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Depositional model in subglacial cavities, Killiney Bay, Ireland. Interactions between sedimentation, deformation and glacial dynamics

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ABSTRACT

Subglacial meltwater drainage and sedimentary processes play a major role in ice-sheet dynamic but there is a lack of study of subglacial environment because modern ice-sheet beds remain inaccessible. Previous authors already intended to provide diagnostic criterion and recent investigations suggest that fluid pressure variations are a key factor in subglacial environment. This paper investigated the late Devensian sedimentary record in order to describe subglacial sedimentological facies associations and deformation features related to fluid overpressures. We used an integrated approach, based on stratigraphy, sedimentology and deformations styles to demonstrate a subglacial depositional model. The studied interval is composed of stratified gravel and sand interbedded with diamicton and boulder pavement, deposited in depressions formed by irregularity of the upper surface of diamicton. Deformation structures include convolutes, dykes and normal micro-faulting. Dykes show different dip directions from vertical, oblique to subhorizontal from which both directions of shortening and extension can be determined. Vertical dykes are formed under pure shear strain related to ice weight only. Oblique dykes imply both ice-bed coupling and simple shear strain between ice and substrate induced by flowing ice related to progressively increasing meltwater drainage intensity. Horizontal dykes are formed when minimum strain is vertical and therefore the overpressure exceeds the weight of overburden. They are associated with high meltwater drainage intensity and ice-bed uncoupling and refer to hydrofracturing. Overall, depositional and deformation sequence also illustrates the increasing intensity of meltwater drainage in small cavity as high energy channelised deposits, and in large cavities where subaqueous fan are deposited under hydraulic jump conditions. Moreover, large cavities represent lee-side cavities formed by fast-flowing ice over an obstacle. Hydrofracturing is likely to occur when a dense fluid, potentially associated with catastrophic drainage of an upstream cavity enters the low-pressure confined environment of a downstream cavity and is injected under pressure in the soft substrate. The studied glacial sequence represents a regional pattern probably related to an allocyclic control on sedimentation linked to long-term glacial dynamics rather than local depositional conditions. Based on these results, we provided a synthetic model linking depositional and deformation processes during ice-sheet growth and decay, but also valid at different timescales from annual to seasonal scale.

1. Introduction

Present-day observations of ice-sheets show that meltwater at the ice-bed interface may be of glacial, supraglacial or subglacial origin (Röthlisberger and Lang, 1987; Paterson, 1994; Fountain et al., 2005; Zwally et al., 2005). Glacier mass-balance influences subglacial meltwater discharge controlling water pressure at the ice-bed interface (Piotrowski et al., 2004, 2006; Boulton et al., 2007a; Denis et al., 2009, 2010). A negative mass-balance is due to high meltwater discharges at the ice-bed interface (IBI), leading to basal water pressure increase, basal friction reduction and an increase in ice-flow velocity. A positive mass-balance corresponds to low meltwater discharge, which draws down basal water pressure, increases basal friction and reduces ice-flow velocity. These discharge patterns vary over different timescales (Lliboutry, 1979; Kamb, 1987; Menzies, 2002; Benn and Evans, 2010). During deglaciation phases, a negative mass-balance increases meltwater discharge and glacier motion leading to ice-sheet decay (Bell, 2008; Lüthi, 2010; Schoof, 2010).

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Over soft-bedded ice-sheets, fluid pressure variations control sediment rheology, modulating substrate deformation (Boulton and Hindmarsh, 1987; Piotrowski et al., 2004). A significant proportion of glacier flow velocity can be imparted to this deformation, promoting rapid ice-flow referred to as ice-streaming, but also normal 'non-streaming' flow (Alley et al., 1987; Bennett, 2003). High fluid pressure exceeding overburden weight creates localised ice-bed uncoupling, leading to ice-flow over a thin meltwater film (Piotrowski and Tulaczyk, 1999; Munro-Stasiuk, 2000; Kamb, 2001). A fast ice-flow over an uneven bed controls subglacial cavities development behind bedrock relief (Weertman, 1964; Lliboutry, 1979; Kamb, 1987; Dardis and Hanvey, 1994; Schoof, 2005). Under present-day ice-sheets, subglacial lakes and smaller water-filled cavities represent substantial amount of meltwater which can be temporary stored or drained by intermittent interconnections (Siegert and Bamber, 2000; Siegert et al., 2005; Wingham et al., 2006; Bell et al., 2007; Fricker et al., 2007).

Subglacial meltwater drainage and sedimentary processes play a major role in ice-sheet dynamic but there is a lack of study of subglacial environment because modern ice-sheet beds remain mainly inaccessible (Menzies and Shilts, 2002; Bennett, 2003; Boulton et al., 2007a, 2007b). The study of Pleistocene ice-sheet deposits and geomorphology provides opportunities to understand subglacial environments. Yet, there is few sedimentological diagnostic criterion to discriminate subglacial from periglacial environments (Brodzikowski and van Loon, 1991; Piotrowski, 1997; Rijsdijk et al., 1999, 2010; van der Meer et al., 1999; Menzies and Shilts, 2002; Piotrowski et al., 2006). Recent investigations of deformation structures demonstrate the effect of fluid pressure variations in subglacial environment (Denis et al., 2009, 2010; Lesemann et al., 2010). However, fluid pressure deformations can be spatially restricted, weak or absent, even in a subglacial environment (Piotrowski et al., 2001, 2004; Iverson et al., 2003). The objective of this study is to define a depositional model in subglacial cavities based on an integrated approach that combines stratigraphy, detailed sedimentological characteristics and deformation styles.

This paper examines architecture, sedimentology and deformation structures of glacial sediments in Killiney Bay, Ireland, an area close to the margin of the British and Irish Ice-Sheet during late Devensian deglaciation. In this area, we have an exceptional record of subglacial large and small cavities environments. The objectives are to describe subglacial sedimentological facies associations and deformation features related to fluid overpressures. Based on these results, we aim to provide diagnostic criterion that help discriminate a subglacial depositional environment in order to link sedimentological characteristics, deformation styles and ice-sheet dynamic.

2. Geological setting

The study is based on the examination of a cliff in Killiney Bay (Fig. 1A), on the East-Central Ireland coastline, 15 km south of Dublin. This exposure corresponds to glacial sediments (Bowen, 1973; Hoare, 1977; Eyles and McCabe, 1989; Warren, 1993; Rijsdijk et al., 1999, 2010), deposited unconformably over Lower Palaeozoic sandstones (Fig. 1B). It is surrounded in the south by a NE–SW ridge (Bray Head) composed of Cambrian metamorphic rocks. Leinster granite, interpreted as a Caledonian intrusion is exposed on the eastern side of the Wicklow Mountains and Killiney Hill. Further north, Dublin lowlands expose Carboniferous Limestones (McConnell et al., 1994).

During the Last Glacial Maximum (Devensian/Midlandian), a huge ice-sheet covered the British Isles and Ireland. Its presence over the study area is attested from 26 ka to 17.3 ka BP (Bowen et al., 2002; McCabe and Clark, 2003; Ballantyne et al., 2006) reaching a maximum extent after 20 ka BP (Ó Cofaigh and Evans, 2007; Evans et al., 2009; Hubbard et al., 2009) (Fig. 2A).

In the study area, glacial paleao ice-flow pattern was characterized by the confluence of the southward-flowing Irish Sea Ice Stream (ISIS), an Irish mainland ice-flow originating in northern and central Ireland and flowing south to south-east, and the local Wicklow Ice Cap over the Wicklow Mountains.

The ISIS did not flow far inland but was constrained along the present-day coastline (Warren, 1993), reaching a maximum inland extent dated at 17.8 ka BP (McCabe and Clark, 2003), after which it rapidly retreated. During the final stages of deglaciation (Fig. 2B), divergent flows (NE–SW to NW–SE) are also reported and are related to the Wicklow Ice Cap (Warren, 1993; Smith and Knight, 2011).

According to Eyles and McCabe (1989), the glacial sequence in Killiney Bay is deposited in a tunnel-valley connected to offshore canyons and related to a subglacial drainage network. A large depression enclosed between bedrock ridges is identified a few kilometres SW of Killiney, near Enniskerry. This depression corresponds to a subglacial lake (Fig. 1A) which belongs to a more regional subglacial meltwater system, nearly 30 km in extension from north to south, parallel to regional ice-flow and composed of interconnected basins linked by bedrock channels (McCabe and Ó Cofaigh, 1994).

Successive studies of the Killiney Bay glacigenic succession have led to hypotheses ranging from marine or glacimarine to terrestrial interpretations, or a combination of all these environments (Rijsdijk et al., 2010, and references therein). Eyles and McCabe (1989) were the first to use a glacigenic lithofacies description to justify a glacimarine environment. Isostatic rebound estimation of relative sea level at +120 m above the present-day level would have allowed glacimarine conditions to develop immediately after the ice-sheet retreated. Sedimentary units were therefore interpreted as part of an ice-proximal glaciomarine system. Recently, Rijsdijk et al. (2010) re-interpreted the glacigenic sequence with a complete glaciotectonic approach based on deformation intensity and style, and macro/microfabric analyses. Their study offers an overview of the complete Killiney Bay section, including every sedimentary units, but mainly focus on deformation structures and the origin of diamictons. Diamictons were interpreted as subglacial tills and proglacial flow tills. Stratified sand and gravel units were interpreted as glaciofluvial deposits and gravel fans in proglacial ponds or lakes, in contact with the glacier margin during a phase of glacier retreat. A later ice-front readvance led the glacier to override previously deposited sediments, overprinting glaciotectonic deformations, and to overconsolidate diamictons (Rijsdijk et al., 1999, 2010).

Shell fragments identified in the sequence (Sollas and Praeger, 1894, in Rijsdijk et al., 2010), belong to 68 taxa dated from the Quaternary and pre-Quaternary, encompassing cold and warm conditions and estuarine to deep water environments. According to Rijsdijk et al. (2010), this fauna is associated with reworked sediments and therefore cannot support the glacimarine interpretation.

3. Stratigraphy and geometry

The cliff ranges from 8 to 12 m in height but some sections have slumped and are inaccessible for analysis. Only 1.3 km out of the complete section was studied carefully by lateral mapping based on panoramic photographs to sketch major sedimentary units and bounding surfaces (Fig. 3A). In this paper, the interval studied is divided into four smaller sections: Shanganagh Park North (SPN) and South (SPS), Corbawn Lane North (CLN) and South (CLS).

The section (Fig. 3B) includes four diamictons (units numbered 2, 4, 5 and 6) and 2 units of gravel and sand (units numbered 1 and 3).

- Unit 1 is mainly located below beach level, is very poorly exposed, and reaches an apparent maximum of 1 m thickness. It is composed of gravels and is erosively overlain by Unit 2.