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Research paper

Global distribution of modern shallow marine shorelines. Implications for exploration and reservoir analogue studies

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A B S T R A C T

Deposits of marginal marine depositional systems make up significant hydrocarbon reservoirs in the rock record. These systems are deposited by a complex interaction between competing depositional processes which can result in heterogeneous and compartmentalized reservoirs. Shallow marine systems are described using a ternary classification describing the relative importance of wave, tide and fluvial processes at the coastline. With the advent of freely available remote sensing data, modern systems are being increasingly used as analogues for the ancient, however to date, there has been no systematic quantification of global modern paralic systems. The aim of the present study has been to map and classify all the world's shorelines by ternary process and to consider the distribution and controls on different shoreline types.

The semi-automated classification of marginal marine clastic shorelines has been achieved by combining data from a series of proxies for the ternary processes. Combined with coastline morphology, an algorithm predicts shoreline classification with an 85% success rate when compared to manual interpretation. Using this algorithm, the global shoreline has been subdivided into 246,777, 5 km segments and the distribution and proportions of these analyzed.

The first order classification subdivides 28% of the world's coastlines as depositional. Within the depositional coastlines 62% are Wave-dominated, 35% Tide-dominated and 3% Fluvial-dominated. Analysis of shoreline type distribution suggests a complex network of inter-related controlling factors. Of these, climate and tectonic setting are reasonably well constrained in the ancient and can be used to predict the probability of a specific shoreline type. In addition to shedding insight into the controls on the distribution of different shoreline types, the results of this study can also be used to identify suitable modern analogues for ancient systems, which in turn can be used to extract data for better reservoir characterization.

1. Introduction

Within sedimentology, paralic and shallow marine depositional systems are traditionally described using a ternary classification based upon the relative importance of fluvial, tidal and wave processes on sculpting the shoreline geomorphology (Galloway, 1975). The different processes will drastically impact the morphology and distribution of sandbodies within a depositional environment and introduce heterogeneity into shallow marine reservoirs (Hampson and Storms, 2003; Ainsworth et al., 2008; Howell et al., 2008; Ainsworth et al., 2011). The advent of freely available, moderate to high quality, remote sensing data has seen a significant increase in the use of modern systems as analogues for the rock record and for hydrocarbon reservoirs in particular. Understanding the distribution of modern shoreline systems and the controls on these distributions at a global scale is therefore highly desirable.

Paralic and shallow marine systems may be classified in a number of different ways. In addition to the ternary plot of Galloway (1975) it is also useful to consider whether the shoreline is in net deposition or net erosion over several distinct timescales. Boyd et al. (1992) subdivided shorelines on whether they were progradational or transgressive noting that there are significant differences in sediment body geometry and distribution between

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the two. Progradational shorelines occur where sediment supply exceeds accommodation and the shoreline moves basinward through time. They are typically deltas or strandplains. Transgressive shorelines, in which accommodation is greater than sediment supply and the shoreline moves landward through time are dominated by barrier islands and estuaries. In addition to the systems described by Boyd et al. (1992), there are also "rocky shorelines" or "high relief transgressive" shorelines (sensu Howell, 2005) which are parts of the coast that are in long term, net erosion over timescales of millions of years. These were not included in the classifications of Galloway (1975) or Boyd et al. (1992) because they do not become a part of the geological record except as unconformity surfaces, their recognition is however important in the modern since they account for a significant proportion of modern coastlines.

Prior to the work of Galloway (1975), Wright and Coleman (1973) classified systems based upon the relative importance of fluvial vs "basinal" processes, this work was superseded by the Galloway (1975) classification. Orton and Reading (1993) extended the ternary plot into a 3rd dimension with grainsize as the additional parameter. Most significantly Ainsworth et al. (2011) further subdivided the ternary diagram and added a systematic method for the description and classification of shorelines which is described below.

Here we present a global classification of shoreline type based upon previously available data on the distribution of wave and tidal processes and, newly generated data on the relative importance of fluvial processes at and away from specific fluvial input points. These parameters have been quantitatively combined to generate a global classification of shoreline type, based upon the first two levels (dominated and influenced) of Ainsworth et al.'s (2011) modification of Galloway's (1975) classification scheme. The results of this global classification can be used to define the importance of parameters such as shelf width, climate, structure, latitude and basinal energy in controlling shoreline type. The resultant maps can also be filtered by parameters such as climate and basin type in order to locate suitable modern analogues for ancient systems.

2. Previous work on global classification of shorelines

The coastal environment is a dynamic zone which lies between the sub-aerial and sub-aqueous realms. From social, economic, climatic, ecological, biochemical and sea-level perspectives; it has been the subject of significant research interest (Costanza et al., 1998; Crossland et al., 2003; Talaue-McManus et al., 2003; Jorgenson and Brown, 2005; Buddemeier et al., 2008; Vafeidis et al., 2008; Bird et al., 2013). The nomenclature used to subdivide and classify shorelines typically reflects the needs of the specific field or study. Previous efforts to produce global shoreline typologies include the LOICZ project for biochemical coastal zonation (Crossland et al., 2003; Buddemeier et al., 2008); vulnerability to sea-level rise (Vafeidis et al., 2008) and littoral marine habitat (Bird et al., 2013) databases. To date there has been very few attempts at global classification of shoreline type in a framework that is appropriate to sedimentology and geomorphological.

The first global classification of shoreline by geomorphology and tectonics was by Inman and Nordstrom (1971). This study classified shorelines as mountainous, narrow-shelf, wide-shelf, deltaic, reef or glaciated coasts, within the newly emergent field of plate tectonics, placing them in collisional, trailing edge and marginal sea settings. Second order classifications subdivide these geomorphological categories into wave erosion, wave deposition, river deposition, wind deposition, glaciated and biogenous at scales of approximately ~100 km Dürr et al. (2011) has expanded and digitized the geomorphological classification of coastlines to categorize regionally, locations of small deltas, large rivers, estuaries, lagoons, tidal systems, arheic settings and fjords. Focusing on the application of global fluvial discharge to estuaries, the study is defined at 0.5° (approximately 50 km) using the boundaries of watershed basins by Vörösmarty et al. (2000a,b) as its shoreline delineation. In addition, the shoreline classification does not aim to characterize any regional scale variability in its analysis of shoreline geomorphology. Hence while shorelines are segmented at scales of 50 km, its dominant classification are typically at scales similar to the delineation by Inman and Nordstrom (1971). For our purpose, these datasets do not provide the level of detail or appropriate nomenclature to efficiently identify suitable modern analogues of the marginal marine.

Regionally, Harris et al. (2002) demonstrated that a distinct statistical variation between wave height, tidal range and fluvial discharge can differentiate recognized classifications of shoreline geomorphology of the Australian coastline. Work by Short (2006) is the result of an impressive 17 year analysis of Australian shorelines (1987–2004) to classify 15 shoreline geomorphologies and their association to four main processes of Wave-dominated, Tide-dominated, Tide-modified and beaches on rocky/coral flats based on tidal range, breaking wave height and manual interpretation of regional maps and aerial photography. Also in Australia, Nanson et al. (2013) made a detailed, manual classification of the marginal marine depositional elements in the Mitchell delta, Gulf of Carpentaria, using the hierarchical and ternary process classification scheme of Ainsworth et al. (2011). Vakarelov and Ainsworth (2011) used the same classification scheme to classify 416 marginal marine systems in Asia by ternary process. To apply a similar manual interpretation at a global scale is impractical. To our knowledge, no previous global classification of shorelines by ternary process currently exists.

The challenge that remains is to apply the ternary process classification (Galloway, 1975; Ainsworth et al., 2011) to the coastlines of the entire world. The goal here is to devise a global ternary plot classification using an automated approach that limits subjective bias and allows for a quantitative study of controlling parameters.

3. Ternary classification of shallow marine systems

The ternary diagram of Galloway (1975) relates the relative influence of fluvial, tide and wave processes on the classification of deltaic environments. Subsequent ternary plot classifications have expanded that concept to describe the range of marginal marine depositional environments (Boyd et al., 1992; Ainsworth et al., 2011). Recent work by Ainsworth et al. (2011) and Vakarelov and Ainsworth (2013) have incorporated a semi-quantitative method to categorize ancient and modern marginal marine systems by the proportion of elements associated with each process. In this schema they also added two additional degrees of granularity describing dominant, influencing and affecting for the main, second order and third order processes on a given shoreline. This schema then states a depositional environment is classified first by the dominant ternary process (W, T or F; e.g., Fluvial-dominated; **F**), then by the secondary process (e.g., Fluvial-dominated, Tide-influenced; **F**t) and finally by the tertiary process (e.g., Fluvial-dominated, Tide-influenced and Wave-affected; **F**t*w*). This schema gives 15 possible classes.

3.1. Predictive ternary process classification

For the purpose of the current worldwide study, we have used a predictive two-tier ternary process classification (dominated and