influence on environmental transitions near the KPB. They documented a perennially warm and wet early Paleocene climate in southwestern Saskatchewan, Canada, contrasting with seasonal drought in the same region during the Late Cretaceous (McIver, 2002; Bamforth et al., 2014). West et al. (2021) attributed this to varying monsoon intensity as the Western Interior Seaway advanced and retreated. The climatic shift in Saskatchewan mirrors the transition from well-drained to wet, poorly drained environments in the Hell Creek area, which could similarly be

attributed to monsoon dynamics. However, it is currently difficult to evaluate a climatic influence on Hell Creek river systems because hydrological data are limited. Further research into Late Cretaceous precipitation and hydroclimate could clarify the climate's role in shaping regional hydrology.

SYNTHESIS AND CONCLUSIONS

Cretaceous–Paleogene boundary (KPB) sediments in the Western Interior of North America record a transition from well-drained settings to poorly drained floodplains featuring ponds and peat bogs. This transition is reflected in the increasing abundance of coal, lignite, and fine-grained sediments across the boundary, indicating a rising abundance of standing water. Because the depositional shift coincides with the Cretaceous–Paleogene mass extinction, it has been suggested that widespread vegetation loss—potentially from wildfires ignited by the bolide impact—led to increased runoff, destabilized riverbanks, and large-scale flooding that could explain the observed changes. However, alternative explanations such as tectonic and sea-level changes have also been proposed.

If the extinction event disrupted river systems and triggered catastrophic flooding, evidence of these changes may be preserved in geological records of river flow across the boundary. We present and analyze a large dataset of 2941 paleocurrent indicators from remotely mapped elongate concretions in the Hell Creek area of eastern Montana. The data show that river systems did not undergo major reorganization at the KPB. Instead, paleocurrents maintained a dominant NW–SE flow direction through the Cretaceous–Paleogene extinction boundary, with a transition to a bimodal NW–SE and SW–NE pattern occurring ~400 k.y. after the boundary. This suggests that although the extinction event coincided with a rising water table, it did not directly trigger large-scale river system changes.

We also introduce a method to distinguish meandering from braided river deposits using paleocurrent distributions, which helps to detect shifts in river planform style. Our analysis reveals no significant change in planform style across the KPB, implying that the extinction did not have significant and lasting effects on river systems in the Western Interior. Instead, the observed paleocurrent patterns may reflect a combination of tectonic influences and short-term hydrological changes. Laramide tectonics may have contributed to long-term drainage evolution, but abrupt, small-scale fluctuations in paleocurrent direction suggest additional short-term controls, such as climate variability.

This work highlights the potential of remote sensing in reconstructing paleoriver evolution with high spatial and temporal resolution, offering new insights into how fluvial systems respond to environmental change.

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