1 Regional-scale paleobathymetry controlled location, but not
2 magnitude, of tidal dynamics in the Late Cretaceous Western
3 Interior Seaway, USA.

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11
12 **ABSTRACT**

13 Despite extensive outcrop and previous sedimentologic study, the role of tidal processes along sandy, wave-
14 and river-dominated shorelines of the North American Cretaceous Western Interior Seaway remains
15 uncertain, particularly for the extensive mid-Campanian (c. 75-77.5 Ma) tidal deposits of Utah and
16 Colorado, USA. Herein paleotidal modelling, paleogeographic reconstructions, and interpretation of
17 depositional process regimes are combined to evaluate the regional-scale (100-1000km) basin
18 physiographic controls on tidal range and currents along these regressive shorelines in the ‘Utah Bight’,
19 southwestern Western Interior Seaway. Paleotidal modelling using a global and astronomically forced tidal
20 model, combined with paleobathymetric sensitivity tests, indicates the location of stratigraphic units
21 preserving pronounced tidal influence only when the seaway had a deep center (~400 m) and southern
22 entrance (>100 m). Maximum tidal velocity vectors under these conditions suggest a dominant south-
23 easterly ebb tide within the ‘Utah Bight’, consistent with the location and orientation of paleocurrent
24 measurements in regressive, tide-influenced deltaic units. The modelled deep paleobathymetry increased
25 tidal inflow into the basin and enhanced local-scale (10-100 km) resonance effects in the ‘Utah Bight’,
26 where an amphidromic cell was located. However, the preservation of bidirectional, mudstone-draped cross

stratification in fine- to medium-grained sandstones requires tides in combination with fluvial currents and/or local tidal amplification below the maximum resolution of model meshes (c. 10 km). These findings suggest that whilst regional-scale controls govern tidal potential within basins, localized physiography exerts an important control on the preservation of tidal signatures in the geologic record.

INTRODUCTION

Despite an exceptional archive of sedimentologic and stratigraphic information, understanding the regional tidal dynamics in the Cretaceous Western Interior Seaway (WIS) of North America has proven challenging. Extensively studied Campanian-aged deposits of regressive and transgressive shorelines variably preserve mixed tide, wave and fluvial processes (e.g. Aschoff and Steel, 2011a; Gomez-Veroiza and Steel, 2010; Steel et al., 2012). Abundant evidence of tidal influence has been recognized in shoreline deposits from a short stratigraphic time interval (c. 77.5–75 Ma) around the NE coast of a large embayment in the southwestern WIS (‘Utah Bight’; Willis and Gabel, 2001; van Cappellet et al., 2016; 2018), especially in maximum regressive deposits (Mellere and Steel, 1995, 2000; Aschoff and Steel, 2011b; Steel et al., 2012). The abundance of tidal deposits in this interval has been interpreted as strong evidence for tidal amplification, perhaps reflecting resonance of tidal amphidromic circulation and/or tectonic changes to basin physiography (Steel et al. 2012; van Cappellet et al. 2018). Whilst local-scale studies on this interval are plentiful, our understanding of regional-scale (100-1000s km) influences on tidal dynamics within the WIS is limited. Paleotidal modelling has previously suggested microtidal tidal ranges in the mid-Campanian WIS (Erickson and Slingerland, 1990). Modern models use highly accurate unstructured meshes and full astronomical forcing for regional-to-global simulations of tidal range and bed shear stress, and have successfully investigated the sensitivity of tides to paleophysiography and the preserved spatio-temporal distribution of tidal deposits (Wells et al., 2005, 2010; Mitchell et al., 2011, Collins et al., 2017; 2018). Herein, we integrate new generalized interpretations of maximum regressive paleoshoreline geometry and the formative process regime of shoreline–shelf deposits

during the *Baculites reduncus* ammonite zone (~76-77Ma), with global paleotidal models of tidal range and tidal bed shear stress. Our aim is to characterize the regional-scale pattern, magnitude, and controls of tidal potential in the southwestern WIS.

GEOLOGIC SETTING

Mid-Campanian sediments of the WIS locally contain interpreted tidal structures in mixed-influence (wave- and tide-dominated) regressive coastal–deltaic strata across multiple high-frequency regressive-transgressive shoreline transits (Willis and Gabel, 2001; Steel et al., 2012; Legler et al., 2014; van Cappellet al., 2016). The Hygiene Sandstone Member and Sego Sandstone are characterized by cross-stratified, fine- to medium-grained sandstones with pervasive mud drapes and bidirectional paleocurrent populations, indicating pronounced tidal influence, whereas the time-equivalent strata of the Iles Formation, Cliff House Sandstone, and Parkman Sandstone Member are interpreted as wave-dominated shoreline–shelf deposits (Fig. 1) (see synthesis in van Cappellet al., 2018). The relative influence of tide, wave, and fluvial (river-mouth) processes thus varied spatially. We investigate the spatial variation in tidal influence along the predominantly wave-dominated shorelines in our model results.

MATERIALS AND METHODS

The ‘base-case’ mid-Campanian physiography of the ‘Utah Bight’ is taken from the paleogeographic reconstruction of van Cappellet al. (2018) for the *Baculites reduncus* ammonite zone (Fig. 1): this illustrates the generalized shoreline position at the maximum regression of a high-frequency regressive-transgressive shoreline transit, and is underpinned by biostratigraphic correlation of marginal- and shallow-marine strata (Supplementary Information). The paleogeography was georeferenced and included within a global mid-Campanian paleogeographic reconstruction (Fig. 2) underpinned by Getech Group plc’s global rigid plate model (e.g. Mazur et al., 2012 - see Supplementary Information).

Previous paleobathymetric reconstructions vary widely and focus on specific time periods within the seaway's history. Prior studies estimated water depths in the center of the WIS at 200–300 m during the early Turonian (Sageman and Arthur, 1994), although local water depth maxima of 150–1000 m have been previously interpreted for other stages (Asquith, 1970; Williams and Stelck, 1975; Erickson and Slingerland, 1990). Consequently, a depth range of 200–400 m was chosen to capture a reasonable range of uncertainty in central seaway depth. The paleogeography of the southern WIS entrance is also uncertain (Young, 1986); Cenomanian-Turonian paleogeographic reconstructions include a topographic high across north Texas (Lowery et al., 2018) but evidence for this topographic high during the Campanian is limited by a lack of outcrop data and by northwards retreat of the seaway during the late Campanian and Maastrichtian (Young, 1986).

To capture the range of paleogeographic uncertainty in both seaway depth and southern entrance physiography, four end-member paleogeographic scenarios of the mid-Campanian WIS were constructed: Scenario 1—a 'base-case' model with a 200 m maximum depth and a shallow (<100 m) southern entrance (Fig. 2a); Scenario 2—the 'base-case' model with a deeper southern entrance (100–200 m) (Fig. 2b); Scenario 3—the 'base-case' model with a deeper central seaway (ca. 400 m) (Fig. 2c); and Scenario 4—a model with a deeper central seaway (ca. 400 m) and southern entrance (100–200 m) (Fig. 2d).

Fluidity (<http://fluidityproject.github.io/>) is a hydrodynamic, finite element ocean model that simulates global astronomical tides, without data assimilation, for three-months simulation time and a spin-up period of 120 hours simulation (Wells et al., 2005; Piggott et al., 2008). Global, multi-scale, three-dimensional computational meshes with a maximum resolution of ca. 10 km are produced using qmesh from paleogeographic DEMs (Avdis et al., 2018). Fluidity has been extensively validated in both modern and ancient environments for tidal amplitude (Wells et al., 2005, 2007, 2010; Collins et al., 2017) and tidal bed shear stress and particle entrainment (Mitchell, et al. 2011; Collins et al., 2018). Modelled tidal velocity vectors also allow the comparison of model results and paleocurrent measurements. A detailed description of model parameters is found in Supplementary Information.

RESULTS

The tidal range in the ‘Utah Bight’ and the surrounding western margin of the WIS is regionally microtidal (<2 m) in all paleogeographic scenarios, consistent with previous modelled estimates (Ericksen and Slingerland, 1990), but mesotidal (2–4 m) along most of the eastern margin of the seaway (Fig. A1a–d).

Modelled bed shear stress in all paleogeographic scenarios (Fig. 3a–d) indicates that tidal currents were capable of transporting up to coarse sand along the unpreserved eastern margin and silt across the southern end of the seaway. The ‘base-case’ model suggests transport of fine silt along the western and north-eastern margin of the ‘Utah Bight’, where the Hygiene Sandstone Member was deposited (Fig. 3a). In paleogeographic scenarios in which the southern seaway entrance (Fig. 3b) or seaway center (Fig. 3c) are deepened, there is increased potential for tidal sediment transport along the western and north-eastern margin of the ‘Utah Bight’, with possible localized transport of fine sand. Scenario 4, which combines both a deeper central seaway and southern entrance, indicates potential for tidal transport of silt where the Sego Sandstone was deposited and up to fine sand in localized areas where the Hygiene Sandstone Member was deposited (Fig. 3d).

The phase pattern of the M2 tide for all modelled paleogeographic scenarios shows a consistent distribution of amphidromic systems within the seaway (e.g. Fig. 3e), including counterclockwise circulation within the ‘Utah Bight’ (van Cappel et al., 2016).

Maximum tidal velocity vectors form a counterclockwise gyre within the seaway in Scenario 4 (Fig. 4a), with strong ($>0.36 \text{ ms}^{-1}$) northwards tidal flow along the eastern coastline and predominantly eastward flow up to 0.27 ms^{-1} in the ‘Utah Bight’ (Fig. 4b). In the Sego Sandstone location, the modelled ESE-directed tidal flow is consistent with ENE- to SE-dominated paleocurrent directions in cross-stratified sandstones in the lower Sego Sandstone (e.g. S₃ sandstone of van Cappel et al., 2016), which are interpreted to record ebb-tide dominance possibly combined with seaward-directed river currents (Fig. 4c).

DISCUSSION

The action of wave processes was pervasive along the mid-Campanian shoreline of the ‘Utah Bight’, with significant fluvial influence near the mouths of large river systems (Fig. 1). However, the model results suggest potentially enhanced tidal influence in the ‘Utah Bight’ at this time, consistent with sedimentologic and stratigraphic observations (Steel et al., 2012), and correctly predict locally pronounced tidal currents where the Sego Sandstone and Hygiene Sandstone were deposited. Sensitivity analyses of regional-scale paleogeographic uncertainty in the mid-Campanian WIS suggest that tidal sediment transport along the shoreline of the ‘Utah Bight’ in the area of Sego Sandstone deposition was only possible when the central seaway and its southern entrance were both relatively deep (Fig. 2d). This is reinforced by the agreement between modelled maximum tidal velocity vectors and paleocurrent measurements of preserved tidal cross-stratification in the Sego Sandstone when the central seaway and southern entrance were deepest (Fig. 4b). For partially enclosed ocean systems such as the WIS, the amount of tidal energy entering the basin is the foremost control on the strength of tidal processes (Collins et al., 2018). Whilst prevailing microtidal conditions (Fig. A1) indicate significant frictional dampening of the incoming tide, consistent with previous paleotidal models of epicontinental seas (Erickson and Slingerland, 1990), an increase in the depth of the southern seaway entrance and basin center also increases tidal bed shear within the ‘Utah Bight’, suggesting decreased damping of incoming tides. Partial or full resonance of the incoming dominant M_2 tide in the ‘Utah Bight’ is also likely to have enhanced tidal processes. Model results are consistent with: (1) the quarter-wavelength oscillation period in all reconstructions, although most strongly in Scenario 4 (c. 450 km width and c. 150 m depth) (van Cappel et al., 2018); and (2) the previously hypothesized amphidromic system (Pugh, 1987) in the ‘Utah Bight’ (Erickson and Slingerland, 1990). These factors suggest that regional-scale basin controls enhanced tidal potential within the WIS and ‘Utah Bight’ during the mid-Campanian and are at least partly responsible for increased preservation of tidal signatures in the associated rock record. Tidal influence preserved in other WIS deposits from embayments, such as the Campanian Shannon Sandstone (Martinsen, 2002) and the Cenomanian Frewens Sandstone (Willis et al., 1999), may also record similarly enhanced tidal processes.

Despite the regional-scale paleogeographic control on tidal processes, the predicted maximum tidal bed shear stress in the ‘Utah Bight’ for all modelled scenarios is insufficient to generate the observed dune-scale cross stratification in fine- to medium-grained sandstones of the lower Sego Sandstone. Although this discrepancy can be attributed to the action of river currents in addition to tides, several other mechanisms, which are not mutually exclusive, may also contribute. First, the seaway bathymetry may have been deeper than all four modelled scenarios, allowing more tidal energy to enter and extend northwards into the seaway. Alternatively, local tidal amplification may have occurred at a scale below the mesh resolution of the paleotidal simulations (maximum of 10 km): tides are commonly interpreted to be amplified locally due to convergence in channels between fluvio-tidal bars (Dalrymple et al., 2003) like those interpreted in the Sego Sandstone (Willis and Gabel, 2001; Legler et al., 2014; van Cappel et al., 2016). Paleotidal models also use a minimum water depth of 10 m to prevent the sea surface intersecting the sea bed during low tide (Wells et al. 2010). Consequently, tidal models cannot fully capture local funnelling and shoaling effects of tides along shorelines, which may be especially pronounced in coastal embayments (Dalrymple and Padman, 2018; Collins et al., 2018).

The combined impact and interaction of regional and local physiography on tidal sedimentation has also been highlighted by paleotidal modelling studies of the Oligo–Miocene seas of SE Asia (Collins et al., 2018) and Early Cretaceous seaways of NW Europe (Wells et al., 2010). Regional physiography controls the first-order tidal potential within a basin, but localized effects may also exert the dominant control on the magnitude and potential preservation of tidal signatures. Critically, the preservation of tidal sediments also depends on the relative magnitude of river, wave and storm processes, which operate on different spatial–temporal scales and in response to different controls.

CONCLUSION

The tidal regime of the Mid-Campanian WIS has been reconstructed using paleogeographies and paleotidal modelling, in order to resolve the basin physiographic controls on pronounced preservation of tidal

signatures in the ‘Utah Bight’. The tidal model indicates higher bed shear stress in locations where stronger tidal currents are interpreted from outcrop data when the seaway center and southern entrance were deep (~400 m and >100 m, respectively), but fails to fully replicate the magnitude of bed shear stress required to generate dunes in fine and medium sand, as interpreted in the Sego Sandstone and Hygiene Sandstone Member. This discrepancy demonstrates that both basin physiography and local effects are important for generating tidal signatures. Paleotidal modelling provides an effective tool for understanding the complex interactions between regional-scale basin physiography and shoreline–shelf process regime, and a reference against which to assess the influence of local tidal amplification.

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References Cited

- Aschoff, J.L., Steel, R.J., 2011a. Anatomy and development of a low-accommodation clastic wedge, upper Cretaceous, Cordilleran Foreland Basin, USA. *Sediment. Geol.*, 236(1-2), p. 1-24
- Aschoff, J.L., Steel, R.J., 2011b. Anomalous clastic wedge development during the Sevier-Laramide transition, North American Cordilleran foreland basin, USA. *Geol Soc Am Bull*, 123(9-10), p. 1822-1835
- Asquith, D.O., 1970. Depositional topography and major marine environments, Late Cretaceous, Wyoming: *Am Assoc Pet Geol Bull* 54, p. 1184-1224
- Avdis, A., Candy, A.S., Hill, J., Kramer, S.C., Piggott, M.D., 2018. Efficient unstructured mesh generation for marine renewable energy applications. *Renew. Energy* 116, p. 842–856
- Cobban, W.A., Walaszczyk, I., Obradovich, J.D., McKinney, K.C., 2006. A USGS Zonal Table for the Upper Cretaceous Middle Cenomanian–Maastrichtian of the Western Interior of the United States Based on Ammonites, Inoceramids, and Radiometric Ages, U.S. Geological Survey Open-File Report 2006-1250, p. 50
- Collins, D.S., Avdis, A., Allison, P.A., Johnson, H.D., Hill, J., Piggott, M.D., 2018. Controls on tidal sedimentation and preservation: Insights from numerical tidal modelling in the Late Oligocene–Miocene South China Sea, Southeast Asia. *Sedimentology*. 65(7), p. 2468-2505
- Collins, D.S., Avdis, A., Allison, P.A., Johnson, H.D., Hill, J., Piggott, M.D., Hassan, M.H.A., Damit, A.R., 2017. Tidal dynamics and mangrove carbon sequestration during the Oligo–Miocene in the South China Sea. *Nat. Commun.* 8, 15698

- Dalrymple, R.W., Baker, E.K., Harris, P.T., Hughes, M.G., 2003. Sedimentology and stratigraphy of a tide-dominated, foreland-basin delta (Fly River, Papua New Guinea), *in* Posamentier, H.W., Sidi, F.H., Darman, H., Nummedal, D., Imbert, P. eds., *Tropical Deltas of Southeast Asia—Sedimentology, Stratigraphy, and Petroleum Geology*. (SEPM) Spec. Publ. 76, p. 147 – 173
- Dalrymple, R.W., Padman, L., 2018. Are tides controlled by latitude?, *in* Fraticelli, C.M., Martinus, A., Suter, J., Markwick, P.J., eds., *Latitudinal Controls on Stratigraphic Models and Sedimentary Concepts*, Soc. Sediment. Res. (SEPM) Spec. Publ.
- Ericksen, M.C., Slingerland, R., 1990. Numerical simulations of tidal and wind-driven circulation in the Cretaceous Interior Seaway of North America. *Geol Soc Am Bull* 102, p. 1499–1516
- Gomez-Veroiza, C.A., Steel, R.J. 2010. Iles Clastic Wedge development and sediment partitioning in a 300 km, fluvial to marine Campanian transect (3my), Western Interior Seaway, SW Wyoming and N Colorado. *Am Assoc Petrol Geol Bull* 94, p. 1349–1377
- Legler, B., Hampson, G.J., Jackson, C.A., Johnson, H.D., Massart, B.Y., Sarginson, M., Ravnas, R., 2014. Facies relationships and stratigraphic architecture of distal, mixed tide-and wave-influenced deltaic deposits: Lower Sego sandstone, western Colorado, USA. *J. Sediment. Res.* 84, p. 605–625
- Lowery, C.M., Leckie, R.M., Bryant, R., Elderbak, K., Parker, A., Polyak, D.E., Schmidt, M., Snoeyenbos-West, O., Sterzinar, E., 2018. The Late Cretaceous Western Interior Seaway as a model for oxygenation change in epicontinental restricted basins. *Earth-Sci. Rev.* 177, p. 545–564
- Martinsen, R.S., 2002. Depositional remnants, part 2: Examples from the Western Interior Cretaceous basin of North America. *AAPG Bulletin* 87, p. 1883-1909
- Mazur, S., Green, C., Stewart, M.G., Whittaker, J.M., Williams, S., Bouatmani, R., 2012. Displacement along the Red River Fault constrained by extension estimates and plate reconstructions. *Tectonics* 31, TC5008
- Mellere, D., Steel, R., 1995. Variability of lowstand wedges and their distinction from forced-regressive wedges in the Mesaverde Group, southeast Wyoming. *Geology*, 23(9), p. 803-806
- Mellere, D., Steel, R., 2000. Style contrast between forced regressive and lowstand/transgressive wedges in the Campanian of south-central Wyoming (Hatfield Member of the Haystack Mountains Formation). *Geol. Soc. London, Spec. Publ.* 172(1), p. 141-162
- Mitchell, A. J., Allison, P. A., Gorman, G. J., Piggott, M. D., Pain, C. C., 2011. Tidal circulation in an ancient epicontinental sea: the Early Jurassic Laurasian Seaway. *Geology*, 39, p. 207–210
- Piggott, M.D., Gorman, G.J., Pain, C.C., Allison, P.A., Candy, A.S., Martin, B.T., Wells, M.R., 2008. A new computational framework for multi-scale ocean modelling based on adapting unstructured meshes. *Int. J. Numer. Methods Fluids* 56, p. 1003–1015
- Pugh, D.T., 1987. *Tides, surges and mean sea-level: a handbook for engineers and scientists*: John Wiley, Chichester, UK, 472 p.
- Sageman, B.B., Arthur, M.A., 1994. Early Turonian paleogeographic/paleobathymetric map, Western Interior, U.S., *in* Caputo, M.V., Peterson, J.A., Franczyk, K.J., eds., *Mesozoic Systems of the Rocky Mountain Region, USA*. p. 458–469
- Steel, R.J., Plink-Bjorklund, P., Aschoff, J., 2012. Tidal deposits of the Campanian Western Interior Seaway, Wyoming, Utah and Colorado, USA, *in* *Principles of Tidal Sedimentology*. Springer, p. 437–471
- van Cappelle, M., Hampson, G.J., Johnson, H.D., 2018. Spatial and temporal evolution of coastal depositional systems and their process regimes: the Campanian of the Western Interior Seaway, USA. *J. Sediment. Res.* 88, p. 873-897
- van Cappelle, M., Stukins, S., Hampson, G.J., Johnson, H.D., 2016. Fluvial to tidal transition in proximal, mixed tide-influenced and wave-influenced deltaic deposits: Cretaceous lower Sego Sandstone, Utah, USA. *Sedimentology* 63, p. 1333–1361
- Wells, M.R., Allison, P.A., Hampson, G.J., Piggott, M.D., Pain, C.C., 2005. Modelling ancient tides: the Upper Carboniferous epi-continental seaway of Northwest Europe. *Sedimentology* 52, p. 715–735

- Wells, M.R., Allison, P.A., Piggott, M.D., Gorman, G.J., Hampson, G.J., Pain, C.C., Fang, F., 2007. Numerical modeling of tides in the late Pennsylvanian midcontinent seaway of North America with implications for hydrography and sedimentation. *J. Sediment. Res.* 77, p. 843–865
- Wells, M.R., Allison, P.A., Piggott, M.D., Hampson, G.J., Pain, C.C., Gorman, G.J., 2010. Tidal modeling of an ancient tide-dominated seaway, part 1: model validation and application to global early Cretaceous (Aptian) tides. *J. Sediment. Res.* 80, p. 393–410
- Williams, G.D., Stelck, C.R., 1975. Speculations on the Cretaceous paleogeography of North America. *Cretac. Syst. West. Inter. N. Am. Geol. Assoc. Can. Spec. Pap.* 13, p. 1–20
- Willis, B.J., Bhattacharya, J.P., Gabel, S.L., and White, C.D., 1999. Architecture of a tide-influenced river delta in the Frontier Formation of central Wyoming, USA. *Sedimentology* 46, p. 667–688
- Willis, B.J., Gabel, S., 2001. Sharp-based, tide-dominated deltas of the Sego Sandstone, Book Cliffs, Utah, USA. *Sedimentology* 48, p. 479–506
- Young, K., 1986. Cretaceous, marine inundations of the San Marcos platform, Texas. *Cretac. Res.* 7, p. 117–140

Figure Captions

Fig. 1.

Paleogeographic map of the WIS around the ‘Utah Bight’, during maximum regression in the *Baculites reduncus* ammonite zone (~77 Ma) (after van Cappel et al., 2018). Interpretations of gross depositional environments are shown in bold colors where constrained by outcrop data, and in faded colors away from outcrop control. Ternary diagrams of interpreted depositional process regime(s) are included where supported by detailed published work on shoreline sandstones at outcrop (see van Cappel et al., 2018 for details). Red numbers indicate units with pronounced tidal signatures. 1: Hygiene Sandstone Member; 2: Sego Sandstone; 3: Parkman Sandstone Member; 4: Iles Formation; 5: Cliff House Sandstone Member.

Fig. 2.

Diagram of the four end-member scenarios used for tidal modelling: A. ‘Base-case’ scenario; B. Base-case with a deeper southern entrance; C. Base-case scenario with a deeper central seaway; D. Model with both deeper central seaway and southern entrance.

Fig. 3.

Bed shear stress results from numerical modelling for the four paleobathymetric scenarios, converted to values for entrainment of various particle sizes: A. 'Base-case' scenario; B. Base-case with a deeper southern entrance; C. Base-case scenario with a deeper central seaway; D. Model with both deeper central seaway and southern entrance. Results show increased movement of sediment with deeper paleobathymetric scenarios. E. Model results for the M_2 tidal phase for Scenario 4 (Figs. 2d, 3d) indicating the formation of an amphidromic point and clockwise circulation cell in the 'Utah Bight'.

Fig. 4.

Modelled vectors of maximum tidal velocity in the WIS for the model with both deeper central seaway and southern entrance (scenario 4) (Figs. 2d, 3d). A. Maximum tidal velocity vectors in the WIS. Vector lengths are scaled to velocity magnitude. B. Maximum tidal velocity vectors within the 'Utah Bight', which are predominately oriented towards the east, suggesting dominance of ebb tidal flow. Within the region of the Sego Sandstone, maximum tidal velocity vectors are oriented towards the SE and ESE. C. Paleocurrent distributions in cross-stratified tidal sandstones of the Sego Sandstone (S_3 sandstone) show a dominant SE orientation (van Cappelle et al., 2016).

1 Hygiene Member (Pierre Shale)
2 Sego Sandstone
Land

0-50 m
50-100 m
100-150 m
150-200 m
200-400 m
>400 m

SUPPLEMENTARY INFORMATION for:

Regional-scale paleobathymetry controlled location, but not magnitude, of tidal dynamics in the Late Cretaceous Western Interior Seaway, USA.

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Construction of Paleogeographies

A global atlas of 1:20,000,000 scale paleogeographic maps (Markwick, 2007), compiled by Getech Globe as part of the ‘Atlases of Global Paleogeography’ project (<http://www.getech.com/globe/>), form the basis of regional-scale, higher fidelity (1:5,000,000), North American paleogeographic and paleobathymetric interpretations. Paleo-positions of tectonic plates are represented by Getech’s in-house global, self-consistent, geodynamic plate model. This model comprises two parts: a global distribution of present-day tectonic plates and a set of finite rotations that describe relative motion between each plate. The boundaries of tectonic plates are sourced from potential field data, from which major structural features have been mapped; each plate is assigned a unique plate ID code, which is used to extract relevant relative motion parameters from the set of finite rotations. Getech uses a rigid plate model, in which the shape of tectonic plates does not change over time. Consequently, any plate deformation through time is expressed as overlap (extension) and underlap (compression) at plate boundaries (Mazur et al., 2012). The motion of one plate relative to another during a given time interval can be represented by an angle of rotation about a fixed semi-axis (Euler Pole) on Earth’s surface, known as a finite rotation. The absolute paleo-position of any given plate, relative to Earth’s spin axis, is calculated by adding finite rotations within a plate hierarchy. Relative motion is constrained from a variety of sources, including oceanic magnetic anomalies, fracture zone orientations, paleomagnetic poles, geologic relationships and tectonic histories of onshore structures.

Basemap production involves rotation of present-day physiographic and cultural data together with geologic information (e.g. well and outcrop point data) and the structural framework. The structural framework in part comprises a rotation of present-day mapped structures, defined by Getech, with gravity, magnetic and structural mapping datasets. Plate positions are further constrained by Getech's high resolution geophysical and structural datasets, which include additional paleomagnetic evidence, ocean floor ages and magnetic anomalies, deep seismic data, published paleogeographic interpretations, and plate modelling experiments. Plate modelling is performed using Gplates and PaleoGIS for ArcGIS (ESRI, 2010). As the WIS is by definition contained within the center of the North American continent, no additional contributions to the underlying plate model in relation to the North American plate were made for this project.

The boundaries between gross depositional environments from the provided global paleogeographies were extracted as paleobathymetric contours and interpolated to form a paleobathymetric grid with a 0.1° (ca 10 km) resolution. Within the Western Interior, paleobathymetric and shoreline contours were adjusted in ArcGIS (ESRI, 2010) according to the paleogeographies of van Cappelle et al. (2018) to generate the four end-member scenarios. In this way, shoreline positions remained the same between the four potential scenarios; only paleobathymetry was altered.

To create meshes for use in tidal modelling, Digital Elevation Map (DEM) rasters had to be produced from the palaeobathymetric contours. DEMs were generated using the Topo to Raster tool in the Spatial Analyst toolbox in ArcGIS (ESRI, 2010). A worldwide mask was defined by Getech, and a boundary land-sea mask shapefile was included to ensure interpolation accuracy.

Model Parameters

Fluidity (<http://fluidityproject.github.io/>) model outputs are as follows: (1) the amplitude of tidal components; (2) tidal range; (3) average and maximum tidal current velocity; (4) the magnitude and direction of average and maximum tidal bed shear stress; and (5) the tidal phase. Tidal harmonic analysis

of the modelled time series of free surface heights is used to determine the amplitude and phase of the four major tidal components (M_2 , S_2 , K_1 and O_1) (Foreman, 1979).

The Coriolis acceleration (f) is used to describe motion of the tidal bulge; this is simplified to:

$$f = 2\Omega \sin\phi \quad (1)$$

where Ω is the rotation rate of the Earth ($7.27 \times 10^{-5} \text{ rad s}^{-1}$) and ϕ is the latitude (Cushman-Roisin & Beckers, 2011). The Earth's rate of rotation (and therefore its day/night cycle) is slowing down at a rate of $1.4 \times 10^{-3} \text{ sec per 100 years}$ due to tidal friction; thus, it is likely that the Cretaceous Earth experienced a 23 hour day. However, the length of day is also affected by irregular variations and is therefore difficult to quantify in the geologic past (Hide and Dickie, 1991). We subsequently follow the protocol of previous tidal modelling studies (e.g. Wells et al. 2005; Mitchell et al. 2010, 2011) and use modern values for the earth's rotation rate.

Tidal range is calculated as the difference between the maximum and minimum free surface heights over the post spin-up simulation period.

“Time-averaged velocity vectors” are calculated from the absolute value of each component and the magnitude of averaged components. The norm of velocity vectors can then be extracted and output as a scalar field recording the maximum value and associated direction over a tidal cycle, which can be graphically displayed on velocity data. This was achieved through use of the Vector Field Calc tool, the regular-points tool, the Point Sampling tool and the Vector Field Renderer tool in QGIS. As the model resolution is a maximum of 10 km (consisting of one arrow per grid cell with a maximum resolution of $10 \times 10 \text{ km}$), comparison of model results to estimates of paleocurrents from field studies are valid at a large-scale and can give interpretations of gross paleocurrent directions.

Tidal bed shear stress (τ) is the frictional force exerted by tides on the sediment surface. Mean and maximum values for the post spin-up simulation period are calculated using:

$$\tau = \rho C_D \bar{u} |\bar{u}| \quad (2)$$

where ρ is the density of water (1023 kg m^{-3}), C_D is the drag coefficient (0.0025), $\bar{u}$ is the tidal current velocity vector, and $|\bar{u}|$ is the depth-averaged magnitude of the tidal current velocity vector (Pingree and Griffiths, 1979; Wells et al., 2007; Mitchell et al., 2011).

As, by definition, bed shear stress exerts a force on the sediment surface, this can influence the deposition of sediment. Bed shear stress magnitudes can therefore be converted to the equivalent grain size that could be entrained by the tidal flow based on the modelled and calculated critical bed shear stress values for sediment transport (Julien, 1998). The basis for this conversion can be found within Table A1.

For further information, a recent extensive review of the modelling parameters used within Fluidity can be found in Collins et al. (2018).

Correlation Framework for Mid-Campanian Strata

The correlation framework that is used herein to reconstruct the paleogeography of mid-Campanian strata (Fig. 1) is taken from the synthesis of van Cappel et al. (2018). Correlation of shallow-marine strata in the WIS uses a well-established ammonite biostratigraphy (Cobban et al., 2006), which has an average age resolution of 0.5 Myr in the Campanian (24 zones in 12 Myr; Krystinik and DeJarnett, 1995). Correlation of shallow-marine strata within each ammonite zone relies on outcrop mapping and sequence stratigraphic interpretations. Although sandstones that record individual regressive-transgressive shoreline transits can be mapped and correlated locally with confidence (e.g. Gomez-Veroiza and Steel, 2010), regional-scale correlation within ammonite zones, for example between outcrop belts that fringe Tertiary Laramide basins, is uncertain (van Cappel et al., 2018). Thus, the paleogeographic reconstruction in Figure 1 portrays a generalized, low-frequency maximum regressive shoreline for the “anomalous clastic wedge” (Aschoff and Steel 2011; Steel et al., 2012), with some degree of time-averaging across multiple high-frequency regressive-transgressive shoreline transits. As the Sego Sandstone, Iles Formation and Hygiene Sandstone Member have a maximum age limit of *Baculites perplexus*, and the Sego Sandstone and Hygiene Sandstone Member have a minimum age limit of *Didymoceras nebrascense*, it is likely that these lithostratigraphic units were partly coincident, and they are thus considered to be coeval at the

resolution of the paleogeographic reconstruction for the *Baculites reduncus* ammonite zone (Fig. 1). A full correlation of appropriate units can be found in Figure A2 (after van Cappellet et al., 2018).

Supplementary References

- Berenbrock, C. and Tranmer, A.W., 2008. Simulation of flow, sediment transport, and sediment mobility of the lower Coeur d'Alene River, Idaho: US Geological Survey Scientific Investigations Report 2008-5093, 163 pp.
- Cushman-Roisin, B. and Beckers, J.M., 2011. Introduction to geophysical fluid dynamics: physical and numerical aspects (Vol. 101). Academic press. 875 pp.
- ESRI, 2010. ArcGIS—a complete integrated system. Environmental Systems Research Institute, Inc Redlands, California.
- Hide, R. and Dickie, J.O., 1991. Earth's variable rotation. *Science*, 253, p. 629–637
- Julien, P. Y. 1998. Erosion and Sedimentation. New York, NY: Cambridge University Press, 280 pp.
- Foreman, M.G.G., 1979. Manual for tidal heights analysis and prediction. Institute of Ocean Sciences, Patricia Bay, BC. 57 pp.
- Krystinik, L.F. and Dejarnett, B.B., 1995. Lateral variability of sequence stratigraphic framework in the Campanian and Lower Maastrichtian of the Western Interior Seaway, in Van Wagoner, J.C., and Bertram, G.T., eds., Sequence Stratigraphy of Foreland Basin Deposits: Outcrop and Subsurface Examples from the Cretaceous of North America: American Association of Petroleum Geologists, Memoir 64, p. 11-26.
- Markwick, P.J., 2007. The palaeogeographic and palaeoclimatic significance of climate proxies for data-model comparisons. in Williams, M., Haywood, A.M., Gregory, F.J. and Schmidt, D.N., eds., Deep-Time Perspectives on Climate Change: Marrying the Signal from Computer Models and Biological Proxies. The Micropaleontological Society Special Publications, The Geological Society, London. p. 251-312.
- Mazur, S., Green, C., Stewart, M.G., Whittaker, J.M., Williams, S., Bouatmani, R., 2012. Displacement along the Red River Fault constrained by extension estimates and plate reconstructions. *Tectonics* 31, TC5008
- Mitchell, A., Uličný, D., Hampson, G.J., Allison, P.A., Gorman, G.J., Piggott, M.D., Wells, M.R., Pain, C.C., 2010. Modelling tidal current-induced bed shear stress and palaeocirculation in an epicontinental seaway: the Bohemian Cretaceous Basin, Central Europe. *Sedimentology* 57, p. 359-388
- Mitchell, A. J., Allison, P. A., Gorman, G. J., Piggott, M. D., Pain, C. C., 2011. Tidal circulation in an ancient epicontinental sea: the Early Jurassic Lurasian Seaway. *Geology*, 39, p. 207–210
- Pingree, R.D., Griffiths, D.K., 1979. Sand transport paths around the British Isles resulting from M 2 and M 4 tidal interactions. *J. Mar. Biol. Assoc. U. K.* 59, 497–513.
- van Cappellet, M., Hampson, G.J., Johnson, H.D., 2018. Spatial and temporal evolution of coastal depositional systems and their process regimes: the Campanian of the Western Interior Seaway, USA. *J. Sediment. Res.* 88, p. 873-897
- Wells, M.R., Allison, P.A., Hampson, G.J., Piggott, M.D., Pain, C.C., 2005. Modelling ancient tides: the Upper Carboniferous epi-continental seaway of Northwest Europe. *Sedimentology* 52, p. 715–735

References included within Figure A2

- Cobban, W.A., Walaszczyk, I., Obradovich, J.D., McKinney, K.C., 2006. A USGS Zonal Table for the Upper Cretaceous Middle Cenomanian–Maastrichtian of the Western Interior of the United States Based on Ammonites, Inoceramids, and Radiometric Ages, U.S. Geological Survey Open-File Report 2006-1250.
- Cobban, W.A., 1969. The Late Cretaceous ammonites *Scaphites leei* Reeside and *Scaphites hippocrepis* (Dekay) in the Western Interior of the United States. U.S. Geological Survey Professional Paper 619, pp. 29.
- Eaton, J.G., 1990. Stratigraphic revision of Campanian (Upper Cretaceous) rocks in the Henry Basin, Utah. *The Mountain Geologist* 27, 27-38.
- Eaton, J.G., 1991. Biostratigraphic framework for the Upper Cretaceous rocks of the Kaiparowits Plateau, southern Utah. in: Nations, J.D., Eaton, J.G. (Eds.), *Stratigraphy, depositional environments, and sedimentary Tectonics of the Western Margin, Cretaceous Western Interior Seaway*. Geological Society of America, Special Paper 260, 47-61.
- Fouch, T. D., Lawton, T. F., Nichols, D. J., Cashion, W. B., Cobban, W. A., 1983. Patterns and timing of synorogenic sedimentation in Upper Cretaceous rocks of central and northeast Utah, in: Reynolds, M., Dolly, E., Spearing, D. R. (Eds.), *Symposium 2–Mesozoic paleogeography of west-central United States: Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section*, 305–336.
- Gill, J.R., Cobban, W.A., 1966. The Red Bird section of the Upper Cretaceous Pierre Shale in Wyoming, with a section on a new echinoid from the Cretaceous Pierre Shale of eastern Wyoming, by Porter M. Kier; U.S. Geological Survey Professional Paper 393-A, pp. 73.
- Gill, J.R., Hail, W.J., Jr., 1975. Stratigraphic sections across Upper Cretaceous Mancos Shale–Mesaverde Group boundary, eastern Utah and western Colorado: U.S. Geological Survey Oil and Gas Investigations Chart OC– 68.
- Gill, J.R., Merewether, E.A. Cobban, W.A., 1970. Stratigraphy and nomenclature of some Upper Cretaceous and Lower Tertiary rocks in south-central Wyoming. *US Geol. Surv. Prof. Paper*, 667, 1-53.
- Izett, G.A., Cobban, W.A., and Gill, J.R., 1971, The Pierre Shale near Kremmling, Colorado, and its correlation to the east and west: U.S. Geological Survey Professional Paper 684-A, pp. 19.
- Jinnah, Z.A., Roberts, E.M., Deino, A.L., Larsen, J.S., Link, P.K., Fanning, C.M., 2009. New ⁴⁰Ar-³⁹Ar and detrital zircon U-Pb ages for the Upper Cretaceous Wahweap and Kaiparowits formations on the Kaiparowits Plateau, Utah: implications for regional correlation, provenance, and biostratigraphy. *Cretaceous Research*, 30(2), 287-299.
- Molenaar, C. M., Cobban, W. A., Merewether, E. A., Pillmore, C. L., Wolfe, D. G., Holbrook, J. M., 2002. Regional stratigraphic cross sections of Cretaceous Rocks from east–central Arizona to the Oklahoma Panhandle, U.S. Geol. Surv. Misc. Field Stud. Map MF2382.
- Merewether, E. A., Dolson, J. C., Hanson, W. B., 1997. Cretaceous stratigraphy in a northeast-trending transect, northern Utah to south-central South Dakota: U.S. Geological Survey Geologic Investigations Map I-2609.
- Roberts, E.M., Deino, A.L., Chan, M.A., 2005. ⁴⁰Ar/³⁹Ar age of the Kaiparowits Formation, southern Utah, and correlation of contemporaneous Campanian strata and vertebrate faunas along the margin of the Western Interior Basin. *Cretaceous Research*, 26(2), 307-318.
- Seymour, D.L., Fielding, C.R., 2013. High resolution correlation of the Upper Cretaceous stratigraphy between the Book Cliffs and the western Henry Mountains Syncline, Utah, USA. *Journal of Sedimentary Research*, 83(6), 475-494.
- Roehler, H. W., 1978. Correlations of coal beds in the Fort Union, Almond, and Rock Springs formations in measured sections of the west flank of the Rock Springs Uplift, Sweetwater County, Wyoming: U. S. Geological Survey.
- Young, R.G., 1955. Sedimentary facies and intertonguing in the Upper Cretaceous of the Book Cliffs, Utah–Colorado. *Geological Society of America Bulletin*, 66(2), 177-202.

197 **Appendix 1: Additional Tables and Figures**

198 Table A1

Particle classification name	Ranges of particle diameters		Shields parameter (dimensionless)	Critical bed shear stress (τ_c) (N/m ²)
	ϕ	mm		
Coarse cobble	-7 – -8	128 – 256	0.054 – 0.054	112 – 223
Fine cobble	-6 – -7	64 – 128	0.052 – 0.054	53.8 – 112
Very coarse gravel	-5 – -6	32 – 64	0.05 – 0.052	25.9 – 53.8
Coarse gravel	-4 – -5	16 – 32	0.047 – 0.05	12.2 – 25.9
Medium gravel	-3 – -4	8 – 16	0.044 – 0.047	5.7 – 12.2
Fine gravel	-2 – -3	4 – 8	0.042 – 0.044	2.7 – 5.7
Very fine gravel	-1 – -2	2 – 4	0.039 – 0.042	1.3 – 2.7
Very coarse sand	0 – -1	1 – 2	0.029 – 0.039	0.47 – 1.3
Coarse sand	1 – 0	0.5 – 1	0.033 – 0.029	0.27 – 0.47
Medium sand	2 – 1	0.25 – 0.5	0.048 – 0.033	0.194 – 0.27
Fine sand	3 – 2	0.125 – 0.25	0.072 – 0.048	0.145 – 0.194
Very fine sand	4 – 3	0.0625 – 0.125	0.109 – 0.072	0.110 – 0.145
Coarse silt	5 – 4	0.0310 – 0.0625	0.165 – 0.109	0.0826 – 0.110
Medium silt	6 – 5	0.0156 – 0.0310	0.25 – 0.165	0.0630 – 0.0826
Fine silt	7 – 6	0.0078 – 0.0156	0.3 – 0.25	0.0378 – 0.0630

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200 Table A1

Table of critical shear stress values necessary for sediment mobility of various particle sizes. Sedimentary particles will be mobile when the bed shear stress exceeds the critical shear stress value. Taken from Berenbrock and Tranmer, 2008, originally modified from Julien, 1998 (Table 7.1).

Fig. A1

Modelled tidal range in the WIS for four paleobathymetric scenarios: A. Base-case scenario; B. Base-case with a deeper southern entrance; C. Base-case scenario with a deeper central seaway; D. Model with both deeper central seaway and deeper southern entrance. Modelled tidal range is very similar for each scenario, although scenarios with deeper southern entrances (B and D) show marginally increased tidal range along the eastern shoreline.

Fig. A2

Chronostratigraphic, biostratigraphic, and lithostratigraphic framework of mid-Campanian strata in the study area, modified from van Cappelle et al. (2018); see van Cappelle et al. (2018) for detailed of synthesis and supporting data. Modelled time interval is highlighted in blue; red text indicates lithostratigraphic units within this interval with interpreted tidal signatures.