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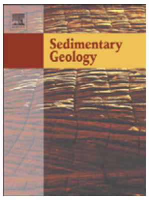

Giant submarine landslide grooves in the Neoproterozoic/Lower Cambrian Phe Formation, northwest Himalaya: Mechanisms of formation and palaeogeographic implications

E. Draganits [a,*], J. Schlaf [b], B. Grasemann [c], T. Argles [d]

[a] *Institute for Engineering Geology, Vienna University of Technology, Karlsplatz 13/203, A-1040 Vienna, Austria*
[b] *Conoco Phillips Petroleum UK Ltd, Exploration and Production, Rubislaw House, Anderson Drive, Aberdeen AB15 6FZ, UK*
[c] *Department of Geodynamics and Sedimentology, University of Vienna, Althanstrasse 14, A-1090 Vienna, Austria*
[d] *Department of Earth Sciences, The Open University, Milton Keynes MK7 6AA, UK*

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ABSTRACT

Giant groove casts have been found in the upper Proterozoic to Lower Cambrian Phe Formation (Haimanta Group), a siliciclastic sandstone/shale succession in the Tethyan Zone of the Higher Himalaya tectonic unit. The grooves are among the largest linear erosion structures related to submarine mass-movements observed in the geologic record. They are up to 4 m wide, about 0.2 m deep and can be traced for more than 35 m without changing their character. The grooves are straight, subparallel to cross-cutting striations with shallow semi-circular cross-sections and well-defined superimposed minor ridges and grooves. Groove casts exist on the soles of several sandstone beds within a 73 m thick logged section, commonly associated with flute casts. Their characteristics were compared with several other types of ancient and modern submarine linear erosion structures. A sand-rich, non-channelized basin floor depositional environment is inferred from the lithofacies, the combination of sedimentary structures, the lack of coarse-grained pebbly facies, the lateral continuity of beds, and the lack of channel structures. The grooves probably formed by laminar debris flows/concentrated density flows dragging blocks of already lithified sediment across the basin floor. When the bedding is structurally rotated back to horizontal, the groove casts show consistent North–South oriented palaeocurrent trends, with South-directed palaeocurrent directions indicated by flute casts. These palaeocurrent orientations contrast with previous palaeogeographic reconstructions of this area, which propose sediment delivery from the South. We therefore suggest a new "double provenance" model for the spatial relationship of late Proterozoic to Early Cambrian strata of the Himalaya, in which Lesser and Tethyan Himalayan age-equivalent sediment was deposited in a connected basin, where the former received detritus from the South, and the latter from a hitherto unknown source in the North. One possible candidate for this northern source is the South China Block and an associated Neoproterozoic volcanic arc.

1. Introduction

Direct observation of modern sedimentary processes associated with deep water gravity flows is hindered by the great water depths and by the flows' sporadic and unpredictable occurrences. Hence deep water depositional environments have mainly been investigated by exploring their ancient deposits in outcrop. Consequently, sedimentary structures from deep water gravity flows (Kuenen, 1957; Dżułyński and Walton, 1965; Allen, 1982), as well as their three-dimensional geometry and vertical stacking patterns (Bouma, 1962; Walker, 1978; Pickering et al., 1986; Mutti, 1992; Reading and Richards, 1994; Stow et al., 1996), have long been well known from outcrop studies. Additionally, the combination of field observations and laboratory experiments (e.g., Dżułyński and Walton, 1965; Mohrig and Marr, 2003; Felix and Peakall, 2006) provide important insights into the physical parameters of deep water gravity flows, resulting in their classification based on fluid rheology, sediment/water ratio, clay content and clast-support mechanisms (e.g., Lowe, 1979; Shanmugam, 2000; Gani, 2004; Amy et al., 2006).

There is a multitude of sole marks observed in the ancient, but only a few achieve the outstanding size of the Indian groove casts described herein. Those most comparable in size and shape are interpreted as having formed from (a) submarine slides/slumps (Kuenen and Sanders, 1956, plate 2); (b) turbidites (Kuenen and Sanders, 1956, plate 3B; Kuenen, 1957, figs. 11, 12; McBride, 1962, figs. 12, 13; Enos, 1969, figs. 6, 8, 11; Hiscott and Middleton 1979, fig. 7; Ricci Lucchi, 1995, plates 98, 99) and (c) iceberg keel marks (Pettijohn and Potter,

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[*] Corresponding author.
E-mail address: Erich.Draganits@tuwien.ac.at (E. Draganits).

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1964, plate 67; Savage, 1972, figs. 2, 4; Aitchison et al., 1988, fig. 5; Rocha-Campos et al., 1994, fig. 17.5; Eyles et al., 1997, fig. 6; Mokhtari Fard and van Loon, 2004).

In recent years the availability and quality of multibeam bathymetric, synthetic aperture side scan sonar, and high resolution 3D seismic data from the ocean floor have dramatically increased, giving important new insights into sedimentary processes taking place on continental slopes and basinal environments. One of the tantalizing results of these geophysical surveys was the unexpected and relatively common existence of linear erosion features on modern ocean floors, for which the term "striations" is used here in a general sense without any genetic implication. Striations have been observed in diverse deep water settings, showing high variability in size and character. Thus different processes behind their formation seem likely.

Interpretations of sub-recent to modern striations observed on the ocean floor by geophysical surveys indicate: (a) submarine slides/slumps and debris flows (Piper et al., 1999, figs. 12, 13; Lastras et al., 2002, fig. 1; Posamentier and Kolla, 2003, figs. 19, 21, 22; Haflidason et al., 2004, fig. 5b; Gee et al., 2005, fig. 3; Gee et al., 2006, figs. 4–6; Gee et al., 2007, figs. 5–7); (b) outrunner blocks related to debris flows (Prior et al., 1984, fig. 7; Nissen et al., 1999, figs. 4–8; Kuijpers et al., 2001, fig. 4; Ilstad et al., 2004, fig. 1); (c) "current furrows" eroded by bottom currents (Hollister et al., 1974; Flood, 1981; 1983; Bryant et al., 2001; Parsons et al., 2004); (d) mega-scale lineations formed by glacial ice streams (e.g., Canals et al., 2000, fig. 2; Anderson et al., 2001, figs. 4, 5, 7; Canals et al., 2003, fig. 2; Dowdeswell et al., 2004, fig. 7; Ottesen et al., 2005, figs. 2–5), and (e) iceberg keel marks (e.g., Weber, 1958, figs. 2–9; Woodworth-Lynas and Dowdeswell, 1994, fig. 18.1; Vogt et al., 1994; Parsons et al., 2004).

Generally, many more striation types are described from modern examples than from fossil ones. Striations made by submarine debris flows, outrunner blocks, and deep water currents are abundantly described from geophysical surveys, but hardly ever noted in the fossil record. In contrast, striations formed by turbidity currents are hardly ever reported from modern geophysical surveys, but are relatively common in the fossil record. Ice keel marks are very common at modern high latitudes, but only a few examples have been recognized in the fossil record (Woodworth-Lynas and Dowdeswell, 1994). These differences probably reflect variations concerning the frequency of different processes that form striations, different preservation potentials, and other factors such as accessibility and resolution of geophysical methods. Some striations like the examples in this study may be impressive in outcrop, but analogous modern examples may be below the resolution of geophysical surveys. Last but not least, the reason that striations are commonly reported in association with turbidites, as compared to debrites, may be related to the loose definition of the term turbidity current in the older literature (Mulder and Alexander, 2001; Shanmugam, 2002; Gani, 2004; Amy et al., 2005a). Beds that have been termed turbidites in the literature include a large spectrum of deposits formed by diverse flow mechanisms (Shanmugam, 2000; Lowe and Guy, 2000; Mulder and Alexander, 2001).

Outcrop studies of ancient submarine gravity flow deposits, on the one hand, provide detailed views of small-scale features compared to geophysical surveys, but the interpretation of their depositional environments and processes is hampered by limited exposure. Modern geophysical surveys, on the other hand, have the advantage that they cover large areas of the sea floor where the environment is known, but they miss details below the resolution of specific methods, and there is little information about the preservation potential and vertical recurrence of these features.

The purpose of this paper is two-fold. Firstly, we describe in detail exceptional, giant groove casts found in an upper Proterozoic/Lower Cambrian sandstone and mudstone succession in the northwest Himalaya, and deduce their formation mechanisms and depositional environment. The grooved surfaces, among the largest linear erosion structures related to submarine gravity flows ever observed in outcrop, provide valuable information about the properties of the ancient sea floor and the dynamics of the overriding submarine gravity flow (Gee et al., 2005).

Secondly, we document south-directed palaeocurrent directions indicated by flute casts associated with the grooves, which fuel the debate over the spatial relationship and provenance of the late Proterozoic/Lower Cambrian sedimentary rocks of the Lesser and Higher Himalayan tectonic units. These data demand a new palaeogeographic reconstruction of the northern Indian continental margin.

2. Geological setting

2.1. Tectonic context

After Gondwana break-up, closure of the Neo-Tethyan Ocean between India and Asia started some 130 Ma ago (Molnar and Tapponier, 1975), ending with India–Asia collision around 55 Ma ago (Guillot et al., 2003). Indian continental crust began to subduct below

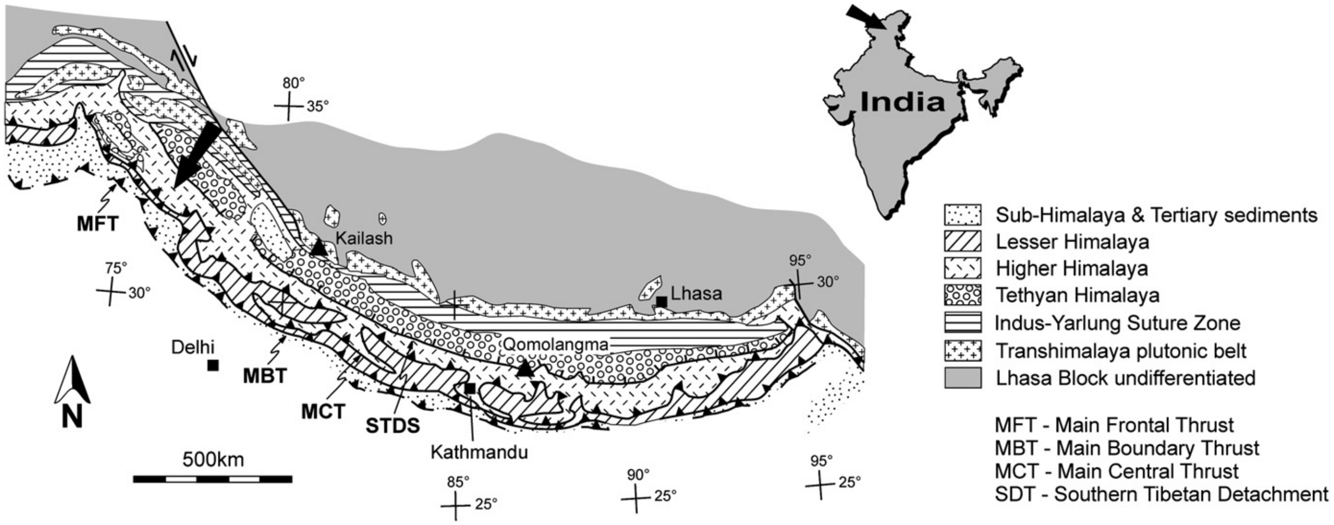

Fig. 1. Generalized tectonic map of the Himalaya (simplified after Hodges, 2000). Arrow indicates the location of the giant groove casts in the Tethyan Zone of the Higher Himalaya tectonic unit.