ASSESSING THE GENESIS OF PERIGLACIAL RAMPARTED DEPRESSIONS THROUGH A MACROSCOPIC AND MICROSCOPIC ANALYSIS OF THEIR INTERNAL STRUCTURES

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ABSTRACT

Perennial frost mounds developed across northern Europe following retreat of the late Quaternary ice sheets (c. 23–19). Their relict forms comprise depressions with surrounding ramparts (periglacial ramparted depressions - PRDs). Although PRD surface geometry is well-documented, their origin is less well-understood. There is little agreement on: i) definitive identification of PRDs, ii) PRD formation processes, and iii) the relationship between different frost-mound types (i.e. pingo, palsa and lithalsa).

For the first time, this research characterises the internal structure of a relict lithalsa in the Ardennes (Belgium-German border), at macro- (e.g. coring, logging) and micro-scales (thin sections) and contextualises this with observations on the hydrological, lithological and topographic setting. Micromorphology enables the study of sedimentary environments and processes of formation. This investigation identifies diagnostic suites of microstructures indicative of frost action, landform development and environmental setting. The results are then applied to suspected PRDs in Norfolk (Walton Common) and Wales (the Cledlyn Valley), for which a likely frost-mound origin is confirmed. This approach: i) identifies the internal structure of PRDs, ii) considers the potential for change in deformation with depth and lateral extent within the rampart, and iii) considers the differences and similarities in micro-textures and structures in a variety of grain sizes across the sites where PRDs occur.

Key microstructures identified, indicative of cryogenic origins, include: i) a vertical to sub-vertical microfabric (e.g. frost-jacked grains), ii) platy-prismatic, sub-angular aggregates, iii) planar deformation (e.g. fragmented domains, frost-cracked grains), and iv) evidence of pore-water movement on thawing of ice and associated grain translocation (e.g. silt and clay cappings). Microstructures attributed to PRD development include: i) a sub-vertical microfabric of similarly inclined elongate grains, associated with tilted strata, ii) microstructures linked to mass-wasting during frost-mound growth or rampart formation (e.g. grain concentrations, grain coatings of silt and clay, curvilinear grain arrangements, skelsepic plasmic fabric), iii) planar structures (e.g. grain lineations, linear concentrations of grains and fragmented domains and fractured grains, that may reflect shear strain during rampart-formation processes), and vi) multiple domains, interpreted as re-homogenisation of sediment caused by frost-mound heave, and subsequent rampart-formation processes.

Consequently, this research identifies and characterises PRDs, which:
i. provides a better understanding of the genesis of PRDs, for the classification of different types of ice-cored hills,

ii. informs palaeoenvironmental reconstruction, since ice-cored hills are diagnostic of former permafrost (frozen ground conditions),

iii. informs civil engineering projects where sediments are disturbed by PRD development (e.g. heave and subsidence).
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In memory of,

Mary Swannell, née Phelan,

a most beloved mother
(1938-2004)
I declare that the research contained in this thesis, unless otherwise formally indicated within the text, is the original work of the author. The thesis has not been previously submitted to this or any other university for a degree, and does not incorporate any material already submitted for a degree.

Signed..................................................

Samantha S. Bromfield

Dated..............................................
Chapter 1: Introduction

1.1 Introduction

1.1.1 Original contribution to knowledge

This research, for the first time, characterises the internal structures of periglacial ramparted depressions (PRDs) at the macro- and micro-scales. It provides detailed information on deformation structures related to the formation (Fig. 1.1A) and decay (Fig. 1.1B) of frost mounds (e.g. lithalsas) in different environmental settings and so contributes to a better understanding of genetic processes. By characterising the internal structures of a known relict lithalsa (in Belgium), the research provides a toolkit for the investigation of suspected relict frost mounds (in Norfolk and Wales, UK) as well as other frost-mound types in future research.

![Fig. 1.1A) Perennial frost mound (hydrostatic pingo) in Yakutia, Sakha Republic (~ 10 m in height); B) PRD ‘23’ in the Tuktoyakyuk Peninsula Area, western Arctic coast, Canada (Mackay, 1998).](image)

Accurate identification of PRDs contributes to a better understanding of formation and decay processes for frost mounds (Gurney, 2000). The presence of PRDs contributes to palaeoenvironmental reconstruction (e.g. in terms of the presence of past permafrost conditions (Ballantyne and Harris, 1994; Gurney, 2000)). PRD identification informs understanding of extra-terrestrial planetary processes as they represent terrestrial analogues (e.g. identification of frost-mound-like structures on Mars would provide data on past extra-terrestrial climatic and hydrological regimes and sedimentary processes (Burr et al., 2009; Soare et al., 2014)). The research is also significant for civil engineering projects, PRDs that are now buried in urban environments could represent an engineering hazard. Currently in the UK, a number of deep (~15–25 m), asymmetric, funnel-shaped hollows discovered during engineering works in the London region, are increasingly being linked to a periglacial, possibly frost-mound, genesis (Banks et al., 2015). Therefore, being able to accurately identify PRDs is useful, not just for understanding formation mechanisms or for
Palaeoenvironmental reconstruction but for practical application (e.g. better hazard planning during civil engineering works).

1.1.2 Periglacial environments and landforms

Periglacial landscapes are challenging to characterise as they often represent a dynamic, paraglacial environment (i.e. transforming from and to glacial and/or temperate environments) (Martini et al., 2011). Today, landscapes described as periglacial are recognised by intense frost action and, often, the presence of permafrost (Washburn, 1979). Globally, > 20% of the present land area is underlain by permafrost, which is predominantly found in Russia, Canada, Alaska and China (French, 2007).

Many present-day, temperate regions world-wide contain palaeo-periglacial landscapes (Chapter 2, section 2.3, Table 2.3). These settings may never have been glaciated, only experiencing periglacial conditions (e.g. southern England), or may have been subject to a single glacial event (e.g. parts of eastern England) or multiple glaciations (e.g. Wales). Given the complexity of characterising a typical periglacial environment, identification of an unequivocal permafrost-derived structure is important for palaeoenvironmental reconstruction because permafrost cannot exist above 0 °C (Washburn, 1980). PRDs are one example of a permafrost-derived periglacial landform that can be used as a palaeoclimatic proxy. These arcuate sediment ridges surrounding a depression (see Chapter 2, section 2.1.2), are collapsed perennial frost mounds and are highly diagnostic of permafrost and so relict periglacial environments (Washburn, 1980; Mackay, 1988).

The identification of relict ground-ice structures is challenging thousands of years later, particularly when they have been: i) subject to paraglacial modification, ii) buried beneath urban landscapes, and/or iii) are located in rural settings subject to human modification (e.g. ploughing). Terminology and classification of perennial frost mounds is often confused (Harry, 1988), and identification in the field between different types (e.g. pingos, palsas, lithalsas) is not always straightforward as the formation processes are not completely understood in each case (Chapter 2, section 2.2.1, v) (Washburn, 1979; Harry and French, 1988). In addition, only the pattern of deformation of certain frost-mound types (e.g. hydrostatic pingos) is well-recorded at the macro-scale (Chapter 2, section 2.2, viii). The absence of a comprehensive conceptual model for the life cycle of each frost-mound type also complicates consideration of potential relationships between the frost-mound types. Consequently, unequivocal identification of perennial frost mounds retrospectively remains a challenge but it is generally accepted that ramparts encircling depressions were once
perennial frost mounds (Chapter 2, section 2.2.3) (Watson, 1971; Washburn, 1979; Mackay, 1988; Pissart, 2003).

1.2 Thesis approach

1.2.1 Methodological approach

The approach adopted in this thesis examines the internal structure of ramparts associated with PRDs, to determine diagnostic suites of microstructures indicative of deformation in different grain sizes and palaeo-periglacial settings, contextualised by macroscopic data. Micromorphology is the microscopic study of unconsolidated sediments using a petrological microscope. It enables the in situ analysis of component parts of a sediment sample (thin section) at the micro-scale (e.g. the arrangement of particles - plasma/matrix (< 25–30 µm in size) and grains/clasts (> 35 µm in size)), their relationship to each other and deformation patterns (van der Meer and Menzies, 2011). Micromorphology is an established technique, developed from soil microscopy (Brewer, 1964; Brewer, 1976; Stoops et al., 2010), that provides data on sediment ‘architecture’, kinematics (i.e. particle motion), deformation conditions, and depositional and post-depositional processes not necessarily apparent at the macro-scale (van der Meer and Menzies, 2011). Micromorphology is key to understanding processes of sedimentary deposition and deformation, and has been successfully used in a range of sedimentary environments (e.g. debris flows (Bertran, 1993; Bertran and Texier, 1999; Lachniet et al., 2001; Menzies and Zaniewski, 2003; Phillips, 2006), lake sediment accumulation (Palmer et al., 2008a), iceberg scours (Linch et al., 2012; Linch and van der Meer, 2014; Linch and Dowdeswell, 2016), and subglacial deformation (Menzies and Maltman, 1992; van der Meer, 1997; Menzies et al., 1997; van der Meer et al., 2003)). In particular, micromorphology has been critical for characterising grain microfabrics and other micro-features (e.g. plasmic fabric, turbate structures) in periglacial sediments and periglacial mass-movement deposits (Harris and Ellis, 1980; Harris, 1985; Bertran, 1993; Bertran and Texier, 1999; Todisco and Bhiry, 2008; van Vliet-Lanoë, 2010).

This thesis examines the micromorphological structure of one known PRD (i.e. a relict lithalsa) and two suspected PRDs, contextualised by macroscopic structures, in different depositional environments (and therefore different grain sizes) and different palaeo-periglacial settings. A definitive set of diagnostic criteria for identifying a relict lithalsa from an unglaciated area, in clayey-silty sediment (Belgium), is presented. These criteria are then applied to two suspected PRDs: i) in a sandy-chalk sediment, from a site not glaciated since the Anglian Stage (c. 480–428 ka) (Norfolk), and ii) in clayey-silt and glacial till, from a site
subject to glacial re-advances (Wales). The potential for distinguishing specific frost-mound types is discussed based on differences in the suite of microstructures identified and the macroscopic geomorphological context.

Previous process-based investigations of PRDs have considered geophysical surveys (e.g. electrical resistivity tomography (ERT), ground penetrating radar (GPR), seismic refraction) alongside data from geomorphological and sedimentological investigations (Harris, 2001; Ross et al., 2007b; Gurney et al., 2010; Ross et al., 2011; Clay, 2015). Results from such investigations suggest that greater discernment of suspected PRDs is possible by integrating near-surface data with sedimentological analysis (e.g. coring), as well as knowledge of the hydrological regime and topographic setting. However, the precise origins of PRDs have not been resolved. This project, employs the technique of micromorphy, contextualised by macroscopic data (e.g. geomorphological, lithology, topographic position, landform density), to understand the genesis of suspected PRDs.

1.3 Aim, objectives and research questions

The overarching aim of this research is to identify the cryogenic origins and formation and/or decay processes of PRDs in different environmental settings by macroscopic and microscopic characterisation of their internal structures.

The research objectives of this project are to:

1. undertake systematic macroscopic analysis based on observations and measurements made in the field (e.g. coring and logging), to characterise PRDs on the basis of their topographic, hydrological and sedimentological setting;

2. identify microstructures from thin sections (e.g. grain coatings and fabrics), in order to characterise the micro-scale texture and structure of PRDs;

3. test whether cryogenic origins can be established and formation processes interpreted using macro- and micro-scale observations;

4. establish similarities and differences in internal structures of PRDs that occur in different environmental settings (e.g. grain size);

5. consider the potential for relationships between specific PRDs (e.g. pingo, lithalsa).
Consequently, the following research questions are posed for this investigation:

1. “Is it possible to identify the cryogenic origins of PRDs by characterising internal microstructural features and relating these to macroscale observations?“

2. “Is it possible to associate internal microstructural features with frost-mound formation and/or decay processes?“

3. “What are the differences and similarities in different environmental settings between macro-scale features and microstructures in PRDs (e.g. grain size), and what does that tell us about formation processes?“

4. “By focussing on cryogenic origins and formation processes, is it possible to identify characteristics of specific PRDs (e.g. pingo, lithalsa), and establish the potential for relationships between them?”

1.4 Thesis structure
This thesis is organised into six chapters:

- Chapter 2: reviews the geomorphology of different frost-mound types in their active and decayed forms. The chapter summarises the life cycle of a perennial frost mound and discusses the associated topographic, sedimentological and cryogenic signatures at macro- and micro-scales. A summary of previous techniques used in PRD research and their limitations is outlined.

- Chapter 3: presents the methods used in this research, including key characteristics influencing site selection and the sampling strategy. Different combinations of techniques were used at different locations, dependent on the sediment type, but the consideration of macro-scale and micro-scale details is consistent across all three sites.

- Chapter 4: introduces the field site of a known PRD (i.e. relict lithalsa), in Konnerzvenn, Belgium. The context of the field site in relation to the depositional and palaeo-periglacial environment is clarified and a summary of previous research is outlined. Macroscopic and microscopic structures are described, analysed and interpreted. Key macro- and micro-scale characteristics are summarised for the identification of relict lithalsas, in clayey-silt, in unglaciated environments.

- Chapters 5 and 6: introduce the field sites in Norfolk and Wales, respectively. Again, the context of the field site, in relation to the depositional and palaeo-periglacial environment, is clarified and a summary of previous research is outlined. Macroscopic
and microscopic structures are described, analysed and interpreted. Key macro- and micro-scale characteristics are summarised and a frost-mound origin for the landforms considered.

- Chapter 7: discusses and compares the results from Norfolk and Wales to the macro- and micro-scale characteristics identified in the known relict lithalsa in Belgium. Structures associated with periglaciation and frost-mound formation and/or decay processes are clarified. The significance of grain size and the palaeo-periglacial setting is considered and the findings are placed in a wider context.

- Chapter 8: concludes the thesis by answering the research questions and outlining areas for future investigation.
Chapter 2: Literature Review - Periglacial Ramparted Depressions (PRDs)

2.1 Periglacial ramparted depressions (PRDs)

2.1.1 Introduction

The aim of this chapter is to define what is meant by periglacial ramparted depressions (PRDs) through clarification of: i) the ground-ice types from which they originate, ii) geomorphological descriptions of their active (perennial frost mound) and inactive (PRD) forms, and iii) a comprehensive review of their life cycle. Topographic, sedimentological and cryogenic signatures related to formation and decay processes and potential associated microstructures are summarised. Previous studies of frost-mound collapse structures, and the methodological approaches used in their investigation, are reviewed to highlight the ambiguity that remains around: i) accurate identification of PRDs as relict frost mounds, ii) evaluation of their genesis, and iii) their classification. The chapter closes by identifying an aspect of PRD investigation yet to be undertaken (i.e. the analysis of their internal structures at the micro-scale, contextualised by macroscopic data).

Perennial frost-mound decay often results in depressions with sediment ramparts (Mackay, 1986; Washburn, 1979), defined here as PRDs. Ramparted depressions found in present-day temperate climates are regularly interpreted as collapsed perennial frost mounds from the last glacial period, following retreat of the Pleistocene ice sheets (c. 23–19 ka). Their presence implies a relict permafrost landscape (Mackay, 1987) and this is used to infer the extent of Late Pleistocene ice sheets. For example, Watson (1972) cited the presence of relict pingos in Cardiganshire, Wales, as evidence that the glacial limit of the Late Devensian lay somewhere to the north of this area. However, decay destroys the original permafrost features and genetically diverse ground depressions (including those unrelated to periglacial processes (e.g. kettle holes)), can appear morphologically the same. Therefore, not all ramparted depressions are relict frost mounds. By contrast, relict permafrost features with diverse morphologies may have common origins (i.e. as pingos, palsas or lithalsas) that are difficult to interpret (Gurney and Worsley, 1997).

2.1.2 Perennial frost mounds

Perennial frost mounds are hills of heaved ground (unconsolidated sediment or bedrock) with an ice core, fed by groundwater (ACGR, 1988). Frost-mound types are distinguished by a number of factors, including: structure, duration, hydraulic regime, ice type and location within specific permafrost zones. For example, frost and icing blisters are transient, formed
in cold-climate conditions, < 1 m high, usually thawing and collapsing after the first summer’s growth, or lasting up to ten years at most (Morse and Burn, 2014). In contrast, pingos develop in continuous and discontinuous permafrost zones, are comparatively large (an average height, when active, of 4.6 m and up to 21 m in northern Alaska (Jones et al., 2012) and up to ~ 50 m high in Canada (Mackay, 1986)), and can endure for centuries (Mackay, 1986).

Perennial frost mounds only form in permafrost environments (Mackay, 1987). Permafrost is perennially cryotic ground - at or below 0 °C for two or more years (ACGR, 1988). Permafrost is not always frozen ground as impure water, due to dissolved solutes, will freeze below 0 °C (Bouyoucos and Mc Cool, 1916; Dash et al., 2006). The freezing temperature is also affected by molecular attraction between sediment particles and water molecules i.e. surface energy. Molecular attraction creates an adsorption layer around sediment particles, particularly in fine-grained sediments, as small pore spaces create an adsorption pressure that depresses the freezing point below 0 °C, to generate a thin liquid (or interfacially premelted) layer (Taber, 1930: Dash et al., 2006; Rempel, 2010). Therefore, a sediment at or below 0 °C can contain both water and ice and so permafrost ground has different mechanical properties depending on the state of the water-ice content (Harris, 1981a; Dash et al., 2006). Permafrost is significant to periglacial geomorphic processes as it confines most liquid water, and thus frost action, to the active layer between the permafrost table and the ground surface (Burn, 1998). The land surface bears the imprint of present and past frost action caused by various ground-ice types as a result of the aggradation and degradation of permafrost (Murton, 2013).

2.1.3 Ground ice
The key ground-ice types significant to perennial frost-mound formation include:

- Pore ice

Ground freezing (permafrost) occurs when pore ice (ice crystal particles) forms (ACGR, 1988). Pore ice forms when water seeps down into sediment or rock pore space, due to low surface tension at the freezing plane, and subsequently freezes around mineral grains (also known as ice cement or interstitial ice) (Mackay, 1972). There are different types of ice cement and cryostructures, which influences how stress is transmitted through sediment (Murton, 2013) (Fig. 2.1). Pore ice commonly occurs in relatively coarse-grained sediment and, on thawing, can leave microscopic voids that may provide an indication of sediment genesis (Murton, 2013).
- Segregation ice

A frost mound’s massive-ice core will comprise, in varying proportions, segregation ice and intrusive ice (Mackay, 1978). Segregation ice generally develops in fine-grained sediment, where water transport occurs in freezing soils due to intermolecular forces that generate a pressure gradient causing liquid water to flow to colder temperatures i.e. the freezing front (Rempel, 2010). (Fig. 2.2). Segregation-ice lenses range from 75 μm to 10 m thick, are often stratified and form in a vertical series due to thermal changes at the freezing front (ACGR, 1988). Thick units of segregated ice are termed massive ice and these can be pure (transparent) or they can contain mineral inclusions and air bubbles (Murton, 2013).

Segregated-ice processes include desiccation, compaction and compression of the sediment. These processes create durable, platy, lenticular structures oriented parallel to the thermal gradient and the ground surface, visible macroscopically (Harris, 1981a) (Fig. 2.3) and microscopically (van Vliet-Lanoë, 1985; 2010) (Fig. 2.4). Heave and subsidence are associated with segregation ice, related to freeze-thaw processes (Rempel, 2010).

![Fig. 2.1 Pore ice divided into ice-cement types in sand (Murton, 2013).](image-url)

![Fig. 2.2 Mechanism for segregated-ice formation, leading to the development of ice lenses (r = mean soil pore radius) (Mackay, 1972).](image-url)

![Fig. 2.3 Macroscopic lenticular cryostructures in silty clay, Alaska. Photograph: Y. Shur, 2010 (French and Shur, 2010).](image-url)
• **Intrusive ice**

A frost mound’s massive-ice core will comprise varying amounts of intrusive ice. Intrusive ice forms when groundwater is either: i) injected into porous unconsolidated sediment or fractured bedrock under artesian pressure, or ii) is expelled in coarse sediment ahead of the freezing front and freezes (Ballantyne and Harris, 1994). It can form thin sill and/or dyke structures (Murton, 2013). Intrusive ice is relatively pure compared with segregated ice (Pollard, 1990). Both segregation and intrusive ice may appear as transitional ice bodies due to fluctuating hydraulic pressure (Murton, 2013).

• **Vein (reticulate) ice**

A frost mound’s outer flank may fracture as it grows. As (melt) water fills the vertical and horizontal fissures and freezes, it has a lattice-like structure called vein ice (Mackay, 1974). It also occurs within certain frost-mound types (e.g. palsas, lithalsas) (Pawelec and Ludwikowska-Kędzia, 2015; Jaworski and Chutkowski, 2015). Vein ice is often found in frozen glaciolacustrine sediments (ACGR, 1988) (Fig. 2.5). Vein ice cryostructures are vertically inclined. Their genetic ground-ice type can be segregated ice and/or dilation-crack ice (Murton, 2013).

• **Wedge ice**

Ice wedges can develop at the periphery of frost mounds (Mackay, 1972). Contraction cracks infill with water that freezes to form thin veinlets of ice. Repeated cracking in the same place creates a wedge. Wedges include vertical to steeply dipping ice that may contain gas bubbles or mineral inclusions (Murton, 2013) (Fig. 2.6).
Dilation-crack ice

Another ice fracture feature that develops during frost-mound formation, due to tensional stresses as the pingo dome grows, is dilation- (or tension) crack ice (Mackay, 1972; 1986; 1998). This forms when surface water infills planar dilation cracks and freezes. It occurs in vertical bands and may contain mineral soil or organic matter (ACGR, 1988). Dilation cracks can be difficult to distinguish from wedge ice when they occur on pingo sides (Murton, 2013).

2.2 Geomorphology, formation and decay processes of perennial frost mounds

2.2.1 Pingos

i. Geomorphology: active form

‘Pingo’ is an Inuit term introduced into the academic literature by Porsild (1938) to describe earth mounds with ice cores, observed in the Northwest Territories (NWT) of Canada (Mackenzie District). It was used for active, decaying and relict forms. ‘Pingo’ is now frequently used as a generic term for any large frost mound growing or decaying in a present-day permafrost environment, a morphological rather than genetic term. Active
Pongos only form in permafrost environments (Mackay, 1972). The three main areas for currently forming pingos are: Alaska, north west Canada and northern Asia (Siberia) (Grosse and Jones, 2011). Other areas include Greenland, Svalbard, Scandinavia, China and Mongolia (Grosse and Jones, 2011). Pingo density ranges from ~ 1 per km² (Alaska) to 8–11 per km² in north west Canada and east Greenland, respectively (Grosse and Jones, 2011). Decayed pingos found in present-day temperate climates (e.g. north west Europe) are referred to as ‘fossil pingos’, ‘pingo scars’, ‘relict pingos’ or ‘pingo remnants’ (Flemal, 1976; De Gans, 1988).

Pongos range from < 100 m diameter (small) to > 200 m (large) (Mackay, 1988). For example, Ibyuk Pingo (Tuktoyaktuk, western Arctic coast, Canada) is a large pingo ~ 50 m high with a basal diameter of 300 m, and is 1,300 ± 200 years old (Mackay, 1986). Based on a topographic survey, analysed using a geographic information system (GIS), Grosse and Jones (2011) estimated that there are over 11,000 pingos on Earth. There are also purported to be extraterrestrial pingo forms on Mars, which is significant as it implies aqueous flow and periglacial processes (Burr et al., 2009; Dundas and McEwan, 2010; Soare et al., 2014).

The pingo summit is often characterised by a star-shaped crater of intersecting dilation cracks and the sediment flanks can incorporate radial dilation cracks (that decrease in size as they run from the top to the pingo periphery), concentric growth rings and peripheral faults (Mackay, 1973; 1978; 1988; Flemal, 1976; De Gans, 1988) (Fig. 2.7). The pingo may also be vegetated. Not all pingos are symmetrical and conical in shape. Pingo morphology can be diverse and include linear forms (Porsild, 1938; Pissart, 1967; O’Brien, 1971; Watson and Watson, 1974; Pissart and French, 1976; Gurney and Worsley, 1997).

Overall the morphology of pingos appears to be governed by their location (e.g. elongate forms correlate with secondary fault lines in Schuchert Dal, east Greenland (O’Brien, 1971).
and valley axes in the Cledlyn Valley, Wales (Watson, 1971), or the geometry of the residual pond on which they grow (Mackay, 1973)). Internally, pingo domes (the overburden) typically have a thickness of ~ $\frac{1}{3}$–$\frac{1}{2}$ of the pingo height (Mackay, 1978). Below the dome is a massive-ice core (a large mass of ground ice); the depth of which can be greater than the pingo mound height (e.g. ~ 65 m below the pingo peak for the Ibyuk Pingo) (Mackay and Stager, 1966). Around the ice core, sediment ranges from well-sorted clay and gravel to diamicton. For example, pingos along the western Arctic coast of Canada typically include a top unit (overburden sediment) of clayey, organic silt, and an intermediate unit of diamicton overlying a lower unit of thick sands – interpreted as lacustrine deposits over glaciofluvial sands (Mackay, 1986) (Fig. 2.8). Internal structures may be deformed and sediment tilted sub-horizontally (Pissart and French, 1976; Mackay, 1978; Pissart and Gangloff, 1984). Pingos can form in a variety of substrate but rarely in highly impermeable sediments (e.g. clay), through which water necessary for pingo formation cannot easily flow (Mackay, 1978).

![Fig. 2.8 Internal structure and composition of the Ibyuk Pingo, Tuktoyaktuk, NWT, Canada. A, B, C denote sedimentological units: A: Top unit (overburden sediment) of clayey, organic silt, B: Intermediate unit of diamicton and; C: Lower unit of thick sands (Mackay, 1986).](image-url)
ii. Formation processes

Pingo formation requires a supply of groundwater under high pore-water pressure to create and maintain a massive-ice core either by:

- a pressure system injecting water into near-surface sediment that rapidly freezes as intrusive ice – causing the overburden to dome and/or;
- the formation of a segregated-ice lens, the layering of which leads to growth and heave (Mackay, 1986).

Pingos are classified on the basis of the hydraulic regime supplying the water that forms the ice core and determines the nature of the ice content.

iii. Hydrostatic pingo (synonymous with 'closed-system' pingo)

Aside from some early debate (e.g. Ryckborst, 1975, 1976; Mackay, 1976), there is general consensus regarding the formation processes for hydrostatic pingos. In areas of continuous permafrost, groundwater moves through unfrozen sediment (talik) insulated by standing water bodies (e.g. lakes) (Fig. 2.9). When the water body is removed, due to lake drainage (e.g. by ice-wedge drainage channels, coastal or river erosion, lake sedimentation), the underlying moisture-rich sediment is exposed to sub-freezing temperatures and permafrost aggrades inwards on all sides (Müller, 1959; Mackay, 1976; 1986; 1987; 1988). Volumetric expansion of freezing water creates hydrostatic (confining) pressure and forces pore water to be expelled (injected). The water freezes and forms an ice core. The ground domes over the ice core to form a mound (Müller, 1959). Heave, due to the volumetric expansion of pore ice alone, is considered insufficient to cause such doming (Mackay, 1973; 1986; 1999).

Instead, dome growth requires segregation ice formation and/or water recharge to enable progressive intrusive ice formation (Mackay, 1973; 1986; 1987; 1998). Growth ceases once the talik is frozen (Müller, 1959). This is the ‘closed-system’ hypothesis developed by Müller (1959) from the concept first introduced by Porsild (1938) (Fig. 2.10). Müller’s hypothesis is verified by the long-term field surveys of Mackay (1973; 1977; 1978; 1986; 1987; 1988; 1997; 1998; 1999; Mackay and Burn 2011) on pingos in the Tuktoyaktuk Peninsula, western Arctic coast, Canada. The mechanics of their formation means that hydrostatic pingos tend to develop as isolated landforms with a low-density occurrence; the processes are not repetitive (Müller, 1959). Hydrostatic pingos of the western Arctic coast have mostly developed in residual ponds underlain by thick sands, whilst some in the Mackenzie Delta have formed in alluvium (Mackay, 1986).
Fig. 2.9 Permafrost environments – vertical cross-section of the transition zone between continuous and discontinuous permafrost (Pidwirny, 2006).

Fig. 2.10 Genesis and collapse of hydrostatic pingos of the Tuktoyaktuk Peninsula area, NWT, Canada (Mackay, 1988).
iv. **Hydraulic pingo (synonymous with ‘open-system’ pingo)**

The formation mechanisms outlined for hydraulic pingos are based on the observations of Leffingwell (1919), in northern Alaska and the work of Müller (1959), in east Greenland (similar types are also found in Spitsbergen, northern Norway). It is usually stated that hydraulic pingos form in areas of discontinuous permafrost where groundwater is injected sub- or supra-permafrost, under artesian pressure, at the foot of a hillslope or on a valley floor (Müller, 1959; Washburn, 1979; Ballantyne and Harris, 1994) (Fig. 2.11). Satellite features frequently develop (i.e. spring flows can lead to seasonal frost mounds forming on the flanks of growing pingos, the development of icings or icing blisters and even the formation of further perennial frost mounds leading to clustered formations) (Müller, 1959; Jaworski and Chutkowski, 2015). However, field studies suggest that growth mechanisms appear to be more complex. Gurney (1998) argued that the pressure of hydraulic head alone is insufficient to deliver the necessary supply of groundwater for hydraulic pingo growth - this would require a complex balance between water pressure, overburden resistance and rate of freezing (Mackay, 1973; 1986). In addition, there is no clear explanation for the movement of groundwater in permafrost zones without the presence of a talik.

![Fig. 2.11 Genesis and collapse of hydraulic pingos (Ross et al., 2007a).](image-url)
Suggested alternative mechanisms for groundwater movement include the presence of geological fault lines (e.g. in Schuchert Dal, north east Greenland (O’Brien, 1971) and Adventdalen, Svalbard (Ross et al., 2007b)), or through possible taliks under polythermal glaciers (Liestøl, 1977; Gurney, 1998).

Finally, hydraulic pingos are reported within a wide range of sediments including bedrock (if it can conduct groundwater) (Müller, 1959; Mackay, 1978) (Fig. 2.12). A plentiful supply of groundwater brought to the surface under hydraulic head can lead to a high density of hydraulic pingos (clustering) and regrowth in sites of collapsed structures (Müller, 1959), leading to intersecting ramparts (Washburn, 1979). The variety of scenarios developing to explain hydraulic pingo growth illustrates that their genesis remains poorly understood (Gurney, 1998). Further investigation of groundwater sources could lead to additional sub-categorisation of this pingo type (Yoshikawa and Harada, 1995; Yoshikawa, 1998).

Fig. 2.12 Rock pingo (NWT, Canada). Photograph: Geological Survey of Canada, no date.

v. Polygenetic pingo
The two established conceptual models for pingo growth do not adequately explain the location, shape nor formation mechanisms of all pingo types. For example, the 18 pingos in the Fish Lake area of south west Banks Island in the NWT of Canada are diverse in form and location (Gurney and Worsley, 1997). Gurney and Worsley (1997) suggested that, in some cases, both hydraulic and hydrostatic mechanisms are at work within the same pingo. In addition, on Prince Patrick Island, NWT, Pissart (1967) identified pingo types that do not conform to existing scenarios for genetic classification: i) on high ground, far from lakes, fed
by groundwater moving within bedrock fractures and ii) very elongated features on low-lying ground. It is also possible that where subsurface talik geometry affects the final morphology of the pingo this relates to different formation mechanisms (Gurney, 1998). Gurney (1998) suggested that the alternative classification of 'polygenetic pingo' should be applied when the mechanism for frost-mound growth is unclear.

vi. Other pingo types

• Submarine pingo

Submarine pingos are similar to hydrostatic pingos in the Mackenzie Delta region and have been reported on, for example, the continental shelf of the Beaufort Sea 120 km north of the Tuktoyaktuk Peninsula, NWT, Canada (Shearer et al., 1971). ‘Shoals’ of irregular-shaped, asymmetric (steeper on one side than the other) underwater mounds (with 0-10 m deep depressions and an average diameter ~ 400 m and height ~ 30 m) occur singly, paired and in groups (Shearer et al., 1971). Shearer et al. (1971) suggested that these are frost mounds that formed in a marine environment. Kopf (2002) suggested a mud-volcano origin (i.e. a dome of 'mud breccia' mobilised with gas and water from depth). More recently, Paull et al. (2007) attributed the submarine features to methane gas venting, illustrated by 'moussey-textured' sediment collected from mound crests, typical of gas hydrate bearing cores (Paull et al., 2011).

Other examples of potential submarine pingos include a group of circular, rimmed features found in 60 m of water off the coast of Anglesey (Wingfield, 1987). Side-scan sonar records have identified suspected PRDs, from 75 to 250 m in diameter and up to 10 m across, in till deposits (Wingfield, 1987). The identification of these features as PRDs is supported by their proximity to submarine patterned ground (Washburn, 1979).

vii. Geomorphology: inactive form

In its initial decayed stage, a pingo is often characterised by a pond-filled crater encircled by sediment ramparts with pingo ice preserved at depth (Mackay, 1988) (Fig. 2.13). Over time, the pond may reduce to boggy marsh sediment - this is a secondary deposit of peat cover unrelated to pingo formation (Flemal, 1976), and ramparts subside (Mackay, 1978). There may be significant evidence of dilation cracking around the circumference of the pingo (Mackay, 1987). An apron of slumped sediment may be present at the pingo periphery (Mackay, 1988).
viii. Growth and decay

Pingo collapse takes tens to hundreds of years as decay can pause, and be reactivated at a much later stage, due to slumped material protecting the ice core (Müller, 1959; Mackay, 1987; 1988; Mackay and Burn, 2011). Therefore, given decay timescales, comprehensive data on growth and rampart formation of pingos are rare. Long-term field studies in Canada conducted on hydrostatic pingos (Mackay 1973; 1977; 1978; 1986; 1987; 1988; 1997; 1998; Mackay and Burn 2011) indicate that the pingo diameter remains the same from inception – causing the steepness of the slopes to progressively increase up to a maximum of ~ 45° (Mackay, 1978). Therefore, pingo growth is higher, rather than higher and wider (Mackay, 1987; 1998). Build-up of pore-fluid pressure can cause the overburden material to rupture above the ice core exacerbating tensional dilation cracks as the sediment is stretched by doming (Mackay, 1987; 1988). The summit can sometimes appear to pulsate as subpermafrost groundwater levels fluctuate beneath the pingo ice core (Mackay, 1977). For pulsating pingos, dilation cracks extend into the surrounding area around the pingo (Mackay, 1977; 1998). Dilation cracks can lead to hydrofracturing and spring flows of pore water that create icing mounds at the pingo edge (a localised icing accumulation of substantial thickness but limited area) (Mackay, 1977; 1998; Yoshikawa, 1998). Survey data indicate that growth rate increases with height (e.g. for the Ibyuk Pingo the peak grows at a rate of 2.3 cm/year but there is no discernible growth below 25 m (Mackay, 1986)). The fastest rates of growth are recorded in the early years of formation (e.g. 1.5 m/year for the first one to two years) (Mackay, 1973). It is growth that causes peripheral faulting and mass-movement of material down the mound (Mackay, 1978; 1986; 1987; 1988). Material may also slump down the slopes of the mound because of permafrost creep (Mackay, 1973).
From field observations, it appears that similar processes can cause decay in all pingo types (Mackay, 1978; 1988; Müller, 1959). Pingo collapse - caused by mechanical failure at the summit, circumference and periphery, as well as thermal erosion – may occur as follows (Mackay, 1973; 1987; 1988; 1998):

- **Summit** – The summit can be ruptured by a pressurised sub-pingo water lens, leading to surface springs and winter icings, or due to tensional forces as the pingo ‘skin’ stretches to breaking point (Mackay, 1986; 1987; 1988). The sediment collapses into the summit crater and sloughs off onto the flanks (Mackay 1988; 1998). Radial dilation cracks, which can develop to relieve the tension from growth, infill with surface water to produce dilation-crack ice and this leads to erosion (Mackay, 1986; 1987; 1998). Mechanical and thermal erosion of the mound occurs from the top down as the ice core is exposed by ruptures, cracks and faults, causing the pingo ice to thaw (Mackay, 1986; 1988). Collapse may also be exacerbated by littoral erosion (e.g. in Schuchert Dal, where the north-western flank of a hydraulic pingo is undercut by the main river channel (O’Brien, 1971; Mackay and Burn, 2011)). Rupture and erosion are a consequence of growth and are irrespective of climate change.

- **Ramparts** – Steep pingo slopes are vulnerable to mass-wasting due to active-layer slides, permafrost creep, gelifluction and slope wash (Mackay, 1973; 1978; 1986; 1988). This can expose the ice core to thaw and further slumping. In addition, internal forces push sediment radially to the sides as the ice lens grows (Mackay, 1973; 1978; 1988). It is probably a combination of these processes that leads to sediment redistribution and rampart formation. The volume of the rampart sediment depends on the original diameter and slope angle of the pingo but is typically equivalent to the volume of the depression (Mackay, 1986; 1988). However, it is possible that the ramparts become subdued or are absent depending on the amount of permafrost present and or the original depth of the pingo (Mackay, 1986; 1988). Relict landforms with only segments of ramparts remaining are considered to be a feature of advanced decay (Holmes et al., 1968). The rampart sediment is derived from the original pingo slopes and should be comparable with that found beneath the basin (Flemal, 1976; Mackay, 1988).

- **Periphery** – Unsorted, slumped deposits from the pingo flank may be carried out to the periphery by a debris flow or short-lived streamflow events (Müller, 1959; Mackay, 1986; 1988). Peripheral ice-wedge casts and radial dilation cracks may also be present (Porsild, 1938; Mackay, 1978; 1987). High-angled normal faulting at the periphery indicates circumferential failure (Mackay, 1978; 1987; 1988).
Internally – As pingo growth is initiated from its centre point, there is significant sediment deformation and layers become tilted within the mound (Mackay, 1978).

Basin – The depth of a fossil pingo basin typically equates to the base of the ice core if it is composed mostly of pure ice (Mackay, 1978). The basin will contain sediment from the frost-mound overburden due to debris flows during mound collapse (Mackay, 1986). Beneath the basin, the presence of frost-susceptible (fine-grained) sediment indicates an ice core formed by segregation ice (Mackay, 1986). Alternatively, the presence of coarse-grained sediment, and the proximity of a water source under pressure, indicates an ice core formed by intrusive ice (Mackay, 1986).

However, decaying hydraulic pingos viewed by the author on a field trip to the Sakha Republic in Siberia (2016), illustrate that not all pingos decay in the same way. A collapse structure resembling a ring (i.e. where the sediment-covered ice core at the centre stands proud whilst sediments intermediate between the ice core and the outer flank slump) was observed (Fig. 2.14). No cracking of sediment at the summit and no radial dilation tension cracks were apparent. It is possible that where pingo collapse is due predominantly to thermal processes, thaw-slump structures will dominate. The range of mechanics involved in pingo decay and collapse illustrates that pingo decline can be complex but, when not part of regional thermokarst activity, it is not in itself an indication of climate change, rather part of the natural life cycle of the frost mound (Washburn, 1979; Mackay, 1988; Worsley and Gurney 1996; Gurney and Worsley, 1997).

2.2.2 Palsas and Lithalsas

i. Geomorphology: active form

‘Palsa’ is a Lappish/Finnish word for a peat hummock with a frozen core rising out of the earth (Seppäla, 1972) and is described by Washburn (1979) as a peaty permafrost mound. Palsas occur in areas of sporadic and discontinuous permafrost. Typical palsas are found in Fenno-Scandinavia, while others occur in the sub-arctic belt surrounding the polar region.
in discontinuous permafrost zones (e.g. Iceland, Canada, Alaska) (Washburn, 1983; Gurney, 2001). Note that permafrost exists only within the palsa or lithalsa itself (French, 2007; Seppälä, 2011). Palsas are generally smaller than pingos, ranging from 0.5 to ~ 7 m high and 2 to 150 m in diameter (Seppälä, 2011). Their morphological form varies widely including: domed (classic palsa shape), elongate winding (string-form), linear ridged (esker-like), palsa plateaux and palsa complexes (Seppälä, 1982; Worsley et al., 1995). In addition, ‘floating palsas’ are described as vegetated, peat islands with permafrost cores, < 0.7 m high (Harris and Nyrose, 1992). Early literature described two distinct types of palsa based on their internal structure (Washburn, 1979):

1. those with a frozen peat core (comprising segregation ice) and peat cover (developed wholly in peat);
2. those with a frozen mineral core of silt (comprising segregation ice) without a peat cover or at most a very thin peat cover (< 10 cm thick) (Pissart, 2000; 2002; Gurney, 2001).

This second category is designated as a ‘mineral palsa’ or a ‘lithalsa’ (Harris, 1993).

Consequently, palsas and lithalsas appear the same externally, except lithalsas have no peat cover and are located in glaciolacustrine, lacustrine, and alluvial sediments (Harris, 1993; Pissart, 2000; 2002; 2003; Gurney, 2001; Wolfe et al., 2014). It could be that lithalsas represent a continuum between pingos and palsas (Worsley et al., 1995; Gurney, 2001). Present-day lithalsas exist in Canada (in the Yukon (Harris S, 1993, 1998), Northwest Territories (Wolfe et al., 2014) and northern Quebec (Calmels et al., 2008a, b; Pissart et al., 2001)) and Russia (Iwahana et al., 2012; Vasil’chuk et al., 2016). Classic palsas and lithalsas have dome shapes with criss-cross cracks that develop into irregular polygons (Seppälä, 1988) (Fig. 2.15). Internally, both palsas and lithalsas comprise a core of perennial ice.
interbedded with mineral or peaty soil. Palsas and lithalsas are often vegetated and their distribution and growth cycle is associated with specific vegetation types (Worsley et al., 1995; Wolfe et al., 2014). Both frost-mound types generally occur in groups surrounded by water channels (Seppälä, 1988), typically located adjacent to ponds and streams (Wolfe et al., 2014).

Mapping of nearly 1800 lithalsas within the Great Slave Lowland, Northwest Territories, Canada (Wolfe et al., 2014) evidences a combination of climatic, sedimentological and hydro-geological factors that influence lithalsa growth and distribution. Key conditions for lithalsa development include: i) widespread discontinuous permafrost, within relatively warm thermal ground conditions of between 0 and -1 °C, ii) fine-grained, frost-susceptible sediment for the formation of segregated ice, and iii) a supply of groundwater for the development of ice lenses (Wolfe et al., 2014).

**ii. Formation mechanisms**

The dominant theory regarding formation (for palsas in organic material and lithalsas in mineral sediment) is that a localised thin cover of snow, attenuated by wind, allows frost to penetrate damp surface cover within a bog, causing freezing at depth (Seppälä, 1988). An insulating layer of dry peat or sediment covering the mound prevents thaw the succeeding summer (Kujala et al., 2008). Freezing causes heave due to the expansion of pore-water ice and ice segregation (Seppälä, 1988; Calmels et al., 2008a and b) (Fig. 2.16). With each successive winter, the frost penetrates deeper and the mound grows until the frozen core touches the base of the bog (Seppälä, 1988).
Multiple drillings in a palsa/lithalsa complex in northern Quebec revealed a thick layer of aggradational ice (~150 cm) just beneath the active layer (~80 cm), overlying a much smaller volume of veined (reticulated) ice, overlying a thick layer of lensed ice (Allard et al., 1996) (Fig. 2.1). Allard et al. (1996) suggested that palsas/lithalsas develop below the active layer by a combination of processes including: i) aggradation of ice, ii) cryosuction, and iii) meteoric water that feeds an ice-rich seam. Alternatively, where a change in vegetation cover allows freezing at depth (due to changes in surface albedo) segregation ice accumulates and the peat cover heaves (Railton and Sparling, 1973). Worsley et al. (1995) reported a successive change in vegetation types as lithalsas develop; dense sedge gives way to Sphagnum cover associated with a reduction in water depth and mound formation. As the mound is elevated by frost heave, the Sphagnum is replaced by different species of heath (and forest species in mature forms) (Worsley et al., 1995). In cases where there is cyclical growth of lithalsas in the same location, this cannot be explained by vegetation succession. Instead, Worsley et al. (1995) suggested that an additional mechanism is required for episodic growth (e.g. groundwater movement via taliks, ensuring water recharge).

There is a counter argument for the formation of palsas that rejects the presence of segregated ice and instead attributes formation to the thermal properties of peat. Kujala et al. (2008) suggested that ice segregation cannot take place in pure peat as it is not frost-susceptible. Instead, Kujala et al. (2008) proposed that peat can act in a frost-susceptible
manner, under the right pressure conditions, to form ice lenses and layers. This process is attributed to the downward flow of water from the active layer as ice thaws. This mechanism allows the development of basal ice layers (interpreted as segregation ice by Allard et al. (1996)) and at certain depths, when silty sediment is reached, ice segregation can occur (Seppälä, 2011). Although the development of basal ice layers is possible in pure peat, as indicated by Kujala et al. (2008), it is likely that palsa mires would contain some frost-susceptible mineral soil incorporated into aggrading peat.

![Fig. 2.17 Distribution of ice in a lithalsa plateau in northern Quebec (Allard et al., 1996).](image)

\[1 = \text{active layer;} \quad 2 = \text{ice-rich layer (50-80\% in volume);} \quad 3 = \text{low ice content (10-30\% volume);} \quad 4 = \text{thick, regularly spaced lenses of segregation ice (50-80\% volume).}\]

Whilst the precise mechanism for palsa/lithalsa formation is debated, it appears that - unlike pingos - palsas and lithalsas grow vertically and laterally and the diameter of their mounds may fluctuate during growth and decay (Mackay, 1978; Pissart & Juvigné, 1980; Pissart et al., 2011). The mechanism for lateral growth is not agreed upon but is probably due to: i) active-layer slides emplacing material on the outer slope of the lithalsa, or ii) ‘frost thrusting’ (Washburn, 1979) (i.e. the displacement of sediment laterally and vertically due to frost heave) (Pissart et al., 2011).

iii. **Decay mechanisms and final form**
As palsas rise above boggy mire they dry out as wind removes any snow cover, leaving the mound surface vulnerable to erosion (Seppälä, 1988). Growth causes radial dilation cracks to form, weakening the stability of the sediment mass (Seppälä, 1988). Continued growth, erosion and slope processes destabilise blocks of sediment that topple into the surrounding mire (Seppälä, 1982). Heath cover may remain during, and sometimes after, thawing and decay but, if removed, this exacerbates erosional processes (Seppälä, 1982). Burrowing
animals (e.g. bears, squirrels) can also contribute to erosional processes (pers. comm. P. Collins, 2015). If a peat cover is present, palsas usually decay from the base, and slump to leave no, or very subdued, ramparts (Seppälä, 1988; Harris and Schmidt, 1994). Hence, there is little to indicate the previous presence of a palsa (Pissart and Gangloff, 1984).

![Fig. 2.18 Stages of lithalsa degradation (northern Quebec). A: Mound diameter is 50 m. B: Depression develops. C: Rampart edge forms. D: PRD (Calmels et al., 2008a).](image)

For lithalsas, growth and the creation of tension cracks promote erosion and solifluction, as sediment blocks slide to the edge (Pissart, 2002; Calmels et al., 2008a). However, the mineral content of the sediment leaves a residual rampart of relatively low dimensions, typically ~ 1 m high, surrounding a depression filled with water and peripheral deposits (Worsley et al., 1995; Calmels et al., 2008a) (Fig. 2.18). The flat and regular bottom of the palsa/lithalsa is interpreted as the consequence of becoming infilled with sediment during mound collapse, whilst the formation of a rampart is attributed to both lateral extension and solifluction (Pissart et al., 2011).

The ramparts comprise overburden material from the lithalsa and have dipping, stratified deposits due to upheaving of the mound during growth (Pissart, 2002). A reconstruction of lithalsa rampart formation is possible following the discovery of a deformed peat lens of ~ 30 cm thick - dated to prior to lithalsa formation - found at the rampart base of a relict lithalsa at Konnerzvenn on the Hautes Fagnes, near the Belgium-German border (Pissart, 2003) (Fig. 2.19). Lithalsa growth creates: i) uplift and lateral displacement of sediment within the mound, ii) silty, sediment run-off on its flanks, and iii) mass-movement.
(solifluction) as the slope steepens (Pissart and Gangloff, 1984) (although the extent to which lateral thrusting rather than solifluction is the key mechanism responsible for rampart development is debatable (Pissart et al., 2011)). Subsequent thaw and collapse causes vertical displacement (a downthrown section) creating a rampart encircling a depression (Fig. 2.20) (Pissart, 2000; 2003).

Fig. 2.19 A section through an elongate lithalsa rampart at Konnerzvenn, Belgium, including a deformed peat lens at the base of the rampart that was deposited prior to lithalsa formation (Pissart and Juvigné, 1980).

Fig. 2.20 Lithalsa growth creates lateral displacement of sediment within the mound as well as by silty, sediment run-off on its flanks (b and c) and mass-movement by solifluction (d to f). Subsequent thaw and collapse enables vertical displacement and creates the final rampart form (g) encircling a depression as detailed above. Letters x and y show the lateral displacement of a silt run-off layer as the mound forms to the right (Pissart, 2000; 2003).

Whilst lithalsa remnants may appear to be similar to those of hydraulic pingos, they are found in higher density groupings, with overlapping ramparts, and only occur in fine-grained material that is conducive to reticulate (Iwahana et al., 2012) and segregation ice formation (Worsley et al., 1995; Pissart, 2002).
2.2.3 Topographic, sedimentological and cryogenic signatures of PRDs

From the preceding text, PRDs exhibit a range of diagnostic features at the macro- and micro-scale.

i. **Key topographic macro-features:**

- The presence of a distinct rampart surrounding a depression (Watson, 1971; Washburn, 1979; Mackay, 1988; Pissart, 2003).
- Clusters of ramparts – as opposed to chains of ring craters formed by kettle holes (Fay, 2002).
- Overlapping/intersecting ramparts – these are significant as they indicate cyclic development rather than glacial melt-out features (Worsley *et al.*, 1995).
- Evidence of a suitable hydrogeological regime acting as the source of the groundwater. Note, it is possible that a PRD has a polygenetic origin for which an explanation of the hydrogeological setting is not yet known due to complexities relating to subpermafrost groundwater movement (Mackay, 1988; Gurney, 1998; Ross *et al.*, 2011). Also, PRDs can be found in hydrological settings that today appear unsuitable due to a change in hydrogeological regime. In such cases, associated relict thermokarst signatures are particularly significant for inferring a suitable hydraulic regime (*e.g.* hummocky ground, palaeolakes).

ii. **Key sedimentological macro-features:**

- Grain size - a substrate of fine-grained sediment suitable for the growth of segregation ice is important for all frost-mound development but especially palsas and lithalsas as they are predominantly formed from segregation ice (Worsley *et al.*, 1995). Note, however, it is possible for segregation ice to form in coarser-grained sediment (*e.g.* medium-grained sand), if there is high subpermafrost pore-water pressure (Murton, 2013).
- Deformation structures within the ramparts (*e.g.* anticlinal features formed as the ground-ice lens developed or degraded) (Pissart, 1963; 2000; 2002; 2003).
- Associated thermokarst indicators of past permafrost – melt-out, soft-sediment deformation and resedimentation structures (*e.g.* ice-wedge casts, involutions – including ball-and-pillow and diapir and flame structures) (Murton and French, 1993; French and Shur, 2010).
- Thawing of frozen ground is also associated with significant mass-wasting of sediments moving downslope by gelifluction, frost creep and active-layer slides, often resulting in sediment deposit aprons at slope bottoms (Harris, 1981a; Mackay, 1988). Shearing during mass-movement causes elongate particles to align
themselves parallel to the direction of the flow, visible macro- and microscopically (Harris, 1985; Bertran and Texier, 1999).

- Frost heave and thaw settlement causes particle realignment at both macro- and micro-scales through rotation and sorting (into layers of coarser and finer particles - banding) (van Vliet-Lanoë, 1998). Thawing leads to waterlogging in soils and sediments (leading to the mobilisation of iron and manganese oxides and hydroxides) and increased porosity (van Vliet-Lanoë, 2010).

### iii. Key periglacial microstructures and fabrics (a glossary of terms is included in Appendix 3.1):

Cryostructures are visible in sediment at the micro-scale and are both indelible and resilient (van Vliet-Lanoë, 1998, 2010; van Vliet-Lanoë et al., 2004; French, 2007). For example:

- Platy or lenticular aggregates (Fig. 2.21)

  Aggregates are groups of sediment particles that bind to each other more strongly than to adjacent particles and they are delineated by the pore space around them, which allows both water and air to move (Brewer, 1964). Aggregates created by freeze-thaw are platy or prismatic structures delineated by smooth-walled, sometimes undulating, fissures (van Vliet-Lanoë, 2010) (Fig. 2.21A). Aggregate thickness and shape depends on their location within the sediment profile (i.e. aggregates become thicker and blockier with depth) and sediment type (e.g. platy structures are found in silt-rich sediments, prismatic structures in poorly drained, more clay-rich sediments and rounded aggregates in very fine silt to clay-rich sediment) (van Vliet-Lanoë, 1985; 2010). Mature platy or blocky aggregates can become granular due to successive frost action, as can aggregates found at the top of the sediment profile, due to frost-susceptibility (i.e. frost mulching) (Bertran and Texier, 1999; van Vliet-Lanoë, 2010). Angular aggregates, encircled by planar fissures, can also be the remains of recticulate ice veins (Fig. 2.21B). ‘Lattice-like’ veins, or reticulate ice, are known to occur in Quaternary thermokarst structures and are attributed to abrupt cooling (Mackay, 1974; van-Vliet-Lanoë et al., 2004, 2017; Iwahana et al., 2012) and can occur in lake and marine clays, glacial tills and mudflow deposits in permafrost areas (Mackay, 1974).
• Banded or foliated fabric (Fig. 2.22)

Repeated episodes of freeze-thaw can cause fragmentation and erosion of aggregates that are translocated down the sediment profile (van Vliet-Lanoë, 2010). Preferentially-sorted, inversely graded particles are one of the characteristics associated with banded plasmic fabric, which is a microstructure indicative of periglacial environments (van Vliet-Lanoë, 2010; Goryachkin et al., 2013).

• Convoluted and fragmented clay coatings (Fig. 2.23)

Brecciated domains of matrix are initially angular and become more rounded after successive freeze-thaw cycles to form fragments of clay or silt coatings that are incorporated into the matrix (van Vliet-Lanoë, 1985; 1998; 2010). Successive episodes of
freeze-thaw facilitates particle translocation down profile during snow melt (van Vliet-Lanoë, 2010).

![Image](image1.png)

**Fig. 2.23** A) Coatings of clay and associated iron oxides (cc) fragmented by experimental cryoturbation; B) Fragments of clay coatings (cc) incorporated into a silty clay groundmass by differential frost heave (northern Quebec) (van Vliet-Lanoë, 2010).

- **Frost cracking** (Fig. 2.24)

Frost shattering of skeleton grains within sediment, minerals and bedrock occurs due to high moisture retention in fissures followed by ice growth (van Vliet-Lanoë, 1985; 1998; 2010).

![Image](image2.png)

**Fig. 2.24** Iron nodule fragmented by ice lensing (van Vliet-Lanoë, 1998).

- **Frost-/stone-jacking** (Fig. 2.25)

In periglacial environments, vertical grains are displaced when ice lensing at the base of a grain successively heaves and rotates the grain above to a sub-vertical or vertical position (van Vliet-Lanoë et al., 1984; van Vliet-Lanoë, 1985; 2010). On thawing, a void space is left at the base, or to the side of the grain (van Vliet-Lanoë et al., 1984; van Vliet-Lanoë, 1985; 2010). Note, however, that frost-jacked grains may be re-aligned by solifluction or slope processes (Harris and Ellis, 1980).
• Silt and clay cappings (Fig. 2.26)

Fine grains can accumulate on the top faces of clasts or aggregates due to particle sorting by ice and translocation by snow water melt on thawing (van Vliet-Lanoë, 2010) (Fig. 2.26). In addition, such grains may display a weak birefringence (Fedorova and Yarilova, 1972) (see below, Plasmic fabric). Ferriargillans (lay concentrations), found deep within frost-affected sediment profiles and which may be layered, are similarly transported by snow melt (van Vliet-Lanoë, 2010).

• Vesicles (Fig. 2.27)

Vesicles are commonly found in frost-susceptible sediment and are variously interpreted as air expelled on freezing (Brewer, 1964; Harris and Ellis, 1980), or as air trapped between ice crystals and within sediment that is expelled and trapped on thawing (van Vliet-Lanoë, 2010). Vesicles are generally round in silt-/silt and sand-rich sediments (Fig. 2.27A) and mammillated in clay-rich sediments (Fig. 2.27B) (van Vliet-Lanoë, 2010). Voids can be enlarged by multiple episodes of freeze-thaw and deform to become vughs (van Vliet-Lanoë, 1998). Some vesicles have elongate forms, which could represent exit routes for expelled air from the sediment (i.e. desiccation cracks) (van Vliet-Lanoë, 1985; 2010).
Plasmic fabric (Fig. 2.28)

Plasmic fabric indicates the deformation history of sediment, whereby clay platelets align in certain geometries in response to external stress. Skelsepic plasmic fabric (Fig. 2.28) occurs when fine silt and clay platelets arrange themselves around skeleton grains and exhibit a birefringent halo (van der Meer, 1993). In periglacial environments, van Vliet-Lanoë (1985) suggests that clays may become reoriented around aggregates and pore surfaces due to pressure exerted by growing ice crystals (see also, Skelsepic plasmic fabric below). It is notable that the presence of Fe-MnO can mask unistrial and skelsepic plasmic fabrics and could inhibit its detection (Jim, 1990).

Fig. 2.28 Skelsepic plasmic fabric around sand grains (Pawelec and Ludwikowska-Kędzia, 2015).

Mass-wasting deposits include the following structures and fabrics at the micro-scale:

- Preferred orientation of elongate grains

Elongate grains oriented parallel/imbricate to the ground surface in the vertical plane, can be caused by progressive downslope movement that occurs along sliding planes, signified by the ice-lens traces (Harris, 1981b; van Vliet-Lanoë, 1985). In addition, platy
aggregates, inclined parallel to the slope surface, are likely to be caused by frost creep and or solifluction (van Vliet-Lanoë, 1985; Bertran and Texier, 1999);

- **Grain concentrations**
  Silt, clay and fine sand cappings will appear around grains if they have been rotated, due to frost heave or solifluction (Harris and Ellis, 1980; van Vliet-Lanoë, 2010). Additionally, grain concentrations are commonly found at the base of slopes due to downslope movement during solifluction (Harris and Ellis, 1980).

- **Rotational structures** (Fig. 2.29)
  Grain turbate and curvilinear structures are present in periglacial slope deposits (Harris and Ellis, 1980; Bertran, 1993; Bertran and Texier, 1999; Lachniet et al., 1999, Carr et al., 2000; Menzies and Zaniewski, 2003; Phillips, 2006; Pawelec and Ludwikowska-Kędzia, 2015). Grain turbates are circular grain arrangements, sometimes around a ‘core stone’ (i.e. clast or grain), that indicate rotational deformation as a consequence of high stress, ductile deformation (van der Meer, 1993; Philips, 2006) (Fig. 2.29A). Discontinuous arcuate arrangements of grains (Fig. 2.29B), are described by Phillips (2006) as rotational structures related to grain turbates occurring in debris-flow deposits caused by localised turbulent flow.

![Fig. 2.29A) Grain turbate (circular arrangement of grains around a soil aggregate) (Pawelec and Ludwikowska-Kędzia, 2015); B) Arcuate arrangements of clasts within homogenised silty clay (Phillips, 2006).](image)

- **Skelsepic plasmic fabric** (Fig. 2.28)
  Flow materials are known to produce poorly developed skelsepic plasmic fabric due to the rotation of particles (Bertran and Texier, 1999). A rampart formed by solifluction in a freeze-thaw environment is, therefore, likely to exhibit some degree of skelsepic plasmic fabric.
• Laminated overland flow deposits (Fig. 2.30)
Displaced sediments found on slopes can form by colluviation (Bertran and Texier, 1999; Mücher et al., 2010) or mass-wasting (Bertran and Texier, 1999). Deposits found on gentle slopes (< 7%) in loess regions, are thought to be transported by overland flow (e.g. slope, hill or rain wash) (Mücher et al., 2010). Stratified laminae in loess deposits (Fig. 2.30) form during heavy rainfall and commonly occur in the upper parts of sediment sections (Bertran and Texier, 1999; Mücher et al., 2010; Pawelec and Ludwikowska-Kędzia, 2015).

![Fig. 2.30 Laminated overland flow deposits in a small colluvial cone Vaise, France. Clay and silt particles occur as sand-sized aggregates juxtaposed to quartz grains as well as secondary infillings in packing voids (Bertran and Texier, 1999).](image)

• Deformation caused by mass displacement (Fig. 2.31)
Mass displacement (e.g. earth slide) occurs along shear planes within sediment. In periglacial environments, sliding occurs following permafrost thaw. Microstructures diagnostic of mass displacement include shear planes, brecciated domains, folding, stretching, fluidisation and remobilisation of sediment (Harris, 1985; Bertran and Texier, 1999; Phillips, 2006).
Fig. 2.31 Ductile deformation of silt and sand laminae in an earth slide Trieves, France (Bertran and Texier, 1999).

Based on the life cycles of perennial frost mounds outlined above and the ice processes that created them, key topographic, sedimentological and cryogenic signatures are summarised to aid detection of macro- and micro-textures/structures in suspected PRDs (Tables 2.1 and 2.2). This synthesis identifies some of the key questions for relict landform identification:

1. What was the mechanism for ice growth (*e.g.* by predominantly intrusive or segregation ice?) and what topographic and/or sedimentological evidence is there for a suitable hydrogeological regime for frost-mound growth?
2. What is the lithology of the substrate (*i.e.* the sediment beneath the basin infill)? This should corroborate the proposed mechanism for ice growth (Flemal, 1976; Mackay, 1988).
3. What is the density of landforms? (High density/overlapping forms implies cyclical growth over relatively short time-scales, which is not usually the case for pingo growth given their slow growth over thousands of years (Mackay, 1986)).
Table 2.1 Topographic characteristics of periglacial ramparted depressions PRDs.

<table>
<thead>
<tr>
<th>Topographic/hydrological setting</th>
<th>Pingo: Hydrostatic</th>
<th>Pingo: Hydraulic</th>
<th>Palsa</th>
<th>Lithalsa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lowland settings, associated with former lake basins.</td>
<td>Areas of topographic relief conducive to a hydraulic gradient (e.g. the bottom of mountain ranges or river valleys or lower hill slopes (south and south-east facing)).</td>
<td>Marshy fens/bogs/valley floors.</td>
<td>Adjacent to ponds and streams</td>
<td></td>
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<tr>
<td>Solitary or low density landforms.</td>
<td>Higher density, commonly mutually interfering.</td>
<td>High density and often with mutually interfering ramparts. Younger features disturb relict forms.</td>
<td>High density and often with mutually interfering ramparts. Younger features disturb relict forms.</td>
<td></td>
</tr>
<tr>
<td>Continuous.</td>
<td>Discontinuous.</td>
<td>Discontinuous or sporadic.</td>
<td>Discontinuous or sporadic.</td>
<td></td>
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<tr>
<td>Medium - fine-grained sediment of sand.</td>
<td>A wide range of sediments (e.g. fluvial, slope deposits, bedrock).</td>
<td>Peaty, silty frost-susceptible sediment.</td>
<td>Shallow organic layer, in a mineral-rich soil.</td>
<td></td>
</tr>
<tr>
<td>Presence of other permafrost phenomena in the vicinity (e.g. ice-wedge casts, thermokarst depressions and soft-sediment deformation structures).</td>
<td>Presence of other permafrost phenomena in the vicinity (e.g. ice-wedge casts and thermokarst depressions and soft-sediment deformation structures).</td>
<td>Peat landscape.</td>
<td>Boggy landscape.</td>
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<tr>
<td>Diagnostic macroscopic sedimentological features</td>
<td>References</td>
<td>Potential associated microscopic features</td>
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<tr>
<td>Pingos (hydraulic and hydrostatic) and Lithalsas</td>
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<tr>
<td>• A rampart encircling a depression: isolated, within clusters or overlapping.</td>
<td>Müller, 1959; Watson, 1971; Mackay, 1988; Worsley <em>et al.</em>, 1995; Gurney, 1998; Pissart, 2002; French, 2007</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Internal rampart deformation structures and stratification and tilting of layers.</td>
<td>Mackay, 1978; 1988</td>
<td>• Shear planes (banding of sediment), micro-faults and folds. Potential variation in deformation with depth.</td>
<td>Harris and Ellis, 1980</td>
<td></td>
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<tr>
<td>• External to the rampart, unsorted sediments derived from mass-wasting and shear failure (<em>e.g.</em> slump and debris-flow material), indicating flow from the direction of the depression.</td>
<td>Mackay, 1988; 1998; van Steijn <em>et al.</em>, 1995; Bertran <em>et al.</em>, 1997; Bertran and Texier, 1999</td>
<td>• Shear planes, orientation of the long-axes of skeleton grains parallel to the orientation of the greatest angle of dip.</td>
<td>Harris and Ellis, 1980; Bertran and Texier, 1999</td>
<td></td>
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<tr>
<td>• High angled-normal faults at the periphery.</td>
<td>Mackay, 1988; 1998</td>
<td>• Skeleton grain coatings, intraclasts present.</td>
<td></td>
<td></td>
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<tr>
<td>• Basin infill could contain different units: material within which the ice core formed and sediment from the overburden that has fallen into the crater.</td>
<td>Mackay, 1988; Mackay, 1987</td>
<td>• Grain turbate structures.</td>
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<tr>
<td>• Fractured plasma and skeleton grains.</td>
<td></td>
<td>• Fractured plasma and skeleton grains.</td>
<td>van Vliet-Lanoë, 2010</td>
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<tr>
<td>• Skelsepic plasmic fabric.</td>
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<td>• Skelsepic plasmic fabric.</td>
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<tr>
<td>• Possible micro-faults and folds, deformation structures (<em>e.g.</em> fractured grains).</td>
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<tr>
<td>• Potential variation in deformation structures with depth, becomingly increasingly disturbed near the bottom and beneath the basin (*?).</td>
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<td>Potential associated microscopic features</td>
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<tr>
<td><strong>Pingos</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>• Deformation structures caused by intrusive ice (e.g. faulting and folding)</td>
<td>Mackay, 1978</td>
<td>• Micro-faults and folds, deformation structures e.g. fractured grains.</td>
<td>van Vliet-Lanoë, 1998; 2010</td>
<td></td>
</tr>
<tr>
<td>• Signs of radial dilation cracks/casts of dilation-ice cracks crossing the rampart at right angles.</td>
<td>Mackay, 1978; 1988; 1998</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>• Circumferential ice-wedge casts.</td>
<td>Porsild, 1938; Mackay, 1987</td>
<td>N/A</td>
<td>N/A</td>
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</tr>
<tr>
<td><strong>Pingos, Palsas and Lithalsas</strong></td>
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<tr>
<td>• Cryostructures caused by segregation ice (e.g. lenses and layers of sediment parallel to the freezing plane)</td>
<td>Harris, 1985</td>
<td>• Platy, lenticular microstructures oriented parallel to the ground surface: planar, wavy and curved (micro-undulations).</td>
<td>Harris, 1981a; van Vliet-Lanoë, 1991; 2010; Goryachkin et al., 2013</td>
<td></td>
</tr>
<tr>
<td>• Shallow basin (&lt; 4 m below the surface outside the rampart), indicative of segregation.</td>
<td>Watson and Watson, 1974</td>
<td>• Pore spaces (packing voids) at the base of rock particles and clay aggregates.</td>
<td>van Vliet-Lanoë, 2010</td>
<td></td>
</tr>
<tr>
<td>• Reticulate (vein) ice</td>
<td></td>
<td>• Silt cappings.</td>
<td>van Vliet-Lanoë, 2010</td>
<td></td>
</tr>
<tr>
<td>• Compression features due to lateral thrusting.</td>
<td></td>
<td>• Vesicles, open fissures, well developed shear planes and narrow – near vertical – cracks</td>
<td>Coutard and Mucher, 1985</td>
<td></td>
</tr>
<tr>
<td>• Lattice-like veins.</td>
<td></td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td><strong>Lithalsas</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>• Lateral growth, demonstrated by displaced sediments at the lithalsa rampart edges.</td>
<td>Pissart and Juvenile, 1980; Pissart <em>et al.</em>, 2011</td>
<td>• Compression features due to lateral thrusting.</td>
<td>Pissart <em>et al.</em>, 2011</td>
<td></td>
</tr>
</tbody>
</table>
2.3 PRDs worldwide

2.3.1 ‘Pingos’ remnants?
Suspected PRDs exist in many regions beyond present-day permafrost limits (e.g. Africa, China, north west Europe, Canada and the USA) (Mackay, 1988). Pissart (1963) generated considerable interest in PRDs with a paper on ‘fossil pingos’ in Wales and Belgium. In Belgium, these features, known as ‘viviers’ (originally described as anthropogenic fish ponds) occur on a plateau along the Belgium-German border as enclosed depressions, filled with peat and surrounded by ramparts of gravelly silt (Pissart, 1956). Pissart (1963; 1994) compared the ‘viviers’ to features located in a glacial valley in Llangurig, mid-west Wales, and described them all as pingo remnants based on: i) similarity in form, ii) common occurrence on gentle sloping ground (≤ 5%), and iii) the structure of the ramparts. Based on morphology, a number of relict ‘pingos’ were subsequently identified across the UK and Ireland, including:

- southwest Wales (Cledlyn Valley) – a group of ~ 20 ‘pingos’ located on the valley floor of Nant Cledlyn; circular-oval, clustered or mutually interfering ramparts – predominantly of diamicton - encircling basins (Watson, 1971; 1972; 1982; Watson and Watson, 1972) and many more throughout Wales (e.g. Bryant and Carpenter, 1987; Campbell and Bowen, 1989; Ballantyne and Harris, 1994; Gurney and Worsley, 1996; Gurney, 2000; Harris, 2002);
- East Anglia (Walton Common) – shallow, mutually interfering depressions in chalk rubble, considered to be of varying ages (Prince, 1962; 1964; Sparks et al., 1972) and others across East Anglia (West et al., 1974; West 1987; 2015);
- Ireland (Near Camaross in County Wexford) (Mitchell, 1971; 1973) – collapsed mounds associated with spring lines at the foot of south facing slopes formed within a diamicton;
- Surrey (Carpenter and Woodcock, 1981) – 9 separate rampart and basin remnants in clusters on a gently sloping valley floor in unconsolidated Cretaceous sands (Lower Greensand).

Despite the early classification of the above listed suspected PRDs as ‘pingos’, this is not definite. Pissart (1974) recognised the disadvantage of identifying landforms based largely on morphology. The ‘viviers’ of the Hautes Fagnes were originally interpreted as hydraulic pingos (Pissart, 1956). However, the high plateau setting of the ‘viviers’ does not correspond to the topographic or hydrological setting required for hydraulic or hydrostatic pingos (e.g. a hillslope or mountainous area to permit a topographic gradient or a relict lake or river.
channel). In addition, the predominantly fine-grained sediment of the ‘viviers’ suggests formation by predominantly segregated ice, indicating that they are not hydraulic pingos. Subsequent awareness of work on mineral palsas in Sweden and northern Quebec (Hudson Bay region), and their similarity with the ‘viviers’ of the Hautes Fagnes, convinced Pissart and Juvigné (1980) to reassess the original interpretation of a pingo origin and reclassify the ‘pingos’ of the Hautes Fagnes as lithalsas.

A selected summary of landforms from across the world, identified as possible relict frost mounds (Table 2.3), illustrates that morphology and topographic setting provide insufficient data alone on which to base a definitive interpretation. Instead it is essential that investigation of relict features focuses on internal structures to establish their origin.

2.4 Summary

The origin of PRDs and diagnostic criteria with which to identify them remains ambiguous. Sedimentological investigations in the UK to date provide macroscopic context for suspected PRDs through coring, trenching and geophysical techniques. However, different interpretations and a paucity of modern analogues means there is little agreement on the origin of PRDs in the UK.

Little is known about the internal structures of acknowledged PRDs due to the lack of natural exposures. Micromorphology is an established technique for assessing strain within a range of sediment types and environmental settings. This project will, for the first time, characterise macroscopically and microscopically two well-preserved suspected PRDs from the UK and a known PRD from Belgium from different palaeo-periglacial settings. This will inform the identification of PRDs and contribute to a better understanding of their genesis.
### Table 2.3 Key characteristics of potential relict frost mounds world-wide.

<table>
<thead>
<tr>
<th>Country</th>
<th>Presumed type</th>
<th>Dimensions</th>
<th>Characteristics</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Africa: central Sahara</td>
<td>• Pingo</td>
<td>• 250 to 350 m diameter.</td>
<td>• Circular. • Occurring in groups. • Substrate: glacial deposits.</td>
<td>Biju-Duval et al., 1981</td>
</tr>
<tr>
<td>Arabia (central and north-western)</td>
<td>• Pingo</td>
<td>• 100 to 300 m diameter and up to 100 m wide.</td>
<td>• Circular. • Substrate: glacial deposits.</td>
<td>Vaslet, 1990</td>
</tr>
<tr>
<td>Belgium: (The Ardennes)</td>
<td>• Lithalsa</td>
<td>• ≤150 m diameter (average of 80 m). • Rampart height ≤ 4 m. • Variable basin depth from 1-2 to – 8 m.</td>
<td>• Circular and oval peat-filled ramparted depressions on flat surfaces; elongate or horse-shoe shaped on slopes. • Occur mostly in groups. • Substrate: Cambrian bedrock of weathered quartzite and phyllites (clay and sandstone) overlain by aeolian loams.</td>
<td>Pissart, 1963; 1965; 1974; 1983; 1994; 2000; 2002; 2003; Bastin et al., 1974</td>
</tr>
<tr>
<td>East Falkland Island (between Swan Inlet and Brenton Loch): (British overseas territory)</td>
<td>• Pingo</td>
<td>• 20 to 120 m diameter. • Rampart height ≤ 2 m and 20 m wide. • Basin depth ~ 3 m.</td>
<td>• Occur singly or in short chains, some interfere. • Substrate: unconsolidated thin stony sandy clay.</td>
<td>Aldiss and Edwards, 1999</td>
</tr>
<tr>
<td>France: (Paris Basin)</td>
<td>• Lithalsas, seasonal frost blisters, spring frost blisters, pingos (?)</td>
<td>• Depressions have median values of 37 m long for elongate forms and 13 m diameter for oval forms. • Basin depth av. 2.5 m with steep sides and a flat bottom.</td>
<td>• Abundant oval and elongated, water-filled depressions without ramparts on a low-relief plateau. • High density ≥ 138 forms. • Located in calcareous alluvium.</td>
<td>Cailleux, 1956; Pissart, 1968; Michel, 1967; Fiemal, 1976; De Gans, 1988; van Vliet-Lanoë et al., 2017</td>
</tr>
<tr>
<td>Western Germany</td>
<td>• Pingo</td>
<td>• 6 to 250 m diameter. • Basin depth up to 8 m.</td>
<td>• Mostly circular (some elongate) ramparts with depressions. • Located on a range of bedrock on both flat and steep (≤ 20 °) slopes.</td>
<td>De Gans, 1988</td>
</tr>
<tr>
<td>Ireland (County Kerry, County Wexford)</td>
<td>• Polygenetic pingo?</td>
<td>• 10 to 100 m diameter.</td>
<td>• Circular to elongate ramparts enclosing basins. • Associated with spring lines and the foot of south-facing slopes. • Occurring individually, in small groups and clusters. • Substrate: diamicton (solifluction deposit?).</td>
<td>Mitchell, 1971; 1973; Coxon and O’ Callaghan, 1987</td>
</tr>
<tr>
<td>Country</td>
<td>Presumed type</td>
<td>Dimensions</td>
<td>Characteristics</td>
<td>References</td>
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<tr>
<td>Netherlands: (Noord-Brabant, Groote Peel)</td>
<td>• Perennial frost mounds?</td>
<td>• Up to 90 m diameter.</td>
<td>• Oval or circular depressions.</td>
<td>Kasse and Bohncke, 1992</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Rampart height 0.5 to 1 m.</td>
<td>• Located on flat to low-relief areas, within small tributary valleys.</td>
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<td></td>
<td></td>
<td>• Basin depth max. 3 m.</td>
<td>• Occurring in groups or as solitary landforms.</td>
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<td></td>
<td></td>
<td></td>
<td>• Substrate: aeolian deposits.</td>
<td></td>
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<tr>
<td>North America: (e.g. British Columbia, Saskatchewan, Alberta, North Dakota)</td>
<td>• Pingo?; Dead-ice supraglacial and subglacial wasting?</td>
<td>• 3-90 m diameter (max. 450 m).</td>
<td>• Circular-oval ‘Prairie mounds’.</td>
<td>Henderson, 1959; Mollard, 2000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Rampart height ranges from 1.5 to 6 m (max. 12 m).</td>
<td>• Occur in clusters or separated by lake flats.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Depression depth range from 0.5 to 3 m.</td>
<td>• Some mounds have depressions; others are flat on top.</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>• Ramparts of clay till and basins infilled with silty lacustrine deposits, as well as lacustrine silt substrates.</td>
<td></td>
</tr>
<tr>
<td>Scandinavia: Sweden</td>
<td>• Frost mounds (palsa, pingo, frost blister?) or lithalsa?</td>
<td>• Diameters range from tens of metres up to 100 m.</td>
<td>• Variety of type and frequency of ramparted circular – oval and elongate ponds.</td>
<td>Rapp and Rudberg, 1960; Åkerman and Malmström, 1986</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Maximum rampart height 4.5 m.</td>
<td>• Located on flat or slightly sloping ground, close to streams.</td>
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<td></td>
<td></td>
<td></td>
<td>• Formed in till.</td>
<td></td>
</tr>
<tr>
<td>Scandinavia: north eastern Norway on the plateau of Finnmarksvidda</td>
<td>• Palsa (lithalsa?)/ pingo?</td>
<td>• Rampart height &lt; 1.5 m.</td>
<td>• Circular to oval lakes occurring in groups.</td>
<td>Svensson, 1969; Åhman, 1976</td>
</tr>
<tr>
<td></td>
<td>• Perhaps a transitional form?</td>
<td>• Diameter &lt; 40 m.</td>
<td>• Shallow depressions in fine-grained, glaciofluvial deposits with lenses of peat.</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>• Located alongside water bodies of irregular shapes in relatively flat valley bottoms.</td>
<td></td>
</tr>
<tr>
<td>Scandinavia: northern Finnish Lapland</td>
<td>• Pingo-like remnants (open-system?)</td>
<td>• 30 to 150 m diameter</td>
<td>• Circular, semi-circular and elongate forms.</td>
<td>Seppälä, 1972</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Rampart heights range from 0.5 to 4.5 m.</td>
<td>• Ponds in some basins, peat bogs in others.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Basin depths unknown.</td>
<td>• Substrate: till.</td>
<td></td>
</tr>
<tr>
<td>UK: England (Tamar Basin - Devon and Cornwall)</td>
<td>• Open-system-like pingo or pingo-palsa transition</td>
<td>• Up to 45 m diameter (circular); 60 m long (elongate).</td>
<td>• Mostly circular in plan view but one elongate form.</td>
<td>Miller, 1990</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Basin depth &lt; 2 m.</td>
<td>• Located in a col.</td>
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<td></td>
<td></td>
<td></td>
<td>• Formed in a silty head derived from shale bedrock.</td>
<td></td>
</tr>
<tr>
<td>Country</td>
<td>Presumed type</td>
<td>Dimensions</td>
<td>Characteristics</td>
<td>References</td>
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</tr>
<tr>
<td>UK: England (East Anglia, East Walton and Wretton)</td>
<td>• Ground-ice mounds</td>
<td>East Walton • Diameters ranging from 10 to 120 m. • Variable rampart height, max. ~ 2 m. • Basin depth max. ~ 3 m.</td>
<td>• Circular and semi-circular ramparts enclosing a pond or marshy depression. • High density, mutually interfering. • Formed in chalk rubble and sand. • Located on gently sloping ground.</td>
<td>Sparks et al., 1972</td>
</tr>
<tr>
<td></td>
<td>• Seasonal/ short lived perennial frost mounds</td>
<td>Wretton • Ramparts are 510 m wide. • Basins ≤ 3 m deep.</td>
<td>• Formed in sandy clay derived from weathered interglacial sediments. Features are associated with ice-wedge casts and cryoturbation structures.</td>
<td>West et al., 1974; West 1987; 2015</td>
</tr>
<tr>
<td>UK: England (Elstead, Surrey)</td>
<td>• Pingo (hydraulic)</td>
<td>• Ramparts 1 m max. high, diameter 100 m max. • An asymmetrical basin: ~ 4 m deep.</td>
<td>• Separate ramparts in a cluster located on a sand substrate.</td>
<td>Carpenter and Woodcock, 1981</td>
</tr>
<tr>
<td>UK: England (West Midlands, Shropshire – Camland Valley, Owlbury)</td>
<td>• Lithalsas</td>
<td>• 40–150 m diameter. • Ramparts 1–1.5 m high.</td>
<td>• 8 circular hollows. • Substrate: glaciolacustrine deposits.</td>
<td>Gurney and Worsley, 1996</td>
</tr>
<tr>
<td>UK: east and west central Wales (e.g. Llangurig and Cledlyn Valleys)</td>
<td>• Pingos (hydraulic).</td>
<td>Llangurig • Diameter from 42 to 120 m. • Rampart height ~ 1.5 m. • Basin depth ~ 6.5 m.</td>
<td>• Generally semi-circular with upslope rampart missing. • Some isolated, others intersecting. • Located in a poorly drained valley floor in angular, poorly washed gravels.</td>
<td>Pissart, 1963; Watson, 1971</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cledlyn Valley • Diameter up to 120 m and 250 m long. • Rampart height ~ 6.5 m • Rampart slopes ≤ 23.5°. • Basin depth up to 11 m+.</td>
<td>• Distinct, circular, semi-circular and elongate ramparts. • Mutually interfering clusters. • Located 165–235 m AOD on valley bottoms or lower valley sides within a diamicton. Hill slopes &lt; 8°.</td>
<td>Watson, 1971; 1982; Watson and Watson, 1972; 1974; Gurney, 1995; Harris, 2001; Ross et al., 2005; 2011</td>
</tr>
</tbody>
</table>
Chapter 3: Field sites and methods

3.1 Overview
The aim of this chapter is to: i) clarify the rationale for field site selection and introduce the study areas, ii) outline the macroscopic (e.g. coring, logging, clast fabric analysis) and microscopic (i.e. thin-section analysis) techniques used to examine PRDs in this study, and iii) specify the micromorphological and coring sampling strategies at each field site. Finally, the significance of bulk-sediment analyses (i.e. grain size, clay mineralogy and carbonate content), for the study of micro-scale sediment deformation, is clarified. A summary of methods used per field site investigation is given at the end of the chapter (Table 3.2).

3.2 Field sites
3.2.1 Site selection
Key field site characteristics were identified (Table 3.1) to meet the aim and objectives of the research project (Chapter 1, section 1.3) and are summarised below. Field sites must:

- contain landforms that have distinct ramparts with an associated depression (Watson, 1971; Washburn, 1979; Mackay, 1988; Pissart, 2003) and constitute well-preserved examples of accepted or suspected PRDs (e.g. in sites of special scientific interest (SSSI));
- be from different palaeo-periglacial environments (i.e. a range of periglacial environments from different geographical locations), to consider the impact of landform location within, and outside, the glacial limit on formation and/or decay mechanisms;
- be located within different sedimentary environments, and thus grain sizes, (i.e. to enable an examination of the significance of grain size on PRD genesis, composition and structures);
- comprise ramparts with minimal post-depositional modifications.

<table>
<thead>
<tr>
<th>Field site and key characteristics</th>
<th>Belgium</th>
<th>Norfolk</th>
<th>Wales</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preservation status of landform location</td>
<td>Nature reserve</td>
<td>SSSI</td>
<td>SSSI</td>
</tr>
<tr>
<td>Depositional environment at the Last Glacial Maximum (LGM) (c. 23–19 ka)</td>
<td>Unglaciated</td>
<td>Glaciated &gt; 150 ka ago but ice free at the LGM (c. 23–19 ka)</td>
<td>Glaciated at the LGM (c. 23–19 ka)</td>
</tr>
<tr>
<td>Superficial sedimentary environment</td>
<td>Aeolian silt</td>
<td>Fluvial silt and sand</td>
<td>Glacial till</td>
</tr>
<tr>
<td>Field site slope angle</td>
<td>~ 1°</td>
<td>~ 0.2°</td>
<td>~ 4°</td>
</tr>
</tbody>
</table>
3.2.2 Field site summaries

Based on key characteristics identified (Table 3.1), field sites were initially identified from desk-top studies (i.e. published works, aerial photographs and the processing of remote-sensing data using GIS techniques) (Bishop et al., 2012; Otto and Smith, 2013) and a subsequent reconnaissance. In all cases, permission was sought from the landowner and relevant agency in relation to protected status. Locations in Belgium and the UK (Norfolk and Wales) (Fig. 3.1), were deemed to meet the field site selection criteria and all sites have compelling reasons why they should form part of the study. Note that all locations are given in decimal degrees, using the World Geodetic System (WGS84).

![Map of field site locations](image)

Fig. 3.1 Field site locations.

i. Belgium: Konnerzvenn, the Hautes Fagnes (High Fens), Ardennes

Situated to the east of Belgium on the Belgium-German border (Fig. 3.1), the Hautes Fagnes is classified as a high plateau (maximum height 694 m above ordnance datum (AOD)) and comprises moorland and forests (Nekrassoff, 2007). Within the Hautes Fagnes is an abundance of relict lithalsas or ‘viviers’ (a term used to describe peaty silt basins, surrounded by a gravelly rampart) (Pissart, 2000; 2003; Pissart et al., 2011). Ground surface mapping confirms that the lithalsa remnants are circular, horseshoe-shaped and elongate with an average diameter of 80 m, ramparts up to 4 m high and basin depths up to 7.5 m. The PRDs in the Hautes Fagnes mainly exist on northern slopes where gradients are less than 5% (Pissart, 2000). The rampart sampled (PRD K) is elongate (~ 240 m long and ~ 75 m at the widest point) and is oriented east to west (Pissart and Juvigné, 1980). The field site is located ~ 585 m AOD (Fig. 3.2).
The Hautes Fagnes location was selected because:

- PRDs here are perfectly preserved rampart and basin remnants of landforms widely agreed to be relict lithalsas (Pissart, 2000, 2003) and are comparable with modern analogues for lithalsas in the Hudson Bay region of Quebec, Canada (Pissart et al., 2011). The Hautes Fagnes is a well-preserved site, protected by National Park status (Département de la Nature et des Forêts). This site provides a means to investigate a lithalssa remnant, in a present-day temperate setting, which enables informed comparisons to be made with ramparts of a less certain origin;
- there is no evidence that the area has been glaciated, so the sediment is not complicated by potential deformation from an overriding ice sheet (Litt et al., 2008; Hughes et al., 2016);
- the site is situated on Cambrian bedrock of quartzite, phyllite and quartzо-phyllite and the ramparts comprise aeolian silt mixed with soliflucted bedrock deposits (Pissart, 2003). This is in contrast to grain sizes examined at the other sites;
- the protected status of the site and its location on a high plateau minimises the effects of human interference and slope movement;
- PRDₖ (at Konnerzvenn) was selected for investigation, in particular, as it is one of the best-preserved landforms in the area. In addition, it is the most accessible and required minimal excavation, thus preserving the feature.
The field site is located within the Nar Valley catchment of west Norfolk (Fig. 3.1). Walton Common is in a lowland plateau setting designated as a site of special scientific interest (SSSI). The topography is low relief, ~15 m above ordnance datum (AOD) at the foot of higher ground to the east (~80 m AOD). This boggy site is classified as valley-head fen (i.e. low lying, alkaline marshland located close to the headwaters of small streams) (Wheeler and Shaw, 2000). Ground surface mapping confirms that the area is densely populated with solitary and overlapping, oval to circular, chalk-rich ramparts (~10 to ~120 m diameter and ≤3 m in height) surrounding dry and ponded shallow depressions (<3 m deep), on very gently sloping ground ~0.2°. There is also a high density of low, elongate ridges (<0.5 m in height). Wheeler and Shaw (2000) report an extensive seepage network in the north north eastern (NNE) part of the Common within a woodland that feeds a stream to the west. The source of the groundwater is not exactly known but it is thought to be supplied to the site from chalk aquifer groundwater discharge travelling from east to west through sandy superficial sediments (Wheeler and Shaw, 2000). Water levels in the basins are highly variable throughout the year (based on observations as part of the current project) but water seepage from springs makes the land permanently boggy. The suspected PRD investigated (PRDWC) is ~80 m in diameter and is conjoined on its north eastern flank with a smaller ovoid rampart (~60 m diameter) to form a figure of eight - both are oriented northeast to south west (52.717231° N, 0.567594° W) (Fig. 3.3).

Walton Common was selected because:

- there is broad acceptance that the landforms here are former ground-ice mounds (Prince, 1962, 1964; Sparks et al., 1972; Pissart, 2000; 2002; Clay, 2015). The suspected PRDs are favourably compared to the relict lithalsas in Lac Hendry, Quebec, Canada (Worsley et al., 1995). Walton Common is a well-preserved, SSSI site;
- the field site is uniquely placed in relation to the previous ice-sheet limits, having been glaciated during the Anglian glaciation (c. 480–428 ka), but ice free during the last, Devensian, glaciation (Clark et al., 2012);
- the superficial geology ranges from none to Nar Valley Formation (clay and silt) overlying Chalk bedrock: West Melbury Marly Chalk and Zig Zag Chalk formations (Gallois, 1994). This contrasts with the grain sizes examined at the other sites;
- the protected status of the site and its location on a low plateau minimises the effects of human interference and slope movement;
• PRD_{WC} was selected as it is the most obvious rampart found on the Common. In addition, it was accessible and presented a minimal risk of flooding from excavation.

![Oblique aerial photograph of Walton Common, Norfolk](image)

**Fig. 3.3** Oblique aerial photograph of Walton Common, Norfolk (Norfolk County Council, 1946). PRD_{WC} is ~ 80 m in diameter. A white cross marks the rampart sampling location and a yellow dot the basin sampling location.

**iii. Wales: Cledlyn Valley (Fig. 3.1)**

The field site is located in south west Wales, in a valley bottom (~ 250 m AOD) (Watson, 1971; Watson and Watson, 1972; Watson and Watson, 1974; Watson, 1982; Campbell and Bowen, 1989; Gurney, 1994; Gurney, 1995; Ross et al., 2005; Ross, 2006). The Cledlyn Valley is an upland setting and the field site is designated as a site of special scientific interest (SSSI). Ground surface mapping confirms that the valley contains a cluster of distinct, sometimes overlapping, circular to elongate suspected periglacial ramparted depressions (PRDs) between 165 and 215 m above ordnance datum (AOD). The ramparts comprise cohesionless sediment (with grains visible to the naked eye) and are located on valley foot slopes of < 6 ° (Ross, 2006). The ramparts range in height from 1 m to 6.5 m, circular forms are 30 m to 120 m in diameter and elongate forms are 150 m to 250 m long (Watson, 1971). Basin depths are variable (from < 2.5 m to > 11 m) (Watson and Watson, 1972). The area has a complex ‘hummocky’ microtopography often associated with glacial terrain (Davies et al., 2006). The Nant Cledlyn (river) cuts through the field site - joined by the Cledlyn Fâch (stream) - running from west to east before turning south at Cwrt Newydd to join the Afon Teifi.
The Cledlyn Valley contains multiple PRDs, probably of Younger Dryas age (Pissart, 1963; Gurney, 1995; Harris, 2001) based on pollen analysis (Handa and Moore, 1976; Harris, 2001; Walker and James, 2001) and radiocarbon dating (Shotton et al., 1975). As part of the current research project, three suspected PRDs are examined (Watson, 1971; Watson and Watson, 1972; Watson and Watson, 1974; Watson, 1982; Campbell and Bowen, 1989; Gurney, 1994; Gurney, 1995): i) a horseshoe-shaped rampart (~ 80 m diameter), with the upslope side missing and overlapping with another PRD on its north eastern flank (PRDCV1) (52.110210° N, 4.234546° W), ii) an elongate form (~ 150 m long and ~ 40 m max. wide), with the upslope rampart missing (PRDCV2) (52.110428° N, 4.233392° W), and iii) a circular form (~ 40 m diameter) partially eroded by fluvial action (PRDCV3) (52.112425° N, 4.230345° W) (Fig. 3.4). The ramparts investigated (up to 6.5 m in height) comprise coarse-grained sediment ramparts (up to ~ 5 m in height), surrounding clayey, silt basins (some in excess of 10 m deep).

The Cledlyn Valley field site was selected because:

- it contains a complex of suspected PRDs considered to be the best example of ‘fossil pingos’ in Britain (Campbell and Bowen, 1989) and is a well-preserved, SSSI site;
- the Cledlyn Valley was subject to successive glaciations including the most recent (Late Devensian, c. 26–10 ka) and the most extensive (Anglian Stage, c. 480–428 ka) (Campbell and Bowen, 1989; Clark et al., 2012). This allows characterisation of PRDs in a periglacial environment contextualised by glacial landforms and sediments;
- the superficial sediment is Devensian-age glacial till derived from the surrounding Palaeozoic bedrock (i.e. Ordovician mudrock) (Davies et al., 2006). This provides an interesting contrast to the grain sizes examined at the other sites selected for this research;
- the protected status of the site and its location on a valley bottom minimises the effects of human interference and slope movement on the suspected PRDs;
- a range of rampart forms was investigated in the Cledlyn Valley (i.e. horseshoe-shaped (PRDCV1), elongate (PRDCV2) and circular (PRDCV3)), to permit comparison across different suspected PRD geometries. The PRDs selected all contain obvious ramparts, unmodified by human activity and were safely accessible.
3.3 Field analyses

3.3.1 Coring methods (basins)
Core samples were taken from PRD basins at each field site to: i) confirm the local stratigraphy, ii) ascertain whether there is a relationship between the basin and rampart material (Mackay, 1988) (i.e. the rampart sediment is derived from the original pingo slopes and should be comparable with that found beneath the basin infill (Flemal, 1976; Mackay, 1988)), and iii) to identify the suspected PRD substrate (Gurney, 1995) (i.e. to infer depositional history and deduce landform genesis). A basin core was taken from as close to the centre as possible to ensure its preservation potential (Frew, 2014). A review of the literature was undertaken to ensure that previous coring sites were avoided. The core was photographed and key sedimentary horizons noted in the field (Frew, 2014).

A vibrocorer was used with a sleeve-lined Stitz corer to collect overlapping sediment samples. Core sleeves were sealed with duct tape (clearly labelled for top, base and depth), transported horizontally and stored in the laboratory cold room. Cores were logged and sampled for clay mineralogy by X-ray diffraction (XRD) (Appendix 3.2), carbonate content by calcimeter analysis (Appendix 3.3) and particle-size distribution (PSD) by laser particle-size analysis (Appendix 3.4) for comparison with the rampart samples. All sediment colour descriptions were made with reference to a Munsell colour chart (Munsell, 1994). When it was not possible to use the vibrocorer (i.e. at the Belgium and Norfolk field sites), due to
water logging or a clast-rich sediment, hand coring was undertaken with a narrow-gouge corer (1 m in length and 30 mm diameter) and extension rods.

3.3.2 Section and pit excavation (ramparts)
The aim of the research project is to identify the cryogenic origins and formation processes of PRDs in different environmental settings by characterising their internal structures. As no landowner would permit mechanical excavation of their land (e.g. use of a digger), sections and pits were cleared and excavated by hand. Locations were selected on the basis that they represented the most preserved part of an obvious rampart. Where natural rampart exposures exist, samples were taken from these (e.g. in the Cledlyn Valley, two ramps (PRDCV2 and PRDCV3), have been eroded by fluvial action, so presenting natural exposures). In such cases, sediment faces were cleared to present a fresh sampling surface and to avoid surface slumps and weathering. Alternatively, pit exposures were excavated into ramparts (PRDCV1). All field site investigations were conducted in accordance with British Standard 5930: Code of Practice for Site Investigations (BSI, 1999). Pits no deeper than 1 m (BSI, 1999) were measured, marked and de-turfed for replacement once backfilled. Topsoil and underlying sediment were removed and kept on a tarpaulin a safe distance from the pit to avoid accident or contamination (BSI, 1999). Sections were logged, photographed and then backfilled.

3.3.3 Macroscopic descriptions
Macroscopic field descriptions were used to assist with the consideration of the depositional environment in each location and to provide the contextual framework for microstructural analysis (van der Meer, 1993). Descriptions took the following forms:

i. Sedimentary logging

At each site sediment was logged using standard lithofacies codes (Eyles et al., 1983) in order to identify different potential units and the local stratigraphy. All macro-scale features were examined for subsequent consideration in respect of PRD growth and/or decay mechanisms (e.g. internal tilting of strata can be caused by heave during frost-mound growth (Pissart and French, 1976; Mackay, 1978; Pissart and Gangloff, 1984)). Colour was recorded using a Munsell colour chart (Munsell, 1994). Other key observations included:

- particle-size range (using the Wentworth scale), proportion, texture and degree of sorting (Hambrey, 1994),
- clast shape (Powers, 1953),
- lithology, to determine provenance (Hubbard and Glasser, 2005),
• depositional structures (e.g. internal bedding features) (Hubbard and Glasser, 2005),
• bed thickness and geometry (Hubbard and Glasser, 2005),
• contacts between units (Hubbard and Glasser, 2005).

ii. Clast-fabric analysis
Fabric analysis relates to the directional properties of sediment (e.g. orientation of clasts or grains). Alongside data on clast morphology, lithology and grain-size classification, fabric analysis contributes towards interpretations regarding facies type, depositional environment, transport processes and palaeoflow (Dowdeswell et al., 1985; Hart, 1994; Benn, 1995; Hubbard and Glasser, 2005).

Measurements were taken from cleared sections and pits in ramparts and recorded using a Suunto MC2 Professional Compass Clinometer adjusted for magnetic declination. To be statistically significant, the dip and strike of up to 50 in-situ prolate clasts (with an elongation ratio of at least 1.5:1), between 30 and 125 mm, from within 0.5 m², are required (Hart and Martinez, 1997; Hubbard and Glasser, 2005; Evans and Benn, 2014). This was only possible at the Cledlyn Valley field site in Wales. In Belgium and Norfolk, there were too few apparent clasts to be statistically significant. In addition, in some lithologies within the Cledlyn Valley field site, clasts were too cemented in the sediment to determine their declination. Subsequently, RocScience® software was used to plot clast orientation as follows:

• rose diagrams (2D) for flow direction;
• polar diagrams, for flow direction, including dip data and;
• countered stereonets, to indicate statistical significance.

iii. Clast-shape, size and roundness analysis
Sediment-transport pathways, facies and depositional environments can be determined by clast shape, particle size and roundness (Sneed and Folk, 1958; Benn, 1994; Benn and Ballantyne, 1994; Graham and Midgley, 2000; Hubbard and Glasser, 2005). To classify clast shape, the three orthogonal axes (long (a-), short (b-) and intermediate (c-)) of 30-50 clasts were measured from pits and section faces and subsequently their ratios plotted on Sneed and Folk (ternary) diagrams (Fig. 3.5) using Tri-plot (Graham and Midgley, 2000). Data on clast roundness are displayed in histograms. This technique was used in both Norfolk and Wales but there were insufficient clasts or the correct size to conduct this analysis in Belgium.
Clast-shape and roundness characteristics are described using the \( C_{40} \) index (percentage clasts with the \( c \)-axes: \( a \)-axes ratio \( \leq 0.4 \)) (Benn and Ballantyne, 1993) and the RA index (percentage of very angular and angular clasts). The \( C_{40} \) and RA indices and their covariance differentiate can be used to infer depositional environments (e.g. blocky clasts with striations and abundant rounded edges are indicative of actively transported clasts in glacial till and slabby-elongate, angular clasts respectively suggest passively transported clasts in glacial till (Benn, 1994)). This analysis is particularly relevant to the field site in the Cledlyn Valley, Wales, which has a regional superficial cover of glacial till (Waters et al., 1997; Bowen, 1999; Bowen, 2005). The RA index can also be useful in non-glacial sites (i.e. Norfolk), when considering sediment-transport mechanisms.

### 3.3.4 Micromorphological sampling

Undisturbed sediment samples were collected using steel Kubiena tins (65 x 40 x 40 mm) with two lids and a cutting edge on one side. These were carefully inserted into cleared sections and pit faces in the field. A spatula or cutting knife was used to cut around the sample to ensure that it was not subject to undue force as the tin was eased into the sediment. Tins were carefully dug out from the back and trimmed. Sample number and orientation were marked clearly on the tin and any remaining void spaces in the sample were carefully filled with fine sand before the sample was sealed to make it air tight to avoid desiccation. Samples were wrapped in brown tape and bubble wrap, to keep them moist, and transported with minimal disturbance to Royal Holloway, University of London (RHUL), for thin sectioning. Where sediment was too gravelly for a tin sample to be extracted due to obstructing clasts (e.g. some till samples in the Cledlyn Valley), a massive
sample was removed using a micropick axe and then trimmed with a scalpel and wrapped and labelled, as for all other samples, and transported for thin sectioning.

3.3.5 Micromorphological and coring sampling strategies

Sampling strategy is influenced by the original project aim and objectives and also the accessibility of sediment. The aim of this research is to identify the cryogenic origins and formation processes of PRDs in different environmental settings by a macroscopic and microscopic characterisation of their internal structures. To meet this aim, undisturbed samples from the vertical and horizontal profile of ramparts were collected in order to consider any changes in deformation, during formation or decay of the frost mound, with depth and/or lateral extent. Where macro-scale structures were present these were also sampled (e.g. around a folded peat lens in the rampart in Konnerzvenn). In the absence of macroscopic structures of interest, representative samples from each lithological unit were taken, to infer the depositional environment and permit consideration of the impact of different grain sizes on deformation microstructures. In addition, a sample of loose sediment was collected, close to each micromorphological sample, for bulk-sediment analyses (i.e. clay mineralogy, carbonate content and PSD) (section 3.5).

For each field site, a representative sample of the regional superficial cover was also collected as a micromorphological control sample (i.e. thin sections were produced from a superficial sediment sample, unaffected by frost-mound formation or decay processes, for comparison with the samples taken from suspected PRDs at each field site). The purpose of the control sample is to assist with the identification of features within the PRD samples that are specifically related to frost-mound formation and/or decay. Present-day soils and weathering profiles were avoided and notes were made of conditions or features which might impact on micro-scale observations (e.g. removal of clasts from sample tins in order to seal them, the presence of roots or biological activity). The micromorphological and coring sampling strategies for each field site are summarised:

i. Belgium: Hautes Fagnes, the Ardennes

Twenty samples were collected for thin sectioning, from a cross-section trenched through a PRD near the Belgian-German border. The rampart had previously been trenched normal to the rampart, so it was possible to sample the horizontal as well as the vertical profile (Fig. 3.6). Sample selection and rationale was conducted to ensure the following:
- representative samples from each lithological unit;
- macroscopic features of interest: i) above and below the undulating peat lens, ii) around the folded tip of the peat lens, and iii) heavily Fe-Mn stained sediment from the basinward flank and;
- samples from vertical and lateral extents to ensure any potential change in deformation in either dimension was captured.

Fig. 3.6 Konnerzvenn: Cross-section through rampart facing south, showing micromorphological sample locations (yellow rectangles) (field of view 8 x 4 m).

In addition, a micromorphological control sample was collected from similar sediment to the rampart (silt and clay), and representative of the regional superficial cover, but unaffected by frost-mound formation processes. As there are no natural exposures of this superficial sediment, an inter-rampart location was selected for the control sample where a natural face had been eroded through the sediment by water run-off from the locality (50.579271 ° N, 6.189130 ° E) (Fig. 3.7).

A core sample was taken close to the inner flank of the frost mound (50.579984 ° N, 6.191586 ° E) (Fig. 3.8). Prolonged rainfall prior to and during field work meant that it was unsafe to core at the centre of the basin.
ii. Walton Common, Norfolk (Fig. 3.3)

Seven thin-section samples were taken from three test pits (1 m³) from the rampart of the same suspected PRD on Walton Common (52.717231 ° N, 0.567594 ° E). As there is no natural exposure of the rampart, pits were selected from the best-preserved sections to provide data from the vertical and lateral profile: i) from the rampart top (PRD\textsubscript{WC2}), ii) base (PRD\textsubscript{WC1}), and iii) headlong into the rampart at the point of a natural breach (PRD\textsubscript{WC3}) (Fig. 3.9). Samples were taken from each lithological unit forming part of the rampart.

Since there are no natural sediment exposures representative of the superficial cover, an inter-rampart control micromorphological sample was taken from undisturbed ground between the ramparts (52.717444 ° N, 0.567328 ° E) (Fig. 3.10). In addition, a basin core sample was taken, from close to the centre of the basin (52.717015 ° N, 0.567685 ° E), using a narrow-gouge corer (Fig. 3.11).
Fig. 3.9A) Walton Common, longitudinal rampart profile with pit locations indicated; B) Pits (Scale: 1 m).
Fig. 3.10 Walton Common control sample A) Test pit: facing 250°, red dashed line indicates location of Kubiena tin; B) Sample collected from sandy layer. Scale (0.3 m high).

Fig. 3.11 A) Walton Common, looking south, into the basin from the rampart; B) Narrow-gouge coring close to the centre of the basin.
iii. **Cledlyn Valley, Wales**

Seven thin-section samples were produced from three suspected PRDs in the Cledlyn Valley. Three obvious ramparts of differing geometries were selected to permit consideration of deformation structures from varying PRD forms. Samples from section faces and a pit were selected as follows:

- **PRD_{CV1}** (Bedwyllyn/Coedlanau-fach) (Pingo U of Watson (1971)) (Fig. 3.4):

  Two micromorphological samples were taken from the upper and lower sections of a horseshoe-shaped rampart (no upslope side), with a maximum height of ~ 5 m, around 80 m in diameter and overlapping with another rampart to the east. A 1 m³ pit was dug into the crest of the rampart, facing north north east, where the ground was undisturbed, ~ 207 m AOD (52.110471 ° N, 4.234127 ° W) (Fig. 3.12A). The gravelly sediment is so compacted that a micropick axe was required to extract a sample, which was then trimmed. A second micromorphological sample was taken from a well-preserved section of the rampart base, facing south east, where the installation of a drainage ditch had created a natural section, ~ 204 m AOD (52.110210 ° N, 4.234546 ° W) (Fig. 3.12B). This provides samples from different lithologies across the vertical profile of PRD_{CV1}.

- **PRD_{CV2}** (Rhydnis) (52.110248 ° N, 4.233392 ° W) (Pingo R of Watson (1971)) (Fig. 3.4):

  A natural exposure through an elongate rampart, ~ 202 m AOD, cut by the Nant Cledlyn (river) was sampled (Figs. 3.13A-C). The rampart is perpendicular to the break of slope and parallel to the valley axis, ~ 150 m long (no upslope side) and has a maximum width of ~ 40 m at the centre. Four samples were collected from this section face, in vertical succession.
Fig. 3.13 Cledlyn Valley: PRD CV 2 A) Top of the rampart. Spade for scale: 1.03 m; B) Middle of the rampart. Tape measure for scale: 1.4 m, and C) Middle-base of the rampart. Tape measure for scale: 1 m.
• **PRD<sub>CV3</sub>** (Ael-Y-Bryn) (52.112425° N, 4.230345° W) (Fig. 3.4):

A 1 m deep section was cleared through the outer rampart of a circular rampart (~ 40 m diameter) ~ 200 m AOD. The section was a natural exposure that had been cut by the Cledlyn Fach (stream). This location was selected because of a particular macrostructure of interest (i.e. a series of gravelly laminations near the base of the rampart (Fig. 3.14)).

• **Control sample**

A micromorphological control sample was taken from a 9 m high coastal cliff at Aberarth, between Dolauarth and Graig Ddu. (52.261302° N, 4.2142512° W) (Fig. 3.15). This location was selected as it is classified as Welsh Ice Till (WIT) (Talbot and Cosgrove, 2011) and is considered to comprise both primary periglacial and paraglacial sediments (reworked by glaciation and deglaciation processes) (Etienne *et al*., 2005) similar to those identified at the field site (Chapter 6).

• **Basin core**

A sediment core was taken from the basin infill of PRD<sub>CV1</sub> (52.110668° N, 4.234352° W) (Fig. 3.16). The vibrocorer was used and reached a depth of ~ 9 m was reached but the corer could not penetrate further due to the presence of pebbles.
Fig. 3.14 Cledlyn Valley: PRD_{CV3} A) Circular rampart eroded by the Cledlyn Fâch stream; B) Sampling location containing a series of layered gravels. Tape measure for scale, 1 m.
Fig. 3.15A) Aberarth, west Wales: Cliffs of glacial till (Talbot and Cosgrove, 2011); B) Cleared cliff section (1 x 0.6 m); micropick axe measures 0.38 m long.
3.4 Microscopic analysis

3.4.1 Thin-section production
The technique for thin-section production followed that of Palmer et al. (2008), developed from Lee and Kemp (1992). The sample was first dried, then impregnated with a polymer resin in a vacuum chamber and left to cure. A solid block formed, which was sawn in half and polished using increasingly finer diamond abrasives and finished on a P1200 silicon carbide paper. The resin impregnated block was bonded to a glass slide ~ 1 mm thick, ground to ~ 50 µm and polished again using diamond abrasives to a thickness of 30 µm. This process produced a thin section (10 x 8 cm) for micromorphological analysis.

3.4.2 Microscopic descriptions
Thin-section analysis was conducted using a Petroscope Leica (Z6 APO) magnification range (x 5 to x 36), Leica DFC camera and Leica Application Suite V 2.7 for digital imaging. Thin-section analysis is based on long-established techniques in soil micromorphology (Brewer, 1964; Bullock et al., 1985; Fitzpatrick, 1993; van der Meer, 1993; Menzies, 2000; Stoops et al., 2010). Consequently, many of the descriptive terms used in sediment micromorphology have their origins in pedology and structural geology – a glossary of
terms is included (Appendix 3.1). In micromorphology, sediment is classified as plasma and S-matrix (Menzies et al., 2010; van der Meer and Menzies, 2011). Of significance is the potential relationship within and between plasma domains and skeleton grains, expressed as microstructures. van der Meer (1993) classified microstructures into those related to the plasma only (plasmic fabric), those related to skeleton grains only (microfabric) and those related to both plasma and skeleton grains (skelsepic plasmic fabric).

Description and analysis of thin sections followed the accepted tradition of characterisation first at the meso-scale: holding the thin section to the light and examining a high-quality scan to develop an overview of lithological units, intermediate-sized structural patterns and the relationship between plasma and S-matrix (van der Meer and Menzies, 2011). This was followed by systematic examination under the microscope and recording of plasma abundance, texture and content; skeleton grain size and shape, void structures (form and proportion); structural features (e.g. sedimentary, deformational). Observations were noted on template sheets recording qualitative and quantitative details. Recording and presentation of data were informed by Carr (2004), Linch (2010) and Linch et al. (2012).

3.4.3 Microfabric analysis
Orientations of apparent long-axes of 50 grains in each thin section were measured following image capture on a Leica microscope (Z6 APO) (Harris and Ellis, 1980; Carr, 2001; Carr and Rose, 2003). Grain orientations were plotted on rose diagrams (2D) and contoured stereonets using RocScience® software. Classification of microfabrics follows that of Brewer (1976):

- Strongly oriented – more than 60% with principal long-axes within a sector of 30 °;
- Moderately oriented – more than 40 to 60% with principal long-axes within a sector of 30 °;
- Weakly oriented – more than 20 to 40% with principal long-axes within a sector of 30 °;
- Unoriented – less than 20% with principal long-axes within a sector of 30 °.

In addition, roundness for 50 skeleton grains was recorded and plotted as bar charts.

3.5 Bulk-sediment analyses
Microscopic analyses must be contextualised by analysing bulk-sediment properties. For example, clay mineralogy and grain size can influence sediment-deformation characteristics
and the optical properties of thin sections under polarised light are affected by carbonate content (Bellinfante et al., 1974). Representative bulk-sediment samples of the in situ material were collected in clearly labelled, airtight bags, typically within the vicinity of thin-section samples. They were subdivided by quartering (Head, 1980) and oven dried (LTE scientific OP250 oven) at 105 °C for 24 hours (British Standards Institution BSI 1377: Part 2 (1990a); Head, 1980). The samples were segregated (< 2 mm; > 2 mm) by dry sieving (BSI, 2009a). The fraction ≤2 mm was analysed for bulk-sediment properties:

i. **Particle-size distribution (PSD)**

Particle-size distribution is the percentages of the various grain sizes present in a sediment. Particle-size properties provide information regarding source material, degree of sorting and the processes of erosion, transport and deposition (Hoey, 2004) which, when combined with data on grain morphology and fabric, provide an insight into the original sedimentary environment. In addition, grain size acts as a constraint on sediment strength and strain response, porosity and permeability (Benn and Evans, 1998). These properties are key to deformation style, intensity and detectability (van der Meer et al., 2003; Hart et al., 2004; Linch and van der Meer, 2013). It is an objective of this research to investigate PRDs in different environmental settings and thus grain sizes, therefore PSD is a key technique. Due to the wide range in grain size of the sediments collected, two techniques were used to determine PSD: i) sieve shaking (for particles > 63 µm) and ii) laser diffraction analysis (for particles < 63 µm) (BSI, 1990b; 1990c; Hubbard and Glasser, 2005; BSI, 2009a; 2009b; Head, 1980) (Appendix 3.2).

ii. **Clay mineralogy (X-ray diffraction (XRD) analysis)**

Plasmic fabric is an indicator of stress applied to a sediment as clay particles orientate themselves in response to the force applied (van der Meer et al., 2003). Plasmic fabric exhibits birefringence under crossed-polarised light and can appear in a range of forms from strong random orientation (omnisepic plasmic fabric) to strong preferred orientation (unistrial plasmic fabric) (van der Meer and Menzies, 2011). In addition, plasmic fabrics are identified in vertisols (soils with a high content of expansive clay e.g. smectite) due to shrink-swell processes (Blokhuis et al., 1970). These take the form of planar voids, masepic, skelsepic, vosepic and unistrial plasmic fabric (Blokhuis et al., 1970; Dalrymple and Jim, 1984; Blokhuis et al., 1990; Hiemstra and Rijsdijk, 2003). Therefore, the presence of smectite (swelling) clays (e.g. montmorillonite, nontrite and saponite) must be identified as it affects the interpretation of deformation structures in thin section. Clay mineralogy was identified using X-ray diffraction (XRD). This is a non-destructive analytical technique which can
identify the mineralogical composition of a material based on its unique atomic arrangement within its crystal structure. This is determined by the angles of diffraction of the X-ray beams that have been projected on to the sample (BSI, 2003; Moore and Reynolds, 1997) (Fig. 3.17). Classification of clay content follows that of Dalrymple and Jim (1984):

- Low: 0-10%;
- Medium: 20-40%;
- High: > 60%.

Dalrymple and Jim (1984) observed that most fabric change occurs at medium clay content and that at low and high contents skeleton grains and clay particles dominate respectively, thus allowing for a narrower range of fabric deformation in these zones. In addition, whilst low clay content reduces birefringent properties of the sediment indicative of deformation processes, these may still be detected by the identification of rotational structures (e.g. turbates (van der Meer et al., 2003)). This makes identification of clay mineralogy and content a significant factor in micromorphological studies. Techniques follow those of Moore and Reynolds (1997) and the British Standard EN 13925-2 (2003) (Appendix 3.3).

Fig. 3.17: X-ray diffraction patterns of smectite clays showing the effect of standard treatments (United States Geological Survey (USGS), 2015).
iii. **Carbonate analysis**

In combination with other features, carbonates are indicators of sediment origin and past history (Menzies *et al.*, 2010). However, primary and secondary carbonates (*e.g.* the re-dissolving and re-precipitation of carbonates), disrupt cross-polarised light as the crystal lattice structure of carbonates causes light to be diffracted at greater angles than those for clay, thus masking birefringence and plasmic fabric in thin sections (Bellinfante *et al.*, 1974). Furthermore, secondary carbonates influence the properties of the sediment, causing it to stiffen, influencing deformational microstructures (van der Meer *et al.*, 2003). Therefore, quantifying the carbonate content of a sample is essential for contextualising micromorphological analysis. In line with guidelines suggested by Linch (2010), > 20% carbonate content is taken as high; < 20% carbonate content is low, although it is noted that as little as 10% can mask birefringence (Linch and van der Meer, 2013). Calcimeter analysis was conducted. The technique follows those of BS EN ISO 10693 (2014) and Eijkelkamp (2012) (Appendix 3.4).

A summary of methods used per field site investigation is given in Table 3.2.

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Chapter 4: Konnerzvenn, the Hautes Fagnes, Belgium

4.1 Introduction

4.1.1 Field site context

The purpose of this investigation is to identify and confirm the diagnostic features of an accepted relict perennial frost mound at the macro- and micro-scale. At this field site, a relict lithalsa is examined at Konnerzvenn (Pissart and Juvigné, 1980; Pissart, 2000; 2003; 2009), ~13 km south east of Eupen, in the province of Liège, near the Belgian-German border (Figs. 4.1A and B). There has been some debate regarding the evidence for glaciation in the Ardennes-Eifel region caused, in part, by the presence of large quartzite boulders on high ground (Stamm, 1912; Fourmarier, 1923) but these are explained by periglacial processes (e.g. freeze-thaw action and gelifraction) that can fracture bedrock and uplift (i.e. frost-jack) stones and boulders (Fourmarier, 1945; Pissart, 1953; van Vliet-Lanoë, 1985). The Scandinavian Ice Sheet (SIS) did not extend beyond the Netherlands and Germany during the Elsterian (Anglian) Stage (c. 424–478 ka) – the oldest and most extensive glaciation in north-central Europe (Litt et al., 2008). During the Last Glacial Maximum (LGM) (c. 23–19 ka), the SIS reached its southern extreme at Denmark and Germany (Hughes et al., 2016), while Belgium formed part of a broad permafrost zone that experienced periglacial conditions only (Vandenberghhe et al., 2014), resulting in extensive aeolian deposits (Kasse, 1997; 2002). Therefore, the entire sequence in this investigation is unequivocally unaffected by glacial processes.

The regional geology of the Ardennes includes inliers of Lower Palaeozoic, mid to late Cambro-Ordovician (c. 501–488 Ma) rocks, which were deformed during the Caledonian (c. 490–390 Ma) and Variscan (c. 290 Ma) orogenies (Geyer et al., 2008) and have subsequently weathered to clays (Verniers et al., 2001). Slate and quartzite rocks of the Revin Group (La Venne Formation, c. 518–495 Ma) are found within the Stavelot-Venn Massif in the field site area (Verniers et al., 2001). This rock unit is heterogeneous with sometimes very clayey and micaceous quartzite and gravel layers (Verniers et al., 2001). Subsequent Cretaceous deposits of the Gulpen Formation (c. 72–66 Ma) are now only present in thin, patchy deposits of clay and flints (Geyer et al., 2008). There is a close correlation between the location of weathered quartzite rocks and the lithalsas of the Hautes Fagnes (Pissart, 2009). Pissart (2009) suggested that the fractured bedrock acted as an aquifer to supply the necessary hydrological environment for lithalsa formation during cold climate conditions. The superficial cover in the Ardennes region is aeolian silt and clay-with flints (Pingot, in press).
Fig. 4.1A) The field site (Konnerzvenn) located within the Hautes Fagnes in Belgium; B) Lidar map with the rampart section under investigation at Konnerzvenn (PRD₃) circled in red (Wallonie, 2016).
4.1.2 Summary of previous research

Pissart (1956) originally proposed a periglacial origin for the PRDs in the Ardennes and initially identified ramparts surrounding peat depressions as pingos dating from the last glacial period (c. 110–11.5 ka). Subsequently, the pingo interpretation was revised to that of a probable palsa without peat Pissart (1974) - and finally to a lithalsa (Pissart et al., 1998) (Chapter 2, section 2.3). Sedimentological, morphological, palynological and mineralogical studies were conducted on the PRDs in the Hautes Fagnes in the Brackvenn and Konnerzven areas (Bastin et al., 1974; Pissart and Juvigné, 1980; Pissart, 1983). Results of pollen analysis of a peat lens within the basin and dating of volcanic minerals, located landform development to the Younger Dryas (c. 12.7 - 11.5 ka) (Mullenders and Gullentops, 1969). At Konnerzven, Pissart and Juvigné (1980) described an elongate rampart (~ 3 m in height) of shattered quartzo-phyllite rubble and clayey silt, parallel to a ground slope of 2.5% and associated with a peat basin of 4.2 m depth. Pollen analysis constrained the basin deposits to the Preboreal stage (10.3–9 ka) of the Holocene (c. 11.5 ka to the present day) (Pissart and Juvigné, 1980). Pissart and Juvigné (1980) described the rampart upper unit as a layer of unstratified, soliflucted, substratum debris emplaced during the Younger Dryas (c. 12.7–11.5 ka). Key to the interpretation of rampart formation (Chapter 2, section 2.2.2, iii), and the chronology of the development of PRDₖ, is the presence of a peat lens (up to 0.32 m thick and 6 m long) buried within the rampart. The peat lens initially follows the slope of the ground and is then folded. The lens undulates until its far (basinward) extremity where it thins and turns back on itself (Pissart and Juvigné, 1980) (Fig. 4.2). Above the peat lens (on the downslope side of the rampart) is a 0.3 m complex of alternating layers of peat and silt that Pissart and Juvigné (1980) interpreted as forming during periods of cooling (aeolian silt) and warming (humid peat). The 0.32 cm thick peat lens, which radiocarbon (¹⁴C) analysis dates to the Bølling-Allerød interstadial (c. 14.7–12.7 ka) (Pissart, 1983), is interpreted as a deposit from a wet hollow (possibly that of an earlier lithalsa (Juvigné and Streele, 2007) that subsequently became the location for (further) frost-mound growth (i.e. adjacent to the current PRD) (Pissart and Juvigné, 1980). Therefore, there are at least two generations of peat - and so possibly lithalsa - development here, with the more recent occurring after the Allerød oscillation (c. 14 ka). This sequence is confirmed by the dating of volcanic ashes found within the peat lens, from the Laacher See eruption (100 km east of the Hautes Fagnes), 11,230 +/- 50 years BP (Pissart and Juvigné, 1980). Lithalsa decay is thought to have resulted in collapse of the mound that formed a rampart, within which the buried deformed peat lens is found, as well as a zone of patchy orange-brown staining associated with ferromanganiferous oxides (Fe-MnO), described as ‘silt tongues’, present on the basinward side (Pissart and Juvigné, 1980) (Fig. 4.2).
Fig. 4.2 Idealised section through the elongate rampart under investigation at Konnerzvenn showing two peat layers. The upper peat layer (1) is Holocene infill (< 11.5 ka). The lower peat layer (2) formed during the Bølling-Allerød interstadial (c. 14.7–12.7 ka) prior to the formation of the current PRD (modified from Pissart and Juvigné (1980)).

Macrofabric analysis shows that pebbles in the external part of the rampart are parallel to the slope (due to solifluction), whilst pebbles in the inner part are perpendicular (possibly due to compression) with a progressive change in orientation in between (Pissart, 1983).

Particle-size analysis shows that rampart sediment is predominantly loess (~ 30 µm), with variable clay content (Pissart, 1983).

4.2 Macroscopic descriptions

4.2.1 Konnerzvenn sediment profile (PRDk)

This elongate rampart (PRDk) is ~ 3 m in height, 10 m across the width and contains a horizontal, undulating peat lens, ~ 1 m from the rampart base. PRDk is characterised by: i) a lower unit of clayey, sandy silt with scattered pebbles; ii) a basinward unit of gravelly, sandy, clayey silt that is heavily stained reddish-brown associated with the presence of Fe-MnO; iii) a middle unit of a sandy, clayey silt containing a complex of fine peat and silt laminae above a buried, thick peat lens; and iv) an upper unit of gravelly, clayey, sandy silt (Figs. 4.3 and 4.4).
Fig. 4.3 Konnerzvenn field site: Rampart section with key areas annotated and an inset showing silt and clay laminae from the middle unit above the thick peat lens.

Fig. 4.4 Konnerzvenn - representative sedimentary logs of the rampart (PRDx): A) central section (upper, middle and lower units).
i. **Rampart PRD** (Fig. 4.4)

- **Rampart lower unit:**
  The rampart lower unit is dark greenish-grey (Gley 4/1), very stiff, pebbly, clayey, sandy silt and there is a distinct change in colour between the lower unit and the overlying middle unit (of peat and silt laminae). The lower unit comprises matrix-supported, poorly sorted pebbles (≤ 33 mm) that are predominantly angular fragments of quartzite and phyllite. The pebbles occur unevenly throughout the rampart lower unit. The lower unit is macroscopically massive.

- **Rampart basinward unit**
  The basinward flank of the rampart contains heavily Fe-MnO stained patches of brown sediment (7.5 YR 4/4-6). This gravelly, sandy, clayey silt unit contains angular pebbles (coarse to very coarse, ≤ 33 mm a-axis) and there is a diffuse and oblique boundary between this and the overlying upper unit.

- **Rampart middle unit:**
  The middle unit contains a 30 cm thick complex of intercalated brown peat (7.5 YR 5/2) and grey clayey silt (7.5 YR 5/1) laminae. There are four silt layers ranging from 12 cm thick at the top to 3.6 cm thick at the bottom. These are interspersed with three peat layers ranging from 0.6 cm thick at the top to 1.8 cm thick at the bottom. Beneath this complex is a thick, undulating peat lens up to 32 cm thick and ~ 2 m long but tapering at both ends. This
buried peat lens contains very fine vertical fissures infilled with silt and orange-brown, Fe-MnO associated staining. Towards the extremity of the thick peat lens (basinward) it thins to 2 cm and turns back on itself (downslope). On the basinward side of the peat lens, the sediment comprises granules and sand (medium to very coarse). There is a diffuse, gradational boundary between the rampart middle unit and the overlying upper unit (gravelly, clayey silt layer) marked by a reduction in clasts.

- **Rampart upper unit:**
The upper unit is brown (7.5 YR 5/4), structureless, matrix-supported sediment comprising gravelly, clayey, sandy silt. There is patchy ferromanganiferous oxide staining of the sediment. Pebbles are generally bladed to blocky, predominantly angular to sub-angular and range from fine to coarse (≤ 35 mm a-axis). Cobbles are also present (≤ 75 mm a-axis). Clast lithology is predominantly quartzite and phyllite fragments.

**ii. Micromorphological control sample**
Between the surrounding ramparts the sediment is a single, massive unit at the macro-scale. It is a gravelly, brown (7.5 YR 5/4) to pale brown (10 YR 6/3) unit of sandy, clayey, silt (Fig. 4.5). Organic material (roots) and Fe-MnO concretions are present within the sediment, resulting in patchy staining.

![Fig. 4.5 Konnerzvenn - location of micromorphological control sample taken from between ramparts from a channel cut through the sediment by water run-off. Tape measure is 1 m long.](image)
iii. Basin core

A core was taken from towards the basin middle (52.717015 ° N, 0.567685 ° E). This revealed ~ 1.5 m of organic peat and gyttja, followed by ~ 0.1 m of clayey, silt containing angular gravels (granules and pebbles). The sediment is stiff and becomes more clast-rich with depth. It was not possible to core below 1.53 m (Fig. 4.6).

4.2.2 Bulk-sediment analyses

i. Particle-size distribution (PSD):

Medium-grained silt (15.6–31 µm) dominates the rampart and there is relatively low (Dalrymple and Jim, 1984) but significant clay content (between 10–20%). Pebbles occur within all but the middle unit. The upper and basinward units are most gravelly (comprising granules and pebble) while the middle unit is more silt-rich (Table 4.1; Fig. 4.7):

ii. Clay Mineralogy (X-ray diffraction (XRD) analysis) (Table 4.2; Fig. 4.8):

XRD analysis identifies that smectite is present in some of the rampart sediment samples (lower unit and possibly the middle unit - where the high shoulder leading into the illite peak in the graph (Fig. 4.8) can indicate a mixed layer clay within which smectite will be present at Angstrom values higher than 10 (Moore and Reynolds, 1997)). Therefore, it is possible that the shrink-swell properties, associated with smectite, could impact on any plasmic fabric present (Dalrymple and Jim, 1984; Blokhuis, 1993; van der Meer et al., 2003), although the quantities present are relatively low (Dalrymple and Jim, 1984).
Fig. 4.6 Konnerzvenn: Basin core description. A) Core depth 0–1.43 m: Organic material (i.e. peat (black-brown) and gyttija (a gel-like, black organic material (5 YR/2.5/1)) with fibrous plant roots; B) Core depth 1.43–1.55 m: At 1.43 m is a transition (marked by a red dashed line) from the organic infill, to a stiff, dark greenish-grey (Gleyt 4/i), pebbly, clayey, silt with angular quartzite and phyllite clasts (6–16 mm a-axis).
Table 4.1: Konnerzvenn: Rampart (PRD<sub>k</sub>) and control sample PSD.

<table>
<thead>
<tr>
<th>Rampart Unit</th>
<th>Upper</th>
<th>Middle</th>
<th>Basinward</th>
<th>Lower</th>
<th>Control sample</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gravelly (pebbles) (10%), clayey (12%), sandy (very fine-grained) (15%), silt (medium to coarse-grained) (62%)</td>
<td>Sandy (very fine-grained) (10%), clayey (12%), sandy (very fine-grained) (15%), silt (medium to coarse-grained) (62%)</td>
<td>Gravelly (pebbles) (13%), Sandy (very fine-grained) (14%), clayey (16%), silt (57%) (medium to coarse-grained)</td>
<td>Gravelly (pebbles) (13%), Sandy (very fine-grained) (14%), clayey (16%), silt (57%) (medium to coarse-grained)</td>
<td>Sandy (very fine-grained) (12%), clayey (20%), silt (68%) (very fine to coarse-grained)</td>
</tr>
</tbody>
</table>

Fig. 4.7 Konnerzvenn: PSD for rampart (PRD<sub>k</sub>) and control sample.

Table 4.2: Konnerzvenn: PRD<sub>k</sub> - XRD analysis of clay mineralogy.

<table>
<thead>
<tr>
<th>Sample location</th>
<th>Smectite</th>
<th>Illite</th>
<th>Chlorite</th>
<th>Kaolinite</th>
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<tr>
<td>Basinward unit</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>Middle unit</td>
<td>?</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>Upper unit</td>
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<tr>
<td>Control sample</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
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</table>
iii. **Carbonate analysis:**

Carbonate content is low (<1%) (Fig. 4.9). Therefore, it is unlikely that anisotropy exhibited by plasmic fabrics (birefringence viewed in cross-polarised light) will be disguised by carbonates during thin-section analysis of the samples (van der Meer et al., 2003).

![XRD spectra](image)

**Fig. 4.8 Konnerzvenn: Key XRD peaks are marked with their Ångström values (a unit of length equal to 0.1 nm).**

![Bar chart](image)

**Fig. 4.9 Konnerzvenn: Rampart (PRD) and control sample carbonate content.**
4.3 Microscopic descriptions

The following sections describe the microscopic texture and structure of the upper, middle and lower units of rampart PRDK, as well as the basinward section of the rampart and the control sample. Table 4.3 summarises data on matrix and skeleton grains. Figs. 4.10, 4.11 and 4.12 summarise thin-section sample location, grain roundness and microfabric data, respectively.

Fig. 4.10 Konnerzvenn field site: PRDk thin-section sample locations. Thin-section references are colour-coded: grey = upper unit; yellow = middle unit (central section); orange = middle unit (basinward section); pink = lower unit and green = basinward unit (image modified from Pissart and Juvigné, 1980).

i. Rampart upper unit (Figs. 4.13, 4.14, 4.15 and 4.16) (Thin sections: K5-1 (top), K6-1, K6-2 and K5-2 (base)):

The rampart upper unit is matrix-rich and comprises skeleton grains of slate and quartzite, which constitute a minor percentage (<10% overall) within the sediment. Grains > 2000 μm and ≤ 15 mm (a-axis) (granules and pebbles) are predominantly elongate and angular to sub-angular. Granules and pebbles are scattered throughout the sediment but can occur sporadically in clusters. Grains in the range < 2000 μm are the most abundant and are generally elongate and very angular to sub-angular. The percentage of very angular and angular particles in the sample (RA index), shows that grains < 500 μm are the most angular (Fig. 4.11). At the top of the upper unit there is a predominance of horizontal to sub-horizontal grains (Fig. 4.13). Below the top of the upper unit, grains < 2000 μm are mostly aligned sub-vertically to vertically with many having a preferential orientation ~ 130–150° (Figs. 4.12 and 4.14). There are a minor but significant number of grain concentrations occurring sporadically throughout the upper rampart unit (Figs. 4.14, 4.15 and 4.16). The matrix is silt-dominated. The silt occurs also as grain coatings (Figs. 4.13A, 4.14A, B and D and 4.15F). Sand and clay are minor matrix constituents. The clay is distributed as matrix
and occurs in highly birefringent fragments (e.g. narrow elongate 'strings' up to 1.8 x 0.4 mm) (Fig. 4.13D), as lenticular domains (Fig. 4.15B), as chaotic and convoluted domains (Fig. 4.16C and G) and around grains. The clay is associated with Fe-MnO throughout the sample. The matrix is dense, from 5 to 10% void space.

Voids are mostly well-developed planar fissures, which are up to 11.4 mm long and 3 mm thick. Most planar fissures are vertical to sub-vertical and many are oriented ~ 130–150 ° (Fig. 4.13B and 4.15E). An exception to this occurs towards the base of the upper rampart unit (Fig. 4.16), where there is a fissure oriented ~ 60 ° rising, diapiric-like, causing dramatic folding to and fragmentation of the surrounding sediment, bending in the downslope direction of the rampart. Packing voids (pore spaces) occur at the base of some grains (e.g. Figs. 4.14D). There are vesicles, some deformed (mammillated), up to 2.6 x 2.2 mm. Vughs (up to 15 x 12 mm) and vesicles are also present in low to moderate abundance.

Towards the top of the upper rampart section the sediment has a granular microstructure (rounded matrix aggregates) up to 4.7 x 4.5 mm (Figs. 4.13C and 4.14C). There are platy aggregates up to 2.6 x 0.7 mm and often inclined ~ 150 ° (Fig. 4.13B and 4.15G) and a few prismatic (angular) aggregates (Figs. 4.16D and E). There is an example of crude layering in the rampart upper unit (Fig. 4.15), with an upper clay-rich layer overlying a silt-rich layer.
Table 4.3 Textures, deformation microstructures and post-depositional features in the rampart and the control sample, Konnerzvenn, Belgium.

Key: * = Well developed; ● = Moderately developed; ○ = Weakly developed. Numbers of circles reflects abundance.

<table>
<thead>
<tr>
<th>Deformation structures</th>
<th>Texture</th>
<th>Voids</th>
<th>Rotation/slump</th>
<th>Planar</th>
<th>Sediment mixing</th>
<th>Pore water</th>
<th>Plasmic fabric</th>
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<tbody>
<tr>
<td></td>
<td>Vertical to sub-vertical microfabric</td>
<td>Grain concentrations</td>
<td>Planar fissures</td>
<td>Chambers and chambers</td>
<td>Vugs</td>
<td>Vesicles</td>
<td>Grain turbates</td>
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Key:

- ● = Well developed
- ○ = Moderately developed
- ○ = Weakly developed

Numbers of circles reflect abundance.
Fig. 4.1A-H) Micro grain roundness: Konnerzvenn. Key: VA = very angular; A = angular; SA = sub-angular; R = rounded; WR = well rounded (n = sample number for grains > 2000 µm, > 500 µm and < 5000 µm respectively; RA = percentage of very angular and angular clasts in a sample).
Fig. 4.1-N Micro grain roundness: Konnerzven. Key: VA = very angular; A = angular; SA = sub-angular; R = rounded; WR = well-rounded (n = sample number for grains > 2000 µm, > 500 µm and < 5000 µm respectively; RA = percentage of very angular and angular clasts in a sample).
Upper rampart unit:

A) Upper rampart unit - top(K5-3): n = 40
B) Upper rampart unit(K6-3): n = 29
C) Upper rampart unit(K6-2): n = 22
D) Upper rampart unit - base(K5-2): n = 23

Middle rampart unit (basinward section):

E) Middle rampart unit (basinward)(K7-1): n = 48
F) Middle rampart unit (basinward)(K7-2): n = 32
G) Middle rampart unit (basinward)(K7-3): n = 45
H) Middle rampart unit (basinward)(K7-4): n = 23

Basinward rampart unit:

I) Basinward unit - top(Ku-3): n = 21
J) Basinward unit - middle(Ku-2): n = 19
K) Basinward unit - base(Ku-3): n = 29

Lower rampart unit (central and downslope sections):

L) Lower rampart unit (central section) (K5-3): n = 20
M) Lower rampart unit (downslope section) (Kuo-3): n = 22
N) Lower rampart unit (downslope section) (Kuo-2): n = 27

Fig. 4.12A-N) Grain microfabric analysis in the > 2000 µm grain-size category of PRD0. Apparent long-axes orientation of skeleton grains in 20° interval classes measured anticlockwise from the horizontal plane, where the top of the thin section measures 90° (n = sample number).
Upper rampart unit:

A) Upper rampart unit - top(K5-1): n = 64
B) Upper rampart unit(K6-1): n = 84
C) Upper rampart unit(K6-2): n = 64
D) Upper rampart unit - base(K5-4): n = 61

Middle rampart unit (basinward section):

E) Middle rampart unit (basinward)(K7-1): n = 80
F) Middle rampart unit (basinward)(K7-2): n = 103
G) Middle rampart unit (basinward)(K7-3): n = 84
H) Middle unit (basinward)(K7-4): n = 75

Basinward rampart unit:

I) Basinward unit - top(Kn-1): n = 73
J) Basinward unit - middle(Kn-2): n = 90
K) Basinward unit - base(Kn-3): n = 74

Lower rampart unit (central and downslope sections):

L) Lower rampart unit (central section) (K5-3): n = 40
M) Lower rampart unit (basinward section) (K5-1): n = 57
N) Lower rampart unit (basinward section) (K5-2): n = 38

Fig. 4.12A-N) Grain microfabric analysis in the > 500 μm grain-size category of PRDk. Apparent long-axes orientation of skeleton grains in 20° interval classes measured anticlockwise from the horizontal plane, where the top of the thin section measures 90° (n = sample number).
Upper rampart unit:

A) Upper rampart unit - top(K5-1): n = 41

B) Upper rampart unit(K6-1): n = 69

C) Upper rampart unit(K6-2): n = 57

D) Upper rampart unit - base(K5-2): n = 39

Middle rampart unit (basinward section):

E) Middle rampart unit (basinward)(K7-1): n = 74

F) Middle rampart unit (basinward)(K7-2): n = 61

G) Middle rampart unit (basinward)(K7-3): n = 34

H) Middle rampart unit (basinward)(K7-4): n = 59

Basinward rampart unit:

I) Basinward unit - top(Kn-1): n = 50

J) Basinward unit - middle(Kn-2): n = 50

K) Basinward unit - base(Kn-3): n = 28

Lower rampart unit (central and downslope sections):

L) Lower rampart unit (central section) (K5-3): n = 20

M) Lower rampart unit (downslope section) (Kn-3): n = 2

N) Lower rampart unit (downslope section) (Kn-2): n = 7

Fig. 4.12A-N) Grain microfabric analysis in the < 500 μm grain-size category of PRDx. Apparent long-axes orientation of skeleton grains in 20° interval classes measured anticlockwise from the horizontal plane, where the top of the thin section measures 90° (n = sample number).
There is a low abundance of grain turbates (i.e. a circular, tangential arrangement of grains with, or without a central core clast or grain (Phillips, 2006)) (e.g. Fig. 4.14A). A more significant rotational microstructure is curvilinear arrangements of clay and silt that are very well developed towards the base of the rampart upper unit (Figs. 4.16A and B). These undulating, silt-rich and clay-rich layers range from 0.4 and 1 mm thick, respectively to 2 and 8 mm thick, respectively.

There are many examples of fragmented clay coatings (Fig. 4.15D) and some fractured grains at the top of the upper rampart unit, but these are not abundant. There is also a moderate to high abundance of fragmented domains of clay and silt (Fig. 4.13D) and disrupted (fragmented and folded) silt and clay laminae (Fig. 4.15C).

There is a low abundance of well-developed intraclasts type III (i.e. reworked fragments of unconsolidated sediment) and one or two grain intraclasts (i.e. a discrete concentration of skeleton grains that, in combination, appear to form a coherent whole) (Fig. 4.16E). There are moderate to abundant examples of multiple domains within the upper unit (e.g. silt and clay domains within clay in pod-like shapes of up to 12.4 x 12.8 mm (Fig. 4.16G)).

There are some examples of concentrated, stratified bands of silt grains that appear to ‘flow’ above gravel skeleton grains (Fig. 4.16F). Silt caps (i.e. occurring on the top of grains) (Fig. 4.14A) and coatings of grains (i.e. occurring on the bottom or sides of grains) (Fig. 4.13A) are moderately abundant and well developed. Clay and Fe-MnO coatings (full and incomplete) and infillings of voids are abundant and occur throughout the upper rampart unit (e.g. Figs. 4.14B and 4.15A).

There are generally weak to moderately well-developed examples of skelsepic and unistrial plasmic fabrics; these are a minor feature of the sediment.
Fig. 4.13A-B) Thin section K5-1 (rampart upper unit- top). Thin section measures 8.1 x 5.6 cm.

A) Silt (Sc) coating on underside of grain, Fe-Mn coated voids (V).

B) Platy aggregates (Ag) oriented 150°, up to 2.6 x 0.7 mm with Fe-Mn coated voids.
C) Granular microstructure - rounded sediment aggregates up to 4.7 x 4.5 mm, with Fe-Mn coating around voids.

D) Highly birefringent clay (Cl) domains (up to 1.8 x 0.4 mm) and clay coating of a vesicle (Ve) (0.3 x 0.3 mm) with associated Fe oxide.

Fig. 4.13C-D) Thin section K5-1 (rampart upper unit - top).
Fig. 4.1A-B) Thin section K6-1 (rampart upper unit). Thin section measures 8.2 x 5.3 cm.

A) Silt capping (Sc) around grain that is a core stone to a partial grain turbate.

B) Cross-layered clay (Cc) and associated Fe-MnO infilling void space. Grain with silt (St) and clay coating (Cc) (marked with a white dotted line) and a silt cap (Sc).
C) Sub-rounded aggregates forming a **granular** micro-structure.

D) Vertical grain with pore space at the base (V). The grain has a silt coating (Sc).

Fig. 4.14C-E) Thin section K6-1 (rampart upper unit).
Fig. 4.15 A-B) Thin section K6-2 (rampart upper unit). Thin section measures 8.2 x 5.7 cm.

A) Clay coating (Cc) infilling pore spaces with silt coating below the clay coating.

B) Clay (Cl) domains within silt, up to 9.2 x 1.4 mm.
C) Disrupted (fragmented and folded) silt and clay laminae, up to 0.3 mm thick, oriented – 140°.

D) Fragmented clay coatings (Cc) up to 0.7 x 0.2 mm.

E) A series of sub-vertically inclined fissures (F), predominantly oriented – 140°, up to 5 x 0.3 mm.

F) Silt and clay coated grain.

G) Lenticular/platy micro-structure.

Fig. 4.15C-F Thin section K6-2 (rampart upper unit).
Fig. 4.16 (A-B) Thin section K5-2 (rampart upper unit - base). Thin section measures 8.3 x 5.7 cm.
C) Chaotic clay domains.

D) Sub-vertically inclined fissures (prismatic to sub-rounded aggregates).

E) Grain intraclast, clay domains (Cl) within silt matrix, prismatic aggregate (Ag).

F) Concentrated silt and clay band ‘flowing’ above grains.

G) Convoluted clay domains (dashed lines) and irregular-shaped clay domain.

Fig. 4.16D-G) Thin section K5-2 (rampart upper unit - base).
ii. **Rampart middle unit** (Figs. 4.17, 4.18, 4.19, 4.20, 4.21, 4.22, 4.23, 4.24)

The middle unit includes samples from the central section above and below the undulating, 0.32 m thick peat lens and from the basinward extremity of the undulating peat lens (Fig. 4.10):

**Central section (K8-4 (top), K8-1, K8-2 and K8-3 (base))**

The rampart middle unit, central section, is finer-grained than anywhere else within the rampart. The matrix-rich sediment is clay and silt-dominated and contains humic material from the peat laminae. At the top of the middle unit, central section, are distorted laminae (up to 3.4 mm thick and 18 mm long) of clay and humic matter (peat), interlaminated with silt. The microfabric is vertical to sub-vertically inclined. Grains are sparse but, where these occur within peat, it is possible to observe enlarged pore spaces around the grains (Fig. 4.18). There are a minor number of grain concentrations occurring sporadically throughout this unit (Fig. 4.17). The matrix is dense but this varies, ranging from 5 to 15% void space. Vughs occur sporadically throughout the sediment in the central section, up to 73 x 6.2 mm and are often mammillated and can be interconnected. There are many examples of well-developed, planar fissures within the sediment, up to 16.8 mm long and 3 mm thick. The planar fissures are sub-vertically inclined and often occur in a series (Figs. 4.17A, 4.18B, 4.19B and C). The sediment has a granular microstructure (angular to rounded matrix aggregates up to 8.3 x 6.6 mm), which is particularly evident within the humic-rich domains of the peat complex (Figs. 4.18A and 4.19A).

There are only a few examples of weakly developed curvilinearations of clay and humic matter (Fig. 4.17B) and even fewer linear domains of grains within the rampart middle unit, central section. The sediment is characterised by sediment mixing (e.g. fluidised and convoluted) domains of silt (Fig. 4.20), distorted domains of clay and organic matter (Fig. 4.20A), disrupted laminae of silt and clay (Fig. 4.17) and disrupted peat laminae with convolute structures (Fig. 4.19). There is a moderate abundance of in-mixing of sediment domains within the middle unit, central section, in the form of remobilised clay and silt (Fig. 4.19D).

Clay and Fe-MnO coatings of voids occur throughout the middle rampart unit in low to moderate abundance. There is a lower number of grain coatings due to the minimal number of grains within the central section of this unit. There are a few weak to moderately well-developed examples of skelsepic and unistrial plasmic fabrics, oriented ~ 140°, which are a minor constituent of the sediment (Fig. 4.18C).
Fig. 4.17A-B) Thin section K8-4 (rampart middle unit – central section (top)). Thin section measures 8.2 x 5.7 cm.
Fig. 4.18A-C) Thin section K8-1 (rampart middle unit – central section). Thin section measures 7.3 x 5.5 cm.

Disrupted domains of silt and clay (up to 18.8 x 5 mm) within humic matrix

Granular microstructure (Fig. A)

Unistrial plasmatic fabric (~ 140°) (Fig. C)

Enlarged void space around grains

Sub-vertically inclined fissures (Fig. B)

Mass of fine horizontal and sub-vertical fissures up to 16.8 mm long and 1.9 mm thick

Sandy (fine) silty (coarse), peat laminae within clayey silt matrix

A) Granular microstructure within clay, silt, humic matrix.

B) Ice lens traces, up to 2.3 x 0.1 mm.

C) Unistrial plasmatic fabric (yellow lines) oriented ~ 140° within silty, clayey, humic matrix.
Fig. 4.19A-B) Thin section K8-2 (rampart middle unit – central section). Thin section measures 8 x 5.4 cm.

Fluidised silt-rich layer  Verticle fissures (Fig. B)
Fe-Mn staining and clay lining of fissures
Deformed layer of silt and clay (Fig. D)
Vertical fissures (Fig. C)
Granular microstructure and vertical fissures

Granular aggregates (Fig. A)
Convoluted structures within peat
Disrupted laminae of peat within a fine sandy, clayey silt micromass

Interconnected vughs up to 73 x 6.2 mm

A) Granular aggregates (Ag) up to 8.3 x 6.6 mm.

B) Vertical fissures (F) up to 12 mm long and 1.3 mm thick.
C) Sub-vertically inclined fissure (5.3 x 0.2 mm).

D) In-mixed clay and silt sediment within a single layer.

Fig. 4.19C-D) Thin section K8-2 (rampart middle unit – central section).
Fig. 4.20 A-B) Thin section K8-3 (rampart middle unit – central section (base)). Thin section measures 8.1 x 5.5 cm.
Basinward section (K7-1, K7-2, K7-3 and K7-4)

The rampart middle unit (basinward section) is matrix-rich. Samples K7-1 and K7-2 are taken from the left and right hand sides, respectively, of the folded peat-lens tip (Fig. 4.10). Samples K7-3 and K7-4 are taken from below the peat-lens tip on the basinward side.

Skeleton grains of slate and quartzite constitute a significant but minor percentage (< 10%) of the sediment but they do appear in concentrations, particularly within the top of the unit on the right-hand side of the peat-lens extremity (Figs. 4.21 and 4.22). Grains > 2000 µm (pebbles) are scattered throughout the sediment but can occur sporadically in clusters. Grains < 2000 µm dominate and are predominantly elongate and very angular to sub-angular. Grains > 500 µm are the most abundant and are generally elongate and are mostly angular (Fig. 4.1). On the left-hand side of the peat-lens tip, many grains are oriented ~ 40–50 °. On the right-hand side is a chaotic mix of vertical to sub-vertical grains either side of a vertical ‘pipe’ of fluidised silt and clay (Fig. 4.22). Below the tip, grains become more vertically inclined and this is particularly evident in grains < 2000 µm (Fig. 4.12). The matrix is silt-dominated. Silt occurs as matrix and grain coatings. Sand and clay are minor matrix constituents. The clay is distributed, unevenly, as matrix in-mixed with the silt and also occurs as fragments of clay coatings (i.e. generally rounded in form, often 0.2 x 0.2 mm). The clay is associated with Fe-MnO deposits throughout the sample. There are zones of micro-undulating silt and clay but these are not well pronounced (Fig. 4.22). The matrix is variably dense, with ~ 5–10% void space.

Voids are mostly planar fissures, up to 30 x 1.8 mm, particularly at the top of the rampart middle unit basinward section. Planar fissures are vertical (Figs. 4.21 and 4.22B), to sub-vertical with no preferred orientation. On the left-hand side of the peat-lens tip is a sub-vertical fissure, oriented ~ 40 °, up to 30 x 1.8 m, above which are fine vertical fissures up to 25 x 0.5 mm (Fig. 4.21). On the right-hand side of the peat-lens tip are a series of fine planar fissures (up to 12.3 x 3.3 mm), forming platy aggregates and cross-cutting intraclasts (Fig. 4.22A). Voids also occur as enlarged spaces below grains (Fig. 4.23). There are some vesicles and mammillated vughs up to 6.9 x 3.5 mm in moderate abundance and moderately developed.

Key features of the sediment within the basinward section of the middle rampart unit are fragmented and remobilised domains of clay and silt that occur either side of the peat-lens tip (most notable on the right-hand side), a few fractured grains, and prismatic and platy aggregates up to 20 x 16 mm) (Figs. 4.21 and 4.22B). With depth, the matrix becomes denser and sediment in-mixing more homogenised, although still patchy.
There are a few grain turbates both with and without core grains, which appear with increasing depth within this basinward section of the rampart middle unit, beneath the extremity of the undulating peat lens (Figs. 4.23 and 4.24). There is a low abundance of planar structures including domains of grains aligned lineally. However, there is a pronounced sub-vertical fissure, oriented ~ 40°, near the top of the peat-lens tip on the left-hand side, possibly indicative of planar shear. There are also many examples of fragmented domains on the right-hand-side of the peat-lens tip, either side of a vertical ‘pipe’ of fluidised clay and silt (80 x 24 mm) (Fig. 4.22). There are one or two examples of well-developed intraclasts: i) type I (matrix), up to 3.5 x 3.3 mm and composed of silt and clay and ii) type III (sediment), up to 4 x 1 mm and composed of disaggregated unconsolidated sediment (Fig. 4.22A). There is abundant in-mixing of sediment domains within the middle unit basinward section with, patchy concentrations of matrix beneath grains and as if ‘flowing’ above grains (Fig. 4.21B).

Silt, clay and Fe-MnO coatings of voids and grains are abundant and occur throughout the unit (Fig. 4.21A and C). Silt occurs as cappings (on top of grains) or coatings (on the sides or base of grains) on some but not all grains. Fe-MnO staining completely coats most vesicles and vughs but only partially coats some fissures and these occur sporadically.

There are moderate to well-developed examples of skelsepic and unistrial plasmic fabric, within the middle unit basinward section. Unistrial plasmic fabric, although a minor constituent of the sediment, is best developed in this unit of the rampart (Fig. 4.21A). Orientation of unistrial plasmic fabric generally varies between 40–60° and 130–160° but in the sample from the right-hand-side of the peat-lens extremity (Fig. 4.10), there are zones of unistrial plasmic fabric oriented near vertical ~ 100°.
Fig. 4.21 Thin section K7-1 (rampart middle unit – basinward section). Thin section measures 8 x 5.5 cm.
Fig. 4.22A-C) Thin section K7-2 (rampart middle unit – basinward section). Thin section measures 8.2 x 5.7 cm.

A) Intraclast type III, a disaggregated raft of laminated silt and clay up to 4 x 1 mm (laminae range from 0.01 to 0.005 mm thick).

B) Platy aggregates, up to 12.3 x 3.3 mm.

Vertical domain of fluidised silt and clay

Type I intraclast (3.5 x 3.3 mm)

Fragmented clay domains

Grain concentration

Fragmented laminae of clay and silt

Grain concentration

Platy aggregates (Fig. B)

Zones of unistrial plasmic fabric, oriented ~ 100°

Type III intraclasts (Fig. A)

Faint curvilinear structures (micro-undulations)
Fig. 4.23 Thin section K7-3 (rampart middle unit – basinward section). Thin section measures 8.1 x 5.5 cm.

Fig. 4.24 Thin section K7-4 (rampart middle unit – basinward section). Thin section measures 8 x 5.5
iii. Rampart basinward unit (Figs. 4.25 and 4.26)

(Thin sections: K11-1 and K11-2):

The rampart basinward unit comprises the most gravelly sediment sampled (coarse to very coarse-grained) although grains remain a minor constituent in this matrix-supported sediment. Grains > 500 µm dominate and are predominantly elongate and angular (Fig. 4.11). The microfabric varies between no preferred orientation with chaotic pebble and matrix arrangements (Fig. 4.26A) and zones of preferential alignment between 130 and 140° (Fig. 4.25). Nonetheless, grains are mostly inclined vertically to sub-vertically. The matrix is silt-rich and comprises patches heavily stained with Fe-MnO. Grains are scattered randomly throughout the sediment. Silt occurs as matrix and grain coatings. Sand and clay are minor matrix constituents. The clay is distributed unevenly as matrix in-mixed with silt, in patchy concentrations (Fig. 4.25B) and also as fragments of clay coatings (i.e. generally rounded in form, often 0.4 x 0.25 mm). The clay is associated with Fe-Mn oxides throughout the sample. The matrix is dense (< 5% voids) and voids occur as planar fissures, many oriented between 130 and 150° and vughs with some vesicles. There are also patches of wavy fissures accompanying the curvilinear arrangement of grains (Fig. 4.26).

Key features of the sediment within the basinward unit include its density, the occurrence of curvilinearations and evidence for sediment mixing and pore-water movement. There are a few weakly developed grain turbates within this basinward unit of the rampart. There are examples of planar structures including arrangements of grains aligned linearly in close proximity (Fig. 4.25) and some curvilinearations (i.e. arcuate linear grain arrangements that form arc shapes within the sediment). Where curvilinear arrangements occur with grains > 2000 µm to form discrete arcs, (Fig. 4.26), this gives a sense of rotation within the sediment. Where the arcuate linear grain arrangements occur continuously within the matrix (silt and clay) and appear to undulate, they are accompanied by wavy fissures (Fig. 4.25A). These micro-undulations can form micro-scale platy aggregates. There are many examples of multiple domains of clay-rich sediment within silt and clay and silt in-mixed (Fig. 4.25). These domains are generally irregular but rounded. Most are up to 3.5 x 3 mm but can be just a few millimetres in dimension. Silt, clay and Fe-MnO coatings of voids and grains are abundant and occur throughout the unit. There is a moderate number of examples of skelsepic and unistrial plasmic fabrics within the basinward unit (Fig. 4.25C). Unistrial plasmic fabric, although a minor constituent of the sediment, is moderately well developed in this unit of the rampart. Orientation of unistrial plasmic fabric generally varies between 40–60° and 130–160°.
Fig. 4.25A-C) Thin section K11-1 (rampart basinward unit). Thin section measures 8.2 x 5.7 cm.

- Faint wavy fissures
- Unistrial plasmic fabric oriented ~140°
- Fissure and grains oriented 130°-140°
- Grain turbate
- Vugly fissures, up to 10.4 x 7 mm
- Grain aggregate
- Wavy fissures/curvilinear arrangement of grains (Fig. A)
- Clay-rich domain
- Unistrial plasmic fabric oriented ~140°
- Grain lineation, oriented ~115°
- Unistrial plasmic fabric (Fig. C)
- Concentrated zones of clay and silt within silt (Fig. B)
- Silt-rich domain
- A) Wavy microfabric (yellow dashed lines).
- B) Concentrated zone of clay and silt within silt.
- C) Unistrial plasmic fabric oriented ~150° (yellow lines).
Fig. 4.26A) Thin section Kit-2 (rampart basinward unit). Thin section measures 8.1 x 5.6 cm.

A) Convoluted domains of clay (Cl) and silt (St) and a lens of chaotically arranged medium to coarse, sand-sized rock fragments.
iv. **Rampart lower unit** (Figs. 4.27 and 4.28, K5-3 and K5-4 (central section, beneath the peat lens after it starts to rise), Figs. 4.29 and 4.30, K10-1 and K10-2 (downslope section):)

Overall, the rampart lower unit is a matrix-rich, dense and compact sediment. The lower unit is separated from the middle unit by an undulating, thick peat lens (~2 m long and up to 0.32 m thick). There is a very low percentage of grains, which occur towards the base of the lower unit. Grains are sub-angular to sub-rounded, ranging from 12.3 to 0.4 mm a-axis (medium gravel to medium sand), but are typically rock fragments ~2 mm in size. The grain shapes range from mostly elongate to equant and they occur sporadically, occasionally concentrated and tilted to form a crude layer (Fig. 4.30). Rock fragment lithology is that of the underlying bedrock (i.e. phyllites and sandstone fragments). Close to the peat lens, grains are mostly oriented horizontally to sub-horizontally (Fig. 4.29). A sub-horizontal microfabric is more pronounced in the rampart lower unit than in any other unit sampled (Fig. 4.12). However, grains are in low numbers in this unit and lower down the profile.

There are also layers identified by an upslope imbrication of grains ~150 ° (Figs. 4.27 and 4.30). Within the lower unit, silt and clay is distributed as matrix, grain coatings and sometimes as fragmented clay ‘strings’ (elongate domains up to 2.6 mm long and 0.9 mm thick) that occur randomly within the sediment with no preferred orientation (Fig. 4.27C) but sometimes with a curvilinear arrangement (Fig. 4.27B). The clay and silt matrix are sometimes homogenised (Fig. 4.29) and sometimes birefringent clay is concentrated in zones where it infills pore spaces.

Void space is low (<10%) and comprises vughs (up to 19.1 mm long and 6.9 mm wide) and, in places, very fine, discontinuous wavy fissures. The wavy fissures appear in concentrated patches within the sediment and are typically 2 mm long and 0.1 mm thick (Fig. 4.27A).

A key feature of the sediment within the rampart lower unit is crude layering. Well below (~30 cm) the peat lens (central section), there is a layer oriented ~150 ° identified by a more gravelly upper layer and a much finer-grained lower layer, the contact for which is marked by an upslope imbrication of grains (Fig. 4.30). A less-defined layer also occurs on the basinward section of the lower rampart unit (Fig. 4.27). Here the layer is identified by finer-grained sediment of silty clay in the upper layer and coarser-grained sediment of gravely silt in the lower layer, and is emphasised by preferentially inclined grains and void spaces upslope ~150 °. The contact is also marked by a very fine Fe-MnO stained fissure on the same inclination as the grains and voids.
There are a few moderately developed grain turbates both with and without core grains (e.g. Fig. 4.29B) and rotation structures that do not form a complete circle. There are a few examples of curvilineations, arrangements of fine to medium-grained sand and silt grains, in a wave-like pattern in ‘strings’ of up to 2 mm long (Figs. 4.27B and 4.28B). Curvilineations are notable within the central section of the lower rampart.

Fragmented and multiple/in-mixed domains of clay and silt also occur mostly on the central section of the lower rampart unit, beneath the peat lens after it starts to rise. This is particularly evident towards the base of this section where there are convoluted and patchy domains of clayey silt within silt (Fig. 4.28). There are a very few examples of fractured grains (Fig. 4.29A). Silt, clay and Fe-MnO coatings of voids and grains are low as grains and voids are in low numbers. There are relatively few examples of weak to moderate unistrial plasmic fabric occurring unevenly within the sediment, from 5 to 11.8 mm long and up to 2 mm thick (Fig. 4.28A). There is no preferred orientation of the unistrial plasmic fabric. Skelsepic plasmic fabric takes the form of a tight-fitting plastering of clay around grains and is clearly seen in association with rotation structures.

v. Control sample (Fig. 4.31)
(Thin section KC):
This intra-rampart sediment is a silt-dominated, matrix-rich, microscopically massive sediment. There are just one or two grains. There are particles of fragmented organic matter (plant remains), that occur unevenly within the sediment. There is abundant orange-brown stained void spaces associated with Fe-MnO-throughout the control sample (~ 30%) (e.g. vertically to sub-vertically inclined chambers (typically 4 x 0.4 mm); vesicles (1.1 x 1.3 mm) and; vughs (up to 8.2 x 3 mm)). There are many fine planar fissures, typically 2.5 x 0.1 mm, mostly vertical. There are localised zones of Fe-MnO staining of the sediment.
Fig. 4.27A-C) Thin section K5-3 (rampart lower unit – central section). Thin section measures 8.1 x 5.6 cm.
Fig. 4.28A-B) Thin section K5-4 (rampart lower unit – central section). Thin section measures 8.1 x 5.7 cm.
Fig. 4.29 Thin section 10-1 (rampart lower unit – downslope section). Thin section measures 8 x 5.6 cm.

A) Fractured grains (yellow double arrows indicate the two halves and point of fracture) and a clay fragment.

B) Grain turbate without a core grain.
Fig. 4.30 Thin section K1o-2 (rampart lower unit – downslope section). Thin section measures 7.6 x 5.6 cm.

Fig. 4.31 Thin section KC (Control sample). Thin section measures 8 x 5.6 cm.
4.4 Interpretation

4.4.1 Macroscopic analysis

The PSD (Table 4.1), demonstrates that the rampart overall is silt-dominated and gravel-poor. However, there is enough variation in the grain-size distribution within the different units of PRD_k to suggest that the rampart comprises three sub-units (Fig. 4.7):

- **Rampart lower unit**
  In contrast to the overlying middle unit, the rampart lower unit has no peat but is clay-rich and contains scattered pebbles. Soft, decomposed, chemically weathered rock that becomes clay-rich, is known as a saprolite and indicates a warm, humid environment (Wilson, 1999). The dark greenish-grey of the clay, as well as reflecting the presence of illite and chlorite (Table 4.2), indicates gleying, caused by waterlogging.

- **Rampart middle unit (middle section)**
  There is a marked difference in sedimentary environment in the rampart middle unit compared to the upper and basinward units, denoted by the absence of coarse-grained particles (> 2000 µm) and presence of peat layers. Alternating laminae of silt and peat demonstrate a cyclical change in environmental conditions. Silt-rich layers indicate cold climate, loessial conditions (Haase et al., 2007), whilst the peat is evidence of wetland conditions (Kurbatov, 1968) – indicating oscillating climate conditions (Rochon et al., 1998). Pissart and Juvigné (1980) suggested that the present landform developed adjacent to boggy ground, which explains the presence of a buried peat lens complex. Juvigné and Stroel (2007) went further and proposed that the thick undulating peat lens, near to the base of the rampart, was once a basin of a previous lithalsa. Given the proximity and overlapping nature of the PRDs in the Hautes Fagnes, this is a possibility and would make this a site of successive generations of lithalsa growth.

- **Rampart upper and basinward units**
  The rampart upper and basinward units comprise gravelly (fine to very coarse-grained phyllites and quartzites), clayey, sandy (very fine-grained) silt (medium to coarse-grained). This diamicton is located at the top of the stratigraphic sequence. As the ice sheet did not advance into this area during the LGM (c. 23–19 ka) (Hughes et al., 2016) and there is no evidence of marine (e.g. marine fossils) or fluvial activity (e.g. scoured channels, cross-stratification), a terrestrial origin for the gravels due to freeze-thaw action (i.e. gelifraction) (van Vliet-Lanoë, 1985), is probable. The field site is located on gentle slopes (< 5%) on high
(585 m AOD), but not the highest, ground in the area (the Signal de Botrange is the highest point in Belgium (694 m AOD) and is located ~ 12 km from the field site). Therefore, it is likely that the poorly sorted sediment in the upper rampart unit is a reworked terrestrial deposit (i.e. solifluction deposit) (Ballantyne and Harris, 1994), derived from the local area, which has been subject to further mass-wasting during frost-mound formation and decay.

Similar to the rampart upper unit, the composition of the basinward unit is the same as, and so probably derived from, the regional bedrock. The clasts are mostly angular to sub-angular, supported by a matrix of illite-chlorite clay (Table 4.2 and Fig. 4.8), which is a product of metamorphosed bedrock (Mason, 1990). Belgium lies within the loess (aeolian silt) belt of central Europe (Kasse, 1997, 2002; Haase et al., 2007). Loess is a wind-blown sediment derived from glacial grinding of rocks (Pye, 1995; Assallay et al., 1998). Therefore, the high silt content of the rampart is attributed to the location of the field site outside of, but close to, the ice sheets of the LGM (c. 23–19 ka) (Hughes et al., 2016). Sediment cores from the surrounding area (Juvigné and Pissart, 1979) confirm that the locality is draped in Quaternary deposits comprising aeolian silt, gravel debris and clay derived from profound chemical alteration of the underlying bedrock (Revin Group, c. 518–495 Ma) during the last glaciation. Orange-brown staining represents Fe-Mn oxidation related to groundwater movement. The heavy Fe-MnO staining and higher proportion of pebbles, in the middle unit (basinward section), suggests that post-depositional changes may have caused localised variations in texture and appearance (van Vliet-Lanoë, 1998). These differences in appearance are possibly related to the collapse of the inner mound during rampart formation as the ice-core melted.

- **Basin core**
  The core sediment, encountered at a depth of 1.43 m, is similar in colour and composition to the lower rampart unit (i.e. dark greenish-grey (Gley1 4/i), clayey, silt with angular, fine gravels of quartzite and phyllites). The obvious source for the gravel is the underlying bedrock, probably fragmented by frost action (van Vliet-Lanoë, 1985). The sediment at the base of the depression is, therefore, interpreted as the same as in the rampart lower unit and so constitutes the PRD substrate (Flemal, 1976; Mackay, 1988).

- **Control sample**
  A control sample was secured for the purposes of comparison with the rampart samples. An inter-rampart location was selected (52.717444 ° N, 0.567328 ° E). The control sample is silt-dominated (fine to coarse-grained) and contains lesser quantities of very fine-grained sand
and clay than the rampart units. The control sample is finer-grained than the more gravelly rampart top unit but close in PSD to the rampart middle unit (albeit more heavily stained with Fe-MnO) (Fig. 4.7). The significant number of chamber-like void spaces is indicative of burrowing activity and is likely to be caused by bioturbation (Mücher et al., 2010).

4.4.2 Microscopic analysis

- **Microfabric**

Aside from the middle (centre) rampart unit (close to the peat lens), there is generally a marked orientation of grains vertically to sub-vertically throughout rampart PRD_k. This is illustrated by: i) vertical grains, often with pore spaces at the base (Fig. 4.14D), ii) sub-vertical grains whose long-axes are oriented downslope (Fig. 4.13A) near the top of the rampart, and iii) sub-vertical grains in association with similarly inclined fissures and contacts between clay-rich and silt-rich layers (Figs. 4.27 and 4.30), near the base of the rampart. In periglacial environments, vertical grains with void spaces near the base are caused by frost-jacking (van Vliet-Lanoë et al., 1984; van Vliet-Lanoë, 1985; 2010) (Chapter 2, section 2.2.3, iii). When not associated with ice-lens traces, elongate grains in the rampart upper unit whose apparent long-axes are oriented parallel to the line of slope could be linked to solifluction or frost creep (Harris and Ellis, 1980) (Chapter 2, section 2.2.3, iii). However, for sub-vertically inclined grains located at depth (towards the base of the rampart) and in close proximity to similarly inclined fissures and lithological contacts, these probably have an association with tilted layers caused by heave during frost-mound growth (Pissart and French, 1976; Mackay, 1978; Pissart and Gangloff, 1984) (section 4.4.2, Stratification). Given the periglacial setting of the Belgium field site at the LGM (c. 23–19 ka), the likely causes of the sub-vertical microfabric of the sediment include: i) frost-jacking of grains, ii) mass-wasting during formatting of the rampart upper unit, and iii) heave of the lower rampart unit.

- **Stratification**

In the rampart upper unit, there are examples of homogenous, parallel laminae of silt and clay up to 1–2 mm thick (e.g. Fig. 4.16A), likely to be laminated colluvium (Mücher et al., 2010) (Chapter 2, section 2.2.3, iii).

There are other examples of very fine-grained stratification above grains in the form of concentrated bands, which drape over grains (e.g. Fig. 4.16F). This feature is interpreted as banded plasmic fabric, indicative of a periglacial environment (van Vliet-Lanoë, 2010) (Chapter 2, section 2.2.3, iii).
There are also examples of larger-scale layers within the upper and lower rampart units, probably linked to frost-mound formation and decay processes. In the rampart upper unit (Fig. 4.15), there is an upper, clay-rich layer above a lower, silt-rich layer oriented ~ 130°. In the lower, silt-rich layer there are concentrations of grains, as well as fragmented clay domains, all inclined upslope in a similar orientation to the layer contact. Another layer is identified in the lower rampart unit, by the juxtaposition of finer and coarser-grained particles oriented sub-vertically (Fig. 4.30) and on the same inclination as nearby grains and fissures that emphasise the tilted layer (e.g. Fig. 4.27). A tilted sediment layer could be an internal feature associated with shearing during mass-movement (Harris, 1985; Bertran and Texier, 1999). Additionally, frost-mound development causes sediment to heave due to pressure exerted by the growing ice lens (Pissart and French, 1976; Mackay, 1978; Pissart and Gangloff, 1984; Pissart, 2002; Pissart et al., 2011). Therefore, tilted layers at the base of the rampart (located beneath the inclined thick peat lens that undulates basinward (Fig. 4.10)), are probably the consequence of sediment heave during frost-mound formation processes. At the top of the rampart, a tilted layer is more likely due to mass-wasting that occurs when frozen ground thaws and results in a downslope movement of sediment by gelifluction, frost creep and active-layer slides (Harris, 1981b; Mackay, 1988; Bertran and Texier, 1999).

- **Grain concentrations**
  There is a low to moderate abundance of weak to well-developed zones of concentrated matrix and grains within the rampart upper and middle units. Preferentially sorted matrix domains can be linked to frost-sorting and translocation, which creates enriched areas of silt and or clay (van Vliet-Lanoë, 2010) (e.g. Fig. 4.21B). Additionally, grain concentrations are commonly found at the base of slopes due to downslope movement during solifluction (Harris and Ellis, 1980) (Chapter 2, section 2.2.3, iii). However, the coarser, grain concentrations are most notable in the rampart middle unit, basinward section (by the undulating, thick, peat-lens tip) (e.g. Fig. 4.22), rather than at the base. It could be that localised rotational stresses, related to the folding of the peat-lens tip as it is dragged back on itself during mass-wasting (when sediment moves downslope as the mound grows (Pissart and Juvigné, 1980)), are responsible for preferentially sorted grain concentrations in the basinward section.

- **Void spaces**
  Void spaces within the sediment of rampart PRDk have a variety of forms. Planar fissures are abundant throughout the rampart sediment. The fissures are probably created by ice lenses that thaw and form stable aggregates that are lenticular, platy and granular-shaped
There are also examples of vesicles (smooth, circular-shaped pores) and vughs (irregular-shaped, deformed (or mammillated) vesicles) within the rampart sediment, particularly in the rampart upper and middle units. Vesicles and vughs (enlarged voids) are commonly found in frost-susceptible sediment (Brewer, 1964; Harris and Ellis, 1980; van Vliet-Lanoë, 2010). Some vesicles in PRDk middle unit have elongate forms, which are interpreted here as desiccation cracks (e.g. Figs. 4.18B and 4.19C) (van Vliet-Lanoë, 1985; 2010) (Chapter 2, section 2.2.3, iii).

Void space at the base of skeleton grains is likely to develop due to frost-jacking (van Vliet-Lanoë, 1985; 2010) (section 4.4.2, Microfabric). Additionally, regular, elongate and tube-shaped fissures dominate the control sample (Fig. 4.31). Channels and chambers are associated with faunal activity or plant root systems (Brewer, 1964). Plant remains occur within some of the elongate voids in the control sample, so a plant-root origin for the chambers is likely.

- **Aggregates**

In the samples from PRDk, well-developed aggregates (assemblages of matrix) occur ranging from granular, toward the top of the rampart, to sub-angular and angular with depth. Aggregates can occur in the upper sequence of soils, surrounded by abundant pore space, and are also known as peds (i.e. natural soil aggregates) (Brewer, 1964). Peds form for a variety of reasons including: compaction from humans and/or animals, the shrink-swell properties of the clay component of the soil, seasonal freeze-thaw and or wetting and drying cycles (Brewer, 1964). There are also examples of void spaces in glacial sediments, within deforming beds beneath glaciers. Aggregates in subglacial sediments have a ‘marble-bed’ structure (i.e. rounded to ellipsoidal aggregates delineated by encircling voids) (van der Meer, 1993; 1997). However, aggregates within glacial sediments are not abundant, due to the compacted nature of basal till. Aggregates are also found in periglacial environments, where it is well known that the development of ice lenses in soils and sediments creates compacted aggregates due to the pressure exerted by ice growth that cryodesiccation (freeze-drying) helps to preserve (van Vliet-Lanoë and Langohr, 1982; van Vliet-Lanoë et al., 1984; van Vliet-Lanoë, 1985) (Chapter 2, section 2.2.3, iii).
As sediment samples were taken from below the soil profile and they are not highly porous, a pedogenic origin does not account for the range of aggregate shapes in PRDk and their inclined orientation. As the SIS did not extend as far as Belgium during the last glaciation (Hughes et al., 2016) and the sediment is not overly compacted, a deforming glacier bed origin for the aggregates is also discounted (van der Meer, 1993). Therefore, the aggregates in the sediment samples at Konnerzvenn are probably formed by cryodesiccation.

In the upper rampart unit, the aggregates are sometimes sub-rounded and more granular in texture (e.g. Figs. 4.13C and 4.14C). A sub-rounded fabric near the profile surface could be due to re-working of the sediment by slope wash or the influence of frost mulching (van Vliet-Lanoë, 1985; Mücher et al., 2010; van Vliet-Lanoë, 2010). Generally, the aggregates observed in the silt-rich material in the rampart upper unit are platy with an inclined orientation (e.g. Fig. 4.13B). Lower down the rampart profile, in peat–rich material, aggregates are more prismatic (e.g. Fig. 4.29). The difference in aggregate shape between the silt and the peat probably reflects a change in sediment type (van Vliet-Lanoë, 1985; 2010).

There are some examples, particularly in the upper rampart unit, where the lenticular aggregates appear to slope, parallel to the surface (e.g. Figs. 4.13B and 4.15G). On gentle slopes, this can be caused by progressive downslope movement that occurs along sliding planes, signified by the ice-lens traces (Harris, 1981b; van Vliet-Lanoë, 1985) (Chapter 2, section 2.2.3, iii).

- **Rotation**

  Grain turbates are found in a range of environments and may develop in a number of ways including: i) subglacial deformation, as a consequence of glacier bed motion (van der Meer, 1993; Hiemstra and Rijsdik, 2003), ii) iceberg scour (Linch et al., 2012), and iii) as slope deposits (subaerial and subaqueous) (Chapter 2, section 2.2.3, iii). A glacial environment has been discounted for this field site, due to its location outside of the last glacial advance (Hughes et al., 2016). Consequently, grain turbate development by deforming glacier bed motion or iceberg scouring is not feasible and the grain turbates identified in rampart PRDk (e.g. Fig. 4.14A), are probably caused by mass-wasting in a periglacial environment (Bertran, 1993).

Lithalsas develop gentle outer slopes - as they are thought to form as a consequence of vertical and lateral displacement (Pissart et al., 2011), rather than predominantly vertical
growth (as is the case for pingos) (Mackay, 1978). Lithalsa slopes are added to during frost-mound decay by mass-wasting, leading to rampart formation. The grain turbates within the rampart (PRD$_K$) are a minor presence (low in abundance and weakly to moderately developed) and occur both with and without core grains. Bertran and Texier (1999) suggested that rotation, in solifluction deposits, can depend on the amount of displacement that occurs rather than rate of movement. Therefore, a low number of grain turbates could develop as ramparts form during lithalsa decay. The low overburden pressure occurring within solifluction deposits could also account for the low number of rotation structures (Menzies et al., 2010). Therefore, rotational structures found within rampart PRD$_K$ could be caused by mass-wasting of the frost mound.

There is generally a low abundance of curvilinear arrangements of grains and matrix within the samples from PRD$_K$. Where curvilinear arrangements occur in grains > 2000 µm (creating discontinuous arc shapes) (e.g. Fig. 4.26, rampart basinward unit), this can give a sense of rotation within the sediment and can occur in debris-flow deposits (Phillips, 2006) (Chapter 2, section 2.2.3, iii). Where the arcuate arrangements occur within the matrix (silt and clay), they can appear to undulate, and are usually associated with wavy fissures (e.g. Fig. 4.16A and B, rampart upper unit). As we know that the environment of formation was periglacial, the fine-grained micro-undulations could have developed following repeated freeze-thaw cycles, which sorted the particles at the micro-scale to form 'banded fabric', or micro-stripes, indicative of frost creep (Chapter 2, section 2.2.3, iii). The arcuate linear grain arrangements in rampart PRD$_K$ occur in the silty, Fe-MnO stained basinward unit. Pissart and Juvigné (1980) described the basinward unit as comprising ‘silt tongues’ caused by deformation during inner-mound collapse. Therefore, arcuate arrangements of grains could indicate rotational forces produced during rampart formation, specifically as part of inner-mound collapse (Chapter 2, section 2.2.3, iii).

- **Planar structures**
  Within rampart PRD$_K$, linear grain arrangements are generally in low abundance. They are best developed within the rampart upper unit and can occur as: i) grain lineations (i.e. grains whose long-axes share a preferred alignment in close proximity but not arranged nose-to-tail), ii) grain stacks (i.e. with grain-to-grain contact), and iii) as linear grain domains (i.e. grains whose apparent long-axes may not share a preferred alignment but whose overall arrangement is linear or lens-like) (Fig. 4.26A). In subglacial environments, grain lineations form due to parallel stress during shearing (Hiemstra and Rijsdijk, 2003; Carr et al., 2006). Lineations can also be associated with rotation structures, such as grain
turbates, where the combination of rotation and planar displacement are related to imposed shear stress (Hiemstra and Rijsdijk, 2003). Hiemstra and Rijsdijk (2003) proposed that matrix and grain rotation require a torque, of which planar displacement (unistrial plasmic fabric and linear grain arrangements) is an indicator, and that planar and rotation structures should be proportionate. The potential association between rotational and planar structures means that the low number of grain lineations, weak unistrial plasmic fabric and the low number of grain turbates (section 4.4.2, Rotation) could be linked. As the field site environment is not subglacial and grain turbates in PRD_k are probably the consequence of solifluction processes (section 4.2.2, Rotation), grain lineations are likely to be related to mass-wasting during rampart-formation processes.

Grain stacks are formed due to perpendicular stresses, as a way of supporting the sediment during shearing processes, and are reported from subglacial environments (Iverson et al., 1996). There are no examples of grain stacks or linear grain domains described for periglacial settings. It is possible that the grain stacks, which occur in the basinward unit of rampart PRD_k, are in response to localised stresses caused by the collapse of the inner mound during rampart-formation processes. Shearing under periglacial conditions might also be associated with translational sliding above a shear surface (e.g. during active-layer detachment (Harris and Lewkowicz, 1993; Bertran and Texier, 1999; Pawelec and Ludwikowska-Kędzia, 2015)).

The linear grain domains that occur within rampart PRD_k are mostly lenses that appear to be ‘injected’ into the surrounding matrix and they are notable in the rampart basinward unit (e.g. Fig. 4.26A). Another prominent feature of the rampart basinward unit is homogenised in-mixed sediment of silt and clay. It is possible that the ‘injection’ structures and the homogenised areas of silt and clay are both linked to soft-sediment deformation (e.g. liquefaction) caused by collapse of the inner mound during frost-mound decay (section 4.4.2, Sediment mixing).

Fragmented domains of laminated clay and silt also occur in rampart PRD_k in moderate numbers and are moderately to well developed (Fig. 4.15B). Fragmented and translocated clay and silt coatings are abundant and occur throughout the sediment profile (Fig. 4.13D and 4.15A and D). As lithalsas develop in a periglacial setting, fragmented aggregates in the PRD is probably due to frost action (Chapter 2, section 2.2.3, iii). However, brecciated microstructures can also be characteristic of weak earth slides (Bertran and Texier, 1999). In addition, the location of some of the fractured domains in close proximity to the folded
peat-lens tip in the middle of the rampart (basinward section) (Fig. 4.22) could suggest that mechanical, shear stress is also responsible for fracturing clay and silt domains here, caused by the downslope movement of overlying sediment during mass-wasting (as reflected in the overturning of the peat-lens tip). A combination of shear stress, freeze-thaw action and mass-wasting could account for the fragmented domains and coatings found in rampart PRDₖ.

Fractured grains occur in very low abundance within the upper, middle and lower rampart units of PRDₖ (e.g. Fig. 4.29A) and are best developed around the peat-lens tip. Fractured grains can indicate abrasion (e.g. by iceberg scour (Linch et al., 2012)) but it has been established that the field site setting is not subglacial. It is known that, in periglacial environments, frost shattering of grains occurs due to high moisture retention in fissures followed by ice growth (van Vliet-Lanoë, 1985; 1998; 2010). Therefore, a freeze-thaw origin for the fractured grains in PRDₖ is likely. It is also possible that the location of the best developed examples, near the folded peat-lens tip, indicates that significant brittle strain is a probable contributing factor to grain fracturing in the middle rampart (basinward section).

- **Sediment mixing**
  Examples of sediment mixing include the development of: i) intraclasts (reworked matrix material, delineated by voids, which appear as a discrete clast (type I)); reworked, mixed sediment sometimes derived from the underlying bedrock (type III); and grain intraclasts (i.e. a discrete concentration of reworked skeleton grains that, in combination, appear to form a coherent whole)) and ii) multiple domains. Intraclasts reworked by rotation occur in subglacial environments (e.g. deforming beds (van der Meer, 1993)) and debris flows (Lachniet et al., 1991). The different intraclasts identified in rampart PRDₖ are low in number but are generally well developed, rounded and mostly occur in the rampart upper unit (e.g. Fig. 4.16G). The intraclasts are found in association with mixed domains of clay and silt, rotational structures (i.e. grain turbates and arcuate arrangements of grains) and convoluted and fractured clay and silt laminae (which have been attributed to colluviation (section 4.4.2, Stratification)). The roundness of the intraclasts (Fig. 4.16E), their location near the top of the profile and the association with intraclast type I with disrupted laminated colluvium, could suggest that they are sediment aggregates reworked by raindrop impacts (Bertran and Texier, 1999; Mümcher et al., 2010; Pawelec and Ludwikowska-Kędzia, 2015). However, rain wash could not account for grain intraclasts. Grain intraclasts in rampart PRDₖ are also associated with circular arrangements of grains (e.g. Fig. 4.13).
Rotation is known to occur during mass-wasting (Bertran, 1993). It is possible that the intraclasts in PRD$_k$ formed during frost-mound formation and decay (i.e. mass-wasting of sediment as the mound heaves and grows and/or as part of rampart formation as the frost mound decays).

There are many examples of soft-sediment deformation structures throughout the rampart profile; these occur in the form of fluidised and remobilised domains of silt and clay. Homogenised multiple domains associated with fluidisation and liquefaction are usually caused by significant external stress (e.g. glacial overriding, seismic disruption and loading or unloading of a sediment overburden) (Mahaney et al., 2004; Phillips, 2006). Whilst there is no evidence to suggest a glacial origin in relation to the field site (Hughes et al., 2016), tectonic activity does occur in eastern Belgium (Lecocq et al., 2008). The strongest known recorded seismic event in the Belgian Ardennes occurred in the seventeenth century near Verviers, ~ 20 km west of the field site in Konnerzvenn, with a magnitude of 6.25 (Lecocq et al., 2008). The Hautes Fagnes continues to be a zone of present-day natural seismic activity and is part of a complex of tectonic sites in the area (Trautwein-Bruns et al., 2010) caused by regional-scale structural weaknesses due to the Caledonian (c. 490–390 Ma) and Variscan (c. 290 Ma) orogenies (Geyer et al., 2008). Seismites (seismically induced soft-sediment structures) are known to cause shallow-depth dewatering in affected sediments that result in intensely folded and chaotic structures at both macro- and micro-scales that have no preferred orientation (e.g. ball-and-pillow structures, flame structures and injection features) (Menzies and Taylor, 2003; Montenat et al., 2007). However, soft-sediment deformation is associated with a range of macro-scale, gravity-driven phenomena (e.g. rock falls, olistostrom and debris flows) (Montenat et al., 2007). Additionally, it might be expected that seismic shocks would create abundant examples of brittle strain deformation at the macro- or micro-scales (e.g. faulting and grain crushing) (Menzies and Taylor, 2003; Montenat et al., 2007). As only some of the features associated with seismites are observed within the lower units of PRD$_k$ (i.e. fluidisation and remobilisation of sediment and a limited number of discrete convoluted structures) and there is no macro-scale expression of seismic activity (i.e. evidence of perturbation such as faulting or fractured rocks etc.), a seismic origin for the soft-sediment deformation that occurs in rampart PRD$_k$ is probably not likely. Deformation micro-structures related to the emplacement of debris-flow deposits include the mixing of fine-grained sediments (e.g. liquefaction, sediment remobilisation and water-escape features (Bertran and Texier, 1999; Philips, 2006)). Many of the features associated with debris-flow deposits are present within rampart PRD$_k$ at the micro-scale: i) disrupted layers of clay, silt and sand and chaotic clay domains, ii) distorted
organic layers within vughy, fluidized silt and clay (middle unit, central section beneath the thick, undulating peat lens (e.g. Fig. 4.20)), a vertical domain or ‘pipe’ of fluidised silt and clay (rampart middle unit, basinward section as the pen-lens tip folds backwards (e.g. Fig. 4.22), iii) convoluted arrangements of clay and silt, injected gravel lenses, vughy fissures and homogenised silt and clay domains (rampart basinward unit (e.g. Figs. 4.25 and 4.26)), and iv) remobilised silt and clay to form flame-like injection structures (rampart lower unit (e.g. Fig. 4.28). Periglacial rampart formation is associated with inner-mound collapse and mass-wasting (Mackay, 1988). It is possible that sediment loading, during mound collapse, could cause silt liquefaction, remobilisation and homogenisation, particularly lower down the sediment profile of rampart PRDκ and basinward (where inner-mound collapse could be fast-moving and represent significant loading). More localised stresses could account for the liquefaction of sediment around the folded peat-lens tip, which Pissart and Juvigné (1980) attributed to drag caused by mass-wasting during frost-mound decay. However, there is no confining pressure in the rampart upper unit that could account for soft-sediment deformation structures found here. An alternative explanation for a number of discrete chaotic and convoluted clay domains which exist within the matrix towards the base of the rampart upper unit (e.g. Figs. 4.16C and G) is that of partial collapse of the matrix induced by cryoturbation, in a similar way to the mechanism proposed for fragmented domains (section 4.4.2, Planar). The fragmented domains are then translocated upon thawing and moved throughout the sediment profile (pers. comm. van Vliet-Lanoë, 2016). A cryogenic origin for these structures is further supported by the fissure that cuts through the laminated colluvial facies in the rampart upper unit (Fig. 4.16). This is probably a desiccation fissure (an exit route for expelled air from the sediment) (section 4.2.2, Voids), related to freeze-thaw (van Vliet-Lanoë, 1985; 2010).

- **Pore-water features: void and grain coatings**
  Ferromanganiferous oxides (Fe-MnO) are remobilised by pore-water movement and precipitate to leave orange-brown staining (e.g. Fe-MnO coating of ice-lens traces (Figs. 4.13D and 4.21A)) (van Vliet-Lanoë, 1998). The fine-grained coatings of many of the rampart sediment grains (e.g. Figs. 4.15A and 4.21C) are silt and clay cappings, which develop following meltwater thaw. Clay concentrations(e.g. Fig. 4.15B), which are sometimes layered, are similarly transported by snow melt (van Vliet-Lanoë, 2010) (Chapter 2, section 2.2.3, iii).
• **Plasmic fabric**

In rampart PRD\textsubscript{K}, both skelsepic and unistrial plasmic fabrics occur in low to moderate numbers throughout the rampart profile and only skelsepic plasmic fabric is well developed in places. As the sediment in rampart PRD\textsubscript{K} is heavily stained with Fe-MnO in places, it is possible that the abundance and development of plasmic fabric is masked. Skelsepic plasmic fabric is common in subglacial environments and is related to rotation that occurs at the base of a glacier bed (Hiemstra and Rijsdijk, 2003). Shrink-swell of clay can also produce skelsepic plasmic fabric (Dalrymple and Jim, 1984). Whilst the XRD analysis indicates that a swelling clay could be present in some of the rampart samples from the middle unit, the dominant clay mineralogy is illite and chlorite and the pattern of fissures identified within the clay-rich fraction of the sediment have specific geometries that can be better explained by ice-lensing and the development of platy and prismatic aggregates (van Vliet-Lanoë and Langohr, 1982; van Vliet-Lanoë et al., 1984; van Vliet-Lanoë, 1985) than shrink-swell (Dalrymple and Jim, 1984) (section 4.4.2, Aggregates) (Chapter 2, section 2.2.3, iii). Flow materials are also known to produce poorly developed skelsepic plasmic fabric due to the rotation of particles (Bertran and Texier, 1999). A rampart formed by solifluction in a freeze-thaw environment is, therefore, likely to exhibit some degree of skelsepic plasmic fabric.

There is an association between unistrial plasmic fabric, grain lineations and rotation structures (Hiemstra and Rijsdijk, 2003) (section 4.4.2, Rotation). It could be that the unistrial plasic fabric observed in rampart PRD\textsubscript{K} is associated with mass-wasting processes that are probably responsible for the grain lineations (section 4.4.2, Planar) and grain turbates (section 4.4.2, Rotation) observed (e.g. Fig. 4.18C).

There are different explanations for different plasmic fabrics. However, the field site location in a periglacial environment makes it likely that frost action is the cause of the skelsepic plasmic fabric present in rampart PRD\textsubscript{K}. Additionally, the rotational and shear stresses associated with slope movement could explain the combination of unistrial plasmic fabric, skelsepic plasmic fabric and rotational structures observed within rampart PRD\textsubscript{K} (Bertran and Texier, 1999; Hiemstra and Rijsdijk, 2003).

**4.5 Discussion**

Macroscopic analysis suggests that sediment within PRD\textsubscript{K} can be split into three lithofacies: i) a saprolite of in-mixed, clayey, loessic silt, at the base, with scattered gravels derived from
the underlying bedrock due to gelification (van Vliet-Lanoë, 1985) overain by, ii) a finer-grained unit of alternating layers of peat and silt (laid down during oscillating cold and warm climate conditions (Rochon et al., 1998)), and iii) silts and gravels in the upper and basinward units (probably derived from nearby solifluction deposits (Ballantyne and Harris, 1994)). The gravelly, clayey silt basin sediment corresponds to that found at the base of the rampart and so is regarded as the substrate for frost-mound formation. This sediment provides a suitable frost-susceptible medium for the formation of segregation ice, required for frost-mound heave in a periglacial environment (Worsley et al., 1995).

The periglacial origin for PRDk in the Hautes Fagnes is confirmed by: i) the presence of distinct ramparts and an associated, shallow, basin (Watson, 1971; Mackay, 1988; Worsley et al., 1995; Gurney, 1998; Pissart, 2002; French, 2007), within a cluster of ramparted depressions (Fay, 2002), that commonly overlap (Worsley et al., 1995), ii) the presence within the rampart of wind-blown loess derived from glacial grinding, indicated by the high volume of grains < 100 μm and ~ 30 μm (Assallay et al., 1998), and iii) the abundance of microstructures derived from freeze-thaw processes (e.g. platy and lenticular aggregates, ‘banded fabric’, ice-lens traces, silt and clay ‘caps’ and coatings, frost-jacked (vertical) grains, fractured (frost-shattered) grains and fragmented clay and silt domains and coatings) (van Vliet-Lanoë and Langohr, 1982; van Vliet-Lanoë, 1985; 1998; 2010; van Vliet-Lanoë et al., 2009). These findings are consistent with diagnostic micro-features of cryoturbation and cryogenic-structure formation reported from relict permafrost sediments elsewhere (e.g. Belgium and northern France (van Vliet and Langohr, 1981; Iwahana et al., 2012)) and in present-day periglacial environments (e.g. Siberia (Goryachkin et al., 2013)) (Chapter 2, Table 2.2).

It is known that lithalsa formation is caused by freezing that heaves the overlying sediment due mainly to ice segregation fed by cryosuction (Seppälä, 1988; Calmels et al., 2008a, 2008b). It is also thought that lithalsas grow vertically and laterally probably due to: i) active-layer slides emplacing material on the outer slope of the lithalsa (Pissart et al., 2011) and, possibly, ii) ‘frost thrusting’ (i.e. the internal displacement of sediment laterally and vertically due to frost heave) (Washburn, 1979; Pissart et al., 2011). Lithalsas decay as growth, and the creation of tension cracks, promotes erosion and solifluction, causing sediment blocks to slide to the edge of the mound (Pissart, 2002; Calmels et al., 2008a; 2008b). Subsequent thaw and collapse causes vertical displacement (a downthrown section), creating a rampart encircling a depression (Chapter 2, Fig. 2.19) (Pissart, 2000; 2003).
Linking the macro-scale processes of lithalsa growth and decay to microstructures observed within PRDk, lithalsa formation and decay can be characterised as follows (Table 4.4):

- At the base of the rampart, sediment is dense and fine-grained with scattered clasts derived from the underlying bedrock (van Vliet-Lanoë, 1985). Within the lower rampart unit, there is an inclined layer beneath a thick undulating peat lens. The inclined layer probably formed during lithalsa formation due to frost heaving (Pissart, 2002). Soft-sediment deformation (i.e. in-mixed, fluidised domains and clay and silt) in the rampart lower unit is possibly caused by one or more events, including frost mound heave and sediment loading during inner-mound collapse and rampart formation (Mahaney et al., 2004; Phillips, 2006).

- The peat-lens complex in the middle of the rampart (alternating laminae of clay and silt above the thick peat lens), indicates changing climatic conditions (Rochon et al., 1998). The changing geometry of the thick peat lens (i.e. uplifted, parallel to the original frost-mound slope during formation, and then subject to drag during solifluction - indicated by the folded peat-lens tip (Pissart and Juvigné, 1980; Pissart and Gangloff, 1984; Elliott and Worsley, 1999)), indicates the mass-wasting of previously soliflucted deposits at the top of the rampart triggered by frost-mound growth.

- At the top of the rampart, the upper unit is identified by a higher clast content (pebbles). At the micro-scale, there are indicators of mass-wasting in the form of: i) a tilted layer, ii) inclined aggregates parallel to the slope surface, iii) rotation structures (e.g. grain turbates), and iv) silt coatings around and beneath grains.
### Table 4.4 Macro- and micro-scale structures identified in PRDx.

<table>
<thead>
<tr>
<th>Rampart unit</th>
<th>Macrostructures</th>
<th>Microstructures</th>
<th>Process interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper</td>
<td>• Poorly-sorted gravelly, clayey silty sediment</td>
<td>• Laminated clay and silt; granular aggregates</td>
<td>• Colluviation on the top of the lithalsa producing stratified deposits and reworking aggregates</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Inclined aggregates on the same inclination as the slope surface;</td>
<td>• Mass-movement due to solifluction during frost-mound formation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Silt coatings around and beneath grains;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Rotational structures (e.g. grain turbates);</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Tilted layers</td>
<td></td>
</tr>
<tr>
<td>Middle (central section)</td>
<td>• Intercalated silt and clay layers</td>
<td>• Intercalated silt and clay layers</td>
<td>• Oscillating climate conditions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Fluidised and in-mixed silt and clay, unistrial plasmic fabric</td>
<td>• Liquefaction and high-stress sediment mixing caused by loading</td>
</tr>
<tr>
<td>Middle (Basinward section)</td>
<td>• Folding of the undulating peat-lens tip</td>
<td>• Highly fragmented and distorted layers of clay and silt</td>
<td>• Brittle strain features caused by heave and then drag as a consequence of frost-mound and subsequent rampart formation</td>
</tr>
<tr>
<td>Basinward (Silt tongues)</td>
<td>• Compact, silt-rich, Fe-MnO stained sediment</td>
<td>• Grain aggregates, grain concentrations, arcuate arrangements of grains</td>
<td>• Compaction during the collapse of the inner mound and rampart formation</td>
</tr>
<tr>
<td>Lower</td>
<td>• Dense, matrix-rich sediment</td>
<td>• Inclined layers with associated fissures on a similar inclination</td>
<td>• Tilted layers created by frost-mound heave processes in the substrate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Grain turbates, fragmented clay domains, unistrial and skelsepic plasmic fabric</td>
<td>• Ductile and brittle strain structures caused by mass-movement of the sediment associated with frost heave</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• In-mixed, fluidised domains and clay and silt, mammillated voids and unistrial plasmic fabric</td>
<td>• Liquefaction and high-stress sediment mixing of the sediment caused by the emplacement of a solifluction lobe higher up the profile</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Prismatic aggregates</td>
<td>• Frost-affected, clay-rich sediment</td>
</tr>
<tr>
<td>All</td>
<td>• Platy aggregates;</td>
<td></td>
<td>• Cryoturbation</td>
</tr>
<tr>
<td></td>
<td>• Irregular, fragmented clay and clay and silt domains;</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Frost-jacked and shattered grains;</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Void and grain 'caps' and coatings of clay and silt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Vesicles;</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Skelsepic plasmic fabric;</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Ice-lens traces and micro-undulating fabric</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The basinward section of the rampart has a similar PSD to the upper rampart unit. The location of this unit on the inner side of the mound, combined with sediment compactness, suggests that it has collapsed from the upper rampart unit to form a downthrown section. The 'silt tongues' described by Pissart and Juvigné (1980), emphasised by heavy orange-brown Fe-MnO staining, are accompanied at the micro-scale by an arcuate arrangement of grains and grain concentrations, which might be caused by inner-mound collapse.

The control sample, in comparison, contains none of the structures identified in the rampart. Instead it contains evidence of biological activity (e.g. plant fragments, tubular voids) and Fe-MnO staining of voids. It is possible, that this sediment has been deposited more recently and so has not been subject to cryogenic processes.

4.6 Conclusions
The PRD investigated at Konnerzvenn in the Hautes Fagnes, Belgium is an accepted relict lithalsa (Pissart, 2000, 2003) and this is supported by comparison of the macro- and microscopic sedimentological signatures identified with those previously identified (Chapter 2, section 2.2.3) and summarised in Table 4.5. Macro-scale factors key to the lithalsa interpretation include:

- a high density complex of distinct ramparts and associated shallow basins (Worsley et al., 1995) in;
- a fine-grained, frost-susceptible substrate (Worsley et al., 1995) and;
- hydrogeological conditions that would permit recharge (Seppälä, 1988; Calmels et al., 2008a; 2008b) (i.e. the PRDs were probably fed by groundwater moving through fractured bedrock (Pissart, 2009)).

Well-developed microstructures attributed to PRD development include:

- tilted strata associated with a sub-vertical microfabric of similarly inclined elongate grains. The inclined layers may be parallel to the flow of mass-wasted sediment (upper rampart unit) (Harris and Ellis, 1980), or have undergone heave during mound growth (lower rampart unit) (Pissart and French, 1976; Mackay, 1978; Pissart and Gangloff, 1984);
- a low to moderate abundance of grain concentrations, linked to mass-wasting during frost-mound growth or rampart formation (Harris and Ellis, 1980);
- a high abundance of grain coatings of silt and clay (i.e. around the grain) (Harris and Ellis, 1980; van Vliet-Lanoë, 2010) and a low to high abundance of well-developed
curvilinear grain arrangements (Phillips, 2006), both due to rotation during rampart formation;

- a low to moderate abundance of planar structures: grain lineations, linear concentrations of grains and fragmented domains and fractured grains, that may reflect shear strain during rampart-formation processes (Iverson et al., 1996);

- a high abundance of multiple domains in the form of sediment in-mixing in the lower rampart, interpreted as re-homogenisation of sediment caused by frost-mound heave, and subsequent rampart, formation processes;

- skelsepic plasmic fabric is well developed in places (e.g. middle unit, basinwards) and could be linked to rotation structures (van der Meer, 1993), particularly during frost-mound collapse.

Microstructures identified within PRD_k can, therefore, be linked to: i) cryogenic processes, ii) frost-mound growth (internal heave and external mound development), and iii) rampart formation during frost-mound decay, and can be used for comparison with field sites where the landforms are of less certain origin. It should be noted, however, that single structures are not diagnostic of a particular process. Rather it is the combination of well-developed, repeated suites of deformation structures, contextualised by macro-scale features that enable deductions about genetic processes leading to their formation.
Table 4.5: Comparison of key sedimentological signatures of the PRD at Konnerzvenn with expected periglacial frost-mound signatures.

<table>
<thead>
<tr>
<th>Diagnostic macroscopic sedimentological features</th>
<th>Expected</th>
<th>Potential associated microscopic features</th>
<th>Konnerzvenn PRD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pingos (hydraulic and hydrostatic) and Lithalsas</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A rampart encircling a depression: isolated, within clusters or overlapping</td>
<td>✓</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Internal rampart deformation structures and stratification and tilting of layers</td>
<td>✓</td>
<td>Shear planes (banding of sediment in layers), micro-faults and folds. Potential variation in deformation with depth.</td>
<td>✓</td>
</tr>
<tr>
<td>External to the rampart, unsorted sediments derived from mass-wasting and shear failure (<em>e.g.</em> slump and debris-flow material)</td>
<td>✓</td>
<td>Shear planes, orientation of the long-axes of skeleton grains parallel to the orientation of the greatest angle of dip.</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Skeleton grain coatings, intraclasts present.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Turbate structures.</td>
<td></td>
</tr>
<tr>
<td>Rampart sediment should be derived from original mound and will be similar to that below the basin.</td>
<td>✓</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Pingos, Palsas and Lithalsas</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cryostructures caused by segregation ice (<em>e.g.</em> lenses and layers of sediment parallel to the freezing plane)</td>
<td>✓</td>
<td>Platy, lenticular microstructures oriented parallel to the ground surface: planar, wavy and curved (micro-undulations).</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pore spaces (packing voids) at the base of rock particles and clay aggregates.</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Silt cappings.</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vesicles, open fissures, well-developed shear planes and narrow – near-vertical – cracks</td>
<td>✓</td>
</tr>
<tr>
<td>Shallow basin (&lt; 4 m below the surface outside the rampart), indicative of segregation rather than intrusive ice.</td>
<td>✓</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Lithalsas</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lateral growth, demonstrated by displaced sediments at the lithalsa rampart edges</td>
<td>✓</td>
<td>Compression features due to lateral thrusting.</td>
<td>?</td>
</tr>
</tbody>
</table>
Chapter 5: Walton Common, west Norfolk, East Anglia

5.1 Introduction

5.1.1 Field site context

East Walton is 10 km east of King’s Lynn within the county of Norfolk, East Anglia (Fig. 5.1).

Walton Common lies to the west of the village on the fenland edges, north of the Nar Valley. A suspected PRD (Sparks et al., 1972; Pissart, 2000; Clay, 2015) is examined in the south west of Walton Common (Chapter 3, Fig. 3.3). The glacial history of East Anglia, located on the south west margin of the North Sea Basin, is complex. The number, timing and pattern of glacial advances are debated, due to oscillating glacial limits, particularly during the mid-Pleistocene (c. 781–126 ka) (Gibbard et al., 2009; Rose, 2009; Clark et al., 2012; Gibbard et al., 2012; Lee et al., 2016). During the Anglian Stage (c. 480–428 ka), the valley of the proto Nar was probably deepened by glacial scour as the ice sheets advanced from the north and west depositing glacial till (Lowestoft Formation) (West and Whiteman, 1986). There is some evidence to suggest an ice lobe extended into the Fenlands, west of King’s Lynn, during the Wolstonian glaciation > 130,000 years ago (i.e. the Tottenhill sand and gravel member) (Gibbard et al., 1992; Gibbard et al., 2009; Gibbard et al., 2012).

However, despite a glacial incursion to the north of King’s Lynn in the Late Devensian (Late Dimlington) (Clark et al., 2012), there is no evidence that East Walton has been glaciated since the Anglian Stage. Instead, it would probably have been the site of an ice dammed
lake (Clark et al., 2012), which subsequently developed into fenland (West and Whiteman, 1986). Nonetheless, East Anglia was subject to multiple cycles of periglaciation, attributed by Bateman et al. (2014) to four key periods: (1) c. 55–60 ka, (2) c. 31–35 ka, (3) c. 20–22 ka, and (4) c. 11–12 ka. This is supported by the existence of abundant relict periglacial associated landforms (e.g. patterned ground and frost mounds) and the localised presence of aeolian coversands (Hoare et al., 2002). Therefore, the sediment in this investigation is unlikely to be affected by glacial processes.

The regional geology is West Melbury Marly Chalk and Zig Zag Chalk Formation (i.e. Cretaceous chalk of the Grey Chalk Sub Group (c. 94–100 Ma) (Gallois, 1994)). The chalk beds gently dip to the east (<1°) and overlie Gault Clay (Gallois, 1994). The clay strata act as an aquiclude (an impermeable sediment layer inhibiting the flow of groundwater) influencing the hydrological regime by retaining water in the area (Wheeler and Shaw, 2000). Superficial cover at Walton Common is classified as the Nar Valley Formation (silt and clay) (BGS, 1986). The Nar Valley deposits date to the Hoxnian interglacial (c. 374–424 ka), following the Anglian period (c. 480–428 ka) (Ventris, 1986). This Formation comprises a range of estuarine sediments (e.g. fluvial, lacustrine, organic and marine deposits), which drape the area as a consequence of the river switching its course multiple times (Ventris, 1986).

5.1.2 Summary of previous research

Prince (1961; 1962; 1964) proposed a periglacial origin for the suspected PRDs in Norfolk as part of an investigation into the origin of abundant pits, ponds and depressions in the region. The first sedimentological and morphological description of the landforms on Walton and Foulden Commons was produced by Sparks et al. (1972). At East Walton, oval to circular and overlapping ramparts of fine chalk rubble and sand are described as variable in size, surrounding basins of Flandrian deposits (c. 11.5 ka to the present-day), chalk rubble and a chalky mud (Sparks et al., 1972). Pollen analysis of basin infills indicated two active periods of formation during the Dimlington (c. 26–13 ka) and Loch Lomond (c. 11–10 ka) Stadials, producing subdued and fresh hollows, respectively (Sparks et al., 1972). The forms at Walton Common are described as fresh hollows developed in areas of relatively shallow permafrost (Sparks et al., 1972). Key to the remnant frost-mound identification by Sparks et al. (1972) was the discovery of a reversed stratigraphy within the outer flank of a rampart (i.e. chalk rubble overlying sand), interpreted as sloughed sediments from a mound during rampart formation. A subsequent review of similar landforms within Norfolk (referred to as ‘pingos’) was conducted by the Norfolk Wildlife Trust and over 200 sites were identified.
(Walmsley, 2008). The majority of sites (~ 60%) are located in Breckland (south Norfolk and north Suffolk), a significant minority are found in west Norfolk (~ 25%) and the remainder in north Norfolk and Broadland (Norfolk Broads) (Walmsley, 2008). West (2015), classified the suspected PRDs into three categories based on their distribution: i) clusters in low valleys, ii) clusters on shallow valley side slopes, and iii) widespread and degraded forms at higher levels.

Caution has been exercised over the identification of a specific frost-mound type for the Norfolk PRDs (Sparks et al., 1972). A re-interpretation of PRDs in Belgium (Pissart and Gangloff, 1984) and Wales (Pissart, 2000; 2003), as lithalsas rather than pingos, was not extended to the landforms at Walton Common (Chapter 2, section 2.3). Nonetheless, Pissart (2000) has acknowledged the similarity in form and density of the Norfolk PRDs to those in Belgium. Conversely, Worsley (1977) suggested an hydraulic pingo origin - although this was subsequently revised to a mineral palsa/lithalsa origin (Worsley et al., 1995). French (1979) did not discount a frost or icing blister interpretation for the landforms on Walton Common (i.e. features that can reach a height of up to 3 m and 48 m diameter due to the movement of water between the icing layers).

More recently, Clay (2015) proposed that the PRDs at Walton Common are hydraulic pingos. Clay (2015) undertook geomorphological mapping, hydrogeological analysis and near-surface geophysical investigations (i.e. electrical resistivity tomography (ERT) and ground penetrating radar (GPR)) at Walton and Thompson Commons (~ 30 km south east of East Walton). The suspected PRDs at these sites are described as geomorphologically similar but geophysical analysis of the ramparts showed differences in their internal structures. Clay (2015) suggested that the Walton Common landforms are hydraulic pingos, based on geophysical data, which depicts clear rampart structures, and the location of the PRDs within sediment interpreted as coarse-grained colluvial valley fill. The suspected PRDs at Thompson Common are classified as lithalsas (based on the presence of less distinct rampart structures and the different geological and hydrological setting of the PRDs). Clay (2015) described Walton Common as a model example of a relict hydraulic pingo site despite acknowledging its uniqueness in terms of density of features. Whilst Clay’s study provides clear internal images of the Walton Common and Thompson Common features, until the geophysical data from the suspected PRDs at both sites are compared to that for known relict PRD features, such as the lithalsa remnants in the Ardennes, a definitive conclusion cannot be drawn.
5.2 Macroscopic descriptions

5.2.1 Walton Common sediment profile (PRD$_{WC}$, control sample and basin core)

PRD$_{WC}$ is an oval-shaped rampart, ~ 2 m in height with a diameter of ~ 80 m. The rampart has a small breach on the flank to the north west and overlaps with a smaller rampart on its north-eastern flank (with a diameter of ~ 60 m). Beneath a deep sandy silty top soil and sandy sub-soil cover, the rampart is characterised by: i) a lower unit of sandy, chalk gravel, above which is ii) an upper unit of gravelly sand (Fig. 5.2).

i. Rampart PRD$_{WC}$ (Fig. 5.2)

- Rampart lower unit:
  The lower unit has a diffuse boundary with the overlying upper unit (gravelly, sand layer) marked by a change in texture (Fig. 5.3A, B, C and D). The lower unit is more compacted than the upper unit and there is a higher pebble and cobble content. It is reached at a depth of ~ 0.95 m from the crest (Fig. 5.3B) (an exposure of 0.35 m was accessed from the inner-rampart flank) (Fig. 5.3D). The lower layer is characterised by a structureless mélange of matrix-supported, sandy (medium-grained), chalky gravel. There is a change in colour from the upper unit to a very pale brown (10 YR 8/2) in the lower unit. As with the overlying unit, clasts are composed of angular flints and sub-rounded carbonates but carbonate clasts dominate in this layer. Clasts are predominantly pebble-sized with some cobbles (flints ≤ 83 mm a-axis; carbonates ≤ 63 mm a-axis). The flints are poorly sorted and the carbonates are moderately well sorted.

- Rampart upper unit:
  There is a clear planar, horizontal boundary between the organic, silt-rich top and sandy sub-soils (dark brown (10 YR 3/3) and dark yellowish-brown (10 YR 4/6), respectively) that overlie the rampart upper unit. This is marked by a change in colour and texture. The rampart upper unit is a matrix-supported, cohesionless (containing particles identifiable with the naked eye) gravelly (mostly flint), sand (predominantly medium-grained) and is a light yellowish-brown (10 YR 6/4)). This layer is of variable thickness (i.e. ~ 0.75 m in thickness at the crest decreasing to ~ 0.65 m wide on the inner-rampart flank, whilst the soil cover increases in thickness) (Figs. 5.3A, B, C and D). There is sediment mixing between this unit and the overlying soil cover; the boundary between the two, in particular, is marked by vertical tongues of dark yellow-brown silt (10 YR 4/6) and brownish-yellow (10 YR 6/8) sand (from 2 to 10 cm long and up to 1.5 cm wide) intruding from the overlying unit.
Concentrated yellowish-brown (10 YR 6/8) sand-rich lenses are unevenly located within the upper unit. These sand-rich domains (horizontal tabular sheets and elongate vertical lenses) are up to 10 cm wide and 50 cm long. Clasts are composed of flint and carbonate granules and pebbles with a few cobbles. The flint gravels range in colour from predominantly orangey-brown to creamy-white. The flints are mostly very angular to sub-angular (Fig. 5.4A), some appear highly polished whilst others have sharp keels and/or are faceted (Figs. 5.5A, B and C). The flints are mostly very bladed to bladed with some elongate (≤ 50 mm a-axis) (Fig. 5.6A). The carbonate clasts are creamy-grey (Fig. 5.6D) and are mostly rounded to sub-rounded (≤ 34 mm a-axis) (Fig. 5.6E). Carbonate particle shape is mostly platy to bladed (Fig. 5.6B).

**Key:**
- Δ Granule/pebble
- □ Sediment in-mixing
- △ Cobble
- Dashed line Sand-rich domains

**Fig. 5.2 Walton Common: Representative sedimentary log of PRD<sub>WC</sub>, where 0 cm = crest of the rampart.**
Fig. 5.3 Walton Common: A) Idealised rampart profile (PRDWC) based on dGPS data showing pit locations; B) Pit 1 at the crest; C) Pit 2 on the outer flank; and D) Pit 3, head-long into the tapered end of the rampart.

Fig. 5.4 Walton Common: Clast roundness. A) Flint gravel (upper unit); B) Carbonate gravel (lower unit) (n = sample number; RA = percentage of very angular and angular clasts in a sample).
5.5 Walton Common: Clast morphology of clasts from PRD<sub>WC</sub>. A) Highly polished sub-rounded flint (sharp keel above smooth facet marked) upper unit); B) Angular flint smooth (sharp keel between two adjacent faces marked) (upper unit); C) Sub-angular creamy-white, polished flint (lower unit); D) Elongate, edge rounded sub-angular flint with pitted surface upper unit); E) Rounded carbonate clast (lower unit). All scales in cm.

Fig. 5.6 Walton Common: Clast-shape. A) Flint gravels (upper unit): n (sample size) = 30, very bladed to bladed; B) Carbonate gravels (lower unit): n = 20, platy to bladed.
ii. *Inter-rampart micromorphological control sample:*

Between the ramparts beneath a deep top soil cover (~0.5 m) is a single, massive, gravelly, brown (7.5 YR 5/4) unit of predominantly medium-grained sand (Fig. 5.7A). There is a distinct planar boundary between the overlying top soil and the underlying sandy layer. However, there is some evidence of sediment mixing (bioturbation) between the two layers. In addition, there are lenses of organic matter within the underlying sandy layer. Within the very dry and granular sand are large angular to sub-angular clasts of orange-brown flint (as were found in the rampart pits). The flint increases in number and size with depth from pebble up to cobble size (≤ 65 mm a-axis). Some of these are highly polished with a silica veneer (Fig. 5.7B).

![Fig. 5.7 Walton Common: A) Control sample location within inter-rampart pit; B) Representative flint recovered from the control sample sediment (angular with a highly polished facet). Scale in cm.](image)

iii. *Basin core:*

A core was taken from the basin middle. There is ~1 m of peat and gyttija, followed by ~2.3 m of chalk interlayered with sand lenses, including scattered pebbles (4–14 mm, a-axis). The chalk becomes firmer and more compact towards the base and it was not possible to core below 3.3 m. Occasional flint clasts occur within the basin sediment (Fig. 5.8).
Fig. 5.8 Walton Common basin core description: A) Core depth 0–1 m: 0.9 m of organic material (i.e. peat (black-brown) and gyttija (a gel-like, black organic material (5 YR/2.5/i)) with fibrous plant roots; B) Core depth 2.86–3 m: Beneath the organic infill, is a fine silty (36%), fine sandy (40%), chalky greyish-white (5 YR/8/1) putty (clayey silt) soft to firm, with carbonate clasts up to 6 mm a-axis. This putty-like chalk increases in firmness with depth and sand lenses (fine to medium-grained) occur periodically creating a slightly coarser-grained texture and giving a yellowish tinge to the chalk in places (2.5 Y 7/3); C) Core depth 3–3.3 m: The chalk becomes less sandy (12%) and more compacted with depth. Sub-angular flint and carbonate granules and pebbles occur up to 14 mm a-axis.

5.2.2 Bulk-sediment analyses

i. **Particle-size distribution (PSD):**

Medium-grained sand (0.25–0.5 mm) dominates the top of the rampart and the sediment becomes more gravel-rich with depth. Silt is present in low quantities (≤ 12%) and a very low clay fraction is found within the rampart (≤ 7%) (Table 5.1; Fig. 5.9):
Table 5.1 Walton Common: Rampart (PRD<sub>WC</sub>) and control sample PSD.

<table>
<thead>
<tr>
<th>Rampart unit</th>
<th>Upper</th>
<th>Lower</th>
<th>Control sample</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Clayey (4%), silty (12%), gravelly (22%), sand (62%) (medium-grained)</td>
<td>Clayey (7%), silty (10%), sand (30%) (medium-grained), gravel (46%)</td>
<td>Gravelly (2%), silty (7%), sand (91%) (fine to medium-grained)</td>
</tr>
</tbody>
</table>

Fig. 5.9 Walton Common: PSD for rampart (PRD<sub>WC</sub>) and control sample.

**ii. Clay mineralogy (X-ray diffraction (XRD) analysis)** (Table 5.2; Fig. 5.10):

XRD analysis identifies that the low quantity of clay (Dalrymple and Jim, 1984) present in the rampart sediment samples is kaolinite, which is derived from the weathering of feldspar (Moore and Reynolds, 1997). Therefore, any shrink-swell properties associated with smectite clays, are unlikely to affect plasmic fabric present (Dalrymple and Jim, 1984; Blokhuis et al., 1990; van der Meer et al., 2003).

Table 5.2 Walton Common: PRD<sub>WC</sub> - XRD analysis of clay mineralogy.

<table>
<thead>
<tr>
<th>Sample location</th>
<th>Smectite</th>
<th>Illite</th>
<th>Chlorite</th>
<th>Kaolinite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper unit</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Trace</td>
</tr>
<tr>
<td>Lower unit</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Trace</td>
</tr>
<tr>
<td>Control sample</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Trace</td>
</tr>
</tbody>
</table>
iii. **Carbonate analysis:**
Carbonate content varies downwards throughout the vertical profile of the rampart ranging from ~15% in the sandy top layer to ~25% at the chalky base (Fig. 5.11). Therefore, it is possible that anisotropism exhibited by plasmic fabrics (birefringence viewed in cross-polarised light) will be disguised by carbonates during thin-section analysis of samples from the mid to base of the rampart (van der Meer *et al.*, 2003).

![XRD Peaks with Ångström Values](image)

**Fig. 5.10 Walton Common: Key XRD peaks are marked with their Ångström values (a unit of length equal to 0.1 nm).**

![Sample Context](image)

**Fig. 5.11 Walton Common: Rampart (PRD\textsubscript{WC}) and control sample carbonate content.**
5.3 Microscopic descriptions

The following sections describe the microscopic texture and structure of the upper and lower units of rampart PRD<sub>WC</sub>, as well as the control sample. Table 5.3 summarises data on matrix and skeleton grains. Figs. 5.12 and 5.13 summarise grain roundness and microfabric data.

i. **Rampart upper unit** (Figs. 5.14, 5.15 and 5.16)

(Thin sections: WC3-i (top), WC2-i-bii (middle), WC2-i-bi (base)):

The rampart upper unit is a cohesionless sediment. There is a minor but significant percentage of flint and carbonate grains throughout the upper unit (< 10%). The percentage of very angular and angular clasts in the sample (RA index) is relatively low and greatest for grains > 2000 µm in the upper and control units (Fig. 5.12). The flint gravel is mostly sub-angular and elongate with some equant grains. Flint occurs throughout the rampart upper unit and sometimes occurs sporadically in clusters. Flint size ranges from 1 to 16.3 mm (a-axis) and particles are mostly aligned sub-vertically to vertically (Figs. 5.14B and 15.16B). Carbonate grains are generally rounded to sub rounded and they range in size from 0.9 to 9.6 mm (a-axis). The carbonates are mostly equant and are located throughout the sediment generally sub-vertically to vertically aligned. Skeleton grains (< 2000 µm) dominate the rampart upper unit and is mostly sand. There is a high density of medium-grained sand, typically 400 µm in size, predominantly sub-rounded. The distribution and texture of sand grains varies across the sediment, sometimes forming coarser or finer, rounded domains (e.g. Fig. 5.16). Towards the base of the rampart upper unit (Fig. 5.16) particles become much finer (very fine sand to coarse-grained silt) rather than medium-grained sand. There is a low to moderate abundance of grain concentrations throughout the upper unit (up to 12 x 11 mm in dimension). The upper rampart matrix comprises silt and micritic cement with a minor clay fraction, which increases down profile (sometimes patchily and sometimes in concentrated zones above and along the long sides some of the larger grains (Figs. 5.15B and 5.16B)) and as grain coatings. However, in places the matrix is so sparse that the sediment is grain-supported in these areas. Towards the base of the rampart upper unit is a tilted layer (~ 140°), emphasised by a difference in grain size: i) coarser silt (lower layer) and ii) medium to coarse-grained sand (upper layer) (Fig. 5.16). At the base of the rampart upper unit, the tilted layer is associated with a strong preferred orientation of grains, linear grain arrangements and nearby fissures that share a similar alignment (between 130 and 150°). Many grains towards the top of the rampart lower unit also share this orientation but there is a wider range of grain inclination at the top of the rampart unit compared to the base.
Table 5.3 Textures, deformation microstructures and post-depositional features in the ramparts and the control sample, Walton Common, Norfolk.

Key: * = Well developed; ● = Moderately developed; ○ = Weakly developed. Numbers of circles reflects abundance.

<table>
<thead>
<tr>
<th>Deformation structures</th>
<th>Texture</th>
<th>Voids</th>
<th>Rotation/slump</th>
<th>Planar</th>
<th>Sediment mixing</th>
<th>Pore water</th>
<th>Plasmic fabric</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vertical to sub-vertical microfabric</td>
<td>Grain concentrations</td>
<td>Planar fissures</td>
<td>Vugs</td>
<td>Vesicles (pore spaces)</td>
<td>Grain turbates</td>
<td>Curvilinearations</td>
</tr>
<tr>
<td>Upper unit</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WC3-1</td>
<td>●●</td>
<td>●</td>
<td>○</td>
<td>*</td>
<td>**</td>
<td>**</td>
<td>●●</td>
</tr>
<tr>
<td>WC2-iiii</td>
<td>●●</td>
<td>●●</td>
<td>●</td>
<td>★</td>
<td>*</td>
<td>★</td>
<td>●●</td>
</tr>
<tr>
<td>WC2-iiii</td>
<td>**</td>
<td>●●</td>
<td>*</td>
<td>★</td>
<td>*</td>
<td>★</td>
<td>●●</td>
</tr>
<tr>
<td>Lower unit</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WC1-ib</td>
<td>**</td>
<td>●</td>
<td>●</td>
<td>○</td>
<td>●</td>
<td>○</td>
<td>●●</td>
</tr>
<tr>
<td>WC1-ia</td>
<td>**</td>
<td>●</td>
<td>●</td>
<td>○</td>
<td>●</td>
<td>○</td>
<td>●●</td>
</tr>
<tr>
<td>Control sample</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WC</td>
<td>●●</td>
<td>●</td>
<td>●</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>●●</td>
</tr>
</tbody>
</table>
Fig. 5.12 Micro-grain roundness: Walton Common. Key: VA = very angular; A = angular; SA = sub-angular; R = rounded; WR = well rounded (n = sample number; RA = percentage of very angular and angular clasts in a sample).
> 2000 μm:

A) Top of upper unit (WC3-i): n = 25

B) Middle of upper unit (WC2-ibii): n = 25

C) Base of upper unit (WC2-ibii): n = 31

D) Top of lower unit (WC1-ib): n = 45

E) Base of lower unit (WC1-ia): n = 14

F) Control sample (WC5): n = 17

> 500 μm:

G) Top of upper unit (WC3-i): n = 72

H) Middle of upper unit (WC2-ibii): n = 61

I) Base of upper unit (WC2-ibii): n = 64

J) Top of lower unit (WC1-ib): n = 76

K) Base of lower unit (WC1-ia): n = 53

L) Control sample (WC5): n = 79

< 500 μm:

M) Top of upper unit (WC3-i): n = 70

N) Middle of upper unit (WC2-ibii): n = 57

O) Base of upper unit (WC2-ibii): n = 53

P) Top of lower unit (WC1-ib): n = 59

Q) Base of lower unit (WC1-ia): n = 57

R) Control sample (WC5): n = 55

Fig. 5.13A)-R) Walton Common: Microfabric analysis of suspected PRDWC and control sample. Apparent long-axes orientation of skeleton grains in 20° interval classes measured anticlockwise from the horizontal plane, where the top of the thin section measures 90° (n = sample number).
Fig. 5.14 Thin section: WC3-1 (rampart upper unit – top). Thin section measures 8 x 5.5 cm.
Fig. 5.15 Thin section WC2-ibii (rampart upper unit - middle). Thin section measures 8 x 5.5 cm.
Fig. 5.16A-C) Thin section Wc2-ibi (rampart upper unit - base). Thin section measures 8 x 5.7 cm.
There is a low to moderate abundance of void spaces occurring as vertical to sub-vertical fissures, rounded chambers, pore spaces and vughs (deformed pore space). Fissures are located unevenly throughout the sediment (from 4 to 45 mm long and 0.2 to 2.2 mm thick), but at the base of the upper rampart unit, in the finer-grained layer of silt and fine sand, there are a few examples whereby planar fissures delineate platy to angular sediment aggregates up to 8.4 x 5 mm (Fig. 5.16C). Also towards the base of the upper unit, is an inclined fissure (20 mm long and 1.5 mm thick) sharing a similar orientation to a tilted layer (110°). There are some vughs (1.9 x 2 to 16.5 x 2.7 mm), which increase in frequency up the vertical profile. There are some packing voids at the base of the upper unit and at the edges of some larger grains. The most significant void texture is the small pore spaces (~ 0.1 mm) between the sand grains. In total, void space constitutes ~ 20–25% and is greatest at the top of the upper unit (i.e. the top of the rampart). Even though the sediment is relatively porous, due to the scarcity of matrix present, grains are densely packed.

A low number of weak to moderately developed grain turbates occur in the middle of the rampart upper unit (Fig. 5.15C), comprised of both pebble and sand fractions. There are also some examples of curvilinear arrangements of grains (i.e. arcuate linear grain arrangements, in close proximity but not touching, which form arc shapes within the sediment and give a sense of rotation), again occurring in both pebble and sand fractions (Fig. 5.15A). There are examples of weak to moderately developed grain lineations (i.e. grains whose long-axes share a preferred alignment in close proximity but not arranged nose-to-tail) and grains stacks (i.e. with grain-to-grain contact) (Figs. 5.14A), up to 2.5 mm long, and a moderate abundance of linear grain domains ranging from 5.6 to 14.9 mm long (i.e. grains whose apparent long-axes may not share a preferred alignment but whose overall arrangement is linear) (Fig. 5.16A). There are a very low number of fractured grains and these occur as both fractured, translocated and fractured, and in situ (Fig. 5.16A).

A low number of intraclasts type III occur (i.e. reworked fragments of unconsolidated sediment) and grain intraclasts, particularly towards the top of the upper unit. The intraclasts are a maximum of 9 x 9.2 mm with diffuse but distinct boundaries. There are examples of sediment mixing, particularly in the upper rampart unit. For example, within the medium-grained sand layer of the upper rampart unit there are a low number of well-developed domains of coarser grains (coarse-grained sand) amidst finer grains (medium-grained sand), in elongate or ovoid forms, ranging in dimension from 12.9 x 6.8 mm to 12.8 x 8.7 mm. In the mid-section of the rampart upper unit (WC2-Ibii) (Fig. 5.15), there are distinct domains of fine-grained sand within a predominantly medium-grained sand
sediment, which occur as a deep wedge (30 mm deep) and as an ovoid-shape (28 by 30 mm) along the same vertical axis (Fig. 5.15). Within these zones there is greater pore space and less matrix than elsewhere within the sediment. Porous domains of finer grains (coarse silt and very fine sand) occur within the coarser grained groundmass (Fig. 5.14). Towards the top of the upper unit (WC3-1) (Fig. 5.14), the sediment is stained an orange-brown in places, which is associated with pore-water movement remobilising ferromanganiferous oxides (Fe-Mn oxides) that precipitate and leave a coating (van Vliet-Lanoë, 1998). The bright colour of the sparse clays even under plane-polarised light (PPL) also indicates the presence of Fe-Mn oxides. The association of the clays with Fe and Mn and the low volume of clay inhibit the detection of any potential birefringence. The sand grains, in particular, are often coated with a carbonate-clay-silt mix.

the rampart lower unit (Figs. 5.17 and 5.18)
(Thin sections: WC1-1b (top), WC1-1a (base)):

The rampart lower unit is characterised by a dense, opaque matrix (< 30 µm) of carbonates, silt and clay within which is a minor but significant percentage of flint and carbonate grains. The flint is poorly sorted, mostly angular to sub-rounded (Fig. 5.12) and concentrated unevenly within the lower rampart sediment. Flint size ranges from > 0.6 to 20.5 mm (a-axis) and these are mostly aligned sub-vertically. The larger flints are oriented ~ 120–140 °, particularly towards the base, often with pore spaces beneath and sometimes with matrix coatings along the grain sides (Fig. 5.18B). The flint clasts are mostly elongate and many are stained orange-brown. Carbonate grains range between > 0.6 and 13.7 mm and are poorly sorted. They are mostly rounded to well rounded and equant. There is a higher incidence of vertically and sub-vertically inclined grains (flints and carbonates) in the lower unit, compared to the upper unit, becoming more vertical up profile (Fig. 5.17). Some of the vertical grains have clear packing voids beneath them (Fig. 5.18B). Many carbonate grains have quartz plastered around them, especially the larger grains. The carbonate grains have a weak preferred orientation ~ 120 °. Despite being a matrix-supported sediment, the skeleton grains are closely packed and comprise abundant, rounded to sub-rounded, medium-grained sand, which are typically 400 µm in size and are distributed throughout the sample. Orientations of the sand grains varies but they are mostly sub-vertical to sub-horizontal and fairly well sorted (Fig. 5.13). A silty calcite dominates the matrix and appears like a speckled, muddy cement distributed unevenly throughout, sometimes as dense concentrations but elsewhere it is absent. The silty calcite also coats some grains. There is a minor feldspar component (microcline and orthoclase), some flakes of muscovite mica and calcite crystals present within the sample.
Fig. 5.17 Thin section WC1-1b (rampart lower unit - top). Thin section measures 8 x 5.5 cm.
Fig. 5.18 Thin section WC1-1a (rampart lower unit - base). Thin section measures 8 x 5.7 cm.
This sand-rich sediment is characterised structurally by layers demarcated by a preferred alignment of larger grains (*i.e.* clasts) within the range of 120–140°. This is particularly marked near the base of the lower rampart (Fig. 5.18). The sediment is compact and the void space is less than in the overlying (upper rampart) unit (< 10%) but increases up profile. Void spaces are unevenly located. They occur as planar fissures (from 2.3 mm long to 0.05 mm and up to 0.2 mm thick), vughs and simple packing voids beneath some skeleton grains.

There are a low number of weakly developed grain turbates (Fig. 5.18C) and a moderate abundance of weak to moderately developed curvilinear arrangement of grains (Fig. 5.17B and C), although less than in the rampart upper unit. A further characteristic of this lower rampart unit is a range of linear grain concentrations of grains: i) grain lineations (*i.e.* grains whose long-axes share a preferred alignment in close proximity but not arranged nose-to-tail) (*e.g.* Figs. 5.17A and C and 5.18A); ii) grain stacks (*i.e.* with grain-to-grain contact), (*e.g.* Fig. 5.17B); and iii) as linear grain domains (*i.e.* grains whose apparent long-axes may not share a preferred alignment but whose overall arrangement is linear) (*e.g.* Fig. 5.18A) and stacks (Fig. 5.17B) up to 3.8 mm long. All linear arrangements are comprised of a variety of grain sizes (*i.e.* sand and gravel). Multiple domains exist of silt and fine-grained sand within a matrix of coarser (medium-grained) sand. These domains have irregular, rounded geometries and are much fewer in number than in the overlying upper rampart unit (Figs. 5.17 and 5.18). The bright colour of the sparse clays even under PPL indicates the presence of Fe-Mn oxides. The association of the clays with Fe and Mn and the high percentage of carbonates present inhibit the detection of birefringence and so if plasmatic fabric is present, it is unlikely to be detected.

***Control sample*** (Fig. 5.19)

(Thin section WC):

The control sample is massive and matrix-supported. There is a minor percentage of flint clasts and very few carbonate grains. The flints are mostly sub-angular to sub rounded and they are concentrated towards the base. Flint size ranges from > 2 to 6.7 mm (a-axis) (*i.e.* granules and pebbles) and they are mostly aligned sub-vertically, oriented between 120–140°. There is an exception to this sub-vertical orientation a third of the way down the control sample, where a crude layer of flint clasts (up to 3 mm in size) is horizontally aligned, with individual particles randomly orientated. There is a high density of rounded to sub-rounded, fine to medium-grained sand grains, distributed throughout, which are
Fig. 5.19 Thin section WC (control sample). Thin section measures 10 x 8 cm.
typically 150–300 μm in size (Fig. 5.19). Generally, sand grains are sub-rounded to rounded, without preferred orientation (Fig. 5.19). The density of the sand varies in random locations. There are some discrete domains where the sand skeleton grains are coarser (coarse-grained sand) within finer-grained domains (medium-grained sand) in elongate or augen-shaped forms, ranging in dimension from 7.8 x 5 mm to 3.3 x 1.7 mm. These concentrations are a minor constituent, visible but not particularly well developed. The control sample sediment comprises very little clay (< 1%), which is distributed randomly as partial grain coatings. There is a minor feldspar component within the sample. The control sample is porous.

Void spaces occur throughout the control sample and constitute ~ 25% overall. Void spaces occur as fissures along the sample base (horizontal, ~ 40 mm long and up to 2 mm thick) and on the side (vertical, ~40 mm long and up to 2 mm thick) and chambers (up to 12 mm long and 3 mm thick. The main void texture is the small pore spaces (predominantly ~ 0.1 x 0.2 mm) that exist between the sand grains. These are mostly simple packing voids (Fig. 5.16A). The sediment is largely structureless. There are a few examples of sand grain stacks up to 1 mm long, randomly distributed and linear grain domains of flint clasts concentrated in a linear geometry, particularly towards the base, with an overall preferred orientation of ~ 120 – 140 ° up to 18.7 mm long (Fig. 5.19B). The bright colour of the sparse clays even under PPL indicates the presence of Fe-Mn oxides. The association of the clays with Fe and Mn and the low volume of clay inhibits the detection of birefringence.

5.4 Interpretation

5.4.1 Macroscopic analysis

The PSD (Table 5.1), demonstrates that the suspected PRD contains two different units (Fig. 5.9).

- Rampart lower unit

The lower unit is more compacted, than the upper rampart unit, and is dominated by chalky gravel with less sand. The degree of fragmentation and the location of the sediment towards the base of the rampart, suggests that the seasonal frost is unlikely to be the cause of the brecciated chalk. Another possibility is that the deposit represents soliflucted material in the valley bottom. However, as this chalky diamicton unit is not found within the control sample (section 5.4.1, iv) (a comparative sample from the same sediment as the rampart but taken from outside of frost-mound formation and decay processes), it suggests
that the chalk has its origin elsewhere. An obvious source for the chalk is the underlying Grey Chalk bedrock that has been uplifted above the local level and brecciated. It is known that ice segregation in fine-grained bedrock (e.g. chalk) causes heave and brecciation (creating angular, platy blocks) during periglacial conditions (Murton et al., 2001; van Vliet-Lanoë et al., 2017) and soft-sediment deformation and mass-wasting on thawing (Murton, 1996).

- Rampart upper unit

The rampart upper unit is of clast-rich (flint dominated) sand (medium-grained). The sand-rich sediment with gravel component (granules and pebbles) suggests a high energy depositional environment. The presence of sub-angular flint with orange-brown staining (attributed to Fe-Mn oxides) is characteristic of river gravels (Gibbard, 1986). Whilst the superficial cover in the field site area is recorded as the Nar Valley Formation (clay and silt) (BGS, 1986), the paucity of clay and low volume of silt present does not support this interpretation. Bordering the field site are other lithostratigraphic units from the Nar Valley Formation that are more relevant as they comprise varying proportions of fluvial sand and gravels (e.g. the Wormegay, Pentney and Marham Members (Bowen, 1999)). However, even a reclassification of the superficial sediments to one of the more gravelly members does not account for the high volume of sand present (over 60% of the total sediment in the rampart upper unit). An alternative interpretation of the superficial cover is that it is aeolian coversand formed during intense periglacial periods (Hoare et al., 2002). Cold climate, sandsheet depositional processes are not completely understood but they are thought to include fluvial and aeolian action (by saltation during windstorms) (Sarre, 1987; Pye, 1995). The location of the field site close to glacial limits and probably an ice-dammed lake (Clark et al., 2012) makes Walton Common an appropriate setting for such a deposit (Koster, 1988). Coversands are generally well-sorted grains that are moderate to well rounded with a mean size of ~ 150–200 µm (fine-grained) and little material < 63 µm (Bateman, 1995). In addition, many of the flints in the rampart upper unit exhibit features associated with the surface morphology of ventifacts (rocks abraded or polished by wind-driven sand) (Knight, 2008). At the macroscale, there are examples of flints with knife-sharp keels above smooth facets (Fig. 5.5A) (Demitroff, 2015) and other examples where the edges of the flints have been weathered by abrasive wind action. At the mesoscale, a highly polished sheen is evident on many of the flint gravels (Fig. 5.5A, B and C), possibly caused by wind-driven sand, ice and or snow abrading and buffering the surface (Knight, 2008). Therefore, the high volume of rounded to well rounded, well-sorted sand (125–500 µm), a nearby abundant source for this and the presence of highly polished (varnished), faceted and keeled flints, interpreted as
ventifacts, suggest that reworking of fluvial deposits by aeolian processes is possible. The sand at the field site does have a higher component of medium-grained sand than is usually associated with coversands (up to 500 µm rather than predominantly 150–200 µm). However, Hoare et al. (2002) suggest that a relatively coarse texture for these aeolian deposits is the consequence of post-depositional frost-mound processes (e.g. debris flows during mound formation and collapse) generating a relatively poorly sorted, coarser-grained sand component.

- **Basin core**
  The core sediment, encountered at a depth of ~ 1 m, is a much finer-grained (sandy-silty) chalk than that found in the rampart, with a putty-like consistency at depth. The obvious source for the chalk is the underlying bedrock, which must have been subject to intense frost action to cause it to become putty-like. Therefore, the sediment at the base of the depression is interpreted as a more deformed version of that in the lower unit of the rampart, that constitutes the substrate within which the suspected PRD developed (Flemal, 1976; Mackay, 1988).

- **Control sample**
  A control sample was secured for the purposes of comparison with the rampart samples. Due to the absence of any natural exposures an inter-rampart location was selected. The control sample is sand dominated (medium-grained) and contains a minor component of flint clasts. Whilst less clast-rich than the rampart upper unit, it is closest in PSD to the upper rather than the lower rampart unit (Fig. 5.10). It is notable that even at a depth of one meter, from an elevation lower than that of the rampart, a chalky diamicton was not encountered. This further supports the suggestion that the rampart substrate is in situ chalk, which has been heaved and frost-shattered. If the landform had developed in coarse-grained colluvial valley in-fill sediment (Clay, 2015) this should be more widespread and appear outside of the rampart.

- **Soil cover**
  A point of note is the deep soil and sub-soil cover encountered both in the rampart and the control sample pits. Bioturbation has caused sediment in-mixing and it is likely that bioturbation, solution and sediment re-mobilisation since the Pleistocene has led to Holocene soil development of Pleistocene sediments (Bateman et al., 2014). This makes analysis of the relict periglacial features at macro- and micro-scales more complex. To counter this, samples were taken from the lowest points possible within each unit (i.e. to
avoid as much as possible soil formation processes) and notes made of any obvious post-depositional activity to contextualise analysis.

5.4.2 Microscopic analysis

- **Microfabric**

There is a moderate abundance of sub-vertically to vertically oriented skeleton grains within rampart PRD_{WC}. This is illustrated by: i) vertical grains with distinct pore spaces at the base and or side (Figs. 5.14B and 5.18B) and ii) grains whose long-axes are inclined sub-vertically (Fig. 5.16B). It is proposed that the PRDs at Walton Common probably developed in a periglacial environment (section 5.4.1). One of the diagnostic microstructures associated with cryoturbation is frost-jacked grains (van Vliet-Lanoë et al., 1984; van Vliet-Lanoë, 1985; 2010) (Chapter 2, section 2.2.3, iii). When not associated with ice-lens traces, sub-vertically inclined grains in close proximity to similarly oriented void spaces and or lithological contacts could be caused by tilting due to heave during frost-mound growth (e.g. at the base of the rampart upper unit (Fig. 5.16) and within the rampart lower unit (Fig. 5.18)) (Pissart and French, 1976; Mackay, 1978; Pissart and Gangloff, 1984).

- **Stratification**

Of particular note, in PRD_{WC}, are the inclined layers at the base of both the rampart upper and lower units, probably linked to frost-mound formation and decay processes. It is particularly evident at the base of the rampart upper unit, where there is a change in grain size (from coarse silt and fine sand to medium-grained sand) (Fig. 5.15). The tilted layer is further emphasised by the upslope inclination of the apparent long-axes of grains parallel to the rampart flank. In the lower rampart unit, tilted layers are indicated by crude bands of similarly oriented sub-vertically inclined grains (Figs. 5.17 and 5.18). Tilted layers are consistent with: i) uplift during frost-mound formation, when they occur deep within the rampart, and ii) redistributed sediment, as part of rampart-formation processes, during frost-mound decay (i.e. mass-wasting), when they occur at the top of the rampart (Mackay, 1978; Pissart and Juvigné, 1980; Harris, 1985; Mackay, 1988; Bertran and Texier, 1999).

- **Grain concentrations**

There is a low to moderate abundance of grain and matrix concentrations, throughout PRD_{WC}. Poorly sorted, porous sediments, could indicate liquefaction (from debris flows) or frost-induced mass-wasting (solifluction) (Bertran and Texier, 1999). As a periglacial origin is proposed for PRD_{WC}, the uneven distribution of scattered clasts (many of which are relatively angular) within finer-grained sediment is possibly caused by solifluction during
rampart-formation processes (Chapter 2, section 2.2.3, iii). Variation in distribution of the matrix could be the result of preferential sorting of grains due to frost action (van Vliet-Lanoë, 2010) (Chapter 2, section 2.2.3, iii). This can also result in silt ‘caps’ and coatings on grains (Fig. 5.16B) (Chapter 2, section 2.2.3, iii), but where it is present sporadically, occurring within the matrix of the top of the upper unit and control sample, it is possibly due to sediment in-mixing due to bioturbation (e.g. redistributed by earthworms (Fitzpatrick, 1993).

- **Void spaces**

Void spaces occur as planar fissures, channels and chambers, vughs and vesicles (pore spaces). There are some examples of planar voids mirroring the same inclination of probable tilted layers (section 5.4.2, Stratification). These inclined void spaces could be associated with shear stresses, as planar fissures can occur along sediment bedding planes or along shears, due to a difference in grain size (van der Meer, 1993; Lachniet et al., 2001; Hiemstra and Rijssdijk, 2003; Carr, 2004). Well-defined, tubular channels and chambers occur in low numbers in the upper rampart unit but are more significant in the control sample. Brewer (1964), proposed that regular, elongate, tube-like fissures can be linked to faunal or plant root systems. In the rampart upper unit, the association of channels and fissures with sediment in-mixing suggests that an earthworm origin for these structures is likely. In the control sample, the proximity of the sample to trees and undergrowth suggests that both a faunal or plant root system could be responsible for the structures (Fig. 5.19). Packing voids occur at the base of some of the larger grains (Figs. 5.14B and 5.18B). These are probably caused by frost-jacking (section 5.4.2, Microfabric). The majority of void spaces within both PRD<sub>WC</sub> and the control sample are classified as ‘vesicles’ due to their rounded shape but are rather preserved pore spaces around loosely packed sediment particles (Fig. 5.19A).

- **Aggregates**

In the samples from PRD<sub>WC</sub> only a few aggregates occur at the base of the rampart upper unit. The aggregates are platy to angular and only occur in the finer-grained sediment (very fine-grained sand to coarse-grained silt) (Fig. 5.16C). In periglacial environments, compacted aggregates are caused by ice lensing (van Vliet-Lanoë and Langohr, 1982; van Vliet-Lanoë et al., 1984; van Vliet-Lanoë, 1985) (Chapter 2, section 2.2.3, iii).
• **Rotation**

Circular grain arrangements (*e.g.* grain turbates) are associated with debris flows within a variety of environments (*e.g.* glacial and sub-aerial/aqueous mass-wasting) (Carr *et al.*, 2000; Hiemstra, 2001; Lachniet *et al.*, 2001; Menzies and Zaniewski, 2003; Phillips, 2006). As a periglacial environment is considered likely for PRD<sub>WC</sub>, the development of grain turbates by sub-aerial mass-wasting is probable (Chapter 2, section 2.2.3, iii). The grain turbate structures within PRD<sub>WC</sub> are weakly developed and low in number in both the upper and lower rampart units (Figs. 5.15C and 5.18C). However, there are many more examples of curvilinear arrangements of grains (Figs. 5.15A and 5.17B). In fine-grained sediments (*i.e.* silt), micro-undulations develop following repeated freeze-thaw cycles, which is indicative of frost creep (van Vliet-Lanoë *et al.*, 1984; van Vliet-Lanoë, 2010) (Chapter 2, section 2.2.3, iii). In coarser-grained sediment, discontinuous arcuate arrangements of grains are described in debris-flow deposits (Phillips, 2006) (Chapter 2, section 2.2.3, iii). However, there is no example in the academic literature for similar frost structures in medium-grained sand. It is possible, therefore, that curvilinear arrangements of grains could be related to mass-wasting but could it could also be that in coarser-grained sediment frost creep is expressed differently and the curvilinear arrangements of sand grains within PRD<sub>WC</sub> are the rest position of grains following freeze-thaw.

• **Planar structures**

Within rampart PRD<sub>WC</sub>, linear grain arrangements occur as grain lineations (*e.g.* Fig. 5.17A and C), ii) grain stacks (*e.g.* Fig. 5.14A), and iii) linear grain domains (Fig. 5.18A). Grain lineations can be associated with grain turbates (Hiemstra and Rijsdijk, 2003) but these are in very low number throughout PRD<sub>WC</sub>. In sub-glacial environments, grain lineations form due to parallel stresses during shearing (Hiemstra and Rijsdijk, 2003; Carr *et al.*, 2006). It is possible, therefore, that an abundance of grain stacks, and lineations indicate localised zones of brittle strain in periglacial environments. As the stress applied has been sufficient to create strong uni-directional orientation of grains, planar structures could be taken as a proxy for shearing (*i.e.* localised readjustment of grains in response to stress during active-layer slides and rampart formation) (Harris and Lewkowicz, 1993; Bertran and Texier, 1999; Pawelec and Ludwikowska-Kędzia, 2015). Fractured grains occur in low abundance and mostly within the rampart upper unit (Fig. 5.16A). In periglacial environments, frost-shattering of grains can occur due to ice growth following moisture retention in clasts (van Vliet-Lanoë, 1985; 1998; 2010) (Chapter 2, section 2.2.3, iii). It is possible that the fractured grains that occur in the upper rampart unit are due to frost action (van Vliet-Lanoë, 1985; 1998; 2010).
• *Sediment mixing*

Intraclasts III (sediment) occur in the rampart upper unit moderately to well developed in low to moderate abundance. Rotation is known to occur during mass-wasting (Bertran, 1993). It is possible that the intraclasts in PRD<sub>WC</sub> formed during frost-mound and rampart formation due to solifluction processes (Chapter 2, section 2.2.3, iii). There are also many examples of multiple domains observed in the rampart upper unit. This corresponds with burrow-like vertical structures, observed in the sediment at the macroscale, that appear to mix overlying sediment deeper within the profile. It is possible that this form of sediment in-mixing is caused by bioturbation (Fitzpatrick, 1993). In general, the mixed domains are more porous than the surrounding matrix, probably as a consequence of biological activity (Fitzpatrick, 1993). This probably indicates Holocene soil development of Pleistocene sediment (Bateman *et al.*, 2014).

• *Pore-water features: void and grain coatings*

The rampart is largely composed of medium-grained sand and associated pore space, which is likely to cause the sediment to be free draining. Nonetheless, concentrated patches of matrix and Fe-MnO staining can occur where drainage is impeded locally (Kühn *et al.*, 2010). Silt coatings occur on all grain sizes (*e.g.* Figs. 5.16B and 5.18) and are diagnostic of frost-affected sediments (van Vliet-Lanoë, 1985; 1998; 2010) (Chapter 2. Section 2.2.3, iii). Vertically, to sub-vertically aligned grains, with silt cappings and packing voids at the base indicate periglacial processes (*i.e.* cryoturbation) (van Vliet-Lanoë, 2010) (Chapter 2. Section 2.2.3, iii).

• *Plasmic fabric*

Within rampart PRD<sub>WC</sub>, examples of skelsepic and unistrial plasmic fabric are found in proximity to sub-vertically inclined grains associated with tilted layers (section 5.4.2, Stratification) but these examples are few and weakly developed. It is possible that both the skelsepic and unistrial plasmic fabrics observed within rampart PRD<sub>WC</sub> are associated with the heave of sediment during rampart formation. It is notable, however, that: i) the clay content of the sediment is low, ii) there is Fe-MnO staining of sediment, which can inhibit the detection of plasmic fabric (Jim, 1990), and iii) there is a high carbonate content, known to disrupt cross-polarised light and so mask birefringence and plasmic fabric in thin sections (Bellinfante *et al.*, 1974).
5.5 Discussion

Macroscopic evidence indicates a local stratigraphy of: i) sandy chalk gravel, overlain by ii) fluvial deposits, subsequently re-worked and contributed to by aeolian coversands. The proposal that the chalk is sourced from the underlying bedrock is supported by data from a 3 m borehole record from the south of the Common, which records a top soil cover of 0.46 m, overlying moist soft chalk clayey silt, overlying firm white clayey silt with chalk lumps (BGS, 2016). In addition, this stratigraphy occurs elsewhere in the region in association with chalkland patterned ground (Bateman et al., 2014). The sandy-silty chalk basin sediment, with a putty-like consistency at depth, corresponds to that found at the base of the rampart and so is regarded as the substrate for frost-mound formation. This sediment provides a suitable frost-susceptible medium for the formation of segregation ice, required for frost-mound heave in a periglacial environment (Worsley et al., 1995).

Key macroscopic indicators that the suspected PRD on Walton Common has a periglacial, and so frost-mound origin, includes: i) its location beyond the edges of the ice-sheet limits during the Last Glacial Maximum (LGM)(~ 23–19 ka) (Clark et al., 2012), ii) the presence of distinct ramparts, with a largely symmetrical form, surrounding a shallow basin (Watson, 1971; Mackay, 1988; Worsley et al., 1995; Gurney, 1998; Pissart, 2002; French, 2007) (i.e. there are no deep penetrations into the chalk bedrock that would be expected with solution hollows or irregular forms indicative of kettle holes, and no deep small pits associated with marl or chalk pits (Sparks et al., 1972)), iii) its location within a cluster of overlapping ramparted depressions - the abundance of coalescing ramparts suggests repeated, cyclical activity on a site with an environment conducive to frost-mound formation (i.e. climatically, hydrologically and lithologically) (Müller, 1959), and iv) the presence of coversands, indicating that the suspected PRDs developed during periglacial conditions (Hoare et al. 2002; Bateman et al., 2014).

Hoare et al. (2002), proposed that the sands draping the suspected PRDs and surrounding area of the Common are correlative with the fine to medium-grained ‘Leziate coversands’, of Loch Lomond Stadial age (12.7–11.5 ka) (the Leziate sand pits are located ~ 8 km west of the field site). However, coversand deposition has been extensive within East Anglia and optically stimulated luminescence (OSL) dating of deposits to the south of Norfolk (e.g. Brettenham Heath (East), Suffolk) evidences earlier activity during the Late Devensian (26-13 ka), particularly around the Greenland Stadial 2a (18–16 ka), which better fits with dates for frost mound development during the Younger Dryas (Bateman et al., 2014).
There is a limited range of microstructures observed within the rampart with low to moderate abundance. It is evident from the analysis of the effect of grain texture on microstructures found in subglacial till (Hart et al., 2004) and ice keel scour (Linch and van der Meer, 2015), that grain size has a bearing on the deformation structures. Not only does grain size have an impact on the strain structures imparted but also on the structures it is possible to observe. This could explain the multiple examples of grain stacks and lineations with preferred alignments but a paucity of plasmic fabric (for which a minimum clay content is required). Nonetheless, it has been possible to discern and characterise deformation across the vertical profile sub-surface.

Microscopic observations from the suspected PRD supporting a frost-mound origin include:

i) the presence of cryoturbated sediment (e.g. frost-jacking of grains, silt cappings and coatings, platy to angular sediment aggregates) and ii) tilted layers created during frost-mound formation with associated planar microstructures (e.g. grain lineations) and rotation structures (e.g. grain turbates). The control sample, by comparison, contains few microstructures. Instead it predominantly contains evidence of faunal and or plant root activity.

5.6 Conclusions

The PRDs at Walton Common are found clustered on a low-lying valley floor. The prevailing hydrological environment indicates that the hydrogeology would have provided a sufficient, spring-fed, water source for the cyclical formation of perennial frost mounds through cryosuction within fine-grained sediment (Seppälä, 1988; Calmels et al., 2008a and b). The chalky gravel diamicton found within the rampart indicates that fine-grained, frost-susceptible chalk (probably sourced from the underlying bedrock and an ideal medium for the development of segregation ice) was probably the substrate within which the landform developed. Segregation ice, fed by water sourced from nearby streams, would have caused frost heave (Mackay, 1973; 1986; 1999), and the development of a lithalsa as follows:

1. Ice segregation within a fine-grained chalk substrate leads to heave and brecciation of the chalk bedrock (illustrated by the development of platy aggregates, frost-jacked grains, silt cappings etc. in the lower rampart unit).

2. As the frost-mound forms, tilted layers develop – internal, microscopic evidence for sediment heave and mound formation includes inclined layers in the chalky lower rampart, repeated in the sands and gravels of the upper rampart, to which
coversands contributed during intense periglacial weathering conditions in west Norfolk, probably in the late Devensian (c. 26–13 ka) (Bateman et al., 1999, 2014).

3. Degradation of the frost mound, due to ice core thaw, causes redistribution of the frost-mound sediment overburden, by mass-wasting, to form ramparts.

4. Holocene soil development into Pleistocene sediments contributes to sediment in-mixing between the rampart units, evidenced by the deep soil cover on the ramparts at Walton Common.

While previous palaeoclimatic reconstructions, suggested that the conditions in East Anglia were not favourable to lithalsa growth during the Younger Dryas (12.7-11.5 ka) (Isarin, 1997; Isarin and Bohncke, 1999) (Chapter 2, section 2.3.1), this is not supported by subsequent climatic and permafrost modelling (Vandenberghhe et al., 2014). Moreover, the field site location is close to the boundary of oscillating Pleistocene ice margins, which further complicates precise reconstructions of palaeo-temperatures. In addition, the acceptance that the older ‘subdued’ frost-mound forms at Walton Common (Sparks et al., 1972) probably are lithalsas (Pissart, 2000), suggests that a lithalsa origin is a credible proposal. A lithalsa origin explains: i) the low broad form of the PRDs (as lithalsa growth is lateral rather than upwards (Pissart et al., 2011)), ii) the shallow basins (due to the presence of a large volume of segregation ice containing mineral material (Watson and Watson, 1972 and 1974)), and iii) the high density of the landforms (the slow growth of pingos over thousands of years (Mackay, 1986), means that for repeated growth to occur at the same site (that has not occurred simultaneously), a pingo origin is unlikely).
Table 5.4 Comparison of sedimentological signatures of the suspected PRDs on Walton Common with expected periglacial frost-mound signatures.

<table>
<thead>
<tr>
<th>Diagnostic macroscopic sedimentological features</th>
<th>Expected</th>
<th>Potential associated microscopic features</th>
<th>Walton Common PRD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pingos (hydraulic and hydrostatic) and Lithalsas</td>
<td>✓</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>A rampart encircling a depression: isolated, within clusters or overlapping. Internal rampart deformation structures and stratification and tilting of layers. External to the rampart, unsorted sediments derived from mass-wasting and shear failure (e.g. slump and debris-flow material).</td>
<td>✓</td>
<td>Shear planes (banding of sediment in layers), micro-faults and folds. Potential variation in deformation with depth. Shear planes, orientation of the long-axes of skeleton grains parallel to the orientation of the greatest angle of dip.</td>
<td>Layers identified ✓</td>
</tr>
<tr>
<td>Rampart sediment should be derived from original mound and will be similar to that below the basin.</td>
<td>✓</td>
<td>N/A</td>
<td>✓</td>
</tr>
<tr>
<td>Pingos, Palsas and Lithalsas</td>
<td>✓</td>
<td>Platy, lenticular microstructures oriented parallel to the ground surface: planar, wavy and curved (micro-undulations). Pore spaces (packing voids) at the base of rock particles and clay aggregates. Silt cappings. Vesicles, open fissures, well-developed shear planes and narrow – near-vertical – cracks</td>
<td>✓</td>
</tr>
<tr>
<td>Shallow basin (&lt; 4 m below the surface outside the rampart), indicative of segregation rather than intrusive ice.</td>
<td>✓</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Lithalsas</td>
<td>✓</td>
<td>Compression features due to lateral thrusting.</td>
<td></td>
</tr>
<tr>
<td>Lateral growth, demonstrated by displaced sediments at the lithalsa rampart edges</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Chapter 6: Cledlyn Valley, south west Wales

6.1 Introduction

6.1.1 Field site context

The field site is located ~ 10 km west of Lampeter, within the county of Ceredigion, south west Wales. Cardigan Bay is to the west and the Afon Teifi (river) is to the south, before flowing westwards to the coast (Figs. 6.1 A and B). It is generally accepted that Wales was subject to repeated glacial advances during the Quaternary period (Etienne et al., 2005) with evidence of two distinct phases in western Wales: i) in the Late Devensian (c. 20 ka) and ii) an earlier advance (before 20 ka) of uncertain age (Davies et al., 2006). The Cledlyn Valley field site is within the proposed limit of the Late Devensian ice sheet (Campbell and Bowen, 1989). In the Late Devensian, the Irish Sea Glacier (ISG) advanced from north east Ireland and south west Scotland (Etienne et al., 2005; Davies et al., 2006). At the same time, the Welsh Ice Cap (ISG) extended westwards from the Cambrian mountains (Campbell and Bowen, 1989; McCarroll and Ballantyne, 2000). The limits and timings of the two ice sheets and their interaction is debated (Bowen, 1973a; 1973b; Hambrey et al., 2001; Etienne et al., 2005), particularly in south west Wales (Watson, 1972; Ballantyne, 2010; Patton et al., 2013). Nonetheless, Patton and Hambrey (2009) identified ISG deposits overlying WIC deposits 55 km north of the Cledlyn Valley field site, at Tonfanau (mid-west Wales), and proposed that Welsh Ice Till (WIT) covered much of the Teifi valley catchment as well as the coast within the counties of Pembrokeshire and Ceredigion in the Late Devensian (Phillips et al., 1994; Hambrey et al., 2001; Clark et al., 2012; Patton et al., 2013). Charlesworth (1929) and Etienne et al. (2005) suggested that a number of glacial lakes (e.g. Llyn Teifi and Llyn Aeron) formed in front of the ISG during the Late Devensian, fed by meltwaters from the ISG and the WIC. This led to the deposition of glaciolacustrine sediments of laminated (Charlesworth, 1929; Jones, 1965) blue-grey to brown clay (Waters et al., 1997). Continued advance of both the ISG and WIC, during the Late Devensian, displaced the lakes and glacial till was deposited over the glaciolacustrine sequence (Etienne et al., 2006). Therefore, it is likely that the sediment in this investigation is affected by glacial processes.

The regional bedrock geology is the Yr Allt Formation of the late Ordovician Period, Ashgill Epoch (450–420 Ma) (Davies et al., 2006). It comprises units of thinly bedded, dark grey, very silty mudstone with siltstone laminae, interlayered with thick sandstone beds (Waters et al., 1997; Sheppard, 2004; Etienne et al., 2005; Davies et al., 2006). The units are highly disturbed and contorted due to complex faulting and folding associated with the
Fig. 6.1A Field site (Cledlyn Valley) and control sample (Aberarth) locations within Ceredigion, Wales (Inset). Fig. 6.1B Field site microtopography (Cledlyn Valley): 1 m Digital Terrain Model (DTM) using Lidar (Environment Agency, 2014). Red dotted lines denote suspected PRD ramparts, the black arrow points to the associated basins.
Caledonian Orogeny (c. 400 Ma) (Waters et al., 1997; Etienne et al., 2005; Davies et al., 2006). Regional superficial sediment is classified as the Elenid Formation and comprises glacigenic deposits: i) Irish Sea Ice Till (ISIT), ii) WIT, and iii) glaciofluvial clayey, sandy gravels, overlain by Holocene deposits (Waters et al., 1997; Bowen, 1999; Bowen, 2005).

6.1.2 Summary of previous research

The Cledlyn Valley suspected PRD group was initially investigated by the Watsons (Watson, 1971; 1972; 1976; 1982; Watson and Watson, 1972; 1974), with detailed sedimentological and morphological descriptions of six of the landforms produced. The landforms were dated to probably around the Younger Dryas (c. 12.7–11.5 ka), based on pollen analysis of the basin infill (Handa and Moore, 1976; Harris, 2001; Walker and James, 2001) and radiocarbon dating (Shotton et al., 1975). Due to a similarity in upland environmental setting and morphology, Pissart (1963) compared suspected PRDs in mid and west Wales (e.g. east of Llangurig), to features in the Hautes Fagnes in the Ardennes (Belgian-German border), the latter of which were initially identified as hydraulic (open system) pingos (Pissart, 1963). A subsequently revised classification of the Belgian landforms to mineral palsa and then lithalsas based on landform density, topographic and hydrological setting, was then extended to the Cledlyn Valley PRDs (Pissart and Gangloff, 1984; Pissart, 2000; 2003) (Chapter 2, section 2.3). Gurney (1994; 1995), proposed that the fine-grained 'basin infill' of the Cledlyn Valley PRDs is the landform substrate and that the rampart sediment is composed of slope deposits. Gurney (1995) suggested that only this interpretation could explain the significant volume of silt within the depression, which is too great to have been derived from the clast-rich ramparts alone. Harris (2001) undertook high resolution, near-surface geophysical investigations in the same area (i.e. resistivity, ground penetrating radar (GPR) and microgravity surveys) and found that there are two different areas of low resistivity (water-bearing) strata beneath the ramparts and the basins up to a depth of 18 m and continuing upslope, indicating clay-rich sediment. Nonetheless, anomalous microgravity readings for the same zones do not corroborate this interpretation and low resistivity readings alone are not proof of identical lithology (Harris, 2001). Therefore, the geophysical analyses permit interpretations of both: i) the movement of water under hydraulic head, flowing beneath a thin permafrost layer, leading to pingo formation (Müller, 1959) and ii) extensive deposits of fine-grained sediment providing an appropriate substrate for lithalsa growth by cryosuction (Seppälä, 1988; Calmels et al., 2008a and b). A subsequent review by Ross (2006), emphasised the glacigenic origin of the superficial sediment (diamicton) in the rampart and Ross (2006) tentatively proposed glaciofluvial deposition in contact with decaying ice (i.e. a kettle hole).
The Cledlyn Valley is central to understanding the occurrence of suspected PRDs in the region (Gurney, 1995) as it contains some of the best developed forms in the UK (Watson, 1972; Bryant and Carpenter, 1987; Campbell and Bowen, 1989; Ballantyne and Harris, 1994). However, previous macroscopic and geophysical investigations have failed to resolve whether the landforms are: i) pingos, formed under hydraulic pressure (Watson, 1971; Watson and Watson, 1974; Watson, 1976), ii) lithalsas formed by ice segregation (cryosuction) (Gurney, 1995; Pissart, 2002; 2003), or iii) glacial landforms (Ross, 2006).

### 6.2 Macroscopic descriptions

#### 6.2.1 Cledlyn Valley sediment profile (PRD<sub>CV1</sub>, CV<sub>2</sub>, CV<sub>3</sub>, control sample CVC and basin core) (Figs. 6.2A, B, C, D and E)

**i. PRD<sub>CV1</sub>**

This horseshoe-shaped rampart comprises: i) a lower unit of sandy, gravelly, clayey silt and ii) an upper unit of clayey, sandy, gravelly silt.

- **Rampart lower unit (Fig. 6.2B):**
  This is a massive, cohesive unit of stiff, clayey, grey (5 Y 6/1) silt with scattered granules and pebbles (angular to sub-angular and sub-rounded), particularly at the base of the section. The overall texture is ~ 85% fines to ~ 15% gravels. Clast size varies between ≥ 2 mm and ≤ 8 mm and lithologies include greywackes (dark, coarse-grained sandstone), sandstones and quartz. The section contains tree and plant roots and iron staining.

- **Rampart upper unit (Fig. 6.2A):**
  The upper unit comprises an olive brown (2.5 Y 4/3) sediment, characterised by a massive, matrix-supported, unsorted, highly compacted, cohesionless sediment of predominantly silty gravel with ~ 60% sand, silt and clay (fines) to ~ 40% gravels. Clast size varies between pebbles (4 to 8 mm) (most abundant) and cobbles. From a depth of ~ 10 cm, patchy orange staining of the sediment occurs, associated with ferromanganiferous oxides (Fe-MnO). The Fe-MnO staining increases with depth and alters the sediment colour to a yellowish brown (10 YR 5/4). Despite the patchy differences in colour, the rampart upper unit sediment has the same texture throughout.

Clasts are fine-grained sand- and siltstone. Many clasts are Fe-MnO-stained and there are striae on more than 50% (Figs. 6.3A and B). The granules and pebbles are predominantly angular, sub-angular and sub-rounded (Fig. 6.4A). The percentage of very angular and
angular clasts in the sample (RA index) is 24%. The clasts are generally very bladed and very platy with a high $C_{40}$ value (the measure of how slabby-elongate a pebble-shape is) at 92 (Fig. 6.5A). Clast fabric demonstrates a north east to south west trend (Fig. 6.6A).

ii. $PRD_{CV2}$ (Fig. 6.2C)
This elongate rampart comprises: i) a lower unit of clayey, sandy, silty gravel, ii) a middle unit of clayey, cobbly, silty, sandy gravel, and iii) an upper unit of clayey, cobbly, sandy, silty gravel.

- Rampart lower unit:
Sub-unit 1 (25 cm thick): At the base of the rampart is a massive, cohesive unit of gleyed clayey, sandy, gravelly, olive grey (5 Y 4/2) silt. The lower rampart unit is cross cut by the Nant Cledlyn (river). Overall, the estimated particle-size fractions of the sediment are 35% gravels (granules, pebbles and cobbles) and 65% clayey, silty sand. The gravels are generally very coarse, tabular and angular to sub-rounded and sub-angular. The upper boundary to this unit undulates and is marked by iron staining.

Analysis of clasts from the rampart upper unit demonstrates that they have a homogenous lithology of fine-grained sandstone and siltstone, many are Fe-MnO-stained and there are striae on more than 50% of those examined, including cross-cutting striae (Fig. 6.3C). The granules and pebbles are mostly sub-angular to sub-rounded and the RA value is low, 13% (Fig. 6.4B). Clast-shape is generally bladed (Fig. 6.5B) and the $C_{40}$ value is high at 88, confirming a slabby-elongate shape. The principal clast orientation is south south east (Fig. 6.6B).

- Rampart middle unit:
Sub-unit 2 (75 cm thick): Sub-unit 3 is underlain by a massive, unsorted, cohesionless sediment. Sub-unit 2 comprises a silty, sandy, reddish brown (5 YR 5/4) matrix with granules, pebbles and cobbles. Sediment within this unit is a chaotic mix of Fe-MnO-stained, pebbles (32–64 mm) within which are many, discontinuous, undulating, lenses of olive grey (5 Y 4/2) silty sand (up to 30 cm long and 10 cm thick), generally oriented south west to north east. Overall, the estimated particle-size fractions of the host sediment are 85% gravels and 15% clayey, silty sand. The upper boundary of this unit is defined by a lens of grey (5 Y 4/2) silty sand and orange-brown, Fe-MnO associated staining along fissile partings.
• Rampart upper unit:
Sub-unit 3 (30 cm thick): This sub-unit comprises a massive, cohesionless, cemented sediment of unsorted gravel (pebbles and cobbles) within a sandy, silty pale brown (10 YR 6/3) matrix. The overall texture is ~ 45% fines to ~ 55% gravels.

iii. \( PRD_{CV3}(\text{Fig. } 6.2D) \)
This circular rampart comprises: i) a lower unit of sandy, clayey, gravelly silt, ii) a middle unit of clayey, silty, cobbly, sandy gravels with a crude layering of elongate pebbles towards the base, and iii) an upper unit of clayey, sandy, silty, gravels.

• Rampart lower unit:
Sub-unit 1 (10 cm thick): At the rampart base, cut by the Cledlyn Fâch (stream), the sub-unit comprises a massive, greenish-grey (Gley1 5/1) sediment. clayey, silty matrix containing angular to sub-angular gravel (pebbles, cobbles and boulders). Overall, the estimated particle-size fractions are ~ 65% fines to ~ 35% gravels.

The clasts have a homogenous lithology of fine-grained sandstone and siltstone with some evidence of striae (~ 25% of the sample) (Fig. 6.3D). Clasts range from very angular to well rounded but are predominantly sub-angular and sub-rounded) with an RA value of 29% (Fig. 6.4C). Gravel-shape is very bladed (Fig. 6.5C) and the \( C_{40} \) value is high at 96. The principal clast orientation is east south east (Fig. 6.6C).

• Rampart middle unit:
Sub-unit 2b (35 cm thick): This unit has a diffuse planar boundary with the overlapping unit (3). The sub-unit is characterised by a massive, unsorted sediment of dark greyish brown (10 YR 5/2) to olive brown (2.5 Y 4/4). Clast size varies between > 2 and 30 mm. Overall, the estimated particle-size fractions are ~ 15% fines to ~ 85% gravels (granules and pebbles).

Sub-unit 2a (35 cm thick): Towards the base of this sub-unit there are crude, rigid layers of elongate pebbles dipping south east by 18 °. Fe-Mn concretions have stained the sediment olive brown (2.5 Y 4/4).

• Rampart upper unit:
Sub-unit 3 (20 cm thick): This sub-unit is a massive, unsorted, matrix-supported olive brown (2.5 Y 4/3) sediment. The overall texture is ~ 50% fines to ~ 50% gravels (granules to cobbles).
iv. Micromorphological control sample (CVC) (Fig. 6.2E)
A single lithofacies is identified, comprising a massive, matrix-supported, poorly sorted, cohesionless sediment. A silty, sandy light olive brown (2.5 Y 5/3) matrix supports a range of clasts from granules to boulders. The fabric is well cemented and very compact. The cobbles appear to be aligned horizontally in crude bands with occasional slumping. Overall, the estimated particle-size fractions are ~ 30% fines to ~ 70% gravels.

The gravels have a limited lithological range of interbedded silt- and mudstones, silt-mud and sandstones but the range includes a much coarser gritstone than observed within the field site (Aberystwyth Grits). There is Fe-Mn staining on many of the clasts and there is some evidence of striae on 25% of the sample (Fig. 6.3E). The pebbles are mostly sub-angular to sub-rounded and the RA value is 19% (Fig. 6.4D). Clast-shape is platy and bladed to very platy and very bladed (Fig. 6.5D) and the $C_{40}$ value is relatively high at 69. The principal clast orientation is to the west (Fig. 6.6D).

v. Basin core (Table. 6.1)
A core of > 8 m was extracted from the basin of PRD_{CV1}. The core is a massive unit of clayey, grey (Gley1, 7) silt (very fine-grained) with scattered clasts of quartz, sand- and siltstone. There is a sharp boundary between the overlying peat (2.14 m thick) and the underlying clayey silt (> 6.75 m) and very little organic material visible within the clayey silt infill.
0–75 cm: One cohesionless, massive unit of olive-brown sediment (2.5 YR 4/3). Gravel size ranges from 5 mm to 70 mm. Clasts are angular to sub-rounded, tabular and elongate. There is patchy staining of the sediment to a yellowish-brown (10 YR 5/4), associated with Fe-MnO. Staining increases with depth.

Key: XXX = Fe-Mn staining; Δ = gravel.

0–40 cm: One cohesive, massive unit of stiff grey sediment (5 Y 6/1). Gravel size ranges from > 2 mm to 5 mm (granules to pebbles). Clasts are angular to sub-rounded and blocky. There are patches of orange-brown staining of the sediment (associated with Fe-MnO).

Key: XXX = Fe-Mn staining; Δ = gravel.

Sub-unit 3 (0–30 cm): A cohesionless, massive, clast-rich unit of compacted pale brown (10 YR 6/3) sediment. At the top of the unit are dark (grey-black) Fe-Mn inclusions. Dominant gravel size ranges from 16–35 mm (coarse to very coarse).

Sub-unit 2 (30–105 cm): A cohesionless, unsorted sediment. The planar upper boundary is marked by a grey (5 Y 4/2) sandy silt deposit and Fe-MnO staining. Dominant gravel size ranges from 2–35 mm.

Sub-unit 1 (105–130 cm): A cohesive unit of clayey, sandy, gravelly olive grey (5 Y 4/2) silt. The upper boundary undulates and is marked by Fe-MnO staining. Gravel size ranges from 2–35 mm.

Key: X = Fe-Mn staining; Δ = gravel
● = Fe-Mn concretions
= Lenses of sandy silt.

Fig. 6.3 Cledlyn Valley: Sedimentary logs. A) PRD_{CV1} - rampart upper unit; B) PRD_{CV1} - rampart lower unit; and C) PRD_{CV2} - rampart upper, middle and lower units.
0–100 cm: A cohesionless, massive, poorly sorted unit of light olive-brown (2.5 Y 4/3) sediment. Gravel size ranges from >4 mm to 70 mm. Clasts are angular to sub-rounded, tabular and elongate and occur in crude horizontal layers.

Key: △ = gravel.

Sub-unit 1 (90–100 cm): A cohesionless, massive, greenish-grey (Gley, 5/1) unit of matrix-supported pebbles (2–50 mm).

Sub-unit 2a (20–55 cm): A cohesionless, massive, dark greyish-brown (to YR 5/2) to olive-brown (2.5 Y 4/4) unit of matrix-supported gravels ranging from >2 to 50 mm. There is a diffuse planar contact with the overlying sub-unit (3).

Sub-unit 2b (55–90 cm): At the base of sub-unit 2 there are crude layers of elongate pebbles dipping south east by 18 degrees.

Sub-unit 3 (0–20 cm): A cohesionless, massive, olive-brown (2.5 Y 4/3) unit of matrix-supported gravels. Gravel size ranges from >2 mm to 30 mm.

Sub-unit 3 (0–20 cm): A cohesionless, massive, olive-brown (2.5 Y 4/3) unit of matrix-supported gravels. Gravel size ranges from >2 mm to 30 mm.

Fig. 6.3 Cledyn Valley: Sedimentary logs. D) PRDCV3 - rampart middle unit; and E) Control sampleCV3.
Fig. 6.3 Cledlyn Valley: Clast morphology. A and B) PRD\textsubscript{CV1} Rampart upper unit; C) PRD\textsubscript{CV2} - rampart upper unit; D) PRD\textsubscript{CV3} - rampart middle unit; E) Control sample\textsubscript{CVC}. 

**A** and **B** show PRD\textsubscript{CV1} Rampart upper unit with **C** showing PRD\textsubscript{CV2} rampart upper unit. **D** illustrates PRD\textsubscript{CV3} rampart middle unit. **E** represents Control sample\textsubscript{CVC}. 

Faceting and Striae present on various clasts are highlighted for observation.
A) PRD$_{CV1}$ - rampart upper unit.

B) PRD$_{CV2}$ - rampart upper unit.

C) PRD$_{CV3}$ - rampart middle unit.

D) Control sample$_{CVC}$.

Fig. 6.4A-D) Cledlyn Valley: Macro clast roundness for suspected PRDs$_{CV1,2}$ and 3 and control sample$_{CVC}$ (n = sample number; RA = angularity index).
A) PRD<sub>CV1</sub> - rampart upper unit (n) = 48: Clasts are very elongate to very platy and very bladed.

Fig. 6.5A) and B) Cledlyn Valley: Clast-shape. For each sample, the high proportion of clasts below the C<sub>40</sub> (red) line confirms their shape as predominantly slabby/elongate to blocky.

B) PRD<sub>CV1</sub> - rampart upper unit (n) = 48: Clasts are very platy to very bladed.

C) PRD<sub>CV3</sub> - rampart middle unit (n) = 27: Clasts are very platy to very bladed.

D) Control sample; CVC - rampart upper unit (n) = 69: Clasts are platy and bladed to very platy and very bladed.

Fig. 6.5C) and D) Cledlyn Valley: Clast-shape. For each sample, the high proportion of clasts below the C<sub>40</sub> (red) line confirms their shape as predominantly slabby/elongate to blocky clasts.
A) PRD<sub>CV1</sub> - rampart upper unit. Contoured stereonet shows a NE-SW trend (n = 50).

B) PRD<sub>CV2</sub> - rampart upper unit. Contoured stereonet shows a NW-SE trend (n = 50).

Fig. 6.6A and B) Cledlyn Valley: Macro clast fabric data plotted on i) Rose diagram showing modal direction, ii) as poles on an equal area stereonet, and iii) contoured to show the trend (n = sample number).
C) PRD<sub>CV3</sub> - rampart middle unit. Contoured stereonet shows NW to SE trend (n = 14).

D) Control<sub>CVC</sub>. Contoured stereonet shows an E to W trend (n = 50).

Fig. 6.6C and D) Cledlyn Valley: Macro clast fabric data plotted on i) Rose diagram showing modal direction, ii) as poles on an equal area stereonet, and iii) contoured to show the trend (n = sample number).
Table 6.1 Cledlyn Valley basin core description

<table>
<thead>
<tr>
<th>Sediment description</th>
<th>Photograph</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core depth 2–3 m: A sharp boundary between overlying organic sediment and massive clayey, grey (Gley1, 7), silt is encountered at 2.6 m (core barrel is 1 m long).</td>
<td></td>
</tr>
<tr>
<td>Core depth 4.26–4.33 m: Fe-MnO staining of massive, grey (Gley1, 7), clayey silt.</td>
<td></td>
</tr>
<tr>
<td>Core depth 5.4–5.5 m: A) Massive, grey (Gley1, 7), clayey silt. B) Faceted, striated, sub-rounded granules and pebbles (up to 40 mm a-axes).</td>
<td></td>
</tr>
<tr>
<td>Core depth 7.25–7.6 m: A selection of very angular to sub-rounded clasts. Size ranges from 0.5 to 5 cm a-axes (pebbles).</td>
<td></td>
</tr>
<tr>
<td>Core depth 8.75–9.10 m: massive, grey (Gley1, 7), clayey silt.</td>
<td></td>
</tr>
</tbody>
</table>

6.2.2 Bulk-sediment analyses

i. Particle-size distribution (PSD):

Samples were collected from each lithological unit within each suspected PRD, the basin core and control sample (Table 6.2; Fig. 6.7):
Table 6.2 Cledlyn Valley: Rampart (PRD<sub>CV1</sub>, CV2 and CV3) basin and control sample PSD.

<table>
<thead>
<tr>
<th>Rampart Unit</th>
<th>Upper</th>
<th>Middle</th>
<th>Lower</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRD&lt;sub&gt;CV1&lt;/sub&gt;</td>
<td>Clayey (13%), sandy (fine-grained) (15%), pebbly (2–8 mm) (35%), silt (fine-grained) (38%)</td>
<td>-</td>
<td>Sandy (fine-grained) (4%), pebbly (2–8 mm) (15%), clayey (24%), silt (fine-grained) (57%)</td>
</tr>
<tr>
<td>PRD&lt;sub&gt;CV2&lt;/sub&gt;</td>
<td>Clayey (4%), cobbly (10%), sandy (coarse-grained) (23%), silty (fine-grained) (23%), pebbles (16–64 mm) (40%)</td>
<td>Clayey (1%), silty (fine to coarse-grained) (5%), sandy (coarse-grained) (9%), cobbly (15%), pebbles (2–64 mm) (70%)</td>
<td>Clayey (5%), sandy (coarse-grained) (17%), silty (fine-grained) (30%), pebbles (2–64 mm) (37%)</td>
</tr>
<tr>
<td>PRD&lt;sub&gt;CV3&lt;/sub&gt;</td>
<td>Clayey (8%), sandy (fine-grained) (9%), silty (fine-grained) (22%), pebbles (4–64 mm) (22%), cobbles (39%)</td>
<td>Clayey (4%), silty (fine-grained) (9%), cobbly (14%), sandy (coarse-grained) (24%), pebbles (4–32 mm) (48%)</td>
<td>Sandy (fine-grained) (14%), clayey (20%), pebbly (32–64 mm) (23%), silt (fine-grained) (43%)</td>
</tr>
<tr>
<td>PRD&lt;sub&gt;CV1&lt;/sub&gt; Basin core</td>
<td>Core depth 239-243 cm: Sandy (fine to coarse-grained) (9%), clayey (35%), silt (fine-grained) (56%)</td>
<td>Core depth 606-610 cm: Clayey (35%), silt (fine-grained) (65%)</td>
<td>Core depth 906-910 cm: Sandy (fine to coarse-grained) (4%), clayey (37%), silt (fine-grained) (50%)</td>
</tr>
<tr>
<td>Control (CVc)</td>
<td>Clayey (11%), sandy (fine-grained) (16%), silty (fine-grained) (23%), granules and pebbles (2–4 mm) (50%)</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Fig. 6.7 Cledlyn Valley: Particle-size distribution for PRD<sub>CV1</sub>, CV2 and CV3, control sample and basin core.
ii. Clay Mineralogy (X-ray diffraction (XRD) analysis) (Table 6.3; Fig. 6.9):

XRD analysis (Moore and Reynolds, 1997) identifies that the mineralogical profile is consistent across the rampart, basin and control sediment samples and that smectite is not present. Therefore, it is unlikely that the shrink-swell properties, associated with smectite, could impact on any plasmic fabric present (Dalrymple and Jim, 1984; Blokhuis et al., 1990; van der Meer et al., 2003). Illite and iron-rich chlorite are known components of Ordovician and Silurian sedimentary rocks including the Lower Palaeozoic mudstones of mid Wales (Evans and Adams, 1975; Milodowski and Zalasiewicz, 1991). Illite-chlorite assemblages are commonly found in WIC deposits (Wealthall et al., 1997) and are a constituent of the Greywacke sandstones found in the Silurian mud- and sandstone bedrock adjacent to the cliffs of glacial till at Aberarth, west Wales (the control site) (Jones and Williams, 1991).

Table 6.3 Cledlyn Valley: (PRDs_{CV1,2,3}), control sample and basin core - XRD analysis of clay mineralogy.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Smectite</th>
<th>Illite</th>
<th>Chlorite</th>
<th>Kaolinite</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRD_{CV1}</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>PRD_{CV2}</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>PRD_{CV3}</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>CVC</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Control sample</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Fig. 6.8 Cledlyn Valley: Key XRD peaks are marked with their Ångström values (a unit of length equal to 0.1 nm).
iii. **Carbonate analysis:**

Carbonate content is low (<1%) (Fig. 6.9). Therefore, it is unlikely that anisotropism exhibited by plasmic fabrics (birefringence viewed in cross-polarised light) will be disguised by carbonates during thin-section analysis of the samples (van der Meer *et al.*, 2003).

![Carbonate content graph](image)

**Fig. 6.9 Cledlyn Valley: Carbonate content for suspected PRDs (CV1, CV2, and CV3), control sample and basin core.**

### 6.3 Microscopic descriptions

The following sections describe the microscopic texture and structure of the three suspected PRDs (CV1, CV2, and CV3) investigated, as well as the control sample. Table 6.4 summarises data on matrix and skeleton grains. Figs. 6.10 and 6.11 summarise grain roundness and microfabric data respectively.

#### i. **PRD<sub>CV1</sub>**

- **Rampart upper unit - thin section CV2-1 (Fig. 6.12):**

  The rampart upper unit is a cohesionless sediment with a minor but significant percentage of silt- and sandstone clasts, > 2000 \(\mu m\) (~35%). Grains > 500 \(\mu m\) but < 2000 \(\mu m\) dominate the sediment, and range in shape from elongate to equant and are predominantly subangular to rounded (Fig. 6.10A). Rounded grains are more dominant in the < 500 \(\mu m\) class. There is no single preferred orientation of grains in any size range but many are subvertically inclined (Fig. 6.11). The groundmass is a fine to medium-grained clayey-silt matrix distributed throughout the thin section. The matrix is very compact with a relatively low void ratio (<10%). The sediment contains a low number of grain concentrations that occur randomly within the sample.
Table 6.4 Textures, deformation microstructures and post-depositional features in the ramparts and the control sample, Cledlyn Valley, Wales.

Key: ◆ = Well developed; ● = Moderately developed; ○ = Weakly developed. Numbers of circles reflects abundance.

<table>
<thead>
<tr>
<th>Deformation structures</th>
<th>Texture</th>
<th>Voids</th>
<th>Rotation/slump</th>
<th>Planar</th>
<th>Sediment mixing</th>
<th>Pore water</th>
<th>Plasmic fabric</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRD1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top: CV2-1</td>
<td>●</td>
<td>○</td>
<td>●</td>
<td>○</td>
<td>○</td>
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<tr>
<td>Base: CV3-1</td>
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<td>○○○</td>
<td>***</td>
<td>***</td>
<td>●</td>
</tr>
<tr>
<td>PRD2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top: CV1a-3</td>
<td>●●●</td>
<td>○</td>
<td>●</td>
<td>○</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Middle: CV1a-2</td>
<td>●●●</td>
<td>○</td>
<td>●</td>
<td>●●●</td>
<td>○</td>
<td>○</td>
<td>●</td>
</tr>
<tr>
<td>Base: CV1a-1</td>
<td>●●</td>
<td>○</td>
<td>●</td>
<td>○○</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>PRD3</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Middle: CV5-1</td>
<td>●●</td>
<td>○</td>
<td>●</td>
<td>●</td>
<td>○</td>
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<tr>
<td>Control sample</td>
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<td>●</td>
<td>●</td>
<td>○</td>
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<td>●</td>
</tr>
<tr>
<td>CVC</td>
<td>●</td>
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</table>
Fig. 6.10 Micro-grain roundness: Cledlyn Valley. Key: VA = very angular; A = angular; SA = sub-angular; R = rounded; WR = well rounded (n = sample number; RA = percentage of very angular and angular clasts in a sample).
Fig. 6.1A-R) Cledlyn Valley: Microfabric analysis of suspected PRDs CV1, CV2 and CV3 and control sample. Apparent long-axes orientation of skeleton grains in 20° interval classes measured anticlockwise from the horizontal plane, where the top of the thin section measures 90° (n = sample number).
A) Weakly developed, spiral-like, rotation structure with core grain.

B) Examples of parallel-walled fissures (from 4.6 x 5.7 mm to 5 x 9.3 mm).


Fig. 6.12A-C) PRD: Thin section CV2-1 (rampart upper unit). Thin section measures 8.7 x 5.7 cm.
The most significant void texture is planar fissures that run both vertically and horizontally (parallel-walled) (Fig. 6.12B) and range in dimensions from 4.6 x 5.7 to 5 x 9.3 mm. There is partial Fe-MnO staining of grains and matrix throughout the sample. Parallel-walled fissures mostly occur from the middle to the base of the sample, encircling angular, blocky aggregates. There are a few mammillated vughs at the top of the sample, and some randomly located smaller vughs, only visible microscopically, which are possibly mammillated vesicles (Kilfeather and van der Meer, 2008).

There is a very low number of grain turbates without core grains at the top (e.g. spiral-like Fig. 6.12A) and near the base of the rampart upper unit. The rotational features occur in proximity to grain concentrations. There is also a low number of grain lineations (i.e. grains whose long-axes share a preferred alignment in close proximity but not arranged nose-to-tail) and linear grain domains (i.e. grains whose apparent long-axes may not share a preferred alignment but whose overall arrangement is linear), sub-vertically inclined from 5 to 150°. A very few fractured grains are present.

There are a few intraclasts type III (sediment), particularly at the top of the upper rampart unit, which range from 0.3 to 2 mm a-axes. Multiple domains are moderately abundant and take the form of highly birefringent rounded patches (from 0.2 x 0.3 mm to 0.5 x 1 mm) and string-like domains of clay (up to 1.8 mm long and 0.05 mm thick) within silt. There is a low number of clay and silt void and grain coatings.

Plasmic fabric mostly occurs as unistrial domains throughout the sample from 1.7 to 3.3 mm long, oriented from 120° to 150° towards the top of the upper rampart unit and from 1.5 to 2.3 mm long at the base of the unit, oriented ~ 30° (e.g. Fig. 6.12 C). There are a very few examples of skelsepic plasmic fabric.

- Rampart lower unit - thin section CV3-1 (Fig. 6.13):

The rampart lower unit is characterised by a dense, cohesive sediment of clayey-silt with some organic material (i.e. plant roots). The lower unit contains sparse, scattered pebbles (e.g. a quartz clast (33 mm a-axis) was removed from the base of the kubiena tin during sampling), but these are in the minority (Fig. 6.13). The sediment is crudely layered clay-rich (at the top and base of the unit) and silt-rich (in the middle of the unit). Clay occurs thought the sample as highly birefringent, linear domains, up to 7 mm long and 0.9 mm thick and as undulating lenticular pods ranging from 0.8 to 22 mm long. The clay domains are often emphasised by significant Fe-MnO staining. There is a little, scattered fine sand.
Fig. 6.13 A-C) PRDcv1: Thin section CV3-1 (rampart lower unit). Thin section measures 8. x 6 cm.

A) Unistrial plasmic fabric, oriented 50°.

B) Highly disrupted platy lenses of clay and silt.

C) Lenticular pods of clay within silt.
The matrix is very compact with a low void ratio (< 5%). The void spaces include planar fissures, up to 18.5 mm long and 0.04 mm thick, in varying orientations from horizontal to sub-vertical (~ 45 °) but they are predominantly sub vertical. There are also a very few chambers from 0.8 to 2.9 mm long and 0.1 to 0.5 mm thick. There is some orange-brown staining of voids associated with ferromanganiferous oxides (Fe-MnO).

The sediment contains highly distorted, platy lenses of clay and silt (Fig. 6.13B) and lenticular, pods of fine silt and clay within a coarser silt matrix (Fig. 6.13C). The sample contains a significant number of unistrial plasmic fabric domains throughout the unit, which are most clearly defined at the top of the sample, from 2 to 3.5 mm up to 11 mm long, 0.1 mm thick and oriented between 50 to 70° (e.g. Fig. 6.13A).

\[ \text{ii. } PRD_{CV2} \]

- Rampart upper unit - thin section CV1a-3 (Fig. 6.14):

The rampart upper unit has a high density, matrix-supported sediment. Skeleton grains > 2000 μm comprise a significant but minor proportion of the sediment, mostly occurring towards the top and middle of the rampart upper unit. These are pebbles, up to a maximum of 35 mm long. The pebbles comprise siltstones with some sand- and mudstones and are mostly elongate to blocky, rounded to well rounded (Fig. 6.14). Grains > 500 μm are mostly elongate to equidimensional and rounded to well rounded with some sub-angular to sub-rounded grains. Grains < 500 μm are mostly equidimensional and sub-rounded to well rounded (Fig 6.10B). Grains are generally sub-vertically aligned, with some vertically oriented (Fig. 6.11) with pore spaces at the base, and sometimes occurring in concentrations. There is a dense matrix of predominantly silt and very fine sand, with patches of clay distributed randomly within the sediment, which contains significant orange-brown staining associated with ferromanganiferous oxides.

The matrix is very compact with a low void ratio (~ 7%). Void spaces are in low abundance, occurring as planar fissures (e.g. a zone of sediment 9 x 5 mm containing well-developed platy aggregates), at the top of the rampart upper unit, and occasionally as parallel-walled fissures ~ 5 x 4 mm in dimension occurring at the top and base of the rampart upper unit. There are a low number of moderately developed vughs from 0.8 x 2 mm to 2.3–4.2 mm, some of which are mammillated, and weakly developed vesicles within the rampart upper unit.
Fig. 6.14 A-C) PRD_{CV2}: Thin section CVia-3 (rampart upper unit). Thin section measures 8.2 x 5.7 cm.
The sediment is characterised by a low number of moderately developed rotation structures (e.g. grain turbates) throughout the sediment with weaker turbates towards the base of the unit, and curvilinear arrangements of grains (i.e. grains in close proximity, but not touching, that form arc shapes within the sediment and give a sense of undulation or rotation). These curvilinear arrangements occur in the top and middle sections of the rampart upper unit. The rampart unit also comprises a low number of moderately developed planar structures such as: i) linear arrangements of grains (e.g. a notable elongate lens-shaped concentration of coarse sand to pebbles (4–8 mm) within silt in the middle of the rampart upper unit), ii) fragmented domains of patchy clay within the silt matrix, and iii) a single example of a fractured grain, at the top of the unit, that is fractured in two and translocated.

There are a few examples of sediment in-mixing in the form of clay domains occurring within the silty matrix up to 11.7 x 17.4 mm in dimension. There is a low abundance of moderately developed Fe-MnO-stained grains, and some void spaces (particularly towards the top of the rampart unit) and silt coatings around some grains. Plasmic fabric is poorly developed and occurs as skelsepic plasmic fabric around a few grains or as weakly developed unistrial plasmic fabric, mostly within the middle of the rampart upper unit, oriented sub-vertically (from 45 to 100°), from 6.5 to 7.2 mm long and ~ 0.03 mm thick.

- Rampart middle unit - thin section CV1a-2 (Fig. 6.15):

  The sediment in the middle of the rampart, is high density, matrix-supported and clast-rich. Skeleton grains > 2000 µm comprise abundant granules and pebbles, ranging from 2.2 to 18.5 mm. The clasts mostly comprise siltstones with some sand and mudstones and range in shape from elongate to blocky, sub-rounded to well rounded. Grains < 2000 µm are mostly equidimensional and angular to well rounded (Fig. 6.10C). Grains are mostly vertical to sub-vertical in crude, concentrated, bands inclined ~ 150° (Fig. 6.11). The largest grains are at the base but there is no grain sorting either across the sample or within the crude bands. Orange-brown Fe-MnO staining decreases with depth, as does the clay content. The clayey silt matrix is compact with a void ratio < 10%. The void spaces are mostly vughs, some of which occur as pore spaces at the base of grains (Fig. 6.15A), a few vesicles and a low number of planar fissures.

  At the top of the unit is a chaotic mélange of granules and pebbles (2–16 mm). Within the rampart middle unit, rotation is emphasised by a moderate abundance of moderately developed grain turbates (Fig. 6.15B) and weakly developed undulating arrangements of grains (e.g. Fig. 6.15C). This undulating arrangement is particularly noticeable mid-way
Fig. 6.15 A-C) PRD<sub>CV</sub>: Thin section CV<sub>1a</sub>-2 (rampart mid-section). Thin section measures 6.8 x 5.8 cm.

- Silt and clay coatings around grains
- Weak unistrial plasmic fabric, oriented ~75°
- Undulating, clast-rich band inclined ~150°
- Vughs
- Grain turbate (Fig. B)
- Grain concentration
- Undulating domain of grains (Fig. C)
- Grain turbate
- Fe-Mn stained, clay-rich sediment
- Clay and silt coatings on grains
- Sub-vertically inclined, elongate grain with void space at base and silt coating (Fig. A)
- Unistrial plasmic fabric oriented ~180°

A) Elongate grain, oriented 165° with silt on underside (yellow solid line) and pore spaces (V) at the base.

B) Grain turbate.

C) Undulating domain of grains (yellow-dashed lines), some with silt coatings (yellow solid line).
down the rampart middle unit, where a clast-rich band has an undulating contact at its base. Arcuate arrangements of grains also occur at the base of the rampart middle unit. Planar structures are low in number and include weakly developed grain lineations and fractured grain. There are few examples of sediment mixing (e.g. sediment intraclasts and multiple domains of clay within silt), and these are weakly developed. There is some coating of grains with silt (on the top and base of grains (Figs. 6.15A and C)) and orange-brown staining associated with Fe-MnO. Very little and weak plasmic fabric development is observed as skelsepic and unistrual plasmic fabric.

- **Rampart lower unit - thin section CVia-1 (Fig. 6.16):**
  The sediment in the rampart lower unit is dense and matrix-supported and contains significant ferromanganiferous staining. Skeleton grains > 2000 μm comprise clasts, ranging from 2.2 to 16.6 mm (granules and pebbles). The clasts mostly comprise siltstones with some sand and mudstones. These grains range in shape from elongate to blocky, sub-rounded to well rounded (Fig. 6.10D). Grains in the range of 500 to 2000 μm are a significant but lower proportion than grains < 500 μm which dominate. Grains < 500 μm and are mostly equidimensional and angular to well rounded (Fig. 6.10D). There is Fe-MnO staining around some but not all clasts and the upper part of the section contains less staining than the base. Overall the grains are aligned sub-vertically (Fig. 6.11), in crude bands ~ 120°, particularly from the middle section to the base (Fig. 6.16). The sediment comprises a fine to medium coarse matrix (clay to coarse silt and fine sand) distributed throughout.

  The matrix is very compact with a low void ratio (< 5%). The voids are mostly small vughs (mostly at the top of the rampart lower unit), some of which are mammillated and planar fissures ranging from 0.88 to 16 mm long, some forming parallel-walls (e.g. Fig. 6.16A). There is slightly more pore space towards the top of the section.

  Microstructures include a moderate abundance of weakly developed grain turbates (e.g. 6.16B) that occur throughout the unit. There are a very few examples of fractured grains. There is limited sediment mixing with a few examples of sediment intraclasts (up to 2.8 mm a-axes) and clay in-mixed with silt at the base of the unit. There are very few, but well-developed, silt coatings around some grains and there is some orange-brown Fe-MnO associated staining around a few grains and some vughs at the top of the lower rampart unit. Plasmic fabric, both skelsepic and unistrual (oriented ~ 40°), is in low abundance but
Fig. 6.16A-D) PRDcv$\lambda$: Thin section CV1a-1 (rampart base). Thin section measures 8 x 5.7 cm.
well developed and occurs towards the top and middle of the section, where the Fe-MnO staining is less apparent (Fig. 6.16C).

iii. PRD$_{CV3}$

- Rampart middle unit - thin section CV5-1 (Fig. 6.17):
The sample was taken from the mid-section of a collapsed suspected PRD adjacent to and above layers of imbricated pebbles. There are few clasts > 2000 µm and their lithology is consistent with those found in other samples from the site: siltstones (some banded) with some sand and mudstones. These grains range in shape from elongate to blocky, sub-rounded to well rounded. The dominant grain size is < 2000 µm but > 500 µm. These grains range in shape from elongate to blocky and are angular to well rounded for grains of < 2000 µm and sub-angular to well rounded for grains > 2000 µm (Fig. 6.10E). Grains less than 500 µm are mostly equidimensional and sub-angular to well rounded. Grains are mostly located within the bottom third of the sample. Overall the grains are aligned sub-vertically (Fig. 6.11). The clayey silt matrix is distributed throughout the thin section and contains significant ferromanganiferous staining. There is crude layering of the sediment between clay-rich, silt-rich and clast-rich bands, oriented ~ 145° emphasised by similarly oriented linear domains of grains (Fig. 6.17). Grain concentrations are moderate in number and are moderately developed. They occur throughout the sediment at the top and base.

The matrix is very compact with a very low void ratio (< 5%) of a few planar fissures and mammillated vughs, which occur at the top of the rampart mid-section. There is a low number of grain turbates (moderately developed), which occur throughout the sample (e.g. Fig. 6.17A). There also occur undulating arrangements of fine to very fine-grained sand, particularly at the base of the section (Fig. 6.17). There are a low number of weak to moderately developed sediment and matrix intraclasts (e.g. Fig. 6.17B) with a-axes up to 3.9 mm. Plasmic fabric is in low abundance and moderately developed, occurring as both skelsepic and unistrial plasmic fabric. Fe-MnO precipitation has stained the sediment this is around only a few clasts and not within vugh spaces.
Fig. 6.17 A-B) PRD_{CV3}: Thin section CV5-1 (rampart mid-section). Thin section measures 8 x 5.7 cm.
iv. **Control sample**

- Base of coastal cliff - thin section CVC (Fig. 6.18):
  
  The control sample comprises clast-rich (~ 50%), matrix-supported sediment. Grains > 2000 µm include varied sizes, up to 35 mm long (very coarse). These grains range in shape from elongate to blocky and are sub-angular to well rounded. Grains < 2000 µm are angular to well rounded (Fig. 6.10F). Across all size ranges there is no single orientation of grains but a general sub-vertical orientation, particularly towards the base of the unit (Fig. 6.11). The matrix is high density, very compact clayey, sandy silt with a low void ratio (< 5%). There is a low number of grain concentrations that occur within the middle of the sample.

The void texture is mostly planar fissures, these are moderately developed but appear in low abundance as fissile partings occurring as parallel-walled fissures (Fig. 6.18). Microstructures are generally characterised by rotation (e.g. grain turbates) that are moderately abundant and moderately developed and mostly occurring towards the top of the control sample. Towards the base of the sample are a few examples of grain lineations, oriented ~ 130 ° and a very few fractured grains. There are a very few examples of sediment intraclasts (ranging from 1 x 0.8 mm to 6 x 3 mm). There is sparse iron staining (bright red) on the tops of some of the clasts. Plasmic fabric is in low abundance and occurs as skelsepic plasmic fabric around a few grains and as moderately developed unistrial plasmic fabric, particularly towards the base of the sample, oriented between ~ 95–130 °.

![Fig. 6.18 Control sample Thin section CVC (base of coastal cliff). Thin section measures 8 x 5.5 cm.](image-url)
6.4 Interpretation

6.4.1 Macroscopic analysis

The PSD (Table 6.2), demonstrates that there is enough variation in the grain-size distribution within each rampart to suggest different units as follows (Fig. 6.7):

1. Lower rampart units (PRDSCV1, CV2 and CV3)

The lower rampart units, occurring within PRDSCV1 and CV3, contain a finer-grained diamicton of clayey silt with scattered pebbles (much finer in PRDCV1). This unit is identified by Gurney (1994; 1995) as a glaciolacustrine deposit, also observed in the basin infills. Whilst there is only a moderate clay to silt content (Dalrymple and Jim, 1984) (Table 6.2) and an absence of observable varves (i.e. silt and clay couplets), associated with glaciolacustrine sediments (Easterbrook, 1999), the variation in gravel size throughout the middle and lower rampart units suggests that these units could be part of a proglacial outwash deposit. The variation in grain size could be the consequence of surges in energy levels of meltwater streams (Owen, 1994; Ross et al., 2007). The high silt content suggests deposition during cold climate conditions with silt deposits probably derived from glacial grinding or intense, cold climate weathering processes (Assallay et al., 1998).

2. Middle rampart units (PRDSCV2 and CV3)

Beneath the upper unit of glacial till, identified in PRDSCV2 and CV3, there is a more clast-rich diamicton, poorly graded, supported by a silty, sandy matrix with very little clay but significant Fe-MnO staining. The unit is compacted but not as cemented as the overlying upper rampart sediments. The significant gravel content of the rampart middle units, (comprising chaotic domains of sediment and lenses of sandy, silty gravel), suggest glaciofluvial deposition. The prevalent ferromanganiferous staining is a common feature of glaciofluvial material within the region, due to their derivation from igneous rocks (Waters et al., 1997). Whilst the clasts are not significantly rounded, as might be expected by fluvial transportation, this could be due to their close proximity to a glacial margin – an ice contact deposit (Culshaw et al., 1991).

3. Upper rampart units (PRDSCV1, CV2, CV3 and control sampleCVC)

In PRDS(CV1,2,3), the uppermost rampart units along with the control sample comprise a diamicton (i.e. poorly sorted, cemented sediment with few pores (Benn and Evans, 1998). Periglacial, frost-shattered head deposits, would probably include a relatively high proportion of angular clasts and a relatively high void ratio (Harris, 1987). However, in all cases, at the Cledlyn Valley field site, the sediment contains a large number of striated and faceted, sub-angular to sub-rounded clasts, in a very compact matrix, which is consistent
with glacially transported debris (Boulton, 1978; Dowdeswell and Sharp, 1986). Therefore,
the sediment is probably a glacial till (Hambrey, 1994)). Superficial deposits in the area
comprise Irish Sea and Welsh Ice Tills (Waters et al., 1997; Bowen, 1999; Bowen, 2005). WIT
is a non-calcereous, coarse-grained sediment ranging from poorly sorted, matrix-supported
gravelly clays to clast-supported clayey gravels (Waters et al., 1997). By contrast, ISIT is
highly calcereous, yellow to reddish brown and is rich in a range of widely sourced erratics,
marine sands, shell fragments and foraminifera (Garrard and Dobson, 1974; Waters et al.,
1997). As clasts within PRDs CV1 and CV2 are derived from local bedrock (mud-, silt- and
sandstone), there is very little carbonate content (see section 6.2.2, iii) and no marine fossils
or foraminifera observed, the sediment is identified as WIT (Waters et al., 1997; Patton and
Hambrey, 2009). There is less gravel and more clayey silt in the uppermost unit of PRD CV1
than for PRD CV2 (Fig. 6.7), but proportionately the clay to silt ratios match well with that of
the control sample, and is consistent with a WIT deposit. Additionally, the fabric
orientation of the control sample is from east to west (Fig. 6.6D) which would support a
Welsh Ice Cap (WIC) origin, as the Irish Sheet Glacier (ISG) broadly moved from north to
south (Etienne et al., 2005; Davies et al., 2006). However, there is no strong, single preferred
orientation of clasts parallel to the direction of ice flow within the suspected PRDs (Figs. 6.7
A-C) and clast-shape is generally elongate rather than blocky (Figs. 6.5 A-D). This could be
due to paraglacial modification, caused by de-glacial redistribution (Bowen, 1973a; 1973b;
Curry and Ballantyne, 1999; Vincent, 1976; Ballantyne and Harris, 1994; Harris, 1996;
Watson, 1996; Harris, 1998; Ballantyne, 2002) and/or as a consequence of frost-mound
decay.

4. Basin infill
The basin infill within PRD CV1 comprises: i) a top unit of Holocene peat and organics with a
sharp planar boundary at the base underlain by, ii) an upper massive, grey, silty clay, which
iii) grades into a lower unit of unsorted gravelly silty clay. The dominant unit of grey, silty
clay is much finer-grained than anything found in the rampart units but is closest to that
observed in the lower rampart unit of PRD CV1. Glacial lake deposits are known to be
widespread in the Afon (Lake) Teifi catchment area, existing beneath glacial tills, deposited
as the advancing ISG and WIC displaced Lake Teifi (Waters et al., 1997). The basin infill is
consistent with Welsh glaciolacustrine deposits in the area (Waters et al., 1997). It is
possible that the clasts within the basin are dropstones. The sharp boundary between the
overlying organic material and the underlying clayey silt, suggests an abrupt change in
climatic conditions (Haase et al., 2007).
6.4.2 Microscopic analysis

i. \( PRD_{CV} \)

- Microfabric
  There is a low abundance of well-developed vertical to sub-vertical microfabric within the rampart upper unit: i) vertical grains with pore spaces at the base and ii) sub-vertical elongate grains. As the field site has been subject to both glacial and periglacial processes, frost-jacking of grains could explain the orientation of some of the grains within the upper rampart unit (Chapter 2, section 2.2.3, iii). If frost-jacking is responsible, it probably occurred during periglacial conditions after the glacier retreated, otherwise such voids might have been overprinted by glacier deformation. When not associated with ice-lens traces at the base or side (i.e. frost-jacking), sub-vertically inclined elongate grains, whose apparent long-axes are oriented parallel to the line of slope, could be linked to solifluction or frost creep (Harris and Ellis, 1980) (Chapter 2, section 2.2.3, iii).

- Stratification
  Within the rampart lower unit, there are both distorted bands of clay-rich sediment in-mixed with silt and distorted bands of silt-rich sediment in-mixed with clay (i.e. an indistinctness of contact between the ‘layers’ and in-mixing of sediment within the ‘layers’ (section 6.4.2, i, Sediment mixing)). Alternating layers of silt- and clay-rich sediment indicates cyclical deposition (i.e. silt/clay couplets deposited rhythmically, possibly varves) and is consistent with glaciolacustrine deposits, which can be found at ice margins or supraglacially (van der Meer et al., 1992; Easterbrook, 1999).

- Grain concentrations
  There is a low abundance of weakly developed grain concentrations in the top to middle sections of the rampart upper unit and none observed in the lower unit. It is possible that the grain concentrations are linked to rampart-formation processes such as mound collapse and mass-wasting during frost-mound formation (Harris and Ellis, 1980; Mackay, 1988) (Chapter 2, section 2.2.3, iii).

- Void spaces
  The sediment in both the upper and lower rampart units is very compact with little void space. In the upper rampart unit void spaces are mostly vughs (at the top of the unit) and from the middle to the base of the unit there are a low to moderate abundance of weak to well-developed parallel-walled fissures. Planar fissures can indicate planes of shear stress within a sediment (Evans and Benn, 2014) and parallel-walled fissures (e.g. Fig. 6.12B) can be
indicative of a 'marble bed' structure commonly developed in basal tills, particularly when found in conjunction with rotation structures (van der Meer et al., 1993; Hiemstra and van der Meer, 1997; Kilfeather and van der Meer, 2008). In the lower rampart unit, the void spaces include very fine, weakly developed, horizontal to sub-vertical planar fissures and very few chambers. The fissures could be remnants of ice lenses that have since collapsed after melting (van Vliet-Lanoë et al., 1984; van Vliet-Lanoë, 1985; 2010). The regular, elongate, tube-like chambers are likely to be linked to faunal or plant root systems Brewer (1964).

- **Aggregates**

Parallel-walled fissures (section 6.4.2, i, Void spaces) occur in the rampart upper unit, encircling angular, blocky aggregates (Fig. 6.12B). Aggregates can develop in periglacial environments due to ice lensing (van Vliet-Lanoë and Langohr, 1982; van Vliet-Lanoë et al., 1984, 2017; van Vliet-Lanoë, 1985) (Chapter 2, section 2.2.3, iii). However, it is also possible that the parallel-walled fissures are the product of shear stresses within a subglacial sediment caused by ice-sheet overriding (Benn and Evans, 1998). This process develops a rounded to ellipsoidal 'marble bed' structure commonly developed in basal tills, particularly when found in conjunction with rotation structures (van der Meer et al., 1993; Hiemstra and van der Meer, 1997; Kilfeather and van der Meer, 2008). As the field site has been the subject of both glacial and periglacial processes, the parallel-walled fissures in the rampart upper unit could be a consequence of any of the processes outlined above.

- **Rotation**

There is a low number of grain turbates in the rampart upper unit (e.g. Fig. 6.12A). Grain turbates and grain concentrations can be associated with glacial deformation, particularly when linked to low porosity (Lafeber, 1964), formed under the pressure of a deforming bed (Kilfeather and van der Meer, 2008). However, there are only weakly developed grain turbates and few grain concentrations apparent in the rampart upper unit. Other deformation processes responsible for grain turbate development include mass-wasting (Carr et al., 2000; Hiemstra, 2001; Lachniet et al., 2001; Menzies and Zaniewski, 2003; Phillips, 2006) (Chapter 2, section 2.2.3, iii). It is possible, therefore, that the rotation structures described are not linked to subglacial processes but rather they are the consequence of sub-aerial, mass-wasting developed during frost-mound formation and/or collapse. In the rampart lower unit, towards the base, are examples of weakly to moderately developed undulating platy lenses of clay. In fine-grained sediments (i.e. silt), micro-undulations can develop following repeated freeze-thaw cycles, which is indicative of frost
creep (van Vliet-Lanoë et al., 1984; Coutard and Mücher, 1985; van Vliet-Lanoë, 2010). It is possible that the sense of undulation created by the curvilinear arrangements of platy clay lenses are caused by frost creep (Chapter 2, section 2.2.3, iii).

- **Planar structures**
  There are very few examples of linear grain arrangements in the rampart upper unit. There are also a few examples of fractured grains, which can be indicative of a brittle strain environment (Hiemstra and Rijsdijk, 2003; Menzies et al., 2006). In glacial environments, fractured quartz grains are highly diagnostic of subglacial processes (Hiemstra and van der Meer, 1997; Mahaney et al., 2004) but these are not evident in PRD\(CV_1\). Fracturing of softer clasts *e.g.* carbonate grains, can also indicate subglacial abrasion (*e.g.* by iceberg scour (Linch et al., 2012)). In periglacial environments, frost shattering of grains occurs due to high moisture retention in fissures within the grains followed by ice growth (van Vliet-Lanoë, 1985; 1998; 2010). As the field site has been subject to both glacial and periglacial environments, the cause of the fractured grains in the rampart upper unit cannot be definitive. A more significant feature of brittle strain is that of abundant, well-developed fragmented domains that occur in the rampart lower unit of clay within a clayey silt matrix. Fragmentation of aggregates can be caused by successive episodes of freeze-thaw action (van Vliet-Lanoë, 1985; 1998; 2010) (Chapter 2, section 2.2.3, iii).

- **Sediment mixing**
  Multiple domains of clay, within a clayey-silt matrix, occur in moderate to high abundance in both the upper and lower rampart units. These clay domains are most well developed in the lower rampart unit within distorted 'layers' of clay-rich sediment in-mixed with silt and silt-rich sediment in-mixed with clay (Figs. 6.14B and C). Platy, lenticular microstructures are associated with segregation ice developed in fine-grained sediment, caused by ice lensing in periglacial environments (van Vliet-Lanoë, 2010) (Chapter 2, section 2.2.3, iii). The presence of distinct but isolated 'pods' could be caused by cryoturbation, the pods are then moved down the sediment profile on thaw (pers. comm. van Vliet-Lanöe, 2016). However, the subsequent fragmentation of these lenses into 'pod' structures could also represent brittle strain (*e.g.* the consequence of stretching and shearing (Philips, 2006)). It is possible that the in-mixing is the result of loading or unloading of a sediment overburden which could have its origin in both subglacial deformation, debris flows caused by mass-wasting of ramparts (Philips, 2006; Montenat et al., 2007), or possibly perturbation during frost-mound formation.
• **Pore-water features: void and grain coatings**

The fine-grained coatings of some of the rampart sediment grains are silt and clay cappings, indicative of a periglacial environment (Chapter 2, section 2.2.3, iii). There is a low abundance of clay and silt grain coatings in the upper rampart unit and a low abundance of void coatings in both the upper and lower units, probably linked to the low number of void spaces.

• **Plasmic fabric**

There is plasmic fabric development within PRD<sub>CV</sub>, which is most apparent as: i) moderately developed skelsepic plasmic fabric in the upper rampart unit and ii) a low to moderate abundance of well-developed unistrial plasmic fabric in the clay-rich, lower rampart unit. Skelsepic plasmic fabric is common in subglacial environments and is related to rotation that occurs at the base of a glacier bed (van der Meer, 1987; Jim, 1990; van der Meer et al.; 1994 Hiemstra and Rijsdijk, 2003). Shrink-swell of clay can also produce skelsepic plasmic fabric (Dalrymple and Jim, 1984), but the XRD analysis (section 6.2.2, ii) indicates that a swelling clay is not present in the rampart samples - the dominant clay mineralogy is chlorite. Also, the low hydraulic conductivity of the matrix (and so low variability in moisture content) makes shrink-swell an unlikely cause of plasmic fabric in these deposits (van der Meer et al., 2003). Skelsepic plasmic fabric can develop around aggregates and pore surfaces in periglacial environments (Vliet-Lanoë, 1985). Finally, flow materials are known to produce poorly developed skelsepic plasmic fabric due to the rotation of particles (Bertran and Texier, 1999). It is also possible that plasmic fabric is masked by the significant Fe-MnO staining (Jim, 1990) but as other features associated with rotation are also only weakly developed within the rampart (e.g. grain turbates), low abundance of skelsepic plasmic fabric could indicate both frost action and mass-movement of the sediment.

Unistrial plasmic fabric (*i.e.* discontinuous lengths of oriented plasmic fabric (van der Meer, 1993)) indicates unidirectional planar shear as a consequence of brittle failure along a shear plane (van der Meer, 1993; Hiemstra and Rijsdijk, 2003). Unistrial plasmic fabric is well developed in both the upper (Fig. 6.12C) and lower (Fig. 6.13A) rampart units but is most abundant within the base of the rampart. When linked to examples of planar structures (*e.g.* fragmented domains of clay pods within silt), it suggests that there has been heavy shearing of the sediment in the lower rampart of PRD<sub>CV</sub>, which could have its origin in both glacial overriding or perturbation of sediments during frost-mound formation.
i. **PRD<sub>CV2</sub>**

- **Microfabric**
  There is a moderate to well-developed vertical to sub-vertical microfabric within PRD<sub>CV2</sub>, that becomes more developed with depth. This occurs as: i) vertical grains, with pore spaces at the base and ii) sub-vertical elongate grains (Fig. 6.14). Given the location of the field site within a palaeo-periglacial zone and at the base of sloping ground on a lower valley bottom, both frost-jacking (van Vliet-Lanoë et al., 1984; van Vliet-Lanoë, 1985; 2010) and mass-wasting (Harris and Ellis, 1980) could account for the vertical to sub-vertical microfabric (Chapter 2, section 2.2.3, iii).

- **Stratification**
  Within the middle unit of PRD<sub>CV2</sub> (Fig. 6.15), is a distinct, undulating, clast-rich band inclined at 150 °, below which elongate pebbles are similarly inclined, indicating crude layering. Within the rampart lower unit, there are a series of crude bands of pebbles inclined at 120 °, although the long-axes of the clasts do not all share this preferred alignment. The location of tilted, crude layers towards the base of the rampart could be indicative of sediment heave during frost-mound formation (Pissart and French, 1976; Mackay, 1978; Pissart and Gangloff, 1984).

- **Grain concentrations**
  There is a low to moderate abundance of weak to moderately developed grain concentrations that increases with depth within PRD<sub>CV2</sub>. As previously discussed (for PRD<sub>CV1</sub>), it is possible that the grain concentrations found towards the base of the rampart are the consequence of mass-wasting during rampart formation (Harris and Ellis, 1980).

- **Void spaces**
  The matrix throughout PRD<sub>CV2</sub> is very compact with a low void ratio. Void spaces are generally in low abundance and are weak to moderately developed, occurring as planar fissures, encircling platy aggregates (Fig. 6.14A), and as parallel-walled fissures (Fig. 6.14B) at the top and base of the rampart upper unit. As the fissures encircle aggregates this structure is discussed below (under Aggregates).

- **Aggregates**
  Although void spaces within glacial sediments are generally very low, due to the compacted nature of basal till, rounded to ellipsoidal aggregates delineated by encircling voids can occur as a marble structure formed within a deforming bed beneath a glacier (van der Meer,
1993; 1997). In PRD$_{CV_2}$ there are a few examples of well-developed parallel-walled fissures in both the rampart upper and lower units that vary between rounded in the upper rampart (Fig. 6.14B) to angular in the lower rampart (Fig. 6.16A). Grain turbates are also associated with marble bed structures, particularly when linked to low porosity (Lafeber, 1964) and these occur in low to moderate abundance within PRD$_{CV_2}$. It is possible, therefore, that the rounded to angular aggregates are caused by subglacial deformation and that the geometry varies with depth (van der Meer et al., 2003). Additionally, in the rampart upper unit is a zone of well-developed platy aggregates in a small area measuring 9 x 5 mm (Fig. 6.14A). Aggregates that develop platy or prismatic structures, and can be caused by freeze-thaw action in periglacial environments (van Vliet-Lanoë, 2010). Given the low number of planar fissures within PRD$_{CV_2}$, it is unsurprising that there is also a low abundance of aggregates. However, the differences in geometry between the aggregates suggest that both glacial and periglacial processes could be responsible for these differently shaped structures.

- **Rotation**
Throughout rampart PRD$_{CV_2}$, there are weak to moderately developed grain turbates (e.g. Fig. 6.15B middle rampart unit and 6.17B lower rampart unit) that increase in abundance with depth. As discussed above, rotation structures in association with parallel-walled fissures can indicate subglacial deformation. Grain concentrations in PRD$_{CV_2}$ are also weakly to moderately developed and there is also a low abundance of weak to well-developed plasmic fabric (associated with grain rotation). However, grain turbates can also be caused by mass-wasting in a periglacial environment (Bertran, 1993) and, in association with grain concentrations, could indicate rampart-formation processes (Mackay, 1978). Other rotational structures include curvilinear arrangements of grains that occur in the top and middle rampart units (e.g. Fig. 6.15C). The origin of arcuate arrangements of grains in coarse-grained sediments is not entirely understood but they have been linked to localised remobilisation of sediment (Phillips, 2006) and could be interpreted as rotational structures related to grain turbates. Again, the palaeo-setting for this field site includes both glacial and periglacial environments. It is not possible to determine whether one or both are responsible for the processes creating the structures within the upper and middle rampart units and whether they are solely the cause of sub-glacial deformation or mass-wasting or both.

- **Planar structures**
There are a few examples of weakly developed linear grain arrangements in the rampart upper and middle units. In subglacial environments, grain lineations form due to parallel
stress during shearing (Hiemstra and Rijsdijk, 2003; Carr et al., 2006). Lineations can also be associated with rotation structures, such as grain turbates, where rotation and planar displacement combine to produce shear stress (Hiemstra and Rijsdijk, 2003). However, in PRD_{CV2} there does not appear to be a proportionate amount of grain lineations to grain turbates, suggesting that a shear-stress origin is more likely for the grain lineations within PRD_{CV2}. There are very few examples of fractured grains in the upper unit, which could indicate a brittle strain environment (Hiemstra and Rijsdijk, 2003; Menzies et al., 2006) or frost shattering in a periglacial environment (van Vliet-Lanoë, 1985; 1998; 2010). There are very few examples of fragmented domains. The low abundance of planar structures means that it is difficult to identify the processes responsible as wholly glacial or periglacial.

- **Sediment mixing**
  There is a moderate abundance of weak to moderately developed patchy domains of clay within areas of predominantly silt matrix that occur throughout PRD_{CV2}. Sporadic, translocated clay domains could have a cryogenic origin (e.g. cryoturbation could be responsible for fragmenting clay deposits, which are then moved down the sediment profile on thaw (pers. comm. van Vliet-Lanoë, 2016). There are very few examples of sediment intraclasts (type III) in the middle and lower rampart units. Intraclasts reworked by rotation occur in both subglacial environments (e.g. deforming beds (van der Meer, 1993)) and debris flows (Lachniet et al., 2001). Therefore, their presence could be linked to both subglacial and debris flows related to frost-mound formation processes (e.g. downslope movement of outer mound deposits as the frost mound forms).

- **Pore-water features: void and grain coatings**
  There is a low number of clay and silt grain coatings throughout PRD_{CV2}, which is best developed in the middle and lower units. The fine-grained coatings of many of the rampart sediment grains (e.g. Figs. 6.16A and C) are silt and clay cappings. These have probably developed following meltwater thaw and rotation (Harris and Ellis, 1980; van Vliet-Lanoë and Langohr, 1982; van Vliet-Lanoë et al., 1984; van Vliet-Lanoë, 2010) (Chapter 2, section 2.2.3, iii).

- **Plasmic fabric**
  There is low abundance of plasmic fabric development within PRD_{CV2}, which occurs as both skelsepic and unistrial plasmic fabric. Both types of fabric are best developed in the rampart lower unit, where the clay content is highest, and both can be linked to shearing in both subglacial (van der Meer, 1987; Jim, 1990; van der Meer et al.; 1994 Hiemstra and Rijsdijk,
2003) and sub-aerial debris-flow environments (Bertran and Texier, 1999) and therefore, may be attributed to either subglacial processes or debris flows related to frost-mound formation, in this investigation.

iii. PRD<sub>CV3</sub>

- **Microfabric**

There is a moderately developed sub-vertical microfabric towards the base of the middle unit of PRD<sub>CV3</sub>. Most examples are elongate clasts with a similar inclination, suggesting that frost-mound heave (Pissart and French, 1976; Mackay, 1978; Pissart and Gangloff, 1984), rather than mass-movement (Harris and Ellis, 1980), or frost-jacking is the cause (van Vliet-Lanoë et al., 1984; van Vliet-Lanoë, 1985; 2010).

- **Stratification**

Crude bands of clay-, silt- and clast-rich sediments occur within PRD<sub>CV3</sub> inclined at ~145°, although this inclination is not the alignment of the a-axes of all grains within the bands. Poorly sorted silty, sandy gravels could be indicative of a glaciofluvial depositional environment (Easterbrook, 1999). Tilted layers can be an internal feature associated with frost-mound development, caused when sediment heaves due to pressure exerted by the growing ice lens (Pissart and French, 1976; Mackay, 1978; Pissart and Gangloff, 1984; Pissart, 2002; Pissart et al., 2011).

- **Grain concentrations**

Clasts are concentrated towards the base of the rampart middle section where they occur in moderate abundance as crude bands (section 6.4.2, iii, Stratification). This could be the consequence of sediment displacement caused by heaving during frost-mound formation (Harris and Ellis, 1980).

- **Void spaces**

Void space is very low, occurring as planar fissures, vughs and vesicles, mostly at the top of the rampart middle unit. Vesicles and vughs (enlarged voids) are commonly found in frost-susceptible sediment (Brewer, 1976; Harris and Ellis, 1980, van Vliet-Lanoë, 2010) (Chapter 2, section 2.2.2, iii).

- **Rotation**

There are a few examples of well-developed grain turbates displaying skelsepic plasmic fabric (section 6.4.2, iii, Plasmic fabric) (e.g. Fig. 6.17A) and moderately abundant and
moderately developed examples of curvilinear arrangements of fine-grained sand. Where arcuate linear grain arrangements occur continuously within the matrix (silt and clay) and appear to undulate, they are often accompanied by wavy fissures (forming micro-scale platy aggregates) and are interpreted as a frost creep structure (van Vliet-Lanoë et al., 1984; van Vliet-Lanoë, 2010) (Chapter 2, section 2.2.3, iii). Within PRD$_{CV3}$, however, there are no accompanying fissures. This could be due to collapse of the sediment once it has thawed (pers. comm. van Vliet-Lanoë, 2016).

• **Planar structures**
Linear concentrations of grains, indicating a brittle strain environment, are in very low abundance within rampart PRD$_{CV3}$ (Hiemstra and Rijsdijk, 2003; Menzies et al., 2006). In subglacial environments, grain lineations form due to parallel stress during shearing (Hiemstra and Rijsdijk, 2003; Carr et al., 2006). However, the low abundance of planar structures means that it is difficult to draw firm conclusions about the processes that have caused them.

• **Sediment mixing**
Sediment mixing within the rampart is illustrated by matrix intraclasts (type I) (e.g. Fig. 6.17B). Matrix intraclasts reworked by rotation occur in subglacial environments (e.g. deforming beds (van der Meer, 1993)) and debris flows (Lachniet et al., 1991). The intraclasts identified in rampart PRD$_{CV3}$ are low in number but are moderately developed, rounded and occur towards the base of the rampart middle unit. The intraclasts are found in association with rotational structures (i.e. grain turbates and curvilinear arrangements of grains) and tilted layers. They are, therefore, interpreted as a consequence of mass-wasting during frost-mound formation and decay (i.e. mass-wasting of sediment as the mound heaves and grows and/or as part of rampart formation as the frost-mound decays) (Bertran, 1993). Multiple domains of clay-, silt- and clast-rich sediment also occur within the middle unit of PRD$_{CV3}$; these are interpreted as crude layers and discussed above (section 6.4.2, iii, Stratification).

• **Pore-water features: void and grain coatings**
There is a very low abundance of weak to moderately developed silt and clay coatings around grains, probably formed during periglacial conditions (van Vliet-Lanoë and Langohr, 1982; van Vliet-Lanoë et al., 1984) (Chapter 2, section 2.2.3, iii).
- **Plasmic fabric**
  Both skelsepic and unistrial plasmic fabric occur within PRDcv2. Skelsepic plasmic fabric is clearly seen around the core grain of a grain turbate (Fig. 6.17A) and so suggests an association with rotation caused by sub-glacial deformation (van der Meer, 1987; Jim, 1990; van der Meer et al.; 1994 Hiemstra and Rijsdijk, 2003) or periglacial mass-wasting during frost-mound development and/or decay (Bertran, 1993). Unistrial plasmic fabric is most apparent near the base of the rampart middle unit in similar orientations to the tilted layers (i.e. 130-140°); this suggests that the fabric could be linked to shearing (van der Meer, 1993; Hiemstra and Rijsdijk, 2003), possibly the consequence of frost-mound formation (e.g. as the mound heaves, sediment layers tilt and shearing occurs as the ice core grows).

iv. **Control** (Fig. 6.18)
- **Microfabric**
  Across all size ranges there is no single orientation of grains but a range of sub-horizontal to sub-vertical orientations. Pore spaces around sub-vertical grains could be the remnants of ice lensing, displacing grains to a more vertical position by frost-jacking, but there are no enlarged pore spaces at the base or side of grains, as is commonly the case in periglacial environments (van Vliet-Lanoë et al., 1984; van Vliet-Lanoë, 1985; 2010).

- **Grain concentrations**
  There is a low abundance of grain concentrations that occur within the middle of the sample. Whilst grain concentrations are commonly found at the base of slopes due to downslope movement during solifluction (Harris and Ellis, 1980), their presence in the control sample is too low to draw any significant conclusions about their origin.

- **Void spaces**
  The matrix is high density and very compact. The void texture is mostly fine, planar fissures, which are moderately developed but occur in low abundance as parallel-walled fissures encircling angular aggregates. A range of possible explanations for this pattern of fissures has been considered: i) remnant reticulate vein ice structures, diagnostic of periglacial environments, ii) remnants of ice lensing resulting in platy to prismatic aggregates caused by freeze-thaw processes in periglacial environments, and iii) the consequence of shear stresses indicative of a developing ‘marble bed’ structure found in subglacial environments. The control sample site would have been subject to both glacial and periglacial processes. It is possible that the fissures were formed in either environment but as the sample was taken from near the base of the cliff succession, the effects of periglaciation might be expected to
be less significant. As there is an association between ‘marble beds’ and rotation structures (section 6.4.2, iii, Rotation), it is possible that there is a subglacial origin for these fissures in this control sample.

- **Aggregates**
There are a very few angular aggregates, reflecting the low number of planar fissures present within the control sample sediment (section 6.4.2, iii, Void spaces).

- **Rotation**
Microstructures indicative of rotation are generally characterised by grain turbates, which are moderately abundant and developed and mostly occur towards the top of the control sample. Grain turbates, when found in association with fractured grains, elongate grains aligned downslope and skelsepic plasmic fabric, are associated with mass-wasted deposits (Bertran and Texier, 1999). However, none of these associative features are found in significant abundance within the control sample sediment. It is possible, therefore, that the grain turbates identified are associated with the parallel-walled fissures discussed above in relation to ‘marble beds’ (van der Meer et al., 1993; Hiemstra and van der Meer, 1997; Kilfeather and van der Meer, 2008).

- **Planar structures**
Towards the base of the sample are a few examples of grain lineations, oriented ~ 130 ° and very few fractured grains. These could be a response to shear stresses within subglacially deformed sediment (Benn and Evans, 1998).

- **Sediment mixing**
There are very few examples of sediment intraclasts (type III) (ranging from 1 x 0.8 mm to 6 x 3 mm). Intraclasts reworked by rotation occur in subglacial environments (e.g. deforming beds (van der Meer, 1993)) and debris flows (Lachniet et al., 1991). The intraclasts identified in the control sample are low in number but are generally well developed and could be linked to the development of a ‘marble bed’.

- **Pore-water features: void and grain coatings**
There is sparse iron staining (bright red) on the tops of some of the grains. Red staining on some grains are indicative of haematite, usually formed in drier aerobic conditions (Pipujol and Burman, 1994) and is a consequence of post-depositional processes.
• **Plasmic fabric**

Plasmic fabric is in low abundance and occurs as skelsepic plasmic fabric around a few grains and as moderately developed unistrial plasmic fabric, particularly towards the base of the sample, oriented between ~ 95 and 130 °. The low abundance of this feature makes it difficult to ascribe a definitive origin, but both skelsepic and unistrial plasmic fabric could be linked to the developing 'marble bed' structure within a subglacial environment (discussed above).

The combination of a low porosity, highly compact matrix containing shear stress features (*e.g.* parallel-walled fissures, edge-to-edge grain contacts), along with weakly developed rotation structures (*e.g.* turbates) (many more than observed in the samples from the Cledlyn Valley site) but with few other distinctive micro-features, is characteristic of glacial till (van der Meer, 1997; Menzies and van der Meer, 1998; Menzies, 2000).

### 6.5 Discussion

Macroscopic indicators (*e.g.* grain-size distribution, sediment sorting, clast provenance (locally derived silt- and sandstones) and surface features of striae and facets) suggest that the suspected PRDs examined in the Cledlyn Valley have formed within glacially derived deposits of: i) glaciolacustrine clayey silt with scattered pebbles (lower rampart units), ii) glaciofluvial sandy, abundant gravels (middle rampart units), and iii) cemented, coarse-grained glacial till subsequently reworked by paraglacial processes (upper rampart units). The basin infill is much finer-grained than any of the rampart deposits but is closest in grain size and texture to that found in the lower rampart unit of PRD$_{CV}$. The coarsening upwards sequence across the lower, middle and upper rampart units, reflects the field site's proximity, in the Late Devensian, to dammed glacial lakes (*e.g.* Lakes Teifi and Aeron) that leave a succession of glaciolacustrine muds, overlain by subglacial and glaciofluvial deposits following meltwater outwash and subsequent glacial overriding (Etienne *et al.*, 2006).

Sedimentological and stratigraphic evidence (*i.e.* the youngest deposit of glacial till overlying the area, forming the upper unit of the PRDs), and the location of the field site within the glacial limits during the Late Devensian (Campbell and Owen, 1989) could imply that the suspected PRDs are glacial landforms (*e.g.* kettle holes (*Ross *et al*., 2007)).

However, a hummocky landscape (indicative of thermokarst (*French*, 2007)), the presence of distinct ramparts surrounding a depression (Watson, 1971; Mackay, 1988; Pissart, 2003) and the presence of clusters of ramparts - as opposed to chains of ring craters formed by kettle holes (*Maizels*, 1992; *Fay*, 2002) - are suggestive of frost-mound development following ice-sheet retreat. In addition, the index of kettle rim morphology proposed by
Maizels (1992), calculates that the rim and height of the kettle increase with sediment concentration, but decrease with depth of burial. Most significant to a frost-mound identification for the suspected PRDs in the Cledlyn Valley, therefore, is the presence of deep basins encircling high ramparts (e.g. particularly PRD_{CV}). In addition, the presence of overlapping/intersecting ramparts indicate cyclic development rather than glacial melt-out features (Worsley et al., 1995). A lower valley hydrogeological setting is also conducive to frost-mound formation (see below).

If a frost-mound genesis is assumed, more difficult to interpret from macro-scale features alone, is frost-mound type. Hydrostatic and hydraulic pingos form in a wide range of coarser-grained sediment types from well-sorted clay and gravel to diamicton (Mackay, 1978), including bedrock for hydraulic pingos (Müller, 1959; Mackay, 1978). Hydrostatic pingos commonly form as solitary or low density landforms within sites of drained lakes (Müller, 1959), which is not relevant to the Cledlyn Valley setting. Alternatively, hydraulic pingos develop in higher density clusters under hydraulic head, and so a location at the foot of a hillslope or on a valley floor is favourable to the development of such a landform (Müller, 1959; Washburn, 1979; Ballantyne and Harris, 1994). However, Mackay (1988), states that there is a direct relationship between the volume of a pingo rampart and the depression infill (i.e. the rampart is typically equivalent to the volume of the depression). If the substrate for the PRDs is the coarse-grained diamicton of the upper ramparts, this does not explain why the basin of PRD_{CV} is so deep (> 11 m) and infilled with a very different sediment type (i.e. fine-grained clayey silt with very few retrieved clasts). Instead, it is logical to assume that heave, associated with frost-mound development, would occur in the most frost-susceptible sediment (Taber, 1930; Takagi, 1980; Rempel, 2010) (i.e. the finer-grained clayey silt at the base of the ramparts). This hypothesis allows a direct connection between the finer-grained lower rampart sediment and the volume of clayey silt in the basin infills (Gurney, 1994; 1995). Lithalsas and palsas (peat-covered), are high-density frost mounds that develop in fine-grained sediments (Washburn, 1979; Pissart, 2000; 2002; Gurney, 2001). The formation of ramparts in lithalsas is attributed to both lateral extension and solifluction (Pissart et al., 2011). The movement of sediment deposits outwards, rather than collapsing inwards, could explain the paucity of pebbles within the basin infill. The absence of a peaty landscape and high ramparts of the Cledlyn Valley PRDs discounts aalsa origin, suggesting a possible lithalsa, as well as hydraulic pingo, origin for the suspected PRDs.
Basin morphology and grain size is another significant factor for the interpretation of frost-mound types. Watson and Watson (1972) attribute shallower basins to a higher segregated ice (and so mineral) content that collapses into the basin on thawing. Deeper depressions are attributed to the presence of larger quantities of pure ice (Watson and Watson, 1972). Basin depth is variable across the Cledlyn Valley suspected PRDs (from 2–5 to >11 m). However, the basin of PRD_{CV1} is in excess of 11 m deep and so this is not in line with a depression caused by segregation ice processes.

It could be that there are remnants of different thermokarst types within the Cledlyn Valley including: i) hydraulic pingos, given the topographic relief of the field site, as well as ii) lithalsas, due to the presence of fine-grained sediments at the rampart base and within the basin infill. It could also be the case that some of the suspected PRDs (e.g. PRD_{CV1}) display equifinal behaviour (Gurney and Worsley, 1997) (i.e. the morphology of a PRD has arisen due to different conditions and processes) and so represents a polygenetic form (Gurney, 1998), possibly caused by fluctuating hydraulic pressure (Murton, 2013) - a question currently under consideration in relation to relict thermokarst in the Paris Basin (van-Vliet-Lanoë et al., 2017).

Microscopic observations of the upper rampart units (e.g. PRD_{CV1} and CV2), and the control sample, confirms a highly dense, low porosity matrix suggestive of subglacial deposition (van der Meer and Laban, 1990; Kilfeather and van der Meer, 2008). There is too little pore space to indicate a periglacial slope deposit (van der Meer et al., 1993) or a flow till origin (Kilfeather and van der Meer, 2008). Crude, inclined layering of pebbles in the middle rampart units (PRD_{CV2} and CV3), could be a key indicator of frost-mound heave and lateral thrusting (Pissart, 1963). Distorted, alternating clay-rich and silt-rich 'layers' within the rampart lower unit (PRD_{CV6}), indicates the possible presence of glaciolacustrine varves (Easterbrook, 1999), subsequently deformed.

There are, therefore, a number of features that could be ascribed to glacial or periglacial processes (or both):

- **Glacial:**
  i. glaciolacustrine, silt/clay couplets (PRD_{CV1}) (observed microscopically).

- **Periglacial:**
  i. sub-vertical microfabric (weakly developed), linked in some cases to frost-jacking (e.g. PRD_{CV1} upper rampart unit and PRD_{CV2} upper, middle and lower rampart units);
ii. grain concentrations (low abundance and weakly developed) possibly caused by mass-wasting during frost-mound formation and or collapse when coarser-grained, but probably linked to frost sorting when finer-grained (e.g. PRD_{CV1} upper rampart unit and PRD_{CV2} upper, middle and lower rampart units);

iii. mammillated vughs and vesicles caused by expulsion of air on thawing of periglacial sediments (e.g. PRD_{CV3});

iv. curvilinear arrangements (e.g. of clay pods in PRD_{CV1} lower rampart) caused by frost creep, and arcuate arrangements of grains (in PRD_{CV2} upper and middle ramparts and PRD_{CV3} middle rampart unit) caused by rotation during frost-mound development;

v. crude layering of grains, possibly occurring during frost-mound heave (e.g. PRD_{CV2} middle and lower rampart units and PRD_{CV3} middle rampart unit);

vi. moderately abundant, well-developed fragmented platy/lenticular clay pods (e.g. PRD_{CV1}, lower rampart) and clay fragments translocated within the sediment matrix following cryoturbation (e.g. PRD_{CV2});

vii. fine-grained coatings of clay and silt around grains developed in periglacial environments during meltwater thaw, probably then rotated during mass-wasting linked to rampart formation (a low abundance observed in all suspected PRDs investigated).

- Glacial or periglacial:
  i. a low abundance of moderately development parallel-walled fissures encircling angular aggregates (e.g. PRD_{CV1} upper rampart) which could represent: i) the remains of vein ice developed in a periglacial environment, ii) the result of segregation ice lensing, a consequence of frost action in a periglacial environment, or iii) a weak ‘marble bed’ structure in a sub-glacial environment;
  ii. a low number of weakly developed grain turbates and grain concentrations that could be caused by glacial overriding or sub-aerial, mass-wasting developed during frost-mound formation and/or collapse (e.g. PRD_{CV1} upper rampart unit, PRD_{CV2} upper, middle and lower rampart units and PRD_{CV3} middle rampart unit);
  iii. sediment mixing caused by glacial overriding of the sediment prior to frost-mound formation or mass-wasting (e.g. PRD_{CV1} lower rampart unit and PRD_{CV2} middle and lower rampart units);
  iv. the development of skelsepic and unistrial plasmic fabric in response to either subglacial deformation or frost-mound formation (observed in all suspected PRDs).
It should be noted that parallel-walled fissures occur in the control sample as well as the suspected PRDs. As the control sample is unaffected by frost-mound formation processes, this could suggest that where these occur in PRDs they have been caused by glacial processes (e.g. subglacial deforming beneath a cold based glacier (van der Meer et al., 2003)). Conversely, microstructures identified within the suspected PRDs that do not occur within the control sample may be associated with periglacial processes i.e. mammillated vughs and vesicles and curvilineations linked with collapsed structures on thaw. It is also possible that glacial overriding in the Cledlyn Valley, prior to frost-mound development in the area, has complicated the microstructures observed within the PRD sediment.

6.6 Conclusions

The local stratigraphy, as investigated within the Cledlyn Valley ramparted depressions, comprises an upper diamicton unit, probably glacial till, overlying units of proglacial gravels and clays. Findings can be summarised as follows:

1. At the macro-scale, the Cledlyn Valley landforms have pronounced ramparts, are mutually interfering and are located in a hydrological and topographic setting which is permissive of a hydraulic pingo origin if the PRDs formed in the coarser-grained diamicton. However, the presence of finer-grained glaciolacustrine deposits at the rampart base, the high density of PRDs and abundant water supply are also conducive to lithalsa formation. It is possible that the suspected PRDs are a mixture of relict lithalsa and relict hydraulic pingo landforms and that PRD$_{CV}$, in particular, is a polygenetic form (due to the presence of glaciolacustrine sediment prone to heave encircling a very deep basin indicative of injection ice), reflecting changing climatic and hydrological conditions indicative of an ice-marginal environment.

2. At the micro-scale, a number of structures are observed that are common to both glacial and periglacial processes. In the Cledlyn Valley a glacial imprint is probably illustrated by examples of parallel-walled fissures and soft-sediment deformation structures at the rampart base (caused by glacial overriding). However, microstructures diagnostic of a periglacial environment are also present (e.g. silt and clay coatings on grains, frost-jacked grains, vesicles and mammillated vughs, curvilinear structures).

3. Macro- and/or microstructures suggestive of frost-mound growth include: i) crude layering towards the base of the ramparts (Pissart and French, 1976; Mackay, 1978;
Pissart and Gangloff, 1984), ii) fractured grains (Bertran, 1993), iii) grain coatings rather than caps (due to rotation) (Bertran, 1993), iv) clay domains fractured and integrated within the matrix (van Vliet-Lanoë, 2010), and v) the presence of skelsepic and unistrial plasmic fabric, diagnostic of grain rotation – indicative of clays reoriented under stress (Evans and Benn, 2014). However, identifying frost-mound type is challenging due to: i) the presence of a cluster of coarse-grained ramparts that are high with deep basins (suggestive of hydraulic pingos) but whose substrate appears to be a fine-grained glaciolacustrine sediment (indicative of lithalsas) and ii) the complexity of the micro-scale sedimentological signatures created by the imprint of both glacial and periglacial processes. It is also probable that the site includes at least one example of a polygenetic PRD (Gurney, 1998).

In summary, the following sequence of events is proposed:

- During the Late Devensian glaciation, the field site was in the proximity of an ice dammed lake resulting in proglacial sedimentation that coarsened upwards (i.e. glaciolacustrine and glaciofluvial deposits) (Patton and Hambrey, 2009);
- Subsequent ice-sheet advance from the WIC, caused subglacial deformation and deposited glacial till (Etienne et al., 2006);
- Following deglaciation, periglacial landforms developed in both fine- and coarse-grained sediments (e.g. frost mounds – lithalsas, and/or hydraulic pingos and/or polygenetic frost mounds) (Watson, 1971; Watson and Watson, 1972; Watson and Watson, 1974; Watson, 1982; Campbell and Bowen, 1989; Gurney, 1994; Gurney, 1995);
- Climatic amelioration led to the development of a thermokarst landscape (e.g. PRDs and hummocky microtopography).

The implication of lithalsa development is significant as they are located on the borders of the continuous permafrost zone (Pissart, 2003). Thus, for Wales the presence of a range of frost-mound types confirms a dynamic, ice-marginal location. Therefore, by using micromorphology, contextualised by macroscopic data (e.g. geomorphological, lithology, topographic position, landform density), it is possible to better understand the genesis of suspected PRDs as well as the environment in which they formed.
Table 6.4 Comparison of sedimentological signatures of the suspected PRDs in the Cledlyn Valley with expected periglacial frost-mound signatures.

<table>
<thead>
<tr>
<th>Diagnostic macroscopic sedimentological features</th>
<th>Expected</th>
<th>Potential associated microscopic features</th>
<th>Cledlyn Valley PRDs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pingos (hydraulic and hydrostatic) and Lithalsas</strong></td>
<td>✓</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>A rampart encircling a depression: isolated, within clusters or overlapping.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Internal rampart deformation structures and stratification and tilting of layers.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>External to the rampart, unsorted sediments derived from mass-wasting and shear failure (e.g. slump and debris-flow material).</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rampart sediment should be derived from original mound and will be similar to that below the basin.</td>
<td>?</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Pingos, Palsas and Lithalsas</strong></td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cryostructures caused by segregation ice (e.g. lenses and layers of sediment parallel to the freezing plane).</td>
<td>✓</td>
<td>Platy, lenticular microstructures oriented parallel to the ground surface: planar, wavy and curved (micro-undulations).</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pore spaces (packing voids) at the base of rock particles and clay aggregates.</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Silt cappings.</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vesicles, open fissures, well-developed shear planes and narrow – near-vertical – cracks</td>
<td>✓</td>
</tr>
<tr>
<td>Shallow basin (&lt; 4 m below the surface outside the rampart), indicative of segregation rather than intrusive ice.</td>
<td>Shallow and deep</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Lithalsas</strong></td>
<td>✓</td>
<td>Compression features due to lateral thrusting.</td>
<td>?</td>
</tr>
<tr>
<td>Lateral growth, demonstrated by displaced sediments at the lithalsa rampart edges</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Chapter 7: Synthesis

7.1 Introduction

The preceding results chapters (4, 5 and 6) outline independent site investigations of periglacial ramparted depressions (PRDs) in Belgium, Norfolk and Wales respectively. The Belgian field site contains an accepted relict lithalsa (Pissart, 2000, 2003). Nonetheless, the characterisation of the PRD at Konnerzvenn was cross-referenced with features identified within the Literature Review (Chapter 2, section 2.2.3) to confirm this interpretation. The same approach was applied to the sites in Norfolk and Wales containing suspected PRDs. In this chapter, the diagnostic suite of microstructures for lithalsa formation and decay processes identified in Chapter 4, is compared to well-developed microstructures identified in the suspected PRDs in Norfolk and Wales (Table 7.1). Variations in the types of microstructures and/or abundance of structures found in PRD\text{WC} and PRD\text{SCV1, CV2, CV3}, compared to PRD\text{K}, are identified. The influence of grain size and palaeo-periglacial setting on the variation in microstructures and/or abundance of structures is considered (section 7.3). For the first time, this research summarises the internal structures of a relict lithalsa by presenting: i) a diagram illustrating schematically the microstructures characteristic of a relict lithalsa in different sections of the PRD stratigraphy (Fig. 7.2) and ii) a table linking microstructures to macro-scale formation and decay processes (Table 7.2). The project demonstrates how the findings can be applied to sites containing suspected PRDs for their identification. The chapter closes with a consideration of the wider significance and possible applications of these research findings.

7.2 Comparison of diagnostic macro- and micro-scale features of a known relict lithalsa (PRD\text{K}) with the suspected PRDs at Walton Common (PRD\text{WC}) and in the Cledlyn Valley (PRD\text{SCV1, CV2, CV3}) (Table 7.1)

At the Norfolk field site, PRD\text{WC} is located within a silty, sandy, chalk gravel overlain by gravelly sand. At the Cledlyn Valley (Welsh) field site, PRD\text{SCV1, CV2, CV3} are located within a substrate of glaciolacustrine silty clay with scattered gravels overlain by glacial till. Based on macroscopic sedimentological signatures previously identified (Chapter 2, section 2.2.3), factors suggesting a frost-mound origin for the PRDs in Norfolk and Wales, include:

- distinct and overlapping ramparts and associated shallow basins in a very high density complex (Worsley et al., 1995) in;
- a range of fine, relatively fine and coarse-grained substrates (Worsley et al., 1995);
The similarities and differences in microstructures identified between the suspected PRDs in Norfolk (PRD<sub>WC</sub>) and in Wales (PRDs<sub>CV1, CV2, CV3</sub>), compared to those of an accepted relict lithalsa in Belgium (PRD<sub>K</sub>) (Table 7.1), are presented and discussed as follows:

### Table 7.1 A comparison of well-developed texture and deformation structures identified within PRDs at all field sites investigated.

<table>
<thead>
<tr>
<th>Texture and deformation structures</th>
<th>Texture</th>
<th>Voids</th>
<th>Rotation/slump</th>
<th>Planar</th>
<th>Sediment mixing</th>
<th>Pore water</th>
<th>Plasmic fabric</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Field site</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Belgium: Konnerzven (PRD&lt;sub&gt;K&lt;/sub&gt;)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Norfolk: Walton Common (PRD&lt;sub&gt;WC&lt;/sub&gt;)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Wales: Cledlyn valley (PRD&lt;sub&gt;CV1, CV2, CV3&lt;/sub&gt;)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

hydrogeological conditions subject to recharge (Seppälä, 1988; Calmels et al., 2008; 2008b).
i. Texture and stratification

Similar to PRD<sub>K</sub>, a vertical to sub-vertical microfabric is apparent in both PRD<sub>WC</sub> and PRD<sub>CV1, CV2, CV3</sub>. The genesis of this microfabric is also thought to be similar at all three field sites in Belgium, Norfolk and Wales: i) vertical grains with pore spaces near the base are interpreted as frost-jacked grains (van Vliet-Lanoë <i>et al.</i>, 1984; van Vliet-Lanoë, 1985; 2010), ii) sub-vertical grains, sharing the same inclination as tilted layers at the top of a rampart, parallel to the flow of mass-wasted sediment, are probably caused by mass-wasting (Bertran and Texier, 1999), during frost-mound formation and decay; and iii) elongate, inclined grains found within a lower rampart unit, are possibly caused by frost heave during mound formation (Pissart and French, 1976; Mackay, 1978; Pissart and Gangloff, 1984). A vertical to sub-vertical microfabric is, therefore, interpreted as indicative of periglacial processes (<i>i.e.</i> freeze-thaw action, causing frost-mound heave and subsequent decay).

In common with PRD<sub>K</sub>, there is stratification in PRD<sub>WC</sub> at the base of both the rampart upper and lower units in the form of inclined layers, indicated by: i) a change in grain size (from coarse silt and fine sand to medium-grained sand) and ii) the upslope inclination of the apparent long-axes of grains parallel to the rampart flank in the upper unit. In the lower rampart unit of PRD<sub>WC</sub>, tilted layers are indicated by crude bands of similarly oriented sub-vertically inclined grains and possibly formed as a consequence of uplift during frost-mound formation (Pissart and French, 1976; Mackay, 1978; Pissart and Gangloff, 1984). In the upper rampart unit of PRD<sub>WC</sub>, tilted layers probably occur due to a redistribution of the sediment, as part of rampart-formation processes during frost-mound decay (<i>i.e.</i> mass-wasting) (Mackay, 1978; Pissart and Juvigné, 1980; Harris, 1985; Mackay, 1988; Bertran and Texier, 1999). In the Cledlyn Valley (PRD<sub>CV1, CV2, CV3</sub>), stratification occurs as disrupted, laminated ‘varves’ at the base of PRD<sub>CV1</sub> and as tilted layers at the base of PRD<sub>CV2</sub> and PRD<sub>CV3</sub> (Pissart and French, 1976; Mackay, 1978; Pissart and Gangloff, 1984). Lamination at the base of a frost mound has only been observed within one PRD at the Cledlyn Valley site, within clayey-silt (PRD<sub>CV1</sub>), and not at the Belgian (PRD<sub>K</sub>) or Norfolk (PRD<sub>WC</sub>) field sites. As, clayey silt sediment is also present at the base of PRD<sub>K</sub>, the lamination in PRD<sub>CV1</sub> is unlikely to be a function of grain size but the consequence of a different depositional environment (<i>i.e.</i> proglacial outwash deposits in the Welsh field site rather than aeolian deposits in the Belgian field site). Tilting of layers within PRD<sub>CV2</sub> and PRD<sub>CV3</sub> in Wales are similar to those observed at the Belgian (PRD<sub>K</sub>) and Norfolk (PRD<sub>WC</sub>) field sites and so are probably a function of frost-mound heave (near the base) and soliflucted deposits during frost-mound growth and
subsequent rampart formation (near the top). The absence of tilted layers in PRD$_{CV1}$ could suggest that different formation processes dominate within this PRD compared to PRD$_{CV2}$ and CV$_3$. In addition, the existence of a deep basin within PRD$_{CV1}$, which is indicative of injection ice common to pingo formation (Watson and Watson, 1972), could suggest that this PRD is a polygenetic frost mound (Gurney, 1998) (i.e. a frost mound that initially formed as a lithalsa in the frost-susceptible fine-grained substrate at the base of the rampart and possibly evolved into an hydraulic pingo - with intrusive ice being the cause of the deep basin in PRD$_{CV1}$). Further research is required to clarify whether lithalsas could represent a continuum between pingos and palsas (Åkerman and Malmström, 1986; Worsley et al., 1995; Gurney, 2001).

Unlike PRD$_K$, there is a low to moderate abundance of moderately developed grain concentrations in PRD$_{WC}$. It is possible that within PRD$_{WC}$, where evidence for bioturbation can be seen macroscopically, this structure has been caused by sediment remobilisation, in part caused by bioturbation (Fitzpatrick, 1993).

ii. Voids and aggregates
Planar fissures encircling platy to angular aggregates are observed at all three field sites (Belgium, Norfolk and Wales). Whilst platy aggregates are in much lower abundance at the Norfolk field site compared to the Belgium field site (i.e. at the base of the rampart upper unit in PRD$_{WC}$ (Norfolk)), they do occur in finer grained (sandy-silt) sediment and their presence is significant as they are probably formed as a consequence of freeze-thaw action in a periglacial environment (van Vliet-Lanoë and Langohr, 1982; van Vliet-Lanoë et al., 1984; van Vliet-Lanoë, 1985). The occurrence of platy aggregates is also very low in the PRDs in the Cledlyn Valley, Wales (e.g. the upper rampart unit of PRD$_{CV2}$). It is possible that more angular aggregates, described as parallel-walled fissures (e.g. PRD$_{CV1}$, upper unit), are either remnants of reticulate vein ice, which developed in a relict permafrost setting (Mackay, 1974), or an example of a developing marble-bed structure – the consequence of subglacial deformation (van der Meer et al., 2003).

As is the case for PRD$_K$, planar fissures are not well developed in the finer-grained lower rampart unit of PRD$_{CV2}$, where one might expect the evidence of relict ice-lensing to be high given the frost-susceptible nature of the sediment. It is possible that sediment mixing (i.e. remobilisation of sediment (Philips, 2006)) in the basinward and lower units has occurred and obscured relict ice lensing due to i) initial mound heave, ii) emplacement of the solifluction overburden during mass-wasting, iii) collapse of the
inner mound, and iv) glacial overriding and reworking of the sediment prior to frost-mound formation, and that these processes have caused the collapse of potential ice-lens traces.

Vughs and vesicles occur throughout PRD$_{WC}$ in Norfolk. The abundant pore space around sand grains in PRD$_{WC}$ is notable, but as a function of grain size rather than as vesicles expelled due to freeze-thaw processes. Unlike PRD$_K$ in Belgium, vughs are more abundant than vesicles within PRD$_{WC}$ and have been linked to significant bioturbation and interpreted as indicating faunal activity (Brewer, 1964). Voids found at the base of vertical to sub-vertical grains in PRD$_{WC}$, are probably relict traces of ice lensing (van Vliet-Lanoë, 1998).

There are many examples of well-developed channels and chambers within PRD$_{WC}$ that do not occur in PRD$_K$ or PRD$_{CV1, CV2, CV3}$. There was a high degree of bioturbation within the rampart at PRD$_{WC}$, observed at the macroscopic scale. It is possible that this difference between the two sites is due to Holocene soil development within Pleistocene sediments in Norfolk (Bateman et al., 2014).

iii. Curvilinear structures
Curvilinear structures in PRD$_{WC}$, probably caused by freeze-thaw action (van Vliet-Lanoë et al., 1984; van Vliet-Lanoë, 2010), are only low to moderate in abundance and moderately developed. Unlike PRD$_K$, curvilinear structures in PRD$_{WC}$ are found mostly in the lower rampart unit, possibly as this is the most frost-affected part of the rampart and least affected by Holocene soil development.

iv. Planar structures
Fractured grains are the only well-developed planar-like structure found within PRD$_{WC}$ and these occur in low abundance (as they do within PRD$_K$). The absence of any other well-developed planar microstructures could indicate a low shear stress regime. However, due to the lithology of grains in PRD$_{WC}$ (carbonates), it is possible that the origin of the fractures is post-depositional weathering processes (e.g. dissolution) (Fitzpatrick, 1993) or frost-cracking as a consequence of frost action (van Vliet-Lanoë, 1985; 1998; 2010), rather than in response to parallel shear stresses (Hiemstra and Rijsdijk, 2003) during PRD formation.
In the Cledlyn Valley, abundant, well-developed fragmented domains of clay within a clayey silt matrix occur in PRD<sub>CV1</sub> (rampart lower unit). Fragmentation of aggregates is probably due to frost action, with the fragments being translocated within the matrix due to cryoturbation (van Vliet-Lanoë, 1985; 1998; 2010). This microstructure has been observed in both the Belgian and Welsh field sites but not in Norfolk, where the clay content of the sediment is very low, and so its presence and development could be a function of grain size (see section 7.3). Unlike the Belgian field site, but similar to Norfolk, other planar features (e.g. grain lineations/linear grain domains) that form in response to parallel stresses during shear (Hiemstra and Rijssdijk, 2003) are in low abundance and weakly developed at the Welsh field site. This could indicate low shear stress.

v. Sediment mixing

Sediment intraclasts occur in low abundance in both PRD<sub>WC</sub> and PRD<sub>K</sub>. It is possible that they are linked to rotation (Lachniet et al., 2001) during frost-mound formation and decay (i.e. mass-wasting of sediment as the mound heaves and grows and/or as part of rampart formation as the frost mound degrades). There is a moderate abundance of sediment mixing in PRD<sub>WC</sub> rampart upper unit only (i.e. intraclasts (Type III) and multiple domains). Unlike PRD<sub>K</sub>, where sediment mixing is linked to mass-wasting of sediment (e.g. during frost-mound development or rampart formation), the in-mixed domains in the upper rampart unit of PRD<sub>WC</sub> appear to be reworked as a consequence of biological activity (Fitzpatrick, 1993) and Holocene soil development. In the Cledlyn Valley, as occurs in PRD<sub>K</sub>, multiple domains of platy, lenticular pods of clay-rich sediment in-mixed with silt, and silt-rich sediment in-mixed with clay, are well developed in PRD<sub>(CV1)</sub> lower rampart unit and throughout PRD<sub>(CV2)</sub>. Platy, lenticular microstructures are associated with segregation ice developed in fine-grained sediment, caused by ice lensing in periglacial environments (van Vliet-Lanoë, 2010). The presence of distinct but isolated ‘pods’ could be caused by cryoturbation, the pods are then moved down the sediment profile on thaw (pers. comm. van Vliet-Lanoë, 2016). However, the subsequent fragmentation of these lenses into ‘pod’ structures could also represent brittle strain (e.g. the consequence of stretching and shearing (Philips, 2006)). It is possible that the in-mixing is the result of loading or unloading of a sediment overburden which could have its origin in both subglacial deformation, debris-flows caused by mass-wasting of ramparts (Phillips, 2006; Montenat et al., 2007), or possibly perturbation during frost-mound formation.
vi. Pore water

Void and grain coatings occur as silt, clay and ferromanganiferous (Fe-MnO) staining in all three field sites (Belgium, Norfolk and Wales). Silt coatings are typically the result of meltwater thaw in periglacial environments (van Vliet-Lanoë and Langohr, 1982; van Vliet-Lanoë et al., 1984) and Fe-MnO-stained grains and sediment can indicate localised waterlogging in otherwise free-draining sandy sediment (Kühn et al., 2010). When the clay and silt occur as coatings rather than caps, it indicates that the sediment was subject to rotation, during frost formation and/or collapse (Bertran and Texier, 1999). Silt coatings represent a key palaeoenvironmental indicator and their presence, not just as caps but around grains, suggests periglacial processes related to freeze-thaw and solifluction.

vii. Plasmic fabric:

Skelsepic plasmic fabric is sparse and weakly developed within PRDWC, compared to PRDk, probably due to a combination of a low clay content (section, 7.3) and Fe-MnO-staining which can inhibit the detection of plasmic fabric (Jim, 1990). In the Cledlyn Valley, similar to PRDk, skelsepic plasmic fabric is weakly to well developed, and could be linked to grain turbates, which suggests an association with rotation. In the Cledlyn Valley, plasmic fabric and rotation could develop during sub-glacial deformation (van der Meer, 1987; Jim, 1990; van der Meer et al., 1994; Hiemstra and Rijsdijk, 2003) or mass-wasting in a periglacial environment (Bertran and Texier, 1999).

In respect of micro-scale features that are well developed in one field site setting only, grain turbates and plasmic fabric are more abundant and better developed in the Welsh field site, within PRDcv3 in particular. In PRDk and PRDwc there are only weakly-developed grain turbates and plasmic fabric in much lower abundance. It is possible that this is due to the influence of sediment grain size on the strain response of sediment (*i.e.* shear stress (van der Meer, 1993; Hiemstra and Rijsdijk, 2003) attributable to frost-mound and or rampart development) (Boulton and Hindmarsh, 1987; van der Meer et al., 2003; Benn and Evans, 1998) (see section 7.3). It could also be the consequence of sub-glacial deformation prior to frost-mound formation which has left a strain imprint within the sediment (van der Meer, 1987; Jim, 1990; van der Meer et al., 1994; Hiemstra and Rijsdijk, 2003) (see section 7.3). In addition, there are less well developed and fewer vughs and vesicles in the sediment at the Cledlyn Valley field site, probably due to the generally lower porosity of glacial tills, and no examples of banded or curvilinear fabric attributed to frost creep, again possibly due to the difference in grain size between the two sites (see section 7.3).
Based on the identification of microstructures attributed to PRD development in PRDₖ (Chapter 4), an established site for relict lithalsas (Pissart, 2000, 2003), similar features identified within PRDs at field sites in Norfolk and Wales (Table 7.1) are attributed to the same processes as follows:

- tilted strata - associated with similarly inclined elongate grains parallel to the flow of mass-wasted sediment (upper rampart units), developed during mound and/or rampart formation, or during mound growth due to frost heave (lower rampart units);

- coatings of silt around (rather than capping) grains - produced under periglacial conditions and associated with mass-wasting during mound formation and rampart development);

- a high abundance of multiple domains in the form of sediment in-mixing in the lower rampart of PRDᵥᵤ, - interpreted as re-homogenisation of sediment caused by frost-mound and subsequent rampart-formation processes.

Based on their occurrence in an accepted relict lithalsa (PRDₖ) (Pissart, 2000; 2003), microstructures in PRDᵥ₃ and/or PRDsᵥᵥᵥ,ᵥᵥᵥ, andᵥᵥᵥ, attributed to a periglacial environment, formed by segregation ice, include:

- frost-jacked grains, caused by ice-lensing;

- platy-prismatic aggregates, encircled by planar voids, produced by ice-lensing;

- curvilinear fabric, caused by frost sorting (PRDᵥ₃);

- fragmented clay and silt domains, and fractured grains, as a consequence of cryoturbation, translocated down profile within the sediment during thaw cycles;

- silt and clay caps, formed during freeze-thaw cycles.

In summary, sampling and analysis at macro- and micro-scales provides a unique insight into the internal structures of suspected relict perennial frost mounds in Norfolk (PRDᵥ₃) and Wales (PRDᵥᵥᵥ,ᵥᵥᵥ, andᵥᵥᵥ). Results confirm: i) a periglacial environment conducive to the development of perennial frost mounds on Walton Common and in the Cledlyn Valley, ii) the presence of microstructures that exhibit a strain history in support of deformation caused by periglacial (Norfolk and Wales) and both periglacial and glacial processes (Wales only), and iii) sufficient commonality with microstructures identified with a known relict lithalsa (PRDₖ), as well as appropriate lithological and hydrogeological environments, to permit a lithalsa origin for PRDᵥ₃ as well as a lithalsa origin for some of the Cledlyn Valley PRDs whilst not precluding a polygenetic origin in the case of PRDᵥᵥᵥ. 
7.3 Significance of other factors

i. Grain size

It is known that grain size can affect the frequency, type and distribution of micromorphological features within a sediment (van der Meer et al., 2003; Hart et al., 2004; Linch and van der Meer, 2014; Linch and Dowdeswell, 2015). Each field site was, therefore, selected from different sedimentary environments to consider the potential range of microstructures that could be present. A range in microstructures could reflect a change or variation in stress applied (Linch and van der Meer, 2014), but can also be explained by differences in sediment grain size and sorting and their influence on the strain response of sediment (Boulton and Hindmarsh, 1987; van der Meer et al., 2003; Benn and Evans, 1998).

For example, a minimum clay content is required for plasmic fabric to be apparent since pure sand will never show a plasmic fabric (van der Meer et al., 2003). Dalrymple and Jim (1984) observe that most plasmic fabric change occurs at medium clay content, and that at low and high contents skeleton grains and clay particles dominate respectively, thus allowing for a narrower range of matrix deformation in these zones. This would explain the paucity of plasmic fabric at the Walton Common field site, which is comprised of sand-rich sediment, as well as the absence of other structures (e.g. fragmented clay aggregates). In addition, plasmic fabric may be obscured in thin section by other substances (e.g. iron and/or manganese staining and the presence of carbonates will obscure birefringence (van der Meer et al., 2003)). However, plasmic fabric is not the sole indicator of deformation (e.g. rotational structures are associated with plasmic fabric in particular) and the presence of grain turbates but not plasmic fabric, in a clay-poor sediment, could still indicate that rotation has occurred. In the Welsh field site, grain turbates and plasmic fabric are more abundant and better developed within PRD$_{CV3}$ than in any other PRD at the other field sites in Belgium and Norfolk. Whilst it is possible that these structures are caused by shear stresses during frost-mound and/or rampart development) (Boulton and Hindmarsh, 1987; van der Meer et al., 2003; Benn and Evans, 1998), the location of the Welsh field site within the glacial limits at the Late Glacial Maximum (LGM) (~ 23–19 ka) may also be relevant. It is possible that the deformation expressed through grain turbates and plasmic fabric development has a subglacial origin (e.g. linked to stresses applied by an overriding ice sheet prior to frost-mound formation) (van der Meer et al., 2003). Other processes linked to particular sedimentary environments within field sites include colluviation in loess deposits in PRD$_{R}$ in Belgium (Mücher et al., 2010).

As the results of this research indicate a likely frost-mound origin for all landforms investigated, it is clear that different sediment types deform to produce different
microstructures. For example, curvilinearizations of matrix (indicative of frost creep) are only evident in fine-grained, clayey-silt sediment fractions, and void spaces are much less abundant in compacted till. However, microstructures indicative of cryoturbation occurring at all three field sites include:

- A vertical to sub-vertical microfabric (e.g. frost-jacked grains),
- Platy-prismatic, sub-angular aggregates,
- Planar deformation (e.g. fragmented domains, frost-cracked grains)
- Pore-water movement on thawing and translocation (e.g. silt and clay cappings).

Microstructures indicative of frost-mound formation and or decay processes that occur across all three field sites include crude layers at the top and base of the rampart, indicated by a lithological contact of tilted sediment, which is often emphasised by similarly inclined grains and void spaces and weak grain turbates. At field sites where clay content is sufficiently high, skelsepic fabric is also apparent. In field sites where well-sorted grains > 2000 µm occur, lineations are more apparent. However, it should be noted that single structures (e.g. silt/clay coatings) are not by themselves a diagnostic indicator of cryoturbation, as this microstructure can also occur as a consequence of, for example, mass-wasting. Again, it is the combination of well-developed, repeated suites of deformation structures, contextualised by macro-scale features that make deductions about genetic processes leading to their formation.

ii. Palaeo-periglacial setting

Each field site was selected from different palaeo-periglacial environmental contexts, to consider the impact of landform location within, and outside, the glacial limit on formation and/or decay mechanisms. The field site at Konnerzvenn, in Belgium, is an unglaciated locality (Litt et al., 2008; Hughes et al., 2016). At Walton Common, in Norfolk, the field site was glaciated during the Anglian Stage (c. 480–428 ka) only (West and Whiteman, 1986; Clark et al., 2012). The Cledlyn Valley field site, south west Wales, is in an area where the limit of the ice sheets is contested (Watson, 1972; Ballantyne, 2010; Patton et al., 2013). The locality has been subject to repeated glacial advances during the Quaternary period (Etienne et al., 2005) and is within the proposed limit of the Late Devensian ice sheet (Campbell and Bowen, 1989). It is apparent from the research findings that periglacial and frost-mound microstructures within the Welsh field site are the most difficult to isolate. The lower abundance of platy aggregates and silt cappings, diagnostic of periglacialization, attest to this. Whilst probable overprinting by subglacial processes (prior to frost-mound formation) has made identification of microstructures attributable to PRD processes
challenging, a suite of structures similar to those identified in a known relict lithalsa exist in the suspected PRDs in Wales (e.g. tilted strata, rotation structures, shear structures and sediment mixing structures. Therefore, it is possible, even when a glacial imprint exists within sediment, to identify a palaeo-periglacial environment and macro- and micro-scale structures attributed to frost-mound formation.

7.4 Summary of characteristics identified as diagnostic of a PRD

Macro-scale features and processes common to all field sites and identified as diagnostic of a PRD (based on three field site investigations), linked to micro-scale structures (Fig. 7.1, Table 7.2), include:

1. A rampart of crude and tilted layers at the top (formed by mass-wasting) and at the base (due to frost heave) exemplified by sub-vertically inclined aggregates and silt and clay coatings occurring on the underside of grains.
2. Micro-scale products of freeze-thaw processes throughout the rampart occurring as platy aggregates (becoming more prismatic with depth and in peat-rich material), undulating and preferentially sorted microfabric (due to frost creep), frost-jacked grains, silt and clay caps, and translocated clay and silt fragments.
3. In the middle of the rampart towards the basin, more fragmented domains may be evident, illustrating a high brittle strain environment.
4. Force exerted on the lower rampart unit during heave and mound collapse is illustrated by significant sediment in-mixing near the base.

This summary also illustrates the variation in microstructures with depth, linked to macro-scale processes.

Features less well developed in PRD_K, but that occur within ramparts at all field sites, include grain turbates. Features that are only well developed at one field site include:

i. PRD_K: Grain concentrations, curvilineations, lineations/linear grain domains, fragmented domains, Intraclast (type I) – probably the consequence of grain size;
ii. PRD_WC: Channels and chambers – a function of Holocene soil development within Pleistocene sediment;
iii. PRD_cv: Grain turbates and unistrial plasmic fabric – possibly the imprint of subglacial deformation.
Fig. 7.1  Macro-scale PRD processes linked to well-developed diagnostic microstructures within a known relict lithalsa in a clayey silt substrate in Konnerzvenn, Belgium (PRD$_6$).
Table 7.2 Macro-scale sedimentological characteristics identified as part of frost-mound formation and decay processes compared to diagnostic microstructures identified within (PRD$_k$).

<table>
<thead>
<tr>
<th>Process</th>
<th>Key macroscopic characteristics</th>
<th>Key microscopic characteristics</th>
<th>Present</th>
<th>Rampart unit location within PRD$_k$ for well-developed microstructures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formation: Damp ground surface freezes downwards, followed by seasonal thaw</td>
<td>• Active-layer cover • Aggradational ice • Vein ice • Segregation ice (Allard et al., 1996)</td>
<td>1. Vein ice-lens traces (<em>i.e.</em> lattice-like veins enircling)</td>
<td></td>
<td>2. Upper, middle (central), middle (basinward) and basinward</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Segregation ice-lens traces (<em>i.e.</em> platy-prismatic aggregates)</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Sub-vertical to vertical micro-fabric (<em>i.e.</em> frost-jacked grains)</td>
<td>✓</td>
<td>3. Upper, middle (central), middle (basinward) and basinward</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. Fragmented clay coatings</td>
<td>✓</td>
<td>4. Upper, middle (central) &amp; lower</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5. Silt and clay coatings of grains and/or voids</td>
<td></td>
<td>5. All</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6. Frost-cracked grains</td>
<td>✓</td>
<td>6. Middle (basinward)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7. Banded fabric (<em>e.g.</em> frost creep and colluviation)</td>
<td>✓</td>
<td>7. Upper</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8. Grain concentrations (<em>i.e.</em> frost sorting of matrix)</td>
<td>✓</td>
<td>8. Upper, middle (central), middle (basinward)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9. Vesicles and or mammillated vughs</td>
<td>✓</td>
<td>9. All</td>
</tr>
<tr>
<td>Ground heaves</td>
<td>• Vertically uplifted sediment (<em>i.e.</em> tilted) and inclined grains (Pissart et al., 2011)</td>
<td>1. Poorly stratified, tilted deposits with an upslope inclination of elongate grains</td>
<td>✓</td>
<td>2. Lower</td>
</tr>
<tr>
<td>Successive ground heave and mass-movement</td>
<td>• Radial dilation cracks on the surface of the mound • Laterally displaced sediment (<em>e.g.</em> redistributed sediment from the mound top to the periphery) (Seppälä, 1988)</td>
<td>1. Poorly stratified, tilted deposits with grains and aggregates parallel to the flow of mass-wasted sediment</td>
<td>✓</td>
<td>1. Upper</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Rotation structures (<em>e.g.</em> grain curvilineations) and skelsepic plasmic fabric around grains</td>
<td>✓</td>
<td>3. Upper, middle (basinward), basinward and lower</td>
</tr>
<tr>
<td>Mound decay</td>
<td>• Rampart encircling a basin (Seppälä, 1988)</td>
<td>1. Planar/brittle strain structures (<em>e.g.</em> brecciated domains)</td>
<td>✓</td>
<td>1. Upper, middle (basinward) and lower</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Fluidisation and remobilisation of sediment</td>
<td>✓</td>
<td>2. Middle (basinward) and lower</td>
</tr>
</tbody>
</table>
7.5 Wider significance

For the first time, this research presents an association of macro- and micro-scale features and structures for the identification of PRDs. This investigation identifies mechanisms associated with formation and decay of frost mounds through an analysis of the internal structures of a relict lithalsa. Results are presented in the form of a schematic showing lateral and vertical variation in structures identified, as well as a table which links structures to frost-mound formation and decay processes (Fig. 7.1, Table 7.2). The findings have been tested by investigating sites containing suspected PRDs, in Norfolk (Walton Common) and Wales (Cledlyn Valley) and comparing those results to the macro- and micro-scale features identified for the relict lithalsa in Belgium (Konnerzvenn). There are several implications to the outcomes of this research.

First, by providing a key to understanding PRD development, this research contributes towards a greater understanding of their genesis and collapse.

Second, this research provides a transferrable methodology that for investigating different frost-mound types in the future and examining whether the different types represent different stages of formation (Worsley et al., 1995), potentially caused by changing environmental conditions (van-Vliet-Lanoë, 2017).

Finally, the requirement for periglacial conditions, for the development of perennial frost mounds, means that the conclusive identification of PRDs in a landscape can assist with reconstructing past permafrost extent (Vandenberghe et al., 2014) and so palaeoenvironmental dynamics, on a global and potentially extra-terrestrial scale (e.g. Burr et al., 2009; Dundas and McEwan, 2010; Soare et al., 2014).
Chapter 8: Conclusion

8.1 Overall conclusions

The following conclusions fulfil the main aim of this thesis, which is to characterise periglacial ramparted depression (PRDs) through a macroscopic and microscopic analysis of their internal structures, contextualised by their topographic, hydrological and sedimentological settings.

Research question 1 asked:

"Is it possible to identify the cryogenic origins of PRDs by characterising internal microstructural features and relating these to macroscale observations?"

Aside from the PRD itself, evidence of cryoturbation was not observed within PRD ramparts at the macro-scale. However, a number of micro-scale features were identified at each field site that indicated frost processes:

- Structures attributed to freeze-thaw processes in all field sites examined include: i) a vertical to sub-vertical microfabric (i.e. frost-jacked grains), ii) platy aggregates, and iii) clay and/or silt grain coatings and/or void coatings.
- Structures attributed to freeze-thaw processes only observed at the type site of an accepted relict lithalsa, in an unglaciated clayey-silt environment, include: i) frost-sorting of fine-grains to produce concentrations of matrix, ii) curvilineations of matrix (i.e. banded plasmic fabric) due to frost creep, and iii) vesicles expelled from frost-affected sediment during freeze-thaw.
- Structures that are well-developed in PRD_k and one other field site (i.e. PRD_{CV}), include: brecciated domains of clay and silt. Fragmented domains have associations with both cryogenic processes and rampart formation during frost-mound decay.

Research question 2 asked:

"Is it possible to associate internal microstructural features with frost-mound formation and/or decay processes?"

A number of features were identified that indicated frost-mound formation and/or decay processes. These are summarised below:

- Structures attributed to PRD formation and decay processes include: i) crude stratification and tilted layers emphasised by similarly inclined elongate grains
and/or voids. These structures occur in the lower and upper rampart units in PRDs at all three field sites, indicating frost-mound heave and displacement, and rampart formation processes due to mass-wasting respectively; ii) coatings of silt around grains that are produced under periglacial conditions and associated with mass-wasting during mound formation and rampart development in rampart upper and middle units; and iii) soft-sediment deformation structures in PRD$_k$ and PRD$_{SCV_s, CV_2}$. This occurs as multiple, remobilised and in-mixed domains of clay and silt in lower rampart units. Soft-sediment deformation, in an unglaciated site, is interpreted as re-homogenisation of sediment due to frost-mound collapse and subsequent rampart development, possibly caused by debris flows. In a site that has been subject to glacial overriding (i.e. the Cledlyn Valley, Wales), subglacial deformation is another potential cause of sediment remobilisation.

- Well-developed planar structures attributed to PRD formation processes, but only observed in an accepted relict lithalsa in an unglaciated clayey-silt environment (i.e. Belgium), include grain lineations and linear grain domains, possibly a response to shear stress during rampart formation processes.
- Microstructures that occur weak to moderately developed in PRD$_k$ and PRD$_{WC}$, but are more developed within the Welsh PRDs, include rotation structures (e.g. grain turbates), which occur in rampart upper units. Grain turbates are associated with skelsepic plasmic fabric and can be linked to frost-mound development and rampart formation processes (e.g. solifluction).

Research question 3 asked:

“What are the differences and similarities in different environmental settings between macro-scale features and microstructures in PRDs (e.g. grain size), and what does that tell us about formation processes?”

- All three field sites are subject to hydrological recharge and contain landforms with ramparts, sometimes overlapping, surrounding depressions comprising multiple sedimentary units. For the identification of relict lithalsas, a fine-grained sediment substrate is required for cryosuction to occur and segregation ice to develop (Dash et al., 2006; Rempel, 2010) – a key component of lithalsa development (Mackay, 1978). However, the overburden of the frost mound may be coarser-grained, depending on subsequent changes to the depositional environment prior to periglaciation. Lithalsas also tend to have relatively shallow basins (< 3 m).
At the micro-scale, evidence of cryoturbation caused by ice segregation, includes platy aggregates, fragmented and translocated clay/silt domains and silt coatings of grains, which occur within fine-grained/frost-susceptible sediment units. Evidence of PRD formation mechanisms at all field sites, and so all grain sizes (i.e. fine-grained (clayey-silt) to coarse-grained (diamicton)), include crude stratification (indicative of frost-mound heave at the rampart base and solifluction in the rampart upper unit), and coatings of silt around grains in the rampart upper unit (due to rotation during mass-wasting).

In equigranular, sand-rich deposits, it is very challenging to unequivocally identify grain structures (e.g. curvilinear arrangements of grains) due to the abundance of similar sized and shaped grains. Similarly, it is difficult to detect frost sorting of grains in homogenous sediments. Plasmic fabric is also obscured in carbonate rich and clay-poor sediments. There are no microstructures attributed to PRD formation processes only observed in a chalky-sandy sediment (PRD<sub>WC</sub>, Norfolk).

Research question 4 asked:
“By focussing on cryogenic origins and formation processes, is it possible to identify characteristics of specific PRDs (e.g. pingo, lithalsa), and establish the potential for relationships between them?”

As the PRD at the field site in Konnerzvenn (Belgium) is widely accepted as a relict lithalsa, the characterisation of its internal structures identifies cryogenic features and microstructures features associated with frost-mound formation and decay. By comparing the macro-scale characteristics and microstructures of PRD<sub>K</sub> to suspected PRDs in Norfolk (PRD<sub>WC</sub>) and Wales (PRD<sub>CV1, CV2, CV3</sub>), there is sufficient commonality to suggest that the suspected PRDs are also relict frost mounds, probably relict lithalsas. However, within the Cledlyn Valley PRDs, there are factors which suggest that PRD<sub>CV1</sub> could be of polygenetic origin. These differences include a depression much deeper than that expected to develop from segregation ice alone and the potential for the PRD substrate to be either a fine-grained glaciolacustrine deposit or coarse-grained glacial till). Until other relict frost-mound types have been similarly characterised it is not yet possible to categorically identify microstructures indicative of other frost-mound types and so confirm, for example, whether lithalsas represent a continuum between palsas and pingos (Worsley <i>et al.</i>, 1995; Gurney, 2001).
8.2 Future research

As a consequence of the results produced by this investigation, a number of areas present themselves as appropriate lines of future inquiry to develop this newly-developed data set further. The investigations outlined below would contribute to: i) a more comprehensive set of micro-scale diagnostic criteria for the identification of specific relict frost-mound types and ii) a better understanding of any differences in genesis and/or formation mechanisms:

- Microscopic examination of currently forming and decaying lithalsas would enable a comparison to be made with the relict structures found in PRDs examined in this research. Examining currently developing, as well as decaying, landforms will provide a comprehensive overview of diagnostic microstructures for lithalsa frost-mound types.

- Microscopic examination of other relict perennial frost-mound types (i.e. pingos (hydraulic and hydrostatic) and palsas) and comparison of deformation structures to those identified in this research, will enable a higher degree of discrimination between different relict frost-mound types, and permit investigation into the possibility of a continuum between forms, with palsas and pingos as end members.

- Microscopic examination of a glacial landform with superficially similar morphology (e.g. rimmed kettle hole) and comparison of the deformation structures to those found in this investigation, will identify the distinction to be made between glacial and periglacial structures. This will be particularly useful in interpreting depositional environments that have been subject to both glacial and periglacial processes.

- Finally, the findings of this research could be applied to the identification of relict frost mounds where the ramparts are no longer present. For example, currently labelled drift-filled, or buried, hollows (DFH) are unexpected depressions in-filled with Quaternary deposits, found in the rock head. DFH are reported from many modern engineering works in London (e.g. the Cross Rail Project (Lenham et al., 2006; Paul, 2009) and the Olympic Park Development (Lee and Aldiss, 2011)) and are potentially a type of relict pingo (Banks et al., 2015). These irregular funnel-shaped features are oval in plan view, are usually steep-sided (> 20° slopes) and up to 500 m wide, extending up to 60 m deep into the bedrock (Banks et al., 2015). DFHs are difficult to detect, particularly in modern urban environments where they have been subsequently buried. Ground investigations may not confirm their presence sub-
surface as the area they cover may not be laterally extensive. Once these infilled depressions are uncovered, their accurate identification is further complicated by the absence of distinctive ramparts. The production of diagnostic criteria for PRDs, demonstrating both vertical and lateral variation, could be used to identify landforms whose ramparts have been eroded or removed. Accurate identification of DFHs would facilitate the development of mitigation strategies for this engineering hazard by clarifying the likely sedimentological and hydrogeological conditions in which PRDs formed (e.g. enabling a better understanding of how PRD development has impacted on the geotechnical properties of sediment and contributing towards the development of a hazard susceptibility map for PRDs (Banks et al., 2015).

Alternative analytical techniques could also be explored for microscopic investigation. For example, 3D μCT tomography (Tarplee et al., 2011), could be used to create 3D models of soft-sediment for the analysis of internal structures and composition. Results could be compared to those examined from micromorphology to assess the precision of μCT tomography across a range of grain sizes (Tarplee et al., 2011, Bendle et al., 2015) and, if successful, validate a less destructive method for future research in this area. In addition, new ‘microstructural mapping’ methods could be applied (i.e. a graphical method for analysing clast microfabrics (Phillips et al., 2011)), to examine potential polyphase deformation.
References


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Harris, C. (2002). Middle and late Quaternary permafrost and periglacial environments in the UK: A review of geological evidence. Cardiff University report to United Kingdom NIREX Ltd.


APPENDICES
Appendix 3.1: Glossary of micromorphological terms
(after: Lachniet et al., 1999; van der Meer, 1993; 1997; Menzies, 1998; 2000; Linch, 2010; van der Meer et al., 2010)

**Asymmetric Pressure Shadow** dark shadow of material on one side of a clast typically tapers with distance from the clast; usually represents an accumulation of fine-grained material (e.g. clay/silt)

**Augen-shapes** any feature that demonstrates a flattened diamond-shape with tapered ends (note, a structure may only demonstrate an augen-shape at one end)

**Birefringence** optical property, used to visualise interference colours (anisotropy) by turning the stage of the microscope; caused by double refraction of light under crossed-polarisers and consequent polarising of the bundles of light

**Boudinage** structure appears pinched along its length; sometimes more than once

**Curvilinear arrangement of grains** arcuate linear grain arrangements that form arc shapes within the sediment

**Curvilinear arrangement of matrix** arcuate linear grain arrangements occur within silt and clay and appear to undulate (they are often accompanied by wavy fissures)

**Cutan** accumulation of material on or against structural elements, walls of pores, etc. in soils or sediments; can be the result of illuviation or crystallisation

**Diamicton** a generic term referring to any non-sorted or poorly-sorted, heterogeneous sediments containing a wide range of particle sizes in a muddy matrix and used when the genetic history of the sediment cannot be ascertained

**Fissility** where material splits easily into thin layers along closely spaced, roughly planar and approximately parallel surfaces

**Flow or Fluid injection** where silt-rich water is injected into fractures, planes of weakness, or pores within the sediment, resulting in a concentration of fines

**Galaxy Tail** elongate grains arranged in a spiral

**Grain Lineations** elongate grains aligned with long axes head-to-tail to form a line without grain-to-grain contacts

**Grain stacks/Bridges** grains are stacked and touching with grain-to-grain contacts

**Clast haloes** skeleton grain/clast is encompassed (fully or partially) by a halo of fine-grained material

**Inclusions** usually irregularly-shaped areas of either sand or silt or clay; relatively smaller in size than multiple domains

**Intraclast Type I** reworked areas of sediment usually not dissimilar to the surrounding matrix delineated by voids; no internal plasmic fabric as pebbles are considered to move as a whole without the internal reorientation of fines

**Intraclast Type II** are similar to intraclasts type I except they demonstrate distinct internal plasmic fabric
**Intraclast Type III** torn-up and reworked fragments of unconsolidated sediment (often ‘foreign’ material) and/or localised reworking of *in situ* material

**Linear grain domains** arrangements of grains whose apparent long axes may not share a preferred alignment but are grouped in a lens

**Marble-bed Structures** arrangement of pebbles (intraclast type I) which are rounded to ellipsoidal in shape, delineated by encircling voids

**Matrix** see plasma

**Multiple Domain** usually large, irregularly-shaped areas of sandy, silty or clayey material that can appear incorporated into each other

**Normal Fault** in laminated sediment where the hanging wall block moves up with respect to the footwall

**Plasma** originally particles of colloidal size (< 2 µm); may consist of clay minerals, oxides, hydroxides of Fe, Al and Mn, soluble salts, etc., in micromorphology it is often used as synonymous with matrix which is all material smaller than the thickness of the thin section and in which, consequently, individual particles can no longer be seen

**Plasmic Fabric** birefringence models of the plasma, based on the optical properties of the particles as well as the optical properties caused by the orientation of particles relative to each other

*bedding parallel* either long, thin, horizontal plasma domains or wide, horizontal beds of birefringence usually stacked in a regular pattern above each other

*(bi)masepic* short plasma domains are mainly oriented in bands in one (masepic) or two (bimasepic) directions

**kinking** orientation of domains is organised in alternating clear and dark parallel bands, caused by a fishbone arrangement of clay particles as a result of compression

**latticepic** plasma separations occur in two, very short, and discontinuous sets, usually oriented approximately at right angles to each other, now thought to be an artefact of the optical system of the microscope

**omnisepic** plasma fabric domains show a full spectrum of oriented directions, irrespective of turning the stage

**silasepic** oriented particles occur only in isolated spots; silt-sized material is dominant

**skelsepic** plasma particles are oriented around a skeleton grain

**unistrial** anisotropic clay with discrete, thin, continuous (*i.e.* long) birefringence bands in one direction

**vosepic plasma** particles are oriented along a fissure or around a void

**Reverse Fault** in laminated sediment where hanging block wall moves down with respect to the footwall block at angles of > 45°

**Section Elements** major and obvious structural characteristics of a thin section usually observable at the macro-scale
Scavenging Turbates one turbate structure is in contact with another and the finer grains of one structure may be captured by the other (see ‘turbates’)

Skeleton Grains single grains which are larger than the thickness of a thin section (> 25–30 µm) and thus can be studied individually

Sheath Fold concentric or oval-shape folded laminae in laminated sediment

Thrust Faults in laminated sediment where hanging block wall moves down with respect to the footwall block at angles of < 45°

Grain turbates typically comprise a central node (e.g. a core stone, around which elongate grains align themselves with their axes parallel to the central node). Note that these structures are not in any way related to iceberg turbates

Water Escape Structure (WES) usually fine-grained material that appears ‘washed’ through the sediment along a specific pathway or a pathway of blotchy or watery sediment or where grains appear reoriented in a preferred pattern by the movement of water through the sediment
Appendix 3.2: Techniques for estimating particle-size distribution (PSD)

i. Sieve shaking

For matrix-rich a minimum of ~ 100 g was collected and a minimum of ~ 1.5 kg where the sample was a heterogeneous mix of clast and matrix (Hubbard and Glasser, 2005; BSI, 2009a, McManus, 1988). Samples were selected on the basis of their representativeness of the lithological unit from which they came and proximity to the site for thin section sampling. Samples were stored in an airtight plastic bag, clearly labelled.

In the laboratory, predominantly clay sediment samples were set aside (and kept moist) for laser particle analysis. All other samples were dried in an oven at 105 °C for 24 hrs (or 60 °C for 36 hrs where organics were present) and when cooled disaggregated using a pestle and mortar; care being taken not too break down primary particles. Mechanical dry sieving was undertaken with reference to the British Standard: 11277 (2009) using a dry sieve shaker (Endecott 1M II). Note that the fraction < 63 µm was analysed using laser diffraction (see ii, below).

Each sieve sleeve was weighed (using Kern FCB 3KO.1 weighing scales which had first been levelled) and the dry sample weighed. Material > 32 mm (very coarse grave and cobbles) was removed by hand and measured. The remaining sediment was passed through the sieve stack comprising sleeves with the following aperture sizes:

- 16 mm (coarse gravel);
- 8 mm (medium gravel);
- 4 mm (fine gravel);
- 2.8 mm (very fine gravel);
- 2 mm (very fine gravel).

Care was taken to spread the sample evenly and not to overload the sieves (sieving in portions where necessary) (BSI, 1990b). Sieve sleeves were fitted tightly and a minimum shaking time of 10 minutes was observed and until all sediment had passed through.

The amount of sample retained on each sleeve was measured to the nearest 0.1 g and the weight of the sieve sleeve deducted to determine the amount passing through. Measurements were recorded in EXCEL and a cumulative frequency curve plotted to show the percentage sediment passing through.

ii. Laser diffraction analysis

For grain sizes ≤ 2 mm, laser diffraction was used to determine size distribution using a Malvern Mastersizer 2000, in accordance with British Standard 13320 (BSI, 2009b). The principle of the laser diffraction technique is that when passed through a laser beam, particles will scatter light with an intensity pattern dependent on particle size. Scattering angles are measured and then transformed mathematically, by software incorporated within
the PSD analyser, to give a volumetric particle size distribution (PSD) (BSI, 2009b). The technique assumes a spherical particle shape and scattering patterns and volumetric measures are predicted on this basis. In order to increase the accuracy of measurements, the Malvern Mastersizer 2000 takes two set of wavelength measurements: scattering angle and angular intensity to improve the accuracy of particle size measurements (Malvern, 2005).

Dried samples were disaggregated using a pestle and mortar and a representative sub sample identified. To ensure accuracy, it is essential that particles do not agglomerate and misrepresent the actual particle size. To prevent this a dispersant of Calgon was mixed with ~2 g of the representative sample, a pipette-full at a time, until a mixture was formed in which the grains were freely moving. The mixture was then added to the Malvern Mastersizer 2000 water bath and the particle size analysed. The water bath was cleaned following each measurement.

According to the requirements for repeatability set down in the British Standard (BSI, 2009b) each test was conducted a minimum of three consecutive times from the same sample and dispersant material and the mean average of the results considered. Results, classified using the Wentworth scale, were combined with those for particles > 2 mm (Ref. 3.3.3 Grain size classification) and plotted as a cumulative percentage passing curve for the entire sample in EXCEL.
Appendix 3.3: XRD technique for identifying clay mineralogy

The clay fraction is separated from the sediment sample and mounted on a glass slide for XRD analysis. Samples may be glycolated where mixed layer clays are present, to identify the possible presence of smectite. Samples were processed using a PANalytical X'Pert-Pro MPD PW3040/60 XRD base system, which uses Nickel (Ni) filtered Cu-Kα radiation to determine the crystal structure of the samples (Panalytical, 2014). The accelerating beam current was set at 40 kV and 40 mA. Phase identification and quantification was conducted using the inbuilt software package X'Pert High Score Plus. This software compares diffraction line profiles (e.g. line position, intensity, area and shape to a reference database of the International Centre for Diffraction (ICDD) (Panalytical, 2014)). Once the software had identified strong mineral matches, a manual process was undertaken to match diffraction patterns with the database until all significant peaks were accounted for. Comparisons of three replicates from each sample were made using the X’Pert Data Viewer software. The identification of the clay minerals present was aided using United States Geological Survey (U.S.G.S.) clay mineral identification X-ray diffraction patterns (2015).
Appendix 3.4: Calcimeter technique for measuring carbonates

Carbonate composition was determined using the Scheibler method in accordance with the British Standard: BS EN ISO 10693 (BSI, 2014) using Eijkelkamp Agrisearch 0.853 calcimeter equipment (Eijkelkamp, 2012). The basic principal is that the addition of hydrochloric acid (HCl) to a sediment sample will decompose any carbonates. The volume present is then measured and compared to the volume of carbon dioxide produced by pure calcium carbonate. The sample size is determined by reacting a small amount (~ 2.5 g) with 1 ml of HCl 4 mol/L and observing the intensity and rate of the reaction. A calibration is then conducted whereby 0.2 and 0.4 g of CaCO₃ is reacted with 7 ml HCl (4 mol) and a constant derived for the volume of CaCO₃ (V₂). Three replicates of each sample is then reacted with 7 ml HCl (4 mol). The repeatability parameters for the determination of carbonate content across two separate measurements are given in (BSI, 2014).

The following equation was then used to calculate the carbonate content:

\[
\text{Calculation: } \%\text{CaCO}_3 = 100 \times \frac{M_2 \times V_1}{M_1 \times V_2}
\]

- \(M_1\) = Sample mass (g) (amount weighed in the conical flask)
- \(M_2\) = average mass of CaCO₃ used for calibration (0.3 g)
- \(V_1\) = Vol of CO₂ in sample (difference in water volume taken from the calcimeter)
- \(V_2\) = Volume from calibration (Usually around 53.5 g)

All determinations were made in the same sitting per site location preventing the need to make adjustments for differences in temperature and air pressure.