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Morphological analysis and evolution of buried tunnel valleys in northeast Alberta, Canada

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A B S T R A C T

Tunnel valleys are large elongated depressions eroded into unconsolidated sediments and bedrock. Tunnel valleys are believed to have been efficient drainage pathways for large volumes of subglacial meltwater, and reflect the interplay between groundwater flow and variations in the hydraulic conductivity of the substrate, and basal meltwater production and associated water pressure variations at the ice-bed interface. Tunnel valleys are therefore an important component of the subglacial hydrological system.

Three-dimensional modelling of geophysical and lithological data has revealed numerous buried valleys eroded into the bedrock unconformity in northeast Alberta, many of which are interpreted to be tunnel valleys. Due to the very high data density used in this modelling, the morphology, orientation and internal architecture of several of these tunnel valleys have been determined.

The northeast Alberta buried tunnel valleys are similar to the open tunnel valleys described along the former margins of the southern Laurentide Ice Sheet. They have high depth to width ratios, with undulating, low gradient longitudinal profiles. Many valleys start and end abruptly, and occur as solitary, straight to slightly sinuous incisions, or form widespread anastomosing networks. Typically, these valleys are between 0.5 and 3 km wide and 10 and 30 m deep, although the depth of incision along some thalwegs exceeds 100 m. Several valleys extend for up to 60 km, but most are between 10 and 30 km long.

Valley fills comprise a range of lithofacies, including stacked sequences of diamict, glaciofluvial sands and gravels and glaciolacustrine silts and clays. Displaced bedrock, presumably of glaciotectonic origin, also occurs within several anastomosing valleys. Several channel bodies are exposed along a number of valley sections suggesting progressive valley development through repeated cycles of sediment discharge. Cut-and-fill structures that are capped by fine-grained sequences of rippled sand and mud-rich drapes within these channel bodies suggest unstable flow regimes within the valley and the discharge of sediment-laden basal meltwater under flood-like conditions followed by wane flow events or periods of lower meltwater discharge, likely concomitant with localized modification by glacial ice. Basal meltwater is inferred to have been released as episodic jökulhlaups beneath the western Laurentide Ice Sheet, which at times re-used existing valley systems, which were spatially and temporally stable features, and at other times incised new valleys.

1. Introduction

A range of formerly glaciated landscapes, in both the mid- and high-latitudes, contain distinctive overdeepened valleys that typically exhibit undulating long profiles and trend oblique to the modern drainage (Visser, 1988; Ehlers and Linke, 1989; Eyles and McCabe, 1989; Moores, 1989; Wingfield, 1990; Sugden et al., 1991; Brennard and Shaw, 1994; Piotrowski, 1994; Clayton et al., 1999; Cutler et al., 2002; Russell et al., 2003; Glasser et al., 2004; Denton and Sugden, 2005; Fisher et al., 2005; Kozlowski et al., 2005; Hooke et al., 2006; Kehew et al., 2012; Van der Vegt et al., 2012). These valleys can be up to 100 km long, 4 km wide and 400 m deep, and occur as integrated, anastomosing networks, or relatively straight, isolated segments (Ó Cofaigh, 1996). Collectively referred to as tunnel valleys, they are inferred to be former drainage

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pathways for large volumes of subglacial meltwater (Piotrowski, 1997). Their formation reflects the interplay between groundwater flow and variations in the hydraulic conductivity of the substrate, as well as basal meltwater production and associated water pressure variations at the ice-bed interface (Alley, 1989; Boulton et al., 1995; Piotrowski, 1997). Tunnel valleys are therefore considered vital components of the subglacial hydrological system, which controls in part, ice sheet dynamics. Consequently, understanding the genesis of tunnel valleys is of crucial importance for the reconstruction and understanding of former ice sheets (Boulton et al., 1995; Piotrowski, 1997; Eyles, 2006; Jørgensen and Sandersen, 2006).

However, although there is a general consensus that tunnel valleys were eroded by large, channelized subglacial meltwater flows that were driven by the hydrostatic gradient of the overlying ice sheet, a number of issues remain (Ehlers and Linke, 1989; Ó Cofaigh, 1996; Huuse and Lykke-Andersen, 2000; Kehew et al., 2012). These include: (1) the mode of meltwater drainage, and whether entire tunnel valley systems formed synchronously, due to the catastrophic discharge of subglacial meltwater (Brennard and Shaw, 1994; Sharpe et al., 2004), or whether tunnel valleys are time-transgressive features, resulting from repeated, more continuous meltwater discharges (Praeg, 2003; Jørgensen and Sandersen, 2006; Lonergan et al., 2006; Kristensen et al., 2008); (2) the influence of direct glacial erosion on valley morphology (Niewiarowski, 1995; Jørgensen and Sandersen, 2006); and (3) the extent to which the substrate permeability and associated variations in groundwater flow influence tunnel valley evolution (Piotrowski, 1994, 1997; Van Dijke and Veldkamp, 1996; Janszen et al., 2012).

Continued research in subglacial processes and tunnel valley formation has benefited from an increase in the availability of subsurface geophysical data (Gabriel et al., 2003; Jørgensen et al., 2003; Sandersen and Jørgensen, 2003; Jørgensen and Sandersen, 2006; Janszen et al., 2012). These studies have highlighted the importance of identifying tunnel valleys buried within the subsurface, since the principal architectural elements of their fills reveal the nature of the flows that passed through them, providing further insights into their genesis (Cutler et al., 2002; Russell et al., 2003). Moreover, sediments associated with infilled tunnel valleys form aquifer systems which are becoming an increasingly important supply of potable groundwater to many cities in North America and Europe (Heinz et al., 2003; Sandersen and Jørgensen, 2003; Mehnert et al., 2004; MacCormack et al., 2005). When combined with increasingly sophisticated modelling and visualisation techniques, this research has enabled buried valleys, and their associated fills to be described in greater detail, leading to a better understanding of their evolution within the subglacial hydrological system (Boulton and Hindmarsh, 1987; Boulton et al., 1995, 2007a,b; Piotrowski, 1997; Piotrowski et al., 1999; Praeg, 2003; Jørgensen and Sandersen, 2006; Lonergan et al., 2006). However, despite the increased utilization of commercially available 2-D and 3-D seismic data, Kristensen et al. (2008) and Kehew et al. (2012) remarked that lithostratigraphic descriptions of the infill sequences of buried tunnel valleys remain relatively scarce. Such descriptions may augment seismic stratigraphic interpretations, and provide further insight into the geological characteristics of tunnel valleys and their modes of formation.

The province of Alberta has experienced rapid expansion of oil and gas exploration in recent years, resulting in a significant increase in the availability of subsurface geologic data. Andriashek and Atkinson (2007) utilized new geophysical and lithological data, and presented a three-dimensional model of the pre-Quaternary bedrock topography in northeast Alberta, focussing particular attention on buried tunnel valleys eroded into the Quaternary unconformity. In this paper, we describe the distribution, morphology and the internal architecture of these buried valleys, and discuss their evolution and possible implications for the subglacial hydrology of a previously uninvestigated region of the western Laurentide Ice Sheet.

2. Study area

2.1. Physiography

The study area occupies ~18 000 km^2 in the Northern Alberta Lowland region of the Interior Plains of Canada, north of the city of Fort McMurray (Fig. 1; Pettapiece, 1986). It is bounded by latitudes 56° 30′ and 57° 30′, and longitudes 110° and 112°. The region is characterized by flat to gently undulating terrain. The morphology of this terrain is largely due to the erosive effects of Paleogene fluvial systems and glaciation during the Quaternary. The major physiographic features include the broad Athabasca River Lowland (220 m above sea level (m asl)) in the central part of the study area, which is flanked by the Birch Mountains (860 m asl) to the northwest, and Muskeg Mountain (650 m asl) to the east (Figs. 1 and 2; Pettapiece, 1986). Less prominent features include the Fort Hills, and the locally high-relief of the Firebag Plains in the eastern edge of the study area, along the Alberta–Saskatchewan border (Fig. 2). Surface drainage radiates from these uplands and is captured by tributaries of the Athabasca and Clearwater rivers which incise the Athabasca River Lowland. The central part of the lowland is characterized by wetlands that are poorly connected to the surface drainage system.

2.2. Geology

The study area is located in the northeast part of the Western Canada Sedimentary Basin (WCSB; Mossop and Shetsen, 1994). The subsurface distribution of bedrock units in the study area is constrained by three major unconformities. These are the pre-Devonian unconformity on the surface of the Precambrian Shield, the sub-Cretaceous unconformity on the surface of Palaeozoic rock units, and the Quaternary unconformity on the surface of Cretaceous rocks, which constitutes the bedrock topography. The geological scope of this paper extends from the Quaternary unconformity, which represents the period of erosion from the Late Cretaceous–Paleogene, to the onset of Quaternary glaciation, and finally Holocene fluvial incision. Three major formations that subcrop on the Quaternary unconformity are described in this paper; the lowermost McMurray Formation, the Clearwater Formation, and the uppermost Grand Rapids Formation (Fig. 3).

The McMurray Formation is mainly comprised of fluvial and estuarine sands (Langenberg et al., 2002; Hein, 2006). In much of the study area, the lowermost sediments of the McMurray Formation are water-bearing. Elsewhere, these sediments are saturated with bitumen of moderate to high grade (Hein, 2006). The lower Clearwater Formation comprises shaley glauconitic sandstone which lies conformably on the McMurray Formation, and interfingers with the overlying clastic sedimentary sequence of the Grand Rapids Formation (Carrigy and Kramers, 1975; Kramers and Prost, 1986).

The study area occupies part of the Athabasca Oil Sands Area, which comprises a ~21.7 billion m^3 deposit of oil-rich bitumen (Fig. 1; Alberta Energy and Utilities Board, 2007). As a result of the rapid expansion of new and existing surface-mine and in-situ extraction operations, the Athabasca Oil Sands Area is now one of the most industrially active regions in North America. Borehole logging associated with regional-scale exploration operations has