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A critical test of the concept of submarine equilibrium profile

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ABSTRACT

The existence of a slope equilibrium profile has been widely used to account for erosional and depositional processes on submarine slopes and turbidite systems. Profiles out-of-equilibrium are commonly observed in actively deforming areas where channels seem to be deflected or diverted by seafloor structures. In this study the concept of the submarine equilibrium profile is tested in an area of extensive surface faulting to examine whether channels adopt an equilibrium-type profile through time. The study area is on the slope of the Nile Delta, which is disrupted by a number of surface-rupturing normal faults. Prior to fault linkage, several submarine channels flowed down the slope and either utilised relay ramps or flowed through fault scarps of the fault array. Where a relay ramp had been utilised, post fault linkage, the channels of the area either avulsed or converged into one major channel in response to a change in the deformed slope profile to a more concave shape. The thalweg of the post fault linkage channel and two slope profiles either side of it are measured in the area of the fault array, to understand how the channel evolved in response to the active faulting. When fault displacement is relatively small the combination of channel erosion and aggradation results in a channel thalweg profile near-equilibrium with predictable modifications of channel dimensions (depth and width) even if sediment supply was infrequent and episodic. It is concluded that turbidite channels can conform to the concept of equilibrium and submarine base level if it is the most energy efficient route for submarine gravity flows downslope. The most energy efficient route will be one where flows bypass the slope without eroding or depositing and move in a direct downslope course towards base level.

1. Introduction

When it comes to defining base level and slope equilibrium there appears to be lack of consensus in the scientific community and as a result interpreters have often assigned their own definitions pointing to the interpretative nature of the concept. The terms "base level" and "equilibrium profile" have been lent to submarine sedimentary processes from the terrestrial fluvial realm and the interchangeable use of the same terms for continental- and marine-based studies can be confusing. Base level in the submarine environment is generally defined as the deepest point in the basin that can be reached by gravity flows (Carter, 1988; Pirmez and Flood, 1995) while some researchers insist on referring to sea level as base level (e.g. Catuneanu, 2002) (Fig. 1).

Pirmez et al. (2000) defined the equilibrium profile as a depth profile created by the erosional and aggradational action of turbidity currents over a period of thousands of years such that the prevailing sediment discharge is carried through the channel with minimum aggradation or degradation (Fig. 1). When trying to determine what type of slope is in a state of 'slope equilibrium', researchers are faced with the added challenge that the ocean system is not a steady-state system and therefore the equilibrium profile itself will also be transient. An equilibrium profile will therefore depend on indirect factors such as ocean current regime, slope stability and strength of near-seafloor sediments amongst other factors that more directly impact the ability of a channel to erode or aggrade to a specific datum, such as power and frequency of flows, geometry of flows and availability of sediment being transported by those flows (Kneller, 2003).

In this paper we consider the equilibrium profile as a notional surface which the channel thalweg evolves towards under a given set of boundary conditions, namely the starting configuration of the thalweg. Where sedimentary transport processes are the dominant shaping mechanism, the equilibrium profile tends to assume a concave-up thalweg profile (Ferry et al., 2005). However, for slopes that are being actively deformed by faulting or folding it is not clear whether the same notional surface governs the

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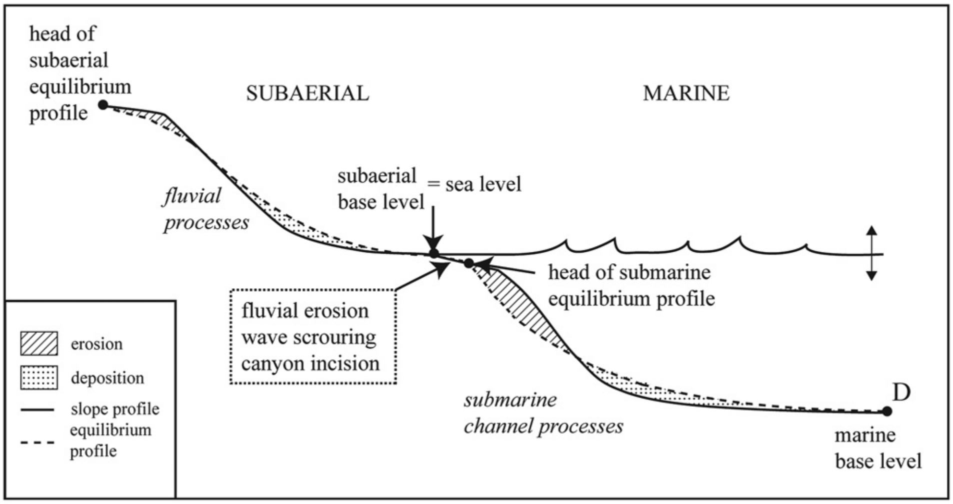

Figure 1. Schematic illustration of subaerial and submarine equilibrium profiles in relation to slope profile and anticipated erosional and depositional processes (modified from Catuneanu (2002), Dietz (1963) and Kneller (2003)).

evolutionary behaviour. Where the rates of tectonic deformation are comparable to the sediment flux, the thalweg profile is likely to smooth irregularities but reflect in part the motion of active structures (Pirmez et al., 2000). But what behaviour could be expected if flow frequency down the channel is low? It could be postulated that whatever the magnitude of the deformation of the slope, the natural tendency of a channel will be to adjust its slope profile until it reaches the equilibrium profile (Ferry et al., 2005). Even during continuous structural growth the profile could well be maintained in a state of disequilibrium but the gravity flows will attempt to bring it to a state of equilibrium through slope adjustments, but this possibility has not been documented in detail, so the specific behaviour is unknown. This study examines this situation, where structural growth is ongoing (normal faults) but sediment supply is intermittent.

2. Submarine channels and seafloor tectonic deformation

Where channels interact with seafloor structures, such as fault escarpments and folds, they are most commonly deflected by them (Catterall et al., 2010; Clark and Cartwright, 2009; Cronin et al., 2005; Cross et al., 2009; Mayall et al., 2010). This observation suggests that pre-existing seafloor topography and/or tectonic movement create slope profiles that are out-of-equilibrium and that the rate of incision is slower than the rate of uplift. For example, on the eastern part of the Nile Delta slope, channels have been shown to respond to topography in four dominant ways; confinement, diversion, deflection and blocking, with no examples of channels cross cutting structures (Clark and Cartwright, 2009).

However, it has often been argued that the longitudinal slope profiles of submarine channels tend towards equilibrium and will erode and/or deposit in their effort to adjust to the equilibrium profile (Ferry et al., 2005; Heiniö and Davies, 2007; Pirmez et al., 2000; Prather et al., 1998). A classic example of this process of adjustment to a notional equilibrium can be seen in the salt-controlled minibasins of the Gulf of Mexico. Here, it has been shown that the seismic facies distribution and stratigraphic relationships follow a fill-and-spill model that is determined by the slope profile and the degree to which any depositional surface approximates to that surface of equilibrium (Prather et al., 1998). Specific examples of conformance to the equilibrium have been explained by local factors where knickpoints are formed. A knickpoint is a disruption in the equilibrium profile and in fluvial systems it is defined as a section of steep gradient between lower gradient sections along a river course (Howard et al., 1994). Heiniö and Davies (2007) identified knickpoints on deeply incised channels on the mid-slope region of the Niger Delta and argued that these result from the deep incision and therefore high degree of confinement of channels, meaning that they cannot migrate laterally in response to the changing morphology and instead the profile adjusts vertically to the equilibrium profile.

Mayall et al. (2010) recently identified the lack of published work on the interaction between *evolving* seafloor structures and synkinematic sedimentary systems. Therefore, it is not clear whether the concept of equilibrium profile is useful when trying to explain channel–structure interactions.

Submarine channels are generally regarded as physiographic connections between canyons that incise the continental slope (whether they are a seaward continuation of a continental river system or not) and the deep ocean floor, where slope gradient becomes less than 1:1000 (Carter, 1988). There have been studies, albeit few in number, regarding the concept of equilibrium profile in submarine channels, which have considered large fans such as the Amazon Fan, the Rhône Fan, the Niger Delta Fan, the Congo Fan (Ferry et al., 2005; Pirmez et al., 2000) as well as the Nile Deep-Sea Fan (Catterall et al., 2010). These settings are dominated by the supply of large amounts of sediment from large subaerial deltas that extend into the deep-water environment. Their submarine equivalents start at the shelf edge and extend for 100's of kilometres downslope. So apart from whether channels adhere to the "law" of adjustment to the equilibrium profile in general the question arises whether that process is also applicable to smaller scale channels with limited and episodic sediment input, not connected to a sediment source on the continental shelf.

The aim of this study is to test the concept of the equilibrium profile on a relatively small submarine channel in the area of the Western Nile Delta that is tectonically modified by a series of syndepositional normal faults distributed along the length of the channel. The channel is part of a network of similar sized channels in this area of the slope, and it does not receive a constant supply of sediments due to its lack of direct connection to the major feeder points near the shelf break. The head of the channel is located approximately 60 km seaward of the shelf break, at 600 m water depth and does not appear to be linked with a delta distributary channel upslope (the Nile Delta), nor does it seem to be directly