Tempestite facies variability and storm-depositional processes across a wide ramp: Towards a polygenetic model for hummocky cross-stratification

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Running title:

Towards a polygenetic model for HCS

ABSTRACT

The hydrodynamic mechanisms responsible for the genesis and facies variability of shallow-marine sandstone storm deposits (tempestites) have been intensely debated, with particular focus on hummocky cross-stratification (HCS). Despite being ubiquitously utilized as diagnostic elements of high-energy storm events, the full formative process spectrum of tempestites and HCS is still to be determined. In this study, detailed sedimentological investigations of >950 discrete tempestites within the Lower Cretaceous Rurikfjellet Formation on Spitsbergen, Svalbard, shed new light on the formation and environmental significance of HCS, and provide a reference for evaluation of tempestite facies models. Three generic types of tempestites are recognized, representing deposition from (i) relatively steady and (ii) highly unsteady storm-wave-generated oscillatory flows or oscillatory-dominated combined-flows, and (iii) various storm-wave-modified hyperpycnal flows (including waxing–waning flows) generated directly from plunging rivers. A low-gradient ramp physiography enhanced both distally progressive deceleration of the hyperpycnal flows and the spatial extent and relative magnitude of wave-added turbulence. Sandstone beds display a wide range of simple and complex configurations of HCS. Features include ripple cross-lamination and "compound" stratification, soft-sediment deformation structures, local shifts to quasi-planar lamination, double draping, metre-scale channelised bed architectures, gravel-rich intervals, inverse-to-normal grading, and vertical alternation of sedimentary structures. A polygenetic model is presented to account for the various configurations of HCS that may commonly be produced during storms by wave oscillations, hyperpycnal flows, and downwelling flows. Inherent storm-wave unsteadiness probably facilitates the generation of a wide range of HCS configurations due to (i) changes in near-bed oscillatory shear stresses related to passing wave groups or tidal water-level variations; (ii) multidirectional combined-flows related to polymodal and time-varying orientations of wave oscillations; and (iii) syndepositional liquefaction related to cyclic wave stress. Previous proximal–distal tempestite facies models may only be applicable to relatively high-gradient shelves, and new models are necessary for low-gradient settings.

Keywords hummocky cross-stratification, swaley cross-stratification, tempestites, hyperpycnites, turbidites, fluid mud

INTRODUCTION

During storms, amplified hydrodynamic conditions may cause anomalously large quantities of sandy sediment to be transported along and across the shore and shelf, resulting in the deposition of typically discrete event beds, called tempestites (Snedden *et al.*, 1988; Snedden & Nummedal, 1991; Myrow, 1992a; Héquette & Hill, 1993). For the past three to four decades, the hydrodynamic mechanisms responsible for the genesis and facies variability of sandy tempestites in inner shelf to lower shoreface environments have been subject of intense debate, with particular focus on the formative processes and environmental significance of hummocky cross-stratification (HCS; e.g. Campbell, 1966; Bourgeois, 1980; Dott & Bourgeois, 1982; Swift *et al.*, 1983; Allen, 1985; Duke, 1985; Nøttvedt & Kreisa, 1987; Leckie & Krystinik, 1989; Southard *et al.*, 1990; Cheel, 1991; Duke *et al.*, 1991; Myrow & Southard, 1996; Dumas & Arnott, 2006; Quin, 2011; Morsilli & Pomar, 2012). This sedimentary structure is common in coarse-grained siltstone to fine-grained sandstone and is predominantly characterised by isotropically oriented laminae that conformably thin and thicken over low-angle (<15°) truncations with convex-up buildups (hummocks) and concave-up depressions (swales), respectively (e.g. Dott & Bourgeois, 1982). The laminae and truncations tend to merge and become conformable when traced laterally. Since its formal introduction by Harms *et al.* (1975), HCS has constituted a key sedimentary structure in shallow-marine facies models, as it has been used as a diagnostic element of storm deposition in distal shelf to shoreface environments. In addition, HCS is generally inferred to be genetically linked with its swale-dominated counterpart, swaley cross-stratification (SCS), which is assumed to reflect more proximal deposition where hummocks may be preferentially eroded (Leckie & Walker, 1982; Dumas & Arnott, 2006). Nevertheless, the full spectrum of formative processes of tempestites in general, and HCS in particular, is still to be understood.

The term *tempestite* traditionally refers to all deposits generated from storm-induced processes, including oscillatory (wave-generated) and unidirectional (predominantly geostrophic and density-induced) currents (e.g. Myrow & Southard, 1996). Within the lower part of the nepheloid bottom boundary layer, combined unidirectional and oscillatory currents exert shear stresses that largely exceed the threshold limit for sand transport (Grant & Madsen, 1979; Héquette & Hill, 1995; Myrow & Southard, 1996). Consequently, these currents may produce a wide range of sedimentary structures, including HCS, and vertical facies arrangements in different types of tempestites (Nøttvedt & Kreisa, 1987; Arnott & Southard, 1990; Cheel, 1991; Duke *et al.*, 1991; Myrow, 1992a), such as wave-modified turbidites (Myrow *et al.*, 2002; Lamb *et al.*, 2008). For thorough reviews of tempestite stratification variability and storm-flow dynamics, the reader is referred to Duke (1990) and Myrow & Southard (1991, 1996).

Based on interpretations from many ancient wave-dominated facies tracts, and insights derived from flume experimental studies (Arnott & Southard, 1990; Southard *et al.*, 1990; Dumas *et al.*, 2005; Dumas & Arnott, 2006), HCS and SCS are generally envisaged to result from complex oscillatory flows and/or storm-wave-generated oscillations that are superimposed on shore-normal downwelling ‘relaxation currents’ (i.e. downwelling storm flows). The downwelling flows are generated in response to coastal setup, and include Coriolis-deflected, shore-oblique geostrophic flows (e.g. Héquette & Hill, 1993). Thus, HCS and SCS are largely considered to represent the combined migration and aggradation of symmetrical to near-symmetrical threedimensional (3D) dunes formed by high-velocity, long-period oscillatory flows or oscillatory-dominated combined-flows between the storm-wave base (SWB) and breaking wave zone (cf. Dashtgard *et al.*, 2012) above the fair-weather wave base (FWWB).

The hydrodynamics of tempestites and HCS are difficult to interpret because (i) field observations are generally limited in vertical and lateral extent with few accounts on basin-wide (up to several hundred kilometres) proximal–distal tempestite facies relationships (e.g. Brenchley *et al.*, 1986); (ii) the restricted size and flow modes of experimental flume tanks inhibit realistic reproduction of storm-depositional processes and bed configurations (e.g. Dumas *et al.*, 2005); (iii) the formation of HCS in modern-day environments cannot be directly observed (Southard *et al.*, 1990); (iv) there are virtually no examples of modern analogues to ancient thick-bedded tempestites, including successions dominated by HCS (Myrow & Southard, 1996); (v) marine sediment box cores of standard spade width are too small for conclusive identification of HCS (Swift *et al.*, 1983); (vi) intra-facies variability of HCS forms a relatively overlooked part of tempestites (Quin, 2011); and (vii) HCS probably represents more than one type of depositional mechanism (e.g. Myrow, 1992a).

In prodeltaic settings, storm-wave-generated oscillatory flows may combine with hyperpycnal flows associated with increased river discharge during floods (Garrison *et al.*, 2013; Wilson & Schieber, 2014; Collins *et al.*, 2017) to produce tempestites exhibiting HCS (Myrow *et al.*, 2002; Pattison, 2005; Pattison & Hoffman, 2008; Lamb *et al.*, 2008) and fluid-mud deposits (Plint, 2014). Thus, HCS has been incorporated into several hyperpycnite facies models (Mutti *et al.*, 2003; Myrow *et al.*, 2008; Zavala *et al.*, 2011). Along with a number of recent accounts of HCS indicative of tidal modulation of near-bed storm-wave intensity (Yang *et al.*, 2005; Basilici *et al.*, 2012a; Vakarelov *et al.*, 2012), and HCS exhibiting storm-wave-generated soft-sediment deformation structures (SSDS; Molina *et al.*, 1998; Alfaro *et al.*, 2002; Chen & Lee, 2013), these findings call for a refinement of storm-depositional facies models.

The Lower Cretaceous (Valanginian – lower Barremian) Rurikfjellet Formation on Spitsbergen, Svalbard, represents a storm-dominated, siliciclastic ramp succession of prodeltaic offshore to lower shoreface facies belts (Dypvik *et al.*, 1991b; Grundvåg *et al.*, 2017). The succession is stratigraphically well constrained (e.g. Dypvik *et al.*, 1991a; Mørk *et al.*, 1999), exposed at numerous localities across Spitsbergen, and cored in several onshore wells (Fig. 1A–C). The Rurikfjellet Formation includes a spectacular variety of tempestites and configurations of HCS, and serves as a rare example for analysis of near-basin-scale facies and depositional process relationships of storm deposits. Inferences drawn from this analysis provide a reference for evaluation of similar successions and general tempestite and HCS facies models.

Objectives of study

Based on detailed sedimentological investigations of >950 discrete tempestites in the Rurikfjellet Formation, the objectives of this study are to (i) document the wide range of observed HCS configurations; (ii) examine the hydrodynamic controls of hyperpycnal sediment transport in a low-gradient setting; (iii) elucidate the role of oscillatory-flow unsteadiness, depositional instabilities and unidirectional-flow pulsation in the generation of some HCS; and (iv) demonstrate how the tempestites form a polygenetic continuum between relatively steady and highly unsteady oscillatory flows and oscillatory-dominated combined-flows and wave-modified hyperpycnal flows, allowing for a new conceptual facies model for HCS.

*[**Fig. 1** around here; <u>portrait, two-column width</u>]*

REGIONAL SETTING AND STRATIGRAPHY

Early Cretaceous basin configuration

The Lower Cretaceous succession in Svalbard is >1000 m thick and divided into the shale-dominated Rurikfjellet (open-marine shelf), sandstone-dominated Helvetiafjellet (fluvio-deltaic to paralic) and heterolithic Carolinefjellet (open-marine shelf) Formations (Fig. 1D; Mørk *et al.*, 1999). The succession formed during long-term (c. 30 myr) deltaic shoreline progradation and subsequent back-stepping in response to a full relative sea-level cycle that was controlled by regional thermo-tectonic uplift and following quiescence or sag-type subsidence (Gjelberg & Steel, 1995; Midtkandal *et al.*, 2007; Midtkandal & Nystuen, 2009). The succession is primarily exposed along the margins of the NNW–SSE-oriented Central Tertiary Basin on Spitsbergen (Fig. 1B).

During the Late Jurassic to Early Cretaceous, Svalbard was situated at approximately 63–66°N as part of the large circum-Arctic Boreal Basin at the northern margin of Pangaea (Torsvik *et al.*, 2002). The basin comprised an epicontinental platform which was characterised by warm–temperate, humid greenhouse conditions (Steel & Worsley, 1984; Gröcke *et al.*, 2003). In the Early Cretaceous, thermo-tectonic uplift in the north, related to the formation of the High Arctic Large Igneous Province (HALIP), caused gentle southwards tilting of the shelf and south-eastwards shoreline migration (Steel & Worsley, 1984; Gjelberg & Steel, 1995; Maher, 2001; Maher *et al.*, 2004). In the Valanginian – early Barremian, deposition of the Rurikfjellet Formation took place with continued regression and open-marine, relatively oxic shelf conditions in the Svalbard area. In the early Barremian, a tectonically controlled relative sea-level fall took place, resulting in pervasive shelf erosion and progradation of the fluvio-deltaic Helvetiafjellet Formation shoreline far towards the S–SE (Gjelberg & Steel, 1995; Midtkandal & Nystuen, 2009; Grundvåg *et al.*, 2017). Consequently, the Rurikfjellet Formation is separated from the Helvetiafjellet Formation by a regionally extensive subaerial unconformity (Fig. 1D; Gjelberg & Steel, 1995; Midtkandal *et al.*, 2008).

Stratigraphy of the Rurikfjellet Formation

The Rurikfjellet Formation is generally c. 200–230 m thick and subdivided into the shale-dominated Wimanfjellet Member and the siltstone- and sandstone-rich Kikutodden Member (Fig. 1D; Midtkandal *et al.*, 2008). The Wimanfjellet Member is generally >170 m thick and consists of relatively homogeneous and sparsely bioturbated offshore shale (Dypvik *et al.*, 1991a), which records transitional shoaling into the Kikutodden Member. The Kikutodden Member is generally <85 m thick and comprises two clastic wedges (Fig. 1B), including (i) a southern relatively coarse-sand-grade clastic wedge of offshore transition to shoreface parasequences (Grundvåg & Olaussen, 2017), and (ii) a northern comparatively fine-sand-grade clastic wedge (Nemec *et al.*, 1988; Grundvåg *et al.*, 2017, 2019), which is dealt with in this study. The northern wedge is generally characterised by laminated, burrowed or structureless shale, which is intercalated with sandstone exhibiting well-developed lamination or HCS (Dypvik *et al.*, 1991b). The shale and sandstone generally stack into metre- to tens-of-metres-thick, coarsening-upwards successions representing prodelta to distal delta front parasequences (Dypvik, 1985; Dypvik *et al.*, 1991b), which hydrodynamically correspond to the offshore transition to lower shoreface zone (cf. Dashtgard *et al.*, 2012). In the northern wedge, the thickness of the member, sandstone content, and number of coarsening-upwards successions decrease towards the ESE (Dypvik *et al.*, 1991b), corresponding to a WNW–ESE-oriented proximal–distal depositional dip.

*[**Table 1** around here; if possible full page landscape including caption heading]*

*[**Fig. 2** around here; portrait, two-column width]*

DATA SET AND METHODS

Fieldwork was carried out over six field seasons between 2013 and 2017 in the north-central, central and south-eastern areas of Spitsbergen, covering a distance of >130 km and a total study area of c. 4171 km^2. These areas comprise the most proximal, intermediate and most distal localities of the Kikutodden Member outcrop belt (Table 1), with respect to the inferred north-western source area (Gjelberg & Steel, 1995; Midtkandal & Nystuen, 2009; Grundvåg *et al.*, 2017, 2019), and roughly parallel the ESE–oriented depositional dip (Fig. 1B).

A total of 36 sedimentological logs (Table 1; Fig. 1B, C) were retrieved by conventional methods from 33 outcrop localities and 3 onshore cores (drilled with a spacing of c. 50 m). The logs comprise 2416 m of measured sections through the Rurikfjellet and lowermost Helvetiafjellet Formations, of which c. 1424 m include time-equivalent sections of the Kikutodden Member (Table 1).

Facies discrimination was carefully executed for each bed (Fig. 2). Each facies represents coherent sedimentary structures that can be interpreted to record specific depositional processes (Table 2), and one bed frequently constitutes two or more facies (Fig. 2). A stack of amalgamated tempestites exhibiting the same facies, and characterised by either juxtaposed sandstone beds or complex intercalation of individual sandstone and shale beds, was generally counted as one bed (Table 1). The degree of bioturbation was recorded using a four-fold subdivision for weathered field exposures (Fig. 2A) and the seven-fold Bioturbation Index (BI) of Taylor & Goldring (1993) for clean field exposures and cores (Fig. 2B). Inferences of palaeoshoreline orientation and sediment transport directions were drawn from a total of 134 palaeocurrent measurements (Fig. 3) collected from sandstone beds ($N = 120$) and sandstone lenses in shale ($N = 14$).

*[**Fig. 3** around here; portrait, one-column width]*

*[**Fig. 4** around here; portrait, one-column width]*

FACIES AND TERMINOLOGY

A total of 12 facies (F1–12; Table 2) stack into beds classified as *very thin* (<0.03 m), *thin* (0.03–0.1 m), *medium* (0.1–0.30 m), *thick* (0.30–1 m) and *very thick* (>1 m). Conformable planar lamination in sandstone beds (F7) representing an intermediate configuration between HCS and distinctly planar lamination is referred to as *quasi-planar lamination* (QPL; Table 2) *sensu* Arnott (1993).

The HCS represents a continuum of configurations with two end-member facies. First, *simple HCS* (F8; Table 2) is characterised by successive hummocky laminae separated by internal truncations (i.e. 3rd-order lamina sets and 2nd-order truncation surfaces *sensu stricto* Dott & Bourgeois, 1982) within a single sandstone bed (Fig. 4A). Simple HCS is predominantly geometrically *isotropic* but also includes (i) *anisotropic* stratification, expressed by low-angle sigmoidal foresets with near-parallel truncations; or (ii) an intermediate configuration between HCS and SCS referred to as *combined HCS–SCS*, characterised by locally dominant (but not superimposed; cf. Leckie & Walker, 1982), low-angle, concave-up scours and swale-conformable lamination. Second, *complex HCS* (F9; Table 2) is characterised by vertical or lateral variations in stratification within a single sandstone bed (Fig. 4B), predominantly expressed by ripple cross-lamination, textural variance or local (several metres) shifts to QPL (cf. Quin, 2011). Complex HCS is commonly associated with pervasive SSDS.

Recurring arrangements of facies allow identification of three types of event beds (tempestites), interpreted to represent fundamentally different depositional processes. The proximal–distal variability of tempestite facies and depositional processes are outlined below.

*[**Table 2** around here; landscape, full page]*

*[**Fig. 5** around here; portrait, two-column width]*

TEMPESTITE TYPES

Type 1 tempestites: Relatively steady flow deposits

Event beds of this type are dominant (comprising c. 89%; Table 1) and consist of very fine- to fine-grained sandstone predominantly characterised by planar lamination (F7), simple HCS (F8) and wave ripple cross-lamination (F10) (Table 2; Fig. 5).

Proximal

In the proximal localities, event beds of this type are generally medium- to very thick-bedded (≤1.05 m) and may extent laterally for >75 m. Medium-bedded sandstone beds are predominantly tabular and display planar lamination to QPL (F7; Figs 5A, 6A), or simple HCS (F8) with local internal anisotropic micro-HCS (*sensu lato* Dott & Bourgeois, 1982) less than 7 cm thick and/or basal gravel and shell lags (Table 2). The sandstone beds are ubiquitously interbedded with sand-streaked shale (F2) and bioturbated sandy shale (F3) (Table 2). Thick sandstone beds generally display sharp bases and simple HCS. The HCS is locally anisotropic and records migration towards the ESE (Figs 3, 5B, 6B). More typically, the HCS is isotropic with pronounced pinch-and-swell architecture and wavelengths of several metres (Figs 5C, 6C), or displays combined HCS–SCS (Fig. 5D). Such beds may taper laterally into (i) gutter casts infilled by simple HCS sandstone; or

(ii) thin sandstone sheets and lenses (Fig. 6C; cf. Midtgaard, 1996) with wave ripple cross-lamination (F10). Thick sandstone beds are commonly amalgamated by either (i) complete juxtaposition and erosional welding of successive beds (Fig. 6D; cf. Dott & Bourgeois, 1982); or (ii) laterally restricted welding of the beds, which adjacently split into two or three separate beds.

Wave, combined-flow (F11) and climbing current (F12) ripples (Table 2) are locally preserved at the top of the sandstone beds (Figs 5C, 6E). The climbing current ripples have a mean migration direction towards the SE (Fig. 3). The wave ripples are predominantly round-crested and 3D, and subordinately sharp-crested and two-dimensional (2D) to near-trochoidal (Fig. 6E).

*[**Fig. 6** around here; <u>portrait, two-column width</u>]*

Intermediate

In the intermediate localities, event beds of this type are predominantly thin- to medium-bedded (although thick to very thick beds also frequently occur) and laterally restricted (<50 m). The sandstone beds are ubiquitously interbedded with homogeneous shale (F1), sand-streaked shale (F2) and bioturbated sandy shale (F3), and generally exhibit sharp-based simple HCS (F8; Fig. 5C) and wave ripple cross-lamination (F10) (Table 2). The lower division of the beds may contain NW–SE-oriented parting lineation or gutter casts (Figs 3, 7A), wave ripple cross-lamination or minor gravel lags (Fig. 5C). The gutter casts rarely exceed c. 10 cm in width and are infilled by massive or planar-laminated sandstone. Amalgamated beds locally exhibit significant pinch-and-swell geometries with reliefs up to c. 0.8 m, manifested by complex intercalation of sandstone and shale (Fig. 7B; cf. Dott & Bourgeois, 1982).

Simple HCS in thin to thick sandstone beds is of shorter wavelength than in the proximal localities and may be purely aggradational (Figs 5C, 7C). Simple HCS beds may also be characterised by combined HCS–SCS (Figs 5D, 7D), which locally displays anisotropy (cf. Datta *et al.*, 1999; Dumas & Arnott, 2006), or contain a lower anisotropic division overlain by an isotropic division. In cases, thin to thick sandstone beds exhibit a different suite of sedimentary structures: Planar lamination or QPL (F7); planar lamination or simple HCS overlain by round-crested 2D or 3D wave ripples (Figs 5E; 7E) or combined-flow ripples (F11); bed tops obliterated by bioturbation with a BI of 3–5, forming fining-upwards bed-sets with shale (F1–3; Fig. 5F); and 3D wave ripple cross-lamination forming a continuum with micro-HCS (*sensu lato* Dott & Bourgeois, 1982; Figs 5G, 7F, G). Less common features include sandstone beds capped by (i) current or climbing current ripples (F12) displaying foreset dip azimuths towards the ESE (Fig. 3); or (ii) homogeneous mudstone (F4; Fig. 7C).

The 2^nd^-order truncations of simple HCS locally enclose various unidirectional ripple cross-lamination displaying relatively scattered foreset dip azimuths (varying with 210°) with a mean orientation towards the SE (Fig. 3).

*[**Fig.** 7 around here; <u>portrait, two-column width</u>]*

Distal

In the distal localities, event beds of this type generally comprise very thin- to thin-bedded siltstone to very fine-grained sandstone (Fig. 8A). Such beds form a continuum between pinch-and-swell lenses displaying wave ripple cross-lamination (F10; Fig. 5H) and discrete beds displaying simple HCS (F8) (Table 2; Fig. 8B). The pinch-and-swell lenses are generally poorly exposed and complexly intercalated with homogeneous shale (F1) and sand-streaked shale (F2) (Table 2; Fig. 8B). Thus, the lenses are not accounted for in the number of investigated event beds (Table 1). The discrete HCS sandstone beds are laterally restricted (<5 m), commonly sharp-based and locally capped by wave or combined-flow ripples (F11).

*[**Fig. 8** around here; <u>portrait, two-third page width</u>]*

Interpretation

The predominance of sandstone beds exhibiting planar lamination (F7), HCS (F8) and wave ripple cross-lamination (F10) indicates that event beds of this type conform to tempestites deposited from storm-wave-generated oscillatory flows or oscillatory-dominated combined-flows (Southard *et al.*, 1990). The regular configurations of the simple HCS suggest that the depositional flows were generally relatively steady and predominantly characterised by high flow intensities. The ubiquitous interbedding of sandstone and shale beds indicates that deposition predominantly occurred between the mean FWWB and SWB, whereas the amalgamated sandstone beds in the proximal localities probably reflect deposition immediately above the FWWB (Dashtgard *et al.*, 2012).

In the proximal localities (Table 1; Fig. 1B), planar-laminated sandstone beds record traction deposition from oscillatory sheet flows (DeCelles & Cavazza, 1992). In the intermediate and distal localities (Table 1; Fig. 1B), the common occurrence of wave ripple cross-lamination records comparatively weaker oscillatory-flow conditions, and the predominance of thin to medium beds indicates lower sediment supply. The distal tempestites were probably deposited immediately above the effective SWB predominantly by wave-generated purely oscillatory flows.

The sharp bases and NW–SE-oriented gutter casts of the tempestites indicate that deposition was generally preceded by erosion of the seabed by strong, offshore-directed unidirectional currents (Myrow, 1992b; Myrow & Southard, 1996; Dumas *et al.*, 2005). Parting lineation was probably formed from high shear stress plane-bed conditions during initial deposition

(Komar & Miller, 1975; Leckie & Krystinik, 1989). Beds exhibiting anisotropic HCS, QPL, and combined-flow (F11) and climbing current (F12) ripples, indicate that the unidirectional currents occasionally affected bulk deposition and were generally characterised by high aggradation rates (Arnott & Southard, 1990). With increasing unidirectional-current speeds and decreasing aggradation rates, hummocky bedforms were locally truncated, resulting in combined HCS–SCS (Dumas & Arnott, 2006).

The vertical facies arrangements of planar lamination or simple HCS overlain by ripples are well-documented features of waning- to late-stage storm flow (e.g. Dott & Bourgeois, 1982; Nøttvedt & Kreisa, 1987; Arnott, 1993; Midtgaard, 1996; Myrow *et al.*, 2002; Lamb *et al.*, 2008). The wave ripples in the bed tops are interpreted to represent a continuum from proximal 2D vortex ripples to intermediate and distal 3D rolling-grain ripples (Table 2; Bagnold, 1946). Locally overlying homogeneous mudstone (F4) probably represents deposition of fluid mud during final-stage storm wane, generated from wave resuspension of previously deposited mud (Ichaso & Dalrymple, 2009), or from rapid settling of flocculated mud from hypopycnal plumes (Parsons *et al.*, 2001) or hyperpycnal flows (Bhattacharya & MacEachern, 2009).

*[**Fig. 9** around here; <u>portrait, two-column width</u>]*

Type 2 tempestites: Highly unsteady flow deposits

Event beds of this type are rare (comprising c. 4%; Table 1) and consist of very fine- to fine-grained sandstone predominantly characterised by complex HCS (F9) (Table 2; Fig. 9).

Proximal

In the proximal localities, event beds of this type are restricted to the Bohemanflya section (Table 1; Fig. 1B), where they are interbedded with sand-streaked shale (F2) or bioturbated sandy shale (F3) (Table 2). The sandstone beds are predominantly thick-bedded (≤0.88 m), sharp-based, and locally erosionally welded with underlying sandstone beds (Fig. 10A). In cases, the beds are characterised by complex amalgamation of sandstone and shale (Fig. 10B). Laterally extensive (>75 m) and isotropic complex HCS (F9) with bed-persistent SSDS dominates (Figs 9A, 10A). The SSDS are characterised by incipient to overturned convolutions of lamina or lamina sets, which generally increase in magnitude of distortion down-crest of the individual hummocky bedforms (Fig. 10A, B). The convolutions predominantly display relatively irregular, centimetre-scale anticlines and synclines. The 1st- and 2nd-order boundaries (*sensu stricto* Dott & Bourgeois, 1982) of the HCS are generally unaffected by the SSDS. The complex HCS is also commonly characterised by wave, combined-flow, or climbing current ripple cross-lamination (Fig. 10A; cf. Arnott, 1992), constituting significant parts of the HCS as ripple trains parallel with the bulk hummocky lamination, thus corresponding to “compound”-type stratification (Figs 2A, 9A, 10C). The climbing current ripple cross-lamination displays opposing migration directions with some towards the NW. In other cases, the hummocky lamina sets grade from sandstone into carbonaceous material (Fig. 10B). The sandstone beds are locally capped by wave ripples (F10) or homogeneous mudstone (F4).

*[**Fig. 10** around here; <u>portrait, two-column width</u>]*

Intermediate

In the intermediate localities, events beds of this type are predominantly medium-bedded and subordinately thin- or thick- to very thick-bedded, and dominated by isotropic complex HCS (F9). These beds are generally more laterally restricted (<50 m) than their proximal counterparts, and commonly display sharp to erosional or irregular bases that may include (i) SSW–NNE-oriented parting lineation; or (ii) in average WSW–ENE-oriented gutter casts infilled by planar-laminated sandstone (Figs 3, 9B). The sandstone beds are characterised by common interbedding with homogeneous shale (F1), sand-streaked shale (F2) and bioturbated sandy shale (F3) (Table 2).

The complex HCS mainly displays two configurations. The first is characterised by lateral translations into QPL (Fig. 9B). This type of complex HCS is locally interbedded with simple HCS (F8) (Fig. 11A). The second comprises wave, combined-flow and/or current ripple cross-lamination; anisotropic micro-HCS; and small-scale SSDS (Figs 2B, 9C, 11B–D). Ripple cross-lamination sets are usually parallel with the bulk hummocky lamination and are sporadically distributed both vertically and laterally within the HCS (Figs 9C, 11B, C). Foreset dip azimuths of unidirectional ripple cross-lamination and anisotropic micro-HCS locally display opposing directions within the same bed (Fig. 11B) but are generally scattered (varying with 250°; Fig. 3). The SSDS are generally centimetre-scale and display various 2D and 3D folds with scattered fold axes (Fig. 3), minor chaotic distortions, and less commonly fully overturned lamination (Fig. 11D). A third and rare variation of the complex HCS contains carbonaceous material either as (i) fully carbonaceous lamina sets (Fig. 11B); or (ii) double-draping expressed by apparently cyclic thickness alternation of sandstone lamina with each lamina draped by carbonaceous detritus (Figs 9D, 11E).

Sandstone beds are locally capped by wave (F10), combined-flow (F11) or climbing current (F12) ripples (Fig. 9B, C), with the latter two characterised by scattered foreset dip azimuths (Fig. 3). The bed tops may be bioturbated (BI 3–5), or more rarely overlain by homogeneous mudstone (F4; Fig. 11C).

Event beds of this type are absent in the distal localities.

*[**Fig. 11** around here; <u>portrait, two-column width</u>]*

Interpretation

The predominance of sandstone beds exhibiting HCS (F9) indicates that event beds of this type conform to tempestites deposited from storm-wave-generated oscillatory flows or oscillatory-dominated combined-flows (Southard *et al.*, 1990). The various configurations of the complex HCS, including transitional stratification and ripple cross-lamination, indicate that the depositional flows were characterised by frequent shifts in flow intensity. It is interpreted that deposition of the tempestites was controlled by highly unsteady waves characterised by significant variations in oscillatory-flow dynamics. The abundant SSDS suggest that liquefaction commonly took place, probably due to high instantaneous sedimentation rates with associated weakening of lamina shear resistance and occasional small-scale slumping (cf. Dalrymple, 1979; Mills, 1983; Owen, 1996). The common interbedding of sandstone and shale beds indicates that deposition predominantly occurred between the mean FWWB and SWB, whereas the amalgamated sandstone beds in the proximal localities probably reflect deposition immediately above the FWWB (Dashtgard *et al.*, 2012).

In the proximal localities (Table 1; Fig. 1B), the tempestite thicknesses probably indicate higher sediment supply, and the abundance of climbing current ripple cross-lamination reflects rapid deposition from suspension. Complex HCS exhibiting wave ripple cross-lamination probably indicates episodic to periodic shifts to lower oscillatory-flow velocities and a shift in bedform stability fields (Midtgaard, 1996). Similarly, the presence of (i) combined-flow, current and climbing current ripple cross-lamination, and (ii) lateral translations to QPL, reflect episodic pulsation of relatively weak and strong unidirectional flows, respectively. Depositional flows were characterised by high aggradation rates (Arnott & Southard, 1990) and occasionally time-varying orientations, both during the course of and between the individual flows, as indicated by the various migration directions of the unidirectional ripples (Fig. 3).

Carbonaceous laminae (Figs 10B, 11B) and double draping (Fig. 11E) in complex HCS are interpreted to reflect suspension fallout of organic debris during a single storm event, respectively by (i) prolonged damping or absence of near-bed wave agitation, and (ii) relatively cyclic fluctuations of oscillatory energy (cf. Leithold & Bourgeois, 1984; Varkarelov *et al.*, 2012).

*[**Fig. 12** around here; portrait, two-column width]*

Type 3 tempestites: Wave-modified hyperpycnites

Event beds of this type are moderately common (comprising c. 7%; Table 1) and consist of homogeneous mudstone (F4) and very fine- to coarse-grained and gravelly sandstone predominantly characterised by (i) graded (F5) and massive (F6) textures; (ii) planar lamination (F7); (iii) simple (F8) and complex (F9) HCS; and (iv) combined-flow (F11) and climbing current (F12) ripple cross-lamination (Table 2; Fig. 12).

Proximal

In the proximal localities, event beds of this type are restricted to the Bohemanflya section (Table 1; Fig. 1B), where they are interbedded with sand-streaked shale (F2) and bioturbated sandy shale (F3) (Table 2). The event beds are characterised by medium- to thick-bedded (≤0.80 m), sharp- to erosional-based sandstone dominated by three configurations of complex HCS (F9).

The first contains compensational cut-and-fill architecture, low-angle (<10°) lateral accretion, and scattered gravel lenses within laterally tapered channel fills (Figs 12A, 13A). Welding of successive sandstone beds is manifested by primary erosional bounding surfaces that translate laterally into secondary conformable bed contacts (Fig. 13A; Dott & Bourgeois, 1982). The channels are <0.8 m thick and <15 m wide; SW–NE-oriented; and display concave-up erosional bases that truncate underlying shale and sandstone beds (Fig. 13A).

The second configuration of complex HCS (Fig. 13B) forms a continuum with QPL (F7; Fig. 13C). The beds are characterised by gravelly to conglomeratic sandstone with markedly erosional bases displaying normal, inverse or inverse-to-normal grading. The beds range in grain size between very fine to coarse sandstone (cf. Datta *et al.*, 1999), which generally also contain either (i) gravel dispersed as individual grains or subtle lenses within the very fine- to coarse-grained lamination of the complex HCS or QPL (Figs 12B, 13A, B); (ii) basal conglomerates which locally are trough cross-stratified (Figs 12B, 13B, C); or (iii) small-scale trough cross-stratification within the bulk lamination of the complex HCS or QPL. The lenses and conglomerates consist of granule- to pebble-sized quartz clasts, coal clasts, and ubiquitous plant debris. The beds are usually capped by sharp-crested wave (F10; Fig. 13B) or combined-flow (F11; Fig. 13C) ripples.

The third configuration of complex HCS is rare and displays laterally restricted (<2 m), vertical alternation of hummocky lamination and E–SE-directed combined-flow and climbing combined-flow ripple cross-lamination (Figs 12C, 13D).

*[**Fig. 13** around here; portrait, two-column width]*

Intermediate

In the intermediate localities, event beds of this type display four facies arrangements, of which two are characterised by thin- to thick-bedded sandstone and two are characterised by very thin- to thin-bedded couplets of sandstone and mudstone. The event beds are characterised by common interbedding with homogeneous shale (F1), sand-streaked shale (F2) and bioturbated sandy shale (F3) (Table 2).

The first sandstone facies arrangement displays vertical alternation of sedimentary structures within the same bed, which occurs in either (i) complex HCS (F9) where the alternation of sedimentary structures is laterally restricted (<1 m; Figs 12C, 14A); or (ii) relatively tabular sandstone beds as laterally persistent facies repetitions (Figs 12C, 14B). Facies of the latter include massive bedding (F6), planar lamination (F7) and simple HCS (F8), and any of these facies alternates upwards with combined-flow (F11) or climbing current (F12) ripple cross-lamination (Figs 12C, 14B). The second sandstone facies arrangement is simpler, predominantly displaying a lower massive division overlain by planar lamination, simple HCS or combined-flow or climbing current ripples (Figs 12D, 14C, 15A). The combined-flow ripples are round-crested and 2D, symmetrical to asymmetrical, and display low-angle convex-up to sigmoidal foresets. Ripple foreset dip azimuths of the two sandstone facies arrangements are oriented roughly towards the E to ESE (Fig. 3).

The first very thin- to thin-bedded facies arrangement is dominated by planar-laminated, wave (F10) or combined-flow ripple cross-laminated sandstone intercalated with homogeneous mudstone (F4) (Figs 2B, 12E, 14D, E, 15B). Boundaries between the sandstone and mudstone are either gradational, sharp to erosional (Fig. 12E), or rarely interlaminated (Fig. 14D). The mudstone is dark grey to black, typically characterised by lateral thickness variations, and locally displays faint biogenic mantle-and-swirl structures (Navichnia; Lobza & Schieber, 1999) of low bioturbation intensities (BI 0–2) (Fig. 14D, E). The second very thin- to thin-bedded facies arrangement (F5) comprises sharp- or erosional-based beds of siltstone to very fine-grained sandstone grading into silty or carbonaceous mudstone (Figs 12F, 14E, 15).

Event beds of this type are absent in the distal localities.

[***Fig. 14** around here; portrait, two-column width]*

[***Fig. 15** around here; portrait, one-column width]*

Interpretation

The common association of HCS, combined-flow (F11) and climbing current (F12) ripples suggests that deposition took place from a combination of wave-generated oscillatory flows and unidirectional currents. The vertical arrangement of facies and frequent occurrence of grading indicate that the unidirectional currents were turbidity currents. Sandstone beds exhibiting inverse-to-normal grading and vertical alternation of sedimentary structures (including complex HCS; F9); terrigenous coal clasts and plant debris; and E- to SE-oriented ripple foreset dip azimuths, suggest that the turbidity currents were formed from riverine hyperpycnal outflows which were episodically waxing and waning (Mulder *et al.*, 2003), and offshore-directed. The homogeneous nature of the very thin- to thin-bedded mudstone (F4) and associated Navichnia indicate soupground conditions (Lobza & Schieber, 1999), consistent with fluid-mud deposition (Bhattacharya & MacEachern, 2009; Wilson & Schieber, 2014). Thus, event beds of this type conform to storm-wave-modified shelf hyperpycnites and turbidites (i.e. tempestites), which were distally waning (Mutti *et al.*, 1996; Myrow *et al.*, 2002; Lamb *et al.*, 2008). The common interbedding of sandstone and shale beds indicates that deposition predominantly occurred between the mean FWWB and SWB (Dashtgard *et al.*, 2012).

The channelised complex HCS in the Bohemanflya section (Figs 1B, 13A) shares numerous architectural similarities with the subaqueous hyperpycnal channel elements documented by Ponce *et al.* (2008) and Eide *et al.* (2015). Lateral accretion and compensational stacking of sandstone bodies imply that the channel architecture was controlled by sustained hyperpycnal flows (e.g. Mutti *et al.*, 2003), which were perhaps helicoidal in nature or influenced by (i) offshore-directed rip currents or downwelling flows (Amos *et al.*, 2003); or (ii) the position and lateral migration of the sediment-feeding point source. Coarse-grained to gravelly sandstone beds indicate higher riverine outflow efficiency (Mutti *et al.*, 2003), and inverse-to-normal grading reflects waxing and waning of turbulent hyperpycnal flows enhanced by strong, steady storm waves (Leckie, 1988).

Sandstone beds exhibiting vertical alternation of sedimentary structures (including complex HCS; Figs 12C, 13D, 14A, B) reflect deposition from waxing and waning combined-flows. The round-crested combined-flow ripples, some with asymmetry and convex-up to sigmoidal foresets, indicate that the flows were episodically current-dominated (Yokokawa, 1995; Mulder *et al.*, 2003). Thus, such beds probably reflect episodes of lower oscillatory-flow intensity, and represent a range of Bouma-like divisions, including T_{bacb}, T_{bcb}, T_{bcbc}, T_{bcbcb}, T_{cbc} and T_{cbcd} (Fig. 12C; Bouma, 1962). Sandstone beds exhibiting a lower massive division (F6) overlain by planar lamination (F7), simple HCS (F8) or ripples (Figs 12D, 14C) are interpreted to represent wave-modified turbidites, including T_{ab}, T_{abc}, T_{ac}, T_{bc} and T_{bcd} subdivisions (Bouma, 1962), which were deposited from wave-enhanced, surge-type turbidity currents (Lamb *et al.*, 2008). The proximal hyperpycnites are relatively thick compared to the intermediate wave-modified turbidites, but their arrangements of sedimentary structures are closely related. Consequently, the intermediate surge-type turbidity currents were probably generated directly from more proximal hyperpycnal flows. The lack of a basal waxing unit may reflect that the temporal flow acceleration was relatively large compared to the magnitude of spatial flow deceleration (Lamb *et al.*, 2008), or that the sediment concentration in the flooding river plume was insufficient to generate a plunging flow during the rising limb of the flood (Mulder *et al.*, 2003; Geyer *et al.*, 2004).

The very thin- to thin-bedded sandstone–mudstone couplets and fine-grained, graded beds (F5; Figs 12E, F, 14D, E, 15) are interpreted to represent deposition from wave-enhanced, low-density turbidity currents (cf. Macquaker *et al.*, 2010; Li *et al.*, 2015), generated directly from plunging rivers or from collapse of flocculated hypopycnal plume muds (Parsons *et al.*, 2001; Plint, 2014). Collectively, the beds correspond to T_{bcde}, T_{bd}, T_{bde}, T_{cd} and T_{cde} divisions of Bouma (1962), $T_{e1–e3}$ divisions of Piper (1978), and $T_{0–8}$ divisions of Stow & Shanmugam (1980).

TEMPESTITE FACIES MODEL

The facies characteristics of the Kikutodden Member suggest that deposition took place from near SWB (by the distal localities) to immediately above FWWB (by the proximal localities) on a storm- and wave-dominated prodelta, within a high-fetch, open-marine setting (Fig. 16). Palaeocurrent measurements collectively indicate that the sediments were shed from a SSW–NNE-oriented shoreline towards the ESE (Figs 1B, 3, 16). Tempestite deposition was relatively patchy across a mud-dominated seabed, which was deposited primarily during fair-weather conditions (Table 2). The regional persistence of the prodeltaic facies belts indicates that the basin was characterised by a low-gradient ramp physiography (Midtkandal & Nystuen, 2009). Dumas & Arnott (2006) estimated that HCS forms in water depths of 13–50 m. Thus, it seems reasonable that the distal sandstone beds represent a SWB depth of at least tens of metres (Fig. 16).

In most of the investigated sections, the tempestites and fair-weather deposits stack into coarsening-upwards successions (Fig. 2), reflecting shoaling and increased proximity to the shoreline (Dypvik *et al.*, 1991b). Nevertheless, bulk proximal–distal facies relationships clearly indicate distally decreasing (i) sediment supply and aggradation rate; (ii) average bed thickness and grain size; and (iii) wave-generated oscillatory (U_o) and cross-shore unidirectional (both downwelling and hyperpycnal flows, U_u) current velocities (Fig. 16). The general lack of erosional surfaces in the distal tempestites is consistent with a distal increase in preservation potential closer to the SWB (Fig. 16; e.g. Dumas & Arnott, 2006). Proximal–intermediate facies and abundance trends of Type 2 and 3 tempestites (Table 1) are interpreted to reflect partial sediment bypass across the proximal areas (cf. Myrow, 1992a) and distally decreasing hyperpycnal-flow pulsation and wave unsteadiness. Recall that these tempestite types are not recognised in the distal sections (Fig. 16). However, considering the thickness (~106 m) of the shale-dominated and age-equivalent (Śliwińska *et al.*, in press) Wimanfjellet Member in the distal locality of Baronfjella (Table 1; Fig. 1B, D), hyperpycnal fluid-mud deposits may constitute parts of the succession (Table 2; Fig. 16).

Type 1 and 2 tempestites exhibiting approximately offshore-directed (ESE) parting lineation, gutter casts, anisotropic HCS and various unidirectional ripples are interpreted to record sediment delivery governed by downwelling flows related to coastal setup (Myrow, 1992b; Héquette & Hill, 1993, 1995), or possibly rip currents, that were superimposed by nearshore waves. Contemporaneous reworking by relatively steady or highly unsteady wave trains controlled the generation of their respective tempestite types (Fig. 16). Type 3 tempestites were probably fed from distributary channels, as suggested by the channelised HCS in the Bohemanflya section formed directly downstream of the sediment-feeding point source (Pattison & Hoffman, 2008; Basilici *et al.*, 2012b; Eide *et al.*, 2015), and distributed by a combination of bottom-hugging hyperpycnal flows and surface hypopycnal plumes (Fig. 16; Parsons *et al.*, 2001; Bhattacharya & MacEachern, 2009) during coupled storm-floods (Wheatcroft, 2000; Collins *et al.*, 2017). The lack of shore-parallel sole marks argues against dominant along-shore or geostrophic processes.

*[**Fig. 16** around here; <u>landscape, full page</u>]*

DISCUSSION

Storm-hyperpycnal sediment transport and distribution in a low-gradient setting

Existing tempestite facies models portray a dominance of oscillatory-generated bedforms in proximal areas and an increased proportion of unidirectional-current-generated bedforms in distal areas due to increased water depth and a corresponding decrease in the near-bed wave orbital velocity (e.g. Dott & Bourgeois, 1982; Myrow *et al.*, 2002; Lamb *et al.*, 2008; Pattison & Hoffman, 2008). However, the distal tempestites of the Rurikfjellet Formation are oscillatory-dominated (Fig. 16), indicating that they do not necessarily conform to the general tempestite facies models, or that the outcrop belt does not extend to areas represented by the most distal parts of these models.

Numerous accounts of hyperpycnal turbidites (e.g. Myrow *et al.*, 2002; Pattison, 2005; Lamb *et al.*, 2008; Basilici *et al.*, 2012b) and fluid-mud deposits (Bhattacharya & MacEachern, 2009; Plint, 2014; Wilson & Schieber, 2014, 2017; Harazim & McIlroy, 2015) in storm-dominated successions have been interpreted to represent wave-enhanced density flows. In these cases, near-bed agitation of waves may support suspension of turbidity currents for large distances across the shelf (e.g. Varban & Plint, 2008) by providing additional turbulence to the flows (e.g. Macquaker *et al.*, 2010). It is speculated that the low gradient of the Rurikfjellet Formation ramp controlled the temporal and spatial evolution of the hyperpycnal flows by enhancing the extent of wave agitation across the seafloor, but at the same time resulted in progressive deceleration of the flows. In the intermediate–distal areas, the relative magnitude of wave-added turbulence was sufficient to cause significant diffusion of the density-driven sediment dispersion into the overlying water column (e.g. Noh & Fernando, 1992; Myrow & Southard, 1996). Hyperpycnal sediment transport was likely further retarded by progressive flow depletion due to sediment deposition, entrainment of ambient seawater, and/or lateral spreading of the flows (e.g. McLeod *et al.*, 1999). The predominance of oscillatory-generated (and lack of current-generated) tempestites in the distal sections of the Rurikfjellet Formation outcrop belt implies that (i) proximal–distal facies relationships of general tempestite facies models may only be applicable to moderate- to high-gradient shelves (cf. Bourgeois, 1980; Swift *et al.*, 1987; Myrow, 1992a); and (ii) new tempestite facies models have to be developed for low-gradient depositional settings.

Nature of wave unsteadiness in generating some complex hummocky cross-stratification

The complex HCS of Type 2 and 3 tempestites forms unusual and distinctive bedding styles (Table 2; Figs 9–11, 12A–C, 13A, B, D, 14A). The superimposition of unidirectional flows on strong, relatively steady wave oscillations is evidenced by complex HCS exhibiting (i) lateral translations from hummocky lamination to QPL within Type 2 tempestites (Fig. 9B), interpreted to indicate downwelling flows (Arnott, 1993); and (ii) channelisation (Fig. 12A) and gravelly inverse-to-normal grading (Fig. 12B) within Type 3 tempestites, interpreted to indicate pulsating hyperpycnal flows. However, other examples of complex HCS were generated by waves characterised by significant unsteadiness. Enigmatic features with important bearings on the nature of wave unsteadiness are (i) ripple cross-lamination; (ii) scattered orientations of palaeocurrent indicators; (iii) tidal sedimentary structures; and (iv) SSDS.

Ripple cross-lamination

The common presence of ripple cross-lamination within complex HCS in Type 2 (Figs 9A, C, 10A, C, 11B, C) and Type 3 tempestites (Figs 12C, 13D, 14A) suggests that the intensity of oscillatory flow was frequently reduced. Similar shifts in oscillatory flow regime were tentatively inferred by Midtgaard (1996) to represent periodic passing of smaller wave groups. In addition, gravity-driven cross-shelf sediment transport enhanced by wave suspension may be inherently pulsating or reversing (Wright *et al.*, 2002; Lamb *et al.*, 2008), which is manifested by (i) high bed shear stresses and turbulent diffusion generated by groups of large waves, and (ii) short-lived, rapid offshore or reversing movement of sediment during lulls between these groups. It is interpreted that during such lulls, weaker oscillatory flows permitted local generation of wave ripples across hummocky bedforms (Fig. 17A). In Type 3 tempestites, the vertical alternation of hummocky lamination and unidirectional ripple cross-lamination reflects the superimposition of hyperpycnal flows (Fig. 17A).

Scattered orientations of palaeocurrent indicators

The ripples within complex HCS of Type 2 tempestites display scattered orientations with local onshore modes (Figs 3, 10A, 11B). Upslope-migrating, small-scale HCS in bathyal turbidites have previously been interpreted to represent antidunes generated by Kelvin-Helmholtz instabilities related to standing waves within thick, stratified turbidity currents (Prave & Duke, 1990; Mulder *et al.*, 2009). This interpretation seems unlikely for the orientations of the ripples within complex HCS, because sediment dispersion caused by the oscillatory-dominated flows probably inhibited density-induced flow stratification. Furthermore, formation of upstream eddy currents is unlikely because the height and crestal brink angle of the hummocks are too small to induce sufficient separation of a lee-side flow (Schatz & Herrmann, 2006; Herbert *et al.*, 2015).

During storms, surface gravity waves approaching shore are commonly refracted, resulting in waves propagating in several directions (Cheel, 1991). The scattered orientations of sole marks and ripples within the complex HCS are interpreted to reflect such multidirectional wave spectra where downwelling flows acted in combination with near-bottom quasi-steady to unsteady reversing oscillatory flows of higher and lower energy, respectively (Fig. 17B; Gray & Benton, 1982; Duke, 1990). Although such waves surely also operate during deposition of some simple HCS, as indicated by 3D wave ripples in Type 1 tempestites, they are apparently particularly important in the formation of complex HCS (Fig. 3). In addition, hummocky topography at the seabed may have resulted in transient breaking of internal waves (Morsilli & Pomar, 2012), and/or flow deflections and ponding causing spatial strength variations (Kneller & McCaffrey, 1999; Tinterri, 2011).

Tidal sedimentary structures

The complex HCS displaying carbonaceous lamina sets (Figs 10B, 11B) reflects significant diminishment of near-bed wave agitation, and carbonaceous double drapes (Figs 9D, 11E) in a few Type 2 tempestites reflects apparently cyclic deposition. Thus, passing wave groups seem unlikely as the formative process of these sedimentary features. Recently, HCS has been reported from modern and ancient open-coast tidal flats, and several studies have interpreted certain ripples, lenses and carbonaceous mudstone draping in ancient HCS tempestites to record tidal water-level variations (Leithold & Bourgeois, 1984; Rasmussen & Dybkjær, 2005; Yang *et al.*, 2005; Basilici *et al.*, 2012a; Vakarelov *et al.*, 2012). Consequently, the carbonaceous lamina sets may reflect (i) suspension fallout of river-supplied organic debris during combined neap tide and final waning-storm stage (Vakarelov *et al.*, 2012), and/or (ii) elevation of the effective SWB (Fig. 17C) and associated damping of wave agitation during tidal flood (Leithold & Bourgeois, 1984). The double-draped HCS might represent daily tidal water-level variations of semi-diurnal inequality during a single storm event (cf. Rasmussen & Dybkjær, 2005). Thus, these beds provide rare examples of probable tidal superimposition in the formation of HCS. As emphasised by Vakarelov *et al.* (2012), tidal modulation of wave-dominated shorelines is generally greatest across wide, low-gradient shelves (such as the Rurikfjellet Formation), but such settings are also prone to complex hydrodynamic processes, inhibiting development of conventional tidal sedimentary structures.

Soft-sediment deformation structures

Soft-sediment deformation structures are well-documented in tempestites and commonly include load casts, ball-and-pillows, pipes and convoluted lamination. In shallow-marine sandstone beds (including tempestites), SSDS have been interpreted to represent liquidization (primarily liquefaction and fluidization) triggered by, for example, earthquakes or tsunamis (Owen, 1987), impulsive stress of breaking waves in nearshore environments (Dalrymple, 1979), rapid introduction and loading of sand onto a muddy seafloor (Eyles & Clark, 1986), or cyclic stress of storm waves (Molina *et al.*, 1998; Alfaro *et al.*, 2002; Chen & Lee, 2013).

The SSDS associated with the complex HCS in Type 2 tempestites are predominantly characterized by small-scale and down-crest distortions as well as incipient to overturned convolutions of lamina or lamina sets (Figs 9A, C, 10A, B, 11B, D). The low surface slopes of the hummocky bedforms (<15°) are considerably less than slipface inclinations of subaqueous dunes (Hunter & Kocurek, 1986), indicating that liquefaction must have governed the loss of sediment shear strength.

The majority of SSDS within the Kikutodden Member are only present in the tempestites (except for two slumps observed in the Bohemanflya section; Fig. 2A), and they are generally restricted to the complex HCS of Type 2 tempestites, even in cases of amalgamation with simple HCS of Type 1 tempestites (Figs 2A, 10A; cf. Molina *et al.*, 1998; Alfaro *et al.*, 2002). Thus, earthquakes are rejected as the triggering mechanism of liquefaction, since these would probably have affected other beds as well. Tsunamis are also excluded, because deposits related to such events generally display other sedimentary characteristics (e.g. Schnyder *et al.*, 2005). Considering that the depositional setting of the Rurikfjellet Formation was generally below FWWB, liquefaction induced by breaking waves is unlikely. The lack of load casts, ball-and-pillows, pipes and deformed 1st- and 2nd-order boundaries in the complex HCS (Figs 9A, C, 10A) also precludes post-depositional slumping or rapid loading of the deposited sand into underlying mud.

Consequently, the most plausible triggering mechanism of liquefaction is interpreted to have been cyclic stress induced by storm waves (Fig. 17D; Molina *et al.*, 1998; Alfaro *et al.*, 2002; Chen & Lee, 2013). During deposition, the consecutive pressure difference between wave crests and troughs may have increased the interstitial pressure of the hummocky sand on the seabed, leading to liquefaction and associated reduction of shear strength (Fig. 17D). The liquefaction probably resulted in sufficient density stratification between laminae to induce short-lived Rayleigh-Taylor instability and associated gravitational adjustment manifested by near-sinusoidal lamina convolutions and small-scale folds (Fig. 17D; Anketell *et al.*, 1970; Allen, 1977). The general lack of deformed 1st- and 2nd-order boundaries suggests the liquefaction primarily occurred during aggradational bedform growth, and that truncation of surficial sand resulted in momentary disruption of the soft-sediment deformation driving force system (*sensu* Owen, 1987), i.e. Rayleigh-Taylor instability.

*[**Fig. 17** around here; landscape, full page]*

A polygenetic model for hummocky cross-stratification

Possible vertical arrangements of sedimentary structures in tempestites have been comprehensively evaluated and interpreted primarily as a function of the ratio between wave-generated oscillatory (U_o) and cross-shore unidirectional (U_u) current velocities (e.g. Dott & Bourgeois, 1982; Nøttvedt & Kreisa, 1987; Leckie & Krystinik, 1989; Arnott & Southard, 1990; Cheel, 1991; Duke *et al.*, 1991; Myrow & Southard, 1991, 1996; Midtgaard, 1996). However, internal characteristics of HCS and SCS have received relatively little attention (Dott & Bourgeois, 1982; Arnott, 1992).

A polygenetic origin of HCS has previously been hypothesized by several authors (Allen & Pound, 1985; Leckie, 1988; Arnott & Southard, 1990; Myrow, 1992a; Morsilli & Pomar, 2012), partly due to its enigmatic occurrence in fluvial (Cotter & Graham, 1991) and deep-sea (Prave & Duke, 1990) strata. Complex HCS is restricted to Type 2 and 3 tempestites, which constitute less than c. 11% of the tempestites encountered in this study (Table 1). Nevertheless, the sedimentary configurations and formative processes of the complex HCS are not entirely consistent with previous generic classifications of HCS, which demonstrates that HCS is polygenetic in origin.

The configurations of HCS within the Rurikfjellet Formation were controlled by the relative influence of storm-wave oscillations, hyperpycnal flows (including sustained waxing–waning flows), and downwelling flows related to coastal setup (Fig. 16). The spectrum of these processes may be displayed by a ternary diagram similar to that presented by Myrow & Southard (1996), which included wave oscillations, density-induced flows (instead of hyperpycnal flows), and geostrophic flows (instead of downwelling flows). However, the generation of complex HCS may also depend on the prevailing degree of oscillatory-flow unsteadiness related to passing and multidirectional wave groups, tidal water-level variations, and cyclic wave stress. Consequently, the full range of possible process combinations is displayed by two connected ternary diagrams (Fig. 18). Since wave oscillations are required for the generation of HCS, a total of six formative flow fields may be predicted from the diagram (Fig. 18). A hypothetical end-member configuration of HCS is constructed for each of these flow fields (Fig. 18) based on the range of HCS displayed in the Rurikfjellet Formation. Although the model does not take into account the full range of shallow-marine hydrodynamic processes (e.g. shore-oblique geostrophic flows), it provides a predictive, process-based classification of some HCS configurations in tempestites. The potentially vast variety of sedimentary configurations produced either by combined oscillatory, downwelling and hyperpycnal flows, or amalgamation from multiple storm events, are omitted from the model (cf. Dott & Bourgeois, 1982; Myrow & Southard, 1996). For thorough reviews of tempestite sole marks, the reader is referred to Beukes (1996) and Myrow & Southard (1996).

1. Simple hummocky cross-stratification generated by relatively steady wave oscillations

The HCS in Type 1 tempestites is predominantly characterised by successive 3rd-order lamina sets and 2nd-order boundaries (Figs 5C, 6C, 7C), which reflect near-continuous aggradation and intermittent truncation of hummocky bedforms beneath relatively steady storm waves (Table 2; Dott & Bourgeois, 1982). Consequently, deposition that is dominated by relatively steady storm-wave oscillations would produce simple, dominantly isotropic HCS (Myrow & Southard, 1996). Given that most deposition occurs during the waning of a storm, tempestites commonly display a lower division of massive bedding or planar lamination to QPL, a middle HCS division, and an upper division of 2D or 3D wave ripples (Figs 5C, 18; e.g. Duke *et al.*, 1991; Midtgaard, 1996). Relatively weak storm-wave oscillations and reduced sediment supply would probably result in thin-bedded micro-HCS (Figs 5G, 7F, G, 8, 18).

2. Simple hummocky cross-stratification generated by relatively steady wave oscillations and downwelling flows

The superimposition of only relatively weak unidirectional currents on wave oscillations causes preferential deposition on one side of a hummock and resulting migration of hummocky bedforms (Arnott & Southard, 1990; Dumas & Arnott, 2006). Consequently, this type of oscillatory-dominated combined-flow is expected to produce anisotropic simple HCS (Myrow & Southard, 1996) displaying shore-oblique (if geostrophically veered) to shore-normal migration directions similar to a few Type 1 tempestites (Table 2; Figs 5B, 6B, 18). With increasing U_o and U_u, preferential truncation of surficial hummocks leads to dominant generation of SCS (Figs 5D, 7D, 18), which is generally assumed to occur in proximal shelf settings (Leckie & Walker, 1982; Dumas & Arnott, 2006).

3. Complex hummocky cross-stratification generated by highly unsteady wave oscillations

The configuration of complex HCS in Type 2 tempestites reflects deposition beneath highly unsteady storm-wave oscillations associated with (i) fluctuating oscillatory-flow intensity related to high-frequency passing of wave groups (Fig. 17A); and (ii) liquefaction due to cyclic stress applied by the storm waves (Fig. 17D). Thus, complex HCS produced solely by such waves would display isotropic “compound” stratification with abundant 2D or 3D wave ripples (Table 2; Figs 9A, 10C, 11C, 18). Syndepositional liquefaction is expected to be common and form SSDS, notably convoluted and contorted hummocky lamination (Figs 9A, 10A, B, 11D, 18). Multidirectional wave spectra with time-varying orientations (Fig. 17B) would probably result in polymodal orientations of wave ripple crests (Fig. 18), linear sole marks and parting lineation (Gray & Benton, 1982).

4. Complex hummocky cross-stratification generated by highly unsteady wave oscillations and downwelling flows

The combination of highly unsteady storm-wave oscillations with unidirectional downwelling flows (cf. Wright *et al.*, 2002) is responsible for a range of the complex HCS configurations within Type 2 tempestites. An end-member configuration of HCS produced from this process combination is expected to display dominantly isotropic dips and sedimentary structures indicative of combined-flow deposition during passing of smaller wave groups (Fig. 17A, B). Sedimentary structures would include localised QPL (Figs 9B, 11A, 18; Arnott & Southard, 1990), anisotropic HCS or SCS, and combined-flow, current or climbing current ripple cross-lamination (Table 2; Figs 9C, 10A, 11B, 18). Subordinate SSDS would probably also occur (Figs 9C, 18). In case that the wave oscillations are multidirectional with time-varying orientations (Fig. 17B), sole marks, gutter casts, parting lineation, and ripple foreset dip azimuths would be characterised by polymodal orientations (Figs 3, 11B, 18).

5. Complex hummocky cross-stratification generated by relatively steady wave oscillations and hyperpycnal flows

Changing the configuration from simple to complex HCS beneath relatively steady storm-wave oscillations would probably require the superimposition of strong hyperpycnal flows. Depending on available coarse material, this process combination would be able to produce relatively coarse-grained, gravel-rich or channelised HCS such as displayed in some Type 3 tempestites (Table 2; Figs 12A, B, 13A, B, 18). The complex HCS would display a range of isotropic and anisotropic configurations. Inverse-to-normal grading (Figs 12B, 13B, 18) is expected if deposition scales with low-frequency (several hours to days) waxing and waning of the hyperpycnal flow during the rising and falling limbs of a simple single-peaked flood. This type of HCS is expected to be relatively common in hyperpycnal-influenced, storm-dominated prodelta successions. The coarse-grained and gravel-rich HCS in the Rurikfjellet Formation (Figs 12A, B, 13A, B) are distinguished from 'wave-formed, coarse-grained ripples' (Leckie, 1988) and 'coarse-grained storm beds' (Cheel & Leckie, 1992), which predominantly exhibit tangential cross-stratification but are interpreted to have formed under the same conditions as fine-grained HCS (Cummings *et al.*, 2009). Datta *et al.* (1999) documented SCS in medium- to coarse-grained sandstone, but the lamina inclination of these structures exceeds that of fine-grained equivalents (i.e. 15°), probably as a result of significant suspension suppression. Bedform phase stability fields are generally produced for single grain sizes (e.g. Arnott & Southard, 1990; Southard *et al.*, 1990; Dumas *et al.*, 2005; Cummings *et al.*, 2009). Thus, the HCS documented in this study to contain coarse material demonstrates that future studies on the stability field of HCS would benefit from considerations of (i) the upper critical level of relatively coarse-sand grain sizes; and (ii) mixed grain-size populations, in which e.g. the formation of fine-grained HCS is possible up to a critical percentage of coarse grains.

6. Complex hummocky cross-stratification generated by highly unsteady wave oscillations and hyperpycnal flows

If the intensity of storm-wave oscillations is sufficiently reduced during lulls between large wave groups, the combination of highly unsteady storm-wave oscillations and hyperpycnal flows may result in a range of combined-flow deposition. Tinterri (2011) discussed various scenarios of combined-flow pulsation in the generation of HCS in hyperpycnal-dominated facies tracts, and Lamb *et al.* (2008) provided a conceptual model for deposition from wave-modified turbidity currents (including pulsating flows). Lamb & Mohrig (2009) found that hyperpycnal-flow velocities do not necessarily scale with the fluvial hydrograph, potentially resulting in multiple waxing and waning divisions within a bed produced during a single-peaked discharge event. Consequently, complex HCS produced during a single storm with either a single or multiple fluvial discharge events would probably display vertically alternating sedimentary structures, similar to the complex HCS of some Type 3 tempestites (Figs 12C, 13D, 14A, 18). The vertical alternation of the sedimentary structures would be laterally restricted, dominantly isotropic, and consist of hummocky lamination or QPL alternating with combined-flow, current or climbing current ripple cross-lamination with offshore-directed foreset dip azimuths (Table 2; Figs 12C, 13D, 14A, 18). In addition, significant damping of wave oscillations caused by tidal elevation of the water level may allow periodic suspension fallout of fluvial-derived, fine-grained material, such as mud and plant debris, resulting in carbonaceous lamina sets (Figs 10B, 11B, 17C). The HCS in the Rurikfjellet Formation implies that (i) detailed inspection of HCS may prove useful for the recognition of wave-modified hyperpycnites generated during coupled storm-floods (*sensu* Collins *et al.*, 2017); (ii)

HCS sandstone beds of hyperpycnal origin may be relatively common (Mutti *et al.*, 1996, 2003); and (iii) tempestites indicative of coupled storm-hyperpycnal deposition are probably overlooked in the stratigraphic record of prodeltaic settings (cf. Pattison, 2005; Pattison & Hoffman, 2008; Lamb *et al.*, 2008; Li *et al.*, 2015).

*[**Fig. 18** around here;* *portrait, full page]*

CONCLUSIONS

A spectacular variety of tempestites is displayed in outcrop and core sections of the Lower Cretaceous Rurikfjellet Formation on Spitsbergen, Svalbard, permitting detailed sedimentological investigations of near-basin-scale facies variability, causative depositional processes, and proposition of a new conceptual polygenetic model for the generation and various configurations of hummocky cross-stratification (HCS).

1 The term *simple HCS* is introduced for HCS characterised by little or no variation in stratification. The term *complex HCS* is introduced for HCS characterised by vertical or lateral variations in stratification, predominantly expressed by ripple cross-lamination, textural variance or local shifts to quasi-planar lamination. Complex HCS is commonly associated with soft-sediment deformation structures.

2 Three types of tempestites are recognised. The tempestites form a genetically related continuum of facies arrangements and record deposition from (i) relatively steady to waning storm-wave-generated oscillatory flows or oscillatory-dominated combined-flows with high aggradation rates (Type 1 tempestites); (ii) storm-wave-generated oscillatory flows with high aggradation rates, characterised by episodic to periodic fluctuations in oscillatory-flow intensity, syndepositional liquefaction, and occasional superimposition of unidirectional flows (Type 2 tempestites); and (iii) various storm-wave-enhanced hyperpycnal flows, including sustained waxing–waning hyperpycnal flows, surge-type turbidity currents, and fluid-mud flows (Type 3 tempestites).

3 Tempestite deposition was relatively patchy and occurred from near storm-wave base to immediately above fair-weather wave base across a storm- and wave-dominated prodeltaic ramp. Sediment delivery was governed by nearshore wave reworking, downwelling flows related to coastal setup, and direct feeding from distributary channels during coupled storm-floods. Facies relationships indicate (i) partial sediment bypass across the proximal areas of the ramp; (ii) increased preservation potential of tempestites in relatively distal areas, and (iii) distally decreasing sediment supply and aggradation rate, bed thickness and grain size, wave-generated oscillatory and cross-shore unidirectional (both downwelling and hyperpycnal flows) current velocities, and hyperpycnal-flow pulsation and wave unsteadiness.

4 A low-gradient ramp physiography significantly inhibited hyperpycnal sediment transport to distal areas by progressively decelerating turbidity currents, while enhancing the spatial extent and relative magnitude of wave-added turbulence. General tempestite facies models are probably only applicable to moderate- to high-gradient shelves.

5 The configuration of complex HCS is inherently related to the commonly unsteady and multidirectional nature of storm-wave oscillations. Reduction of near-bed oscillatory shear stresses may be governed by tidal elevation of the water level or passing of lower energy wave groups, permitting formation of finer-grained drapes and ripples, respectively. The ripples and resulting cross-lamination may record superimposition of downwelling or hyperpycnal flows. Cyclic stress applied by storm waves may result in syndepositional liquefaction and associated soft-sediment deformation. The generation of complex HCS beneath relatively steady waves requires the superimposition of strong hyperpycnal flows.

6 A new polygenetic model for HCS provides a process-based classification of potentially important configurations produced by relatively steady and highly unsteady wave oscillations, hyperpycnal flows (including waxing–waning flows), and downwelling flows during storms. The variability of HCS configurations documented in this study has previously been overlooked but allows for precise hydrodynamic and environmental interpretations of tempestites. Future studies on the generation of HCS may benefit from considerations of coarse-grained sand fractions and mixed grain-size populations.

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FIGURE CAPTIONS

Fig. 1. Section distribution and lithostratigraphy of the Lower Cretaceous succession on Spitsbergen. (A) Map of Svalbard. (B) Simplified geological map of central to southern Spitsbergen, indicating the distribution of Lower Cretaceous strata and clastic wedges, and main structural elements (based on Dallmann, 1999 and Grundvåg *et al.*, 2017); localities used in this study and their proximal–distal zonation; and mean sediment transport direction based on representative rose diagrams of this study (see Fig. 3). Ag, Agardhaksla; Ba, Baronfjella; BFZ, Billefjorden Fault Zone; Bo, Bohemanflya; CTB, Central Tertiary Basin; LFZ, Lomfjorden Fault Zone; Ra, Ramfjellet; Sy, Sylfjellet. (C) Terrain model (modified from the Norwegian Polar Institute, https://geodata.npolar.no) of the area in the vicinity of Longyearbyen (the largest settlement in Svalbard), indicating the position of intermediate localities, onshore wells DH-4, DH-5 and DH-6, and log traces. White, semi-transparent areas are glaciers. (D) Lithostratigraphic chart of the Middle Jurassic (MJ) – Lower Cretaceous succession oriented parallel to the depositional dip (WNW–ESE) of the study area, as indicated in (B), and extended towards the S. The Rurikfjellet Formation is deliberately highlighted with darker colours. The chart is compiled from Parker (1967), Nagy (1970), Steel & Worsley (1984), Dypvik *et al.* (1991a), Gjelberg & Steel (1995), Koevoets *et al.* (2018), Śliwińska *et al.* (in press) and data from this study, and modified from Grundvåg *et al.* (2019). Mb, Formally defined member; mb, Informally defined member; R–T trends, Regressive–transgressive trends.

Fig. 2. Representative logs of the tempestite-bearing upper part of the Rurikfjellet Formation from the proximal outcrop locality Bohemanflya (A) and the intermediate core DH-4 (B), including bioturbation curves. A representative log from the distal localities is shown in Fig. 8. The Rurikfjellet Formation consists of prodelta to distal delta front facies belts, which hydrodynamically correspond to the offshore and offshore transition to lower shoreface zones. Detailed inset logs of sandstone-rich intervals in the Kikutodden Member with corresponding facies distribution plots elucidate intra-bed changes in depositional processes. Owing to weathering, the bioturbation intensity (Bi) of the Bohemanflya succession includes the levels of absent (a), sparse (s), moderate (m) and intense (i), whereas the clean surface of core DH-4 allowed utilisation of a seven-fold Bioturbation Index (BI). Boxed numbers indicate figures with photos of the corresponding beds. The accompanying legend is also applicable to Figs 4–6, 8–13, 15 and 17. HCS, Hummocky cross-stratification; QPL, Quasi-planar lamination; SCS, Swaley cross-stratification; SSDS, Soft-sediment deformation structures.

Fig. 3. Rose diagrams of all palaeocurrent measurements ($N = 128$) from sandstone lenses in shale ($N = 14$) and sandstone tempestites ($N = 114$) in 5° increments. Encircled numbers indicate the number of measurements. The strike of wave and combined-flow ripple crests collectively indicates a SSW–NNE-oriented palaeoshoreline. The bidirectional and unidirectional current proxies collectively indicate a mean sediment transport towards the ESE. Measurements of ripple cross-lamination in HCS, i.e. combined-flow, current and climbing current ripple cross-lamination, and anisotropic micro-HCS (*sensu lato* Dott & Bourgeois, 1982), can be used to refine depositional process interpretations for each tempestite type. Notice the scattered measurements and apparent lack of preferential sediment transport direction of Type 2 tempestites compared to the other tempestite types. The three rose diagrams of the unidirectional current proxies divided into

tempestite types, and the two cumulative rose diagrams, serve as additional graphic data representations, but should not be accounted for in the total number ($N = 114$) of tempestite palaeocurrent measurements.

Fig. 4. Conceptual line drawings of simple (F8) and complex (F9) HCS defined in this study. (A) Simple HCS is characterised by little or no variation in stratification, displaying successive 3rd-order hummocky lamina sets separated by internal 2nd-order truncation surfaces (*sensu stricto* Dott & Bourgeois, 1982). (B) Complex HCS is characterised by vertical or lateral variations in stratification within lamina sets, predominantly displaying various ripple cross-lamination or local shifts to quasi-planar lamination (QPL), and is commonly associated with soft-sediment deformation structures (SSDS).

Fig. 5. Representative line drawings of Type 1 tempestites divided into their predominance in the proximal (A–C), intermediate (C–G) and distal (H) localities. The line drawings are accompanied by references to representative figures; description of general characteristics, variations, and abundance and thickness trends; and a general process interpretation. In the line drawings, encircled numbers represent facies numbers (Table 2), scale bars represent estimated general averages, and biogenic sedimentary structures are generally omitted. HCS, Hummocky cross-stratification; SCS, Swaley cross-stratification; SSDS, Soft-sediment deformation structures.

Fig. 6. Representative sedimentological log and photos (from Bohemanflya) of proximal Type 1 tempestites. The stratigraphic positions of the photographed beds are given in Fig. 2A. (A) The Sylfjellet section contains abundant distinctly planar-laminated (PL) and quasi-planar-laminated (QPL) sandstone beds (F7), and an example of combined HCS–SCS (F8). (B) Thick-bedded

anisotropic simple HCS (F8). Knife (20.5 cm) for scale. (C) Medium- to thick-bedded sandstone exhibiting pronounced pinch-and-swell architecture of isotropic simple HCS (F8) and lateral tapering. Rifle (1.1 m) for scale. (D) Thick-bedded sandstone of erosionally welded simple HCS (F8). Knife (20.5 cm) resting on 1st-order truncation. (E) Oblique bedding-plane view of successive 2D, near-trochoidal wave ripples (F10). Pocket knife (8.5 cm) for scale.

Fig. 7. Representative photos of intermediate Type 1 tempestites. (A) Rare example of large gutter cast at the base of medium- to thick-bedded simple HCS (F8), Forkastningsfjellet. (B) Thick-bedded amalgamation of simple HCS sandstone (F8) and relict shale lenses, Konusen. (C) Rare example of vertical bedform aggradation without internal 2nd-order truncations in medium-bedded, isotropic simple HCS (F8), Revneset. Notice the subtle, low-angle downlap of laminae and the overlying homogeneous mudstone (interpreted to represent a fluid-mud deposit; F4) with a wave-scoured erosional base and lateral thickness variations. (D) Sharp-based, medium- to thick-bedded sandstone exhibiting combined HCS–SCS (F8), Revneset. Knife (20.5 cm) for scale. (E) Exceptional example of a vertical waning-storm facies arrangement, Revneset, which includes an erosional 1st-order base (lower dashed line), a lower simple HCS division (F8), and a conformably overlying upper division of climbing 3D wave ripple cross-lamination (CLWR; F10). Shale (F3) related to final-stage storm wane or subsequent fair-weather conditions is erosionally truncated by the base of an overlying tempestite (upper dashed line). (F) Thin-bedded wave ripple cross-lamination (F10) to micro-HCS, exhibiting a combination of bundled, bidirectional and pinch-and-swell lamination, Hanaskogdalen. Pocket knife (8.5 cm) for scale. (G) Thin- to medium-bedded micro-HCS (F8; *sensu lato* Dott & Bourgeois, 1982), Konusen, exhibiting small-scale sinusoidal lamina growth and low-angle 2nd-order truncations, with *Nereites missouriensis* (*N*) and *Skolithos* (*S*).

Fig. 8. Representative sedimentological log and photo of distal Type 1 tempestites at Baronfjella. (A) The stratigraphy of the distal sections is shale-dominated and sandstone beds are relatively sparse and consist entirely of Type 1 tempestites. (B) The uppermost part of the succession is characterised by a complex intercalation of fair-weather shale deposits (F1, 2) and very thin- to thin-bedded, pinch-and-swell siltstone and sandstone lenses (F10; white arrows), which thicken and coarsen into simple HCS sandstone beds (F8). Upper part of rifle (1.1 m in full length) for scale.

Fig. 9. Representative line drawings of Type 2 tempestites divided into their predominance in the proximal (A) and intermediate (B–D) localities. The line drawings are accompanied by references to representative figures; description of general characteristics, variations, and abundance and thickness trends; and a general process interpretation. In the line drawings, encircled numbers represent facies numbers (Table 2), scale bars represent estimated general averages, and biogenic sedimentary structures are omitted. HCS, Hummocky cross-stratification; SSDS, Soft-sediment deformation structures.

Fig. 10. Representative photos and line drawing of proximal Type 2 tempestites at Bohemanflya. The stratigraphic positions of the beds are given in Fig. 2A. (A) Intricate configuration of thick-bedded complex HCS (F9) characterised by pronounced soft-sediment deformation structures (SSDS) and an internal climbing current ripple train (accompanying photo and line drawing) above a depositional swale. The bed is erosionally welded with underlying simple HCS (F8) of a Type 1 tempestite. Knife (20.5 cm) for scale. (B) Complex HCS (F9) displaying thick-bedded amalgamation. The HCS is characterised by SSDS, a rare example of a carbonaceous lamina set, and relict lenses of truncated shale. (C) When traced laterally, the bed in (B) locally displays

"compound"-type HCS (F9) in which significant parts of the stratification are constituted by wave (WR) and climbing current (CLCR) ripple cross-lamination parallel with the bulk hummocky lamination (HL). Pocket knife (8.5 cm) for scale.

Fig. 11. Representative line drawing and photos of intermediate Type 2 tempestites. (A) Line drawing of architectural transition between thick-bedded simple (F8) and complex (F9) HCS, Revneset. The complex HCS displays a lateral shift to quasi-planar lamination. (B) Very thick-bedded complex HCS (F9) displaying soft-sediment deformation structures (SSDS), including down-crest lamina distortion, a carbonaceous lamina set, and alternation between hummocky lamination (HL), combined-flow (CFR) and wave (WR) ripple cross-lamination, indicative of oscillatory- and combined-flow fluctuations, Wimanfjellet. The combined-flow ripple cross-lamination displays opposing foreset dip directions (white arrows). (C) Complex HCS (F9) displaying alternation between hummocky lamination (HL) and wave ripple cross-lamination (WR), indicative of oscillatory-flow pulsation, core DH-4 (stratigraphic position in Fig. 2B). The bed is overlain by homogeneous mudstone (HM), with mantle-and-swirl burrows (Navichnia; Na), interpreted to represent a wave-generated fluid-mud deposit (F4). (D) Convoluted lamination in complex HCS (F9), core DH-4 (stratigraphic position in Fig. 2B). (E) Example of double draping (white arrows) in complex HCS (F9), core DH-6.

Fig. 12. Representative line drawings of Type 3 tempestites divided into their predominance in the proximal (A–C) and intermediate (C–F) localities. The line drawings are accompanied by references to representative figures; description of general characteristics, variations, and abundance and thickness trends; and a general process interpretation. In the line drawings, encircled numbers represent facies numbers (Table 2), scale bars represent estimated general averages, and biogenic

sedimentary structures are omitted. Notice the wax–wane configuration of complex HCS (F9) in (B) and (C). HCS, Hummocky cross-stratification.

Fig. 13. Representative photos and line drawings of proximal Type 3 tempestites at Bohemanflya. The stratigraphic positions of the beds are given in Fig. 2A. (A) Overview photo and accompanying delineation of a thick-bedded, hyperpycnal sandstone channel element, characterised by compensational cut-and-fill architecture and lateral accretion of complex HCS (F9) with scattered gravel lenses. (B) Thick-bedded wax–wane configuration of complex HCS (F9) displaying basal conglomeratic trough cross-stratification (TC), coarse-grained and gravel-rich HCS (cHCS), and fine-grained HCS (fHCS), which is capped by sharp-crested wave ripples, close to the base of the Helvetiafjellet Formation. Encircled pocket knife (8.5 cm) for scale. (C) Wax–wane configuration of a sharp-based, medium-bedded, gravel-rich quasi-planar-laminated sandstone bed (F7) with abundant coal clasts, organic debris and a sharp-crested combined-flow ripple at the bed top. Pocket knife (8.5 cm) for scale. (D) Overview photo and detailed inset line drawing of a medium-bedded complex HCS sandstone bed (F9) displaying a laterally restricted T_{bcbcb} wax–wane configuration of alternating hummocky lamination (HL), combined-flow (CFR) and climbing combined-flow (CLCFR) ripple cross-lamination. Pocket knife (8.5 cm), resting at bed top, for scale.

Fig. 14. Representative photos of intermediate Type 3 tempestites. (A) Overview and detailed inset photos of medium-bedded complex HCS (F9) exhibiting a laterally restricted T_{bcbc} wax–wane configuration of alternating hummocky lamination (HL) and climbing current ripple cross-lamination (CLCR), Janssonhaugen. (B) Medium-bedded sandstone displaying a Bouma-like T_{bacb} wax–wane facies arrangement consisting of planar lamination (PL; F7), massive sandstone (M; F6), anisotropic micro-HCS (mHCS; F8) and bioturbated, relict HCS (rHCS; F8), Konusen. Pencil for

scale. (C) Thick-bedded sandstone displaying a Bouma-like T_{abc} facies arrangement consisting of massive sandstone (M; F6), planar lamination (PL; F7) and combined-flow ripples (CFR; F11), Mälardalen. Pocket knife (8.5 cm), resting at bed top, for scale. (D) Rare core (DH-5) example of simple HCS (F8) grading into and interlaminated with homogeneous mudstone (HM; F4) interpreted to represent a fluid-mud deposit. This resembles the $T_{0–8}$ turbidite sequence of Stow & Shanmugam (1980), including convoluted (T_1), irregular (T_2), regular (T_3) and indistinct (T_4) lamination grading into muddier deposits ($T_{5–8}$), which suggests coupling of storm-related oscillatory and hyperpycnal flows during deposition. Notice the mantle-and-swirl burrows (Navichnia; Na) in the homogeneous mudstone. (E) Core (DH-4; stratigraphic position in Fig. 2B) example of various very thin- to thin-bedded turbidites conforming to the divisions of Bouma (1962), Piper (1978) and Stow & Shanmugam (1980), demarcated to the right of the photo. The succession includes simple HCS (F8) and homogeneous mudstone (HM; F4) interpreted to represent a wave-generated fluid-mud deposit; fine-grained, graded turbidites (FGT; F5), with basal wave ripple cross-lamination (WR) in the lower bed; and a very thin-bedded hyperpycnite (TBH), which comprises combined-flow ripple cross-laminated sandstone (CFR; F11) and homogeneous mudstone (HM; F4), with Navichnia (Na) and post-depositional *Chondrites* (*C*), interpreted to represent a fluid-mud deposit.

Fig. 15. Representative sedimentological logs of intermediate sections in Hanaskogdalen (A) and Mälardalen (B) with abundant Type 3 tempestites. Stratification and interpreted waxing and waning of hyperpycnal turbidity currents are indicated for each bed. The beds include fine-grained, graded $T_{e1–3}$ turbidites of Piper (1978); Bouma-like facies arrangements generated by wave-modified surge-type turbidity currents; and wax–wane hyperpycnites, thin-bedded hyperpycnites and fluid-

mud deposits. Notice the abundance of wave-generated fluid-mud deposits (blue arrows) within the successions.

Fig. 16. Facies model of the Rurikfjellet Formation tempestites indicating the proximal–distal distribution of tempestite types, depositional environments, sediment supply, bed thickness and grain size, tempestite preservation potential, and storm-depositional processes inferred for the investigated outcrop belt of c. 130 km length. Deposition took place from near storm-wave base to immediately above fair-weather wave base across a prodeltaic, low-gradient ramp. Sand and proximal gravel were fed from a combination of nearshore wave reworking, downwelling flows related to coastal setup (resulting in shore-normal gutter casts and parting lineation), and hyperpycnal discharge from distributary channels. Deposition was predominantly controlled by relatively steady storm-wave trains, resulting in wide-spread sand sheets of Type 1 tempestites (predominant seabed colour in the model). Due to the low gradient of the ramp, wave-enhanced hyperpycnal turbidity currents were generally not able to transport sediment further than the intermediate areas, except for some mud-dominated flows. Fluid muds were frequently deposited from various hyperpycnal flows, hypopycnal plumes, or resuspension by storm waves. Drafting is partly inspired by Reynolds (1992) and Plint (2014).

Fig. 17. Conceptual model for the sequential generation (from bottom to top) of various complex HCS within Type 2 and 3 tempestites. The stratification is probably commonly controlled by highly unsteady waves, related to (A) passing wave groups of lower flow regime resulting in wave (WR), combined-flow (CFR) or climbing current (CLCR) ripple cross-lamination; (B) multidirectional wave groups and combined-flows with time-varying orientations resulting in combined-flow (CFR) and climbing current (CLCR) ripple cross-lamination with opposing foreset dip directions; (C) tidal

water-level variations where elevation of the water level and effective storm-wave base (SWB) results in suspension fallout of organic debris and, consequently, deposition of carbonaceous laminae; and (D) cyclic wave stress where the consecutive pressure difference between wave crests and troughs (Δp) results in liquefaction and associated gravitational adjustment and soft-sediment deformation (SSD) of the sand with corresponding generation of soft-sediment deformation structures (SSDS).

Fig. 18. Polygenetic model for various possible simple and complex configurations of hummocky cross-stratification (HCS) controlled by the relative influence of relatively steady and highly unsteady storm-wave oscillations, sustained hyperpycnal flows (including waxing–waning flows), and downwelling flows (which may be geostrophically veered due to Coriolis deflection) related to coastal setup. The spectrum of these processes represents a modified and extended version of the ternary diagram presented by Myrow & Southard (1996), which allows prediction of six formative flow fields and corresponding configurations of HCS and swaley cross-stratification (SCS) in tempestites corresponding to the relatively steady (Type 1 tempestites) and highly unsteady (Type 2 tempestites) flow deposits and wave-modified hyperpycnites (Type 3 tempestites) documented in this study. Conceptual flow curves illustrate the generation of the vertical configurations as a function of the velocity (U) of the oscillatory (U_o) and unidirectional (U_u) flows through time (t). Configuration (1) illustrates a representative arrangement of facies within an entire tempestite sandstone bed from its base to top. In comparison, configurations (2)–(6) illustrate 3D cross-sections through HCS only (i.e. not necessarily from tempestite bed base to top), in particular to emphasise the sporadic distribution of internal ripples. Notice the importance of various internal ripples and soft-sediment deformation structures (SSDS) in configurations (3), (4) and (6), and the local quasi-planar lamination (QPL) in configurations (4) and (6).