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Research paper

Depositional processes and stratigraphic architecture within a coarse-grained rift-margin turbidite system: The Wollaston Forland Group, east Greenland

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A B S T R A C T

The Wollaston Forland Basin, NE Greenland, is a half-graben with a Middle Jurassic to Lower Cretaceous basin-fill. In this outcrop study we investigate the facies, architectural elements, depositional environments and sediment delivery systems of the deep marine syn-rift succession. Coarse-grained sand and gravel, as well as large boulders, were emplaced by rock-falls, debris flows and turbulent flows sourced from the immediate footwall. The bulk of these sediments were point-sourced and accumulated in a system of coalescing fans that formed a clastic wedge along the boundary fault system. In addition, this clastic wedge was supplied by a sand-rich turbidite system that is interpreted to have entered the basin axially, possibly via a prominent relay ramp within the main fault system. The proximal part of the clastic wedge consists of a steeply dipping, conformable succession of thick-bedded deposits from gravity flows that transformed down-slope from laminar to turbulent flow behaviour. Pervasive scour-and-fill features are observed at the base of the depositional slope of the clastic wedge, c. 5 km into the basin. These scour-fills are interpreted to have formed from high-density turbulent flows that were forced to decelerate and likely became subject to a hydraulic jump, forming plunge pools at the base of slope. The distal part of the wedge represents a basin plain environment and is characterised by a series of crude fining upward successions that are interpreted to reflect changes in the rate of accommodation generation and sediment supply, following from periodic increases in fault activity. This study demonstrates how rift basin physiography directly influences the behaviour of gravity flows. Conceptual models for the stratigraphic response to periodic fault activity, and the transformation and deposition of coarse-grained gravity flows in a deep water basin with strong contrasts in slope gradients, are presented and discussed.

1. Introduction

Subaqueous gravity flows (Middleton and Hampton, 1973), or density flows (Mulder and Alexander, 2001), such as debris flows and turbulent flows form key transport mechanisms for sediment supplied to submerged basins. Gravity flows are traditionally classified according to support mechanism during flow, distinguishing between matrix strength, dispersive pressure, hindered settling, buoyancy and fluid turbulence (e.g. Lowe, 1982). Support mechanism may change during flow, from plastic behaviour in dense, laminar flows to Newtonian behaviour in diluted turbulent flows, and back (Fisher, 1983). Turbulent flows may change flow regime between super- and sub-critical flows (e.g. Postma and Cartigny, 2014; Covault et al., 2014). Concentrations of mud or mudstone clasts may develop within turbulent flows, commonly as

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a consequence of scouring of a mud-prone substrate. This process is associated with turbulence damping and may ultimately result in the transformation of parts of the flow into a cohesive flow and the deposition of a 'linked debrite' (Lowe and Guy, 2000; Haughton et al., 2003, 2009; Hodgson, 2009; Patacci et al., 2014). It has been demonstrated from mapping individual deposits how flow type and regime in single events can vary in time and space (Talling et al., 2007; Postma et al., 2009; Breien et al., 2010; Sumner et al., 2012; Marini et al., 2015). Talling et al. (2012) pointed out that the classification according to support mechanism is problematic, as it is difficult to determine the dominant support type of both modern and ancient deposits, and proposed a classification scheme based on depositional aspects such as lithology, grading and lamination rather than flow characteristics. Recent advances in understanding of submarine gravity flows were summarised by Talling et al. (2015), along with directions on future research topics which include deposition at the hydraulic jump and turbulence damping (Cantero et al., 2012; Talling et al., 2015). Conceptual models for depositional systems in deep water rift basins predict that sediment is primarily derived from erosion of an uplifted footwall and/or from axial feeder systems (e.g. Ravnås and Steel, 1998; Gawthorpe and Leeder, 2000). Sediments are typically transported into the deepest parts of a basin by gravity flows. Subaqueous sedimentation has been studied in modern deep subaqueous rift systems such as Lake Baikal (Colman et al., 2003), the Gulf of Corinth (Lykousis et al., 2007) and the East African Rift (Lyons et al., 2011; Karp et al., 2012), as well as in ancient subsurface analogues such as the Upper Jurassic Brae-Miller trend in the Viking Graben (Turner et al., 1987) and the Lower Cretaceous of the Tamtsag Basin in Mongolia (Zhou et al., 2014). Gravity flow deposits in both modern deep water environments and in the subsurface are hidden from direct observation; therefore outcrop studies of ancient gravity flow deposits play a key role in understanding flow processes and sediment transport in deep marine and lacustrine rift environments. The Upper Jurassic–Lower Cretaceous Wollaston Forland Group exposed in East Greenland provides an excellent record of a deep marine rift system that comprises a wide range of gravity flow deposits in proximal to distal settings (Surlyk, 1978a, 1984).

In this paper we use field observations from the Wollaston Forland Group to investigate depositional systems in an ancient deep water rift basin. The objective of the study is to further the understanding of the behaviour of coarse-grained gravity flows released into a steep-walled, deep water basin and to constrain depositional architecture and facies variability of such flows on outcrop scale. The large variety of facies is discussed in terms of depositional processes and basin development: was deposition mainly from high-density turbulent flows or from debris flows? Is there evidence of flow transformations and hydraulic jumps? Because the basin is characterised by a steep, high-relief fault scarp and a hanging wall dip-slope with a significantly lower angle, it is expected that the basin physiography had a direct impact on flow behaviour through for instance confining and deflecting individual flows. The various deposits are linked to depositional environments, and the spatial relationships between these environments are analysed in order to determine whether the basin was mainly fed from the footwall, or from an axial system, or if there is evidence of interaction between different feeder systems. Finally, the investigated system is compared with modern Lake Baikal in Siberia, Russia which has some similar characteristics (Colman et al., 2003). This deep lacustrine rift basin shows some fundamental similarities with the Wollaston Forland Group in East Greenland in terms of basin physiography that may shed new light on the investigated deep marine rift system.

2. Geological setting

The East Greenland passive continental margin forms part of the northern North Atlantic rift system that developed between Norway and Greenland over a protracted period of episodic crustal thinning in Late Palaeozoic–Cenozoic times (Doré et al., 1999). Rift episodes occurred in Devonian–Carboniferous and Permian–-Triassic times (Ziegler, 1988; Hartz et al., 2002). Another major rift episode took place between Middle Jurassic (Bajocian) and Early Cretaceous (Valanginian) times (Coward et al., 2003). In East Greenland, the Jurassic–Cretaceous rift event was most pronounced north of Kong Oscar Fjord (e.g. Surlyk and Noe-Nygaard, 2001; Surlyk, 2003), resulting in the formation of a series of strongly tilted fault blocks (Vischer, 1943; Maync, 1947, 1949; Surlyk, 1978a, 1990).

During Jurassic–Cretaceous rifting, a north to south trending border fault system developed that extends for several hundred kilometres along the coast of East Greenland (Fig. 1; Surlyk and Noe-Nygaard, 2001; Surlyk, 2003). This right-stepping normal fault system separates the Laurentian Shield, containing the remnants of the Caledonian Orogen, as well as the abandoned Carboniferous–Triassic grabens in the west, from the Jurassic–Cretaceous rift basins in the east (Vischer, 1943; Surlyk, 1990; Stemmerik et al., 1992). This fault system is represented by the east-dipping Clavering–Dombjerg–Thomsen Land fault zone in Wollaston Forland. This normal fault zone formed the Wollaston Forland extensional basin, a *c.* 40 km wide, 100 km long westward tilted graben that was connected to the Norwegian – Greenland Sea towards the south (Surlyk, 1978a; Surlyk and Korstgård, 2013). The footwall west of the Dombjerg- and Thomsen Land fault segments (Fig. 1) consists of Caledonian migmatite gneiss, amphibolite and pegmatite, whereas the basin itself is characterised by Middle Jurassic to Lower Cretaceous siliciclastic sediments (Maync, 1947; Surlyk, 1978a, 1984) and Palaeocene-Eocene extrusive volcanics (Noe-Nygaard, 1976). Along with the other Late Palaeozoic–Mesozoic basins along the eastern coast of East Greenland, the Wollaston Forland Basin was uplifted several kilometres during the late Cenozoic (Christiansen et al., 1992) and glaciated (Bennike et al., 2008).

The Bajocian to early Volgian early rift phase was accompanied by a regional marine transgression of the crystalline pediment in the study area (Surlyk, 2003; Surlyk and Korstgård, 2013). A deep marine depocentre formed along the Clavering–Dombjerg–Thomsen Land fault zone that was bordered to the east by the rotated crest of the Kuhn block (Fig. 1; Surlyk and Korstgård, 2013). The hanging wall dip-slope, made up of inclined, partly eroded early rift strata, was onlapped by a wedge of sedimentary breccia, conglomerate and pebbly sandstone and interbedded basinal mudstone. The sediments of this wedge represent syn-rift deposition and belong to the Wollaston Forland Group that extends from the footwall to the basin axis *c.* 15 km to the east. The group is subdivided into the Lindemans Bugt Formation and the Palnatokes Bjerg Formation (Fig. 1; Surlyk, 1978a).

3. Sedimentological analysis of the Wollaston Forland Group

The study area is located south of Lindemans Fjord in Wollaston Forland, northern East Greenland (Figs. 1 and 2). The outcrops are of variable quality and most measured sections are confined to cliff sections exposed on ridges and in river gullies. The dataset consists of extensive photographic coverage and measured sedimentological logs that were acquired during field campaigns in the summers of 1994 and 2014. Fieldwork consisted of measuring sedimentological profiles at the bed-scale as well as architectural analysis of cliff sections. These measurements include descriptions of rock