Where does the time go? Assessing the chronostratigraphic fidelity of sedimentary geological outcrops in the Pliocene–Pleistocene Red Crag Formation, eastern England

Neil S. Davies1*, Anthony P. Shillito1 & William J. McMahon2
1 Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge CB2 3EQ, UK
2 Faculty of Geosciences, Utrecht University, Princetonlaan 8a, Utrecht 3584 CB, Netherlands
* Correspondence: nsd27@cam.ac.uk

Abstract: It is widely understood that Earth’s stratigraphic record is an incomplete record of time, but the implications that this has for interpreting sedimentary outcrop have received little attention. Here we consider how time is preserved at outcrop using the Neogene–Quaternary Red Crag Formation, England. The Red Crag Formation hosts sedimentological and ichnological proxies that can be used to assess the time taken to accumulate outcrop expressions of strata, as ancient depositional environments fluctuated between states of deposition, erosion and stasis. We use these to estimate how much time is preserved at outcrop scale and find that every outcrop provides only a vanishingly small window onto unanchored weeks to months within the 600–800 kyr of ‘Crag-time’. Much of the apparently missing time may be accounted for by the parts of the formation at subcrop, rather than outcrop: stratigraphic time has not been lost, but is hidden. The time-completeness of the Red Crag Formation at outcrop appears analogous to that recorded in much older rock units, implying that direct comparison between strata of all ages is valid and that perceived stratigraphic incompleteness is an inconsequential barrier to viewing the outcrop sedimentary-stratigraphic record as a truthful chronicle of Earth history.

Supplementary material: Further details of the regional geology and specific information on outcrops are available at https://doi.org/10.6084/m9.figshare.c.4561001

Received 29 March 2019; revised 24 June 2019; accepted 28 June 2019

It has been recognized for over a century that Earth’s stratigraphic record is time-incomplete, and that vertical successions of sedimentary strata are punctuated with autogenic processes (Barrell 1917; Dott 1983). Unconformities and diastems riddle the rock record at a variety of scales (Miall 2015) and such gaps, of often unknown extent and duration, have implications for considering strata as a record of elapsed geological time. They can skew estimates of ancient rates of sedimentation or climate change (Sadler 1981; Kemp et al. 2015; Miall 2015; Toby et al. 2019), can mean that allogenic signals have been shredded by autogenic processes (Jerolmack & Paola 2010; Foreman & Straub 2017; Hajek & Straub 2017), and can add a further layer of incompleteness to a fossil record already rendered lacking by taphonomic filters (Kowalewski et al. 2015; Durkin et al. 2017; Davies & Shillito 2018). A better understanding of time-length scales that present at rock outcrop is needed because it is common practice for geologists to focus attention at the scale of an individual outcrop or group of outcrops, which provide the most tangible point of contact for understanding the physical sedimentary records of ancient environments, and their intensive properties (e.g. palaeontological or geochemical signatures).

The purpose of this contribution is to investigate time at outcrop by describing field observations that act as proxies for time-completeness, using examples from the Neogene–Quaternary Red Crag Formation of eastern England, a sub-tidal sedimentary succession that is known from a number of discrete, small outcrops.

The Red Crag Formation

The Red Crag Formation is the second oldest unit of the late Cenozoic Crag Group, which crops out in eastern England (McMillan et al. 2011; Lee et al. 2015; Mathers & Hamblin 2015) and consists of four discrete transgressive formations (the others, from oldest to youngest, being the Coralline Crag, Norwich Crag and Wroxham Crag formations) (Fig. 1). Each of the formations is separated by regional unconformities and all were deposited in open marine settings near the landward head of the Crag Basin, a localized embayment in the SW corner of what is now the North Sea. Although there is some uncertainty in the Red Crag Formation’s precise age, the oldest parts of the unit are agreed to be

with deposition of strata elsewhere within the same deposcentre (Runkel et al. 2008; Reesink et al. 2015; Gani 2017).

These emerging understandings have potentially major implications for the way we interpret the geological record (e.g. Miall 2014; Hampson et al. 2015; Durkin et al. 2017; Davies & Shillito 2018; Kocurek & Day 2018). A better understanding of time-length scales that present at rock outcrop is needed because it is common practice for geologists to focus attention at the scale of an individual outcrop or group of outcrops, which provide the most tangible point of contact for understanding the physical sedimentary records of ancient environments, and their intensive properties (e.g. palaeontological or geochemical signatures).

The purpose of this contribution is to investigate time at outcrop by describing field observations that act as proxies for time-completeness, using examples from the Neogene–Quaternary Red Crag Formation of eastern England, a sub-tidal sedimentary succession that is known from a number of discrete, small outcrops.

The Red Crag Formation

The Red Crag Formation is the second oldest unit of the late Cenozoic Crag Group, which crops out in eastern England (McMillan et al. 2011; Lee et al. 2015; Mathers & Hamblin 2015) and consists of four discrete transgressive formations (the others, from oldest to youngest, being the Coralline Crag, Norwich Crag and Wroxham Crag formations) (Fig. 1). Each of the formations is separated by regional unconformities and all were deposited in open marine settings near the landward head of the Crag Basin, a localized embayment in the SW corner of what is now the North Sea. Although there is some uncertainty in the Red Crag Formation’s precise age, the oldest parts of the unit are agreed to be
The latest Pliocene (Piacenzian) and the youngest are earliest Pleistocene (Gelasian), and the duration of Red Crag deposition is consistently reported to be between 600 and 800 kyr (e.g., Zalasiewicz et al. 1988; Hallam & Maher 1994; Gibbard et al. 1998; Head 1998; Maher & Hallam 2005; Williams et al. 2009; Wood 2009; Wood et al. 2009; McMillan et al. 2011; Riches 2012; Mathers & Hamblin 2015). Additionally, it has long been recognized that the unit is diachronous and becomes older southwards (Riches 2012); its oldest strata (an outlier at Walton-on-the-Naze, Essex) may be separated from the rest of the unit by an unconformity (e.g., Wood et al. 2009).

Lithologically, the Red Crag Formation consists of poorly sorted, semi-consolidated, coarse-grained shelly quartz and carbonate sands that are dark green and glauconitic at depth but have been weathered to an iron-stained orange–red colour at outcrop (Humphreys & Balson 1985; McMillan et al. 2011). The sediment usually has an extremely high content of aragonitic and calcitic shell debris, although at some locations the upper part of the unit has been decalcified to pure quartz sand as a result of later Pleistocene soil development (Kendall & Clegg 2000). Variable palaeocurrent indicators, large-scale cross-bedding, bioturbation, and sedimentary structures including flaser bedding and bidirectional cross-strata indicate that the unit was primarily deposited by migrating large-scale subtidal sandwaves (Figs 2 and 3) (Dixon 1979, 2005, 2011; Mathers & Zalasiewicz 1988; Zalasiewicz et al. 1988; Balson et al. 1991; Hamblin et al. 1997).

Fig. 1. Stratigraphic context and regional outcrop extent of the Crag Group, with detailed geological maps showing selected study sites and the local extent of Red Crag Formation exposure (BC, Bawdsey cliffs; BK, Buckanay Farm; BM, Boyton Marshes; CG, Capel Green; CH, Chillesford; NZ, Walton-on-the-Naze). It should be noted that ages on stratigraphic column are approximate and maximum thicknesses are from borehole data only. Individual Crag Group formations are considered to have internal unconformities. No outcrop exists where a full transect through the known stratigraphy occurs.

Fig. 2. Selected sedimentary characteristics of the Red Crag Formation. (a) Heterolithic wavy tidal bedding: muddy horizons record deposition during tidal stillstands. Boyton Marshes. Visible part of ruler is 90 cm. (b) Small-scale reversing cross-stratification. Palaeoflow shown for sets highlighted in red and green (depiction of palaeocurrent direction after Davies et al. 2018). Shottisham. Scale bar is 10 cm. (c) Large-scale reversing cross-stratification. Palaeoflow shown for sets highlighted in red and green (depiction of palaeocurrent direction after Davies et al. 2018). Neutral Farm. Person is 185 cm. (d) Reworked phosphatic pebbles (e.g. within circled area) within shell-rich lithofacies. Buckanay Farm. Scale bar is 10 cm. (e) Typical shell-rich lithology predominantly composed of variably complete shelly fragments of bivalves and gastropods. Buckanay Farm. Scale bar is 10 cm. (f) Decalcified quartz rich lithology at top of exposed Red Crag Formation, exhibiting evidence of cryoturbation. Walton-on-the-Naze. Scale bar is 10 cm.
Outcrops of the Red Crag Formation

Outcrops of the Red Crag Formation are typically of limited extent, but of good quality for discerning its internal sedimentary architecture (Fig. 4). No single outcrop approaches the full 40 m thickness of the unit, but this can be ascertained from some of the hundreds of boreholes that have been made across unexposed parts of the regional outcrop belt (Fig. 5; British Geological Survey 2018). Two primary types of exposed outcrop exist and have formed the focus of this study: (1) crag pits (six outcrops; Fig. 4a), which are static inland exposures formerly quarried for agricultural and aggregate purposes (O’Connor & Ford 2001); (2) coastal outcrops (two outcrops; Fig. 4b and c), which comprise dynamic natural exposures of small cliffs that are frequently reworked by wave activity along a highly erodible and recessive coastline (Environment Agency 2015).

Significantly for later discussion in this paper, the vertical cliff faces exposed in both types of outcrop are of limited extent: crag pits have a mean height and lateral extent of 5.5 m and 93.5 m respectively, whereas coastal outcrops have equivalent dimensions of 9 m and 1555 m.

Further details of the regional geology and specific information on outcrops are available in the supplementary material.

Sedimentation states and the preservation of time

The sedimentary-stratigraphic record has long been considered to be an archive of elapsed time: put simply, deposited sediment ‘preserves time’ and erosion of that sediment ‘removes time’. A time interval is generally considered preserved when a sedimentary deposit representing any time from that interval remains in the stratigraphic column at the location of interest (Strauss & Sadler 1989; Paola et al. 2018). However, this definition of preserved time is complicated by the recognition that not all time at a given location would have equated to a period of deposition or erosion; in fact, many sedimentary systems will have existed in a condition of sedimentary stasis for the majority of the time they were active (Dott 1983; Tipper 2015; Foreman & Straub 2017; Paola et al. 2018).

Tipper (2015) has suggested that time spent in stasis cannot be preserved because there is nothing to be preserved. Yet although this may be conceptually true for understanding how synthetic vertical stratigraphic columns record time, it is unsatisfactory for explaining real-world sedimentary rock outcrops. If a sedimentary surface, persisting for a duration of sedimentary stasis in an active environment, is not eroded, then that surface has the potential to accrue information generated by processes and events occurring as time passes during the stasis interval: for example, as multiple generations of surficial ichnological, microbial and abiotic sedimentary structures, or as distinct geochemical or pedogenic vertical profiles (Miall & Arush 2001; Barnett & Wright 2008; Christ et al. 2012; Davies et al. 2017; Davies & Shillito 2018; Paola et al. 2018; Shillito & Davies 2019). Where such signatures can be identified alongside signatures of erosion and deposition, it becomes possible to broadly estimate the duration of accrual of a package of sedimentary strata as preserved at a given outcrop, with implications for how representative that outcrop may be of ancient sedimentary environment.

Stratigraphic signatures of sedimentation states in the Red Crag at outcrop

Time spent in different sedimentation states is recorded in different ways in the sedimentary-stratigraphic signatures of the Red Crag.
negative record of time, recording the erasure of time records that once existed (Sadler 1999). Within the Red Crag Formation, none of the studied outcrops contain major erosional surfaces (i.e. extending the full width of an exposure), so there is little direct evidence of wholesale deletion of depositional records at outcrop scale (Fig. 6).

Sedimentary stasis is revealed in the Red Crag Formation as bounding surfaces that record a synoptic topography from the time of deposition (Paola et al. 2018). These can sometimes be recognized by the preservation of complete bedforms with convex top surfaces, often with evidence that later sediment was draped over the antecedent substrate morphology (Fig. 7).

More commonly, the extensive Red Crag ichnofauna (Fig. 3, Table 1) gives clues to sedimentary stasis. Every buried horizon in the unit provides evidence that intervals of stasis punctuated the deposition of the Red Crag Formation, because the colonization of a substrate requires time for organisms to excavate sediment without disturbance from erosion or deposition (Goldring 1960; Buck 1985; Frey & Goldring 1992; Pollard et al. 1993; Davies & Shillito 2018).

As complete vertical burrows may be impossible to distinguish from truncated burrows without bedding plane evidence (e.g. Goldring 1960; Hallam & Swett 1966; Buck 1985; Wetzel & Aigner 1986; Nara 1997; Davies et al. 2009) (lacking in the unconsolidated Red Crag Formation), burrows can be determined to be complete only when they intersect with synoptic topographies (e.g. inclined burrows intersecting with foresets or dune lee slopes: Fig. 8; Pollard et al. 1993). However, even where they are only preserved in truncated form, they are direct evidence that deposition was not continuous, and instead alternated with a state of stasis (+ erosion) (Fig. 8).

Sedimentation states cannot be maintained in perpetuity so, at any given location, states of deposition (D), erosion (E) and stasis (S) will be in spatial and temporal flux while the sedimentation system is active. Compound sedimentation states reflect this variability (i.e. D–E–D, D–S–E–D, D–S–D and D–E–S–D) and can be deduced by close scrutiny of signatures that mark the transition between two strata, which by definition must each record deposition (D). Such signatures of compound sedimentation states are common and highly variable within the Red Crag Formation (Fig. 9), as a direct result of their depositional environment and the narrow frame of reference provided by outcrop.

Why are signatures of compound sedimentation states common and variable in Red Crag outcrops?

Tipper (2015) introduced the concept of ‘point sedimentation systems’ to explain time-completeness in vertical synthetic stratigraphic columns, referring to a specific point (in a mathematical sense) within the space of a sedimentary environment, variably subject to erosion, deposition and stasis. For the purpose of

---

**Fig. 4.** Outcrop style of the Red Crag Formation. (a) Largest crag pit visited in this study: Buckanay Farm, exposing c. 8 m of vertical section over an area of c. 200 m². (b) Coastal outcrop near Bawdsey Manor (south end of Bawdsey cliffs), showing 10 m high cliffs that are no longer retreating owing to sea defences, and are increasingly overgrown with vegetation. (c) Coastal outcrop near East Lane (north end of Bawdsey cliffs). Dynamic coastline with c. 5 m high cliffs. Photograph was taken in January 2014, since when (at the time of the most recent visit, October 2018) there has been c. 3 m of cliff retreat in places, and beach sediment has built up to a height of 3 m in front of the cliff face.

**Fig. 5.** Stratigraphic cross-section of eastern Suffolk, showing the limited spatial extent of Crag Group knowable from core and outcrop, relative to its inferred abundance at depth. Thickness of Crag varies owing to underlying topography and later incision or erosion. Location of outcrops is approximate relative to line of section (BC, Bawdsey cliffs; BK, Buckanay Farm; SH, Shottisham; CG, Capel Green; NF, Neutral Farm; BM, Boyton Marshes). Core data used to construct section from British Geological Survey (2018). Cores shown are: 1, TM34SW21; 2, TMSW20; 3, TM34SW23; 4, TM34SW19; 5, TM34SW18; 6, TM34SW17; 7, TM34NW24; 8, TM34NE11A; 9, TM34NE16; 10, TM34NE20; 11, TM34NE23; 12, TM35SE75. Point A is located at 51°59.41.1′N, 01°24.51.2′E; Point B is located at 52°04.04.9′N, 01°25.16.22′E; Point C is located at 52°07.04.8′N, 01°24.53.6′E.
if the reversed current is weak) can generate pause planes within little as 10–20 min duration. Tidal stillstands, which are typically the most common surfaces, are large enough to be directly discernible owing to erosional truncation and limited outcrop size. However, the minimum height (i.e. the vertical distance between the top and bottom of a foreset) of different bedforms is calculable. For the largest cross-bedded units known, the rate of migration was probably in excess of 3 m every 12 h, meaning that the time taken to deposit the layer that extends for half the width of the present outcrop (Fig. 4a) would have been at most 15 days.

**Estimating the duration of sedimentation states**

Red Crag Formation outcrops are amalgams of signatures of different sedimentation states and compound sedimentation states. By estimating how long each recorded sedimentation state lasted, it is possible to estimate the time it took to accrue the sedimentary strata that constitute a particular outcrop.

**Deposition**

Many Red Crag outcrops record the deposits of sandwaves, which, in modern tidal settings, can migrate a distance equivalent to their average height within a single tidal cycle of c. 12 h (Dalrymple 1984). The average height of ancient Red Crag sand waves is not directly discernible owing to erosional truncation and limited outcrop size. However, the minimum height (i.e. the vertical distance between the top and bottom of a foreset) of different bedforms is calculable. For the largest cross-bedded units known, the rate of migration was probably in excess of 3 m every 12 h, meaning that the time taken to deposit the layer that extends for half the width of the present outcrop (Fig. 4a) would have been at most 15 days.

**Erosion**

Whereas stratigraphic time lost to erosion may be unknowable, the duration of erosive events can be estimated. Certain erosional surfaces in the Red Crag Formation appear to be intrinsically linked to tidal timescales; for example, internal erosional surfaces within cosets of cross-beding (Fig. 10) most probably reflect erosional pause planes (Boersma & Terwindt 1981). Like reversing cross-strata, the frequency of repetition of these could be semi-diurnal or longer term, but the duration of erosion for individual surfaces would have been accommodated within one tidal reversal (i.e. an interval of hours).

**Stasis**

We know very little about time represented by ordinary surfaces with no signs of stasis (Dott 1983). As these are typically the most common surfaces, it is only possible to estimate the minimum duration of stasis for an outcrop succession. In the Red Crag Formation, this is allowed by the consideration of burrowed...

---

**Fig. 6.** Erosional surfaces (shown in pink) indicating where previously recorded time has been erased (identified by discordance of laminae), and acting as bounding surfaces between sedimentary records of deposition. The small scale of these features should be noted: they are instances of intensive erosional diastems, rather than regional (or even outcrop-wide) unconformities. (a) Largest erosional surface visible in any of the visited crag outcrops; concave scoured base to large cross-bedded dune set. Buckanay Farm. Scale bar is 2 m. (b) Concave scoured base to smaller bedform. In this instance the erosional surface truncates a horizon (shown in blue) that has been colonized by Polykladichinus trace-makers (box). The order of sedimentation states here was thus: 1, deposition (below blue horizon); 2, stasis (colonization of blue horizon); 3, deposition (above blue horizon); 4, erosion (partial erasure of stages 1–3); 5, deposition (above pink horizon). Boyton Marshes. Scale bar is 50 cm. (c) Planar erosional surface representing levelling of earlier dune tops. Boyton Marshes. Metre-stick for scale.
surfaces. The burrowing rate of different individual tracemakers in modern shallow marine settings has received only limited attention (Dafoe et al. 2008; Gingras et al. 2008b), but a selection of quantified rates is shown in Table 1. These can be used to estimate the minimum time that the system was in stasis, by calculating how long it would take for the fastest-burrowing potential tracemaker to excavate the largest burrow along a given stasis surface, where the internal volume of the burrows can be roughly approximated as one or more cylinders ($\pi r^2h$, where $r$ is burrow radius and $h$ is burrow length).

The time taken to excavate particular individuals of the known ichnogenera (Table 2) provides a very approximate and conservative minimum estimate of the time spent in stasis. The most important conclusion here is that burrow formation is a geologically rapid process that occurs only during sedimentary stasis (Table 3), but there a number of caveats to these estimates, namely: (1) it is impossible to unravel the temporal sequence of the generation of a suite of individual burrows along the same stasis surface; (2) the speed at which burrows are excavated depends on factors such as grain size; (3) estimates are made with reference to the limited data published on burrowing rates; (4) very large dwelling burrows (e.g. Psilonichnus) are problematic because stasis is most likely to have persisted for an unknown interval after the burrow was excavated, and while the tracemakers were continuing to use the burrows as

Fig. 7. Synoptic topography at different scales within the Red Crag Formation and indicative of true substrates or chronostratigraphic surfaces. (a, b) Cross-sectional view of undulating bedforms, possibly generated during aggradational conditions under supercritical flow. Surfaces highlighted blue preserve the instantaneous topography from the time of deposition (pink line highlights erosional surface). Boyton Marshes. Person is 170 cm. (c–e) Synoptic topography of small bedforms, shown in blue, white area in (c) is enlarged in (e). Some horizons appear to preserve original bedform morphology, supported by their colonization by Cylindrichnus with preserved ‘trumpet’ form at top (t), suggestive of proximity to original apertural opening on the seafloor (Hallam & Swett 1966; Davies et al. 2009). Horizons shown in black are more ambiguous. Additionally, there may have been some minor reworking of the bedform crests during tidal reversals, suggested by superimposed, reversed ripple cross-lamination (r). Scale bar is 20 cm. Boyton Marshes.

<table>
<thead>
<tr>
<th>Ichnotaxon</th>
<th>Dimensions</th>
<th>Likely tracemaker</th>
<th>Abundance</th>
<th>Description</th>
<th>Locations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylindrichnus isp.</td>
<td>W 55 mm; L 225 mm</td>
<td>Polychaete</td>
<td>30</td>
<td>Concentrically lined burrow with conical aperture and heterolithic fill of sandstone, mudstone and shell fragments</td>
<td>BK, BM, NZ</td>
</tr>
<tr>
<td>Diopatrichnus isp.</td>
<td>W 12 mm; L 100 mm</td>
<td>Annelid or crustacean</td>
<td>15</td>
<td>Small subvertical burrow lined obliquely with shell fragments</td>
<td>BK, CG, NZ</td>
</tr>
<tr>
<td>Macaronichnus segregatus</td>
<td>W 3 mm; L 25 mm</td>
<td>Polychaete</td>
<td>&gt;100</td>
<td>Small, unbranched subvertical to subhorizontal burrow with heterolithic infill. Occurs in dense patches, frequently cross-cutting</td>
<td>BK, BM, SH, NZ</td>
</tr>
<tr>
<td>Polykladichnus irregularis</td>
<td>W 13 mm; L 230 mm</td>
<td>Polychaete</td>
<td>30</td>
<td>Y-shaped burrow with a muddy infill. Often in association with Skolithos</td>
<td>BM, CG, CH, NF</td>
</tr>
<tr>
<td>Psilonichnus upsilon</td>
<td>W 60 mm; L 1400 mm</td>
<td>Crustacean</td>
<td>20</td>
<td>Large, occasionally branching subvertical burrow, with spiralling of the sediment laminae surrounding a fine core</td>
<td>BM, NZ</td>
</tr>
<tr>
<td>Skolithos linearis</td>
<td>W 12 mm; L 180 mm</td>
<td>Annelid or crustacean</td>
<td>&gt;100</td>
<td>Unlined, unbranched vertical burrow, with a structureless muddy infill. Often in association with Polykladichnus</td>
<td>BK, BM, CG, CH, NF, SH, NZ</td>
</tr>
<tr>
<td>Teichichnus rectus</td>
<td>W 38 mm; L 47 mm</td>
<td>Annelid</td>
<td>5</td>
<td>Burrow with stacked arcuate spreite composed of mudstone</td>
<td>NZ</td>
</tr>
<tr>
<td>Thalassinoides isp.</td>
<td>W 33 mm; L 700 mm</td>
<td>Crustacean</td>
<td>5</td>
<td>Complex burrow network with a mudstone infill</td>
<td>NZ</td>
</tr>
</tbody>
</table>

Trace fossils are illustrated in Figure 3. Dimensions reported are the mean of examples observed in the study. Likely tracemakers are identified based upon information given by Clifton & Thompson (1978), Humphreys & Balson (1988), Gingras et al. (2008a), Buatois et al. (2017) and Knaust (2018). Abundance reports the approximate number of each ichnotaxon observed across all field locations visited during this study.
Fig. 8. Trace fossils as indicators of sedimentary stasis. (a, b) Multiple horizons of *Skolithos* burrows (shown in different colours) attesting to non-steady sedimentation. There were at least seven episodes of stasis (± erosion) during the interval taken to deposit this 70 cm package of sediment. Walton-on-the-Naze. Metre stick for scale. (c, d) Intervals of stasis that were followed by intervals of erosion are seen where incomplete *Skolithos* burrows terminate against constructed erosional boundaries (shown in pink). In contrast, some cross-strata foresets can be seen to be colonized by apparently complete *Skolithos*, oriented relative to the dipping foreset (blue). These imply that the tracemaker constructed its burrow relative to the inclined substrate and that some of the foresets themselves are synoptic topographies (Pollard *et al.* 1993). In other words, these dunes were not in continual motion and there were intervals where the dune lee slope persisted as a true substrate and could be colonized; such irregular motion of dunes is not uncommon in tidal settings (e.g. Allen *et al.* 1994). Capel Green. Scale bar is 1 m.

Fig. 9. Signatures of compound sedimentation states recorded in the Red Crag Formation. (a) Sand deposition (D1), followed by heterolithic wavy tidal bedding, lithology arising from fluctuations of deposition and stasis (i.e. tidal stillstand) (Ds2). Subsequently, these layers have been partially eroded; however, erosion was discontinuous and followed by a short interval of stasis, which has preserved the aspect of the collapsing wavy bedding (Es3), subsequently interred as the sedimentation state reverted to deposition (D4). Capel Green. Visible part of ruler is 80 cm. (b) *Cylindrichnus* burrow within heterolithic wavy tidal bedding (see Fig. 2a for location). During intervals of stasis, tracemaker thickens its burrow (S), but after interval of deposition (D) adjusts to newly elevated seafloor, resulting in pinching and thickening of burrow within heterolithic sediment (Nara 1997). Boyton Marshes. Pen is 14 cm long. (c) Cross-bedding with *Macaronichnus* burrows along individual foresets (e.g. along light blue lines), attesting to punctuated dune migration. Dune top has subsequently been truncated by erosion (dark blue line), but this was followed by a more prolonged interval of stasis, attested to by the denser abundance of *Macaronichnus* along the horizontal erosional plane. The negligible tiering of *Macaronichnus*, and horizontal distribution, indicates that these were emplaced during post-erosional stasis and are not contemporaneous with the less dense, diagonally oriented, examples along the foresets. Buckanay Farm. Ruler is 20 cm long. (d) Example of deposition and erosion with no evidence for intervals of stasis. Erosional surface (pink) is followed by bedforms climbing at an angle of 10–15°. These record a continuous state of deposition (at a high rate of sedimentation), but one that is intrinsically linked to the erosion of bedforms (i.e. reworking of migration ripple trains); hence the resultant stratigraphy is dominated by constructed boundaries rather than synoptic topography. Boyton Marshes. Visible part of ruler is 1 m long.
domiciles. Burrowing rates of modern crabs (the suspected *Psilonichnus* tracemakers; Humphreys & Balson 1988) have been calculated only as the time taken for an individual to fully bury their carapace in sediment (e.g. McLay & Osborne 1985; Lastra et al. 2002), and estimates of excavation rates at depth (where overburden and compressive force chains of packed grains impede burrowing speed; Dorgan et al. 2006) have not been reported. As an approximation of excavation speed for the largest *Psilonichnus*, we here use the maximum invertebrate rate reported in Table 2 of 10 cm$^3$ h$^{-1}$, although the margins of error here may be large.

**Time taken to deposit individual outcrops of the Red Crag Formation**

Precisely determining the time taken to deposit an individual outcrop of the Red Crag Formation is impeded by (1) the inability to accurately determine sequences of events during stasis from their physical records, (2) the inability to confidently calculate original dune height from preserved foresets, and (3) a reliance on potentially imperfect modern analogues. Despite this, the lack of major erosional surfaces at outcrop suggests that little time has been destroyed and lost at outcrop-scale and is instead missing owing to stasis. Equally, that time spent in stasis appears to have been relatively short because there is a lack of complete bioturbation reworking of primary sedimentary structures or shell material, and no evidence for palimpsesting of multiple generations of burrows at the same horizon, despite the Red Crag seas supporting an abundant infauna. The lack of evidence for prolonged bioturbation implies that horizons were probably in stasis on timescales no longer than hours to days (Table 2), and probably reflect tidal current quiescence on semi-diurnal or synodic timeframes (Kvale 2012).

Figures 10 and 11 show how the entire sediment piles that form pit outcrops of the Red Crag Formation can reasonably be estimated to have accumulated over time intervals of days to months. Thus, when we encounter the unit as an individual outcrop, we are dealing with sediment accrued over very minor time intervals, well within the range of human experience. This observation seems counterintuitive when we consider that the time taken to deposit the Red Crag Formation, as an entire stratigraphic entity, was 600–800 kyr, equating to average sedimentation rates of 0.5–0.66 cm ka$^{-1}$ to deposit the unit’s full 40 m thickness. However, as noted by Miall (2015), such quantified average sedimentation rates are essentially meaningless: it is an understanding of the instantaneous sedimentation rate (taken to deposit a particular bedform or sedimentary bed)?

**Table 2. Burrowing speeds of modern invertebrates**

<table>
<thead>
<tr>
<th>Organism</th>
<th>Burrowing speed (cm$^3$ h$^{-1}$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Bivalves</td>
<td>0.5</td>
</tr>
<tr>
<td>B</td>
<td>Arthropods</td>
<td>0.2</td>
</tr>
<tr>
<td>C</td>
<td>Echinoderms</td>
<td>0.05</td>
</tr>
<tr>
<td>D</td>
<td>Polychaetes</td>
<td>0.01</td>
</tr>
</tbody>
</table>

**Fig. 10.** Outcrop at Capel Green, showing surfaces arising from erosion and stasis and estimated duration of formation (scale bar is 2 m). Approximate minimum time to deposit complete package of sediment visible in yellow box was c. 35 days (828 h of deposition and stasis, plus unknown time lost to erosion). Order of events: 1, Ss1 (201 h); 2, Dp1 (120 h, including at least six increments of instantaneous stasis); 3, Es1 (unknown missing time); 4, Dp2 (108 h, including Ss2–4 (9 h each) and at least six increments of instantaneous stasis); 5, Es2 (unknown missing time); 6, Dp3 (64 h, including Ss5 (9 h) and at least 15 increments of instantaneous stasis); 7, Es3 (unknown missing time); 8, Ss6 (9 h); 9, Dp4 (not estimated, limited architectural evidence); 10, Ss7 (326 h). Durations of stasis surfaces (Ss) and depositional packages (Dp) are gauged as follows (unburrowed foresets are not numbered, and are assumed to represent instantaneous stasis time intervals at minimum). Time is estimated only for those packages fully exposed in the cliff face (i.e. no consideration is given to strata at the top or bottom of the outcrop where exposure is obscured or truncated and elapsed time cannot be confidently estimated). Ss1: *Polykladichnus* burrows: maximum dimensions: approximate volume 100.5 cm$^3$ (maximum length 32 cm (i.e. 16 cm long U-shape), maximum width 2 cm); excavation time 201 h (probably polychaete tracemaker, maximum burrowing rate of 0.5 cm$^3$ h$^{-1}$). Ss2–6: *Dnopatrichnus* burrows: maximum dimensions: approximate volume 18 cm$^3$ (maximum length 10 cm, maximum width 1.5 cm); excavation time 9 h (possible crustacean tracemaker, maximum burrowing rate of 2 cm$^3$ h$^{-1}$). Ss7: *Cylindrichnus* burrows: maximum dimensions: approximate volume 163 cm$^3$ (maximum length 13 cm, maximum width 4 cm); excavation time 326 h (probably polychaete tracemaker, maximum burrowing rate of 0.5 cm$^3$ h$^{-1}$). Dp1: minimum sand wave height 100 cm; lateral extent 10 m; time to migrate (at 100 cm per 12 h) 120 h. Dp2: minimum sand wave height 75 cm; lateral extent 675 cm; time to migrate (at 75 cm per 12 h) 108 h. Dp3: minimum sand wave height 75 cm; lateral extent 400 cm; time to migrate (at 75 cm per 12 h) 64 h.
Psilonichnus 3f 1382.3 B (6911) 138
3e 15.08 D (1508) 30
3d 0.06 D 6 1
Macaronichnus
Diopatrichnus 3b 4.02 B 20 2

Where does the time go? Discussion
As every individual outcrop of the Red Crag Formation reveals only a maximum of a few months in the life of the active sedimentary environment, they provide vanishingly small windows into the 600–800 kyr of total ‘Crag-time’. Two obvious questions arise from this understanding: (1) Where did the vast majority of Crag-time end up, if not preserved at outcrop? (2) If we have such small windows, how can we trust them to be representative of what was really happening during Crag-time?

With respect to the first question, part of the answer lies in the time-length scale of the exposed outcrops that we are viewing: the window on time that we have is miniscule, but so is the window on space. For example, the outcrop at Capel Green (Fig. 10) may reveal as little as 35 days out of 292 million days (800 kyr) of Crag-time, but then the spatial area of the outcrop is only 156 m² out of c. >4 billion m² of Crag Group (as mapped onshore). When we consider that stratigraphic time is smeared laterally over an outcrop belt (Runkel et al. 2008; Reesink et al. 2015; Gani 2017; Davies & Skillicorn 2018), the null hypothesis is that it is highly improbable that any two outcrops record the exact same time interval: they are all floating pockets of preserved time with no hope of being accurately chronostratigraphically anchored within the 600–800 kyr boundaries of net Crag-time (Fig. 12). This opens the possibility that the fraction of preserved Crag-time may not be negligible after all: we simply cannot access the majority of the mapping unit as it is concealed as subcrop. In other words, time is not lost, but hidden. We can see strata only from the vantages of outcrop or core, but these are tiny windows relative to the bulk volume of sediment that is still preserved today (e.g. Fig. 5). It is simply impossible to see all of the internalized physical strata hidden behind cliff faces and between outcrop exposures or cores. We contend that those ancient sedimentary products that can be witnessed today do not record temporally rare events, but rather that the observable outcrop exposure of sedimentary product is a spatially rare phenomenon: relative to the extent of (1) the ancient depositional environment and (2) the full extent of its unexposed lithostratigraphic corollaries.

The outcrops of the Red Crag record exposures of ‘days’, but are they representative of ‘every day’ process during the interval of deposition? The null hypothesis must be that they are, because of the strong similarity between the different exposed outcrops, which all contain a comparable array of tidal sedimentary structures and trace fossils (Figs 2 and 3). This attests to the likelihood that mundane, non-unique conditions were persistent for most of Crag-time (i.e. the ‘strange ordinariness’ discussed by Paola et al. 2018). Exposed outcrops are random samples of the net volume of a succession: if...
they are all telling the same story, despite having been deposited on month-timescales that are separated by unknowable intervals of time, then it is highly probable that they are preserving the ‘norm’ rather than exceptions.
environments of the previous crags. Each of the older units is separated by an unconformity that marks intermittent disruption in the continuity of shallow marine deposition: in the case of the unconformity between the most recent crag (Wroxham) and the present, this is associated with glacioeustatic relative sea-level fall. The unconformities, corresponding to the Group 2 unconformities (104–105 years) of Miall (2016), reflect only retreat of crag deposition away from our present-biased frame of reference (i.e. the onshore outcrop belt), and offshore parts of the North Sea will have seen continuous deposition throughout some of the unconformity intervals. As such, the received perspective that we are now ‘post-crag’ may be a bias from living in the present, and onshore, and could be no different from the apparent post-crag conditions that would have been perceived had we been undertaking geological investigations on land during the interval of unconformity generation between, say, the Red and Norwich crags. The extensive, inter-formation unconformities are distinguished from the intensive, intra-formation discontinuities (e.g. Fig. 6) because (1) their trigger was external to the depositional system (e.g. sea-level change rather than autogenic recycling of sediment piles within a sedimentary environment) and (2) they diminish time-completeness regionally, whereas intensive unconformities remain most important in diminishing time-completeness within individual outcrops.

One marked difference between the interval between the Wroxham Crag and today (compared with the unconformity intervals bounding the Red Crag) is that sediments that post-date the Wroxham Crag Formation currently exist onshore, most notably the 0.4 Ma environments of the previous crags. Each of the older units is separated by an unconformity that marks intermittent disruption in the continuity of shallow marine deposition: in the case of the unconformity between the most recent crag (Wroxham) and the present, this is associated with glacioeustatic relative sea-level fall. The unconformities, corresponding to the Group 2 unconformities (104–105 years) of Miall (2016), reflect only retreat of crag deposition away from our present-biased frame of reference (i.e. the onshore outcrop belt), and offshore parts of the North Sea will have seen continuous deposition throughout some of the unconformity intervals. As such, the received perspective that we are now ‘post-crag’ may be a bias from living in the present, and onshore, and could be no different from the apparent post-crag conditions that would have been perceived had we been undertaking geological investigations on land during the interval of unconformity generation between, say, the Red and Norwich crags. The extensive, inter-formation unconformities are distinguished from the intensive, intra-formation discontinuities (e.g. Fig. 6) because (1) their trigger was external to the depositional system (e.g. sea-level change rather than autogenic recycling of sediment piles within a sedimentary environment) and (2) they diminish time-completeness regionally, whereas intensive unconformities remain most important in diminishing time-completeness within individual outcrops.

One marked difference between the interval between the Wroxham Crag and today (compared with the unconformity intervals bounding the Red Crag) is that sediments that post-date the Wroxham Crag Formation currently exist onshore, most notably the 0.4 Ma
Anglian glacial deposits (Lee et al. 2015). However, a large fraction of the Crag Group outcrop belt has negligible or patchy cover from younger sediments, so a future rise in relative sea-level could theoretically transplant subtidal sandwave deposits immediately on top of similar facies of the ancient crag formations. The extensive erosional unconformity separating the ‘future crag’ from the ancient crag would, in many places, be indistinguishable in its character from the preceding unconformities that separate the formations of the Crag Group (although it would potentially be marked in places with spatially restricted alluvial and glacial ‘members’).

Implications for the preservation of time in older formations

The notion that crag deposition may be a work in progress is speculative but geologically rational, and has implications for time-preservation in older strata. The duration of crag deposition, whether finished or not, corresponds to the persistence or persistent reappearance of marine conditions in the southwestern North Sea region over the last c. 5 myr (Lee et al. 2018); an interval of time inferior to the duration of many stratigraphic formations in the

Fig. 16. Comparison of Red Crag signatures with older subtidal strata. (a) Erosive-based cross-bedding at Bucknay Farm, sitting within horizontally laminated burrowed sands. (b) Erosive-based cross-bedding sitting within horizontally laminated burrowed sands within the Silurian Tumblagooda Sandstone, Kalbarri, Western Australia. Both images shown at same scale. It should be noted that the Red Crag is c. 2.6 Ma and the Tumblagooda Sandstone is c. 425 Ma, yet at outcrop scale both reveal similar sedimentary facies that would have been deposited over month(s) timescales.

Fig. 17. Tidal signatures in the Paleoproterozoic (c. 1.7 Ga) Baraboo Quartzite, Devil’s Lake, Wisconsin, USA. Despite their far greater antiquity, the timescales of formation of these features are directly analogous to similar features in the Red Crag Formation, and currently exposed outcrops are equally unanchored pockets of human timescales within the interval of Baraboo deposition. (a) About 15 packages of small dune cross-strata, each reflecting migration rates in days to weeks. (b) Reversing cross-strata, each set of which must have been deposited on a timescale of no more than weeks. (c) True substrate recording instantaneous conditions of current ripples preserved as synoptic topography.
geological record. Significantly, the sedimentological characteristics of the Red Crag Formation that show that its outcrops were deposited on human timescales are also common in much more ancient strata, deposited in similar sedimentary environments (Fig. 16). Lithified ancient strata may differ from the crag through forming much thicker successions (formed over longer intervals, in tectonic settings more prone to subsidence), and sometimes being exposed at vertical scales in which extensive unconformities are more apparent, but fundamentally they are composed of similar building blocks, with potentially similar spatial extent of outcrop and time significance, to the Red Crag Formation.

This understanding shifts how we understand the chronostratigraphic fidelity of ancient strata. Ager (1986) ended a paper concerning the time significance of a 10 m thick debris-flow deposit in Jurassic strata with the conclusion that ‘it all happened one Tuesday afternoon’. Notwithstanding that Ager’s (1986) sentiment has been widely disputed (e.g. Fletcher et al. 1986; Sheddont 2006), in the Red Crag Formation it seems more likely that any individual outcrop all happened one ‘February going into March’, a subtle but critical difference revealing strata not as dramatic events, but as sediment piles deposited both quickly and unexceptionally. This removes a level of perceived incompleteness from the ancient record and suggests that any given outcrop is most probably representative of normal conditions, particularly when similar facies signatures are replicated in multiple discrete outcrops of the same unit.

This ‘bias towards the boring’ in preserved strata means that we can trust the fidelity of the signatures within such outcrops more than is commonly perceived. The intensive properties of even Precambrian strata at outcrop should be just as time-complete as the Red Crag Formation at outcrop: any outcrop can still be a monthly or sub-annual-timescale sedimentation. In other words, sedimentary strata of any age are directly comparable, recording outcrops provide windows onto miniscule areas of space (relative to the duration of deposition of the formation), but this is only because in Jurassic strata with the conclusion that

Acknowledgements

This paper was improved by useful reviews from A. Miall and L. Herringshaw, and comments from editor A. Hartley.

Funding

A.P.S. was supported by the Natural Environment Research Council (grant number NE/L002507/1).

Author contributions

NSD: Conceptualization (Lead), Data curation (Lead), Formal analysis (Lead), Investigation (Equal), Methodology (Lead), Project administration (Lead), Supervision (Lead), Validation (Lead), Visualization (Lead), Writing – Original Draft (Lead), Writing – Review & Editing (Equal). APS: Conceptualization (Supporting), Formal analysis (Supporting), Investigation (Equal), Visualization (Supporting), Writing – Original Draft (Supporting), Writing – Review & Editing (Supporting). WMJ: Conceptualization (Supporting), Formal analysis (Supporting), Investigation (Equal), Methodology (Supporting), Validation (Supporting), Visualization (Supporting), Writing – Original Draft (Supporting), Writing – Review & Editing (Supporting).

Scientific editing by Adrian Hartley

References


