Marine and Petroleum Geology 67 (2015) 852–879

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Review article

Genesis and character of thin-bedded turbidites associated with submarine channels

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ARTICLE INFO

Article history:
Received 28 January 2015
Received in revised form
11 May 2015
Accepted 8 June 2015
Available online 20 June 2015

Keywords:
Submarine channels
Thin-bedded turbidites
Levees
Terraces
External levees
Internal levees
Depositional terraces
Hydrocarbons
Reservoir
Ichnology

ABSTRACT

Submarine channel-related thin-bedded turbidites are deposited in environments such as external levees, internal levees, depositional terraces and at times of channel abandonment. Thin-bedded turbidites are defined as beds that are less than 10 cm thick, but the described environments can at times contain beds up to 100 cm thick which would be classified as medium- or thick-bedded. This paper addresses examples of these environments from the modern seafloor, outcrop and the subsurface to suggest criteria that assist in the differentiation of levees and terraces from an architectural, sedimentological, ichnological and hydrocarbon reservoir perspective. External levees confine channel belts and are elongate sedimentary deposits that are a product of over-spill of turbidity currents from the channel belt they confine. External levees often have predictable vertical, lateral and downstream changes in thickness and sand content but are commonly modified by collapse of the inner external levee into the channel, by collapse on the outer external levee, by sediment waves, and by interaction of external levees with topographic features such as other channels, other external levees, basin margins or previous slump/slide blocks, which can greatly modify the sand distribution within them.

A combination of internal levees, depositional terraces and slide blocks of external levee sediment make up thin-bedded turbidites within channel belts. We differentiate between wedge-shaped internal levees and topographically flat or subdued depositional terraces, whose differing geometries and sand distribution reflect the fact that the flow processes involved in the formation of these deposits are different. The characteristic wedge shape of an internal levee requires sufficient space within the channel belt for the over-spilling current to spread, decelerate and deposit the majority of its silt and sand grade suspended sediment before reaching the bounding topography of the channel belt. In the case of depositional terraces the space available in the channel belt is insufficient for the current to decelerate and deposit the majority of its sediment before reaching the bounding topography of the channel belt, creating confined sheet-like deposits.

External levees, internal levees and depositional terraces have distinct sedimentological characteristics such as sand bed thickness trends and sedimentary structures that can be used to distinguish them. Together with sedimentological characteristics, in some systems these thin-bedded turbidite deposits contain distinctive trace fossil assemblages, where channel proximal deposits such as proximal external levees, internal levees and depositional terraces can have much higher ichnodiversity than sand-rich channel axes and more mud-dominated outer external levees.

The depositional sites for internal levees and depositional terraces within channel belts can be formed by various processes such as entrenchment, point bar accretion, meander bend cut-off, channel margin failure, or changes in the flow parameters. These processes can result in elevated surfaces within the confines of the channel belt that subsequently become prone to the deposition of over-bank deposits.

The development and preservation of levees and terraces is closely related to the evolution of the channel belt as a whole, which is controlled both by allogenic mechanisms (such as sea-level

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http://dx.doi.org/10.1016/j.marpetgeo.2015.06.007

fluctuations, changes in turbidity current size and sediment calibre, and changes in the equilibrium profile of the channel), and by autogenic mechanisms (such as channel avulsion and resulting knick-point migration). Where preserved in the rock record thin-bedded turbidites have been uncommon primary targets for hydrocarbon field development, since most efforts have focused on the channel-fills which have the highest proportion of sand. However, thin-bedded turbidites can contain large amounts of sand, of which individual beds can be very laterally continuous, and hence can make significant secondary reservoir targets.

1. Introduction

The deep marine depositional environment can be defined as the region of sea floor that is dominated by gravity-driven processes of sediment transport, including sediment gravity flows and gravity settling. It is below storm wave base, though is commonly affected by internal waves and tides, and by geostrophic thermohaline currents (e.g. Rebesco et al., 2014). On continental margins with a well-developed shelf the deep marine environment starts at the shelf break (the bathymetric inflection between the shelf and slope) and includes the continental slope, continental rise, basin floor and abyssal plain (e.g. Pickering et al., 1989). It is the most extensive depositional environment on earth, and certainly one of the most diverse, but due to water depths ranging up to several thousand metres it is extremely difficult to study. Some of the most striking features of the continental slope are submarine canyons and channels which act as conduits for the transport of sediment from the shelf to the basin floor (e.g. Mutti and Normark, 1991). Canyons and channels were first noticed when echo sounders were introduced for deep-water surveys in the 1920s (Daly, 1936), which led to decades of extensive deep-water research (e.g. Walker, 1978) but aroused particular interest from the hydrocarbon industry when large volumes of sand were encountered down-dip of muddy slopes, e.g. in Angola and the northern Gulf of Mexico (Mutti, 1977; Weimer and Slatt, 2004). The dominant mechanisms of downslope sediment transport through canyons and channels are sediment gravity flows, which are driven by the action of gravity on their excess density with respect to the ambient seawater (Middleton and Hampton, 1973). Among the most common types of sediment gravity flows are *turbidity currents*, where the excess density is due to sediment held in suspension largely by turbulence generated by the motion of the current (Middleton and Hampton, 1976).

The structure of turbidity currents, especially their grain-size and density stratification (e.g. Meiburg and Kneller, 2010), is such that – in slope environments at least – coarse-grained and/or thicker bedded turbidites are largely confined within channels, whereas the surrounding over-bank regions commonly receive sedimentation from the upper, more dilute and finer-grained portion of the current, producing thin-bedded turbidites. Deep-water channels are thus commonly associated with thin-bedded turbidites, often as inter-bedded sands, silts and muds, deposited in environments such as levees and terraces adjacent to the channels. However, on the modern seafloor thin-bedded turbidites are also commonly encountered within channels where they would have been deposited by relatively small, presumably channelized turbidity currents or by over-spill from adjacent channels. The potential for preservation of these intra-channel thin-bedded deposits in the stratigraphic record, however, is low since large turbidity currents flowing down the channels (whose coarser-grained and thicker or amalgamated deposits dominate the channel fill) will flush out these finer-grained deposits. Thin-bedded turbidites are defined as beds that are less than 10 cm thick, but in environments such as levees and terraces medium to thick beds (up to 100 cm thick) (e.g. Ingram, 1954) also occur. The general characteristics of channel-related thin-bedded turbidites have been defined through many outcrop, seismic and seafloor studies, but such studies also reveal the variety and complexities of these deposits.

This paper reviews previous studies of thin-bedded, fine-grained sediments in submarine channel environments in order to highlight the variety in terms of their morphology, architecture, depositional processes, and lithology. It is also necessary to provide standardised terminology that can be used to describe the architectural elements of submarine channels and over-bank environments. The general structure and stratification of turbidity currents are addressed together with a discussion of over-spilling processes and deposition on levees and terraces. Examples of levees and terraces from the modern seafloor, outcrop and the subsurface are used to suggest criteria that assist in the differentiation of levees and terraces from architectural, sedimentological and ichnological perspectives. Allogenic and autogenic controls on levee and terrace development are provided to help clarify the stratigraphic placement of these architectural elements within the systematic evolution of a channel-levee system. Finally, the hydrocarbon reservoir characteristics of thin-bedded turbidites are discussed as they can include significant volumes of reservoir quality sand within laterally extensive sand beds.

1.1. Nomenclature

Gaining consensus on the nomenclature of downslope conduits and sedimentary accumulations formed by deposition within and around them is problematic. We attempt to make a clear differentiation between, on the one hand, downslope conduits as they appear at the sea floor and, on the other hand, the depositional bodies that may result in the stratigraphic record. For the purposes of this review, we use the term *canyon* to refer to a large scale erosional conduit (Shepard, 1981) with limited development of external levees, which is common in upper to mid slope settings; such features at the seafloor have often been referred to as valleys. The term *channel* refers to a negative feature at the sea floor, acting as a downslope conduit, with or without well-developed external levees, whose length in a downslope direction is orders of magnitude greater than its width, and which may be either erosional or aggradational; it is typically of smaller scale than a canyon (within which a channel may be contained). Channels with their associated *levees* are commonly called *channel-levee systems*; channel-levee systems that are not contained within canyons are typical of the middle slope to basin floor.

Since channels may migrate laterally and/or aggrade, the composite bodies of sediment resulting from deposition within a channel often have geometries and aspect ratios that bear little or no relationship to those of the channel as it appeared on the sea floor at any one time (Fig. 1 in Morris and Normark, 2000). Sediment bodies that have the same geometry and aspect ratio as the channel itself are likely to form only during abandonment of the