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Subglacial to proglacial depositional environments in an Ordovician glacial tunnel valley, Alnif, Morocco

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ABSTRACT

This paper presents the sedimentary analysis of an exceptional Ordovician glacial tunnel valley in the eastern part of the Anti-Atlas. The valley infill comprises two major glacial erosion surfaces (striated pavements) each overlain by a fining-upward glacial unit. These units are composed of five distinct facies associations, recording the evolution from subglacial to proglacial environments, and an additional sixth facies association, overtopping the tunnel valley infill, and associated with post-glacial environments. The tunnel valley infill also records a transitional environment between the subglacial and proglacial settings, which is compared with the Antarctic ice-sheet margin. These three environments are defined by the position of the grounding line and the coupling line. The new proposed depositional model also differs from usual Ordovician depositional models in which the main tunnel valley infill is interpreted as essentially proglacial outwash deposits, in a range of glaciomarine to glaciofluvial environments. Overall, a substantial part of the valley infill (~50% of volume) was deposited in a subglacial setting. The sedimentary bodies could form potentially thick and laterally extended, although these were limited by the shape and extent of the subglacial accommodation space. Finally, the sedimentary record, when compared with regional analogues, also provides information for the palaeogeographic reconstruction of the Ordovician ice-sheet in this region.

1. Introduction

The exceptional outcrop quality of the Upper Ordovician succession from the Western Sahara to the Arabian Peninsula has revealed widespread evidence of glacial sedimentation (Beuf et al., 1971; Deynoux, 1980; Hambrey, 1985; McDougall and Martin, 2000; Hirst et al., 2002; Ghienne, 2003; Le Heron et al., 2004; Denis et al., 2007). Based on that evidence, the Ordovician Maximum Extent of glaciation (OME) has been well mapped (Fig. 1A). A Hirnantian ice sheet covered most of Western Gondwana. It experienced ice front oscillations that can be grouped into two major ice sheet advances separated by a major ice sheet recessions (McDougall and Martin, 2000; Sutcliffe et al., 2000; Ghienne et al., 2003; Denis et al., 2007). Previously, evidence for Upper Ordovician glacial deposits has already been presented in the Central Anti-Atlas (Destombes, 1968; Hamoumi, 1999; Sutcliffe et al., 2001; Le Heron, 2007; Loi et al., 2010). It has been suggested that an ice-stream system flowed north-westwards in the vicinity of the study area (Fig. 1B; Le Heron et al., 2007).

Glacigenic successions of Upper Ordovician age have thus been well studied by the academic community and the oil industry (Sutcliffe et al., 2000; Ghienne, 2003; Eschard et al., 2005; Le Heron et al., 2006; Page et al., 2007; Tournier et al., 2010). In addition to the outcrop belt, the deposits continue into the subsurface of the Saharan Platform where subcrops occur in a number of intracratonic basins (Le Heron and Craig, 2008). Within the Ordovician sedimentary succession, although the deposits are heterogeneous, the tunnel valley fill is sandstone-dominated. These deposits potentially form substantial hydrocarbon reservoirs, where they are potentially overlain by the Silurian shales, which are hydrocarbon source rocks and seals (Davidson et al., 2000; Lüning et al., 2000). The growing economic interest in tunnel valleys has prompted a number of studies documenting their morphology and the nature of their infill, based mainly on Quaternary analogues. Likewise, subsurface data in North Africa reveals thick anastomosing channel networks (Le Heron and Craig, 2008) comparable to palaeovalley complexes preserved at outcrop (Beuf et al., 1971; Vaslet, 1990; Ghienne et al., 2003; Le Heron et al., 2004).

The aim of this study is to present new data based on investigations of an exceptional Ordovician glacial tunnel valley record in the eastern part of the Anti-Atlas. The architecture and the sedimentological and deformational features of the glacial infill are described and interpreted

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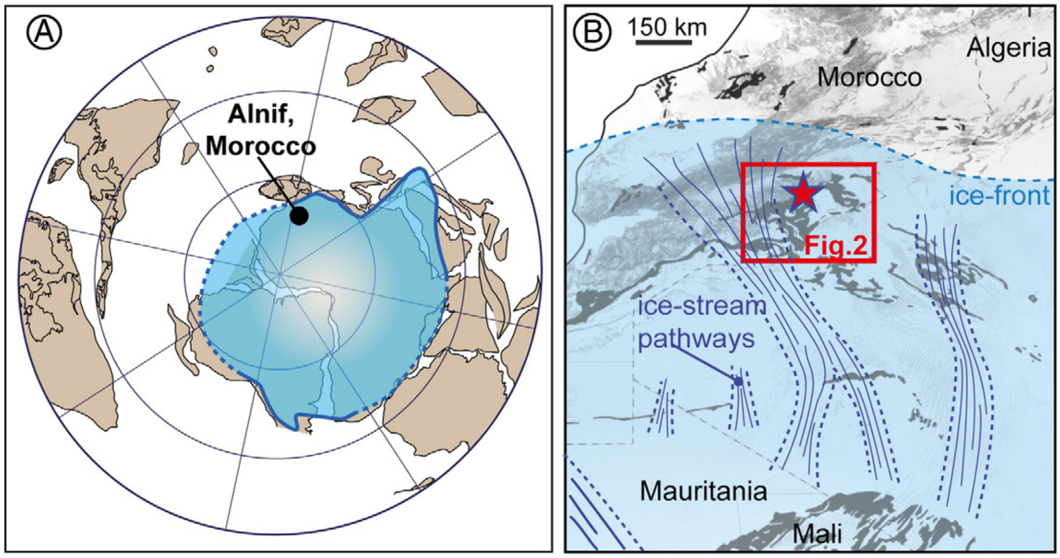

Fig. 1. A) Palaeogeographic reconstruction for the latest Ordovician (~440 Ma) adapted from Cocks and Torsvik (2002). The extent of the Hirnantian ice-sheet is modified from Ghienne et al. (2007). Main line refers to well constrained ice-sheet limits whereas dash line refers to more controversial ice-sheet limits. B) Detailed palaeogeographic reconstruction of the ice sheet over Morocco with the location of the study area (red asterisk), the reconstructed ice-sheet extent and the position of the reconstructed palaeo ice-streams (Ghienne et al., 2007; Le Heron et al., 2007).

to build a new depositional model based on recent developments in glaciology, including new observations and concepts developed from the Antarctic ice-sheet. The depositional model of the Alnif tunnel valley infill is compared with other tunnel valley infill and placed within the chronological framework of the Hirnantian glaciation in this part of Morocco in order to address implications for palaeographic reconstructions for ice-sheets.

2. Geological background

2.1. Structural situation

The Anti-Atlas belt is a large antiform structure (Fig. 2) striking NE–SW formed by the Late Carboniferous–Permian compression event. It exposes Palaeozoic rocks as well as older basement lithologies (Piqué, 2001). The Panafrican suture (referred to as the Major Anti-Atlas Suture or Anti-Atlas Major Fault) resulted from the collision between the West African Craton and the Reguibat Shield during the Panafrican compressive phase (Black and Fabre, 1980; Ennih and Liégeois, 2001; Coward and Ries, 2003). Other structural trends include N–S to NW–SE striking faults in the vicinity of the Ougarta Range, progressively deflected towards an E–W direction in the Moroccan Anti-Atlas region. These oblique trends reflect the accretion of terranes on both the northern and western sides of the craton (Burkhard et al., 2006). Following the Panafrican compression, the Early Palaeozoic was characterised by relative tectonic stability, although evidence of limited extensional tectonic activity continuing into the earliest Cambrian is reported (Burkhard et al., 2006). From the Late Cambrian to the Ordovician, an extensional tectonic regime led to the development of NE–SW to E–W-oriented graben and half-graben structures (Zagora graben) related to the reactivation of Panafrican structures (Robert-Charrue and Burkhard, 2008). The Caledonian compressive phase, at the transition from Silurian to Early Devonian, led to the complete differentiation of large basins. By the end of the Early Palaeozoic, the Hercynian compression phase, oriented SSE–NNW, led to the folding, uplift and subsequent partial erosion of the Palaeozoic cover. The Anti-Atlas Palaeozoic cover is unconformably overlain by Mesozoic and Cenozoic series, forming gently dipping plateaus called 'Hamadas' (i.e. Tindouf, Draoura and Guir). The present-day elevated topography of the Anti-Atlas range is the consequence of both the Variscan orogeny and Late Eocene to Miocene–Early Pliocene uplift, corresponding to a structural inversion (Frizon de Lamotte et al., 2000; Ellouz et al., 2003). Atlasic compression is mostly constrained in the High-Atlas, Rift and Meseta regions, north of the South Atlas Fault, suggesting that the Anti-Atlas structure is mostly inherited from the Hercynian tectonic phase, although the recent Atlasic compression led to significant uplift of the Palaeozoic series (Piqué, 2001).

2.2. Regional stratigraphy of preglacial and glacial deposits

In the Central Anti-Atlas, Ordovician lithostratigraphic and biostratigraphic frameworks were defined by Destombes (1968) and Destombes et al. (1985). In the present paper, the initial stratigraphic nomenclature is modified following international stratigraphic code (Fig. 3). Three lithostratigraphic groups are defined: the lower Bani Group, a sandstone-dominated succession; the Ktaoua Group, a shale-dominated succession, and finally the upper Bani Group, which corresponds to a second sandstone-dominated succession. The upper Bani Group is described in the Djebel Foum Larjamme (Destombes et al., 1985; Le Heron, 2007). In this area, the Upper Ordovician deposits start with the preglacial argillaceous Ktaoua Group at the base. This is overlain by the lower formation of the upper Bani Group, which is characterised by bioturbated sandstones. The sedimentary record ends with glacigenic rocks, which are defined as the upper formation of the upper Bani Group, deposited above an unconformity cutting into the lower formation of the upper Bani Group. According to Le Heron (2007), this unconformity defines a series of tunnel valleys (0.5 km to 1 km wide, up to 100 m deep) that were cut into the preglacial formations by high hydrostatic pressure beneath the ice sheet and filled with glacigenic sediments deposited in a shallow marine or continental environment.

Recently, a high-frequency eustatic signal has been proposed for the Upper Ordovician, based on new high-resolution data from stratigraphic sequence analysis of the Bou Ingarf section (Loi et al., 2010). Although no glacial sediments are preserved and possibly none were deposited here before the Hirnantian, the three major (>40 m) forced regressions identified at the base of this section probably record an increase in ice-sheet volume during the Katian. The end-Ordovician glaciation is characterised by two distinct regressive/transgressive or glacial/interglacial phases. The first phase reflects changes from a restricted marine to a shoreface environment, with no evidence of glacial deposits. The second phase starts with an abrupt erosion surface and includes a system of